The Abdus Salam
International Centre
for Theoretical Physics

2356-2

Targeted Training Activity: ENSO-Monsoon in the Current and Future Climate

30 July - 10 August, 2012

Predictability and Prediction of Indian Summer Monsoon Rainfall

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ICTP, Trieste, Italy, 30 July, 2012

Predictability and Prediction of Indian Summer Monsoon Rainfall

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Center for Ocean-Land-Atmosphere Studies (COLA)

Institute of Global Environment and Society (IGES)

30 July 2012

COLA Center for Ocean-Land-Atmosphere Studies

George Mason University

Outline

1. Introduction

Monsoon Climatology

ENSO-Monsoon Relationship

Has ENSO-Monsoon Relationship Broken Down?

Possible Influence of Indian Ocean SST

Influence of Intraseasonal Variations

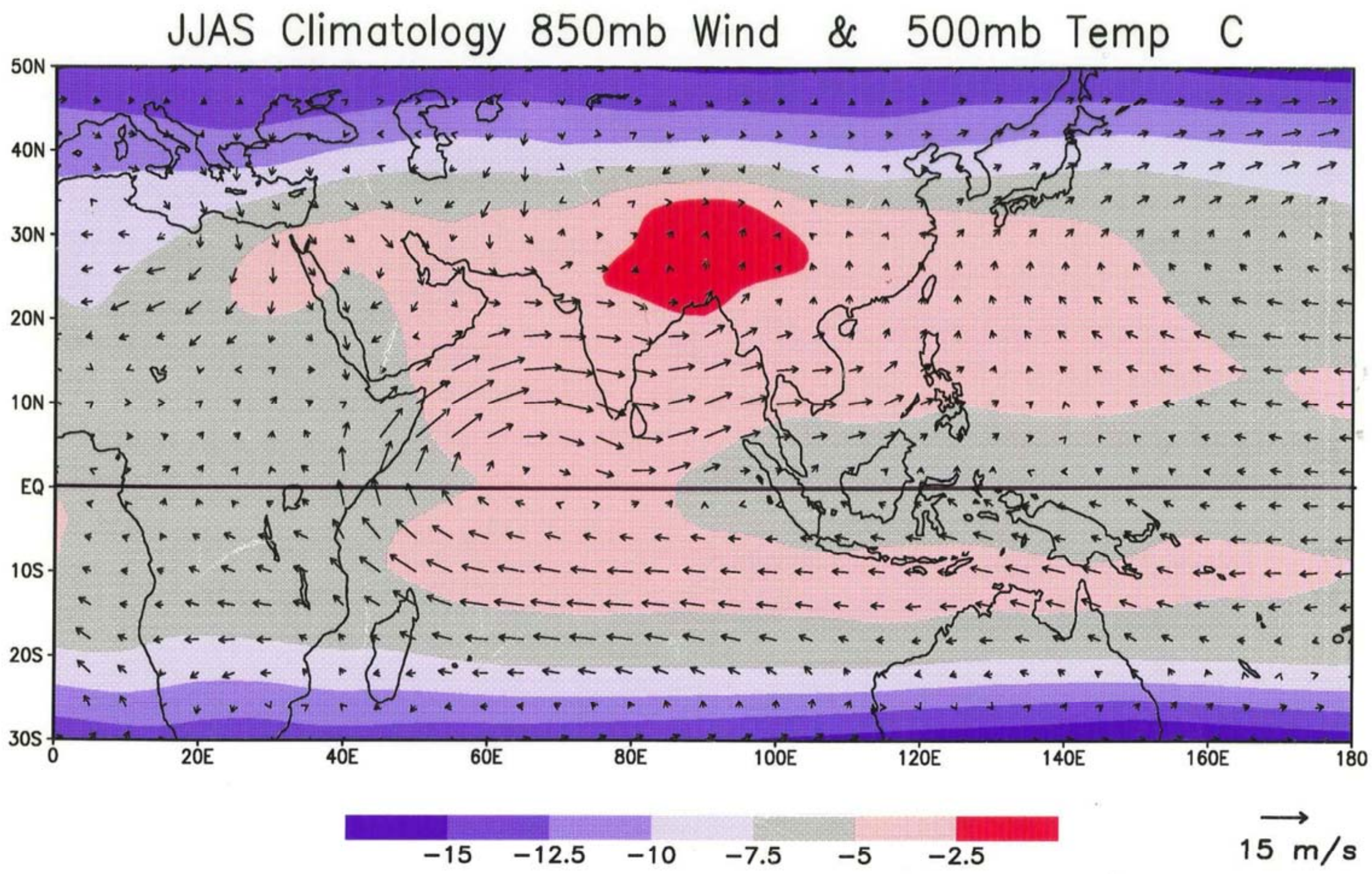
2. Prediction of Indian Summer Monsoon Rainfall (ISMR)

Statistical Prediction

Dynamical Prediction

(Model Fidelity and Predictability)

3. Summary



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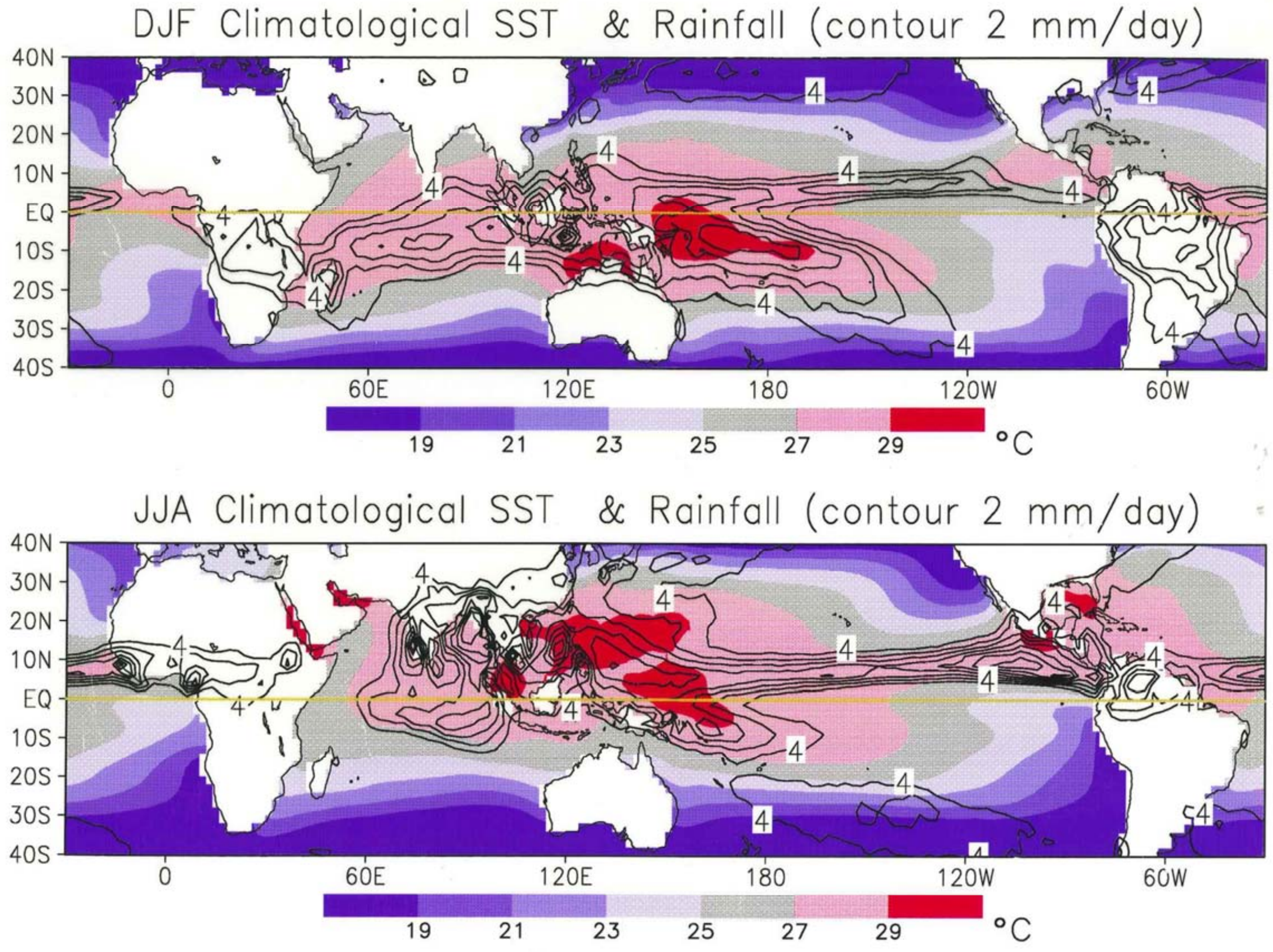

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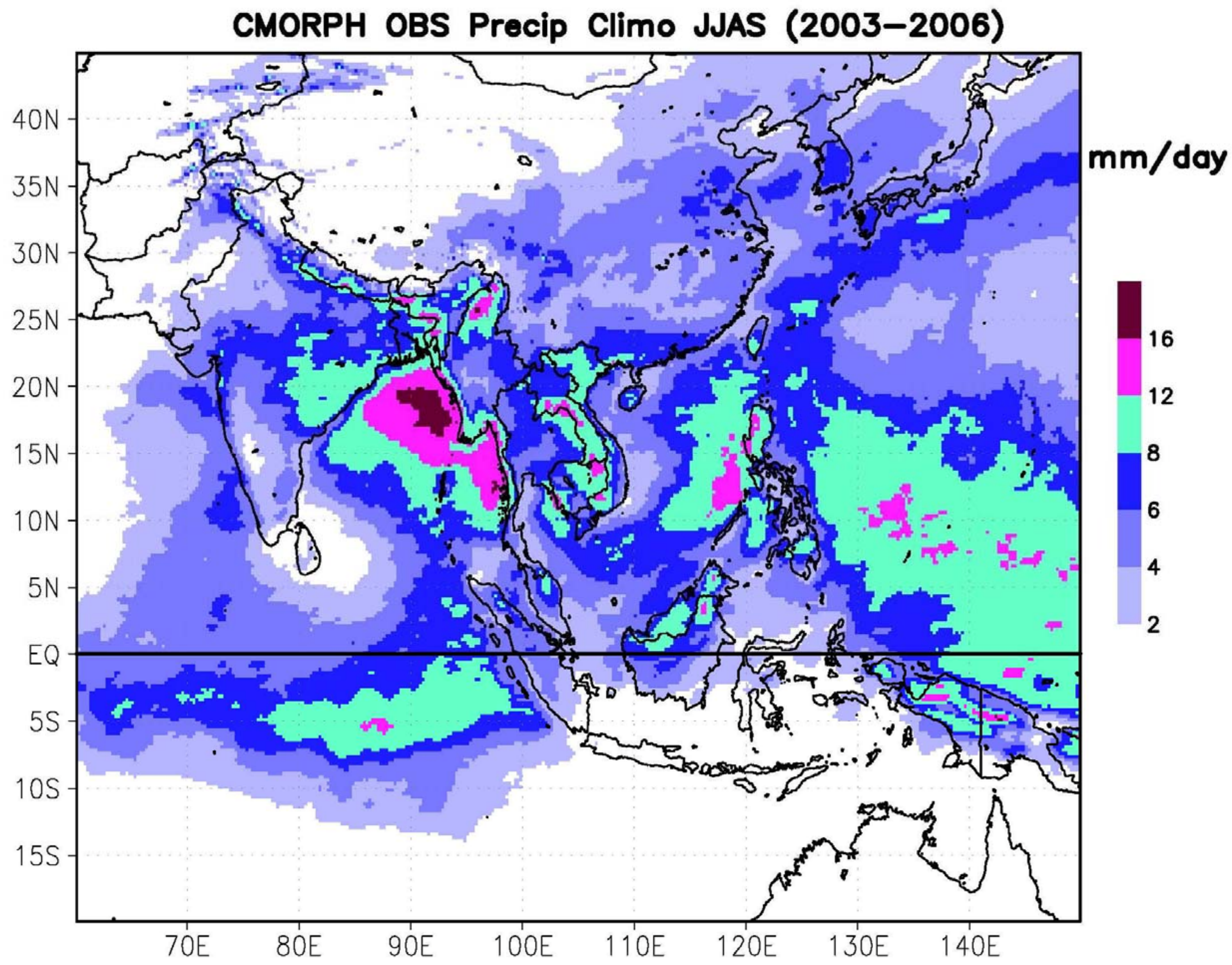

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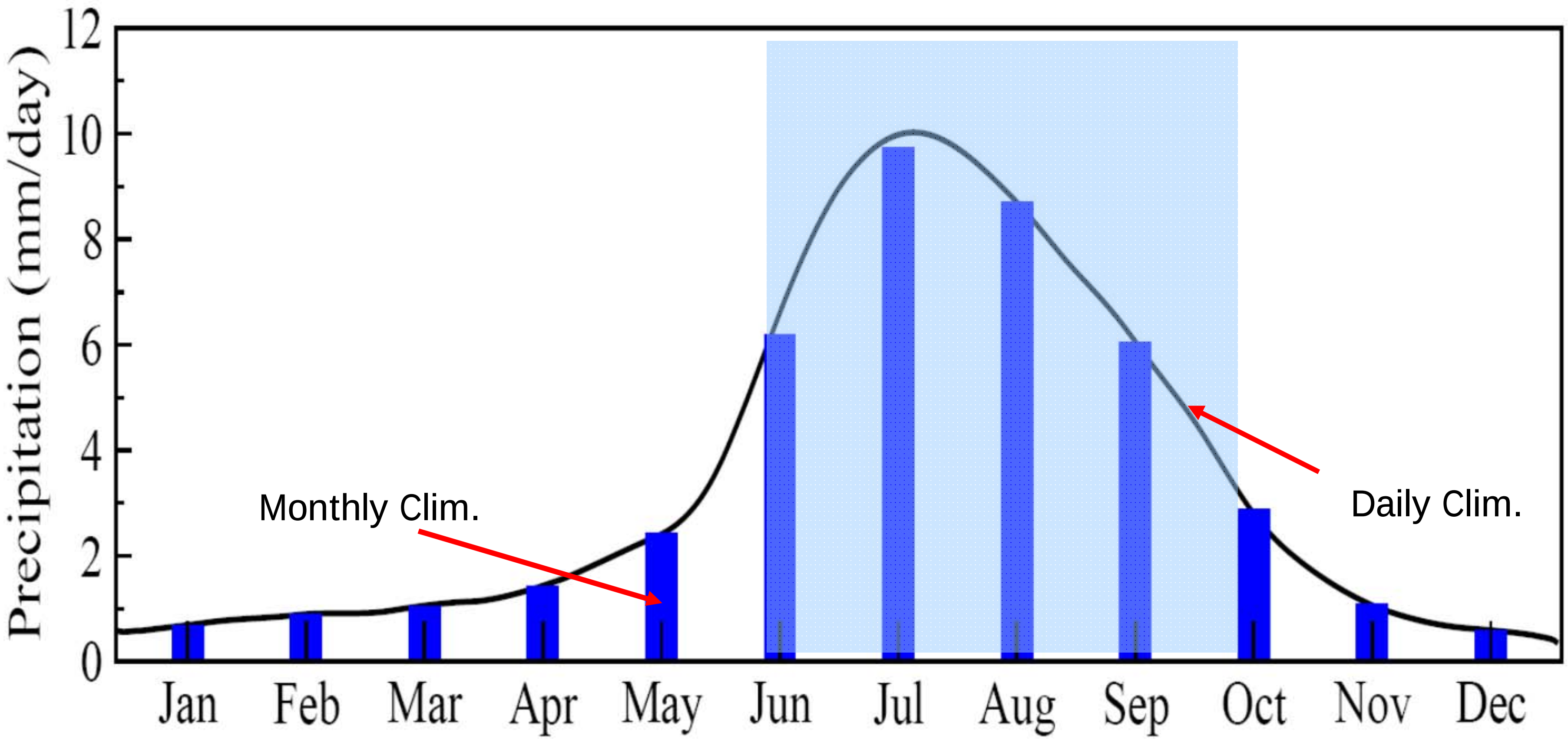
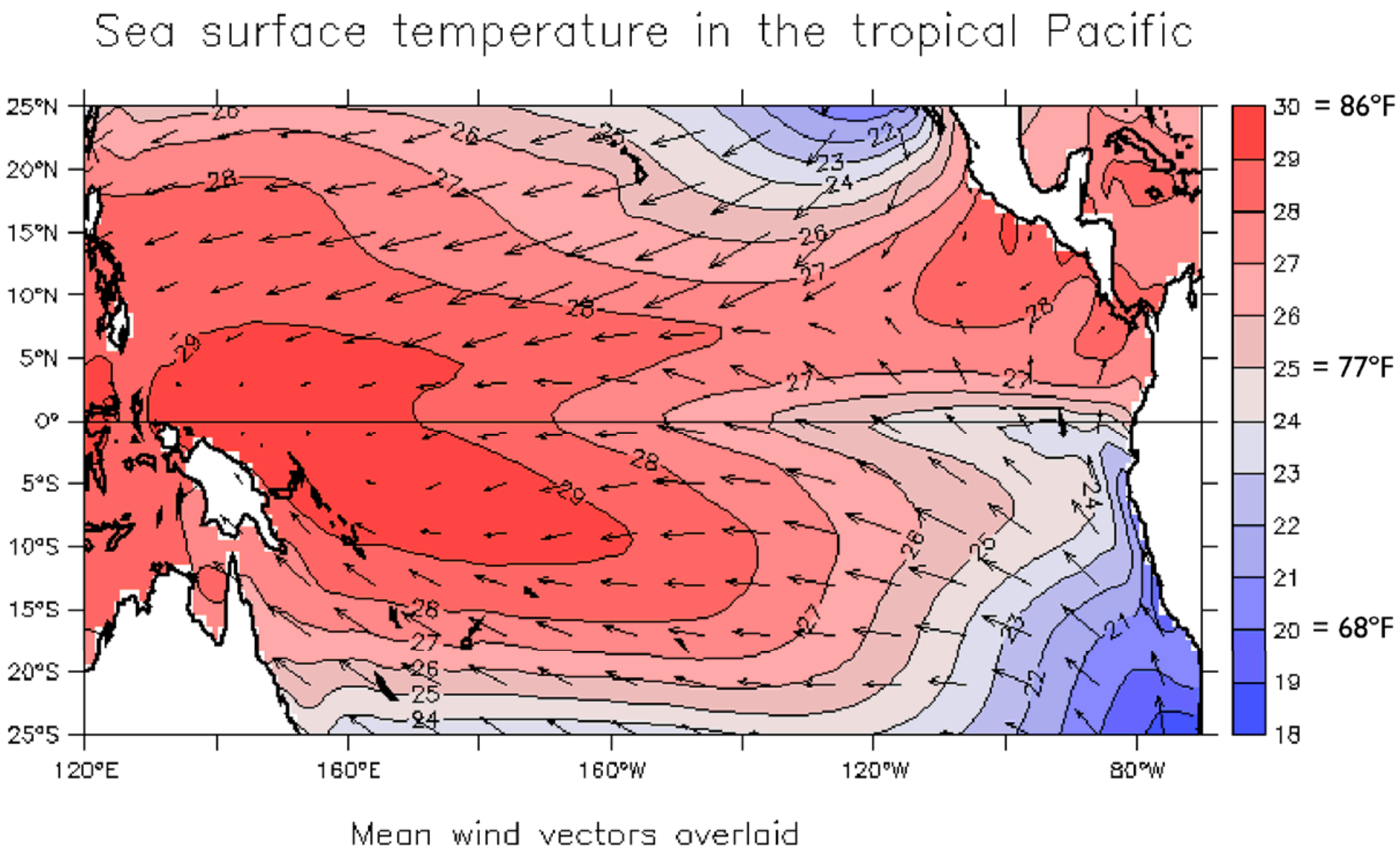
Annual cycle of Rainfall over India



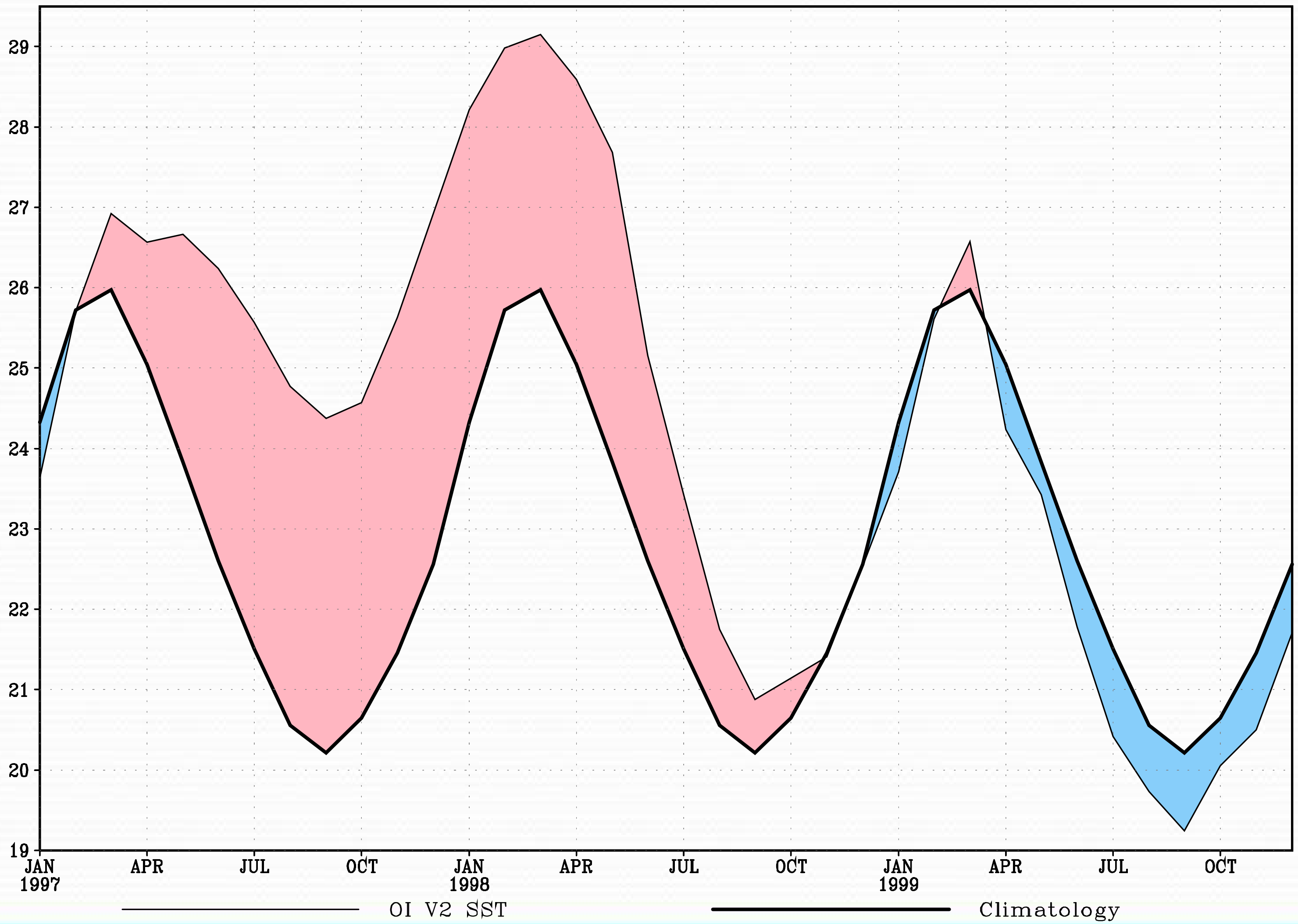
The normal situation:

- The warmest water is not at the equator!
- There is a roughly 5°C (9°F) temperature contrast from west to east.
- Winds blow from the cooler to the warmer water, and converge on the West Pacific Warm Pool.

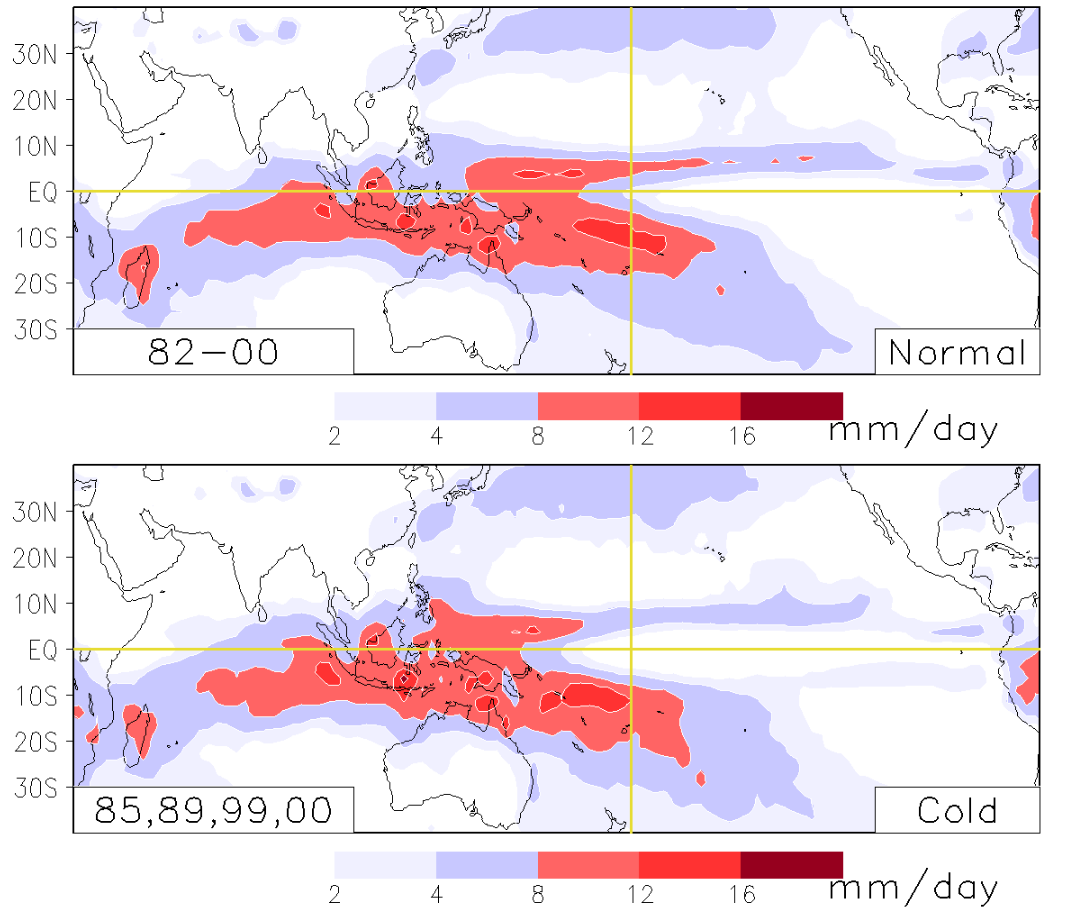


Sea Surface Temperature and Climatology

(NINO12, 90°-80°W, 10°S-Eq.)



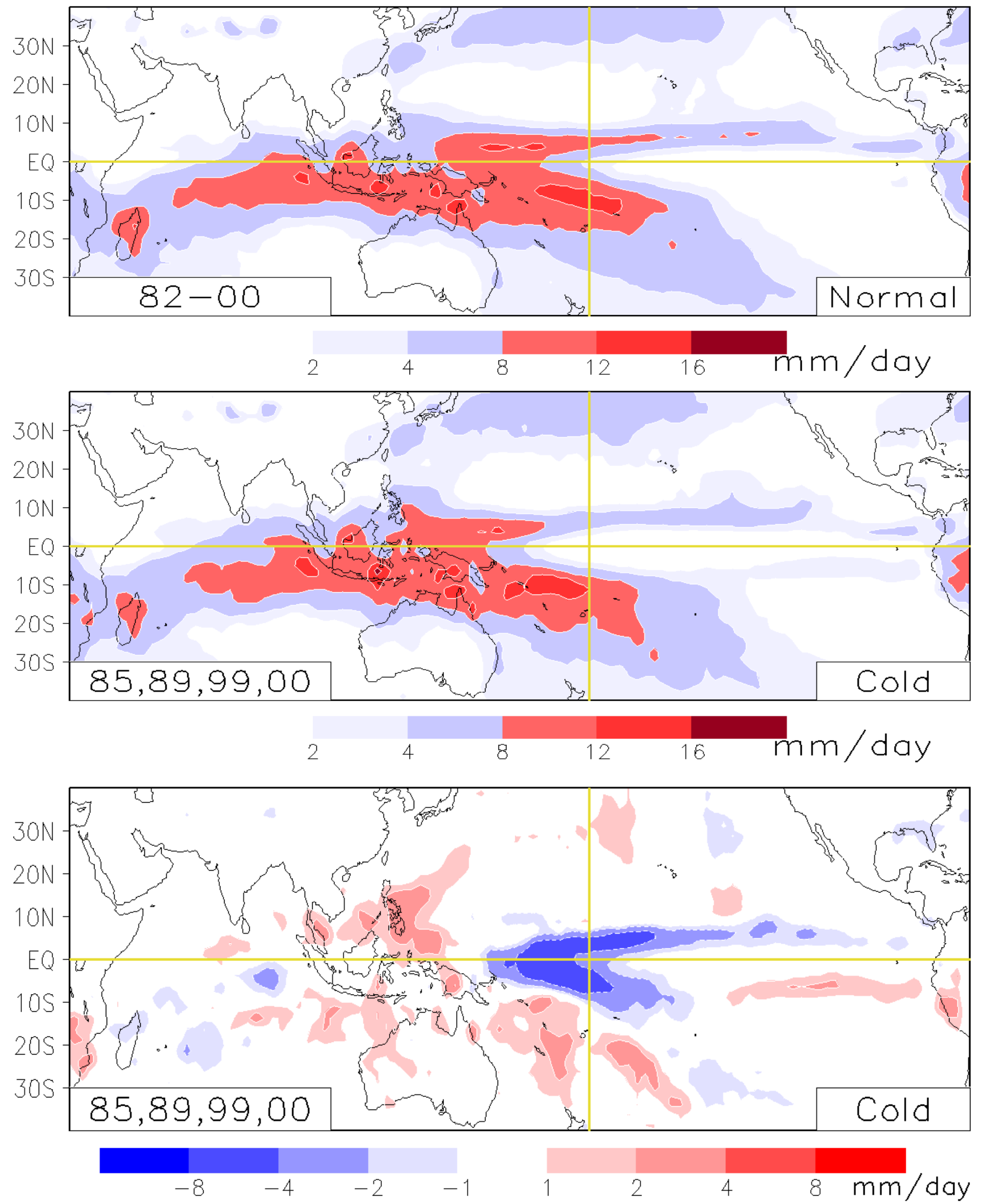
JFM CMAP Precipitation



Normal

La Nina

JFM CMAP Precipitation

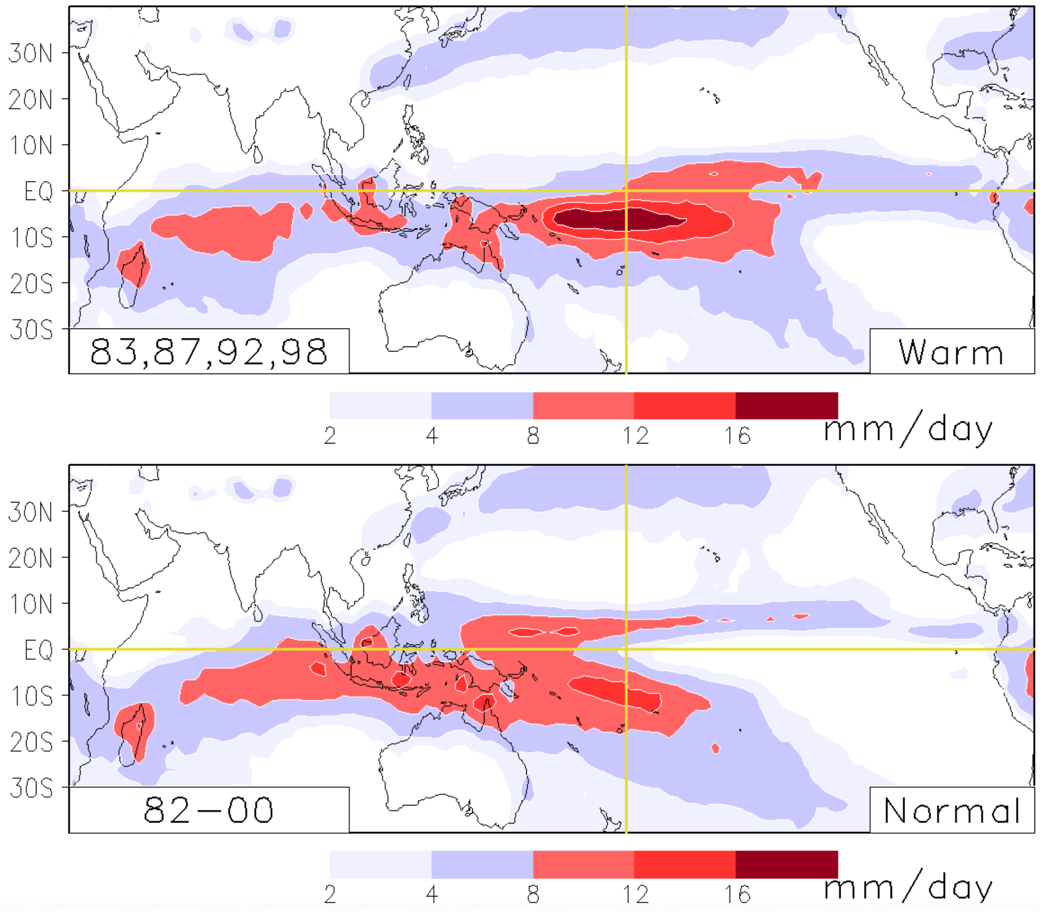


Normal

La Nina

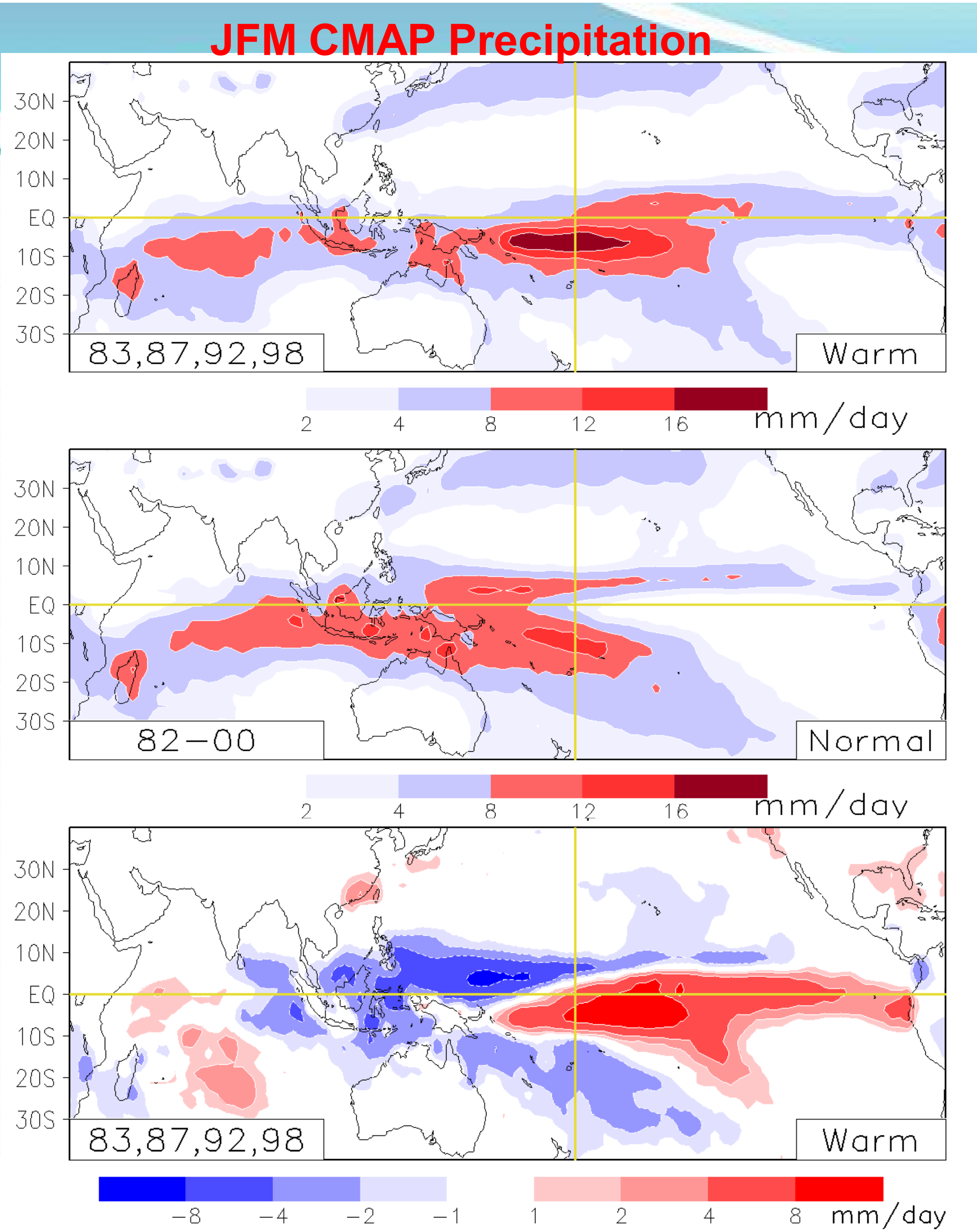
Cold – Normal

JFM CMAP Precipitation



El Nino

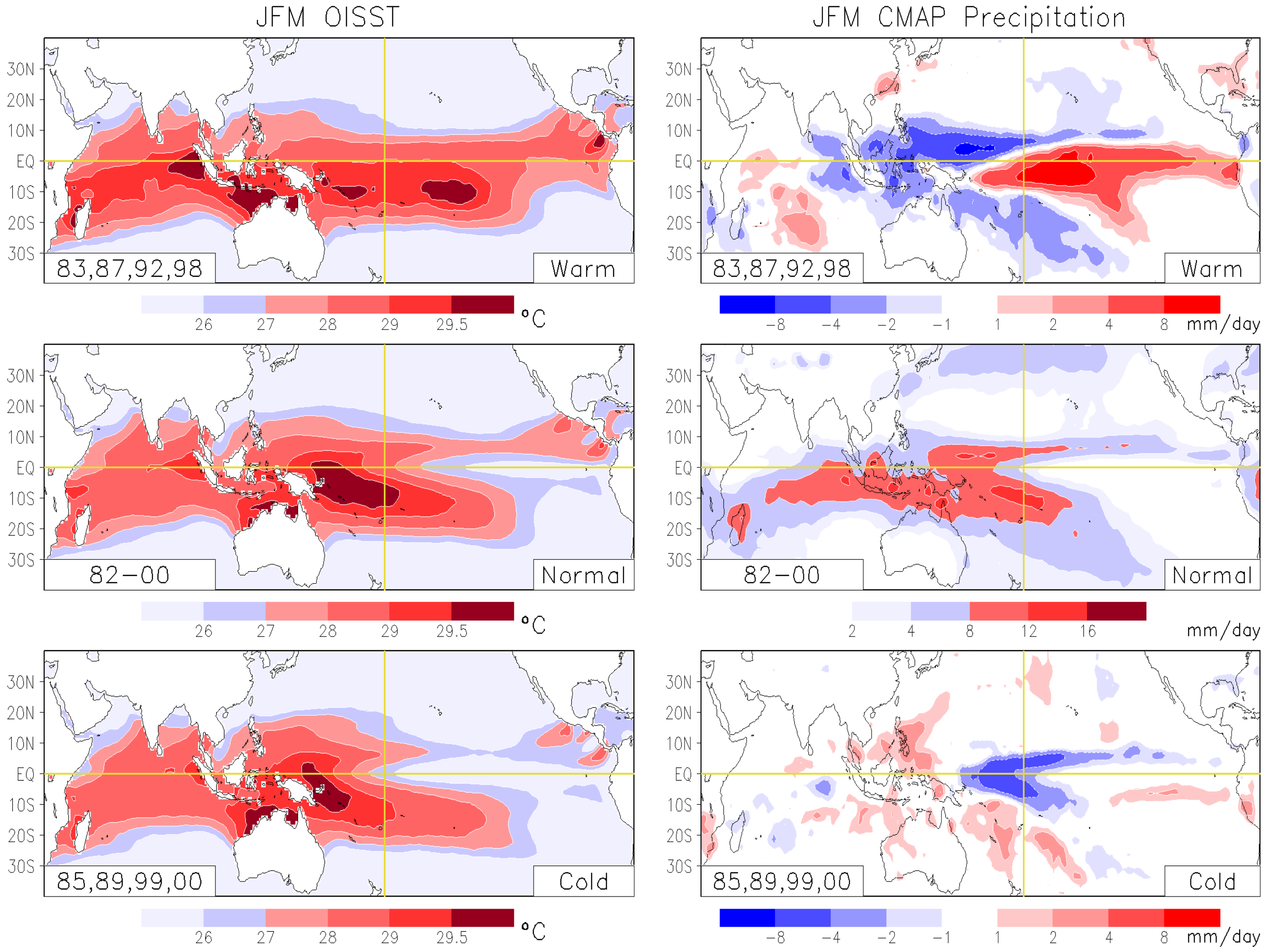
Normal

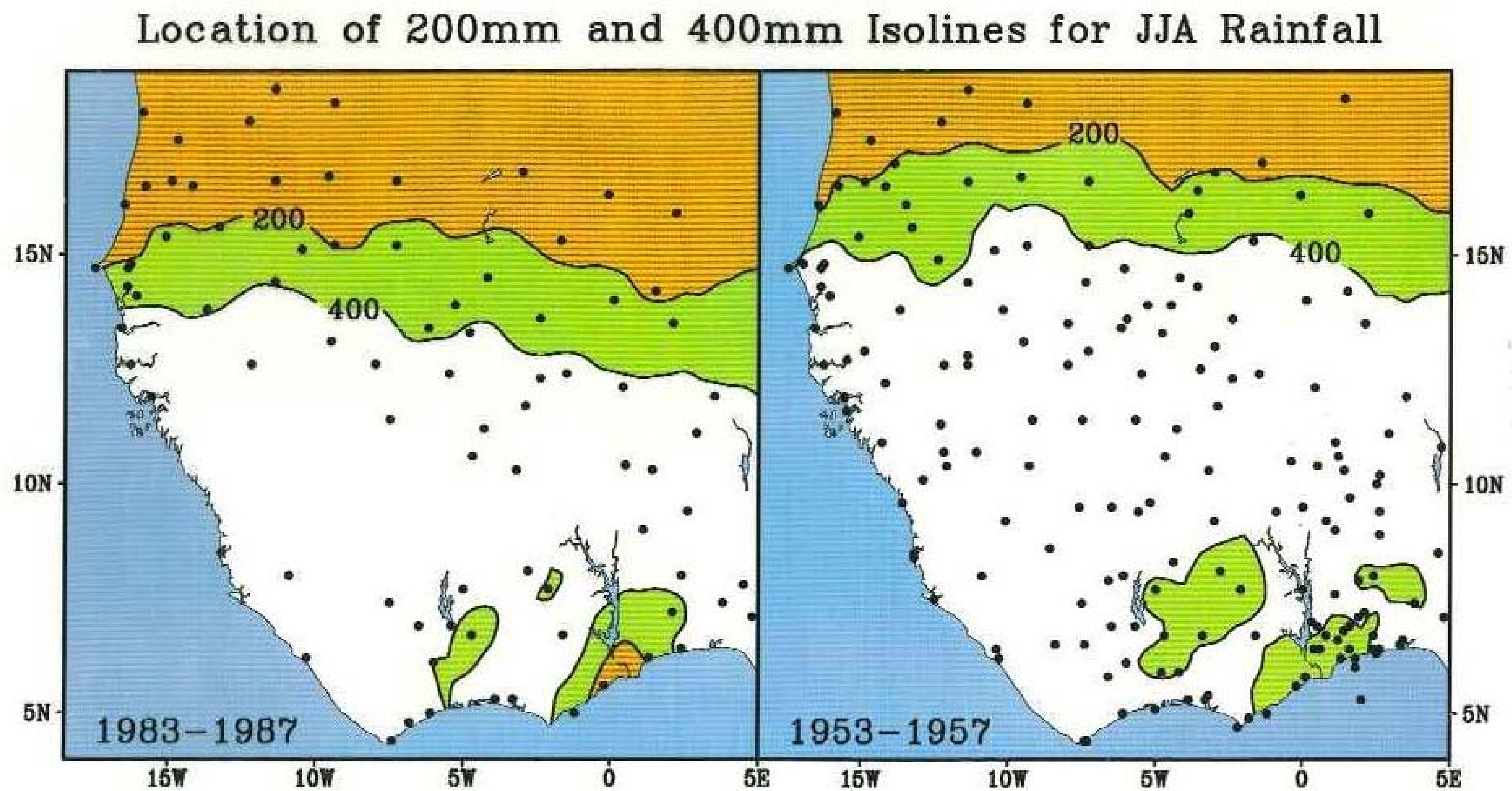


El Nino

Normal

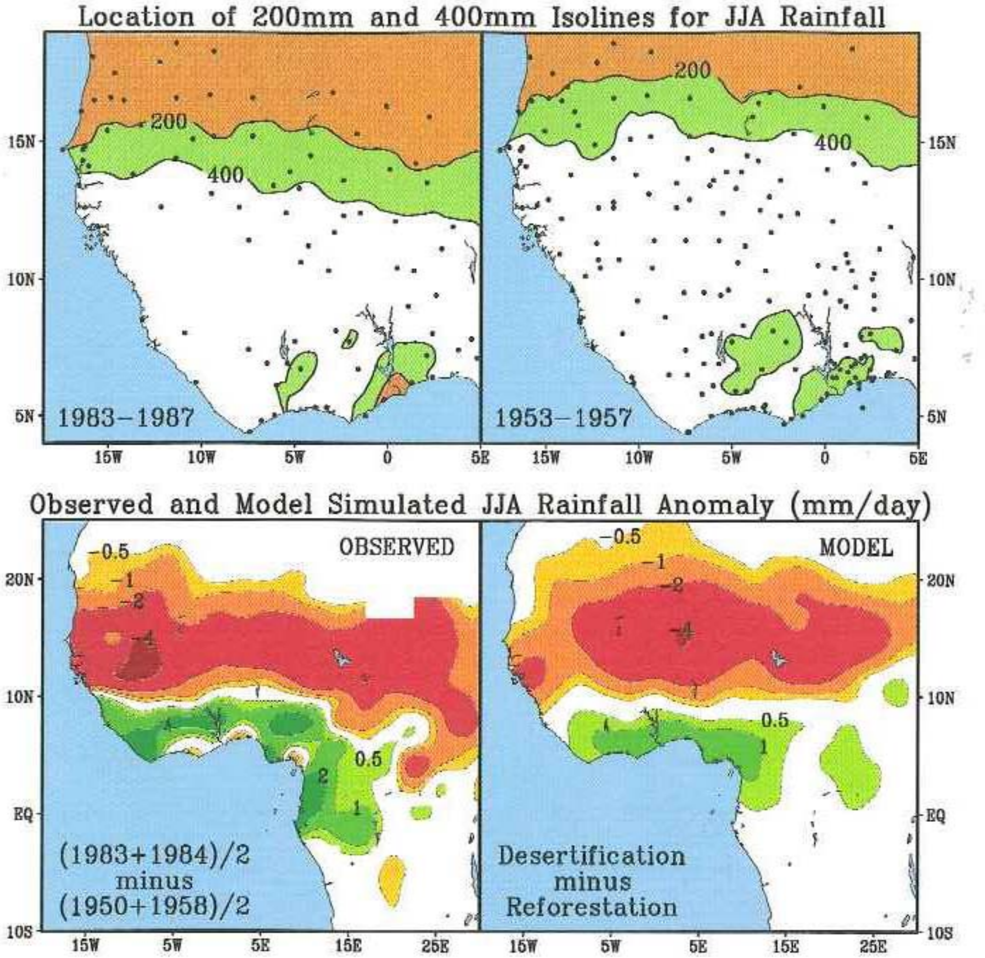
El Nino − Normal


JFM OISST
JFM CMAP Precipitation
30N
20N
10N
EQ
10S
20S
30S
83,87,92,98
Warm
82–00
Normal
85,89,99,00
Cold
26 27 28 29 29.5 °C
−8 −4 −2 −1 1 2 4 8 mm/day
2 4 8 12 16 mm/day



Location of 200mm and 400mm Isolines for JJA Rainfall
200
400
1983-1987
1953-1957
15N
10N
5N
15W
10W
5W
0
5E

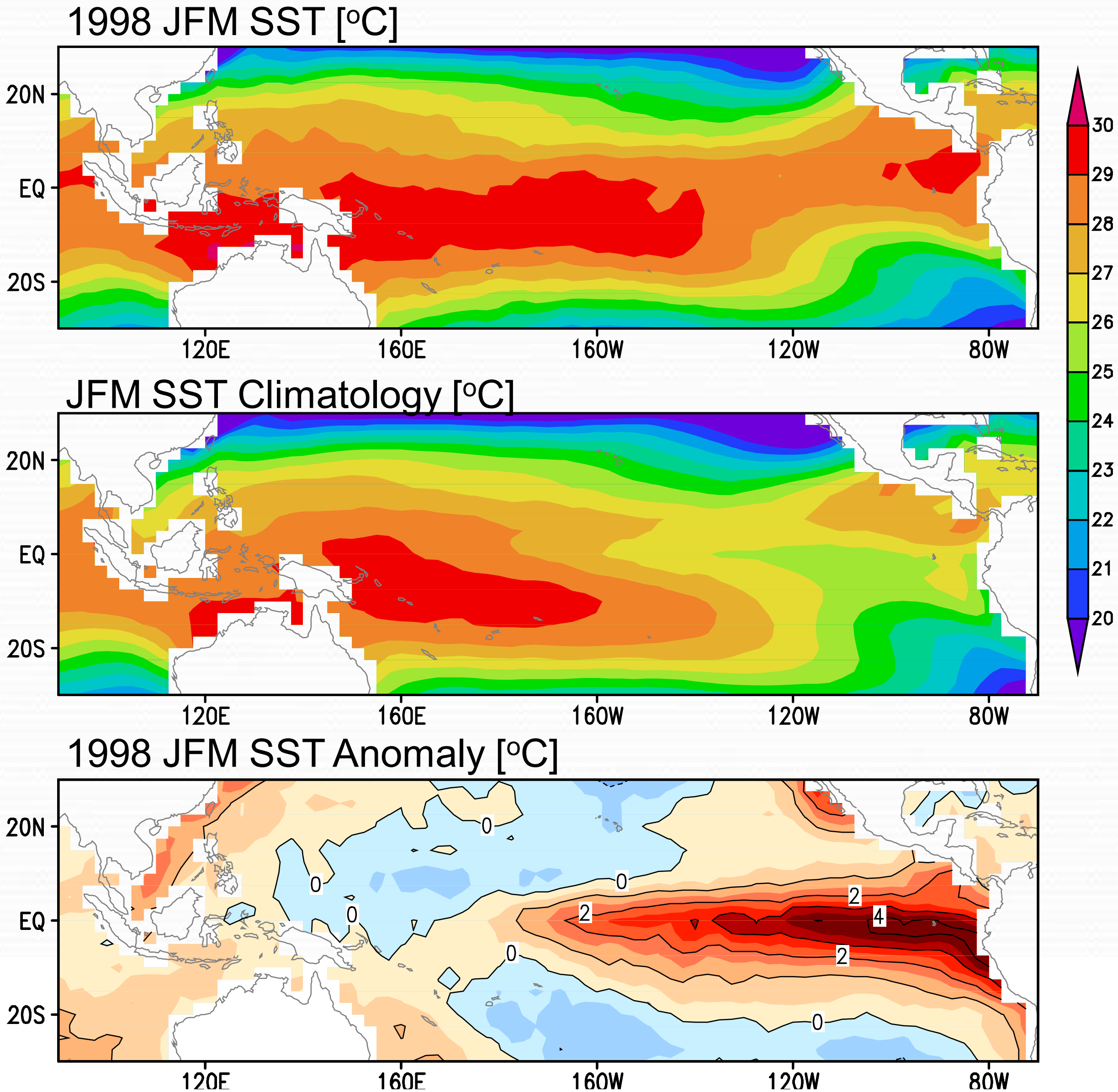
RAINFALL OBSERVATIONS SHOW A SOUTHWARD EXPANSION OF SAHARA



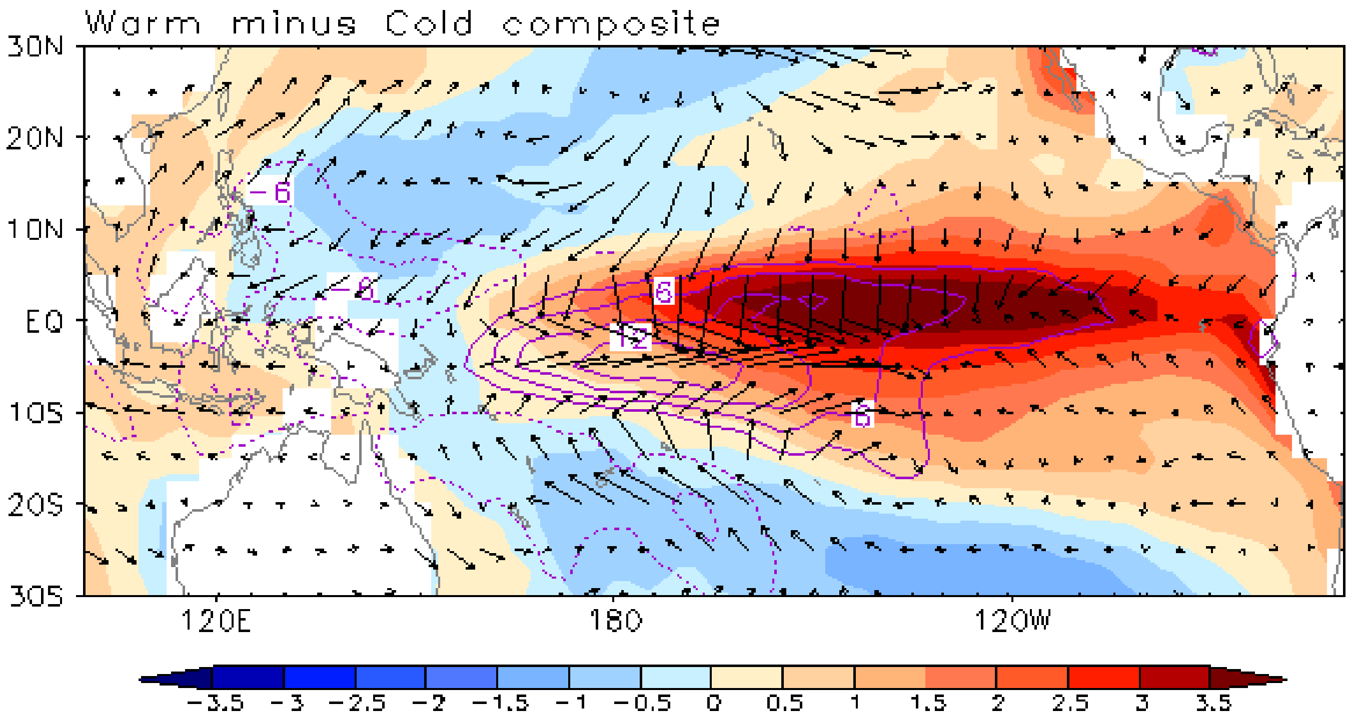
COLA model simulations show that land surface degradation is a major factor in perpetuation of the sub–Sahara drought.

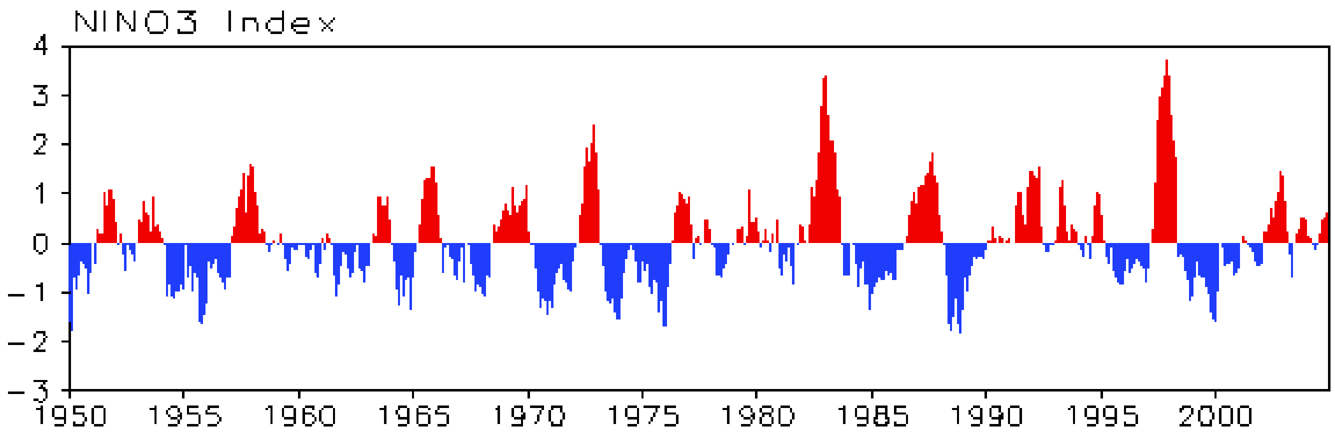
ENS0-Monsoon Relationship

El Nino/Southern Oscillation



El Nino/Southern Oscillation





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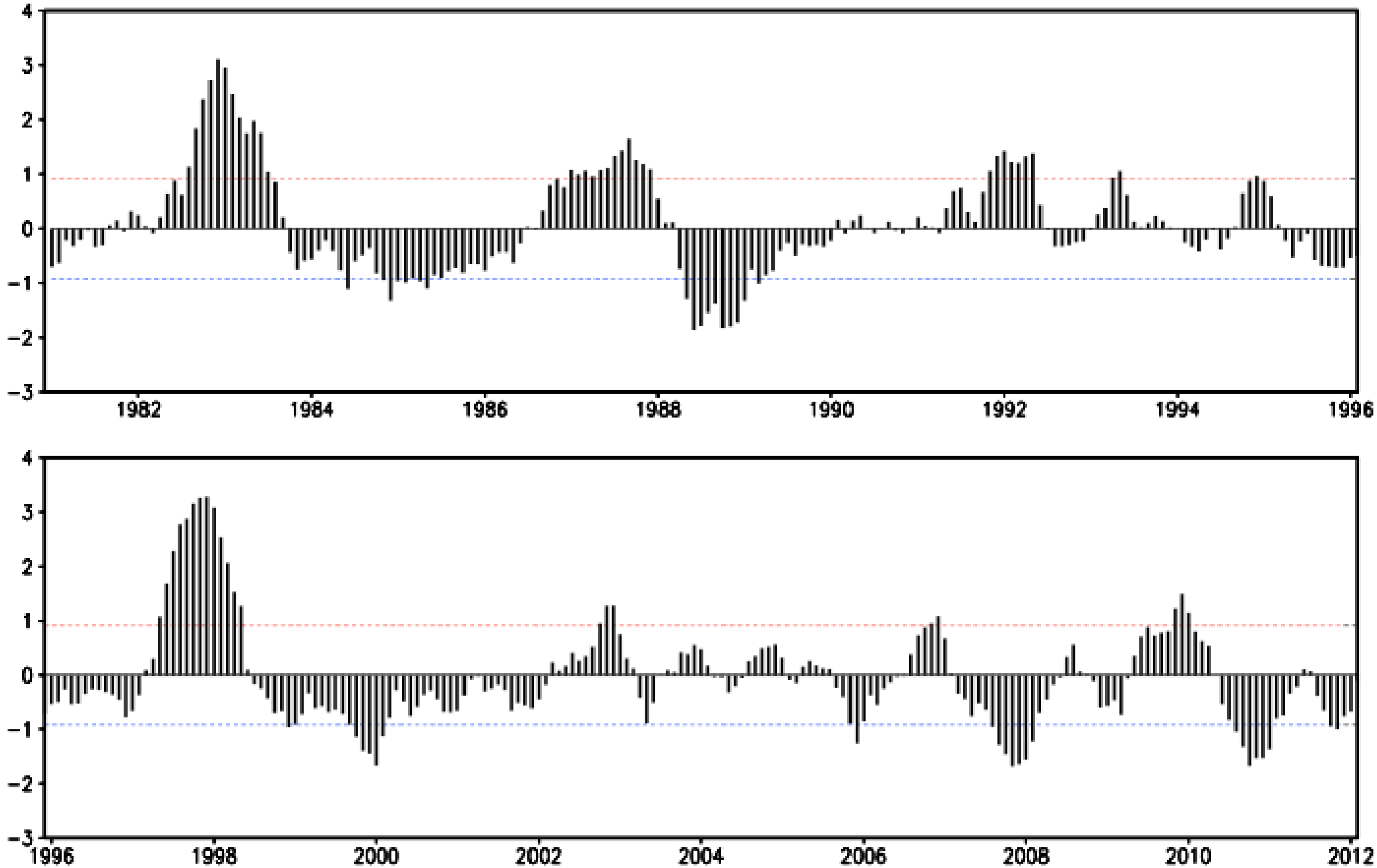
Interannual Variability of Tropical Pacific SSTA (°C)

(NINO3, 150°-90°W, 5°S-5°N)



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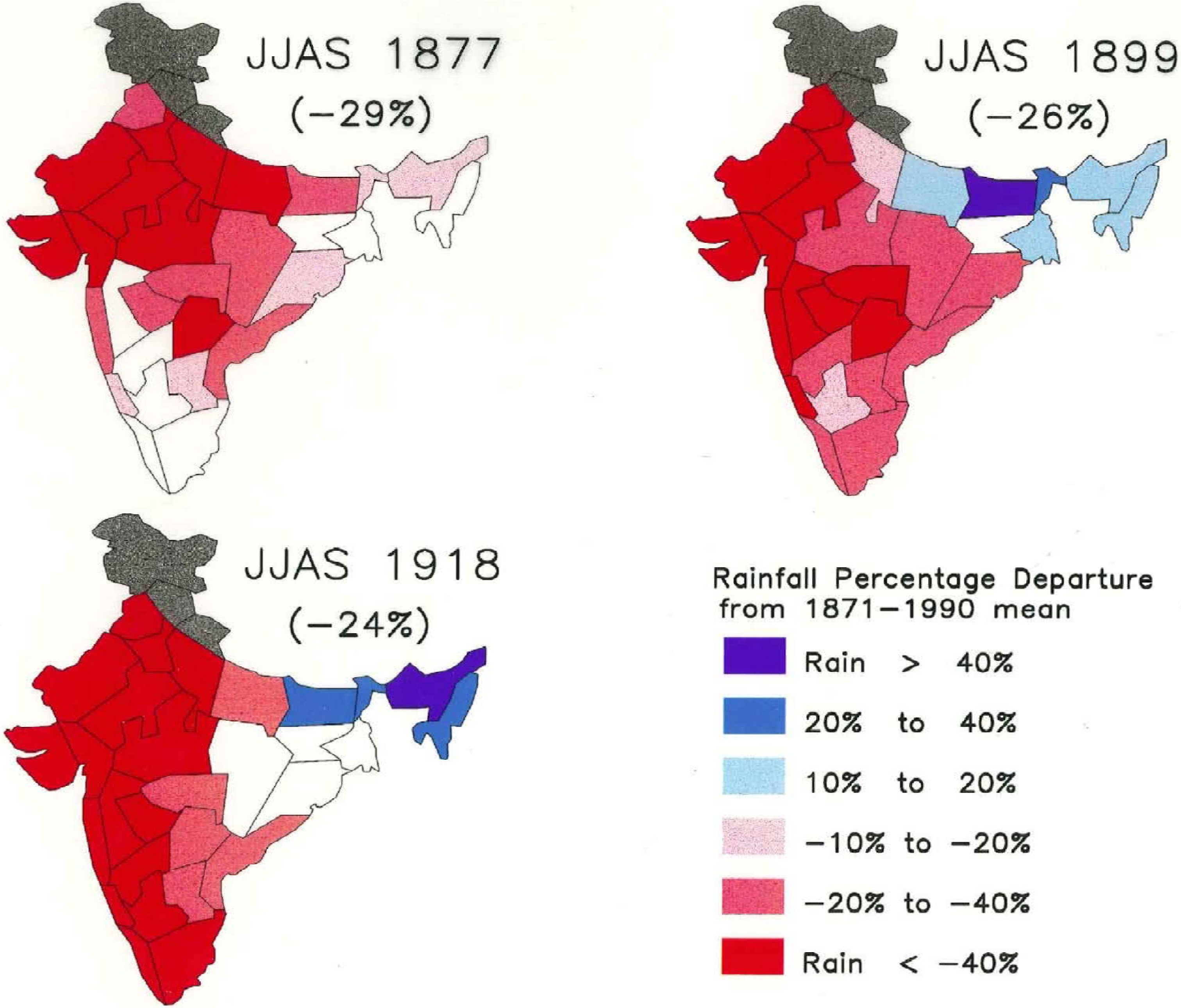
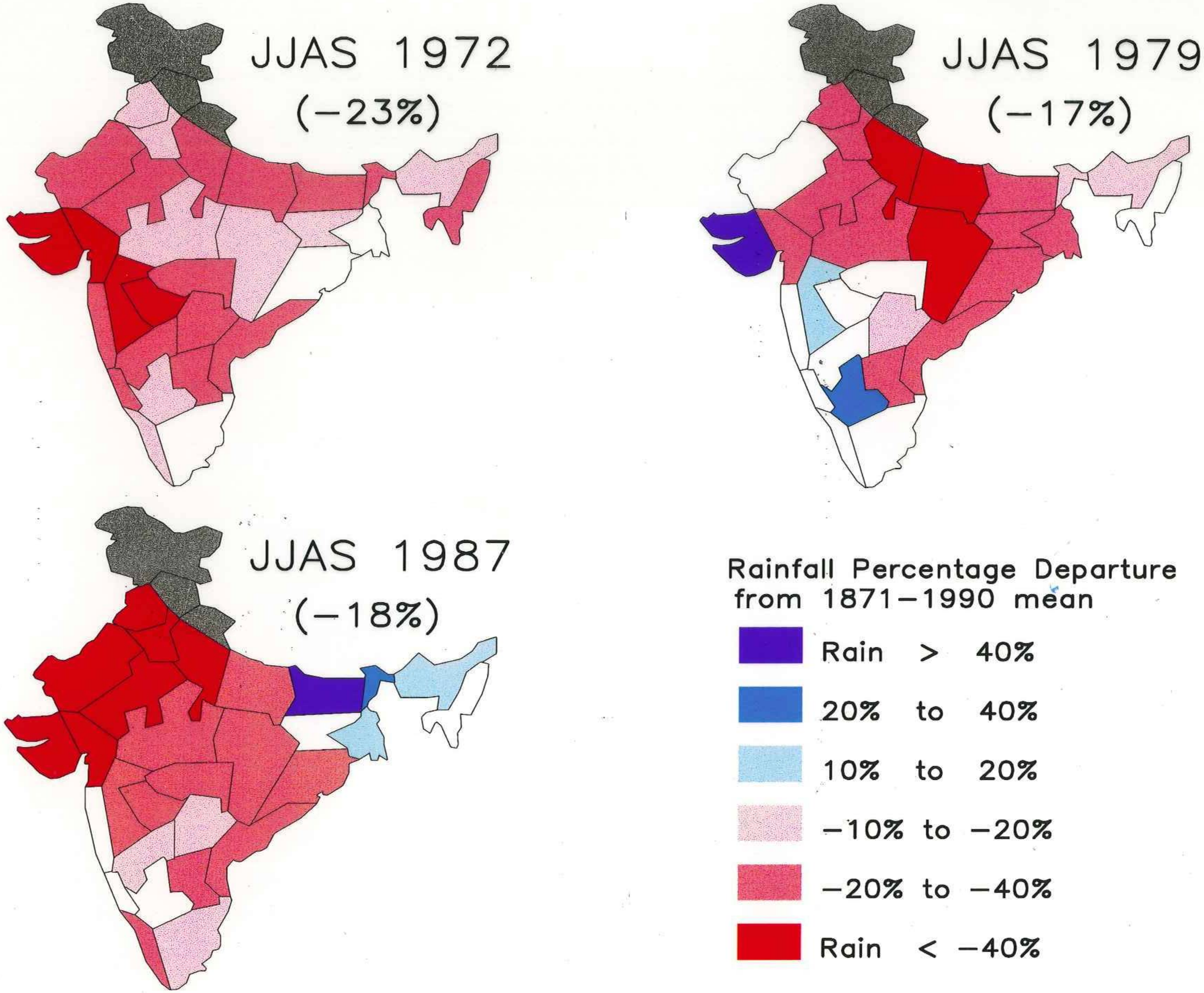
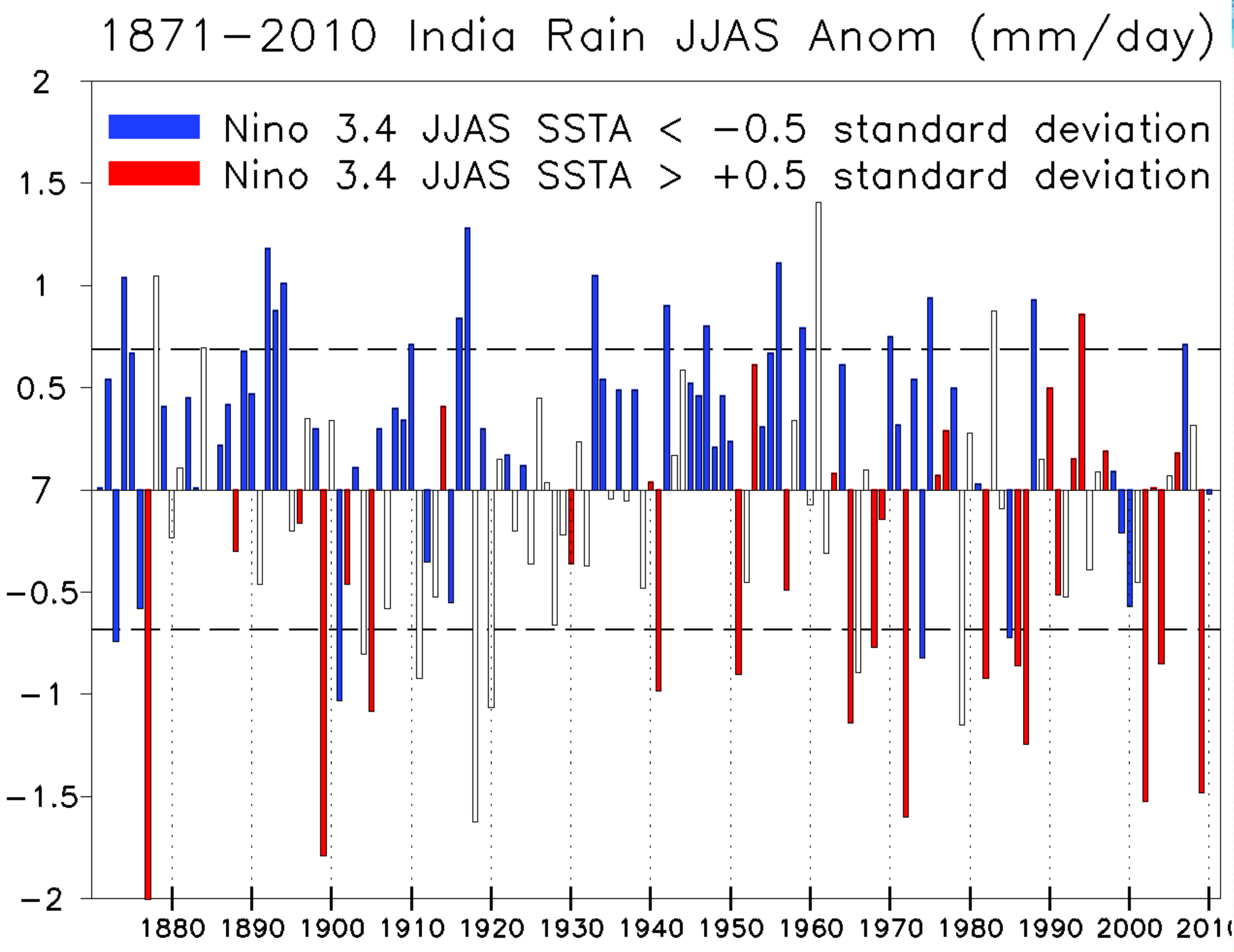
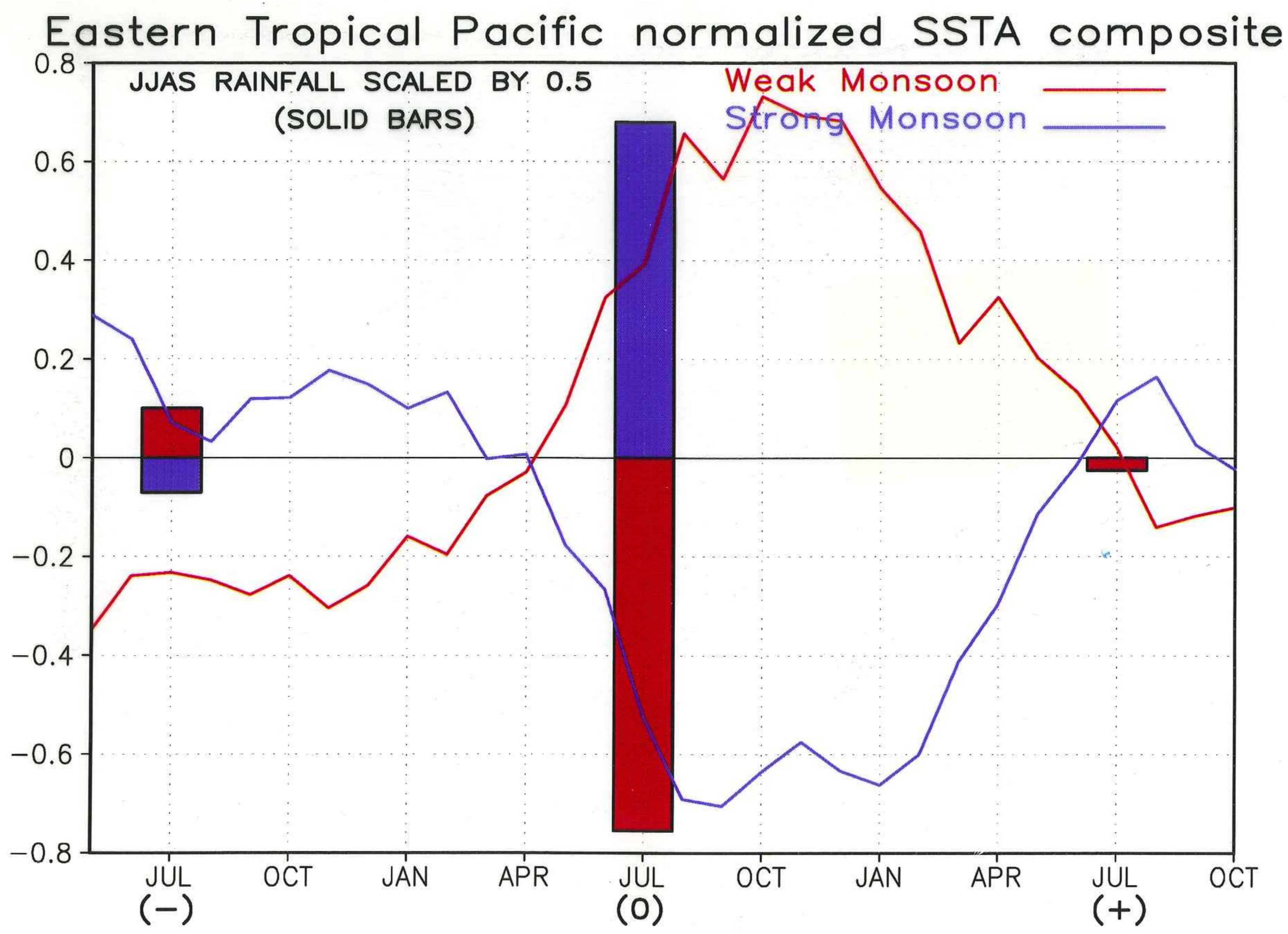

JJAS 1877
(−29%)
JJAS 1899
(−26%)
JJAS 1918
(−24%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%



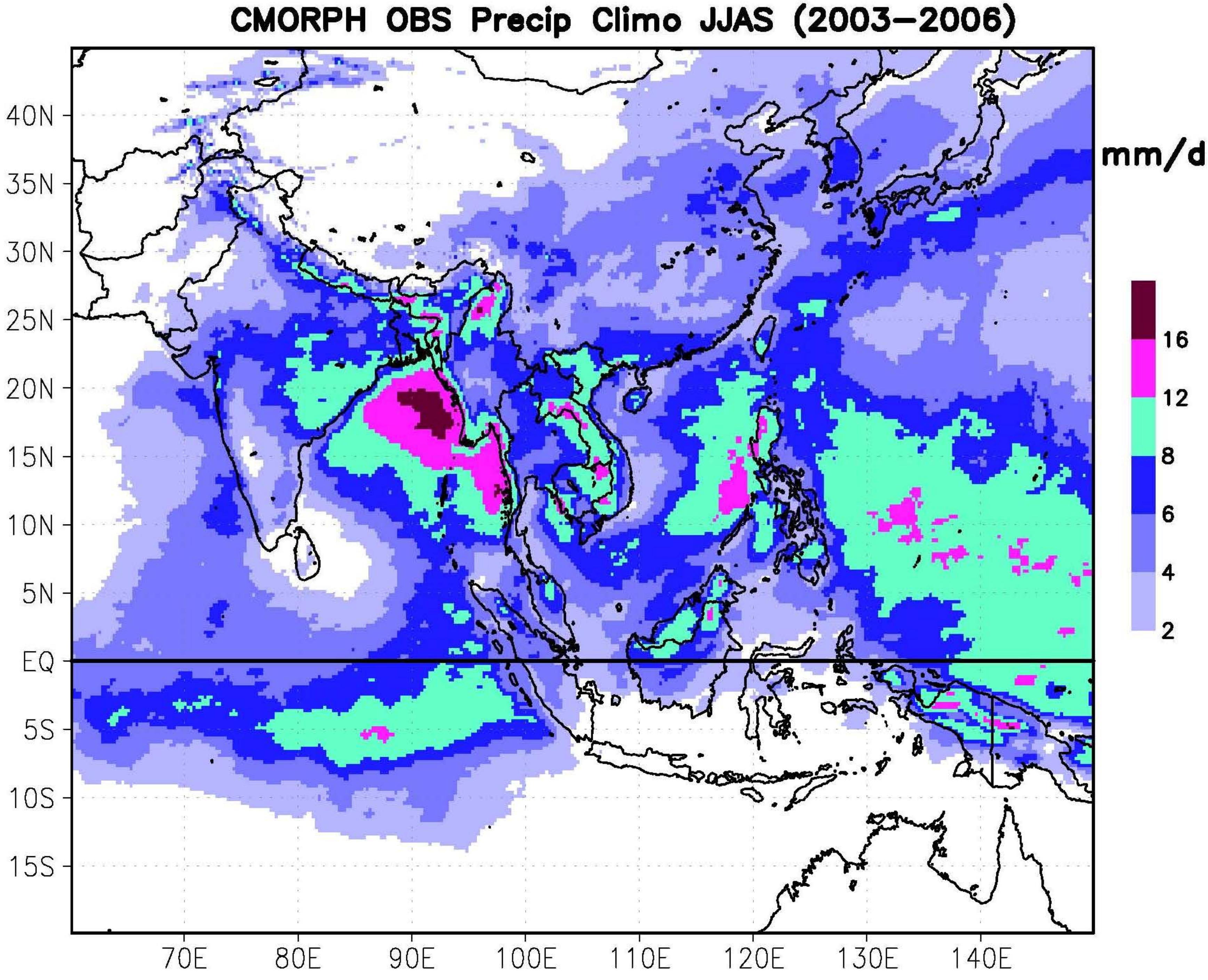
JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%



1871–2010 India Rain JJAS Anom (mm/day)
Nino 3.4 JJAS SSTA < −0.5 standard deviation
Nino 3.4 JJAS SSTA > +0.5 standard deviation
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010



Eastern Tropical Pacific normalized SSTA composite
JJAS RAINFALL SCALED BY 0.5
(SOLID BARS)
Weak Monsoon
Strong Monsoon
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
JUL
(−)
OCT
JAN
APR
JUL
(0)
OCT
JAN
APR
JUL
(+)
OCT

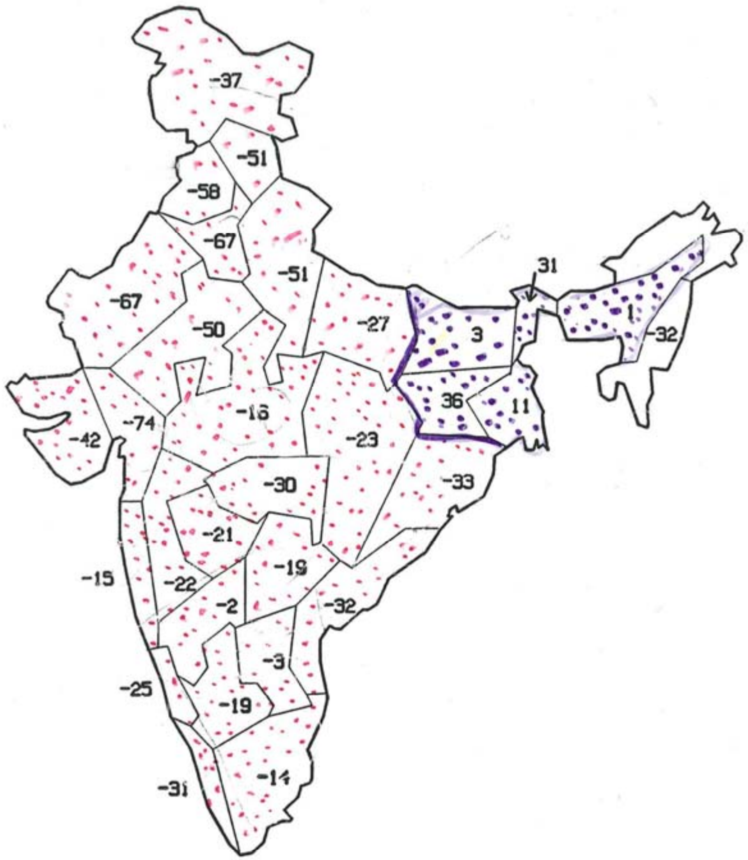


CMORPH OBS Precip Climo JJAS (2003–2006)
mm/d
16
12
8
6
4
2
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
70E
80E
90E
100E
110E
120E
130E
140E

JJAS

MONSOON RAINFALL 1987

PERCENTAGE DEPARTURE FROM NORMAL



PERSISTENCE OF RAINFALL IN ANOMALOUS MONSOON SEASONS

(a) ALL-INDIA RAINFALL

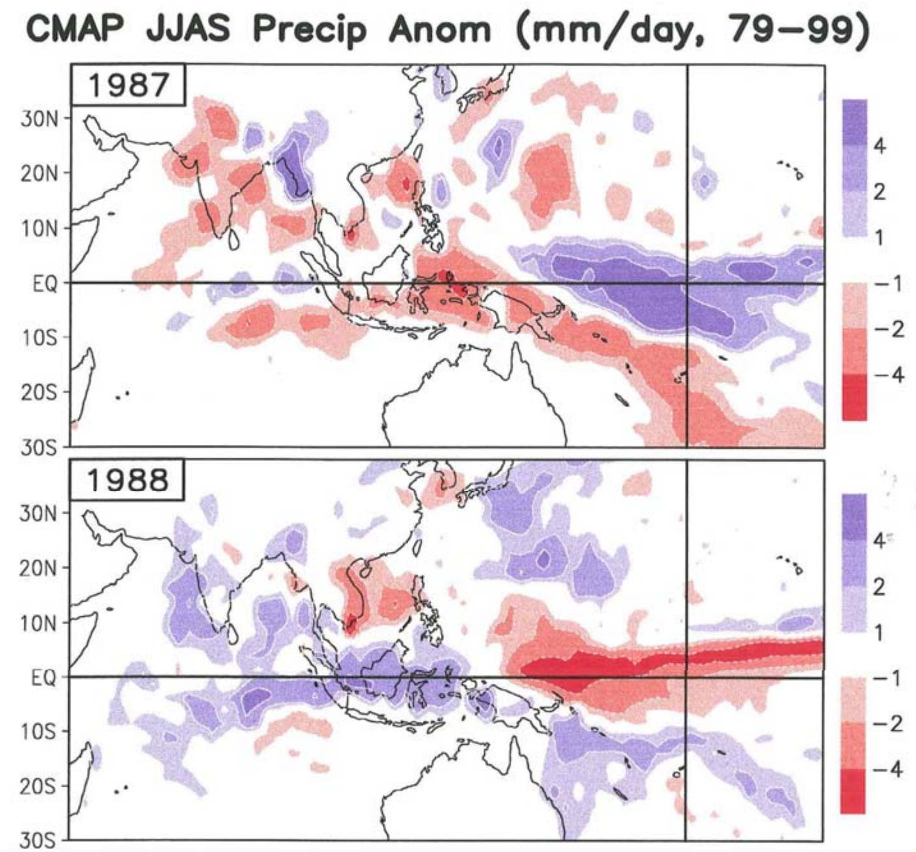
Heavy Rain Years						Deficient Rain Years					
Year	Total	Jun	Jul	Aug	Sep	Year	Total	Jun	Jul	Aug	Sep
1874	1.46	1.76	0.89	-0.26	0.93	1873	-1.13	-1.38	-0.27	-0.76	-0.14
1878	1.48	-0.90	0.54	2.49	1.09	1877	-2.96	-0.58	-3.21	-2.25	-0.60
1892	1.66	-0.15	1.08	1.63	1.12	1899	-2.66	0.87	-2.35	-2.58	-1.82
1893	1.23	2.14	-0.48	-0.33	1.44	1901	-1.55	-1.33	-1.41	0.40	-1.20
1894	1.42	1.46	1.01	-0.05	0.82	1904	-1.21	0.44	-0.73	-1.21	-1.18
1916	1.17	0.98	-0.44	1.20	0.86	1905	-1.62	-1.99	-0.78	-1.00	0.10
1917	1.81	1.39	-0.75	0.83	2.56	1911	-1.38	0.79	-3.29	-0.85	0.22
1933	1.47	1.06	-0.47	1.74	0.93	1918	-2.40	0.49	-3.56	-0.60	-1.72
1942	1.26	0.28	1.31	0.97	0.26	1920	-1.59	-0.57	0.47	-2.10	-1.29
1947	1.11	-1.11	0.45	1.37	1.71	1928	-1.01	-0.26	0.25	-1.18	-1.03
1956	1.56	1.22	1.83	0.27	0.24	1941	-1.48	0.02	-1.53	-0.88	-0.92
1959	1.09	-0.17	1.27	0.17	1.18	1951	-1.35	-0.23	-0.54	-0.93	-1.30
1961	2.00	0.64	1.14	0.79	1.91	1965	-1.70	-1.45	-0.20	-1.41	-0.74
1970	1.04	1.30	-1.40	1.44	0.96	1966	-1.34	0.06	-1.00	-1.18	-0.86
1975	1.32	0.46	0.43	0.55	1.50	1968	-1.17	-0.74	0.39	-1.27	-0.95
1983	1.23	-0.70	-0.02	1.30	2.11	1972	-2.38	-1.12	-2.46	-0.68	-1.10
1988	1.30	-0.19	1.33	0.85	0.91	1974	-1.24	-1.57	-0.02	-0.40	-0.81
1994	1.02	1.42	1.14	0.57	-0.79	1979	-1.72	-0.55	-1.32	-1.16	-0.83
						1982	-1.40	-0.93	-1.58	0.65	-1.32
						1985	-1.10	-0.63	-0.57	-0.65	-0.62
						1986	-1.30	0.38	-0.98	-0.78	-1.52
						1987	-1.85	-1.30	-1.84	-0.17	-0.88

El Nino

La Nina

In either heavy or deficient rainfall years (> 1sd), the monthly values tend to be either enhanced or depressed throughout the monsoon season

1



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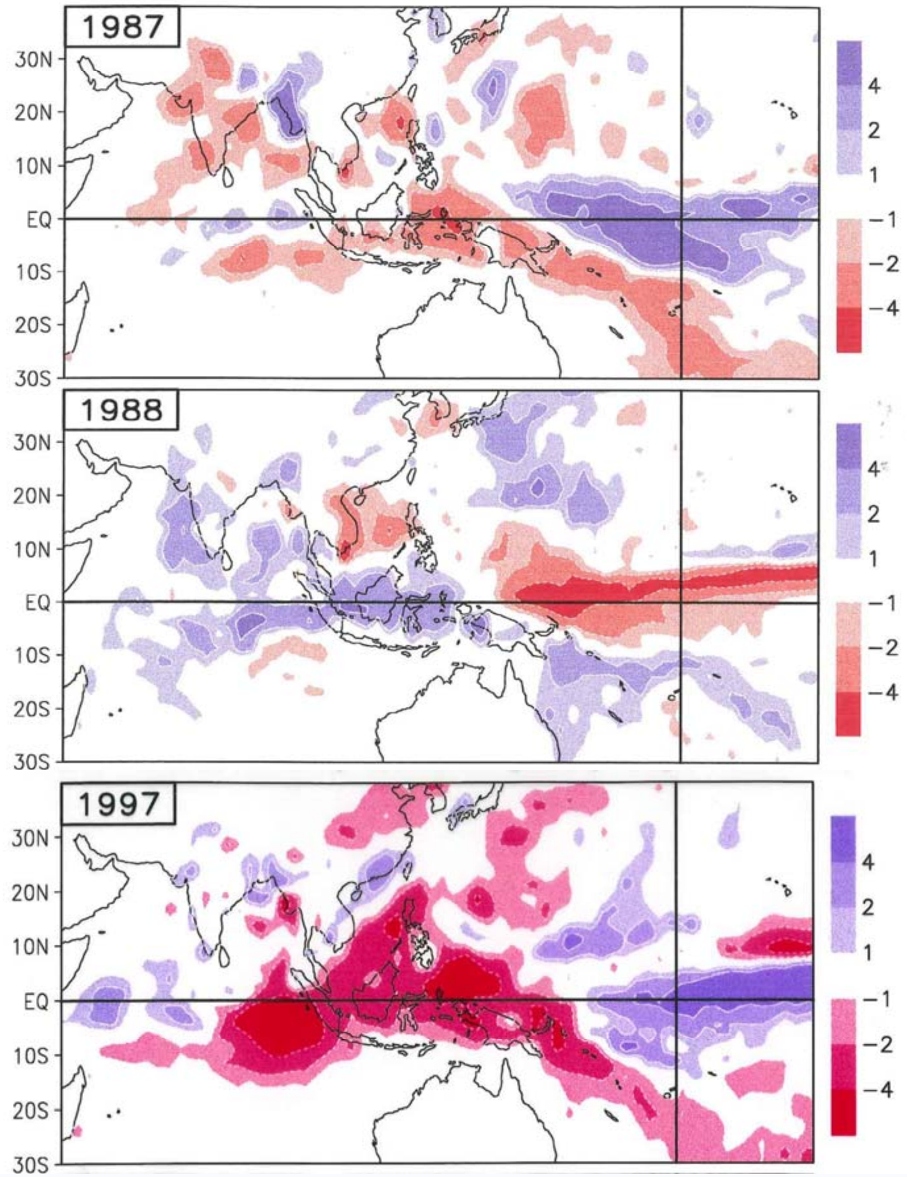
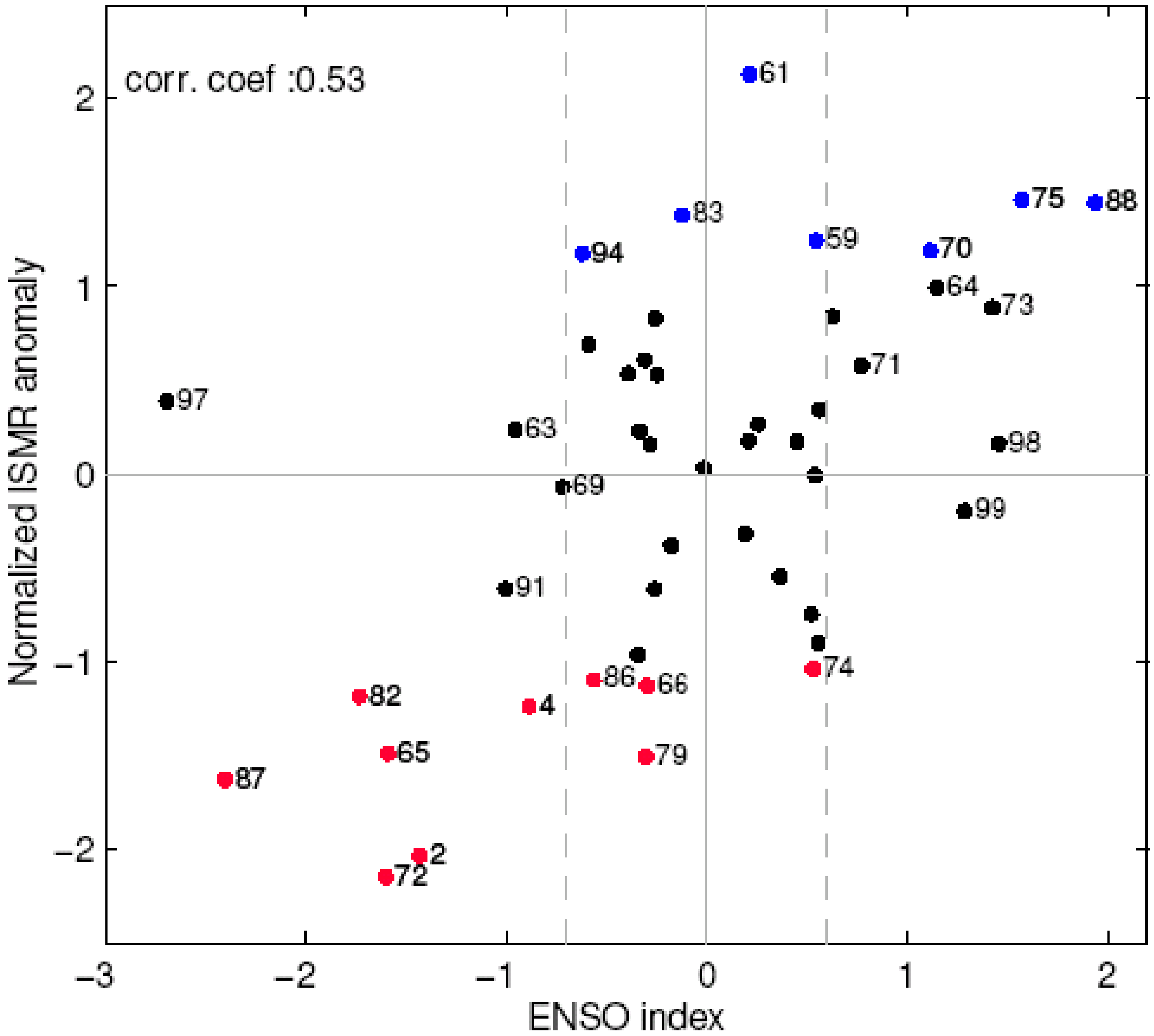
CMAP JJAS Precip Anom (mm/day, 79–99)



ENSO and Monsoon rainfall over India



No droughts

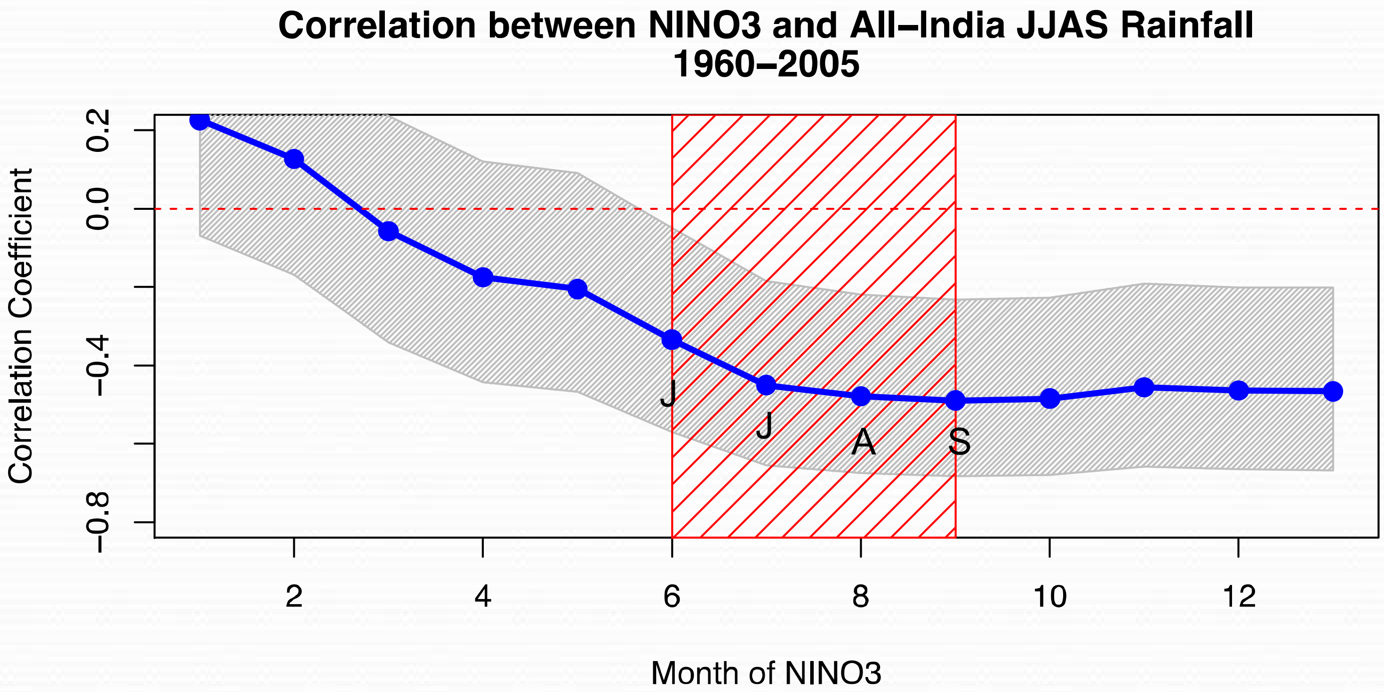
when ENSO index >1

No excess rainfall

when ENSO index < -1

But several extremes when -1< ENSO Index < 1

Gadgil et al., GRL2004

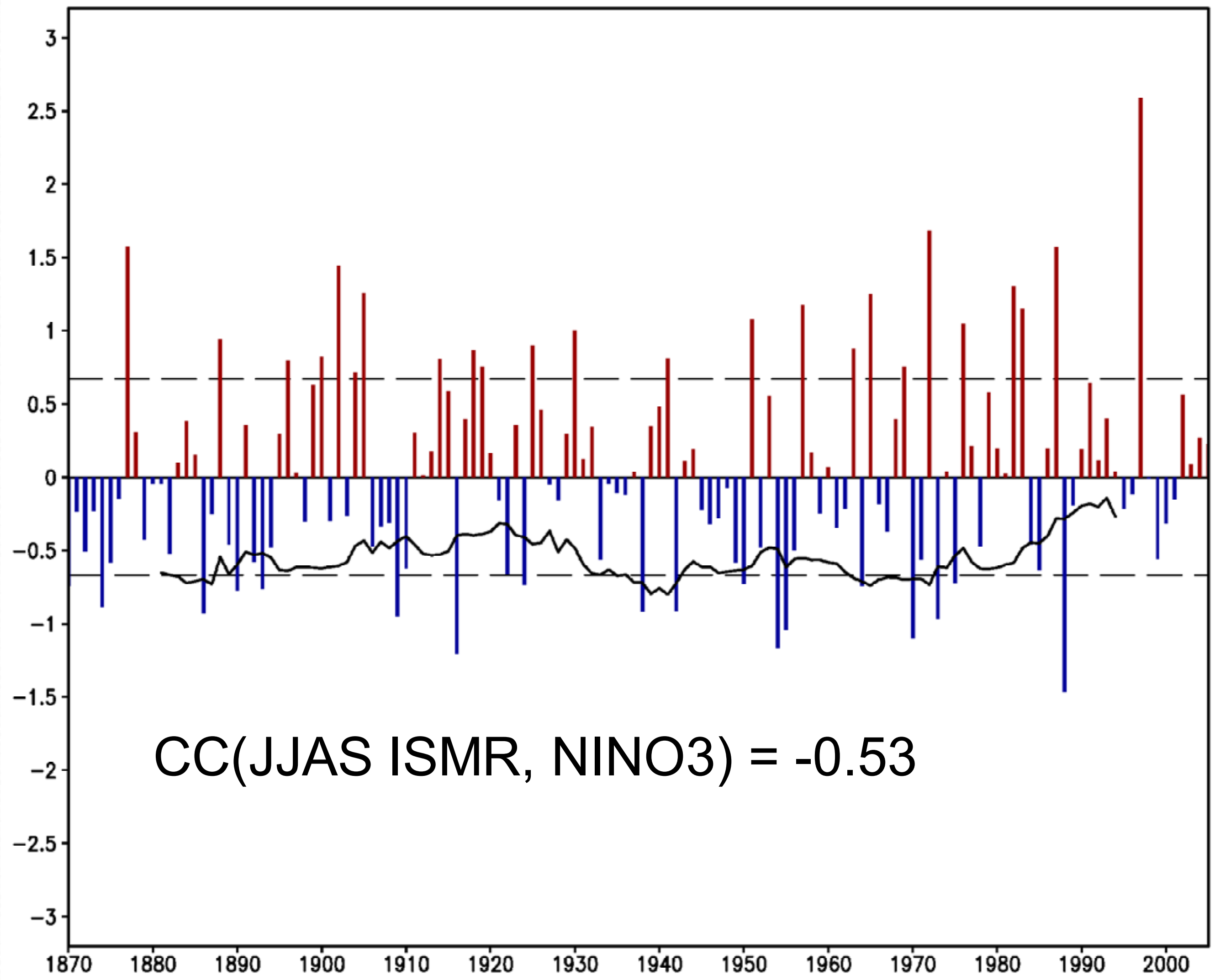


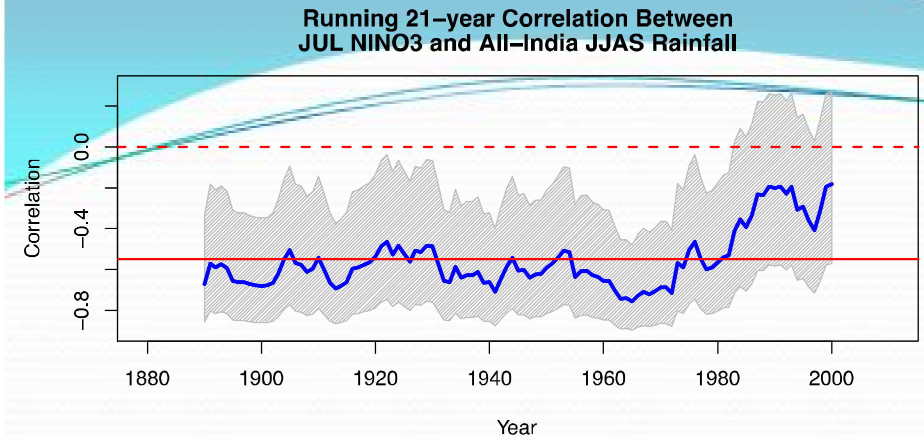
Time lagged correlation between all-India JJAS Monsoon Rainfall and the NINO3 index during the period 1960-2005. The red hatching indicates the JJAS period, the horizontal red dashed line indicates zero, and the grey shading indicates the 95% confidence interval for the time lagged correlation.

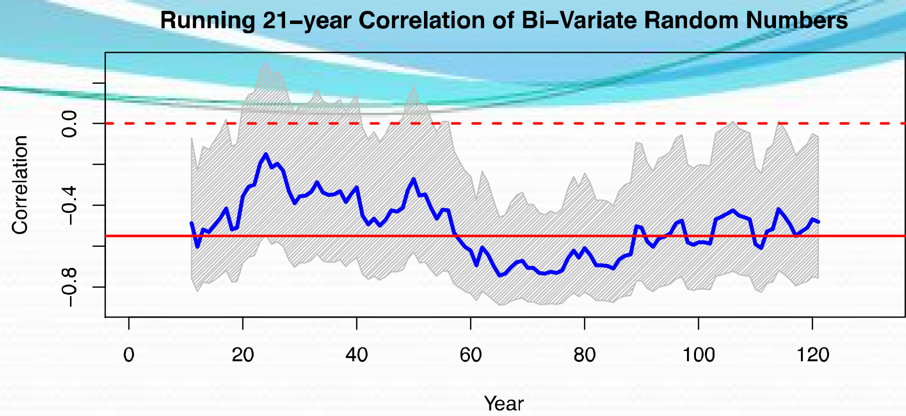
Has ENSO-Monsoon relationship broken down?

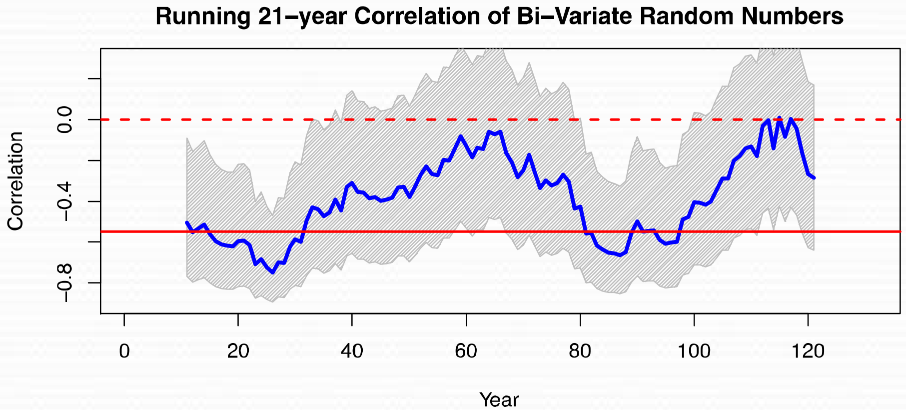
No; it is sampling variability.

JJAS NINO3 (°C) wrt 1871-1970 Mean









21-year running cc: obs. all India JJAS rainfall and July NINO3 (top left);

Simulated pairs of bi-variate random variables with population correlation -0.54 (top right, bottom left)

$$y = \rho x + w\sqrt{1-\rho^2}$$

where *x* and *w* are independent, normally distributed random variables with unit variance, and ρ is a constant (less than or = 1).
Population correlation between random pairs of variables (*x* and *y*) produced by this model, will be equal to ρ.

Center of Ocean-Land-Atmosphere studies

CREW Center for Research on Environment and Water

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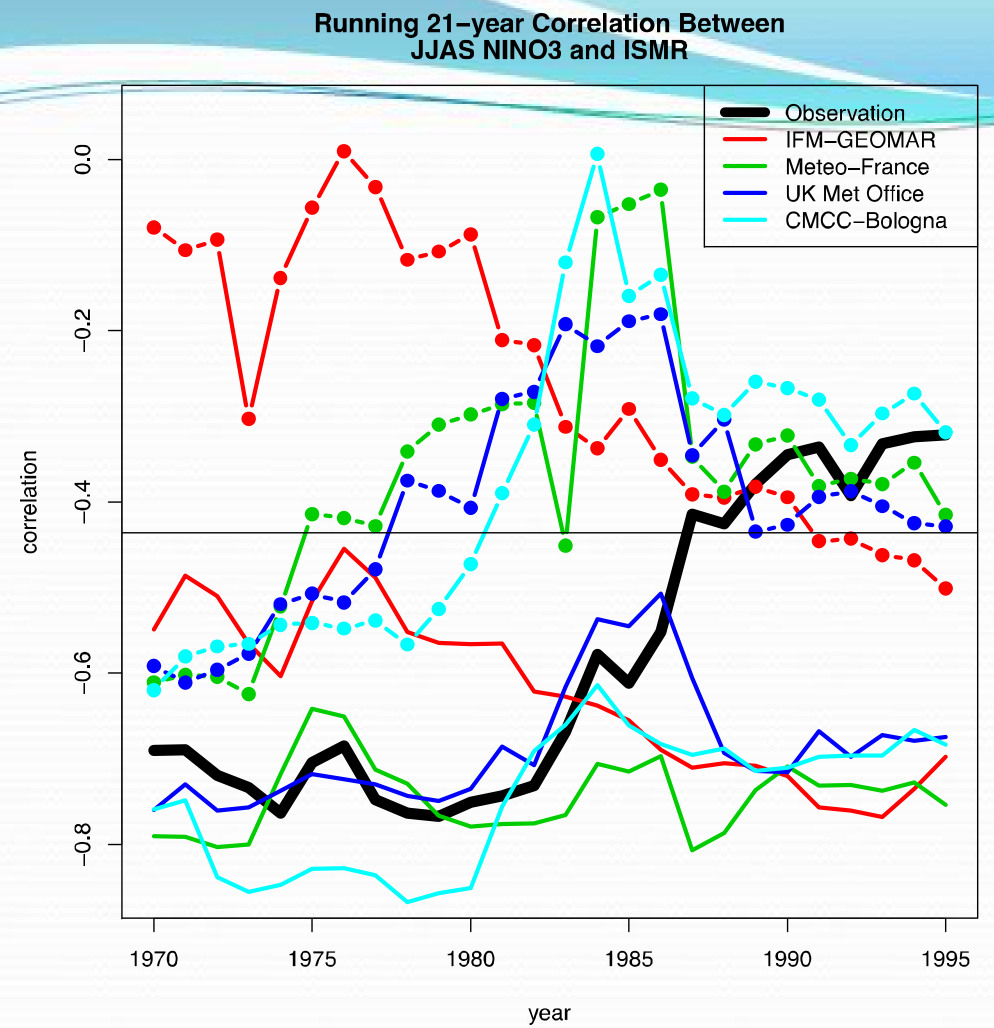

Running 21-year correlations between observed ISMR and observed July NINO3 (thick black), between ensemble mean ISMR and ensemble mean JJAS NINO3 (colored solid lines), and between ISMR and JJAS NINO3 of a selected ensemble member from each model (dots connected by solid lines). All-India rainfall in dynamical models is defined as the total land precipitation within 70E − 90E and 10N − 25N. The center year of the 21-year period is plotted on the horizontal axis. The 5% significance threshold for a 21-year correlation is shown as a thin horizontal black line.

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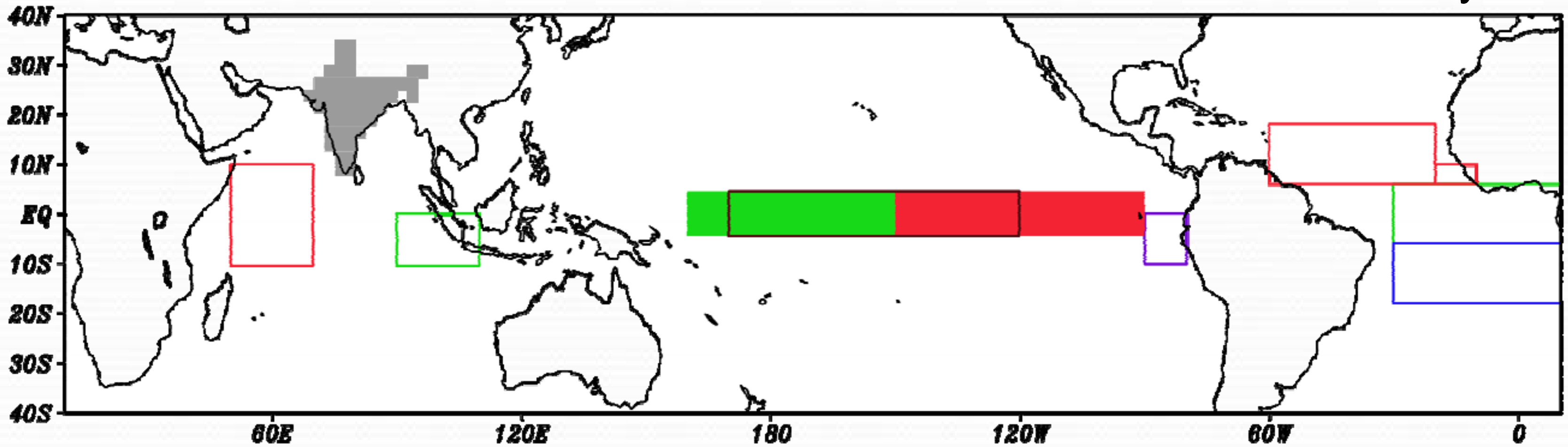
Possible Influence of Indian Ocean SST Anomalies on Predictability of Summer Monsoon Rainfall

Lakshmi Krishnamurthy GMU



Indian Ocean:

DMIWEST: (50E–70E, 10N–10S)

DMIEAST: (90E–110E, 0–10S)

DMI: (DMIWEST – DMIEAST)

Pacific Ocean:

NINO12: (90W–80W, 0–10S)

NINO3: (150W–90W, 5N–5S)

NINO3.4: (170W–120W, 5N–5S)

NINO4: (160E–150W, 5N–5S)

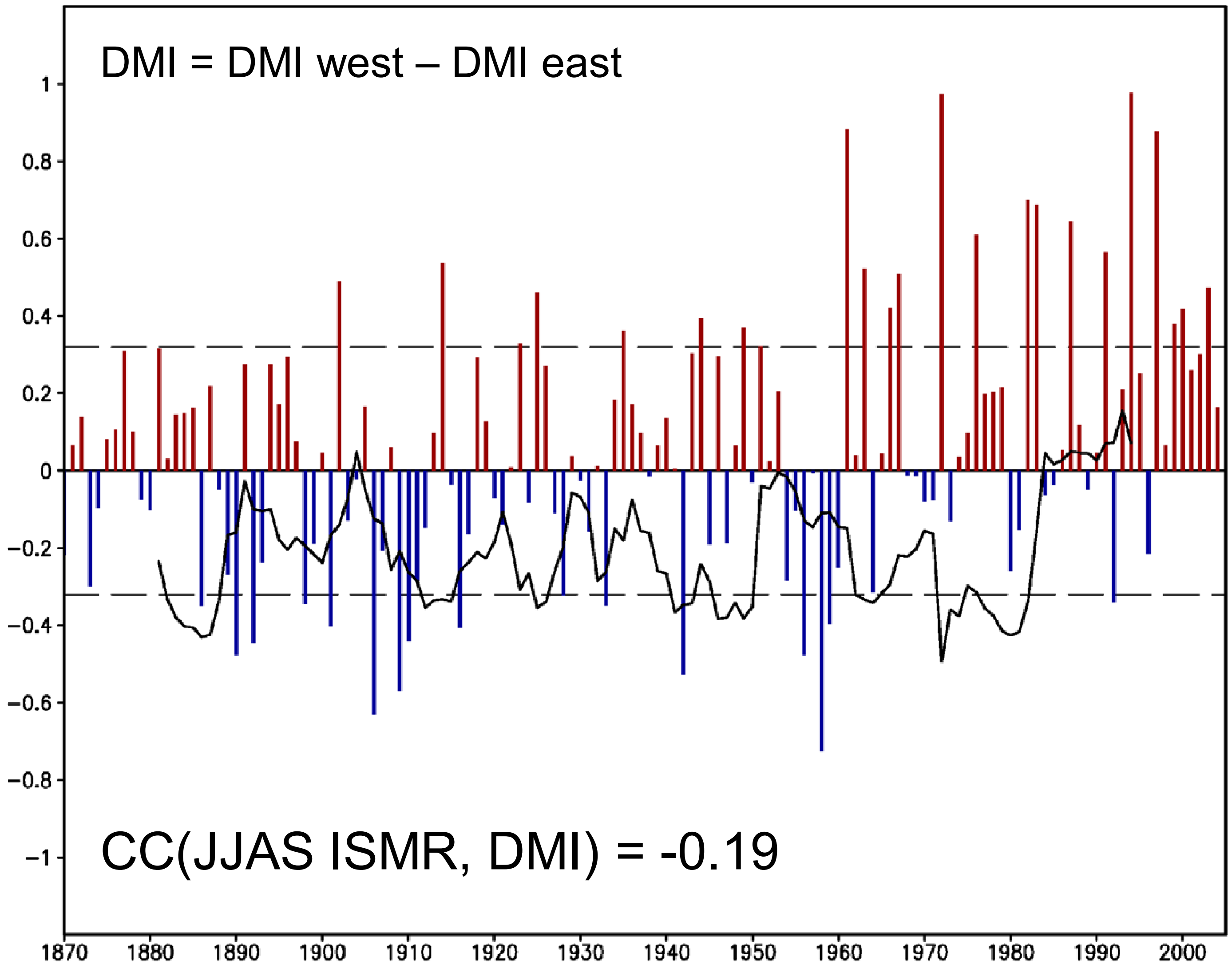
Atlantic Ocean:

NTA: (60W–20W, 6N–18N) and
(20W–10W, 6N–10N)

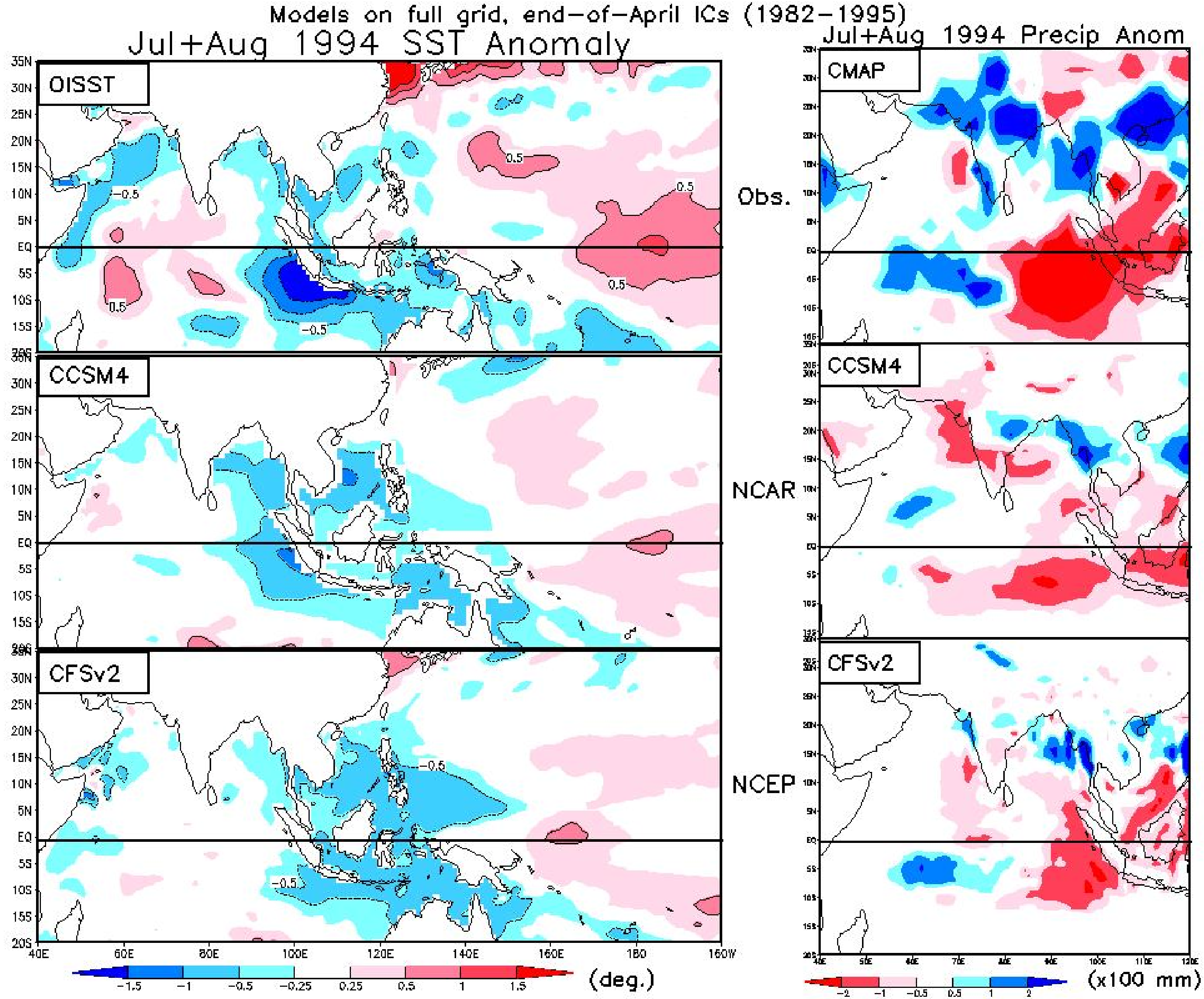
EA: (30W–10E, 6N–6S)

STA: (30W–10E, 6S–18S)

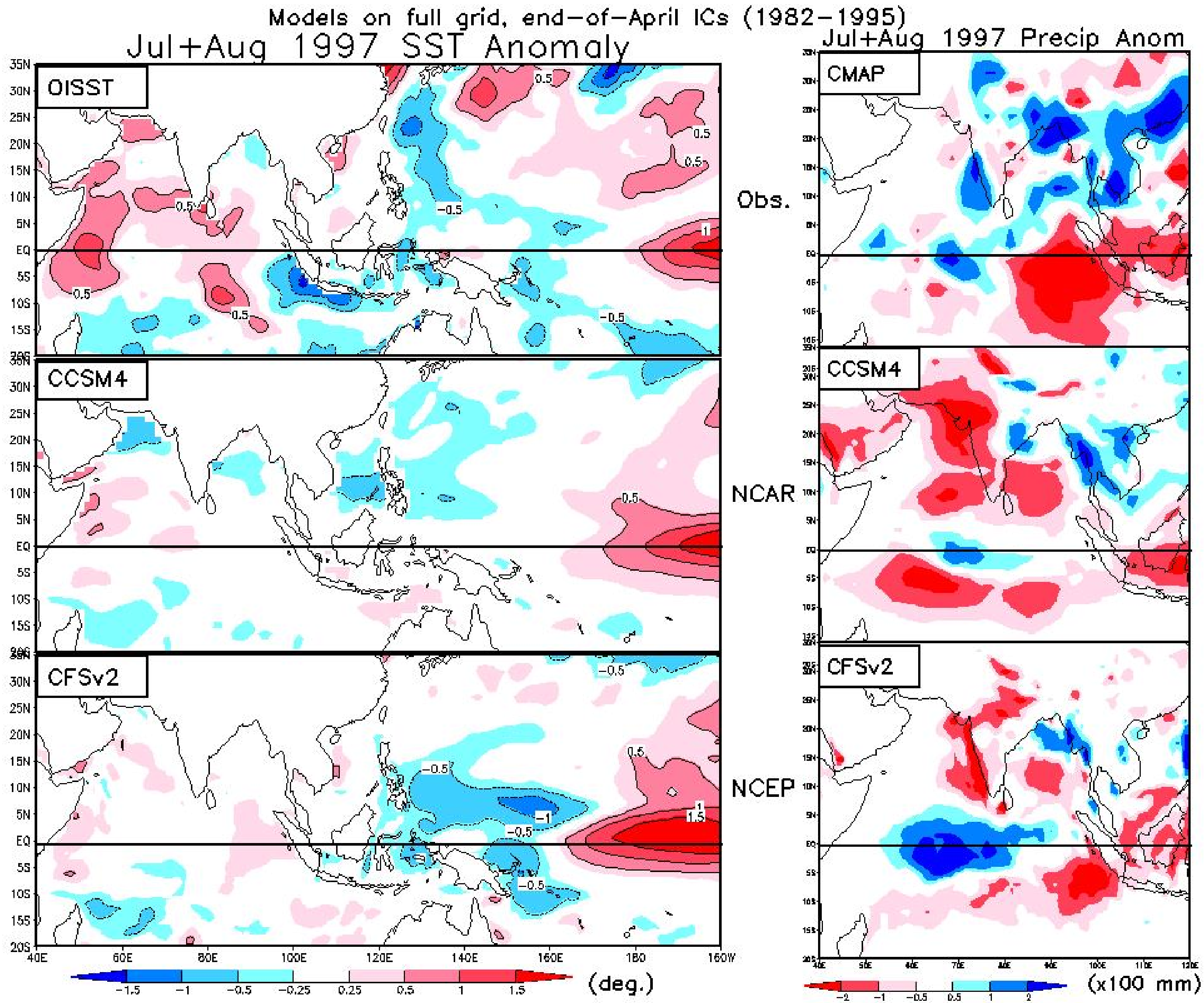
JJAS DMI (° C) wrt 1871-1970 Mean



1994


Models on full grid, end-of-April ICs (1982-1995)
Jul+Aug 1994 SST Anomaly
OISST
CCSM4
CFSv2
Obs.
NCAR
NCEP
(deg.)
Jul+Aug 1994 Precip Anom
CMAP
CCSM4
CFSv2
(x100 mm)

1997


Models on full grid, end-of-April ICs (1982-1995)
Jul+Aug 1997 SST Anomaly
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Obs.
NCAR
NCEP
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
40E
60E
80E
100E
120E
140E
160E
180
160W
-1.5
-1
-0.5
-0.25
0.25
0.5
1
1.5
(deg.)
-2
-1
-0.5
0.5
1
2
(x100 mm)

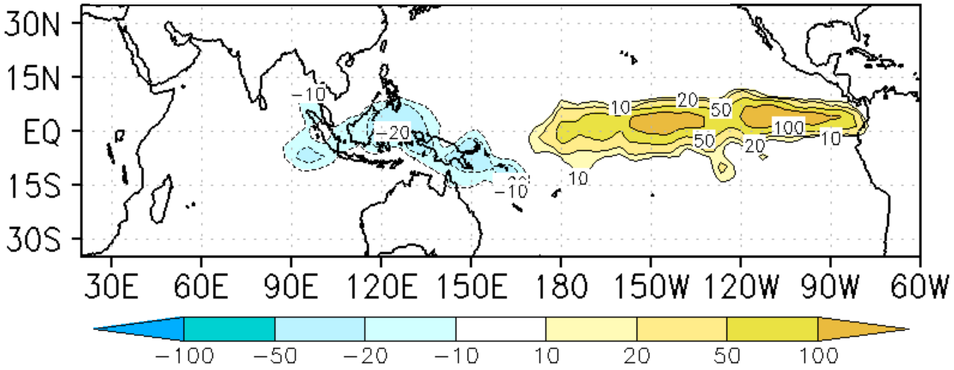
The Atmospheric Influence of Tropical Diabatic Heating Associated with Developing ENSO on Indian Monsoon

Youkyoung Jang (Ph D Thesis)
(George Mason University)

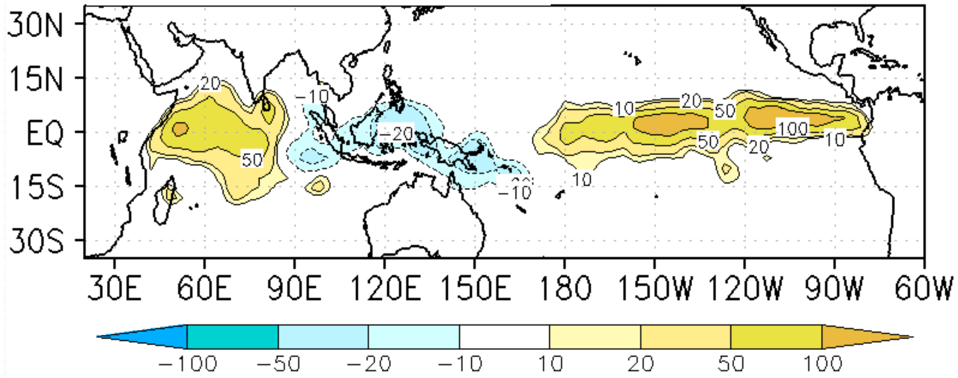
AGCM is run with climatological SST with, and without a prescribed diabatic heating/cooling anomaly over **West Pacific** and **Indian Ocean** derived from observed ENSO events.

Pacific Only vs. Pacific + Indian Ocean

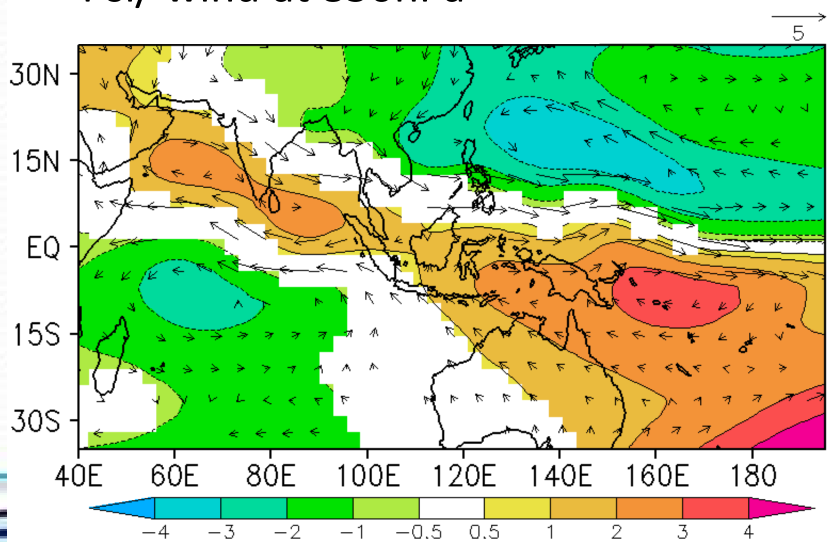
- 1997 Pacific forcing(only) W/m^2



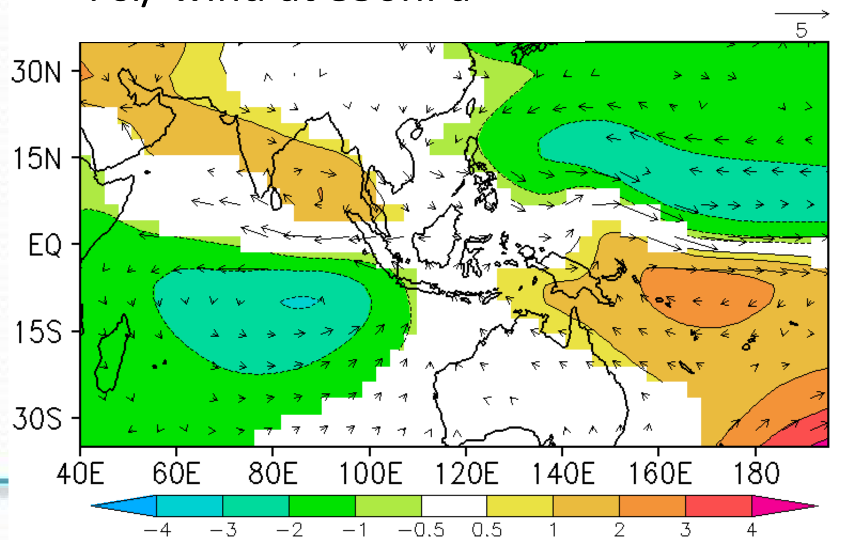
- 1997 Pacific + IO forcing W/m^2



- Response:
  Psi/ wind at 850hPa



- Response:
  Psi/ wind at 850hPa



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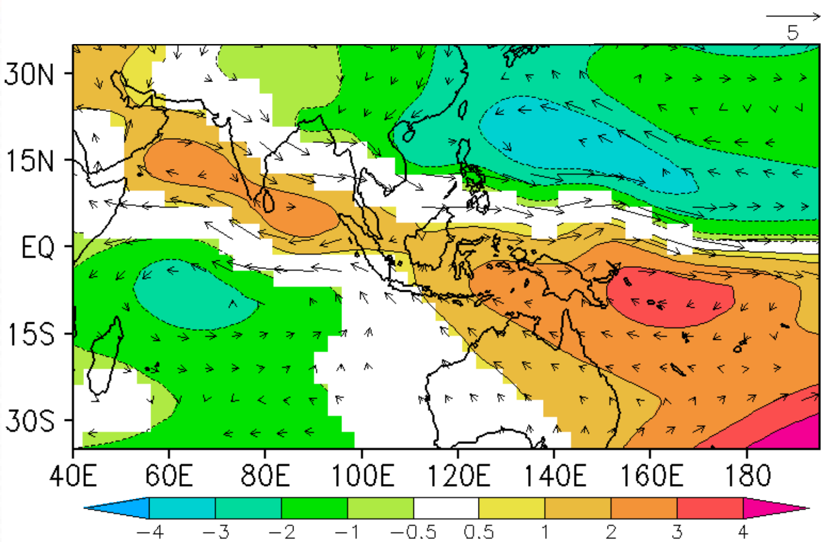
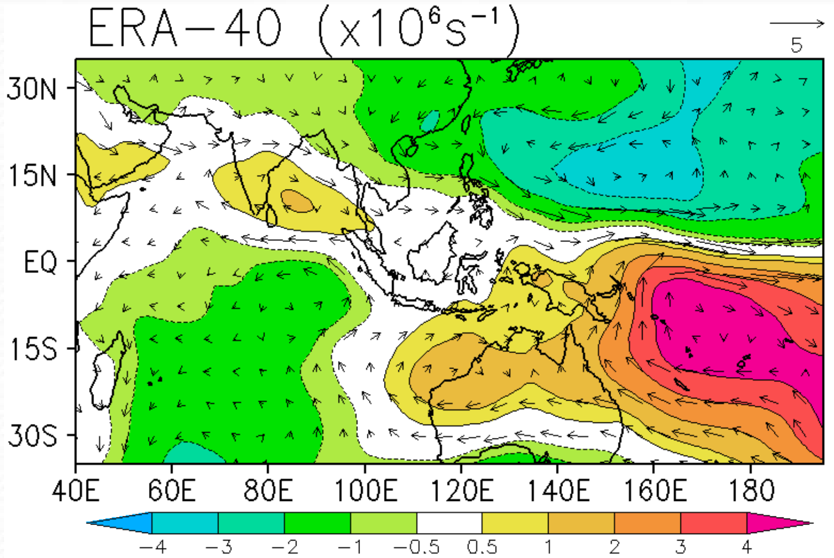
Pacific Only vs. Pacific + Indian Ocean

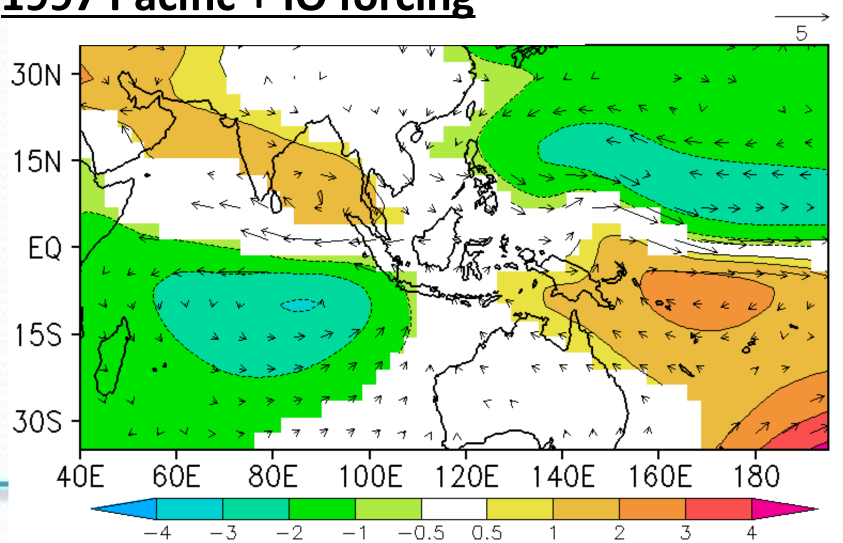
➢ **1997 Pacific forcing only**



➢ **Observation**



➢ **1997 Pacific + IO forcing**



- **Streamfunction (x1e6s^{-1}) at 850hPa**
- **Wind (m/s) at 850hPa**

COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

Influence of Intraseasonal Variations

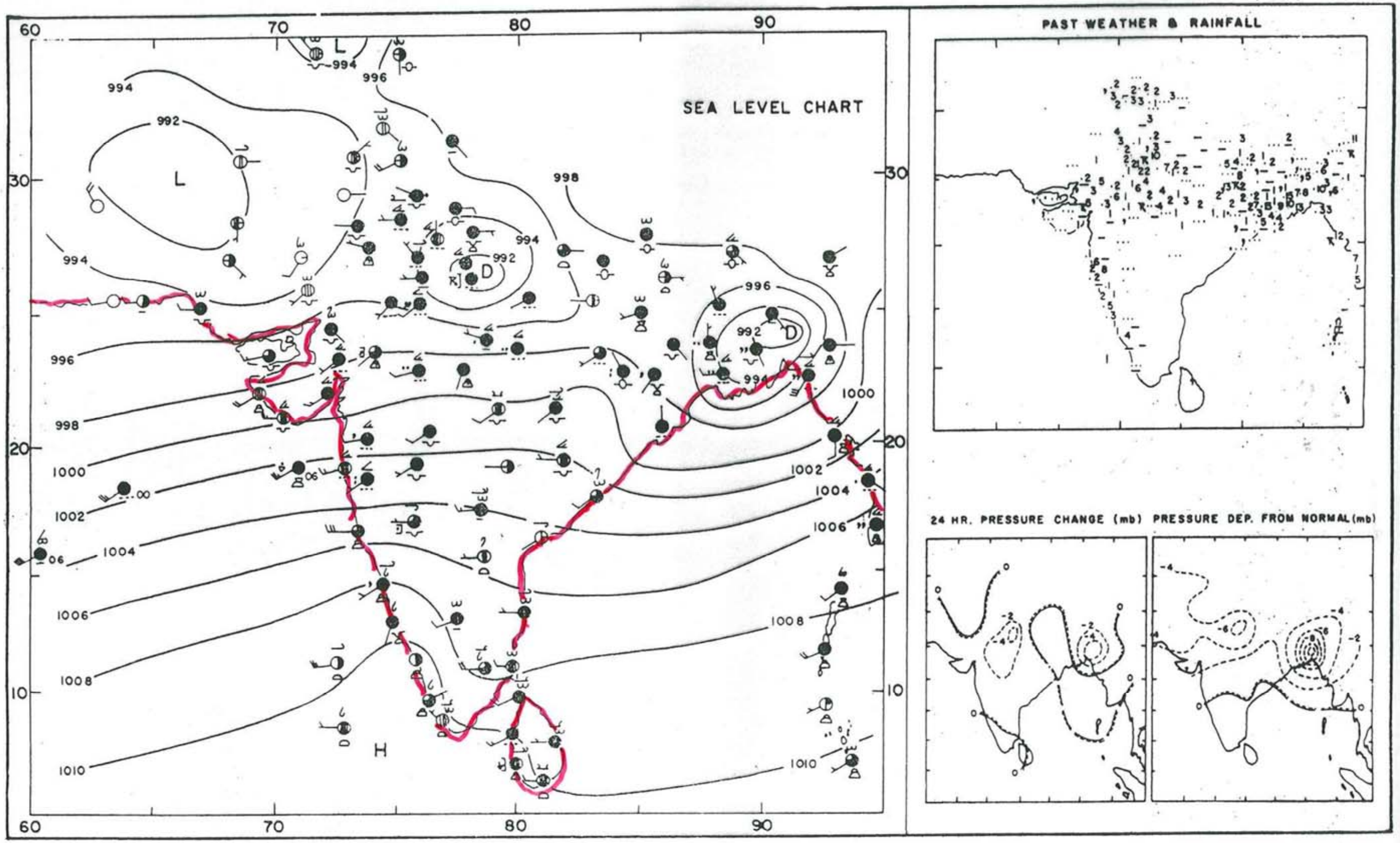
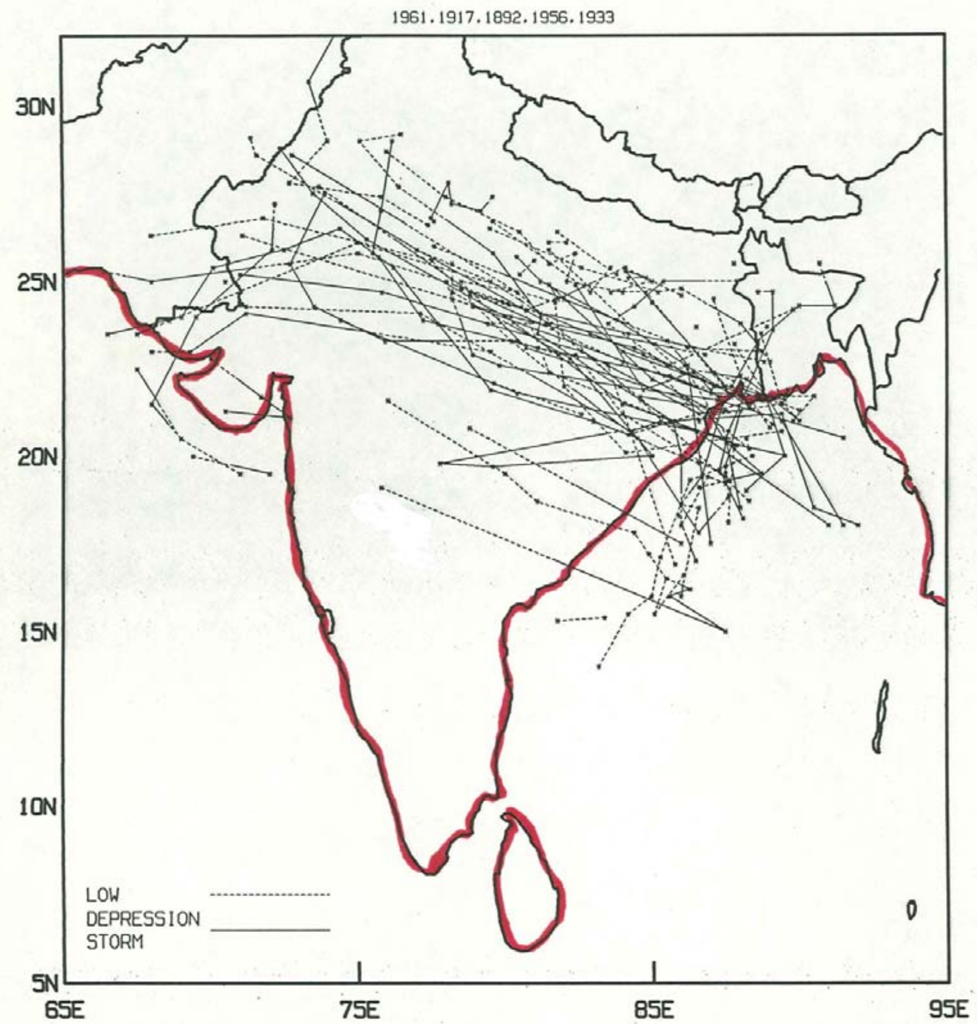
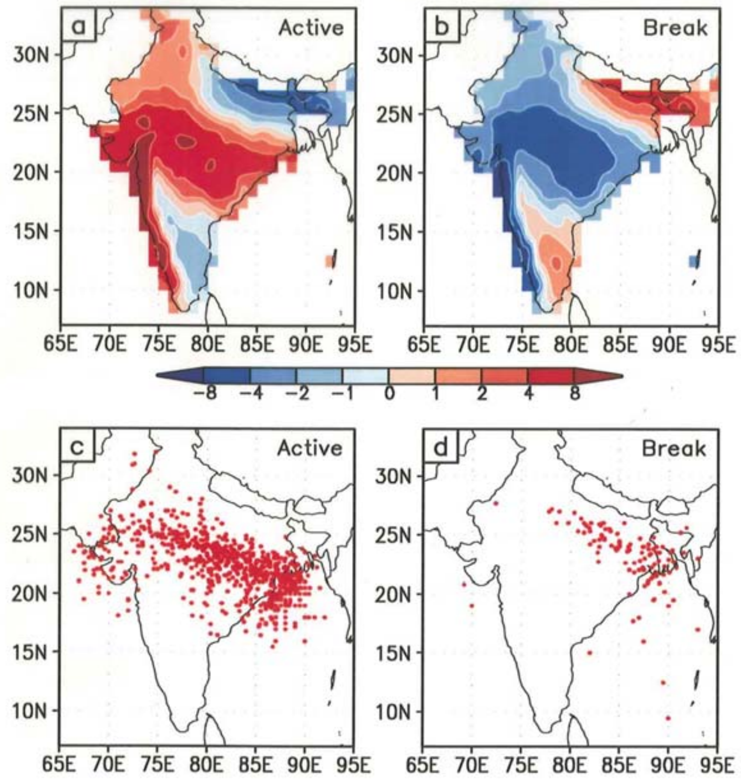


Fig.9.7(h) Synoptic charts 0300 GMT 10 July 1968.

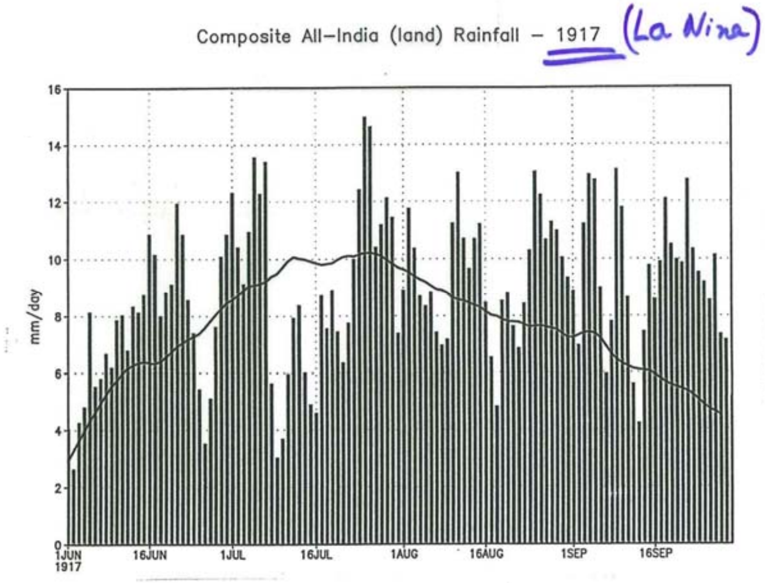
FIVE HIGHEST MONSOON RAINFALL

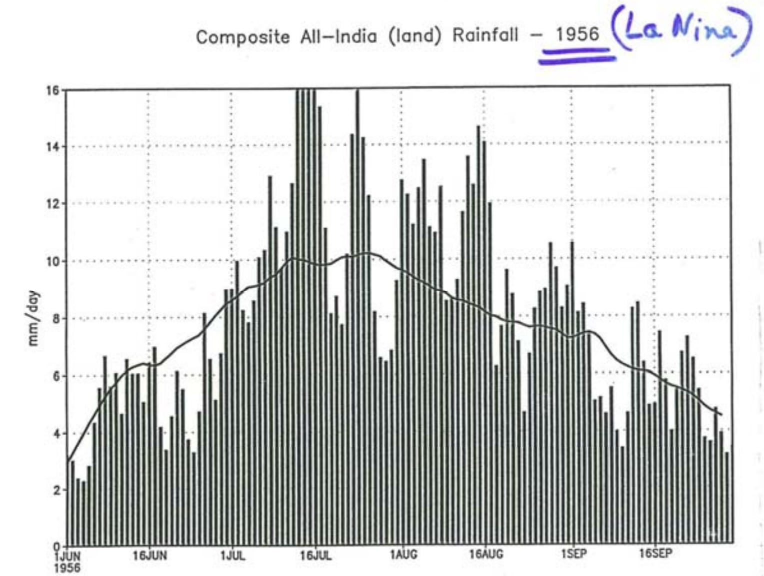


Active and Break Composites of Rainfall and Depressions

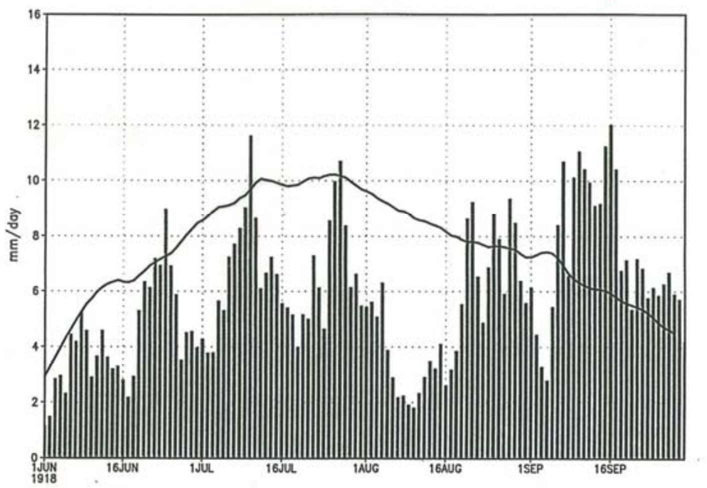


(a) Active composite and (b) break composite of daily rainfall (mm day^{-1}) over India, and (c) active composite and (d) break composite of low pressure systems (depressions only) during JJAS 1901-1970. The active (break) phase is defined when the daily all-India average rainfall is above (below) a threshold of one half of the standard deviation of all-India average rainfall for at least five consecutive days. The composites are averages over all active/break days during 1901-70.

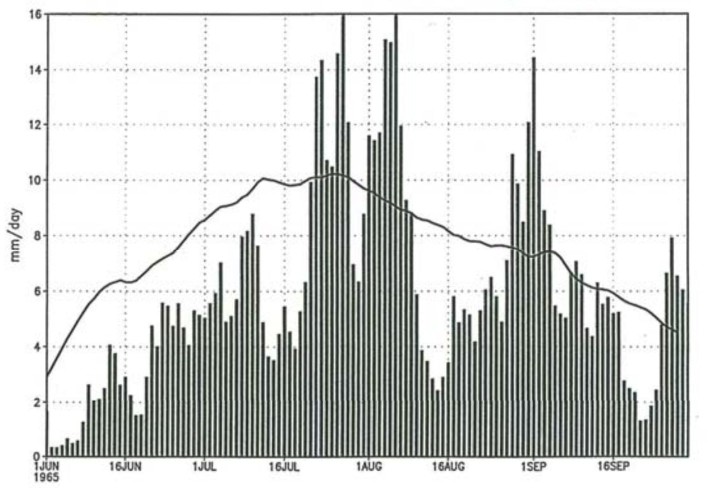

Composite All-India (land) Rainfall – 1917 (La Nina)
mm/day
16
14
12
10
8
6
4
2
0
1JUN 1917
16JUN
1JUL
16JUL
1AUG
16AUG
1SEP
16SEP


Composite All-India (land) Rainfall – 1956 (La Nina)
mm/day
16
14
12
10
8
6
4
2
0
1JUN 1956
16JUN
1JUL
16JUL
1AUG
16AUG
1SEP
16SEP

Composite All-India (land) Rainfall – 1918 (El Nino)



Composite All-India (land) Rainfall – 1965 (El Nino)



Statistical Prediction of ISMR

What is the skill of historical (operational) forecasts issued in April/May

for ISMR?

“Much has been done since 1880… but much more needs to be done.”

Sir Gilbert Thomas Walker
(1868-1958)

History of Forecasting Indian Summer Monsoon Rainfall (ISMR)

1877: Major ENSO; ISMR; highly deficient; great famine

1886: First official forecast (Blanford: high Spring snow cover − low ISMR)

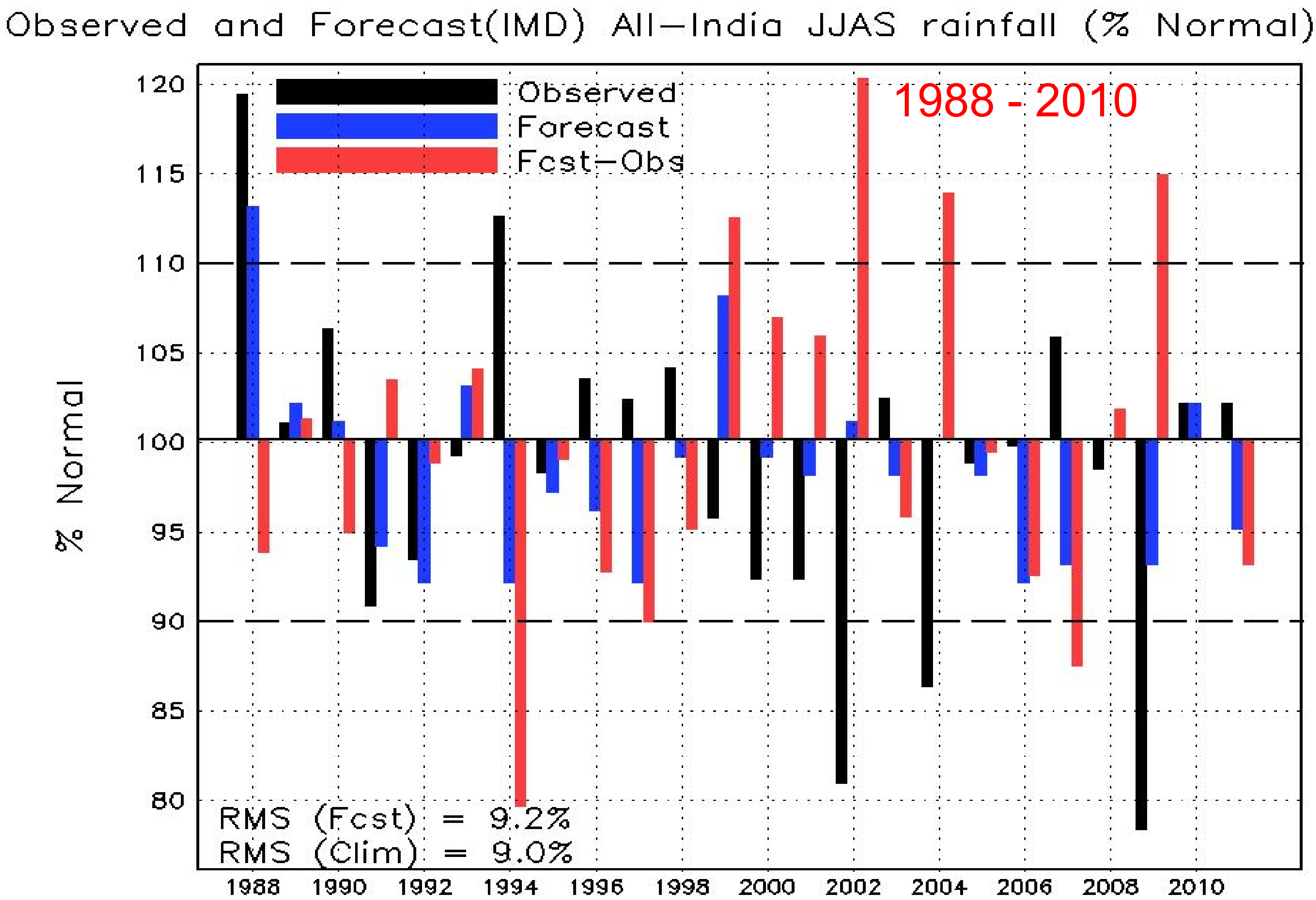
1899: Another major ENSO; another great famine

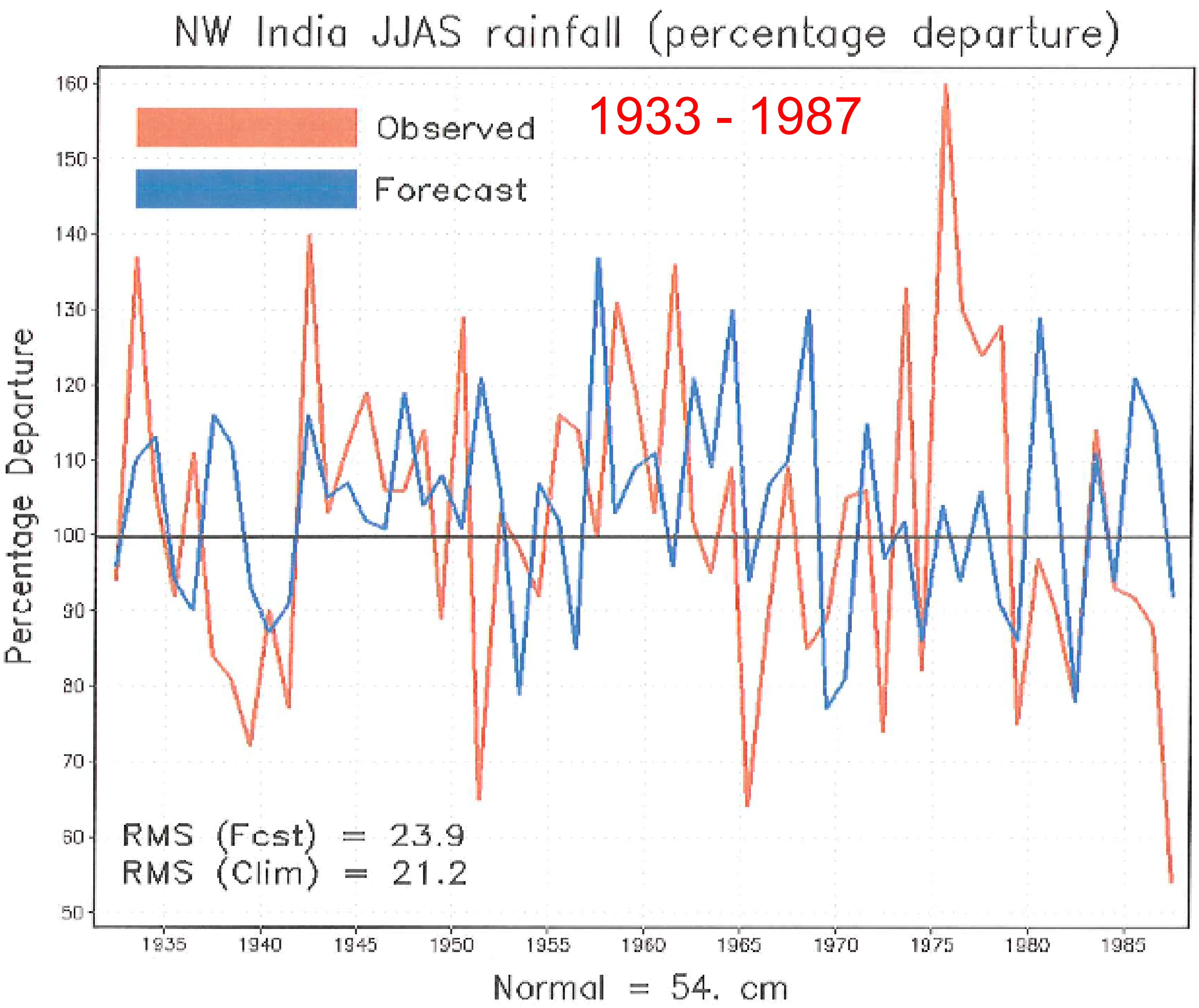
1904: Gilbert Walker joined IMD (DGO: 1904-1924)
Regression Equations to predict ISMR
Discovered Southern Oscillation & Northern Oscillations

1924-2011: IMD: Regression Equations (16,8,6 predictors)

2009: Artificial skill; too many predictors; Data fishing (DelSole)

2012: IMD: Regression Equations + Dynamical Models

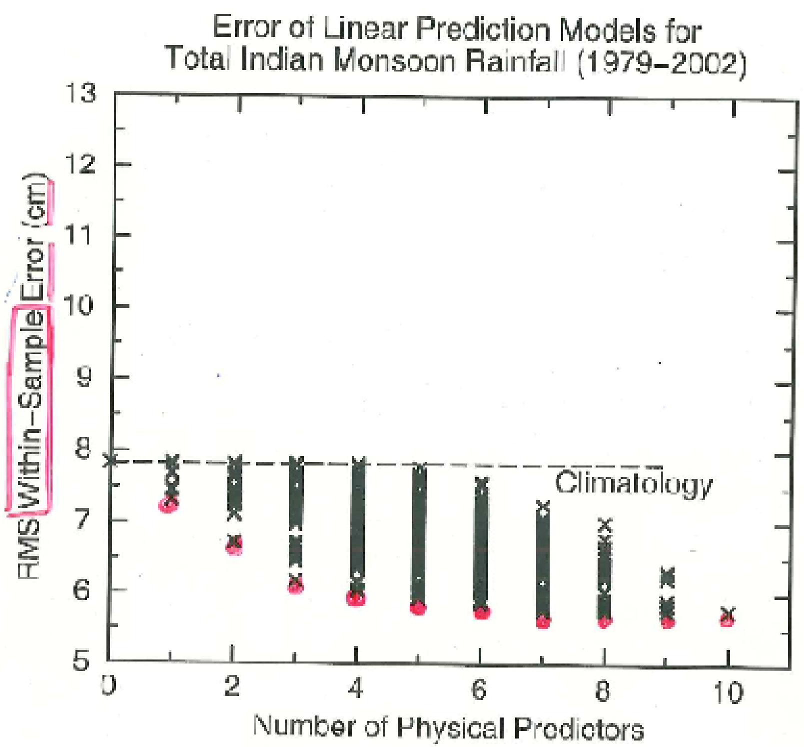

Observed and Forecast(IMD) All-India JJAS rainfall (% Normal)
Observed
Forecast
Fcst-Obs
1988 - 2010
% Normal
120
115
110
105
100
95
90
85
80
RMS (Fcst) = 9.2%
RMS (Clim) = 9.0%
1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010

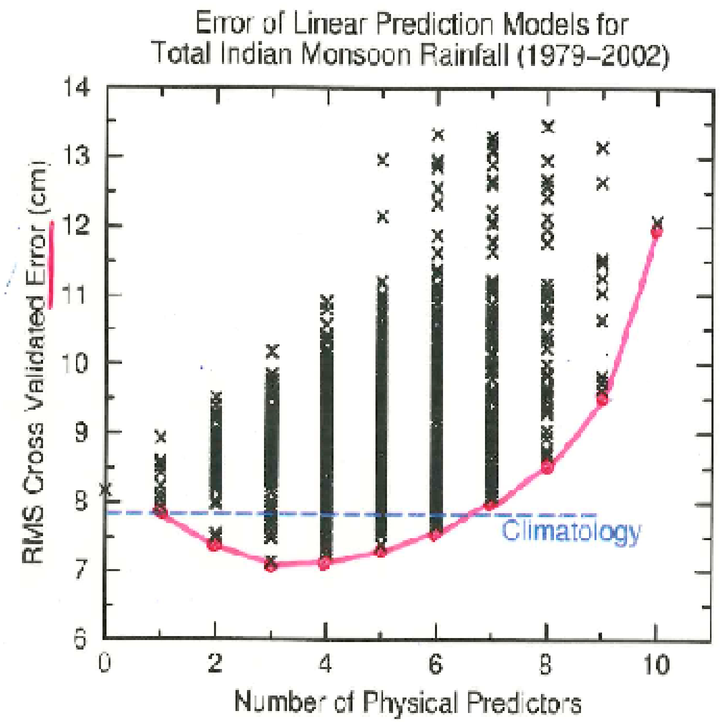

NW India JJAS rainfall (percentage departure)
1933 - 1987
Observed
Forecast
Percentage Departure
160
150
140
130
120
110
100
90
80
70
60
50
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
RMS (Fcst) = 23.9
RMS (Clim) = 21.2
Normal = 54. cm

Possible causes for failure of skillful empirical forecasts:

1. Questionable procedures for selecting predictors (fishing!)

2. Too many predictors (over-fitting)


Error of Linear Prediction Models for
Total Indian Monsoon Rainfall (1979–2002)
RMS Within-Sample Error (cm)
Climatology
Number of Physical Predictors


Error of Linear Prediction Models for
Total Indian Monsoon Rainfall (1979–2002)
RMS Cross Validated Error (cm)
Climatology
Number of Physical Predictors

DelSole and Shukla (2012)

•**Canonical Correlation Analysis (CCA) for 1880-1959 for May SST & Indian Subdivisional rainfall. (No Skill)**

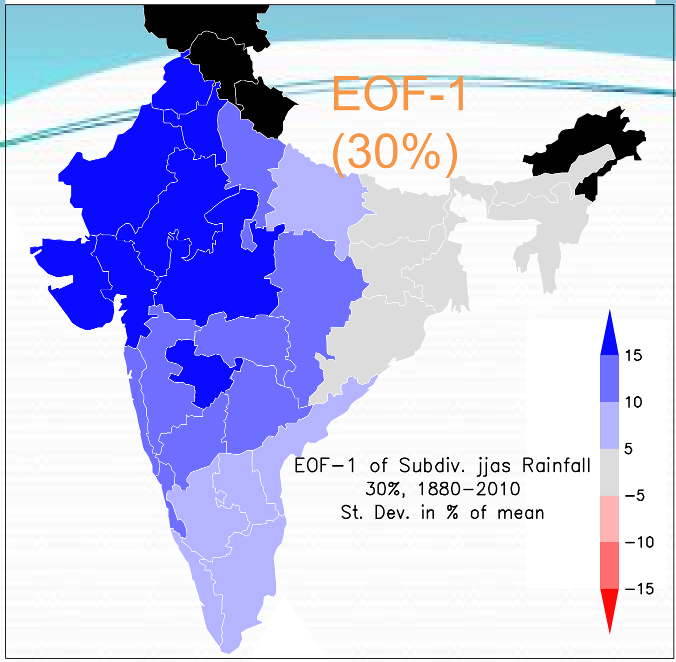
•**CCA: May SST and all India rainfall (1880-1959): 3 SST patterns; significant skill. In-sample CC = 0.54.**

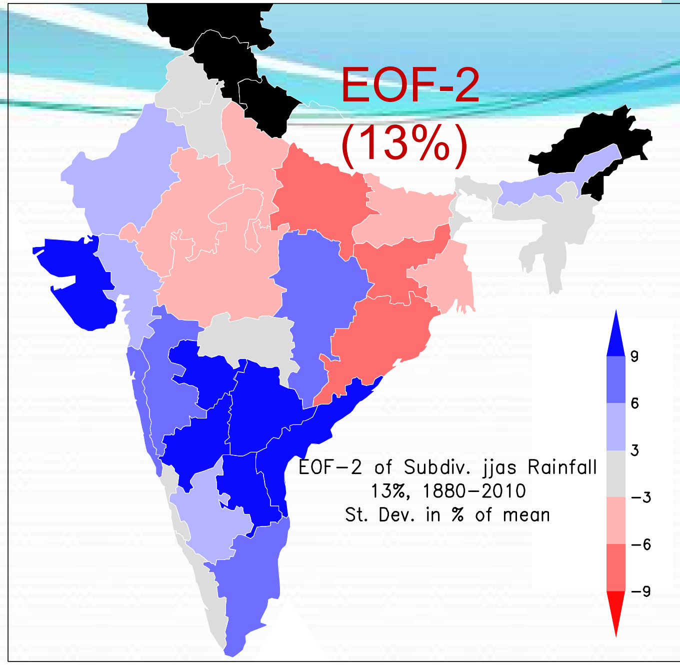
(This is the highest possible CC using antecedent SST.)

•**No skill in independent sample for 1960-2005.**

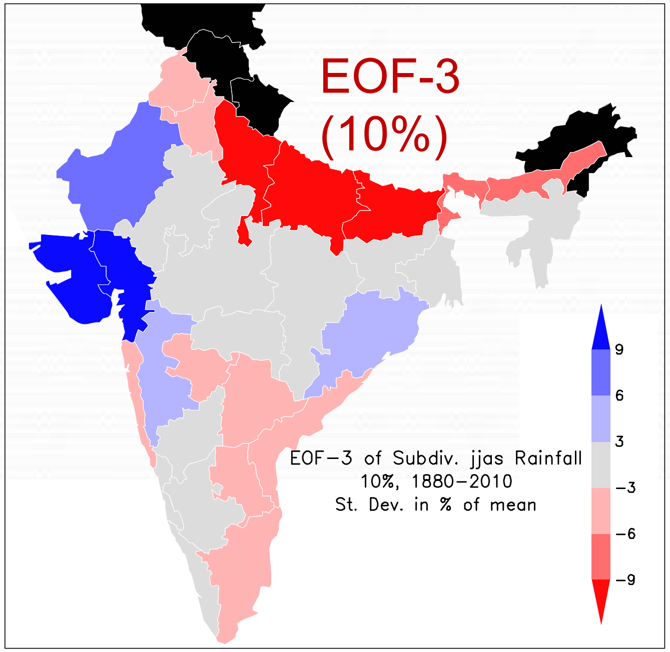
No skill even in the In-Sample CCA for 1960-2005

(Statistical prediction has no future!)

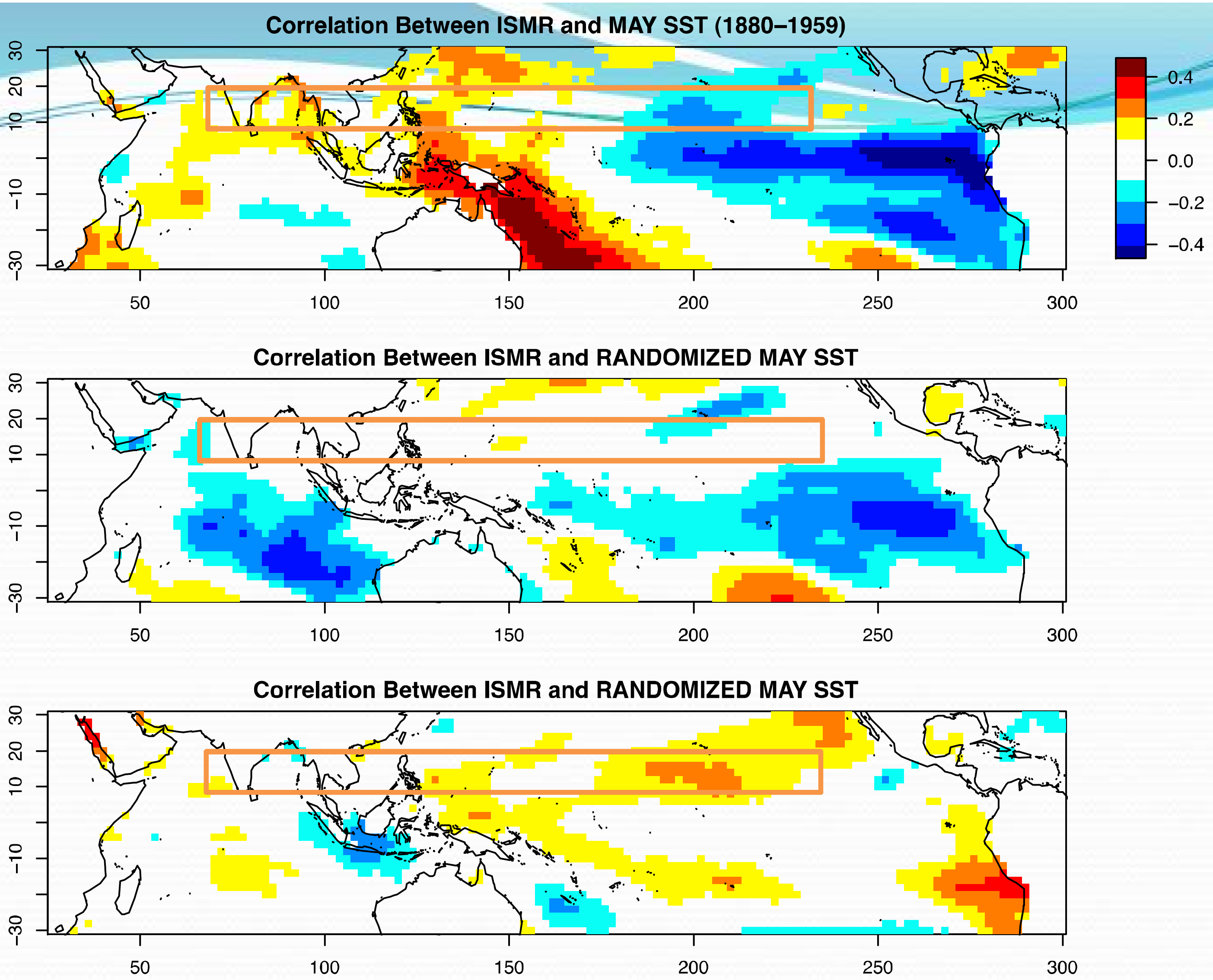




CCA: NO Skill



EOFs of subdivisional JJAS rainfall (1880-2010)



Correlation between JJAS all-Indian Monsoon Rainfall and May tropical sea surface temperature during the period 1880-1959 (top), and analogous correlation maps derived from randomized May SST fields (middle and bottom panels). The same color scale is used in each panel. Insignificant correlations have been masked out.

DelSole and Shukla (2012)

- Canonical Correlation Analysis (CCA) for 1880-1959 for May SST & Indian Subdivisional rainfall. (No Skill)

- CCA: May SST and all India rainfall (1880-1959): 3 SST patterns; significant skill. In-sample CC = 0.54.

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Prospects for Dynamical Prediction of JJAS Mean Monsoon Rainfall

- Model Fidelity and Predictability

- Hindcasts using CFS and ENSEMBLES Models

Hypothesis

Models that simulate climatology "better" make better predictions.

Definition: Fidelity refers to the degree to which the climatology of the forecasts (including the mean and variance) matches the observed climatology

Climate Model Fidelity and Predictability

Relative Entropy: The relative entropy between two distributions, $p_1(x)$ and $p_2(x)$, is defined as

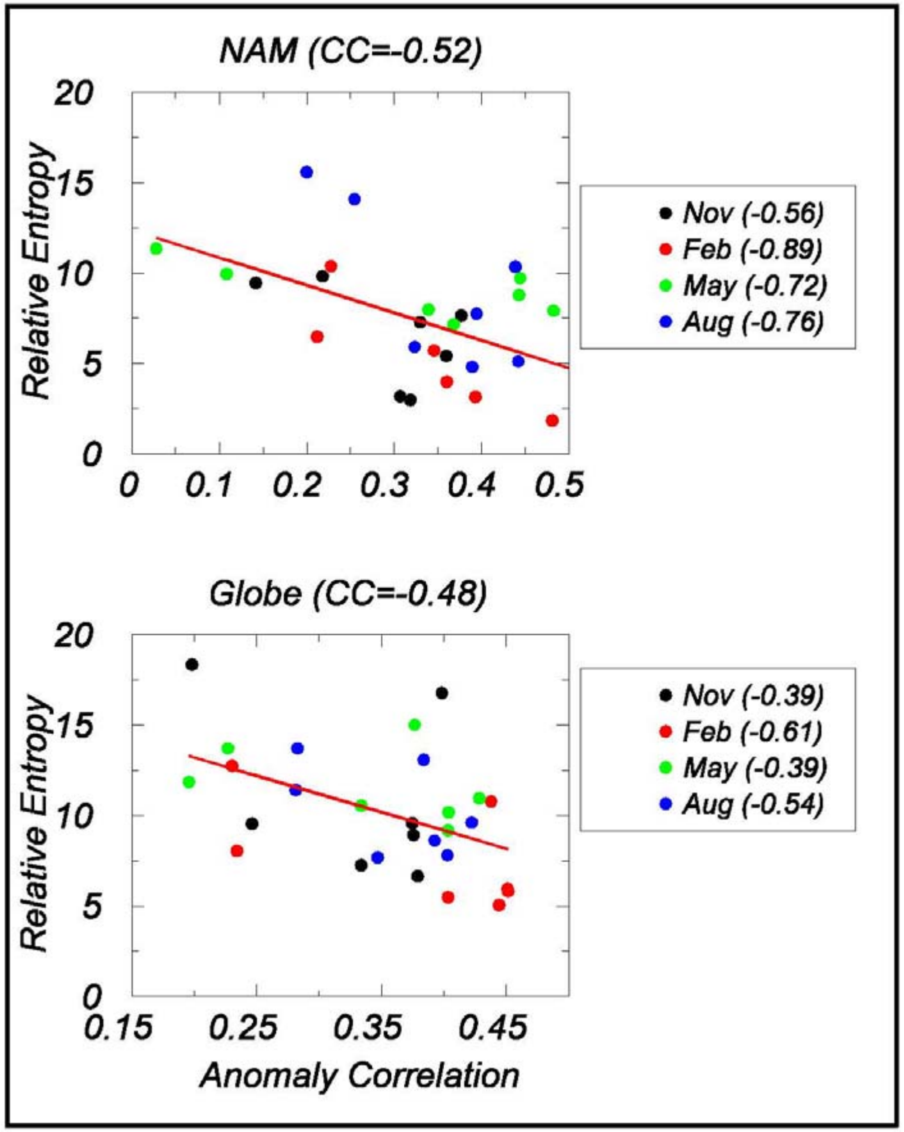
$$R(p_1, p_2) = \int_{R^M} p_1 \log\left(\frac{p_1}{p_2}\right) dx \qquad (1)$$

where the integral is a multiple integral over the range of the *M*-dimensional vector *x*.

$$R(p_1, p_2) = \frac{1}{2}\log\left(\frac{|\Sigma_2|}{|\Sigma_1|}\right) + \frac{1}{2} Tr\left\{\Sigma_1\left(\Sigma_2^{-1} - \Sigma_1^{-1}\right)\right\} + \sum_{k=1}^{4}\frac{1}{2}\left(\mu_1^k - \mu_2^k\right)^T \Sigma_1^{-1}\left(\mu_1^k - \mu_2^k\right) \qquad (2)$$

where μ_j^k is the mean of $p_j(x)$ in the *k*th season, representing the annual cycle, Σj is the covariance matrix of $p_j(x)$, assumed independent of season and based on seasonal anomalies. The distribution of observed temperature is appropriately identified with p_1, and the distribution of model simulated temperature with p_2.

Fidelity vs. Skill



Fidelity vs. Skill
DEMETER 1980-2001
Seasonal Forecasts

7 models, 4 initial conditions

Lead Time = 0 months

Fidelity and Skill are related.

Models with poor climatology tend to have poor skill.

Models with better climatology tend to have better skill.

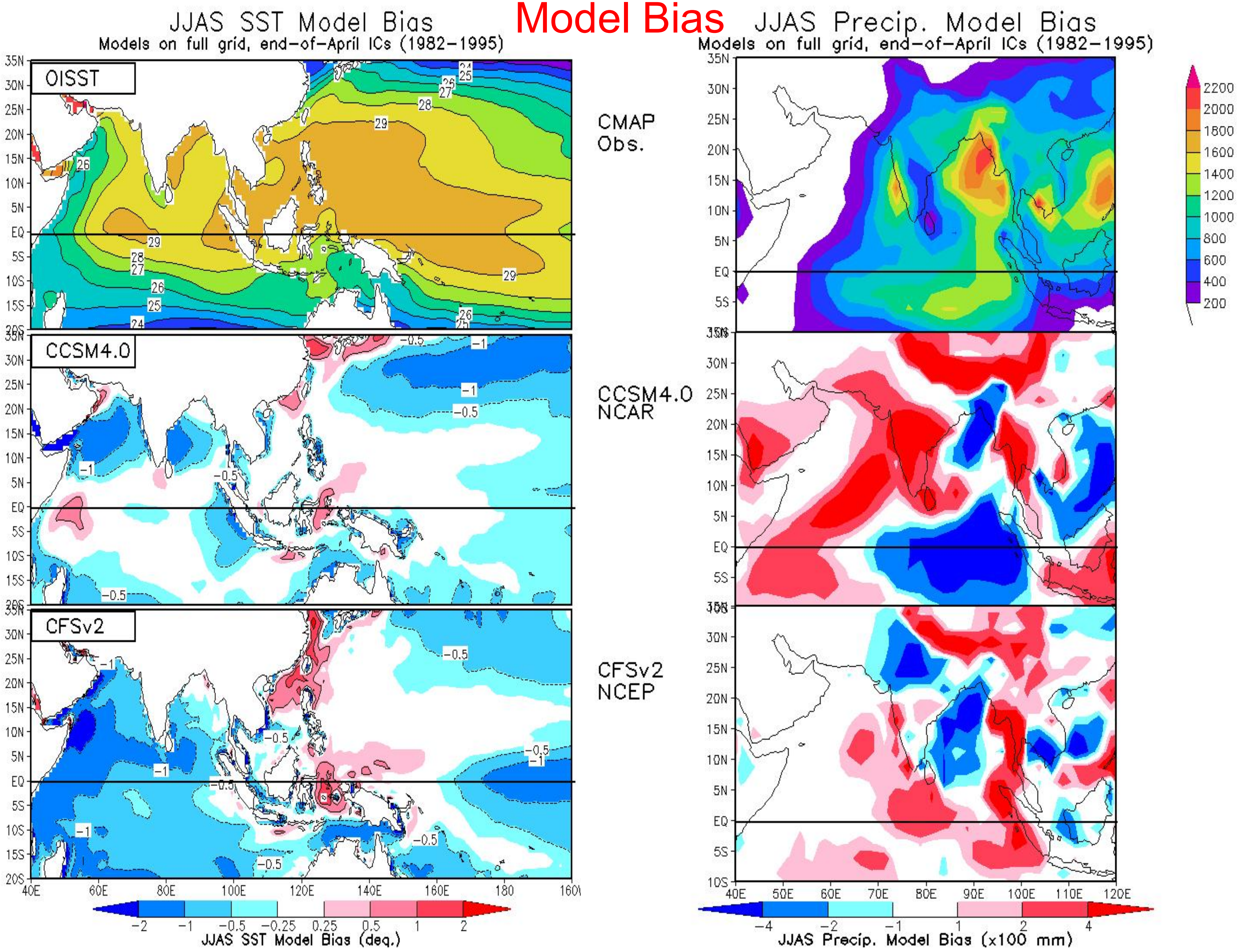
Courtesy of Tim DelSole

Fundamental barriers to advancing weather and climate diagnosis and prediction on timescales from days to years are (partly) (almost entirely?) attributable to gaps in knowledge and the limited capability of contemporary operational and research numerical prediction systems to represent precipitating convection and its multi-scale organization, particularly in the tropics.

(Moncrieff, Shapiro, Slingo, Molteni, 2007)

Low skills in current dynamical seasonal predictions are not due to intrinsic limits of predictability, but due to large errors in ICs and models.
(a la NWP: large dedicated effort; slow & steady progress)

Model Bias



JJAS SST Model Bias
Models on full grid, end-of-April ICs (1982–1995)
JJAS Precip. Model Bias
Models on full grid, end-of-April ICs (1982–1995)
OISST
CCSM4.0
CFSv2
CMAP Obs.
CCSM4.0 NCAR
CFSv2 NCEP
JJAS SST Model Bias (deg.)
JJAS Precip. Model Bias (x100 mm)

Dynamical Seasonal Prediction (DSP)

Source of predictability: Dynamical memory of atmos. IC
+ Boundary forcing (SST, SW, snow, sea ice)

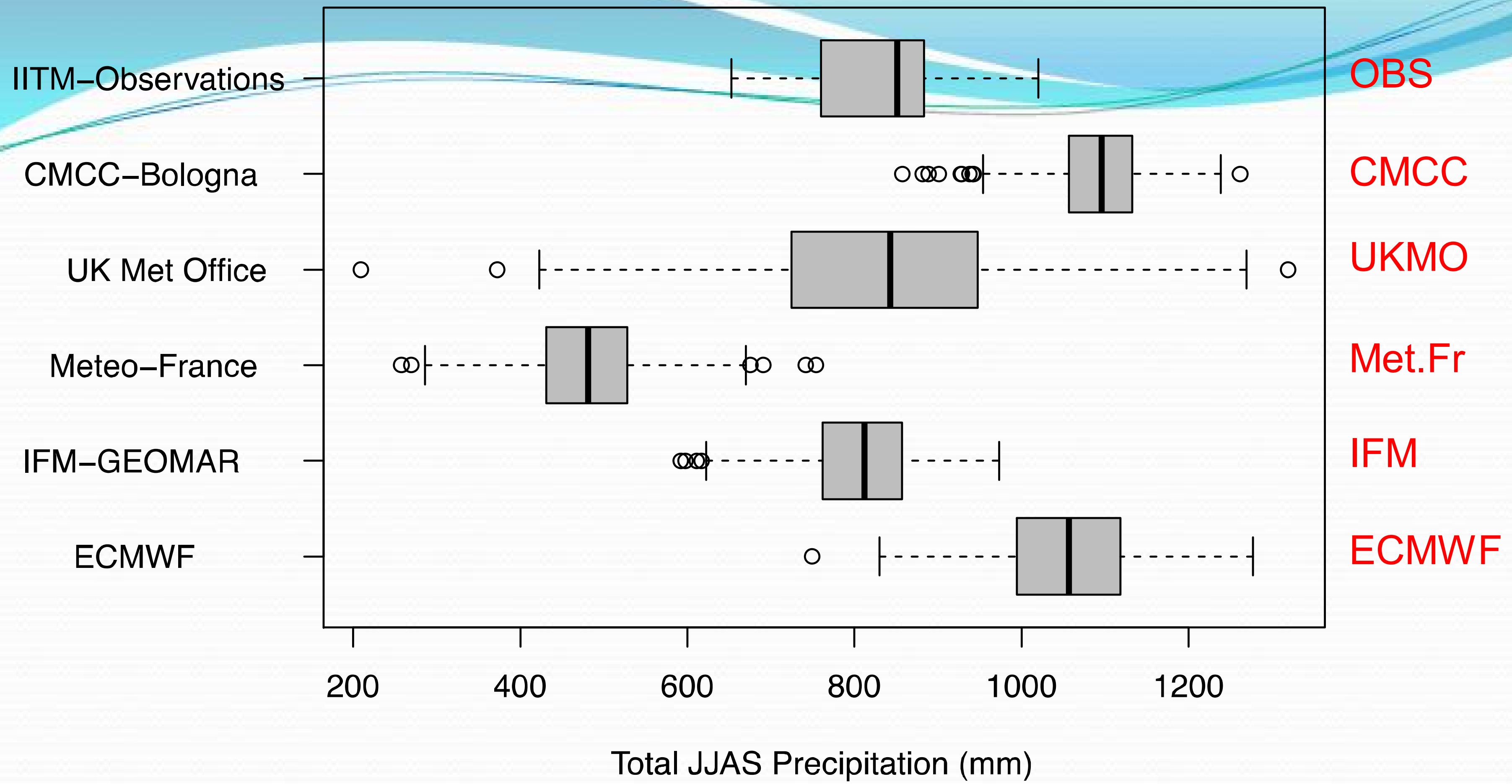
DSP = NWP + IC of Ocean, Land, Atmosphere

- *dynamically coupled and consistent IC*
- *Global ocean (especially upper ocean); sea ice (volume)*
- *Global Atmos. including stratosphere (IC)*
- *Global GHG (especially CO_2, O_3)*
- *Global land (soil moisture, vegetation, snow depth) IC*

Tier 1: Fully coupled models (CGCM) to predict Boundary Forcing

Tier 2: Predict Boundary Forcing separately; use AGCM

- **(NWP=Atmos. IC + SST IC)**



Box- and whisker- plot of JJAS all India rainfall (mm) for 1960-2005: Observed (IITM) and hindcasts from ENSEMBLES project. Centerline is the median, first and last quartile as the ends of the rectangle, and data not included in the whiskers are open circles.

Analysis of Variance: F as a measure of predictability
5 CGCMs, 46 years, 9 ensembles

Measure of predictability is

$$F = E\frac{\hat{\sigma}_S^2}{\hat{\sigma}_N^2}$$

where

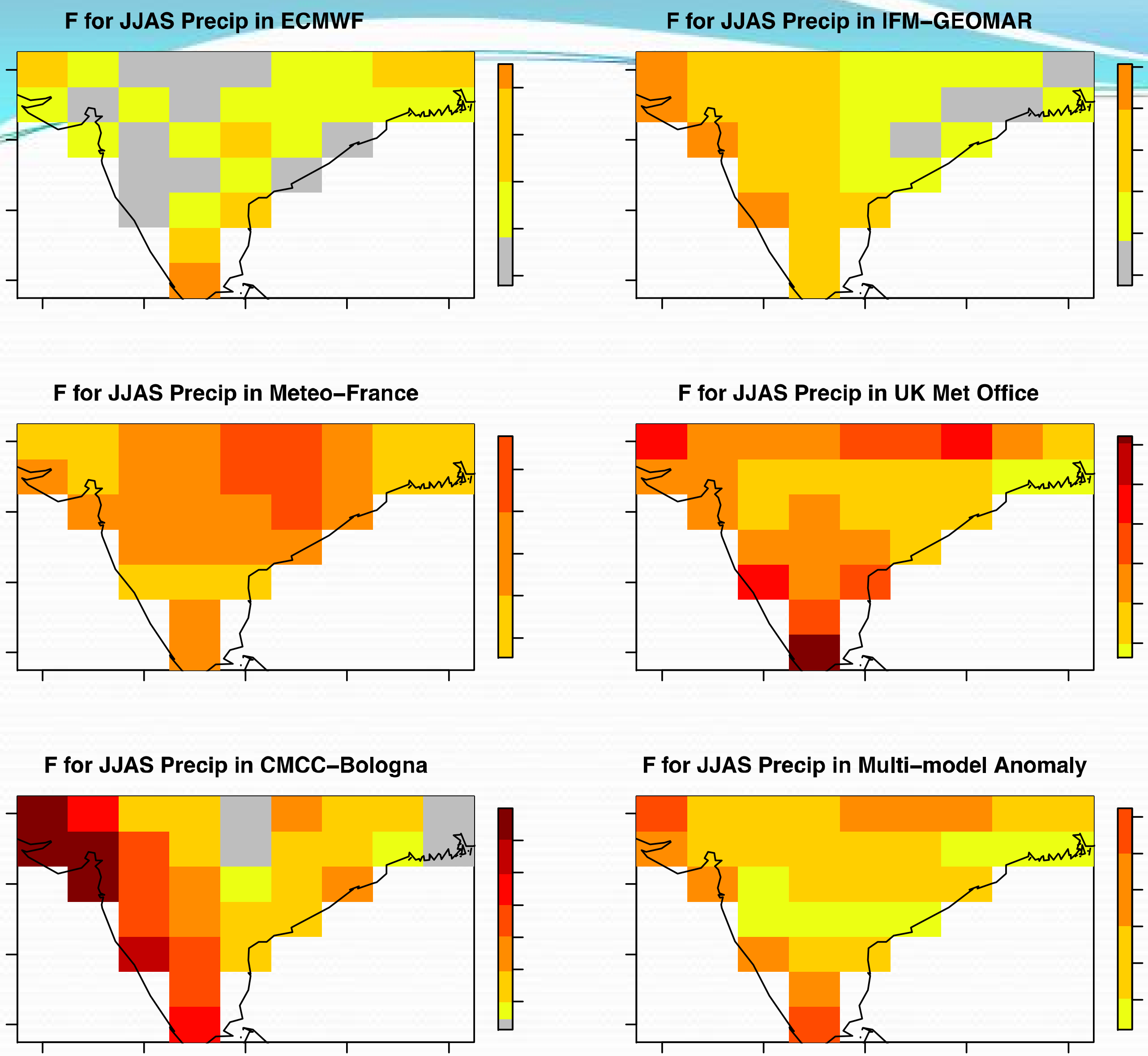
$$\hat{\sigma}_S^2 = \frac{1}{Y-1}\sum_{y=1}^{Y}\left(P_{y,e} - \overline{\overline{P}}\right)^2$$

$$\hat{\sigma}_N^2 = \frac{1}{Y(E-1)}\sum_{y=1}^{Y}\sum_{e=1}^{E}\left(P_{y,e} - \overline{P}_y\right)^2$$

$$\overline{P}_y = \frac{1}{E}\sum_{e=1}^{E} P_{y,e}$$

$$\overline{\overline{P}} = \frac{1}{Y}\sum_{y=1}^{Y}\overline{P}_y$$

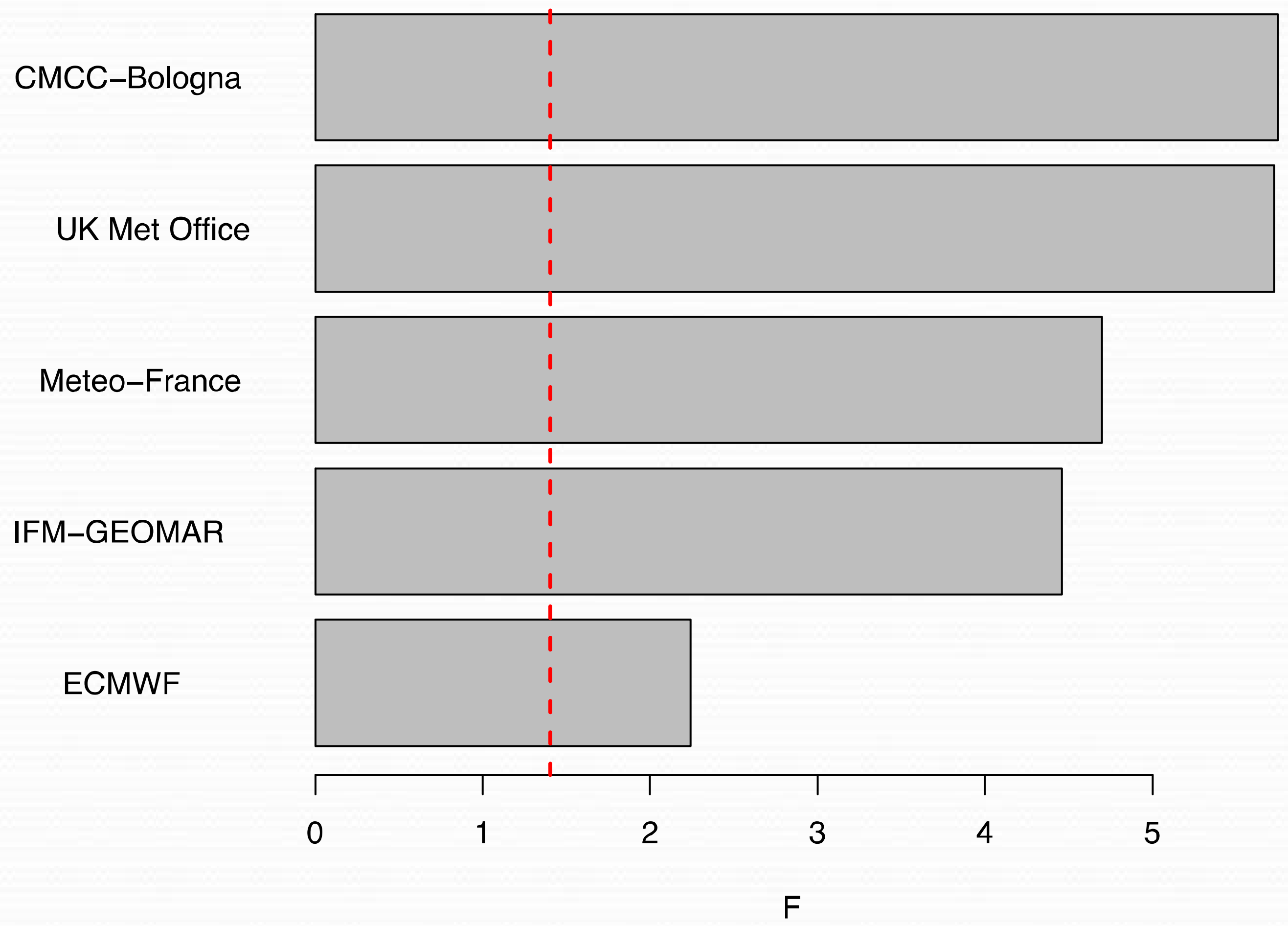
For samples drawn independently from the same normal distribution, and for $Y = 46$ and $E = 9$, the 5% significance threshold of F is 1.40

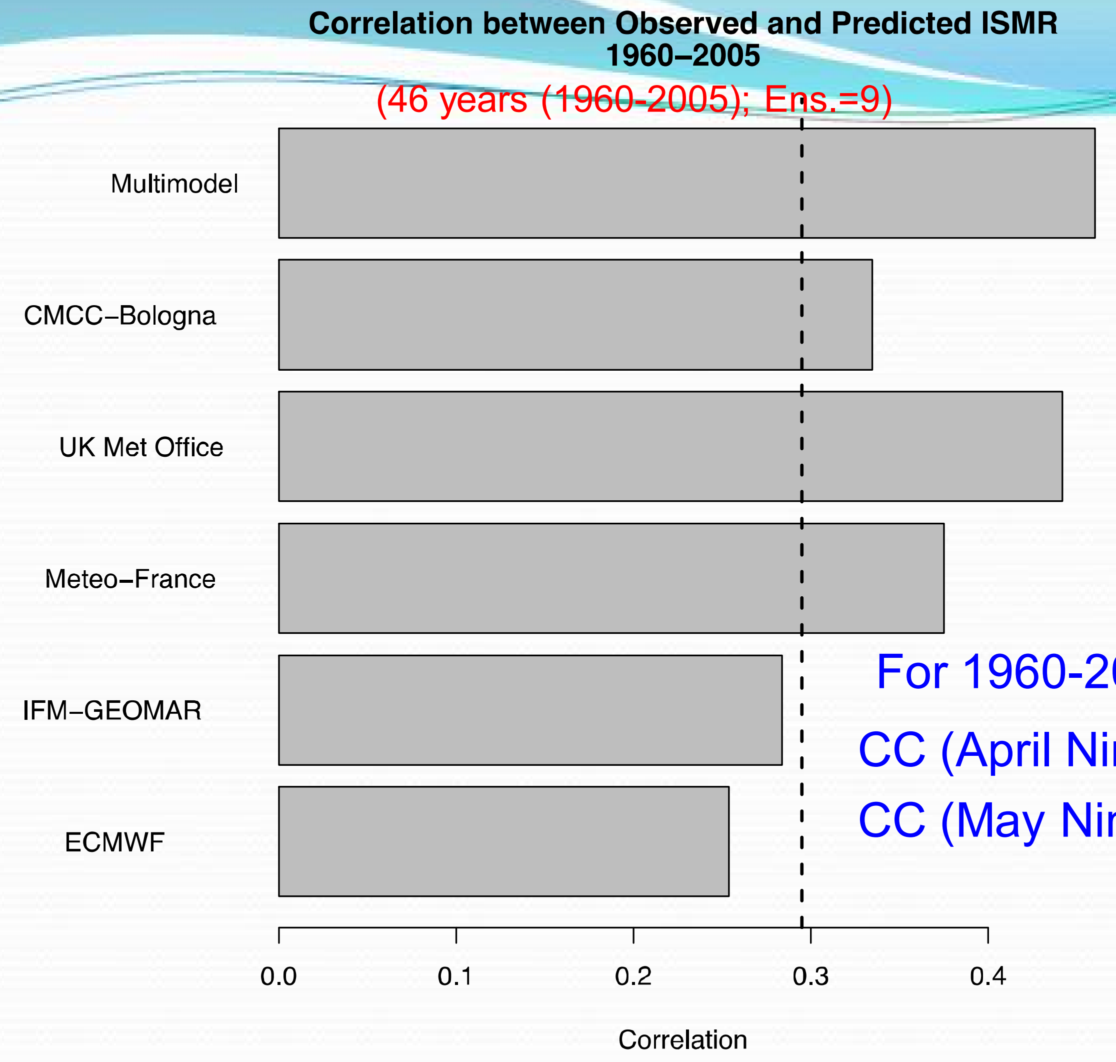


F-values for JJAS precip. For 46-years and 9 ensemble members the 5% significance is F=1.4. Gray color indicates not statistically significant at 95% confidence interval.

F values for JJAS All–India Rainfall from ENSEMBLES

(46 years (1960-2005); Ens.=9)





For 1960-2005 Obs,

CC (April Nino3, ISMR): −0.18

CC (May Nino3, ISMR): −0.21

Correlation between observed and predicted JJAS all-India rainfall for hindcasts in the ENSEMBLES data set for the period 1960-2005. All-India rainfall in dynamical models is defined as the total land precipitation within 70E − 90E and 10N − 25N .

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CREW Center for Research on Environment and Water

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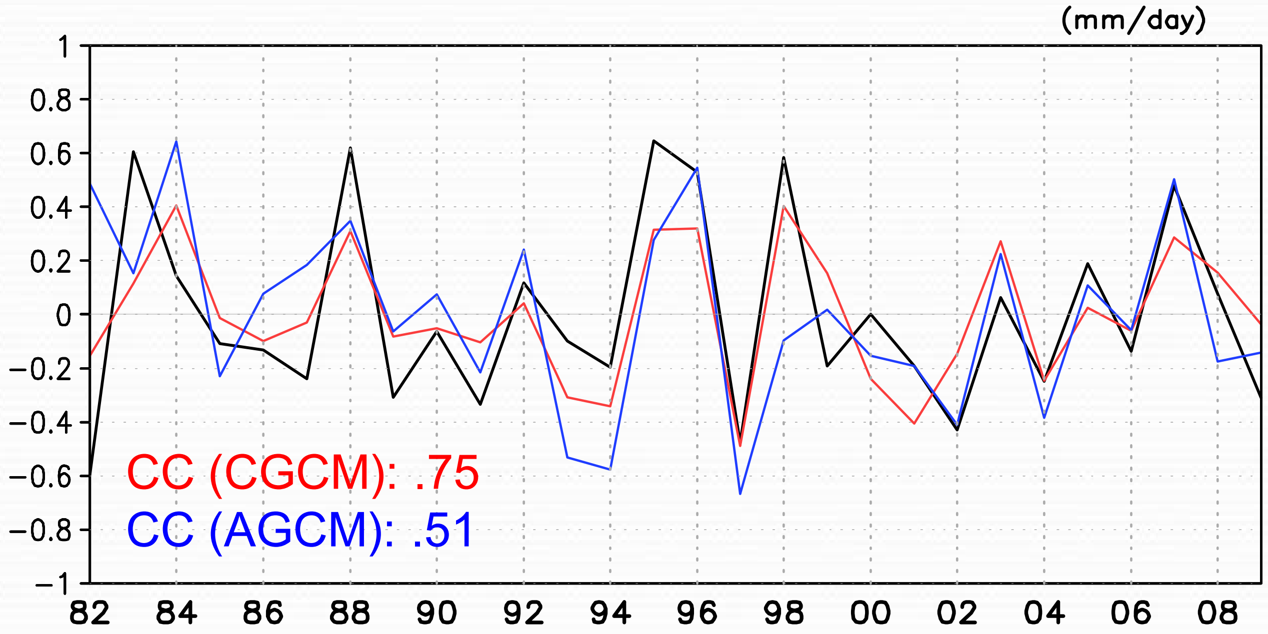
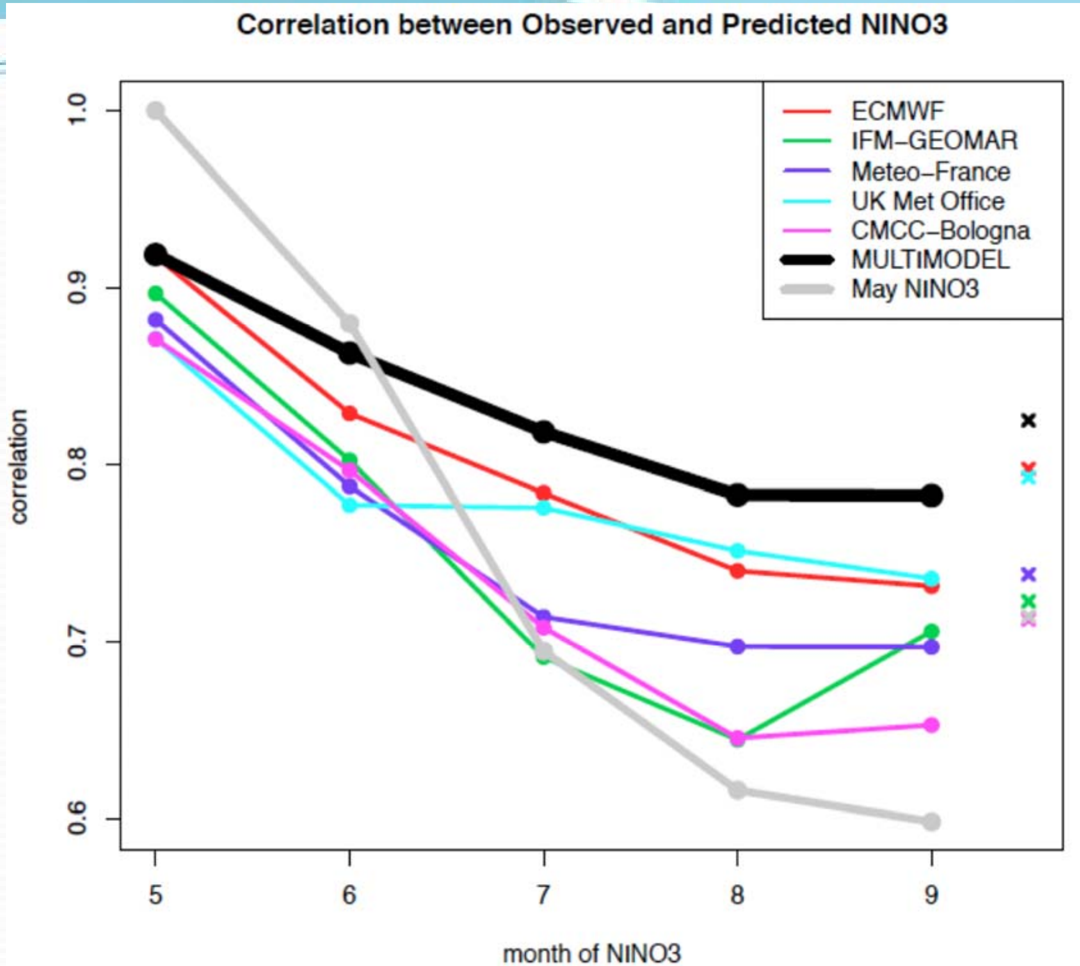
Seasonal Forecasts (1Apr IC) with CGCM(CFS) & AGCM(GFS)

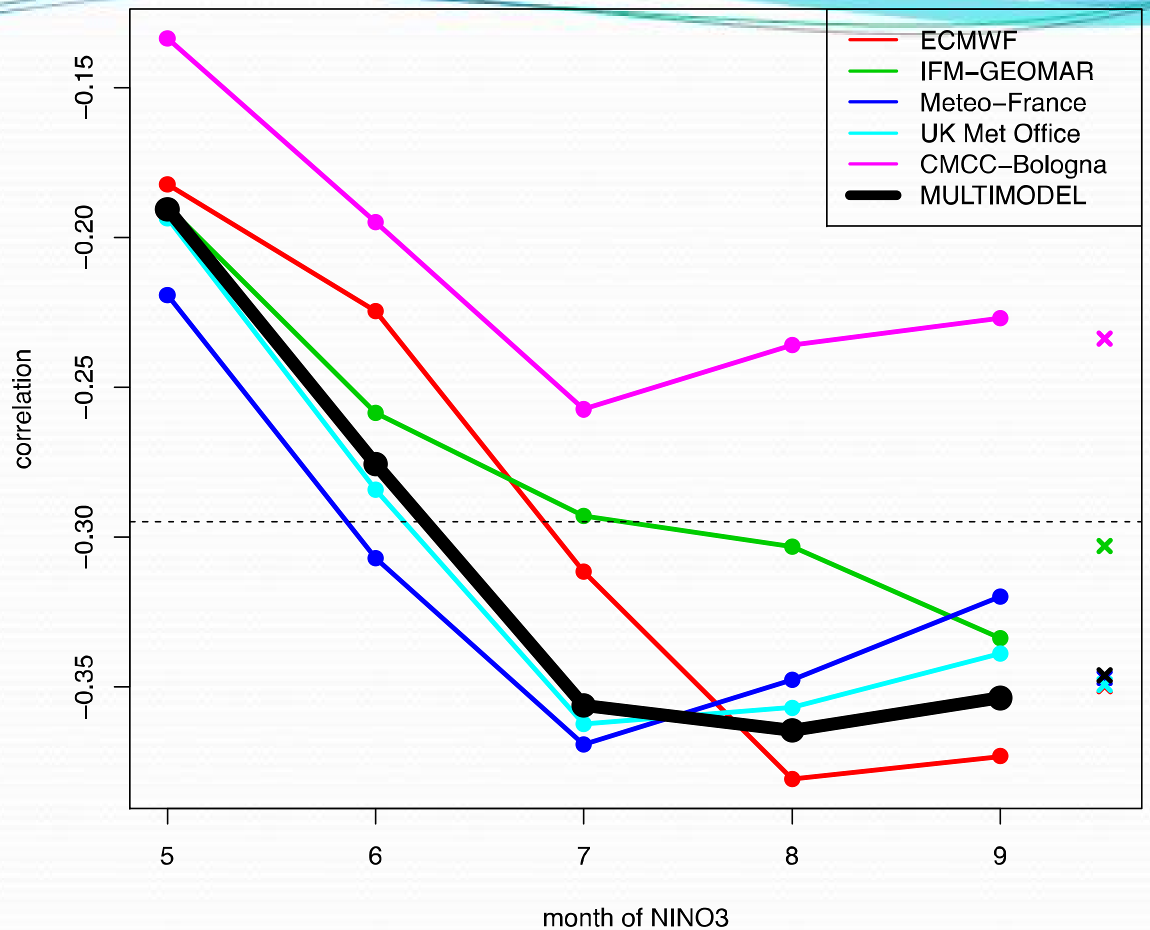
ISMR (40E–120E,10S–35N)



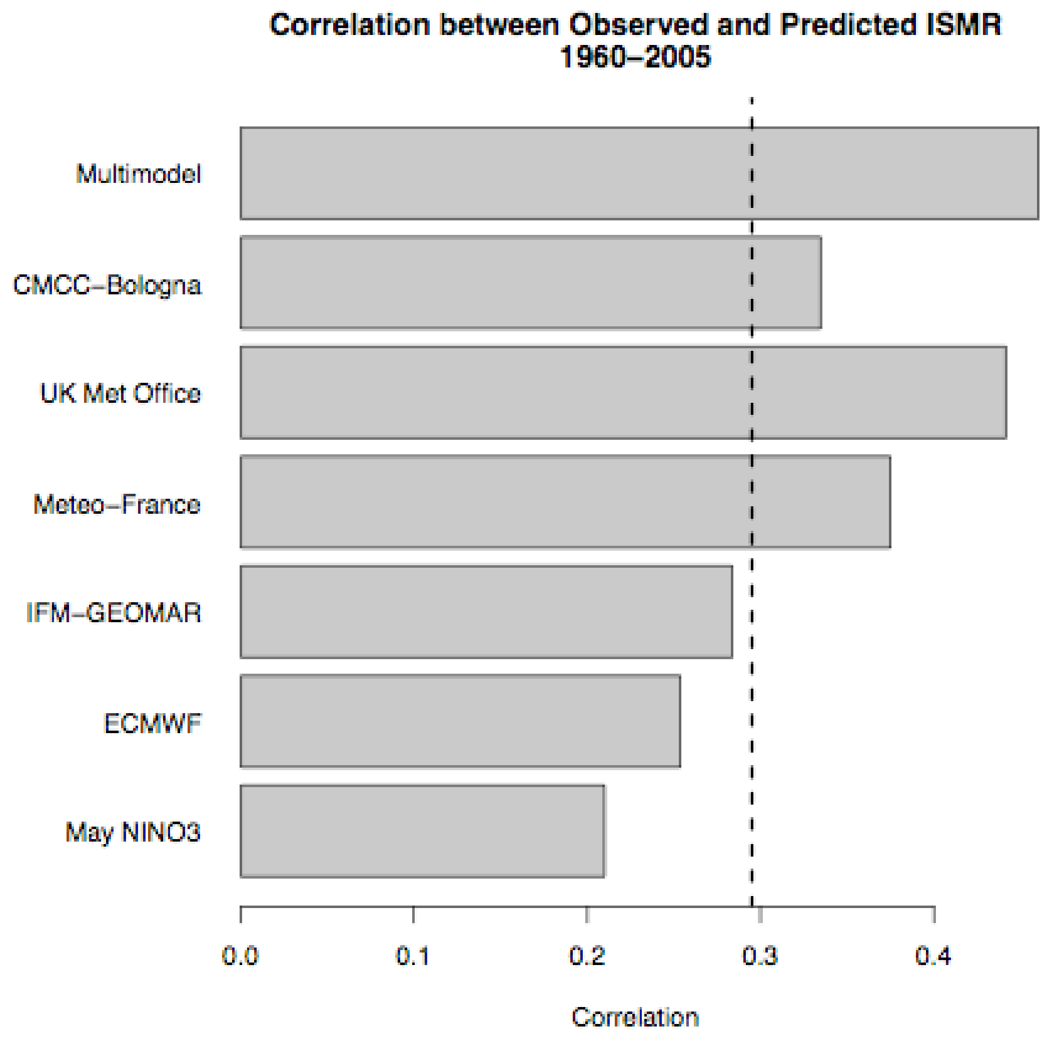
	Observation	CFS(ORA–S4)–Coupled	GFS(ORA–S4)–AGCM
MEAN	5.1	5.6	5.5
StdDev	0.35	0.24	0.34
ACC		0.75	0.51
RMSE		0.23	0.34



Correlation between observed NINO3, and ensemble mean NINO3 predicted by the ENSEMBLES models, for hindcasts in the period 1960-2005, as a function of calendar month. Also shown is the correlation between observed NINO3 and the least squares prediction of NINO3 based on the observed May NINO3 value (thick grey). The 'x'-symbols on the far right give the correlations between the observed and predicted JJAS NINO3 index.



Correlation between observed JJAS all-India rainfall, and ensemble mean model predicted NINO3 index, for hindcasts from the ENSEMBLES data set during 1960-2005. The 'x'-symbols on the far right give the correlations for the JJAS NINO3 index in each model. The correlation with the mean of all models is shown as "multimodel."



(46 years (1960-2005); Ens.=9)

For 1960-2005 Obs,

CC (April Nino3, ISMR): −0.18

CC (May Nino3, ISMR): −0.21

Correlation between observed and predicted JJAS all-India rainfall for hindcasts in the ENSEMBLES data set for the period 1960-2005. All-India rainfall in dynamical models is defined as the total land precipitation within 70E − 90E and 10N − 25N .

Last row shows empirical prediction using observed May NINO3.

Summary

•Canonical Correlation Analysis (CCA) for 1880-1959 for May SST & Indian Subdivisional rainfall. (No Skill)

•CCA: May SST and all India rainfall (1880-1959): 3 SST patterns; significant skill. In-sample CC = 0.54.

(This is the highest possible CC using antecedent SST.)

•No skill in independent sample for 1960-2005.

No skill even in the In-Sample CCA for 1960-2005

(Statistical prediction has no future!)

Summary

• **Model's ability to simulate SST and Q in West Pacific and Indian Ocean are critical for accurate monsoon prediction.**

• **Analysis of Variance (F test) calculation for 5 coupled model ("ENSEMBLES" Project) seasonal predictions for 46 years, 9 member ensembles show high predictability ISMR, but skill of hindcast for 1960-2005 is rather modest.**

• **Coupled O-A models for monsoon prediction is the future.**

THANK YOU!

ANY QUESTIONS?

Statements & Conjectures

- **The apparent breakdown of ENSO – Monsoon correlation could be due, in large part, to sampling variability.**

- **Realistic Land ICs enhance weekly-monthly predictions**

(high resolution land rainfall data required)

- **Model predictability depends on model's fidelity to simulate climate.**

- **Intraseasonal variations appear to be due, in part, to coupled convection-dynamics interactions. Realistic simulation of diabatic heat sources in West-Pac. & IO will be required for ISO prediction.**

Statements & Conjectures

- **ENSO prediction skill is sensitive to ocean IC (NCEP, ECMWF).**

- **AGCM forced with SST predicted by coupled O-A models have comparable skill, but larger variance.**

(coupling damps the heat flux variability)

- **Low skills in current dynamical seasonal predictions are not due to intrinsic limits of predictability, but due to large errors in ICs and models.**

(a la NWP: large dedicated effort; slow & steady progress)

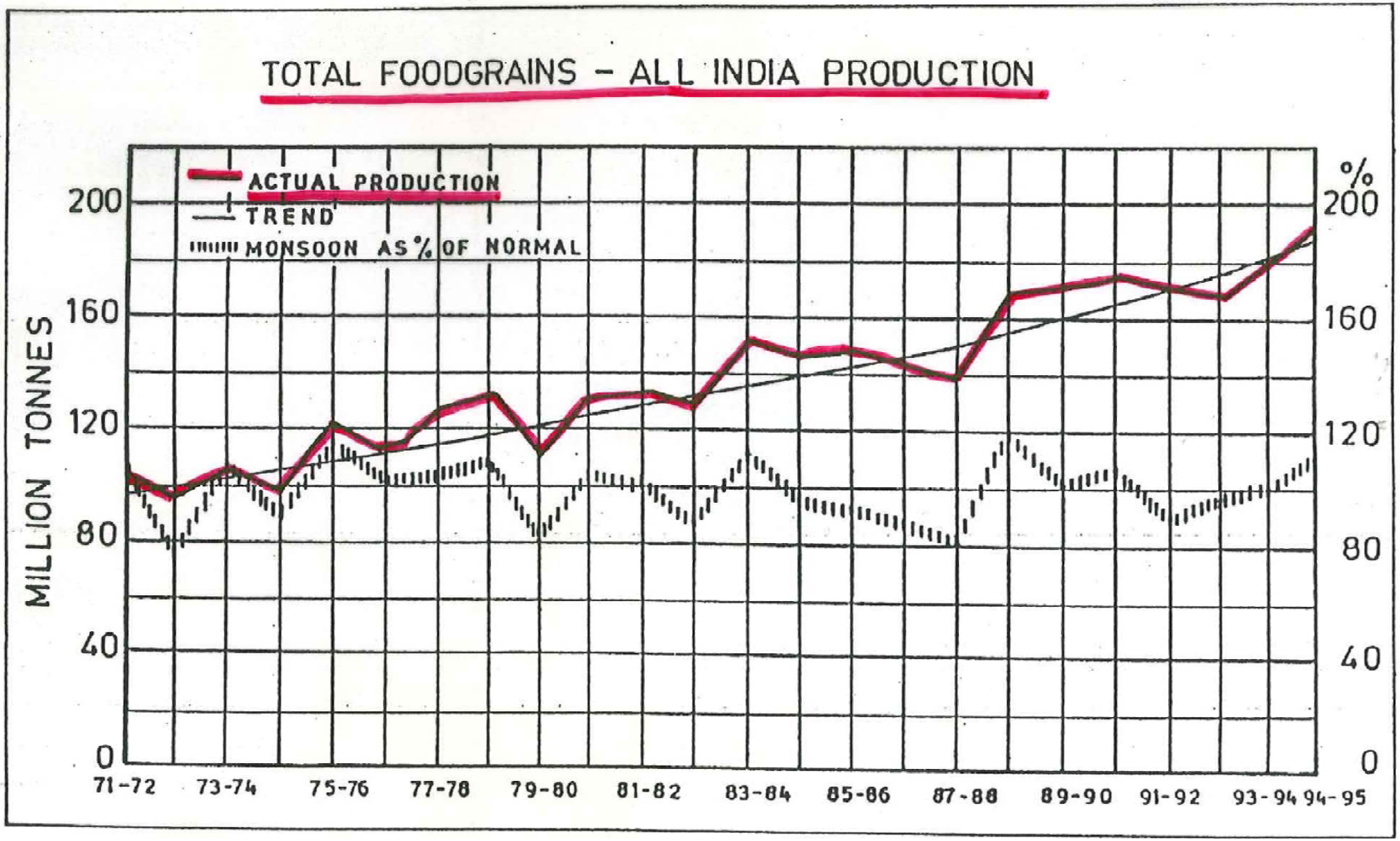
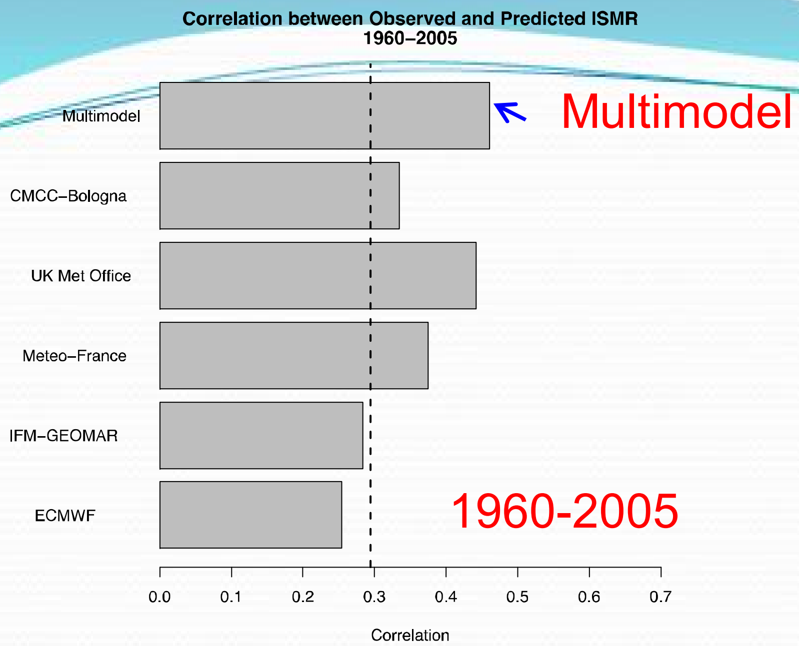
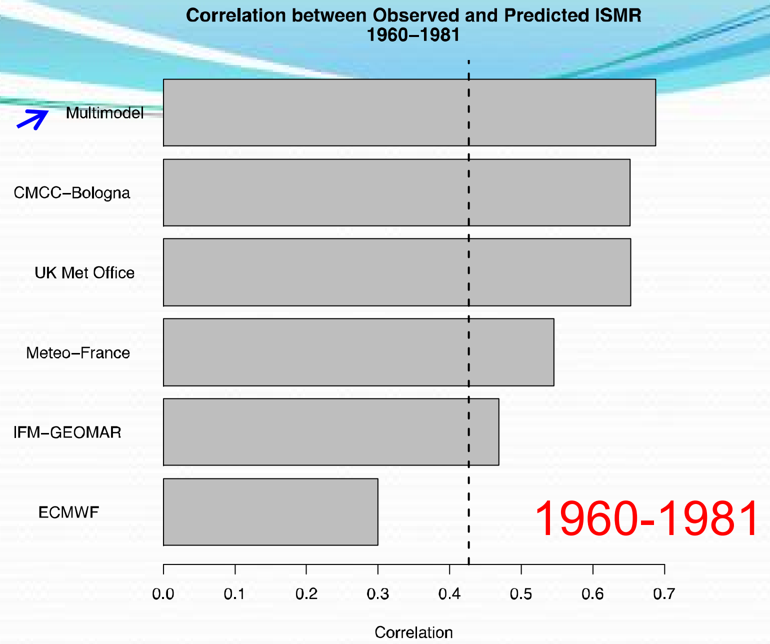

TOTAL FOODGRAINS - ALL INDIA PRODUCTION
ACTUAL PRODUCTION
TREND
MONSOON AS % OF NORMAL
MILLION TONNES
%
200
160
120
80
40
0
71-72
73-74
75-76
77-78
79-80
81-82
83-84
85-86
87-88
89-90
91-92
93-94
94-95

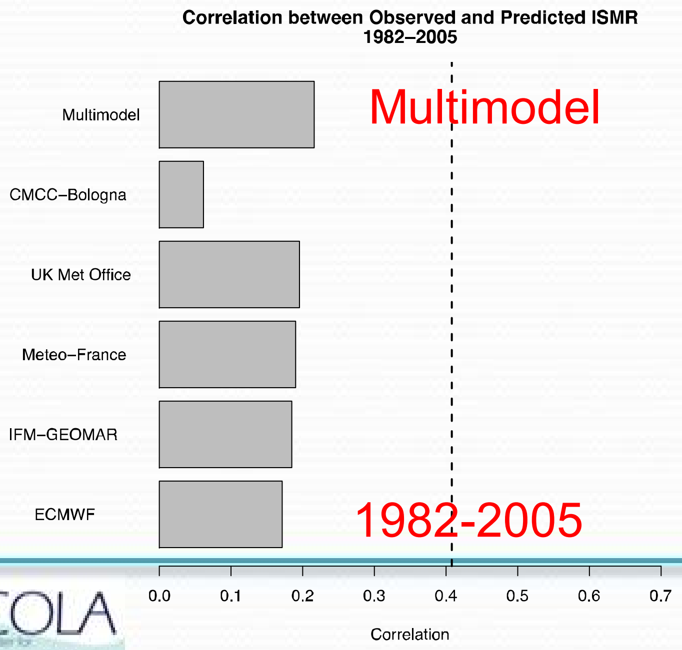
Fig. 16



Correlation between Observed and Predicted ISMR
1960–2005
Multimodel
CMCC–Bologna
UK Met Office
Meteo–France
IFM–GEOMAR
ECMWF
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Correlation
Multimodel
1960-2005



Correlation between Observed and Predicted ISMR
1960–1981
Multimodel
CMCC–Bologna
UK Met Office
Meteo–France
IFM–GEOMAR
ECMWF
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Correlation
1960-1981

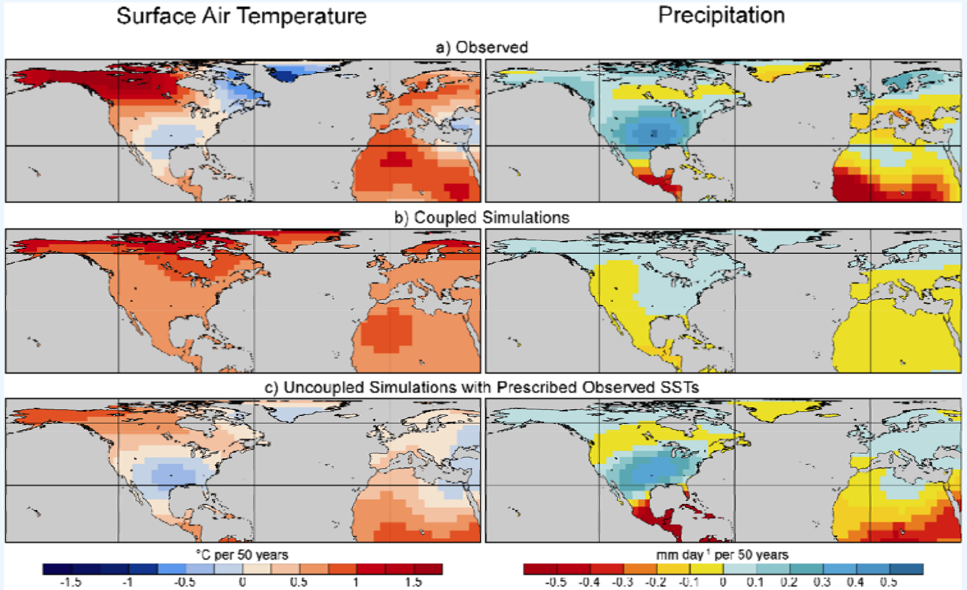


Correlation between Observed and Predicted ISMR
1982–2005
Multimodel
CMCC–Bologna
UK Met Office
Meteo–France
IFM–GEOMAR
ECMWF
Multimodel
1982-2005
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Correlation

Correlation between JJAS All-India Rainfall and SST indices

	1880-1959			1960-2005		
SST Predictor	April	May	JJAS	April	May	JJAS
canonical predictor trained in 1960-2005	–	–	–	NA	NA	0.39*
canonical predictor trained in 1880-1959	0.47*	0.54	0.66	0.10	0.15	**0.34**
NINO3	-0.21	**-0.41**	**-0.60**	-0.18	-0.21	**-0.45**
canonical tendency predictor trained in 1960-2005 (w/ Jan)	–	–	–	0.46*	0.54*	0.6
NINO3 tendency (w/ Jan)	**0.24**	**0.43**	**0.60**	**0.44**	0.38	**0.51**

Trends of annual-mean Surface Air Temperatures and Precipitation over 1951-1999



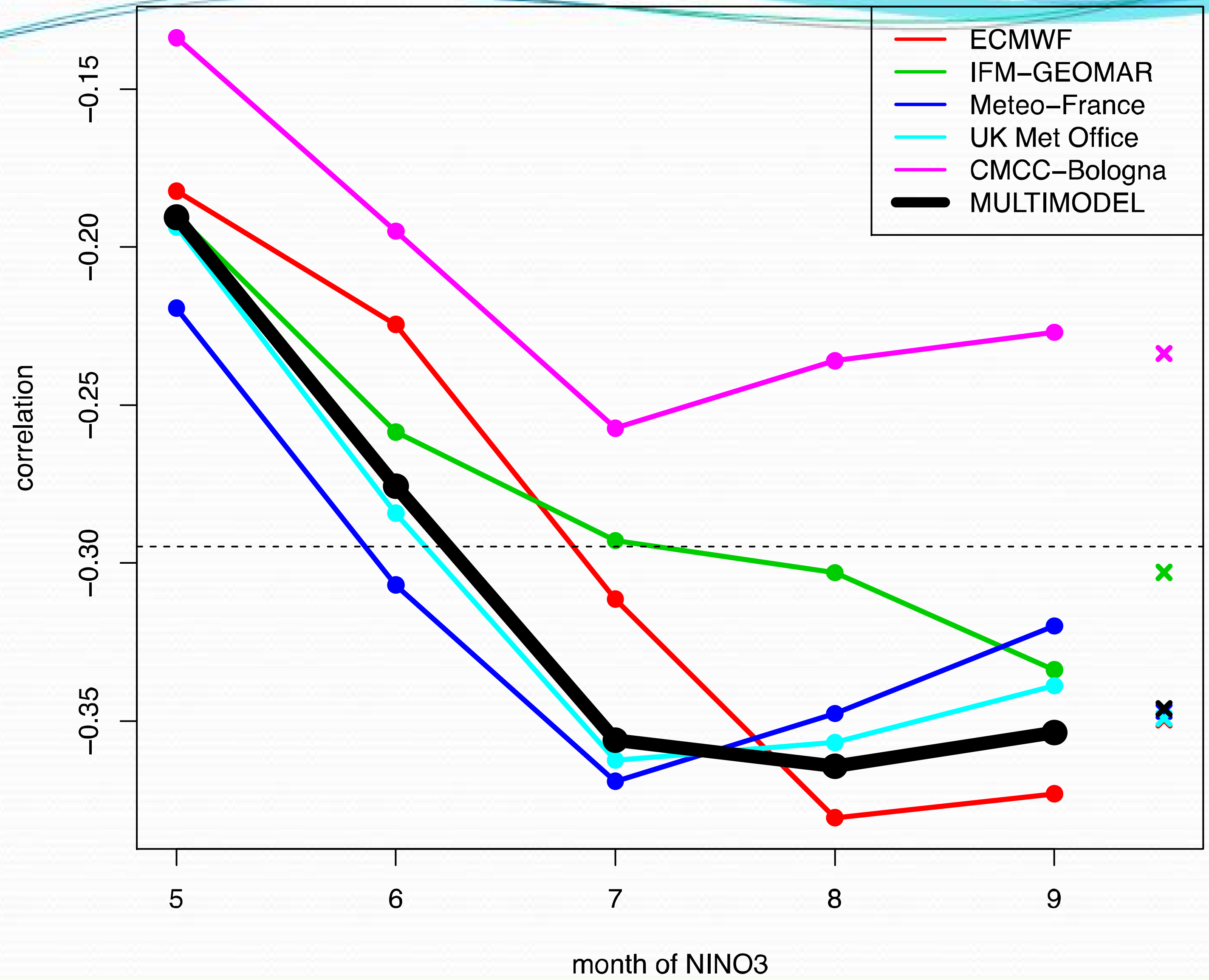
Observed Trends

Multi-model ensemble-mean trends in 76 **COUPLED** climate model simulations with prescribed observed radiative forcings

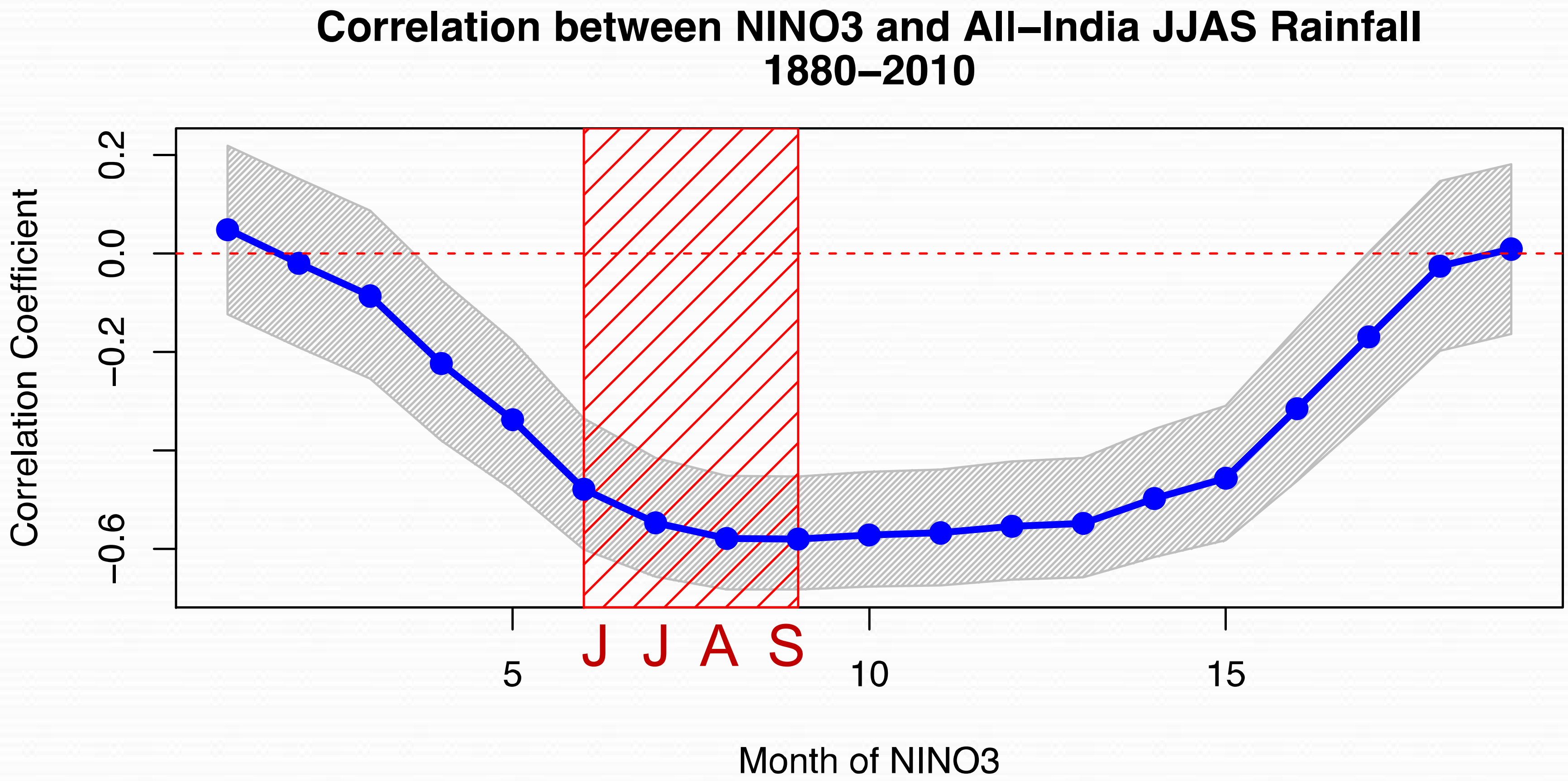
Multi-model ensemble-mean trends in 87 **UNCOUPLED** atmospheric GCM simulations with prescribed observed global or tropical SSTs, but no explicitly specified radiative forcings.

From Shin and Sardeshmukh Climate Dynamics 2011

Correlation between Observed JJAS all India rainfall and Model NINO3



Center of Ocean-Land-Atmosphere studies



Correlation between NINO3 and All–India JJAS Rainfall
1880–2010
Correlation Coefficient
0.2
0.0
−0.2
−0.6
J J A S
5
10
15
Month of NINO3

From Cyclone Resolving Global Models to Cloud System Resolving Global Models

1. **Planetary Scale Resolving Models (1970~):** ***Δx~*****500Km**
2. **Cyclone Resolving Models (1980~):** ***Δx~*****100-300Km**
3. **Mesoscale Resolving Models (1990~):** ***Δx~*****10-30Km**
4. **Cloud System Resolving Models (2000 ~):** ***Δx~*****3-5Km**

Organized Convection → Cloud System → Mesoscale System → Synoptic Scale → Planetary Scale

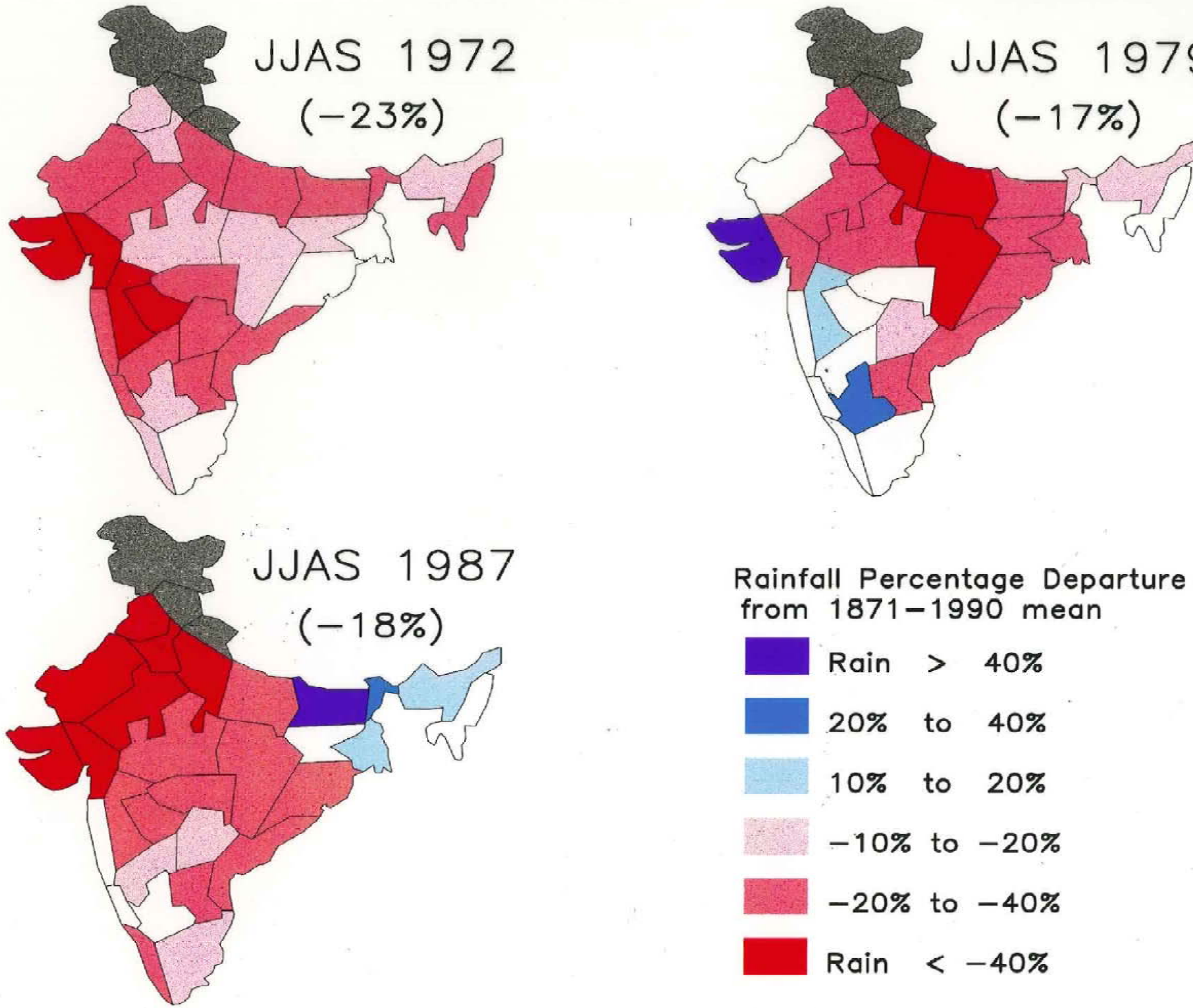
Convective Heating → MJO → ENSO → Climate Change

Towards a Hypothetical "Perfect" Model

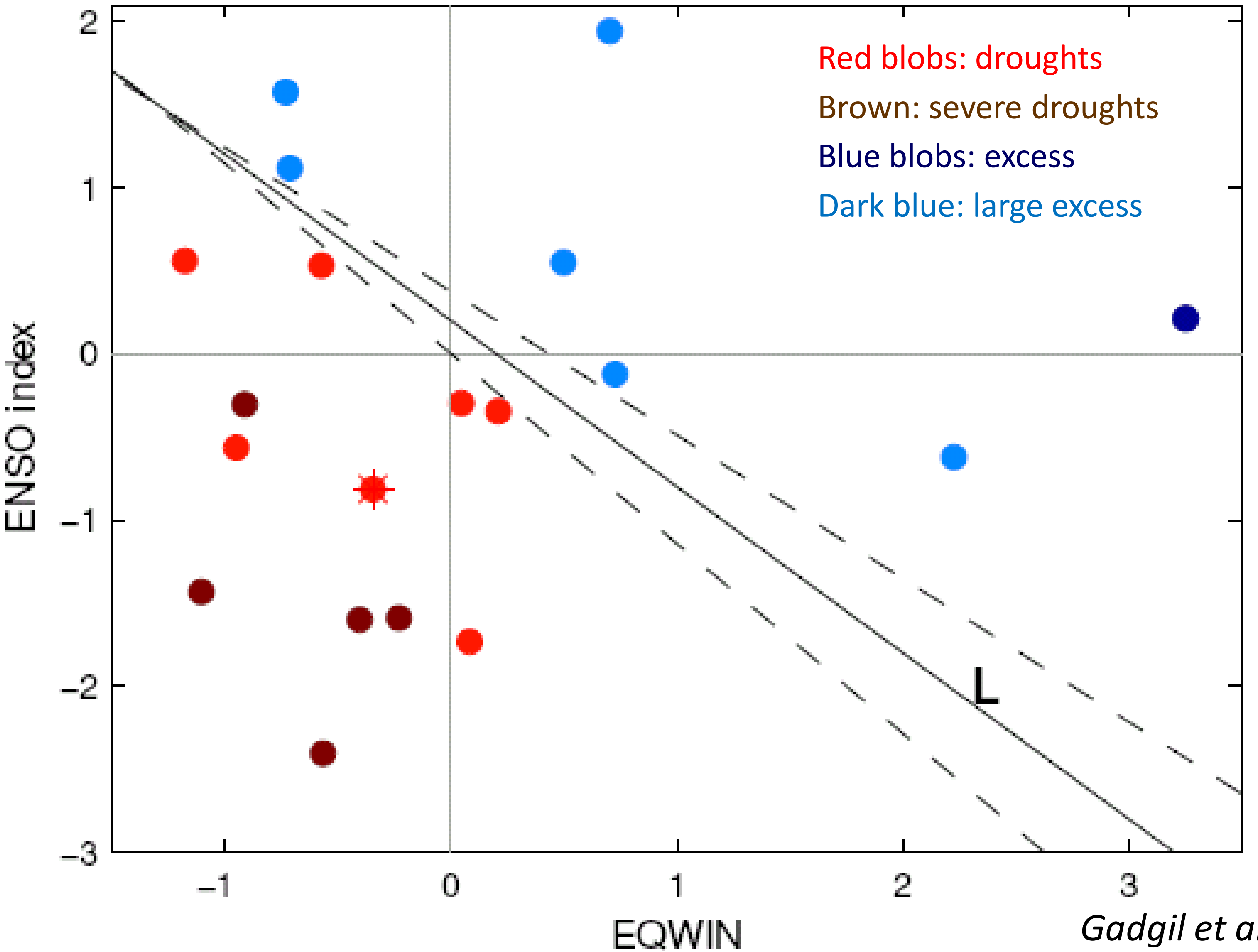
- **Replicate the statistical properties of the past observed climate**
  - **Means, variances, covariances, and patterns of covariability**

- **Utilize this model to estimate the limits of predicting the sequential evolution of climate variability**

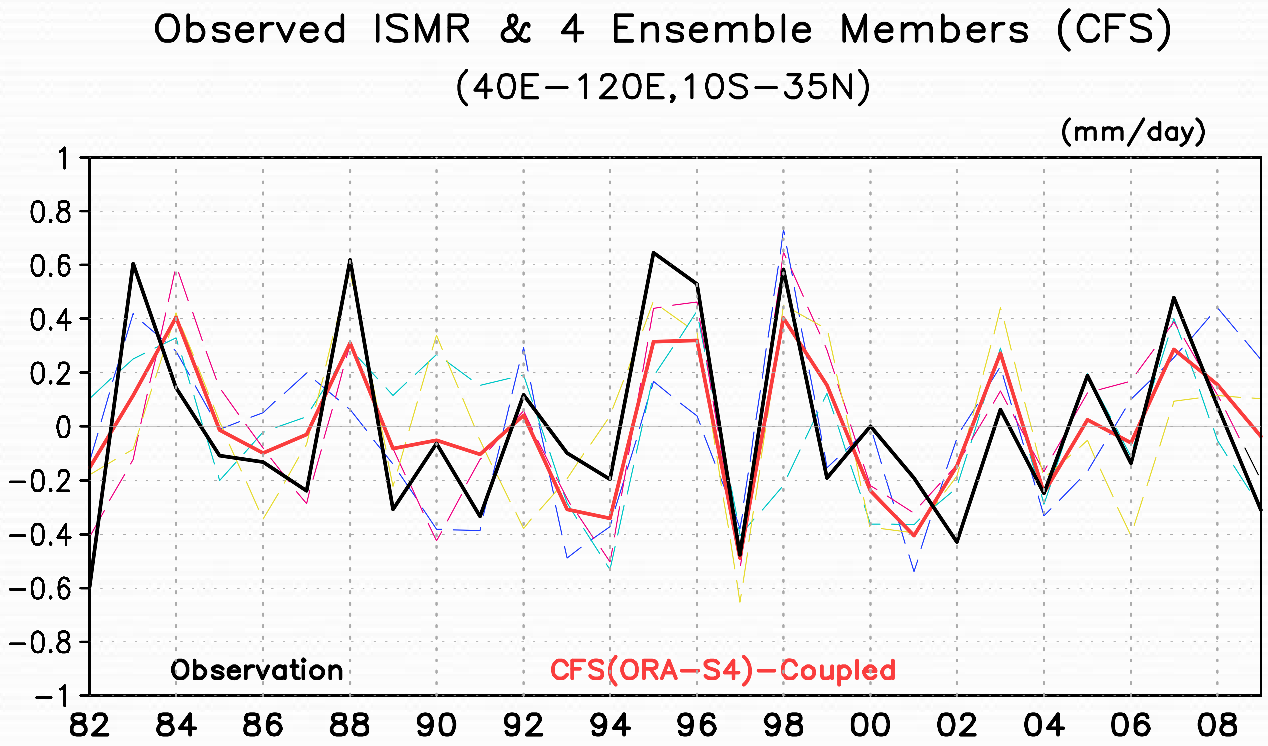
- **Better model $\rightarrow$ Better prediction (??)**

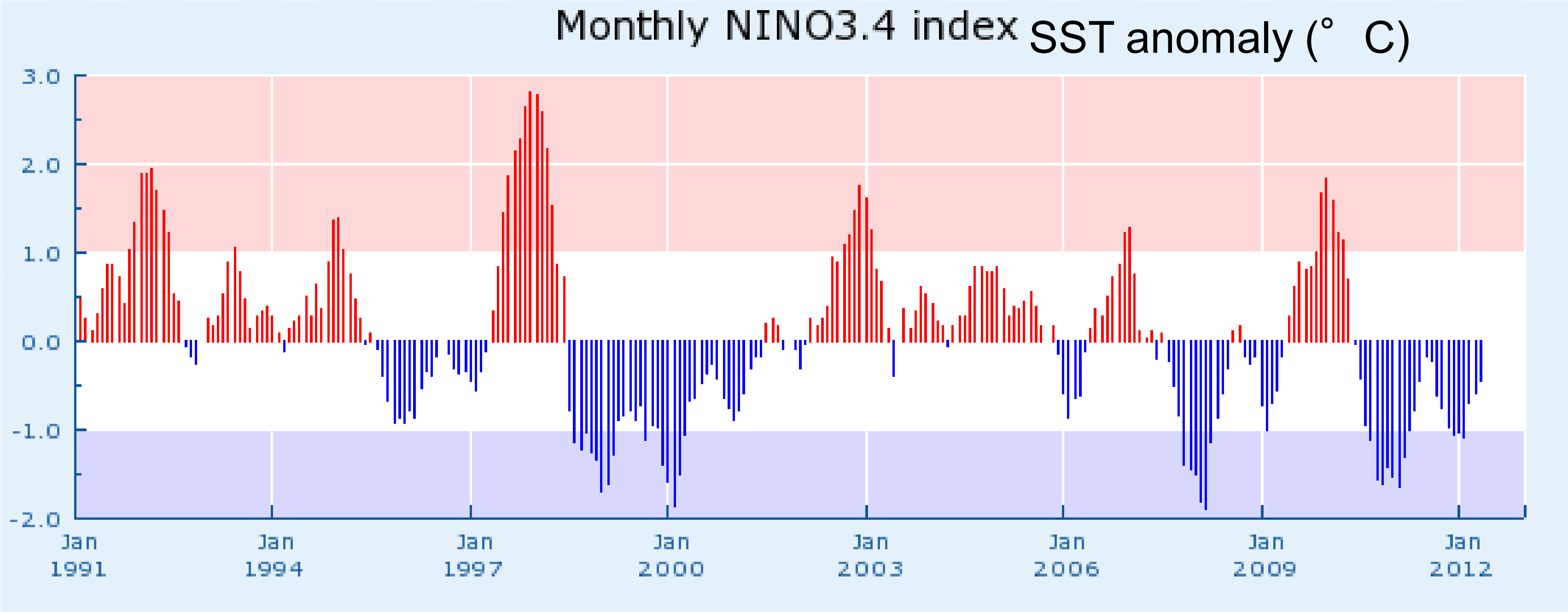

JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%

ENSO, EQWIN, and Monsoon rainfall over India

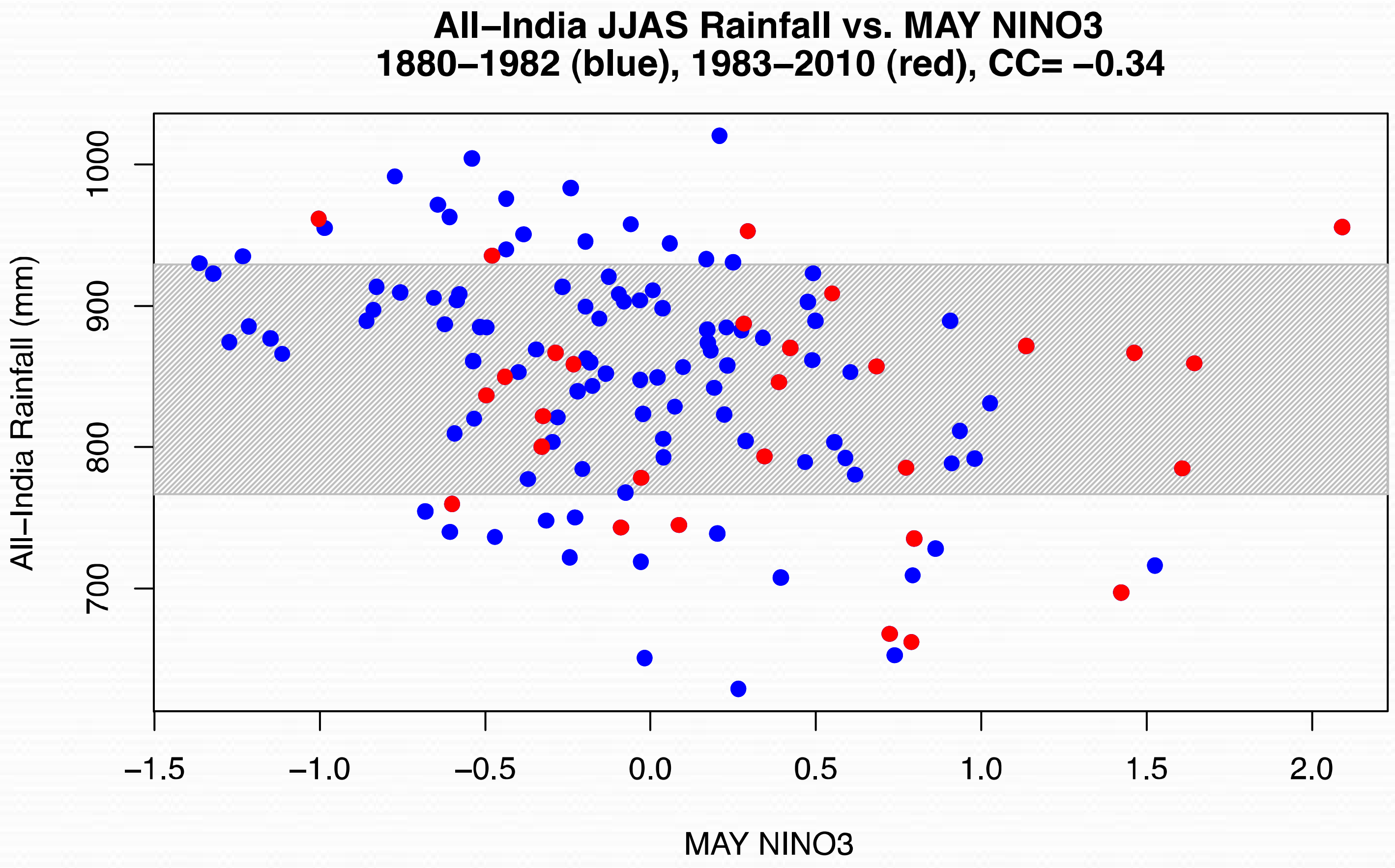


Gadgil et al., GRL2004

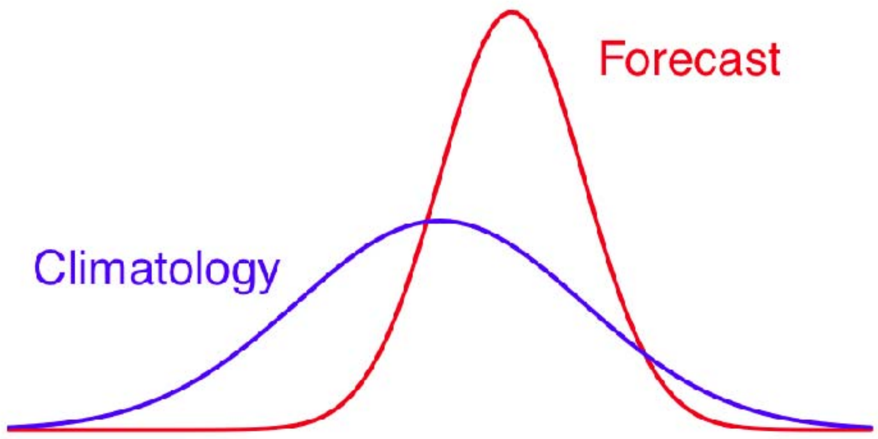

Observed ISMR & 4 Ensemble Members (CFS)
(40E–120E,10S–35N)
(mm/day)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
82
84
86
88
90
92
94
96
98
00
02
04
06
08
Observation
CFS(ORA–S4)–Coupled



weatherzone.com


All–India JJAS Rainfall vs. MAY NINO3
1880–1982 (blue), 1983–2010 (red), CC= –0.34
All–India Rainfall (mm)
1000
900
800
700
–1.5
–1.0
–0.5
0.0
0.5
1.0
1.5
2.0
MAY NINO3

Fundamental Definition of Predictability

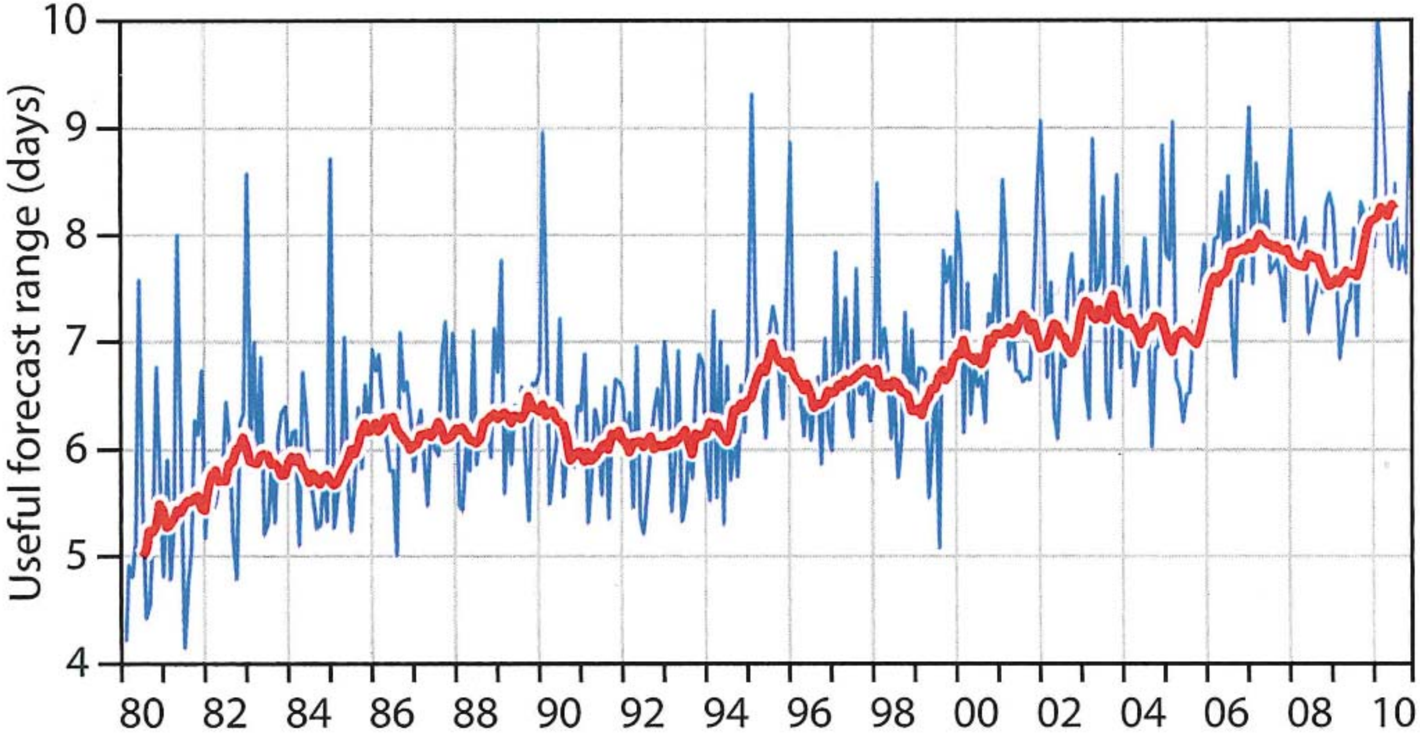


A variable $y_{t+\tau}$ is **defined** to be unpredictable at lead τ if, for all x_t,

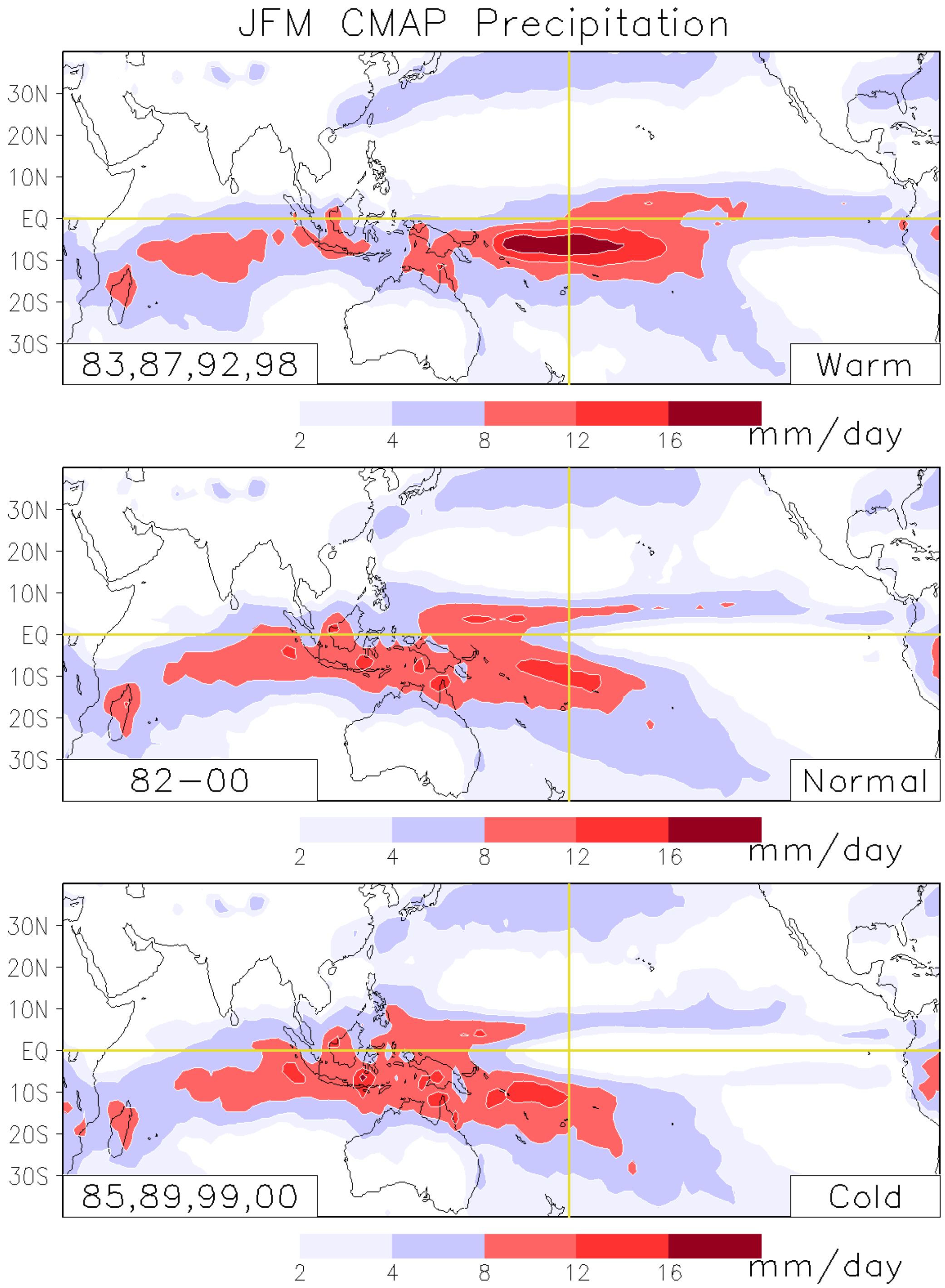
$$p(y_{t+\tau}|x_t) \quad = \quad p(y_{t+\tau})$$

forecast distribution — *climatological distribution*

ECMWF Forecast System: Useful Skill for Europe



Record performance of the deterministic forecasting system. *The useful range of the deterministic forecasts for Europe reached its highest ever monthly value in February 2010. Overall the performance has been consistently good during 2010. The useful forecast range is determined by the time at which the anomaly correlation for 500 hPa height operational forecasts at 12 UTC reached 60%.*



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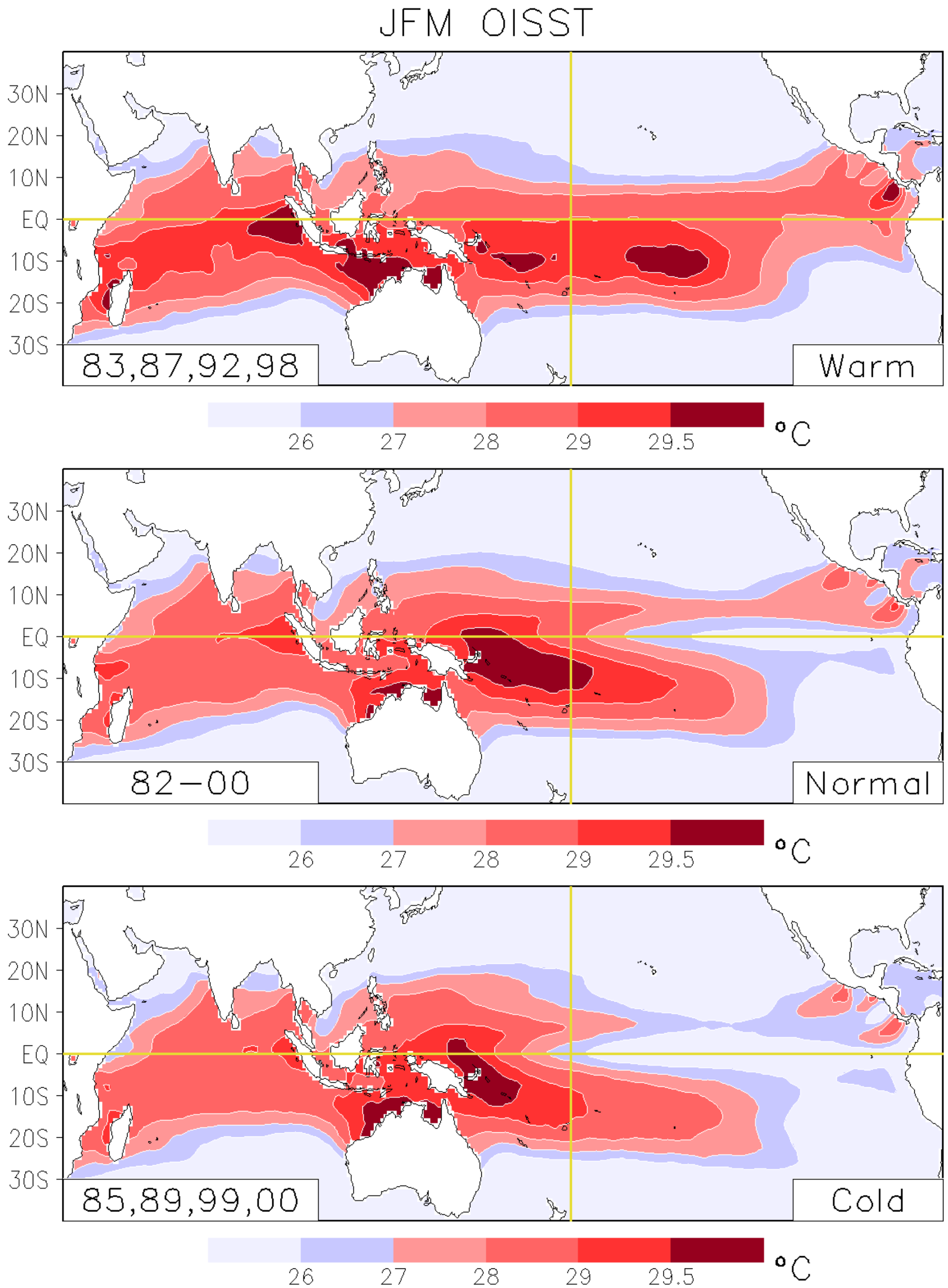
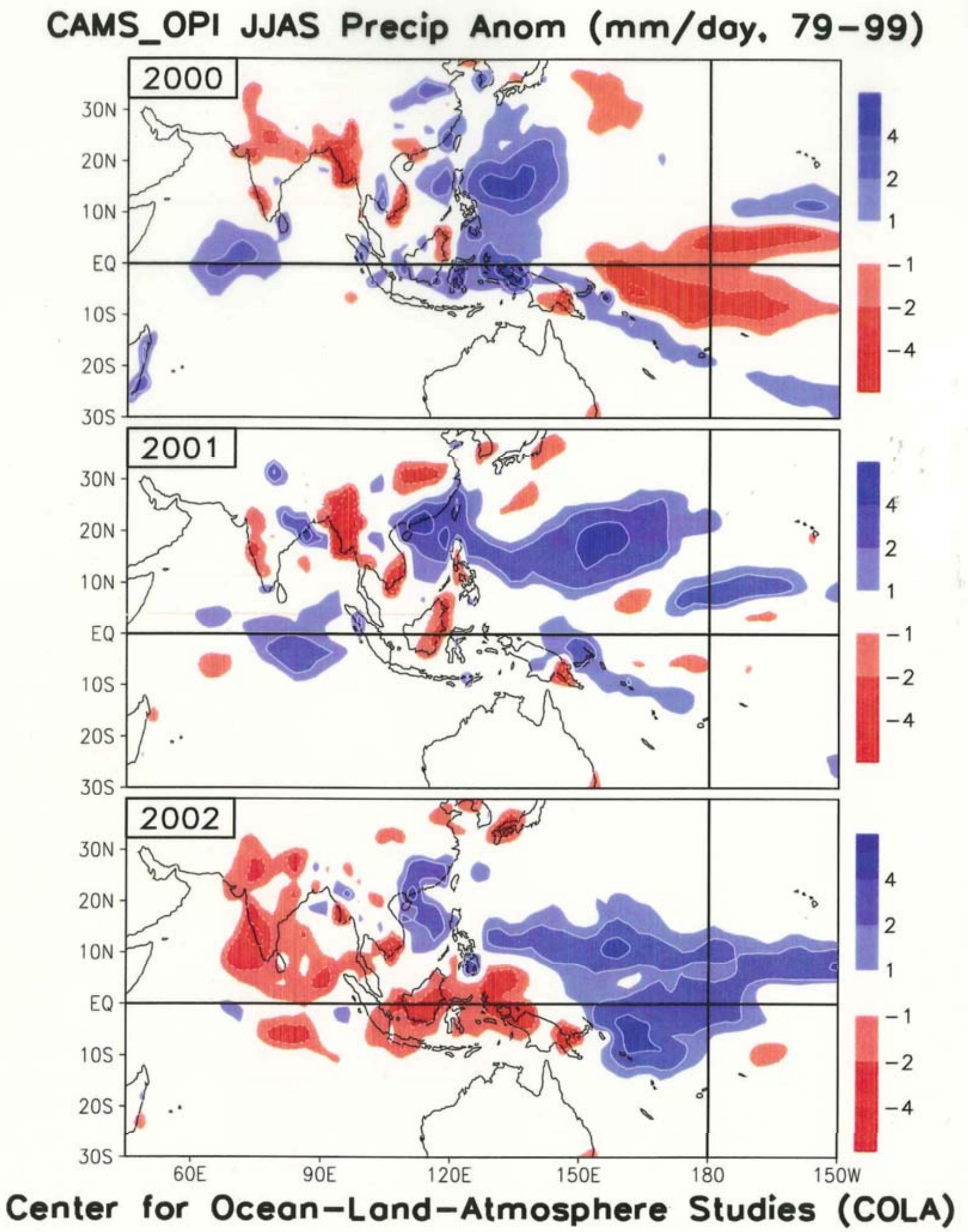

JFM OISST
30N
20N
10N
EQ
10S
20S
30S
83,87,92,98
Warm
26
27
28
29
29.5
°C
82–00
Normal
85,89,99,00
Cold



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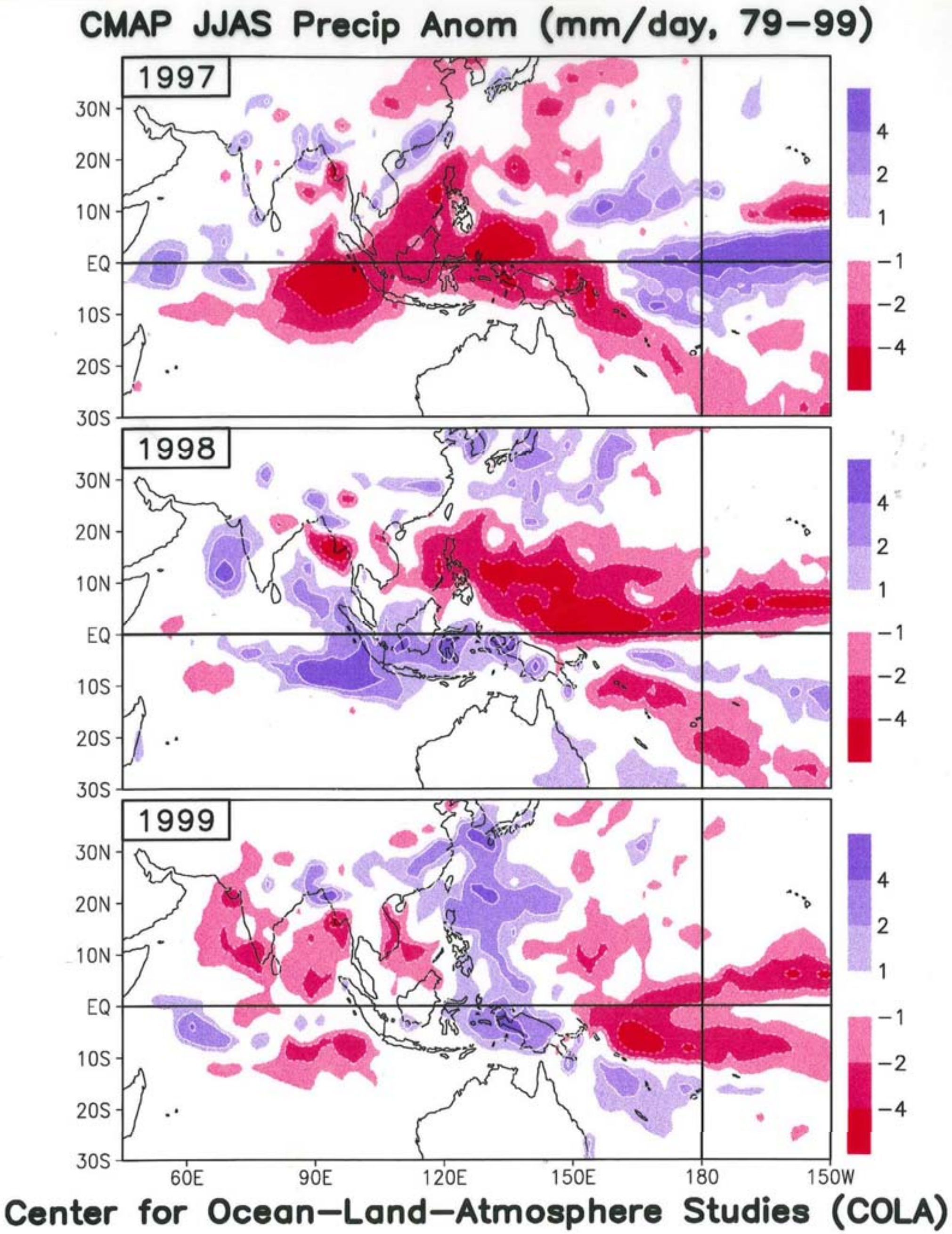
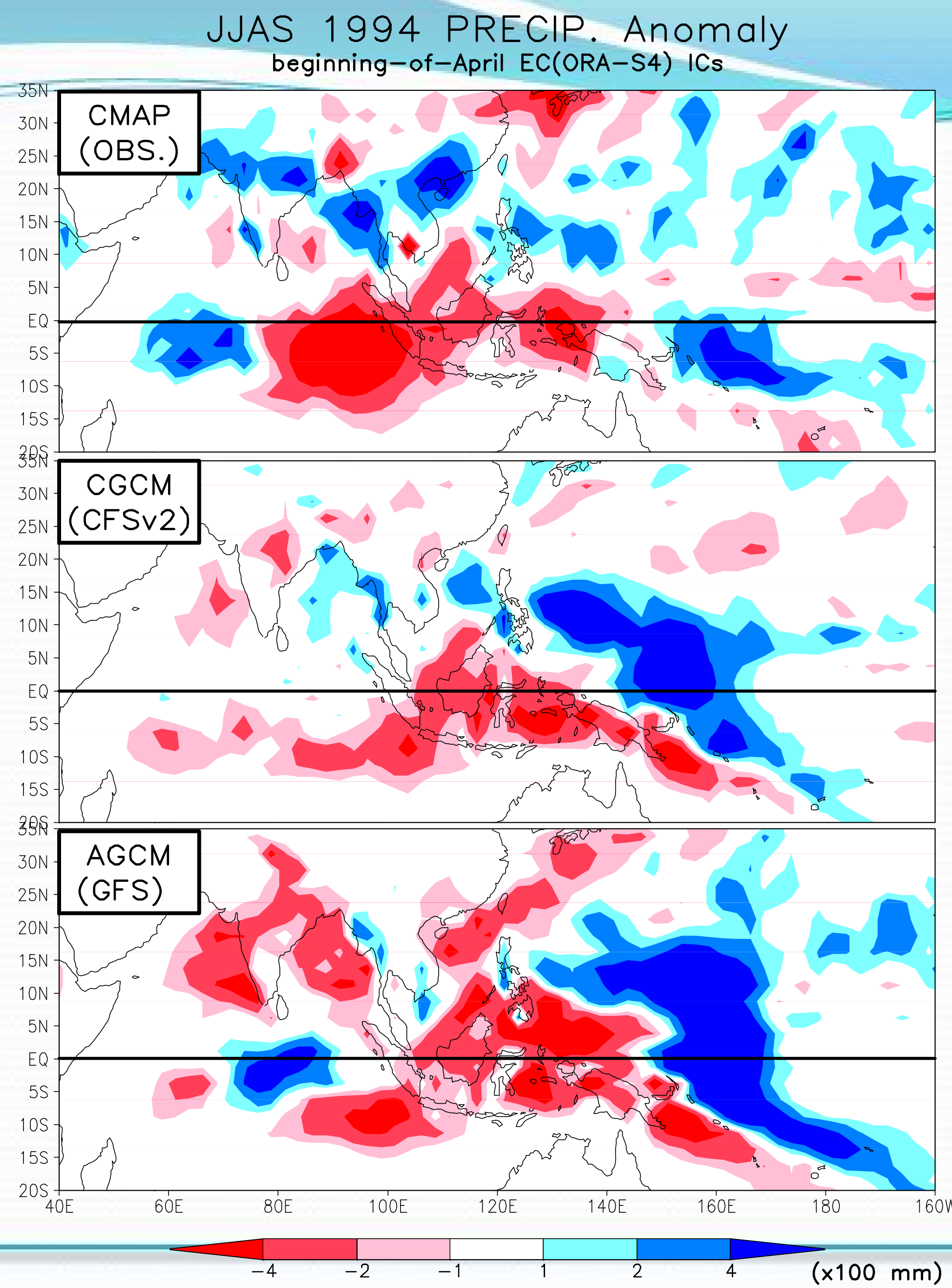

CMAP JJAS Precip Anom (mm/day, 79–99)
1997
1998
1999
30N
20N
10N
EQ
10S
20S
30S
60E
90E
120E
150E
180
150W
4
2
1
−1
−2
−4
Center for Ocean–Land–Atmosphere Studies (COLA)

The Tale of Two Monsoon Seasons

All India JJAS Monsoon Rainfall as % of Normal

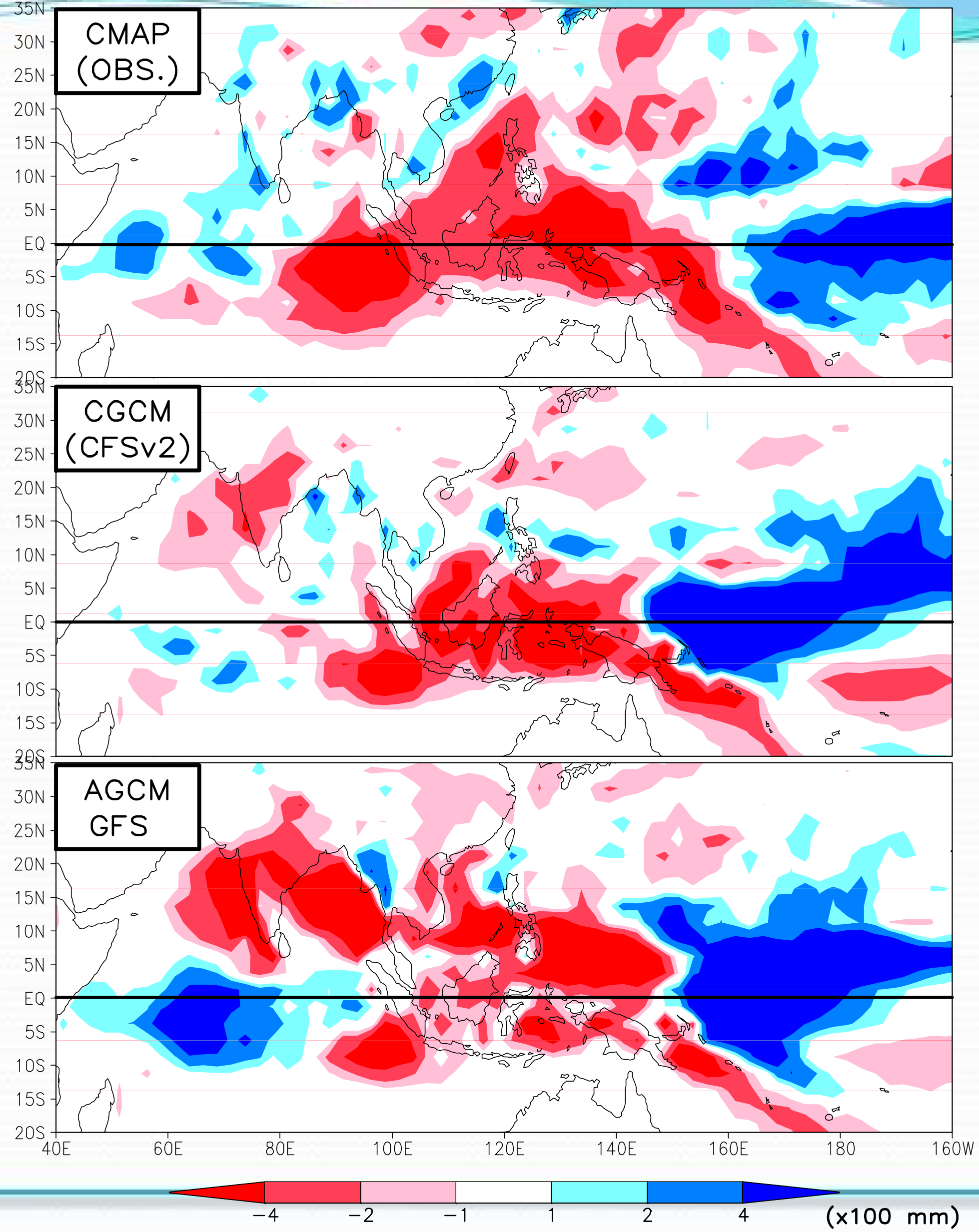
	Actual	Forecast (IMD)
1994	**+13 %**	**-8 %**
1997	**+2 %**	**-8 %**



JJAS 1994 PRECIP. Anomaly
beginning-of-April EC(ORA-S4) ICs
CMAP (OBS.)
CGCM (CFSv2)
AGCM (GFS)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
40E
60E
80E
100E
120E
140E
160E
180
160W
-4
-2
-1
1
2
4
(x100 mm)

JJAS 1997 PRECIP. Anomaly

beginning–of–April EC(ORA–S4) ICs



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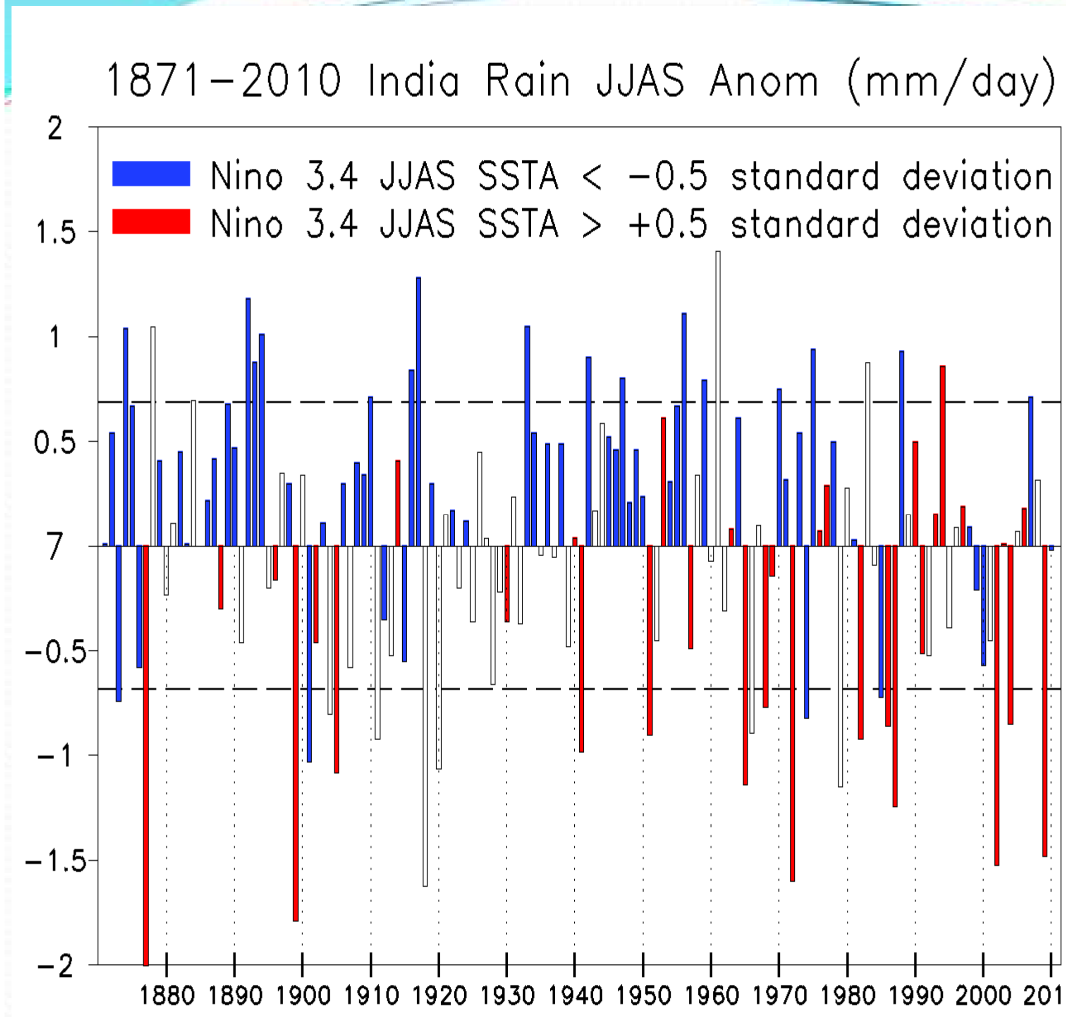
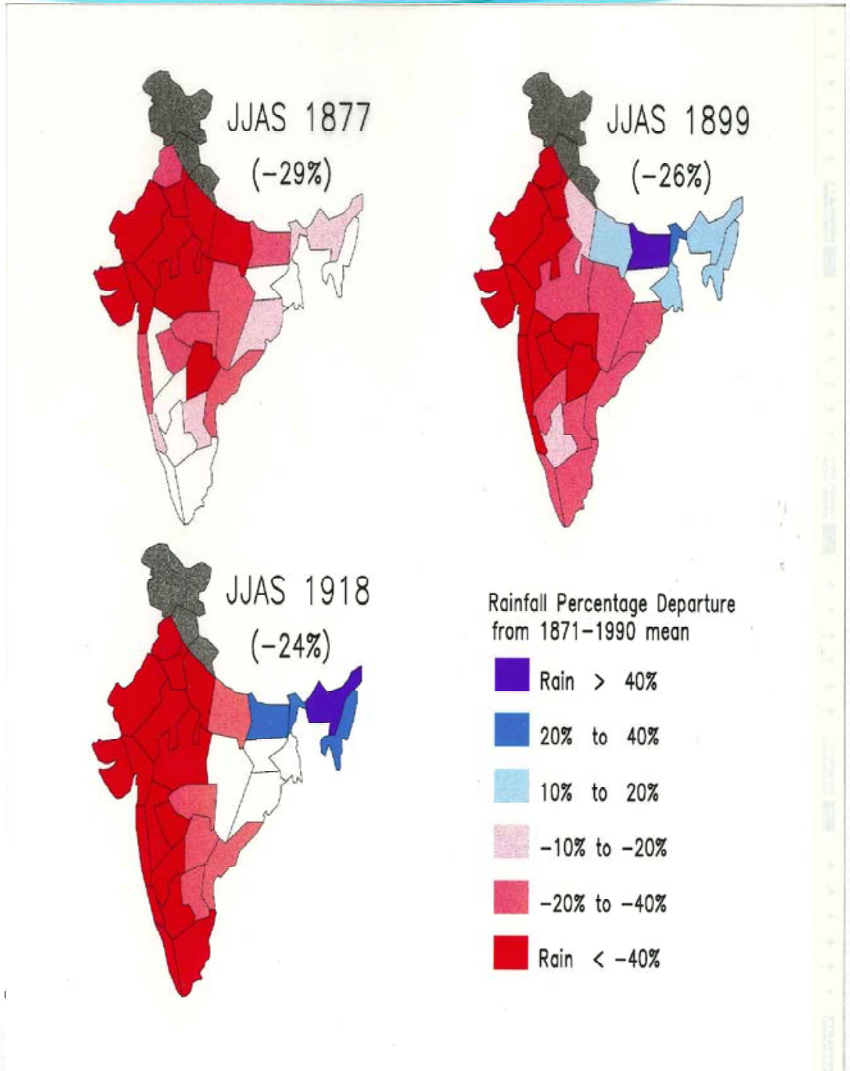


1871-2010 India Rain JJAS Anom (mm/day)
Nino 3.4 JJAS SSTA < -0.5 standard deviation
Nino 3.4 JJAS SSTA > +0.5 standard deviation
2
1.5
1
0.5
7
-0.5
-1
-1.5
-2
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 201



JJAS 1877
(-29%)
JJAS 1899
(-26%)
JJAS 1918
(-24%)
Rainfall Percentage Departure from 1871-1990 mean
Rain > 40%
20% to 40%
10% to 20%
-10% to -20%
-20% to -40%
Rain < -40%