ENSO - Monsoon Teleconnections:
Reforecasting the 1972-73 ENSO and Asian Summer Monsoon

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ICTP, October 27, 2016

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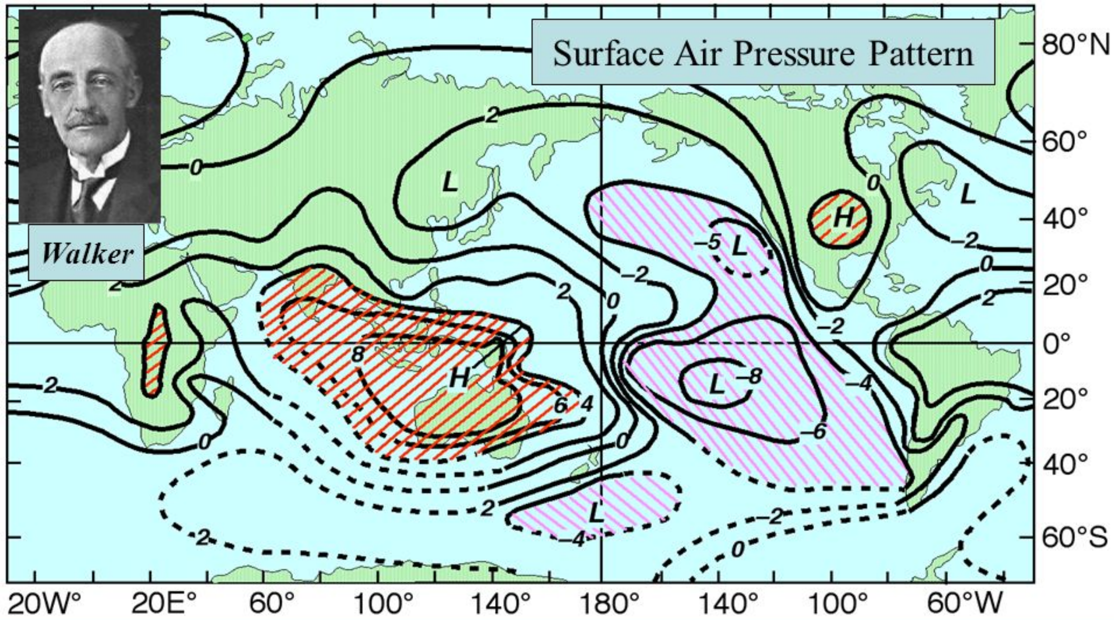
The Southern Oscillation



Correlation coefficient with respect to Darwin sea level pressure

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Rasmusson, 1984

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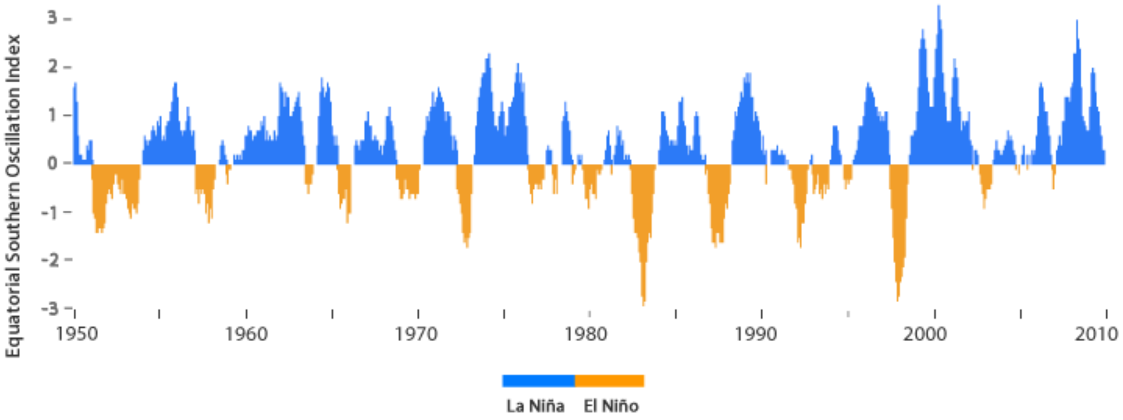
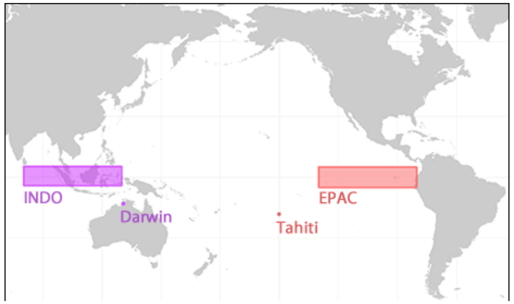
Equatorial Southern Oscillation Index (SOI)



Similarly, the Equatorial Southern Oscillation Index or EQSOI represents the difference in air pressure measured over the eastern and western Pacific. The EQSOI is calculated as the difference in standardized mean sea level pressure over a swath of the eastern equatorial Pacific Ocean (5°N-5°S, 80°W-130°W) and another swath that spans Indonesia (5°N-5°S, 90°E-140°E).

SOI = EPAC *minus* **INDO**



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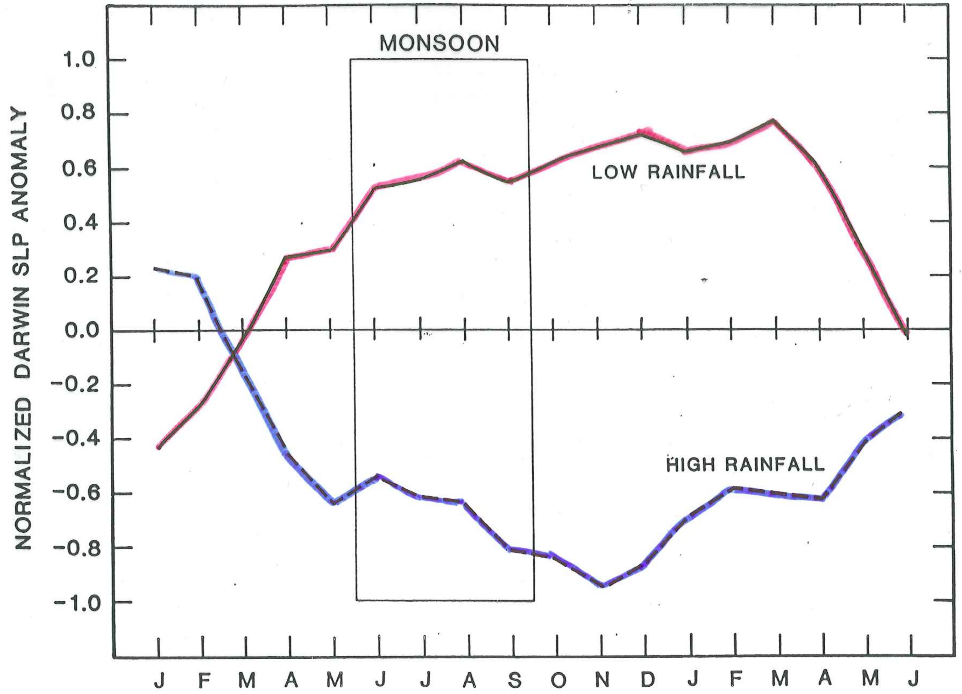
ENSO has large amplitude after the monsoon season: to predict monsoon, we must predict ENSO first



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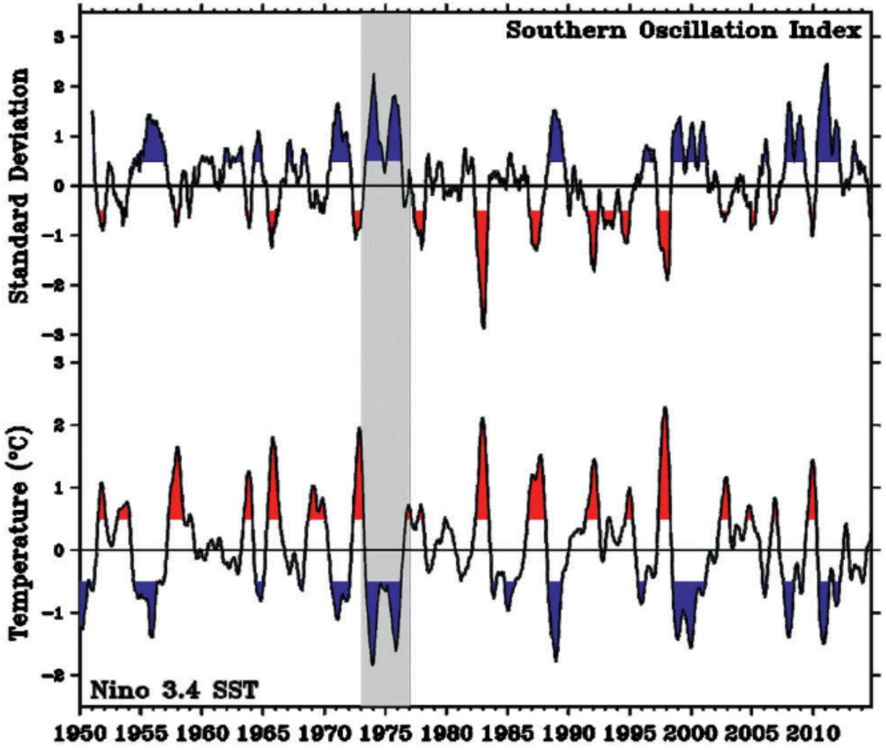
SOI and Nino 3.4 SST

ENSO occur on irregular basis, ~ 4-7 years



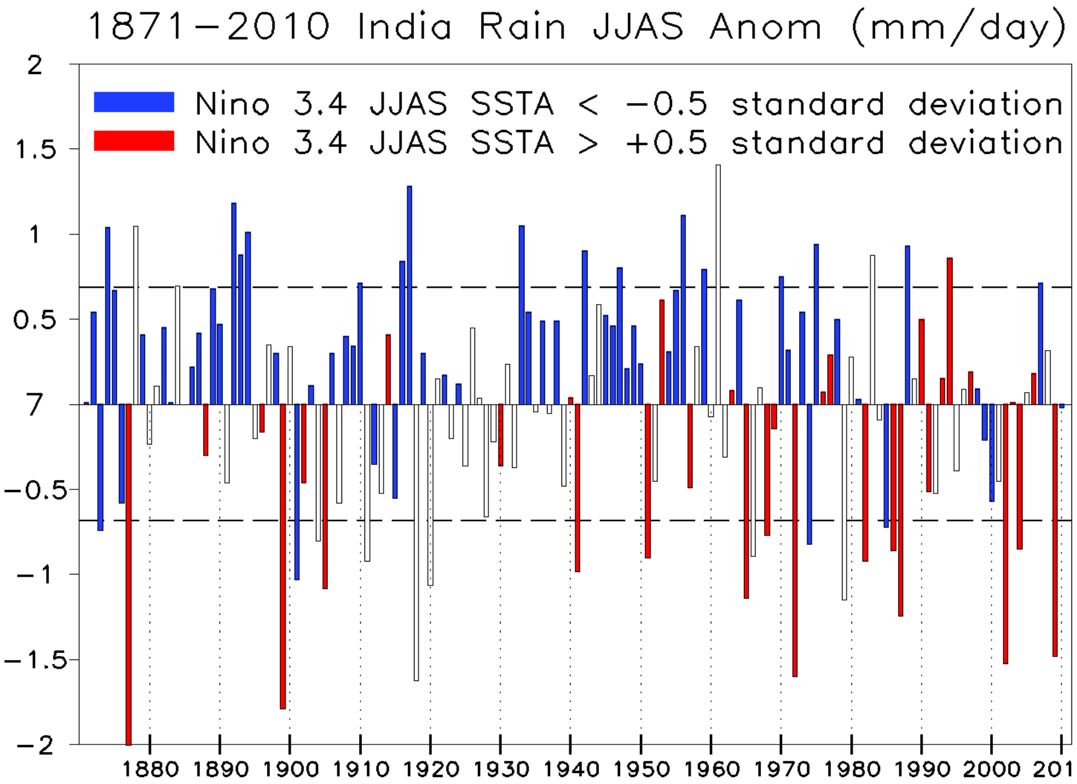
SOI:

Tahiti – Darwin
SLP

Nino 3.4

5N – 5S; 120 – 170 W

Interannual Variability of Indian Summer Monsoon Rainfall



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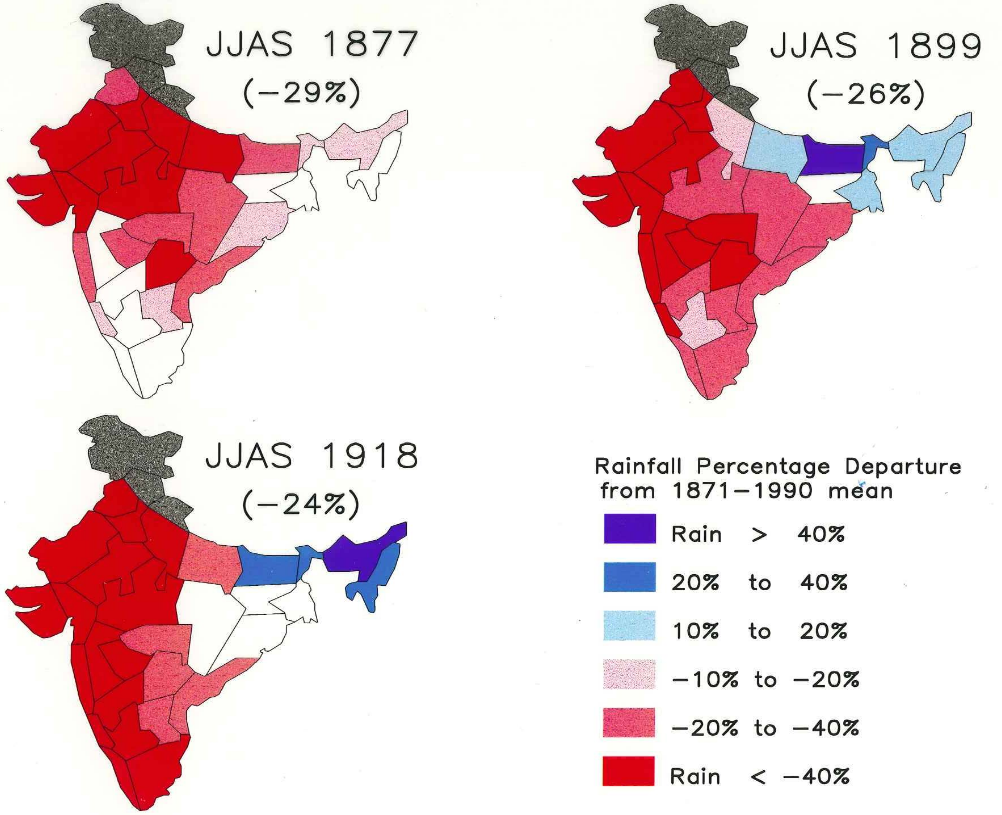
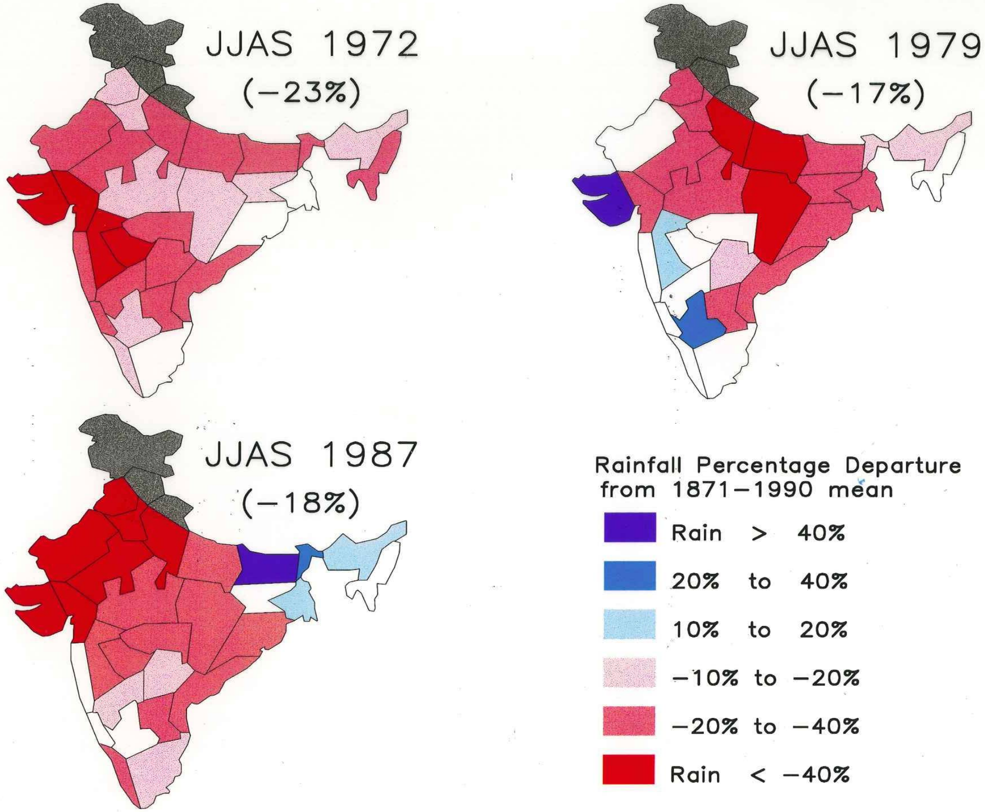
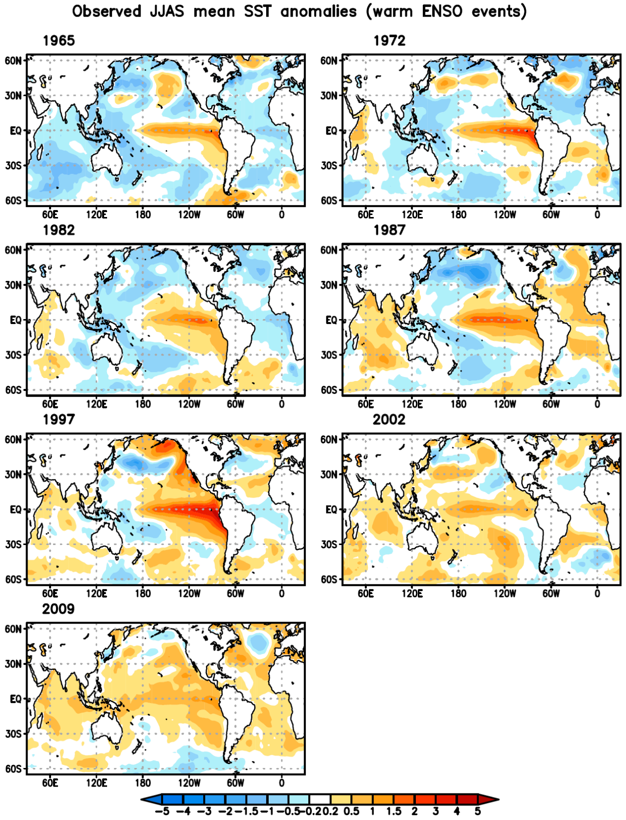

JJAS 1877
(−29%)
JJAS 1899
(−26%)
JJAS 1918
(−24%)
Rainfall Percentage Departure from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%

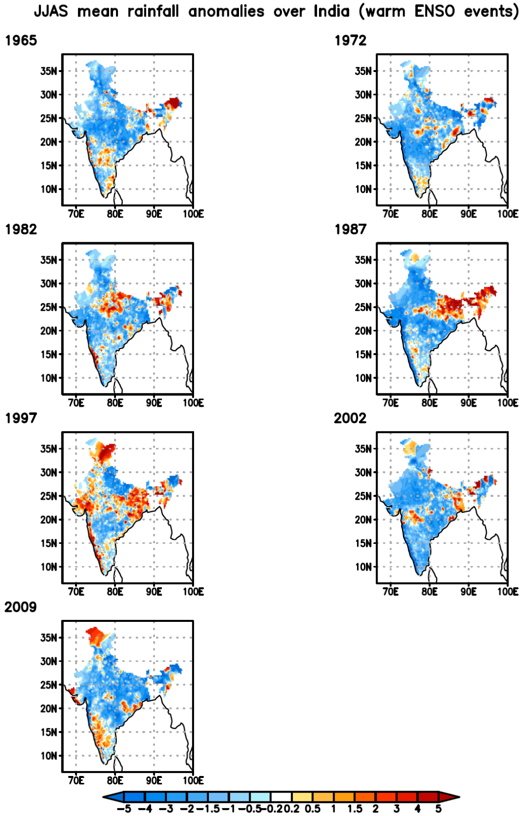

JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%

JJAS Mean Anomalies (Warm El Nino Events)

SST [^oC]


Observed JJAS mean SST anomalies (warm ENSO events)

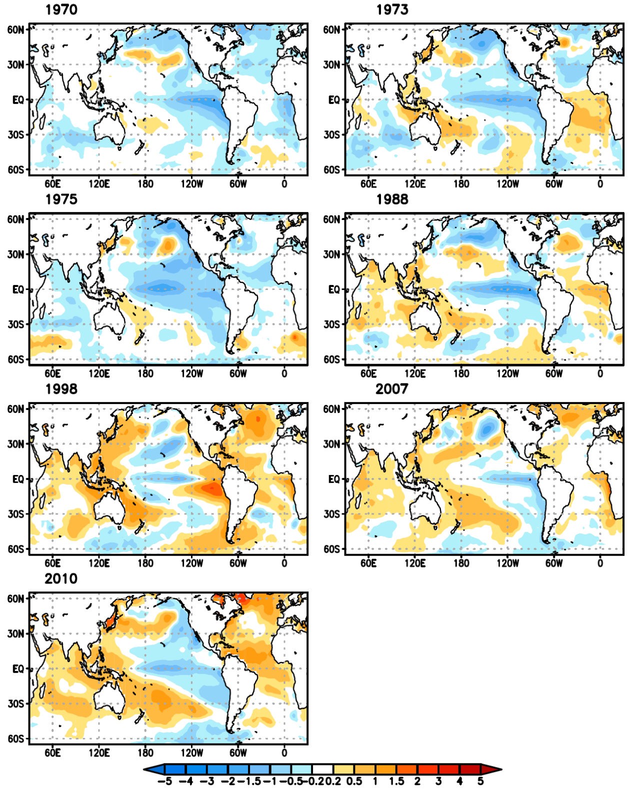
Precipitation [mm/day]


JJAS mean rainfall anomalies over India (warm ENSO events)

JJAS Mean Anomalies (Cold La Nina Events)

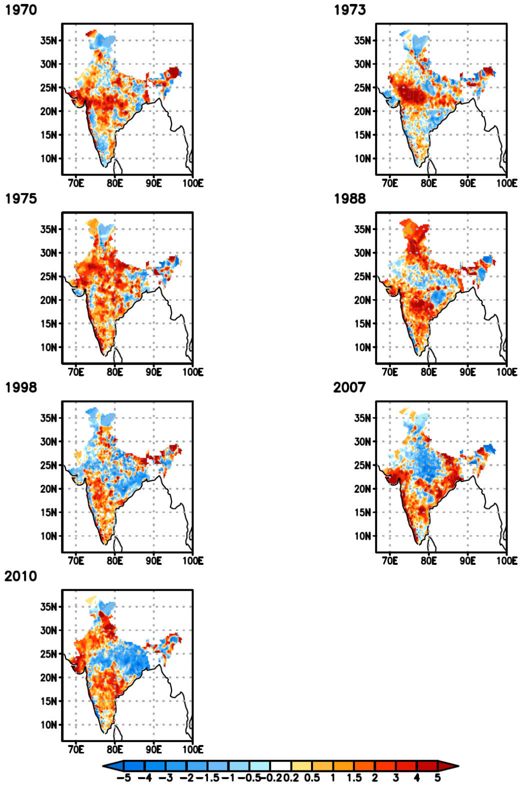
SST [^{o}C]

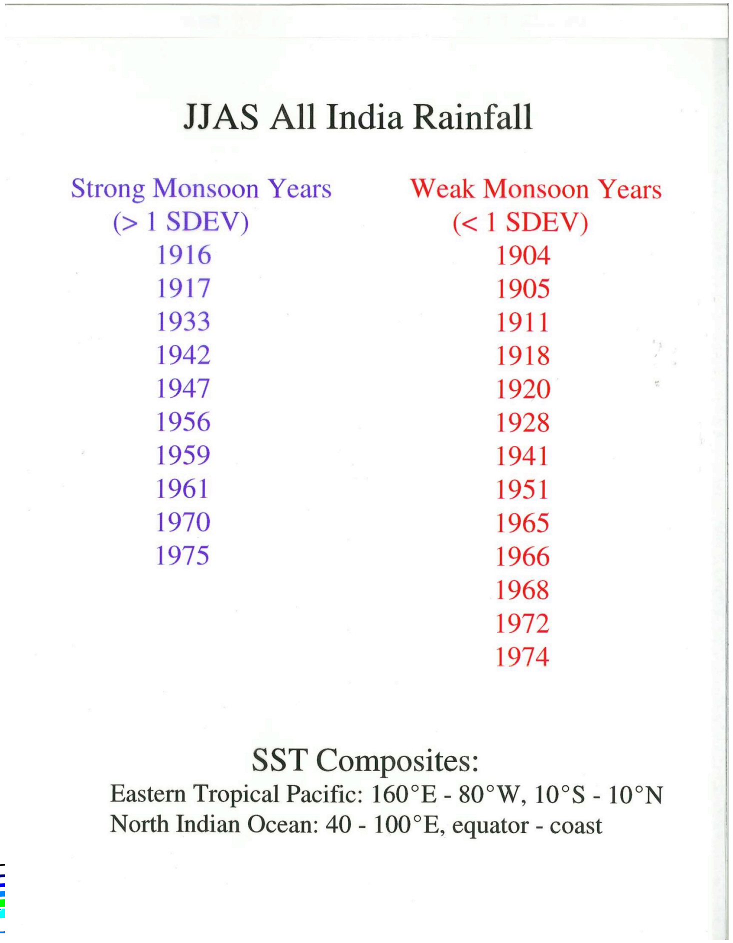
Observed JJAS mean SST anomalies (cold ENSO events)



Precipitation [mm/day]

JJAS mean rainfall anomalies over India (cold ENSO events)



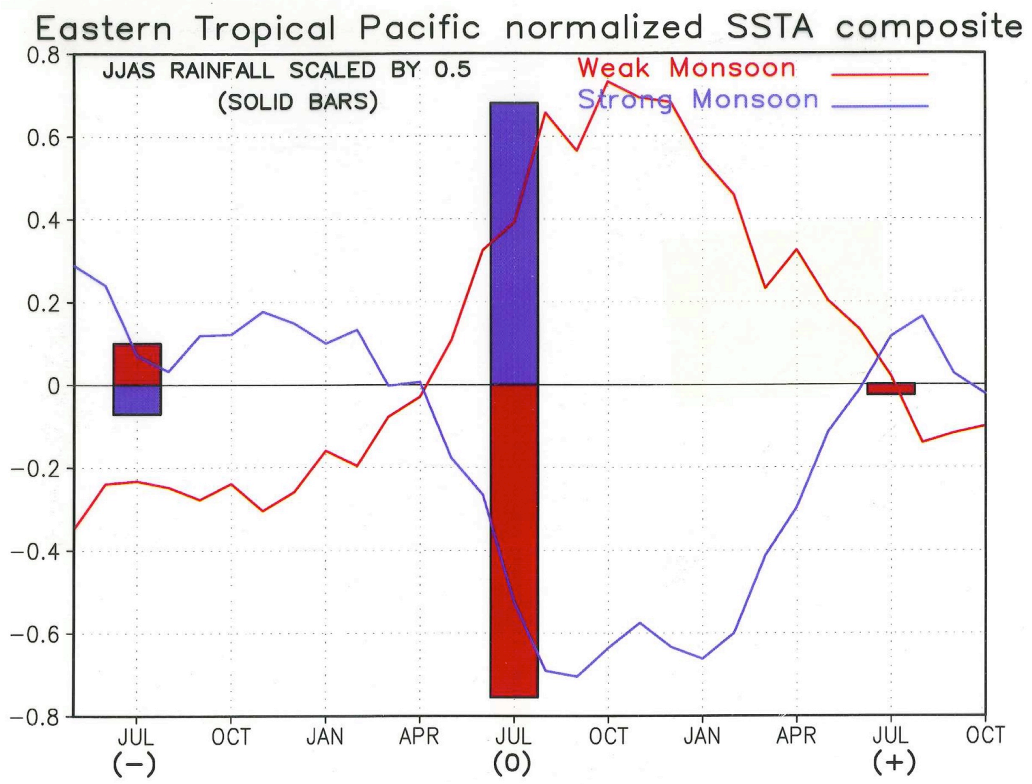


JJAS All India Rainfall

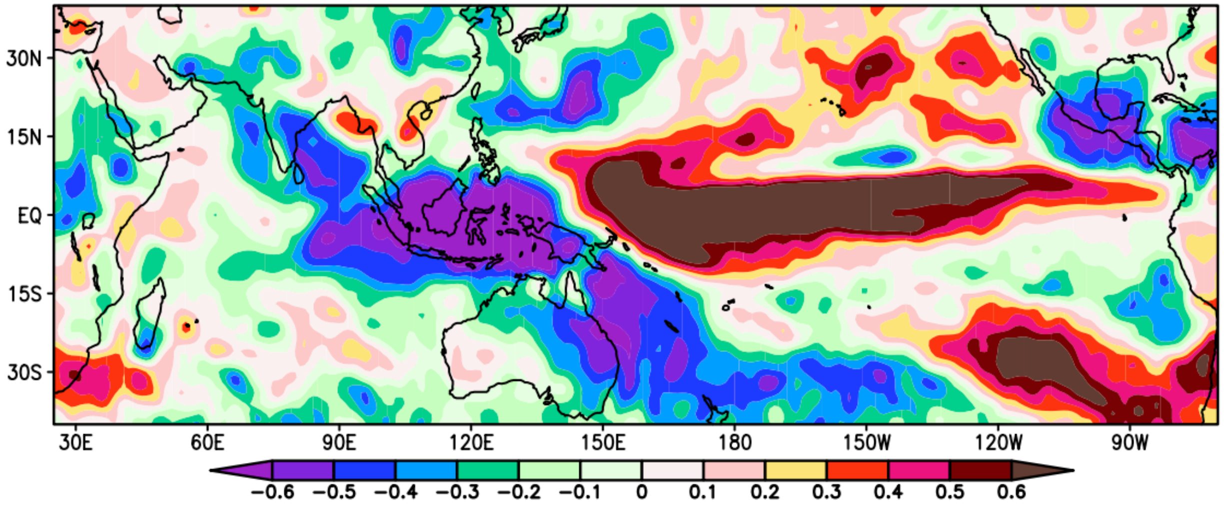
Strong Monsoon Years (> 1 SDEV)	Weak Monsoon Years (< 1 SDEV)
1916	1904
1917	1905
1933	1911
1942	1918
1947	1920
1956	1928
1959	1941
1961	1951
1970	1965
1975	1966
	1968
	1972
	1974

SST Composites:

Eastern Tropical Pacific: 160°E - 80°W, 10°S - 10°N
North Indian Ocean: 40 - 100°E, equator - coast


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

Correlation Coefficient between Nino 3.4 SSTA and Observed Precip for JJAS (1981-2010)



Ravi P. Shukla & Huang (2015)

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Mechanisms Proposed to Explain ENSO-Monsoon Teleconnection

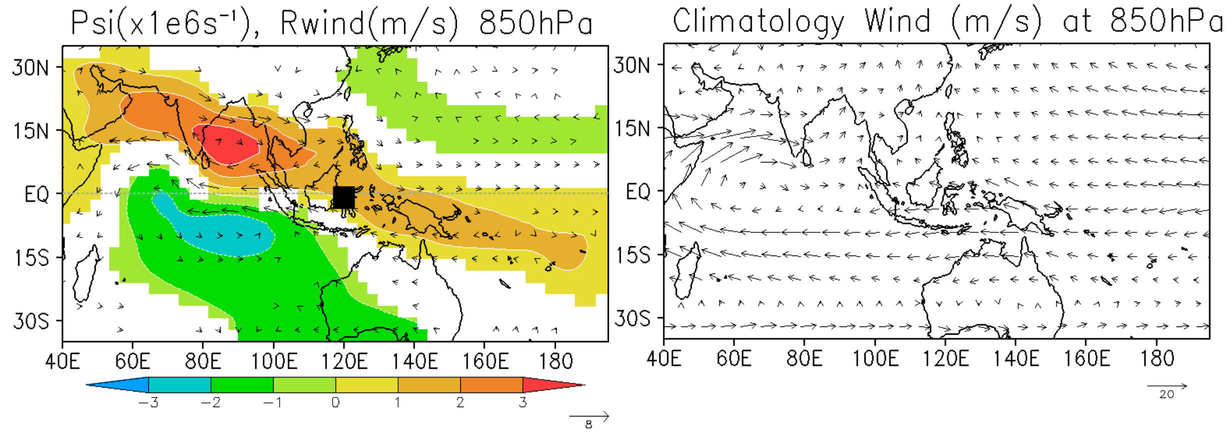
1. **Gill response to forced heating $(\delta SST - \delta Q)$ in the presence of mean wind, and mean wind shear**
   (Wang et al, 2003; Li and Wang, 2013; Jang and Straus 2013)

2. **Modulation of Walker circulation and local Hadley circulation by ENSO forced $(\delta SST - \delta Q \rightarrow \delta V)$ circulation anomalies**
   (Slingo and Annamalai, 2000; and Pillai and Annamalai, 2012)

3. **ENSO-Monsoon interaction through tropospheric biennial oscillation**
   (Meehl, 1997; Arblaster and Meehl, 2002)

Cooling Exp: GCM effect

- **WP Cooling ~ Weakens the monsoon flow**

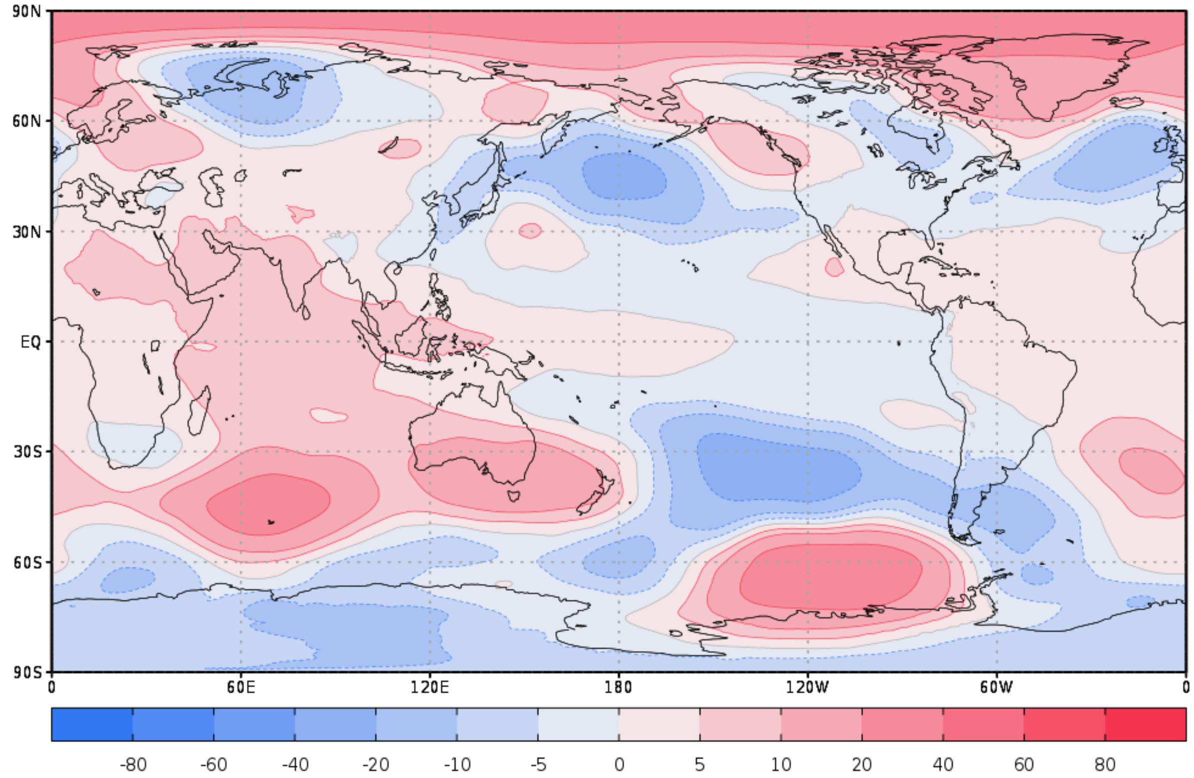


Experiments from Jang and Straus with added cooling at 120^{o}E.

Jang, Y. and D. M. Straus, 2013: Tropical Stationary Wave Response to ENSO: Diabatic Heating Influences on the Indian Summer Monsoon. J. Atmos. Sci., 30, 193-222.

JJA 700mb Height Anomaly for Warm Events

1982 1987 1997 2002 2009 2015



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57-Year (1958-2014) Reforecasts

- The first time a seasonal reforecast of this length is conducted using CFSv2
- Extends the seasonal reforecasts to ENSO events in 1960s-70s
- Examines predictability at different phases of climate change and multidecadal variability (60s-70s, 80s-90s, 2000-)

B. Huang, C.-S. Shin, J. Shukla, L. Marx, M. A. Balmaseda, S. Halder, P. A. Dirmeyer, J. L. Kinter III, 2016: Reforecasting the ENSO Events in the Past Fifty-Seven Years (1958-2014). *J. Climate*, submitted

57 years (1958-2014) CFSv2 Reforecast Experiment

Initial Conditions (ICs)

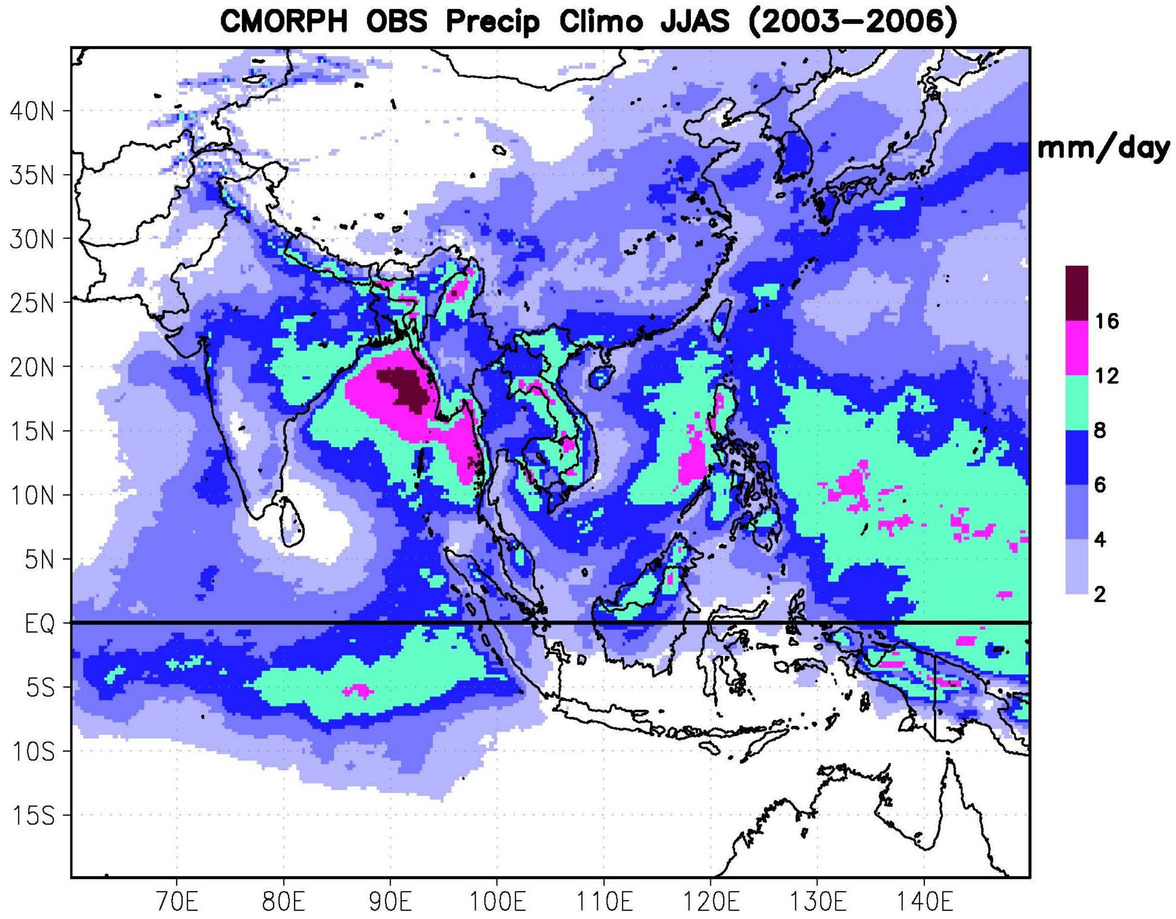
	1958-1978	1979-2014	
Atmosphere	**ERA-40**	**CFSR**	**4 members** (The first 4 days of each month)
Land	**NASA GLDAS2**		
Sea Ice	**CFSR** (January 1, 1979, April 1, 1979, July 1, 1979, October 1, 1980)		
Ocean	**ORA-S4**		**5 members***

* Perturbed through ocean data assimilation.

20 total ensemble members

Reforecast Duration: 12 months (total model years: **4560**)

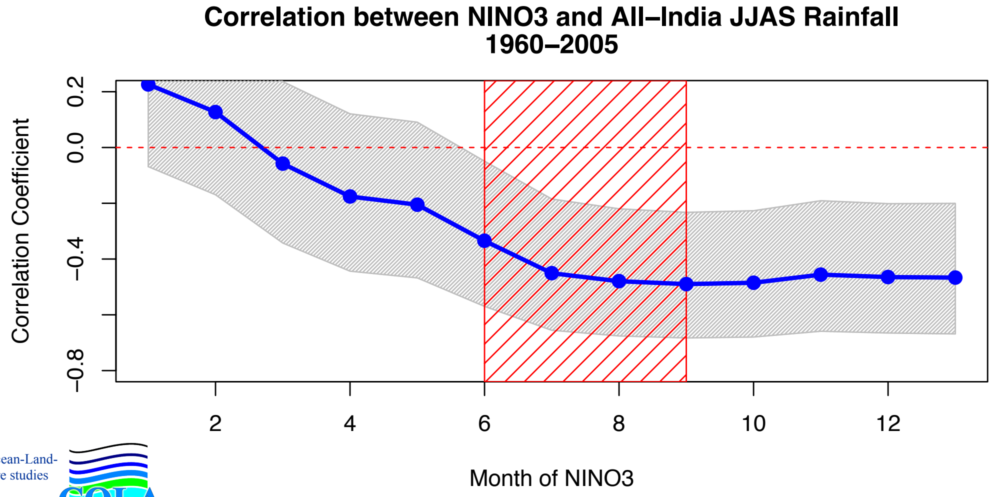
Output:
Monthly mean (12 months)
Daily (90 days, selected atmosphere and ocean fields)


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

C

In Spite of Large Biases in Simulated SST, Predictions of SST Anomalies Have Some Skill
In Some Cases

Small Skill in Predicted SST is Enough to Give Statistically Significant Skill in Predicted Monsoon Rainfall

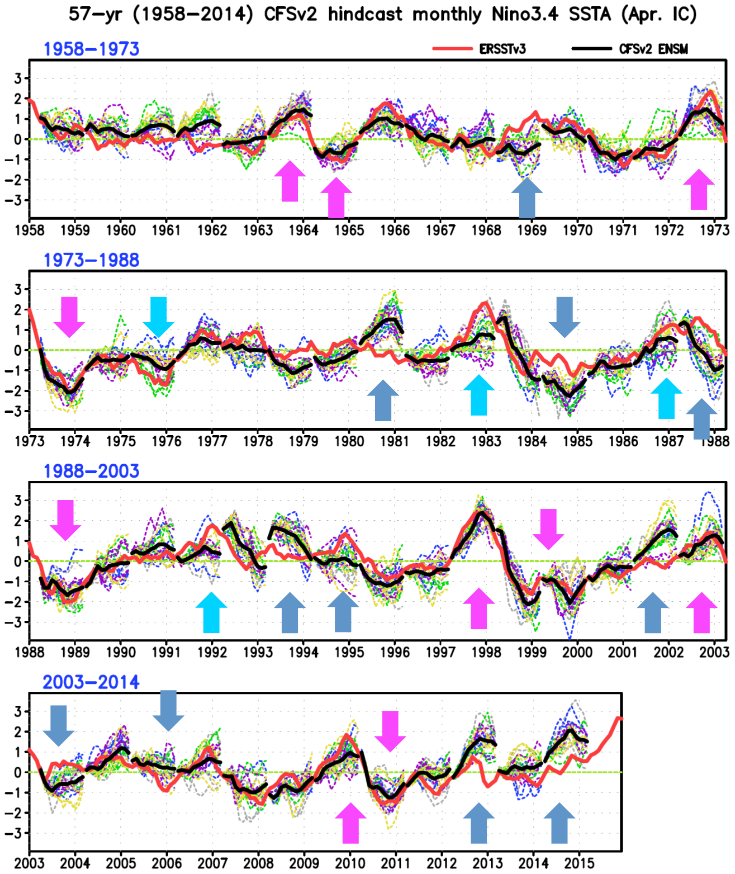


April IC

predicted events

More missed events and false alarms in 1979-2014

Underestimate ENSO growth



ERSSTv3

CFSv2 ENSM

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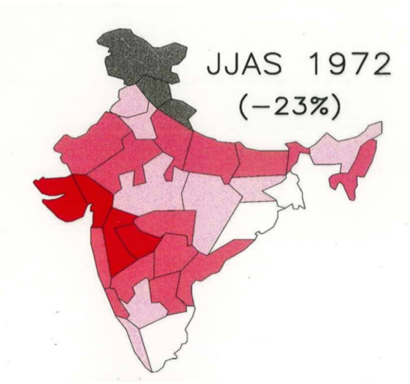
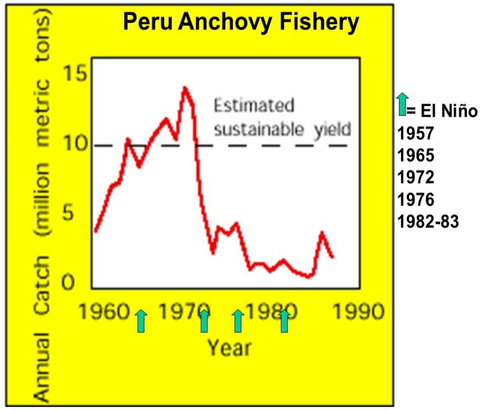
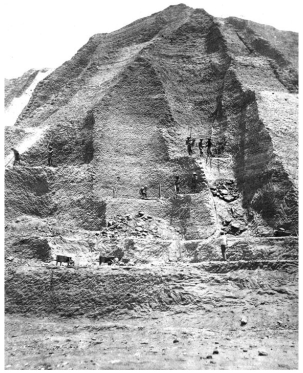
Reforecasting 1972-73 ENSO and Monsoon

1972-73 El Nino Devastates Peruvian Fisheries; Causes Severe Drought Over India







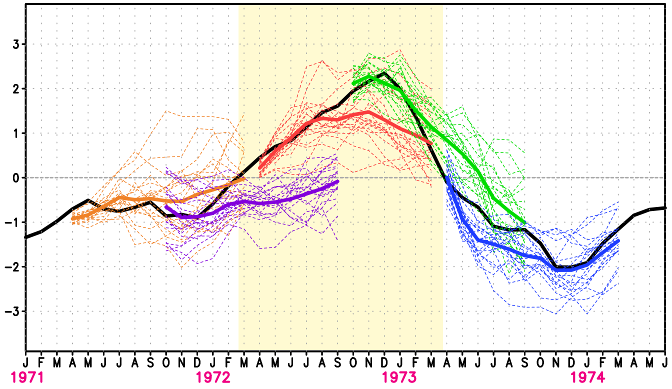
Guano Mountain (1860) in Peru
– 60 ft tall

Observed and Forecast SST Anomalies for April and October IC (CFSv2)

Strong Warm & Cold events

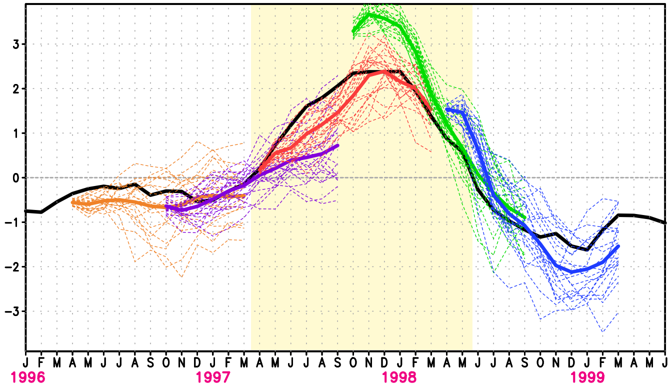
1971-1974

(a) 1971–1974



1996-1999

(b) 1996–1999



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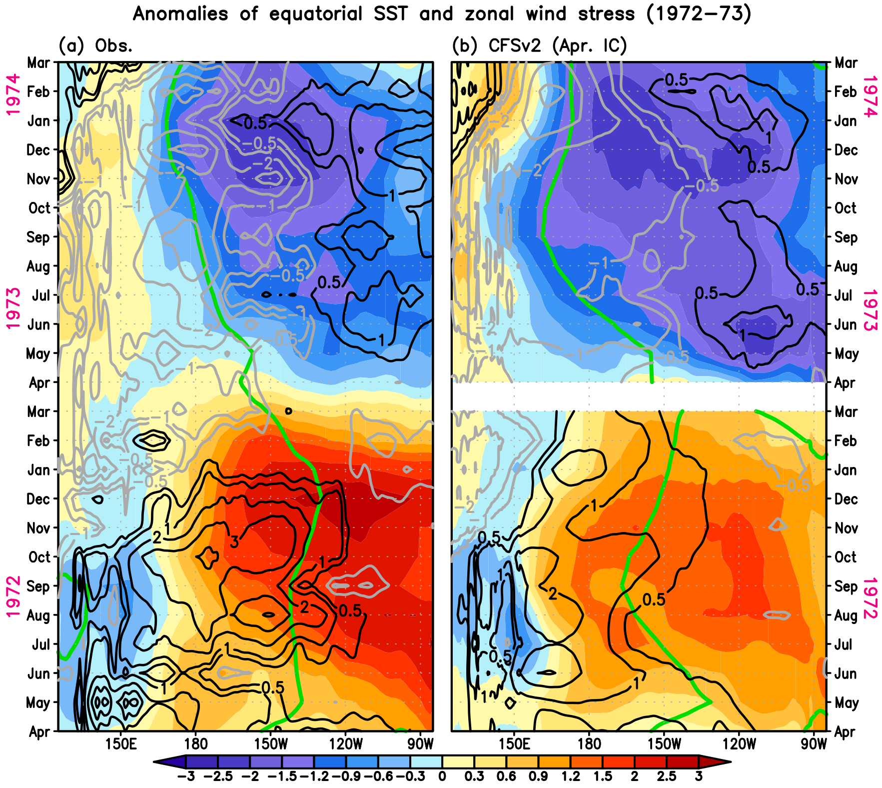
Observed and Predicted SST Anomalies for 1972-74

April IC

Observed

CFSv2



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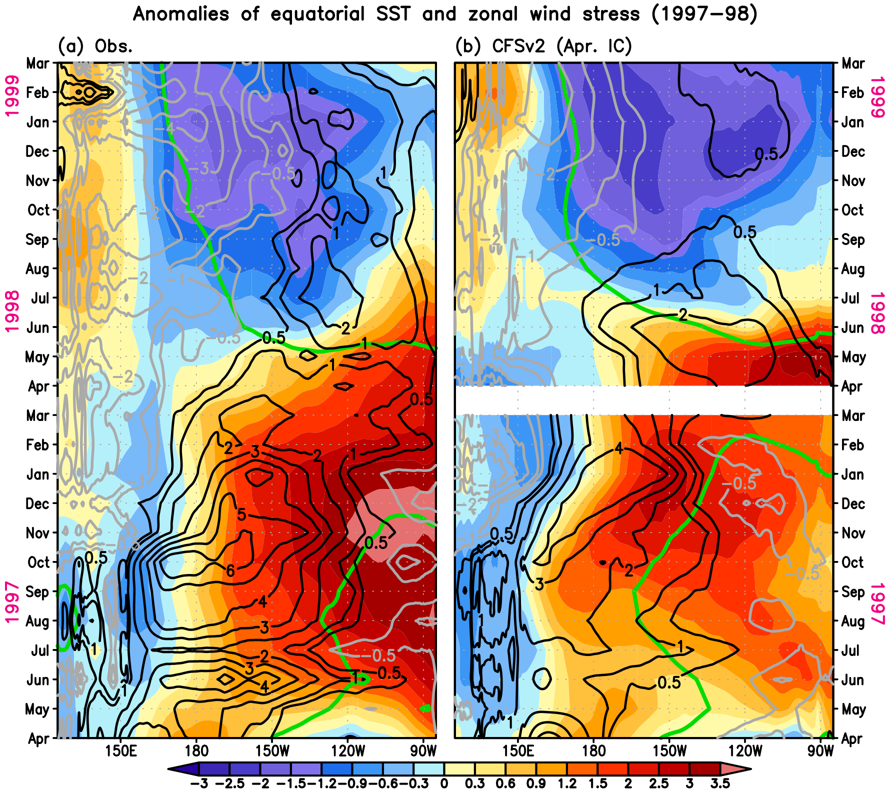
Observed and Predicted SST Anomalies for 1997-99

April IC

Observed

CFSv2



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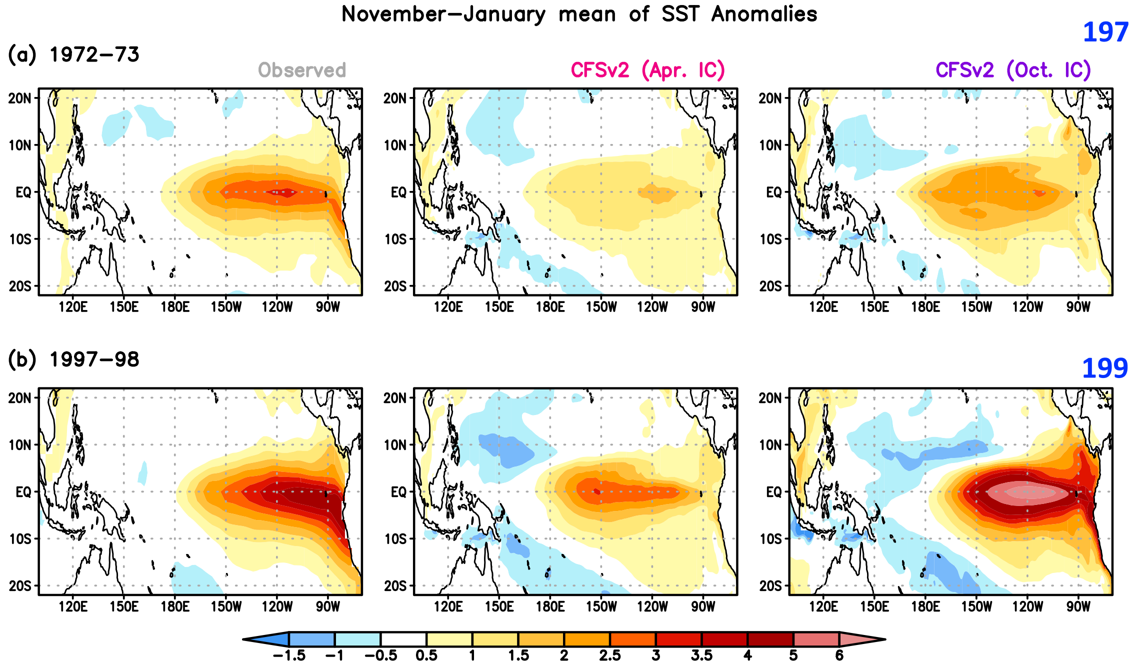
NDJ SST Anomalies

Observed **Forecast (Apr. IC)** **Forecast (Oct. IC)**



1972-73

1997-98

C

ENSO - Monsoon Teleconnections

Sometimes they work marvelously,
and sometimes they fail miserably.

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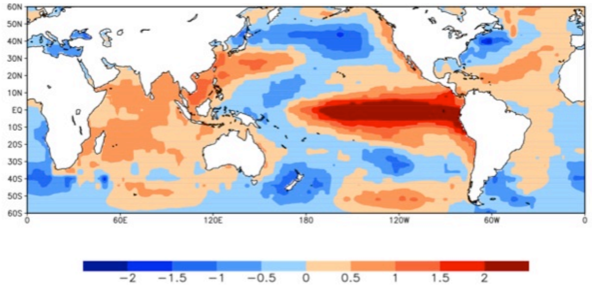
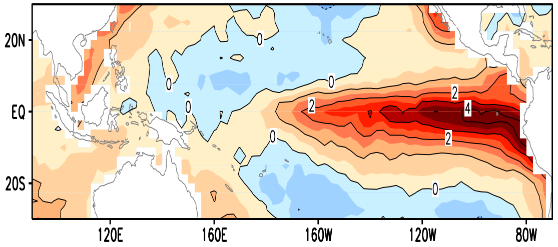
ENSO & ISMR for JJAS 1877 and 1997

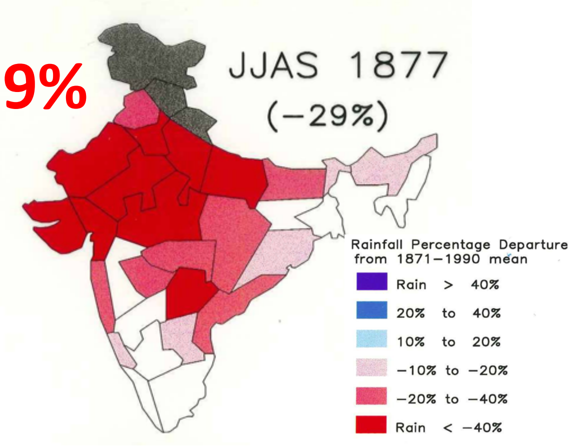
1877

1997

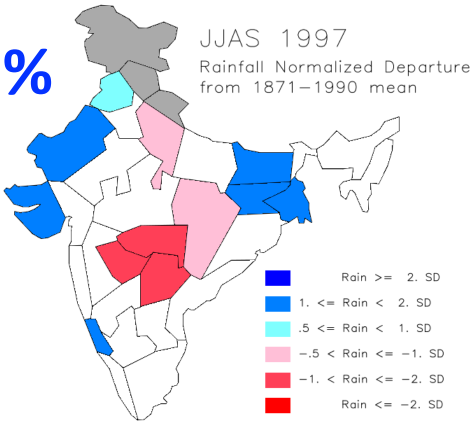




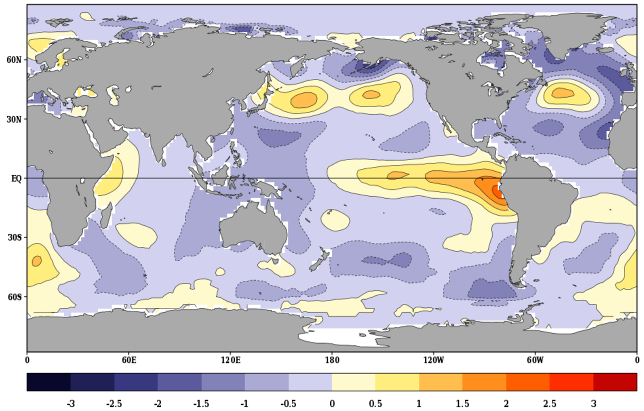
- 29%



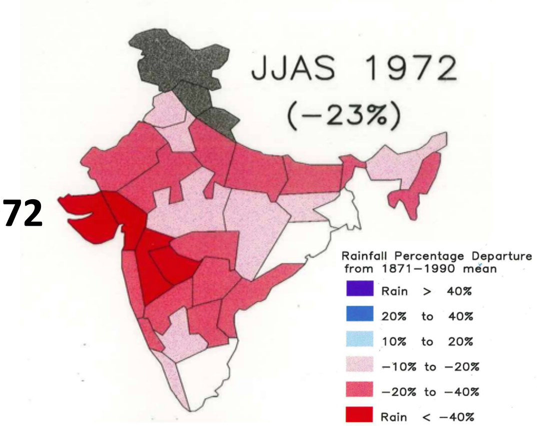
+ 2%

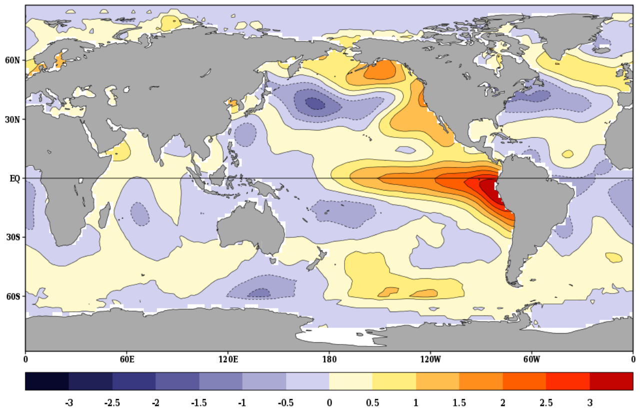


JJA Mean SST and Precip. Anomaly for 1972 and 1997

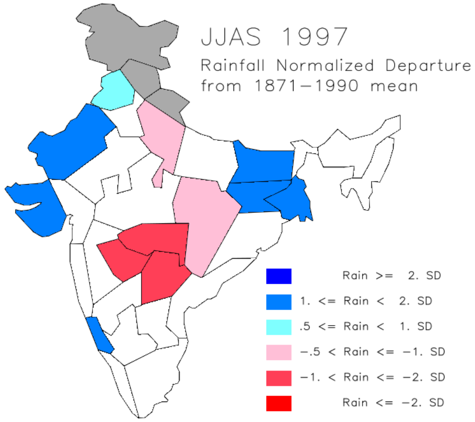


1972

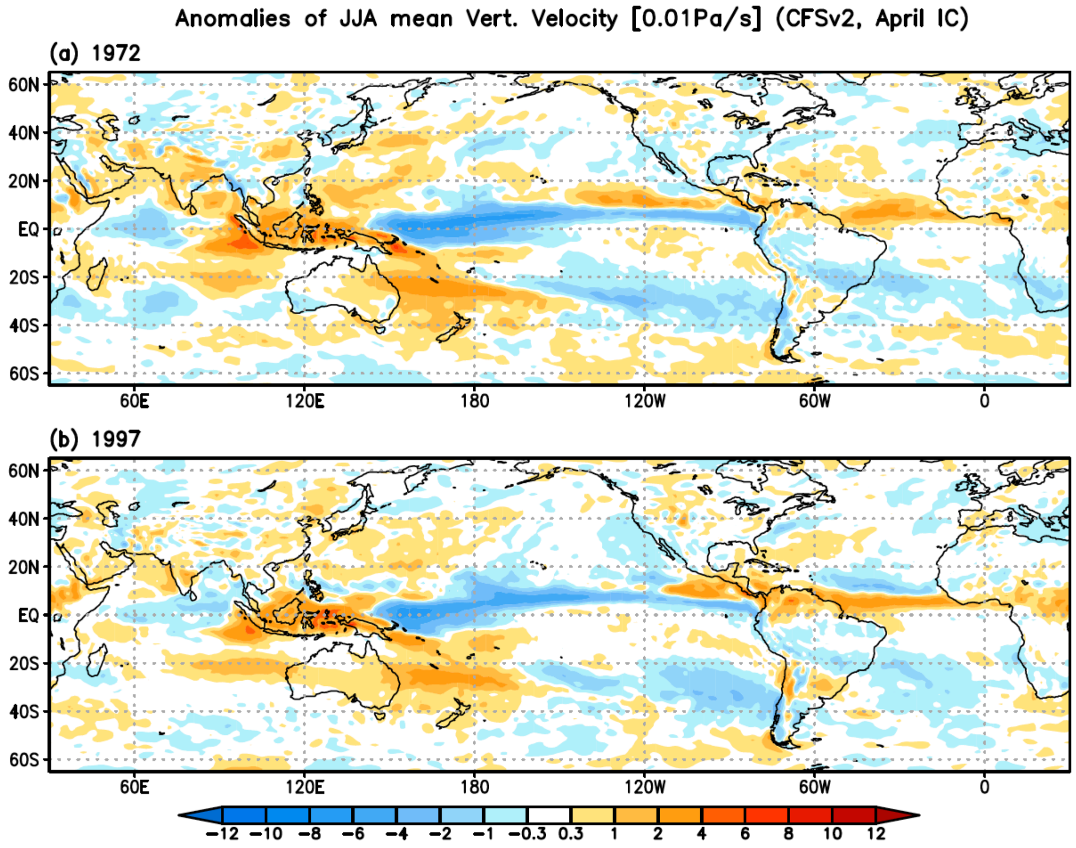




1997



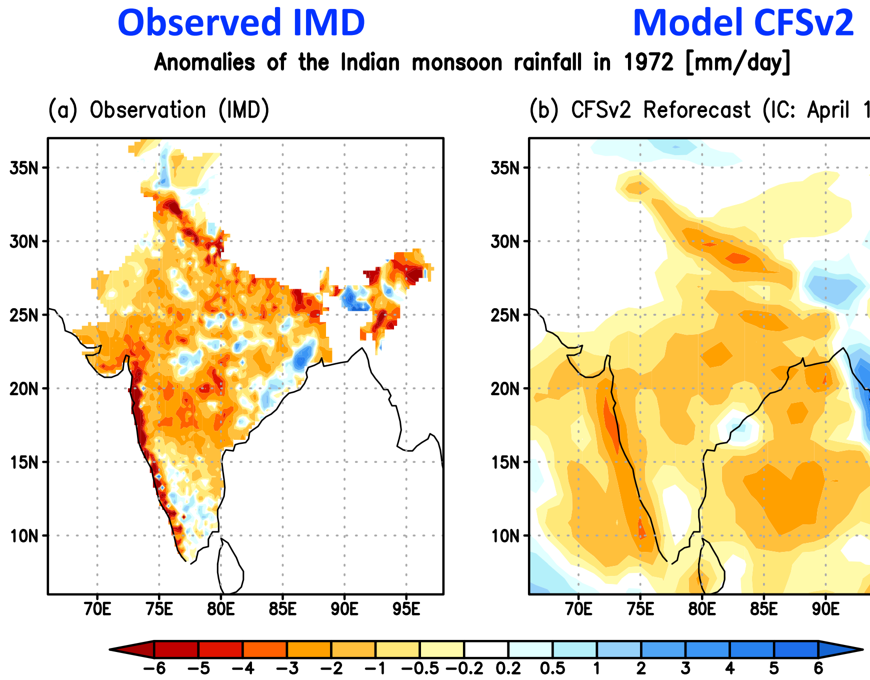
JJA Mean Vertical Velocity (omega) for 1972 and 1997



1972

1997

Forecast (April 72, IC) and Observed (IMD) Rainfall Anomalies for JJAS 1972 (mm/day)



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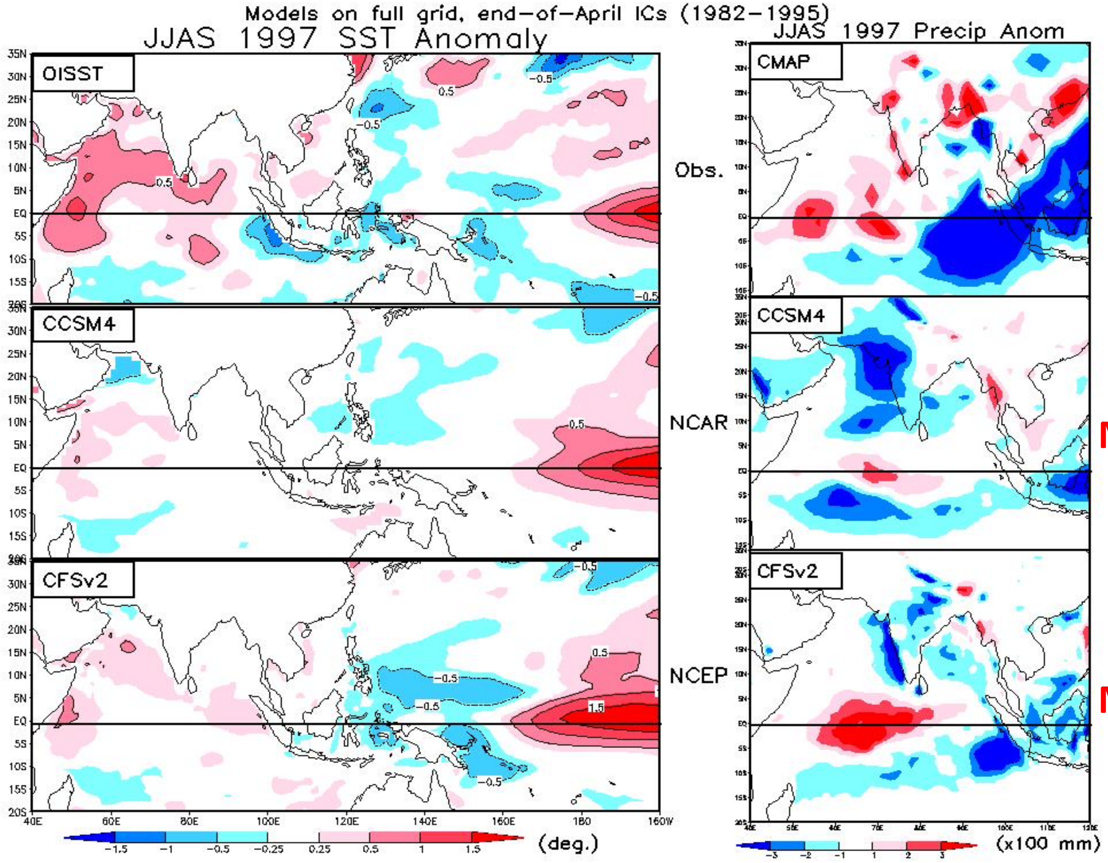
Forecast SSTA & Precip. Anomaly for JJAS 1997



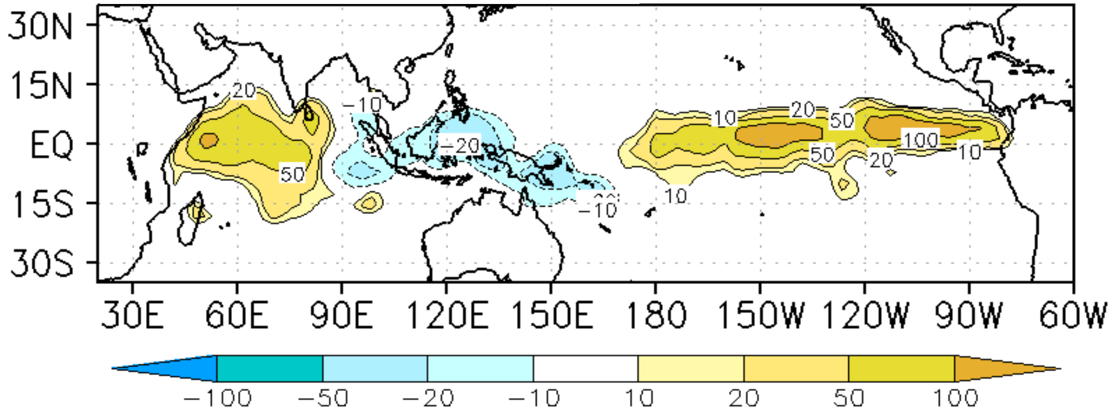
Obs.

Model

Model

1997 Diabatic Heating Anomaly (W/m^2)

(Based on Observations)



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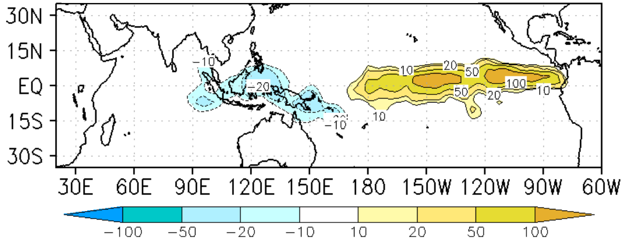
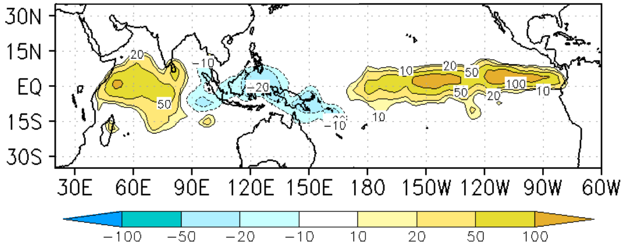
Pacific Only vs. Pacific + Indian Ocean

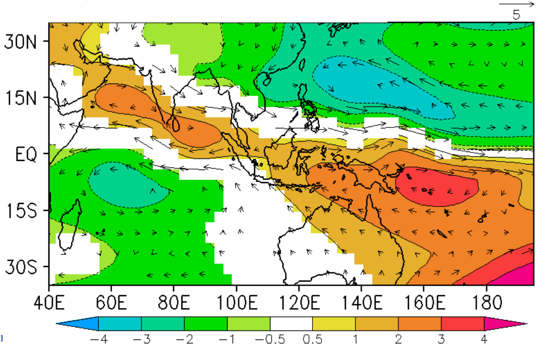
- 1997 Pacific forcing(only) W/m^2



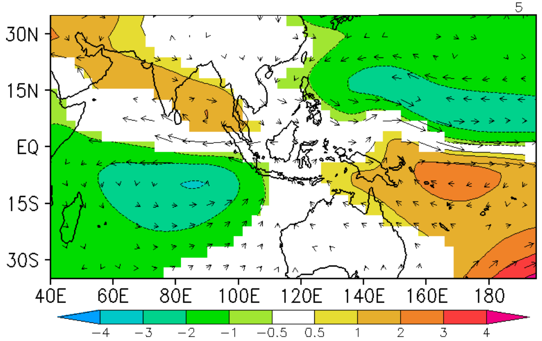
- 1997 Pacific + IO forcing W/m^2



- Response:
  Psi/ wind at 850hPa



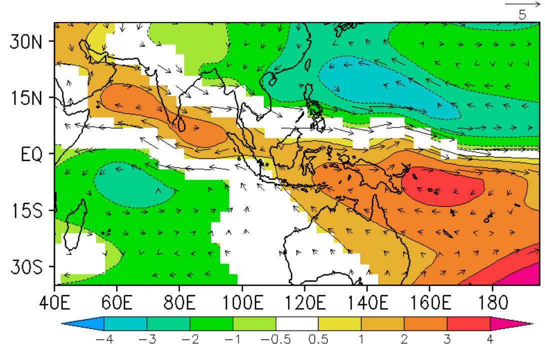
- Response:
  Psi/ wind at 850hPa



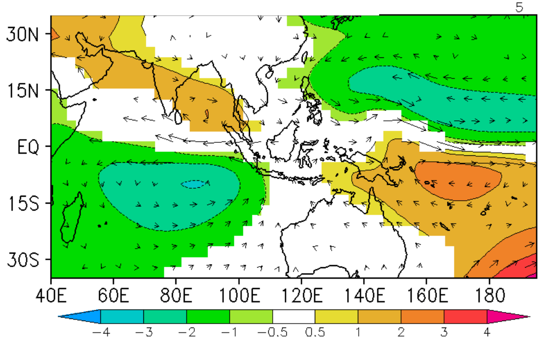
Pacific Only vs. Pacific + Indian Ocean
1997 ENSO

- The Pacific heating and cooling associated with 1997/98 El Nino produced a weaker monsoon circulation (drought!) over India. However, the superpostion of Pacific El Nino and Indian Ocean warming produced a normal monsoon circulation over India.

➢ Response:
Psi/ wind at 850hPa



➢ Response:
Psi/ wind at 850hPa



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Comments

- **There is significant unrealized seasonal predictability. The most dominant obstacle in realizing the potential predictability of short-term climate variations is inaccurate models, and unbalanced initial conditions rather than an intrinsic limit of predictability. *(Models with higher fidelity have higher prediction skill.)***

- **Advances in NWP did not come by some major theoretical or conceptual breakthrough; it came by comprehensive, persistent, and simultaneous efforts in prediction, model development and predictability research.**

- **To enhance predictive understanding, a vigorous, collaborative, and simultaneous effort is needed for model development, predictability research, and seamless prediction of weather and climate.**

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Summary

- **After 50 years of climate modeling, models have just begun to show some skill in prediction of seasonal mean rainfall over India, (Current statistical method have no demonstrable skill)**
- **The reasons for dramatic breakdown of ENSO-Monsoon Teleconnections in some years is not well understood.**
- **Realistic simulation of SST and diabatic heat sources in West-Pacific & IO appear to be important for accurate seasonal mean monsoon rainfall prediction, and intraseasonal variations during the monsoon season.**

THANK YOU!

ANY QUESTIONS?

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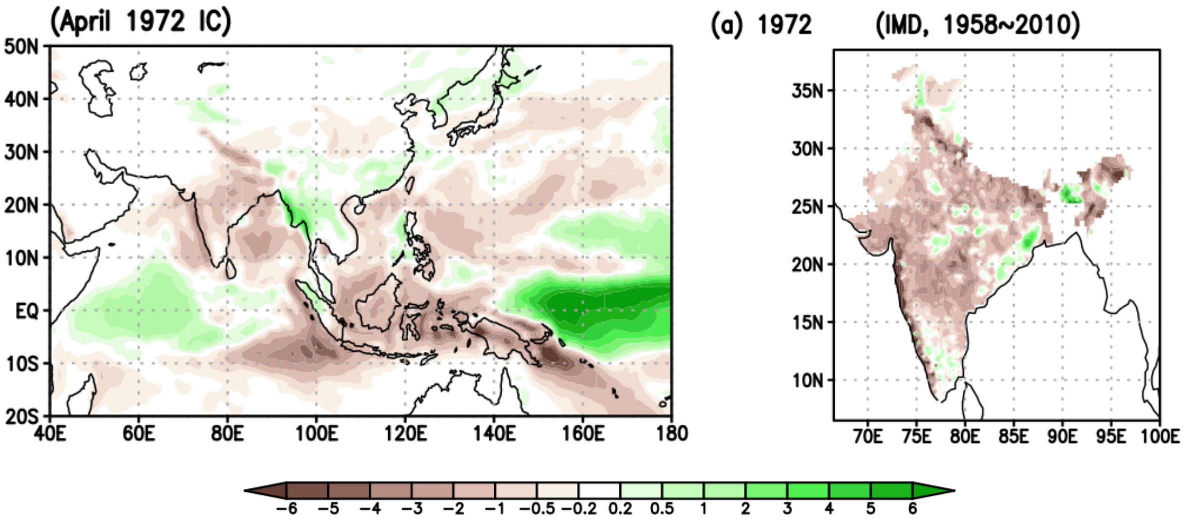
Forecast (April 72, IC) and Observed (IMD) Rainfall Anomalies for JJAS 1972 (mm/day)



Forecast Model Anomaly CFSv2

Observed Anomaly IMD

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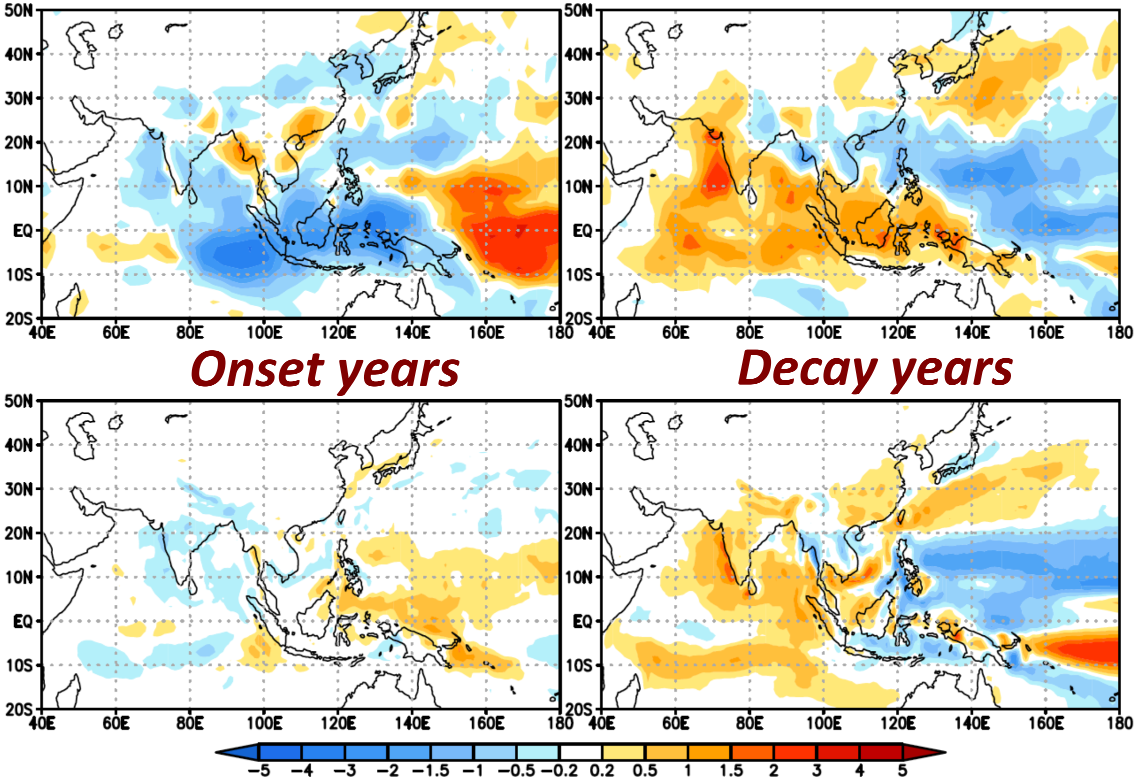
Composite anomalies of monsoon rainfall in all warm events



Observation

CFSv2 (Jan. IC)

Onset years

Decay years

('82-83, '87-88, '91-92, '94-95, '97-98, '02-03, '06-07)

Monsoon is more predictable in the summer after a major El Niño event

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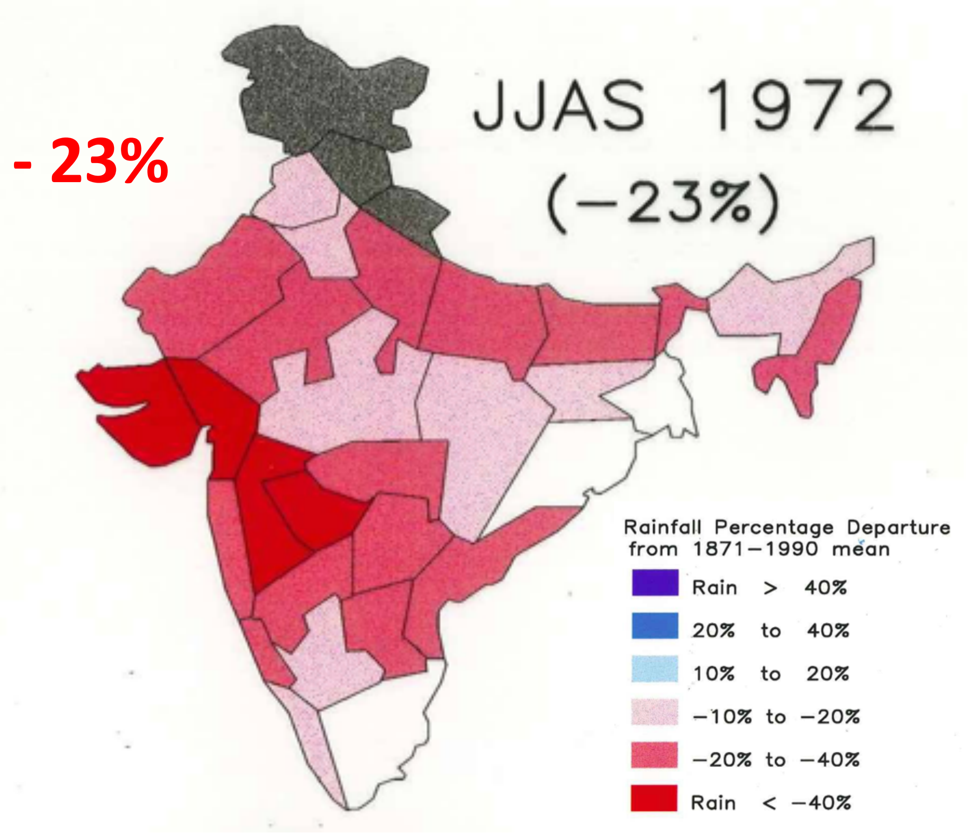
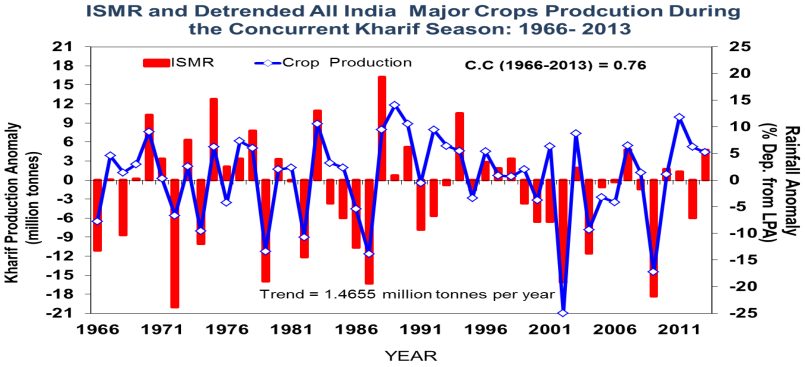
JJAS Rainfall Anomalies Over India

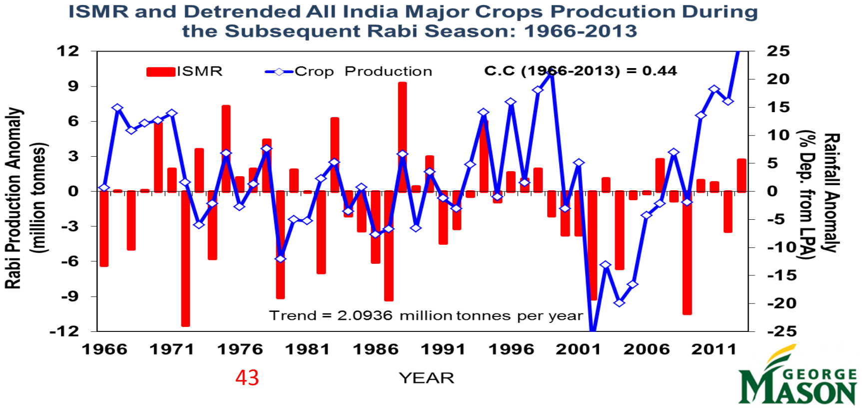
- 23%



Monsoon Rainfall & Agriculture (India)


ISMR and Detrended All India Major Crops Prodcution During the Concurrent Kharif Season: 1966- 2013

Crop production deviation for any year is a measure of the impact of the monsoon rainfall of that year.


ISMR and Detrended All India Major Crops Prodcution During the Subsequent Rabi Season: 1966-2013

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Predictive Understanding

Prediction Skill and Predictability as a Metric of Understanding

- To enhance predictive understanding, a vigorous, collaborative, and simultaneous effort is needed for model development, predictability research, and seamless prediction of weather and climate. Diagnostic evaluation and prediction must be an integral part of model development.

- Advances in NWP did not come by some major theoretical or conceptual breakthrough; it came by comprehensive, persistent, and simultaneous efforts in prediction, model development and predictability research by a team of qualified scientists.

  (A similar effort for Dynamical Seasonal Prediction is needed.)

Summary

- The most dominant obstacle in realizing the potential predictability of short-term climate variations is inaccurate models, and unbalanced initial conditions rather than an intrinsic limit of predictability.

  (Models with higher fidelity have higher prediction skill.)

- There is significant unrealized seasonal predictability.

- A multi-institutional (multinational) enhanced research effort and computational infrastructure is needed to develop the next generation of high fidelity climate models for improved climate predictions, utilization of space observations, and to suggest policies and strategies for adaptation and mitigation.

Summary

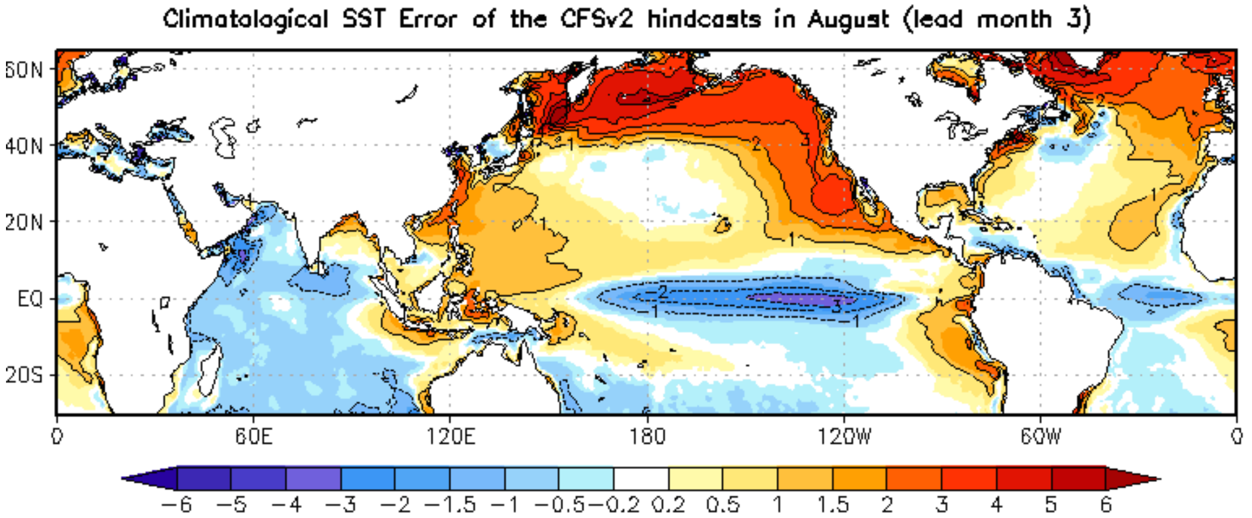
- ENSO prediction skill is comparable between 1958-78 and 1979-2014.
- The growth of some ENSO events is underestimated, possibly duo to cold bias.
- ENSO skill decreases more quickly in spring during 1958-78 (model events persist longer).
- RMS errors are larger during summer-fall in 1979-2014 (overshooting strong events).

In Spite of Large Biases in Simulated SST, Predictions of SST Anomalies Have Some Skill
In Some Cases

Small Skill in Predicted SST is Enough to Give Statistically Significant Skill in Predicted Monsoon Rainfall

That is why statistical models using April/May SST to predict JJAS monsoon rainfall have no skill, but coupled models with April/May initial conditions of A & O have statistically significant skill

SST Bias in 3 Month Forecasts (CFSv2), 1982-2008, I.C. May, 1


Climatological SST Error of the CFSv2 hindcasts in August (lead month 3)

CFSv2 hindcasts (1982-2008)

Atmospheric and Land ICs : first 4 days in May (4 ensemble members), CFSR
Ocean ICs : NEMO reanalysis

Observation *: daily NOAA OI SST ver2*

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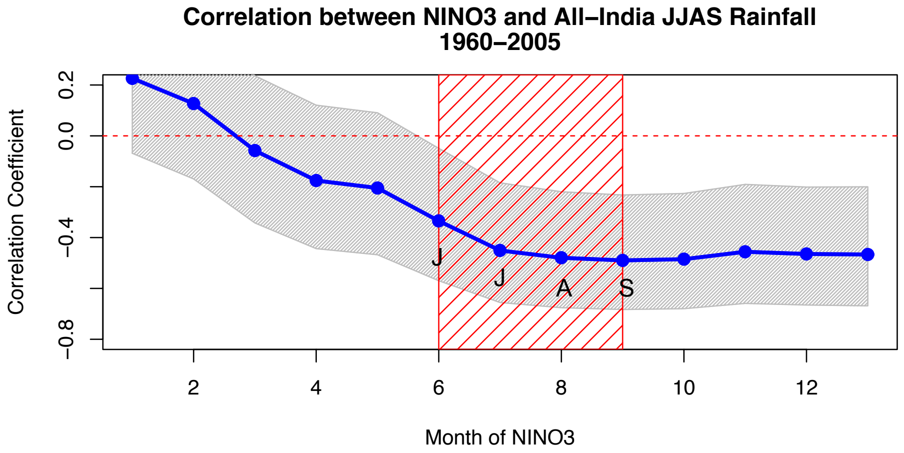

Correlation between NINO3 and All–India JJAS Rainfall
1960–2005

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.

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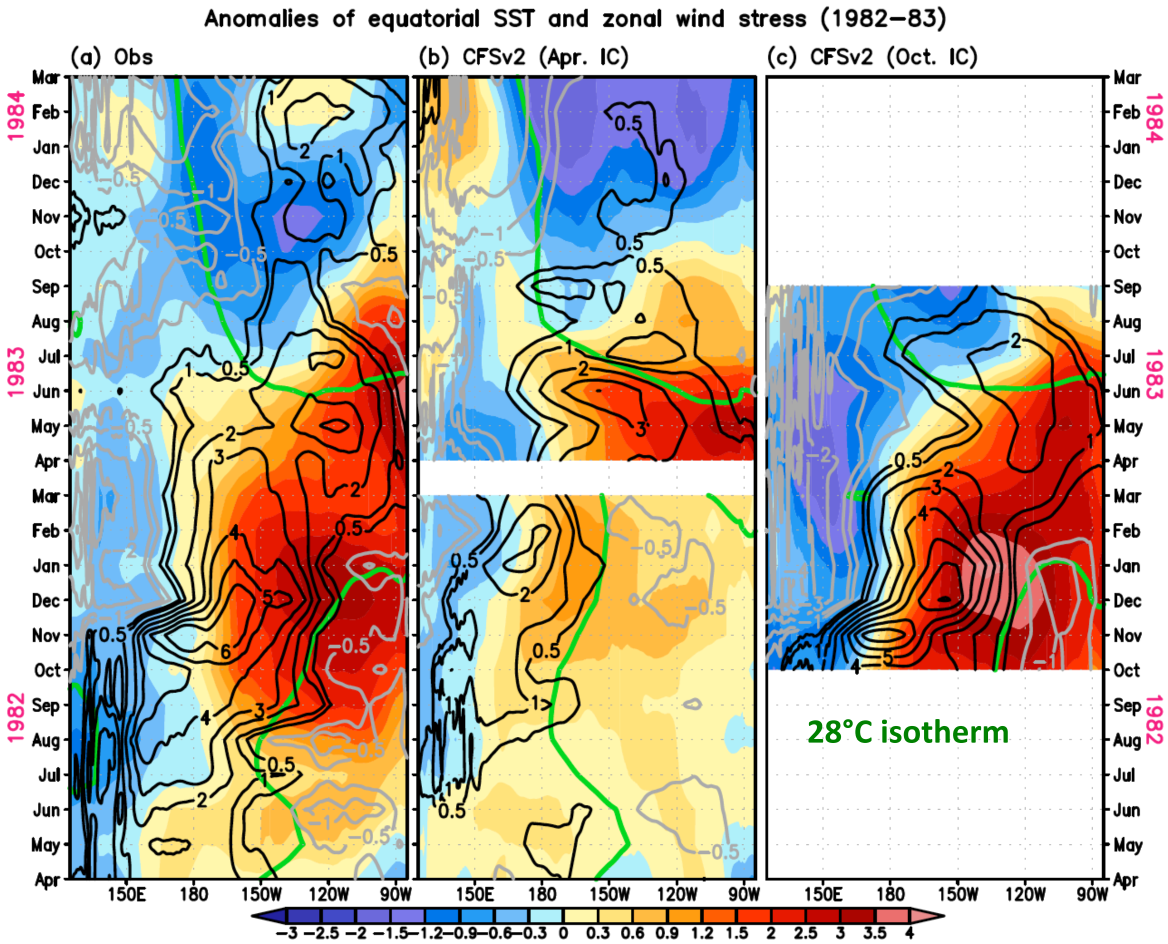
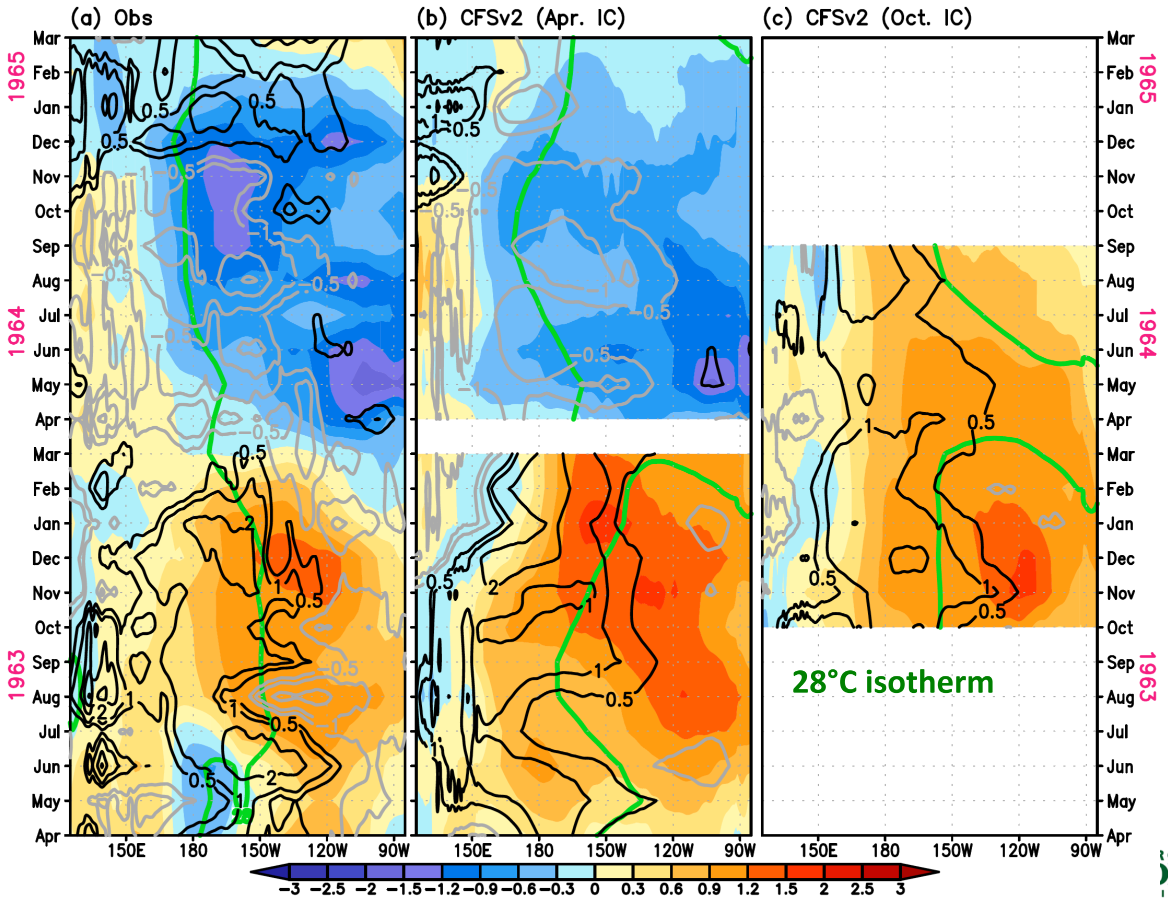


28°C isotherm

Cen
At

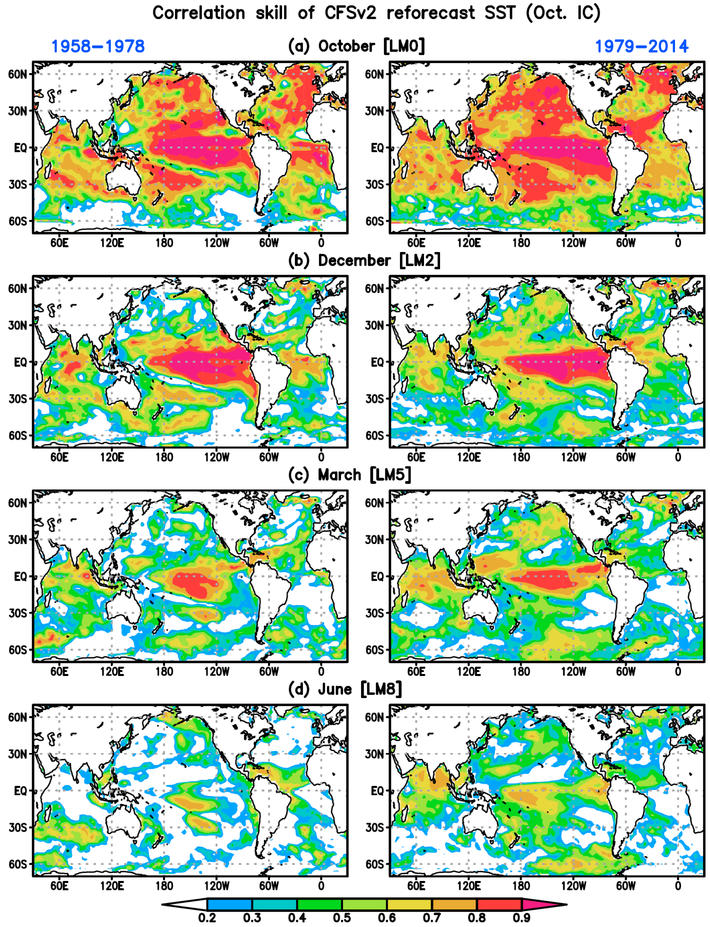
Anomalies of equatorial SST and zonal wind stress (1963–64)



28°C isotherm

Oct. IC

1958-1978



1979-2014

Verified against ERSSTv3

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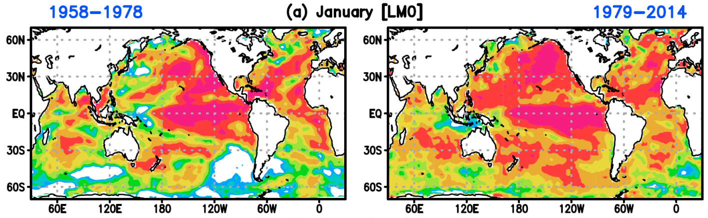
Jan. IC

1958-1978

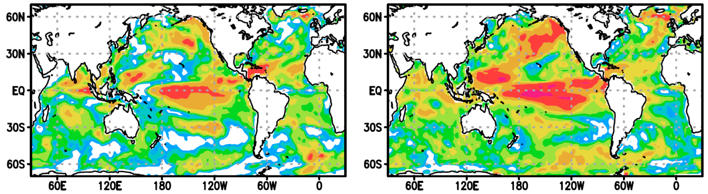
1979-2014

Correlation skill of CFSv2 reforecast SST (Jan. IC)

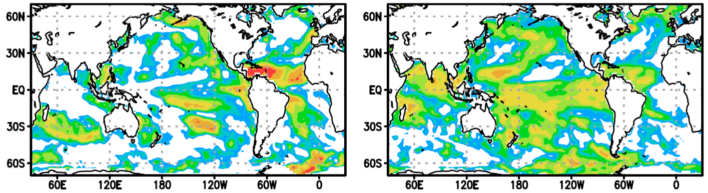
(a) January [LM0]



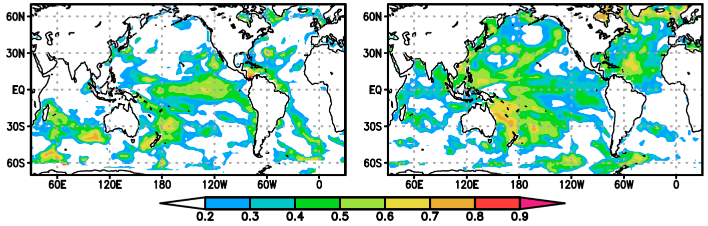
(b) March [LM2]



(c) June [LM5]



(d) September [LM8]



Verified against ERSSTv3

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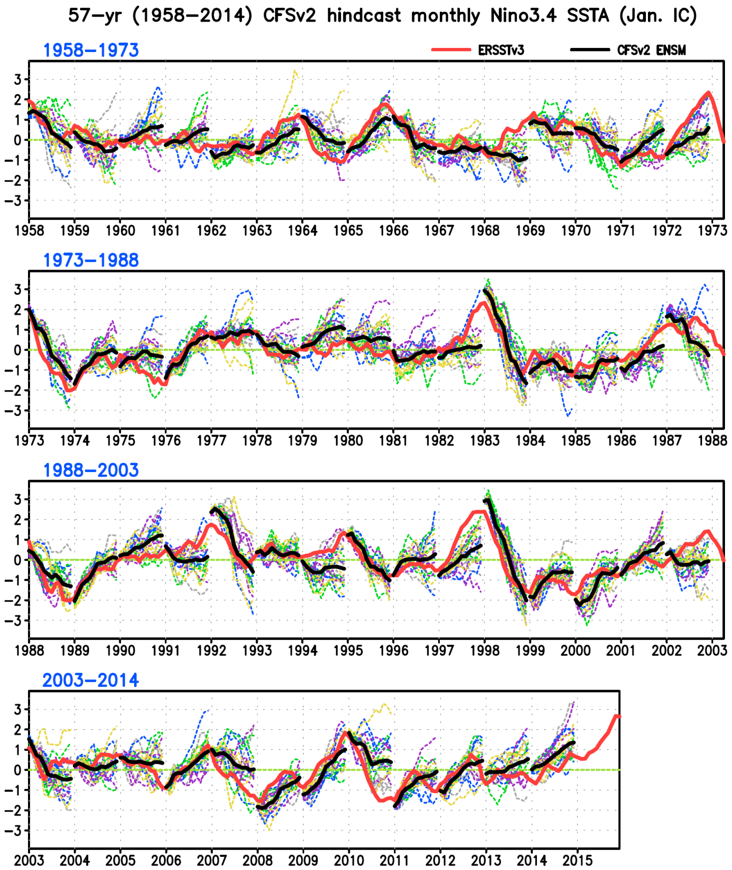
Jan. IC



ERSSTv3

CFSv2 ENSM

Ensemble spread is the greatest.
(higher uncertainty)

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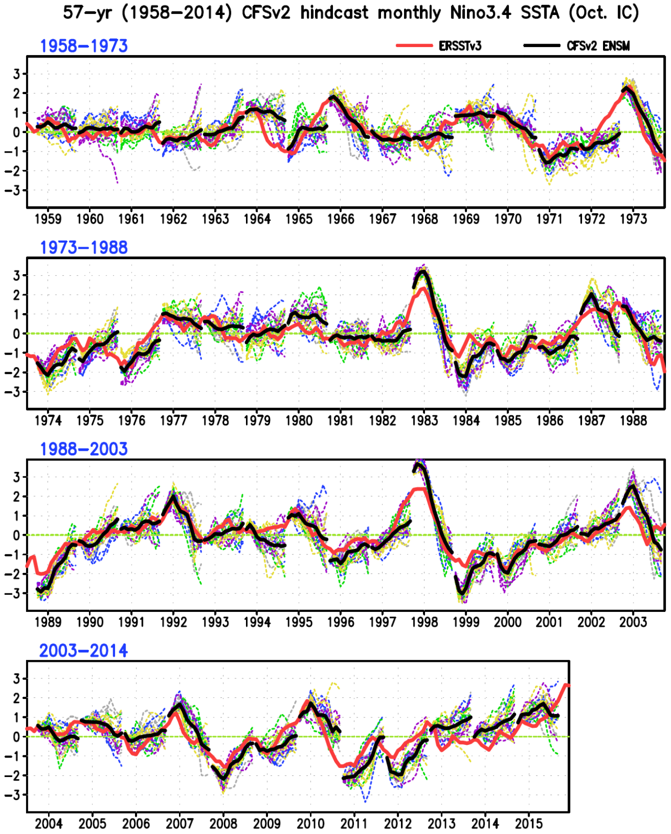
Observed and **Forecast (Oct IC)** Nino 3.4, 1958-2014



57–yr (1958–2014) CFSv2 hindcast monthly Nino3.4 SSTA (Oct. IC)

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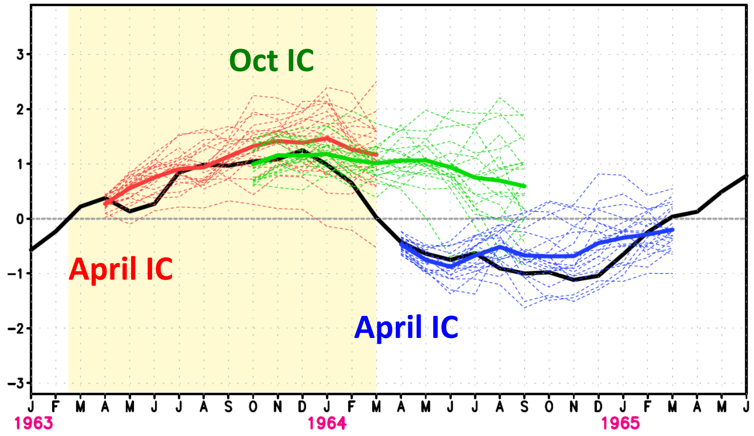
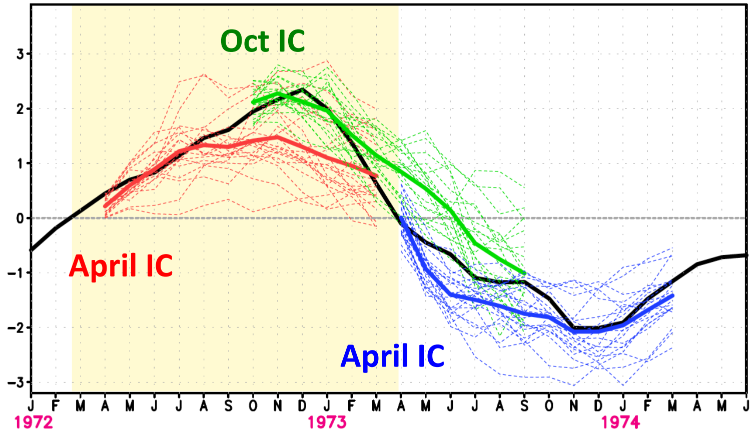
(a) 1963–1965



(b) 1972–1974



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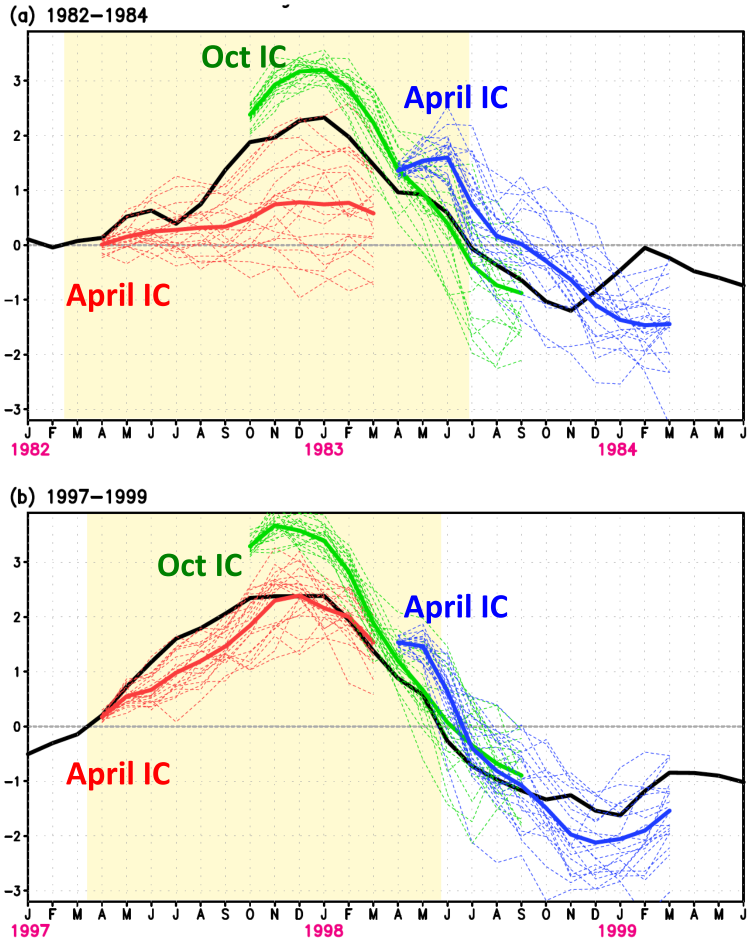
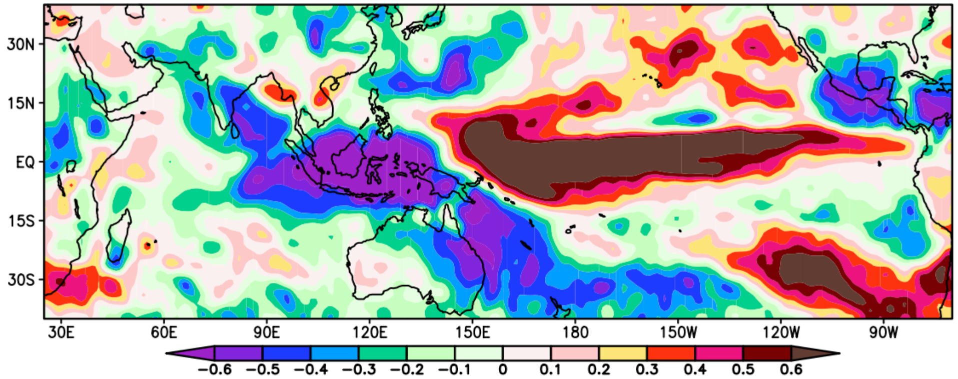
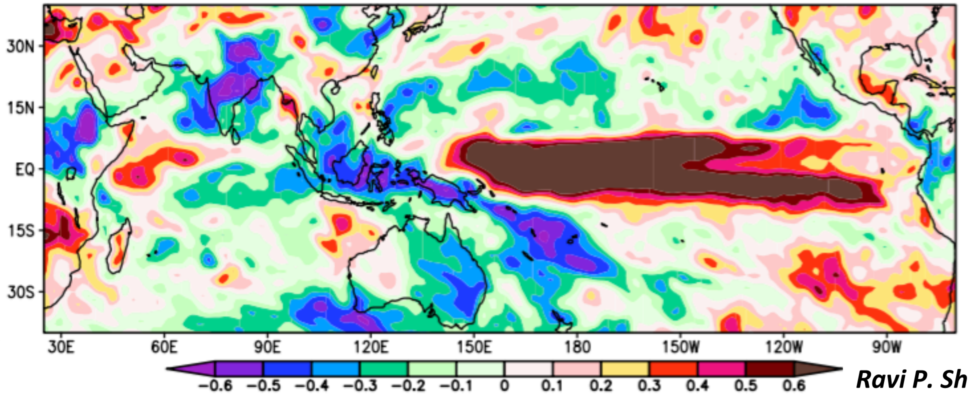

(a) 1982–1984
Oct IC
April IC
April IC
3
2
1
0
−1
−2
−3
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1982
1983
1984
(b) 1997–1999
Oct IC
April IC
April IC
3
2
1
0
−1
−2
−3
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1997
1998
1999

Correlation Coefficient between Nino 3.4 SSTA and Precipitation for JJAS (1981-2010)



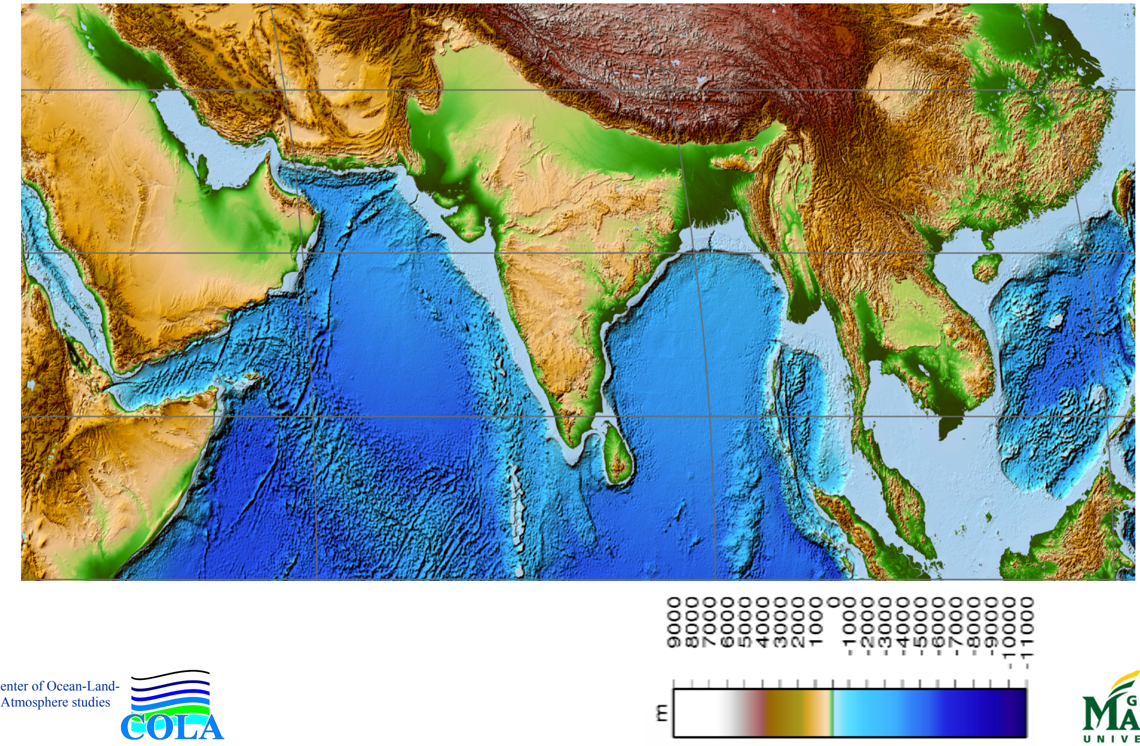
Observed



CFSv2

Ravi P. Shukla & Huang (2015)

Orography



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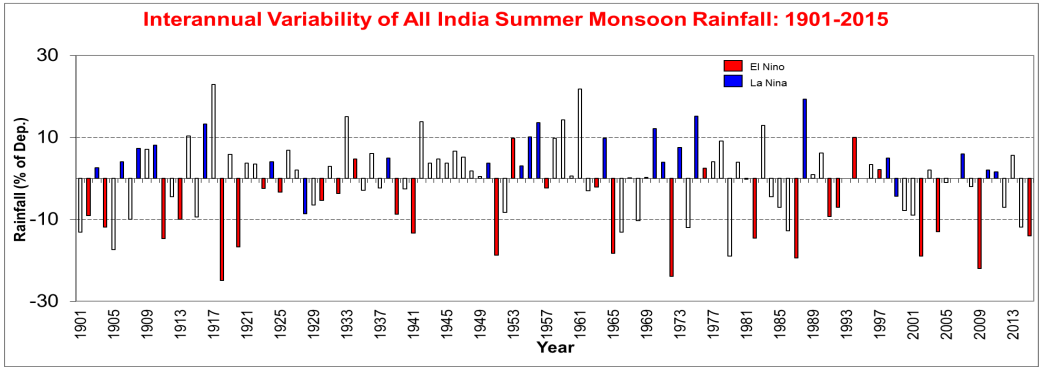
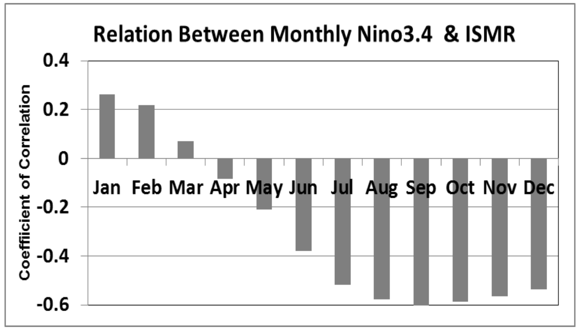
El Nino vs Monsoon

Red Bars: El Nino Years **Blue Bars: La Nina Years**


Interannual Variability of All India Summer Monsoon Rainfall: 1901-2015


Relation Between Monthly Nino3.4 & ISMR

In general, ENSO has inverse relationship with Indian summer monsoon. During the warm phase of the ENSO (El Nino), monsoon is weaker than normal and during the cold phase of the ENSO (La Nina), monsoon is stronger than normal. The intensity of the events also decides the amount of impact.

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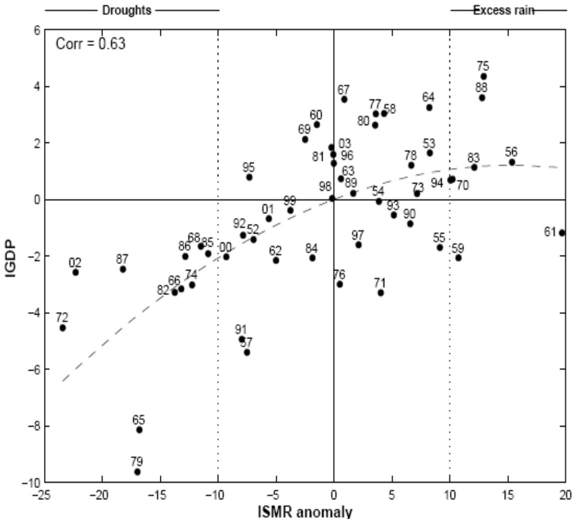
Indian GDP and Summer Monsoon Rainfall

Impact of a severe drought on GDP remains 2 to 5% throughout, despite the substantial decrease in the contribution of agriculture to GDP over the five decades (**Gadgil and Gadgil 2006**)



IGDP by sector (2012-13)
agriculture: 13.7%,
industry: 21.5%,
services: 64.8%

Labour force by occupation

agriculture: 49%,
industry: 20%,
services: 31%
(2012 est.)

SOURCE: WWW.TRADINGECONOMICS.COM | WORLD BANK GROUP

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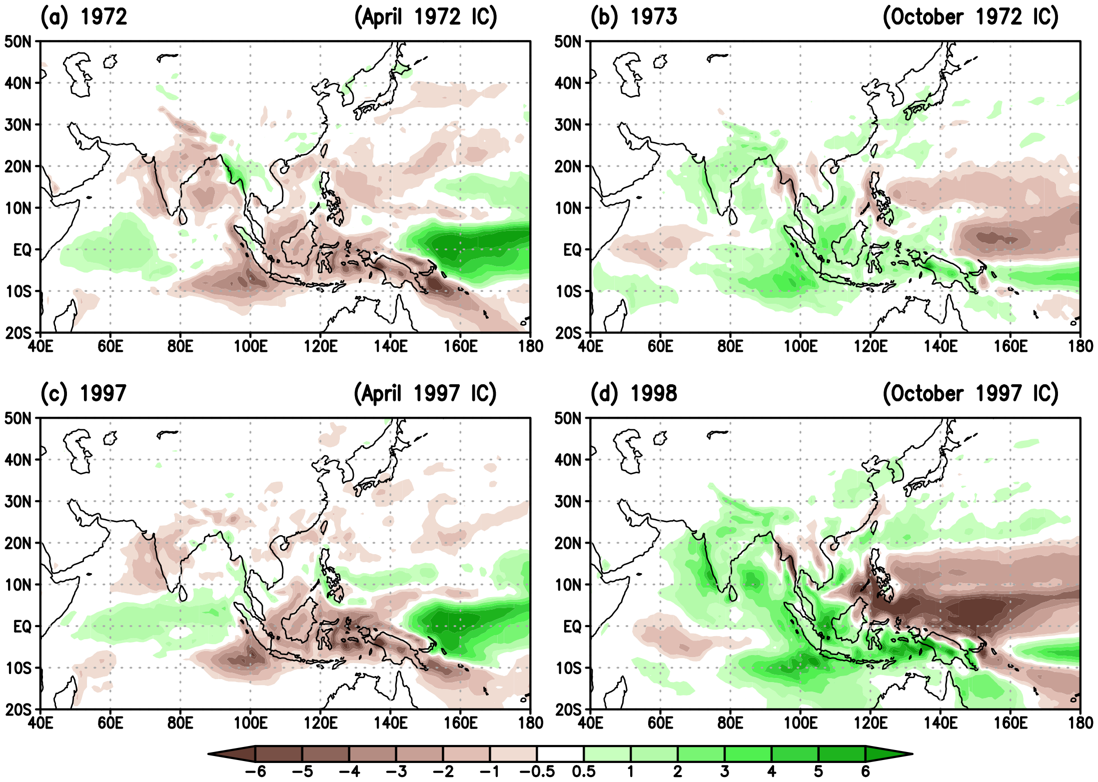
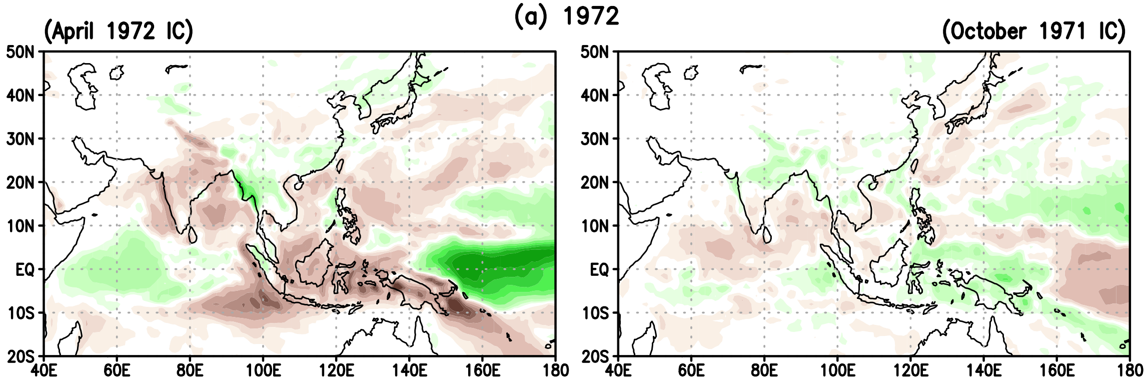
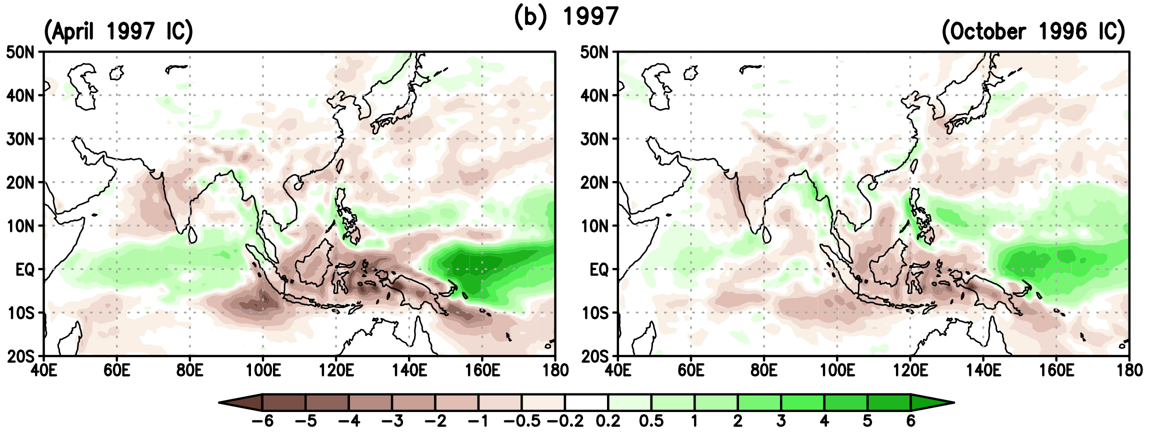
Predicted JJAS mean rainfall anomalies [mm/day]

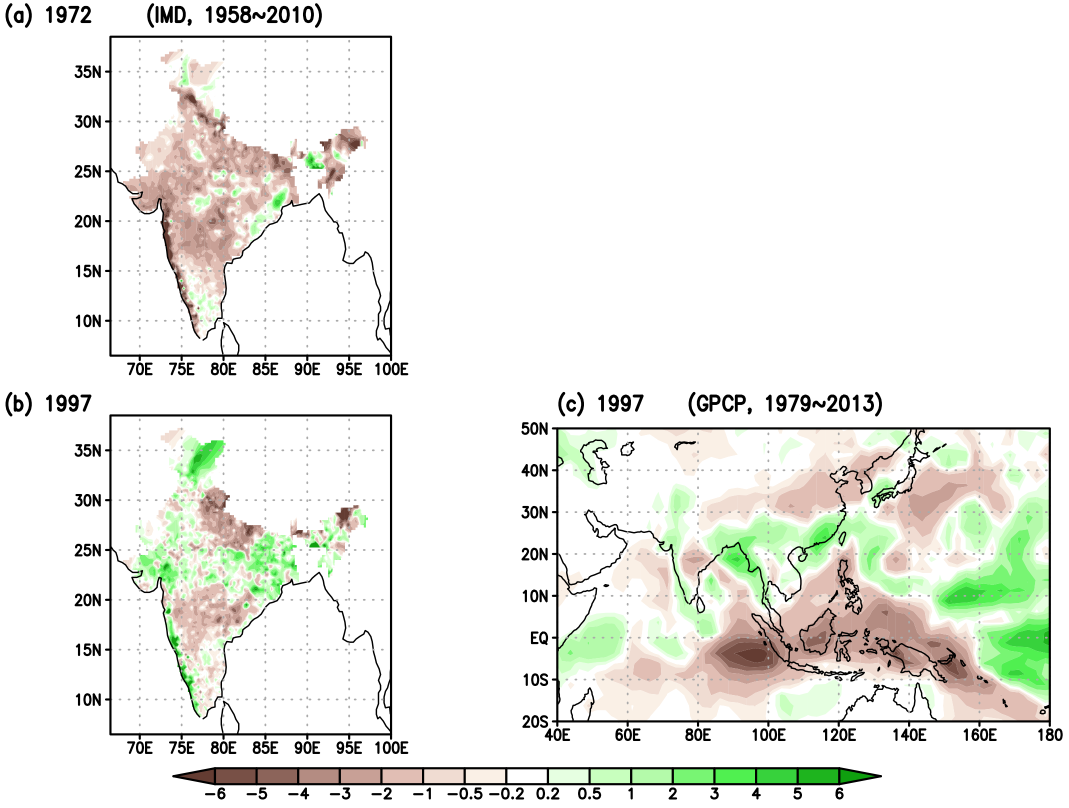


Predicted JJAS mean rainfall anomalies [mm/day]


(a) 1972


(b) 1997

Observed JJAS mean rainfall anomalies [mm/day]



El Nino vs Monsoon

Year	Jun	Jul	Aug	Sep	JJAS	El Nino strength
1951	86.4	81.1	87.9	67.1	81.3	ME
1953	101	112	119	100	**110**	WE
1957	89.2	101	113	77.9	97.6	SE
1963	88.4	84.7	122	94.2	97.9	ME
1965	66.7	95.2	77.3	79.2	81.8	SE
1969	76.5	107	106	103	100	WE
1972	73.3	68.8	85.9	76.4	76.1	SE
1982	83.2	76.9	109	67.8	85.5	ME
1987	78.4	71.2	96.3	74.9	80.6	SE
1991	109	91.3	95.5	66.2	90.7	ME
1997	106	98.4	109	93.9	102	SE
2002	109	45.8	98.3	87.1	80.8	ME
2004	99.2	80.1	95.7	70	86.2	WE
2009	52.8	95.7	73.5	79.8	78.2	WE
2015	115.9	83.6	78.2	75.8	85.7	SE

- **In general, Indian SW monsoon is weaker than normal during the El Nino years.**
- **No one to one association between EL Nino and ISMR.**
- **However there is stronger inverse relationship between El Nino and rainfall during later half of the monsoon season (particularly with September rainfall)**

- During 1951-2015, there were 15 El Nino years.
- 9 El Nino years - deficient (less than 90%) season rainfall
- 4 El Nino years 90 to 100%
- 2 El Nino years it was above 100% (which includes 1997 one of the strongest El Nino years of the last century).
- No El Nino years was associated with the excess monsoon rainfall

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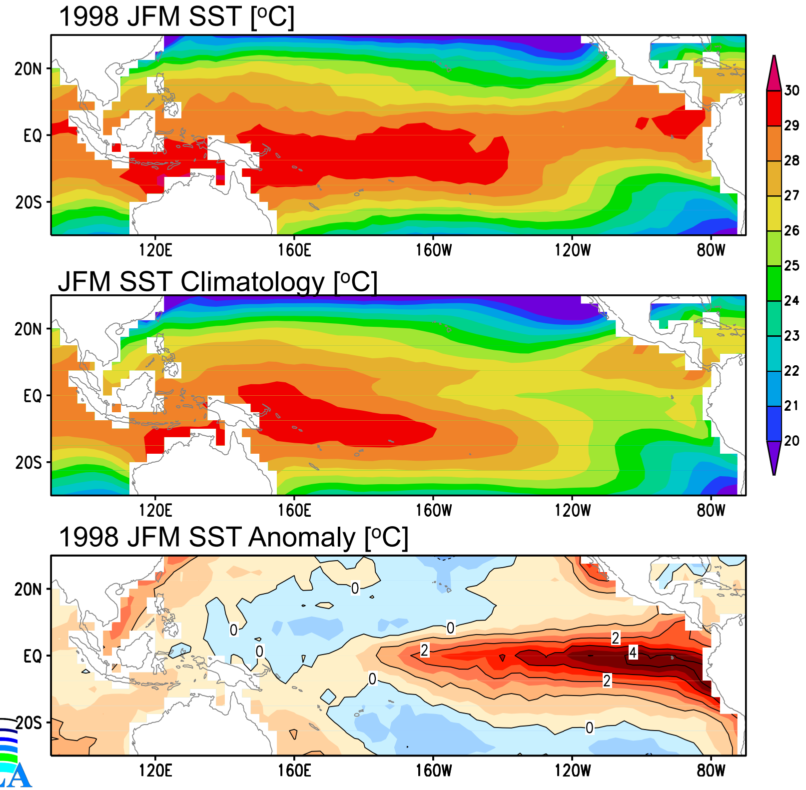
El Nino/Southern Oscillation

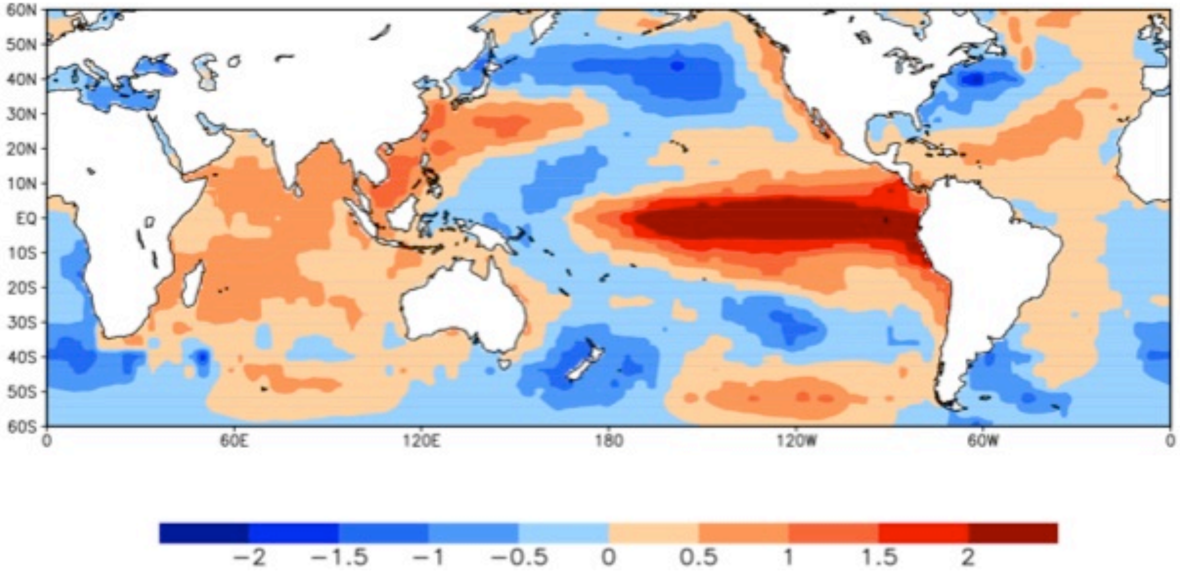


1998 JFM SST [ºC]

JFM SST Climatology [ºC]

1998 JFM SST Anomaly [ºC]

SST Anomaly (°C) for DJF 1877



Courtesy of Lakshmi Krishnamurti

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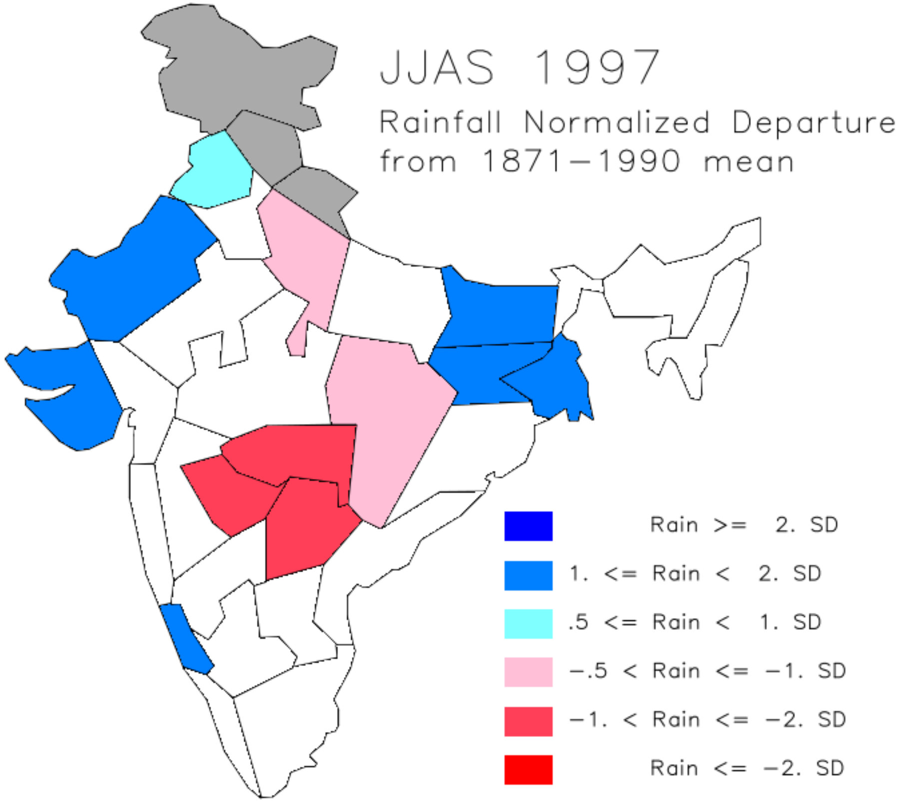
JJAS Rainfall Anomalies Over India



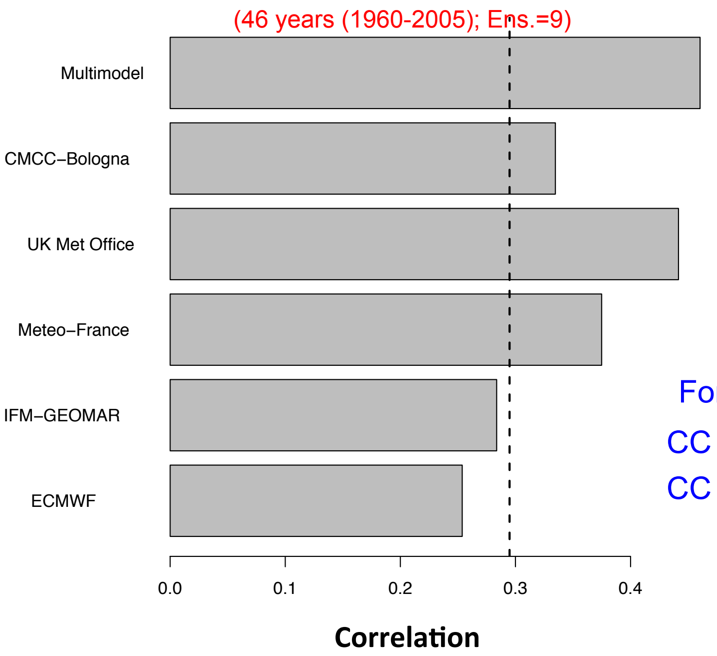
In Spite of Large Biases in Simulated SST, Predictions of SST Anomalies Have Some Skill
In Some Cases

Small Skill in Predicted SST is Enough to Give Statistically Significant Skill in Predicted Monsoon Rainfall

Ensembles Project

(70E – 90E & 10N – 25N)

Correlation between Observed and Predicted ISMR
1960–2005



For 1960-2005 Obs,

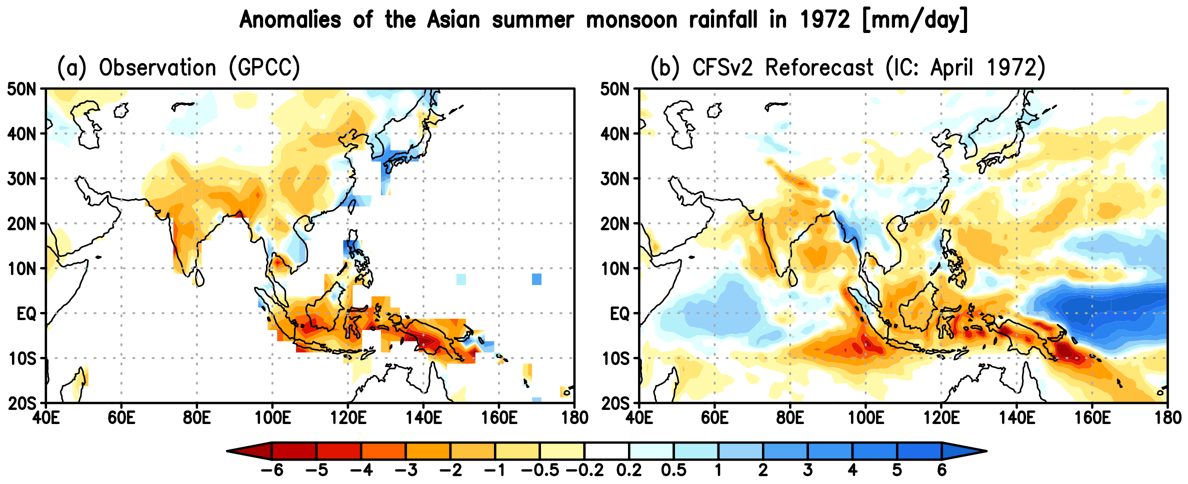
CC (April Nino3, ISMR): −0.18

CC (May Nino3, ISMR): −0.21

After 50 years of modeling, and in spite of large systematic errors in SST and precipitation, climate models show a small but statistically significant skill for dynamical prediction of Indian summer monsoon rainfall.

Forecast (April 72, IC) and Observed (IMD) Rainfall Anomalies for JJAS 1972 (mm/day)

Observed GPCC **Model CFSv2**



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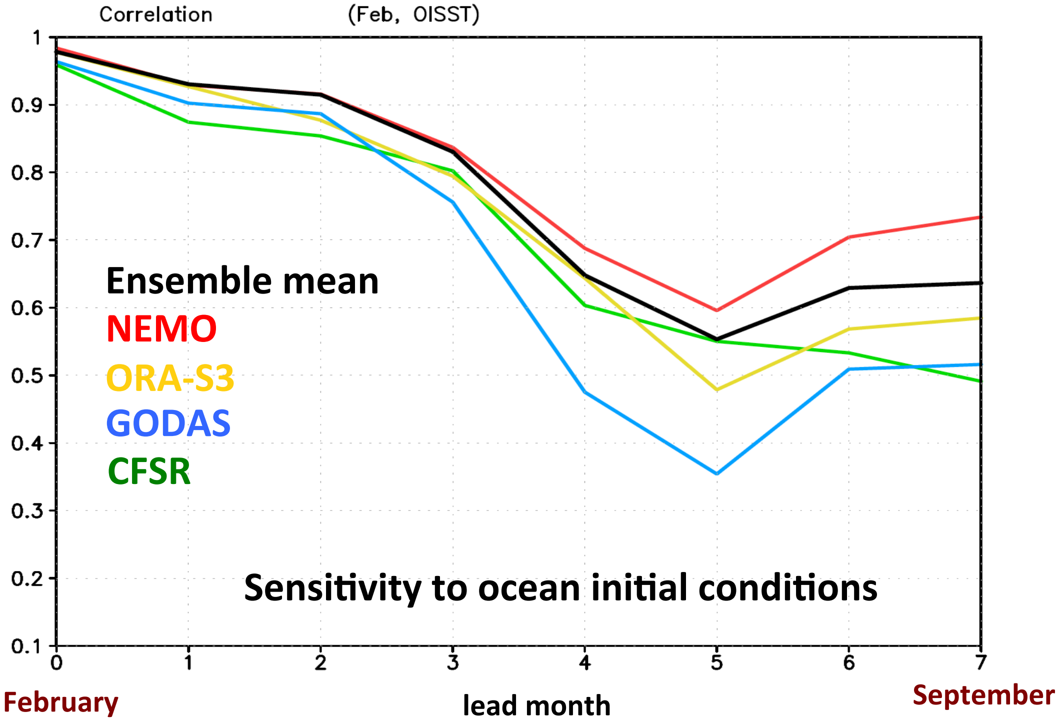
CFSv2 Prediction skill of Nino3.4 SSTA (1982-2008)



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Initial conditions are important!

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

Youkyoung Jang (Ph D Thesis)
Department of Atmospheric, Oceanic and Earth Science
George Mason University
Spring 2011

Committee
Dr. David M. Straus (Chair)
Dr. Timothy DelSole
Dr. Ben P. Kirtman
Dr. Timothy Sauer
Dr. J. Shukla

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Method

Control Runs (20 years)

- non-SOM : climatological SST*
- SOM: slab ocean model over the western Pacific and Indian Ocean other basins with climatological SST

*change in Walker circulation induced by added heating

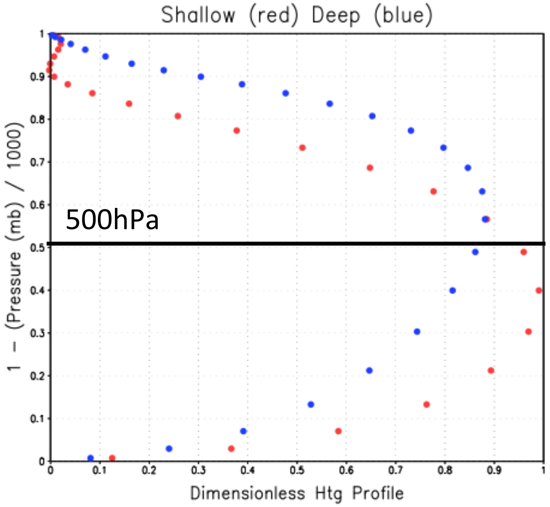
Forced Runs

Q (total heating rate) = Q (AGCM) + Q (Added heating)

- Q (AGCM): feedback from dynamics on heating
- Responses defined as Forced Exp - Control Run
- Forced experiments with SOM and non-SOM
- **Focused on Seasonal Mean (MJJA)**

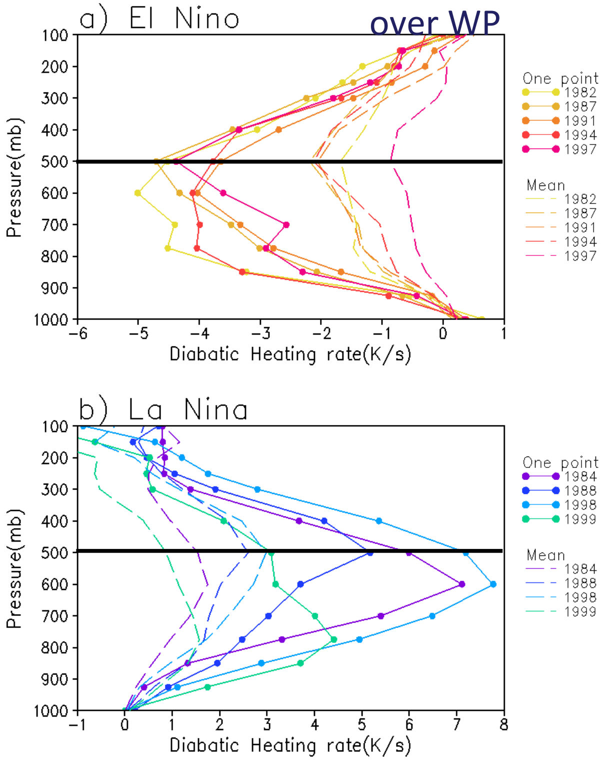
Vertical structure (K/day)

- **Model**



500hPa

- **Observation**



over WP

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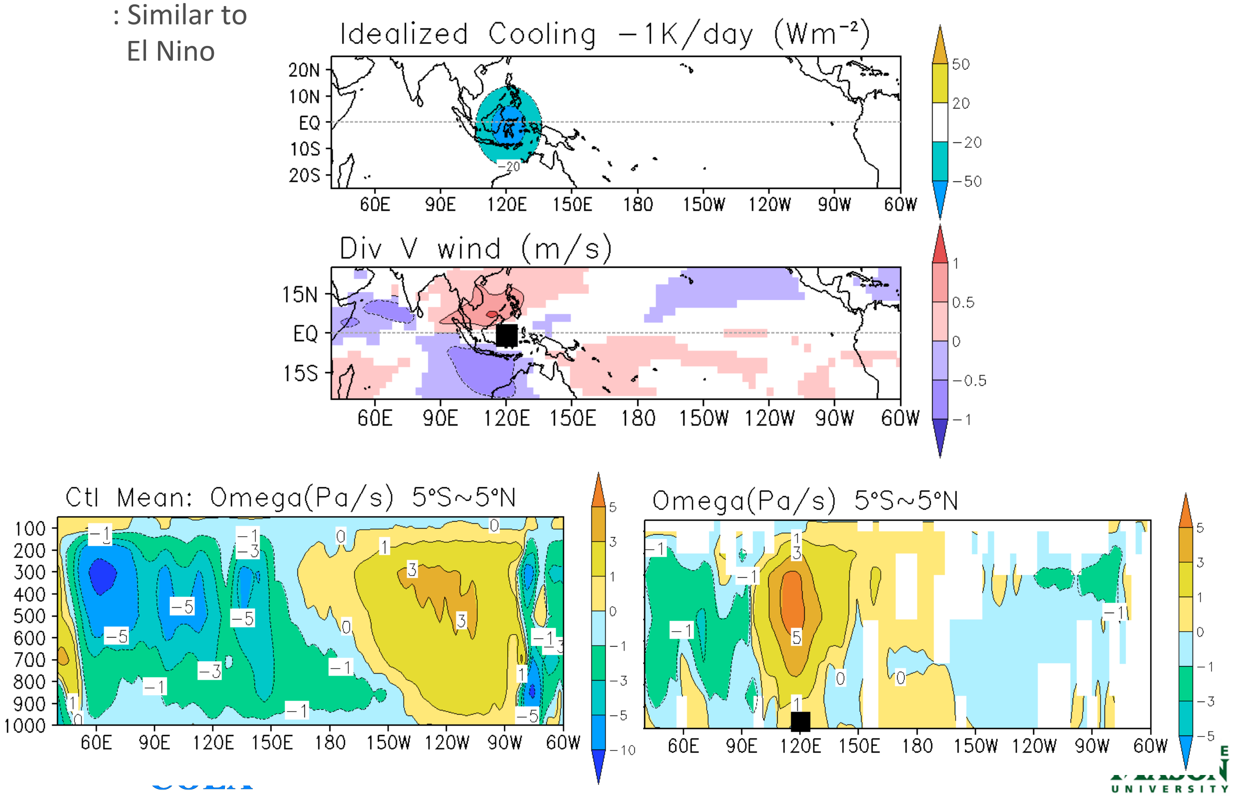
Cooling Exp: GCM effect

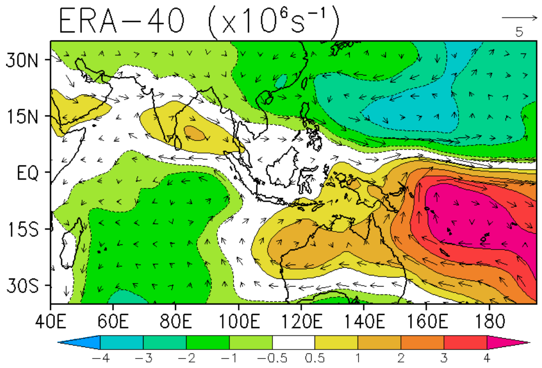
- Western Pacific Cooling ~ Descending motion

  : Similar to
  El Nino



Idealized Cooling (WP), Heating (IO)

- **Observation**



- **Streamfunction (x1e6s^{-1}) at 850hPa**

- **Wind (m/s) at 850hPa**

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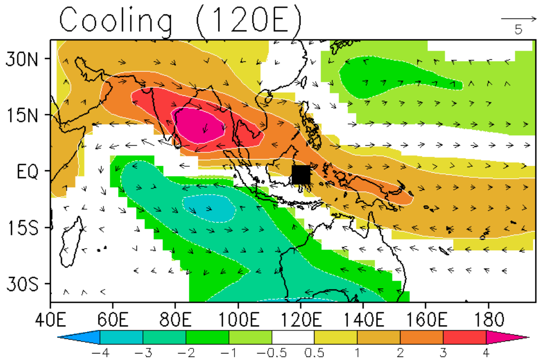
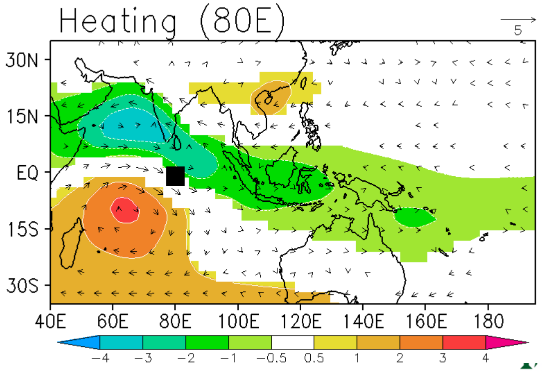
- **Two Idealized forcing Exps**

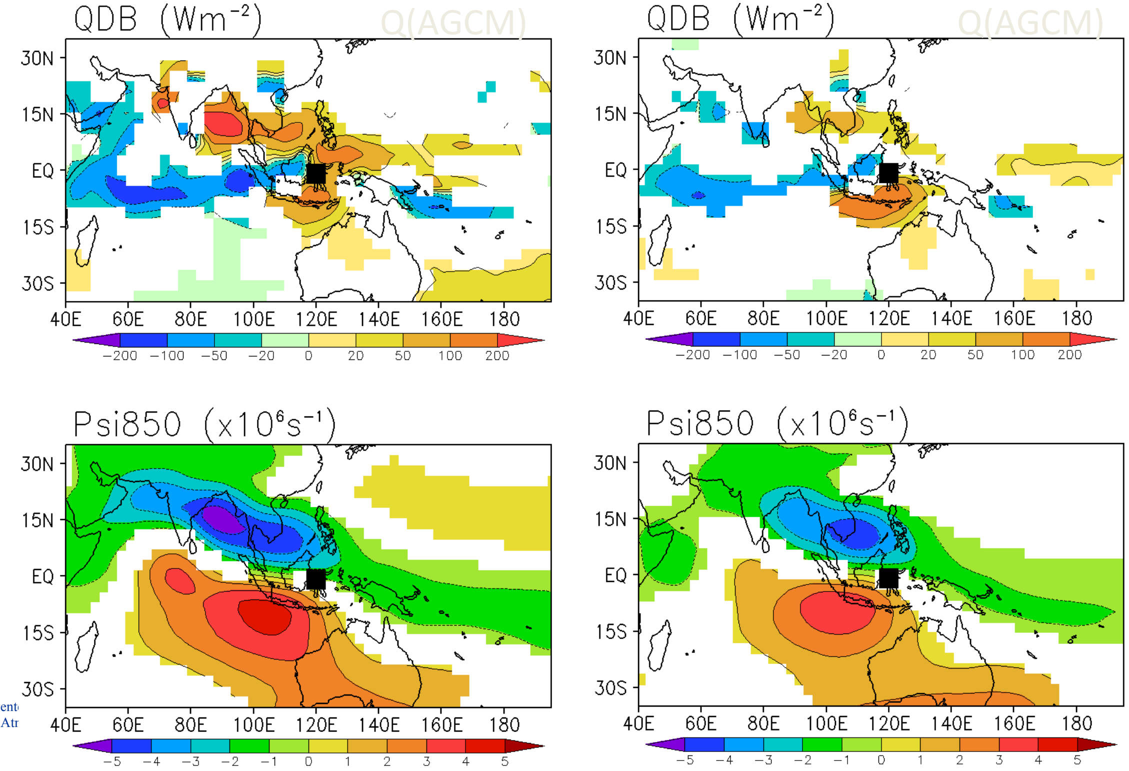




Air-Sea Interaction: Heating

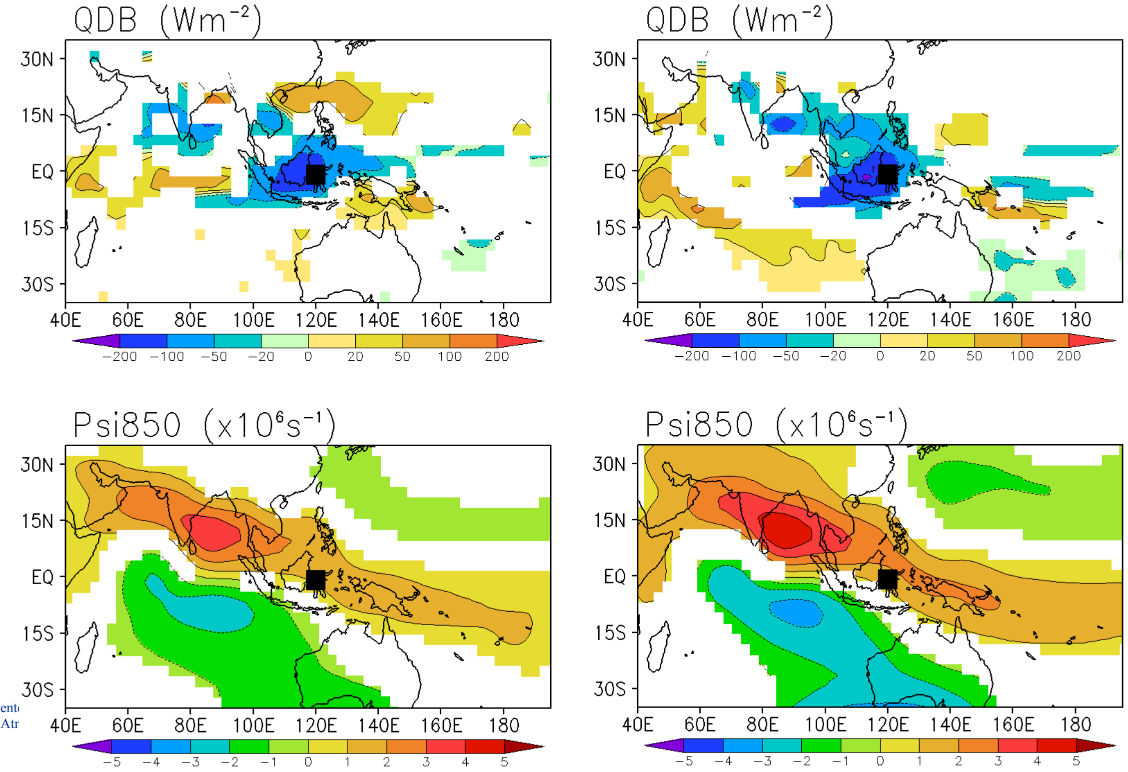
Negative Feedback

Clim SST **Slab Ocean Model**



Air-Sea Interaction: Cooling

Postive Feedback



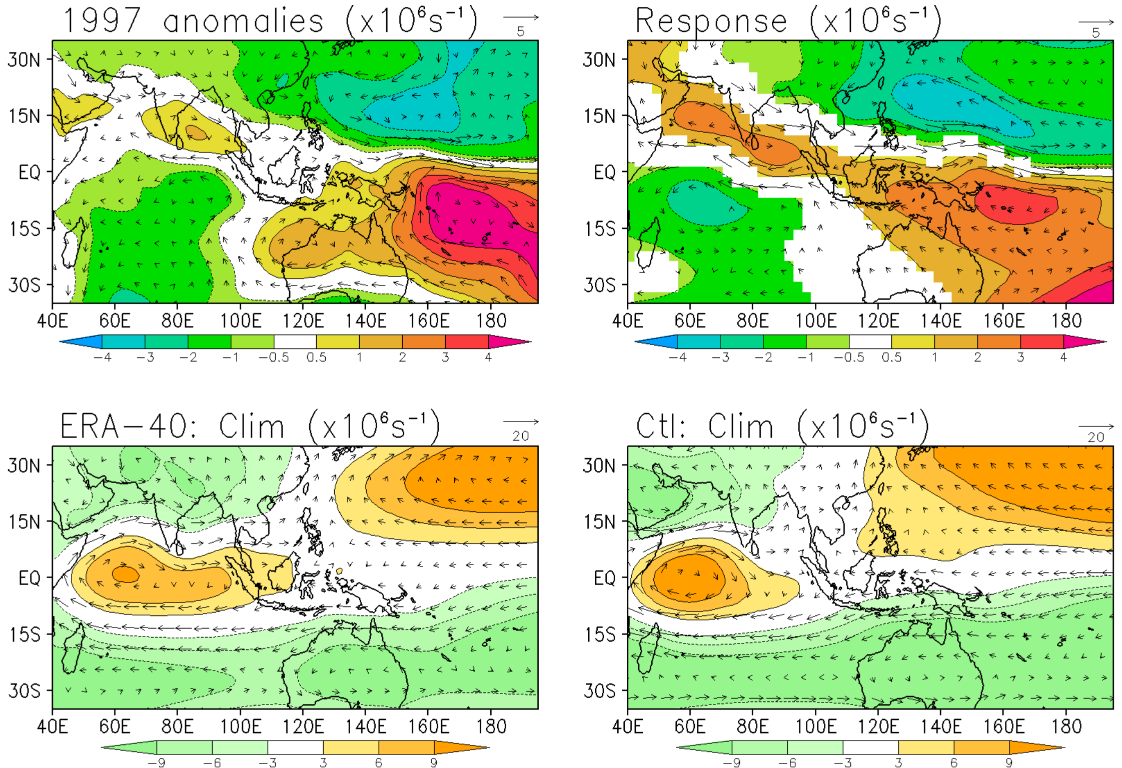
Clim SST

Slab Ocean Model

Steramfunction and Wind

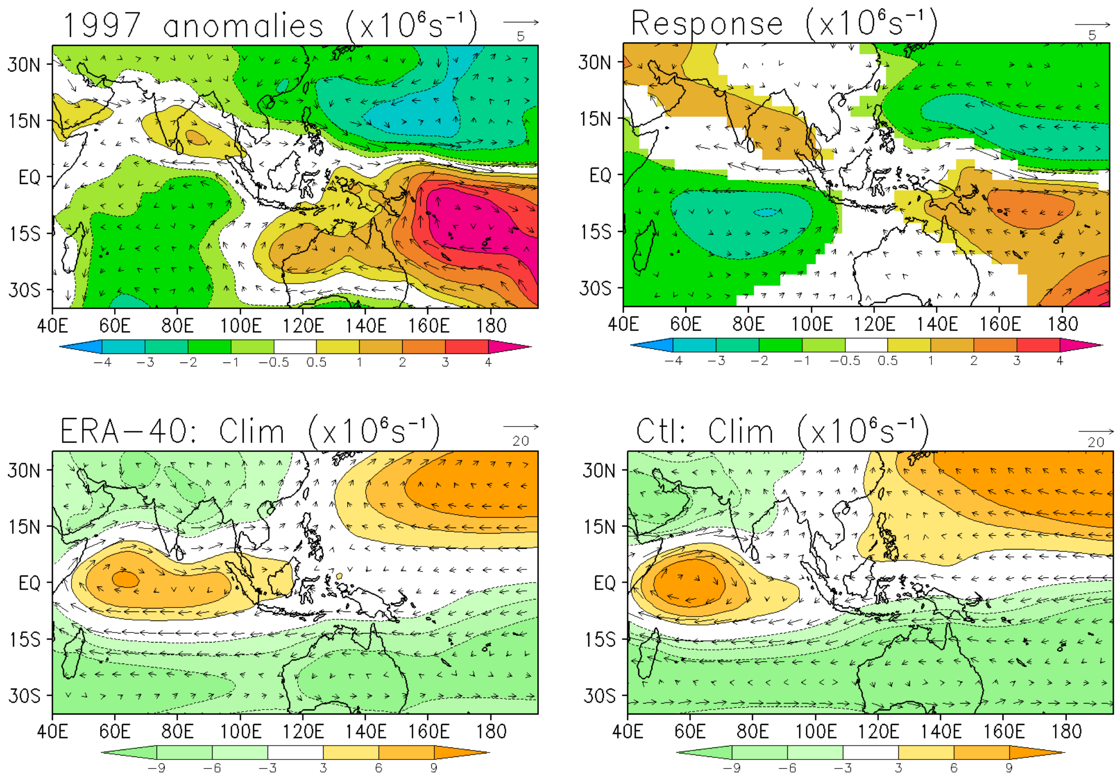
Observation

Pacific Only



Steramfunction and Wind

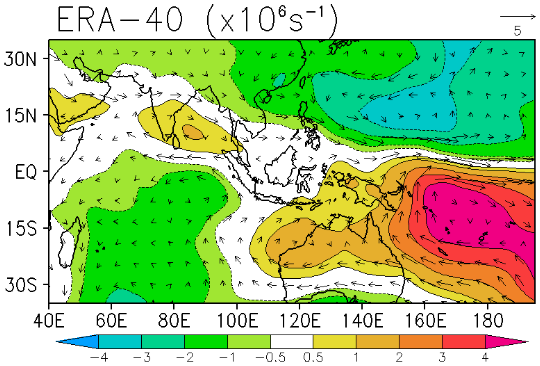
Observation **Pacific + IO**



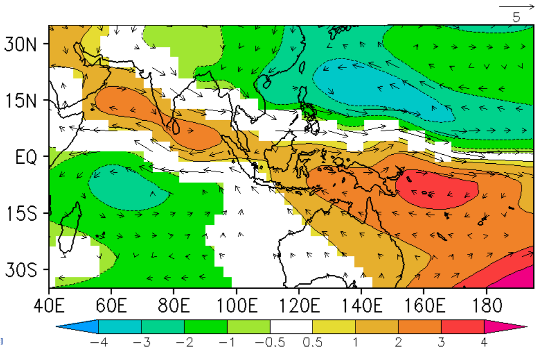
Pacific Only vs. Pacific + Indian Ocean

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

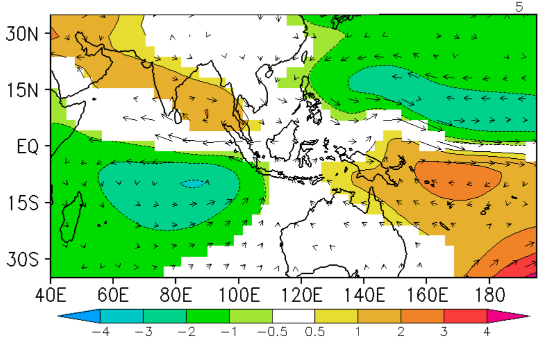
➢ **Observation**



➢ **1997 Pacific forcing only**

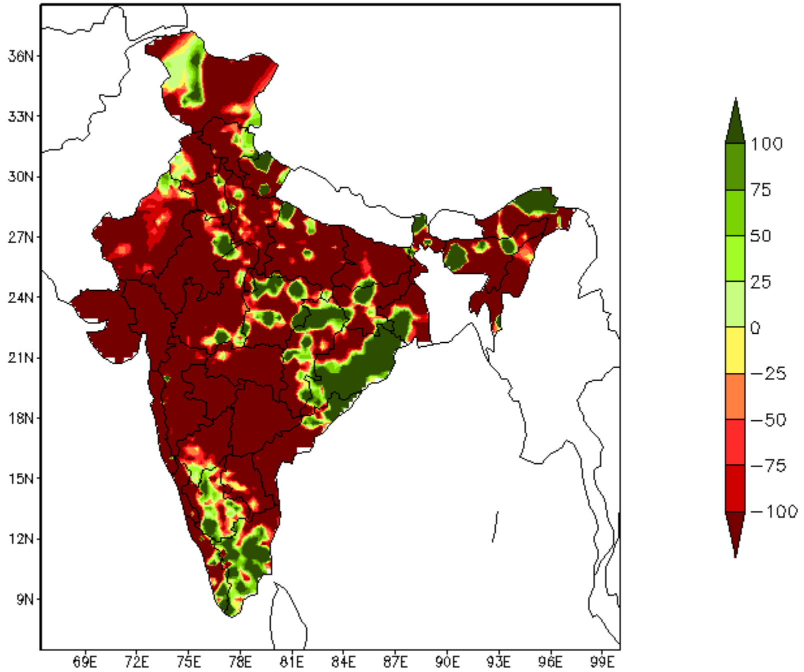


➢ **1997 Pacific + IO forcing**



COMPOSITE JJAS RAINFALL ANOMALY(in mm)
FOR 1972 OVER INDIA

ISMR = -24%
of LPA



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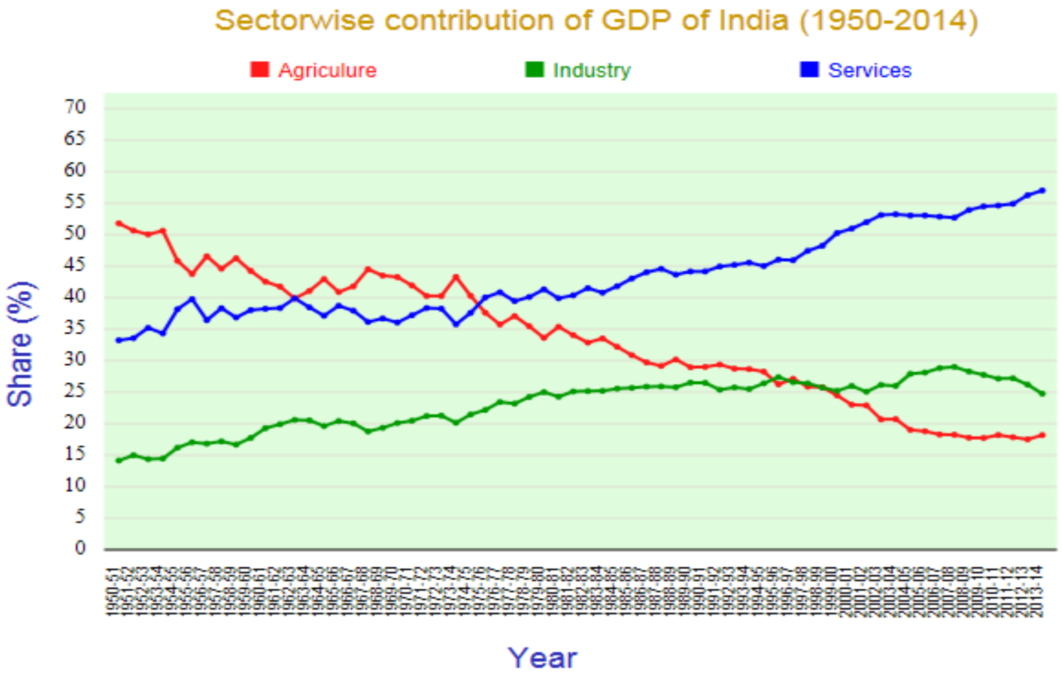
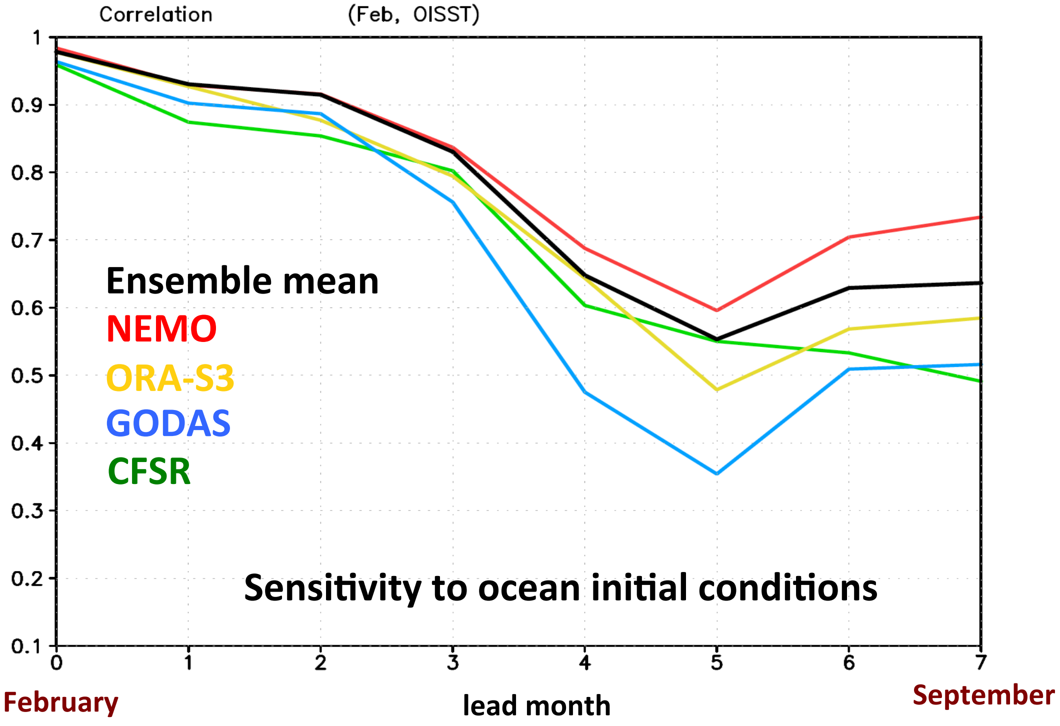
Indian GDP: Agriculture, Industry, Services

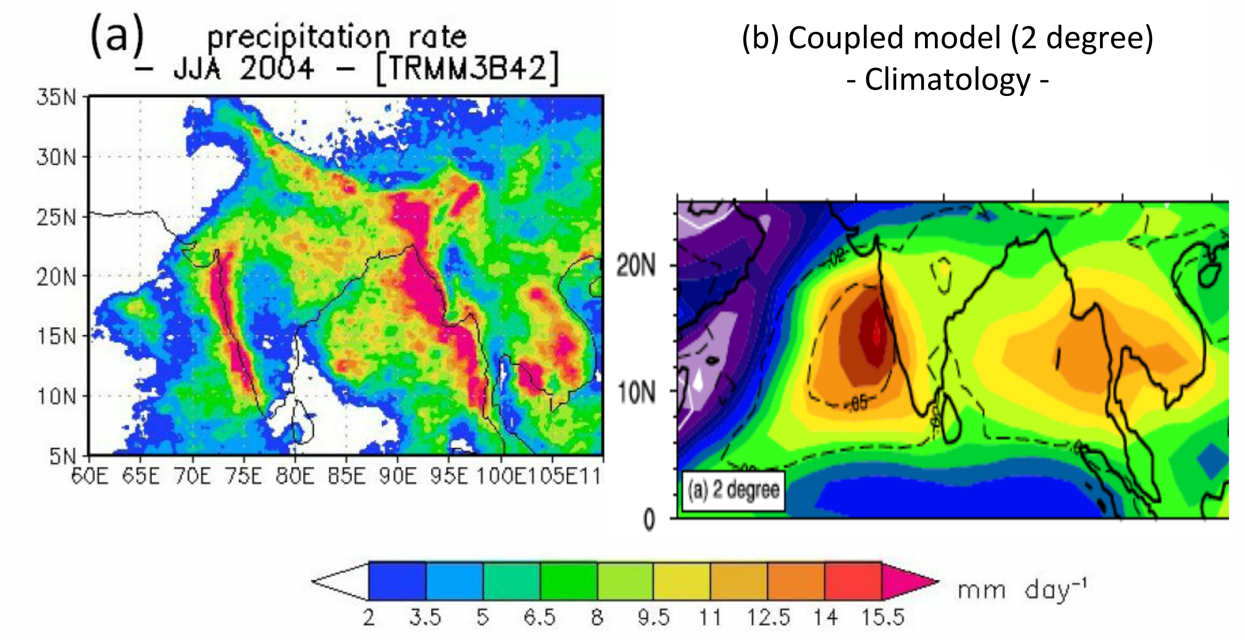


CFSv2 Prediction skill of Nino3.4 SSTA (1982-2008)

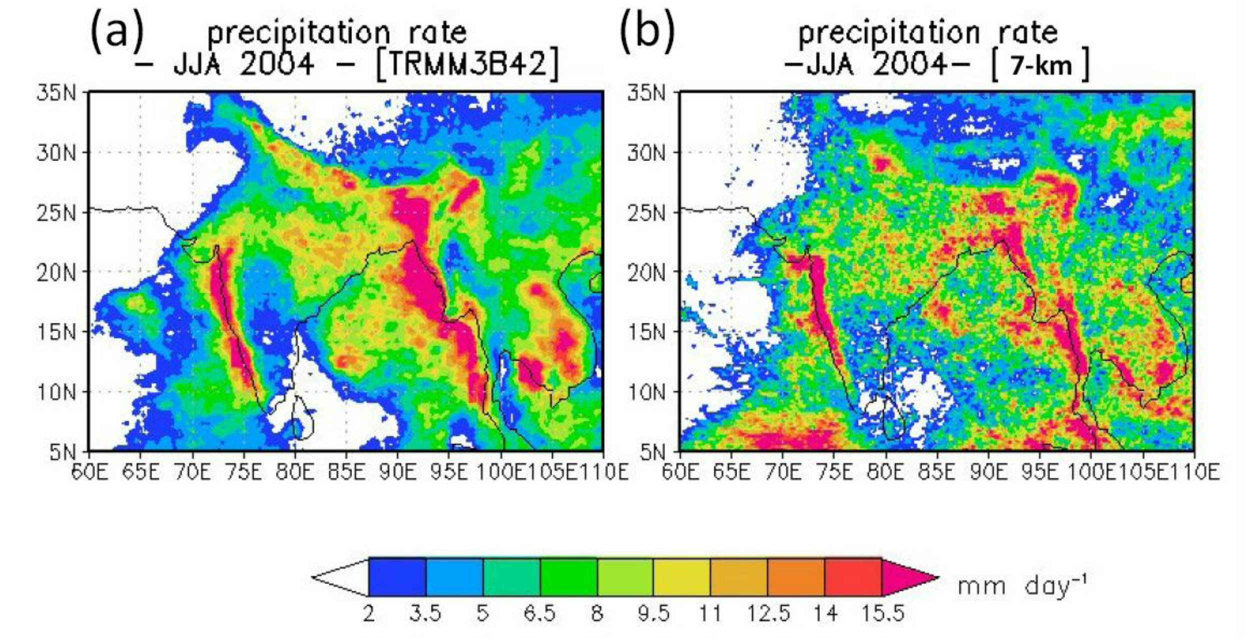


Initial conditions are important!

Monsoon Rainfall in Low Resolution Model



Monsoon Rainfall in High Resolution Model



Oouchi et al. 2009: (a) Observed and (b) simulated precipitation rate over the Indo-China monsoon region as June-July-August average (in units of mm day -1). The observed precipitation is from TRMM_3B42, and the simulation is for 7km-mesh run.

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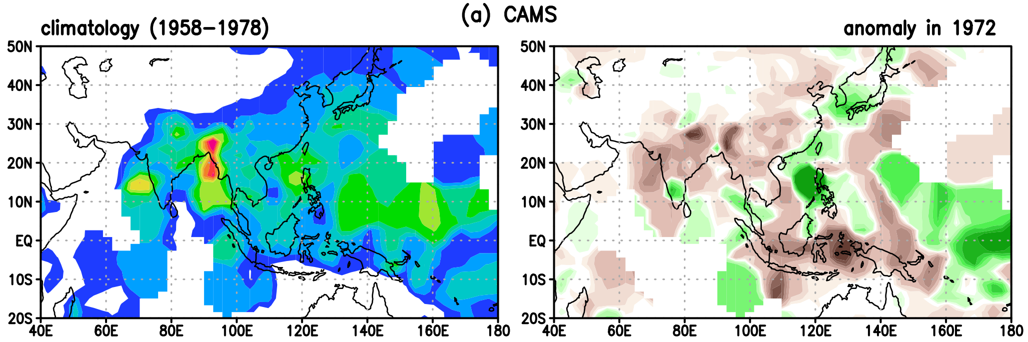
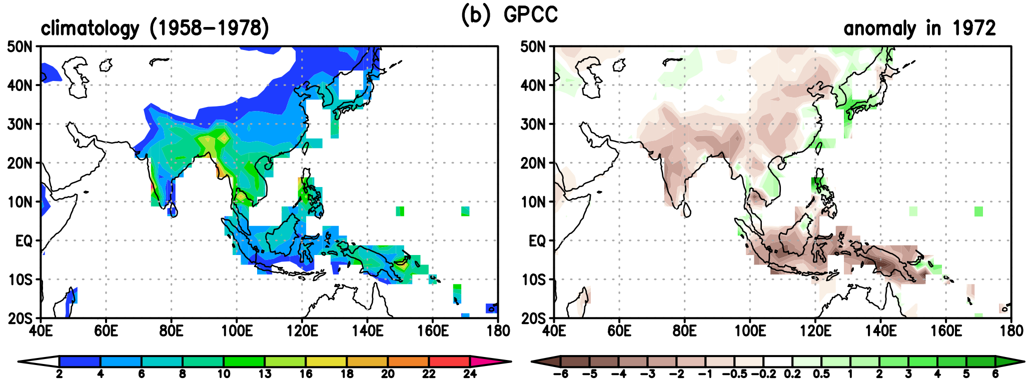
Observed JJAS mean rainfall [mm/day]

(a) CAMS

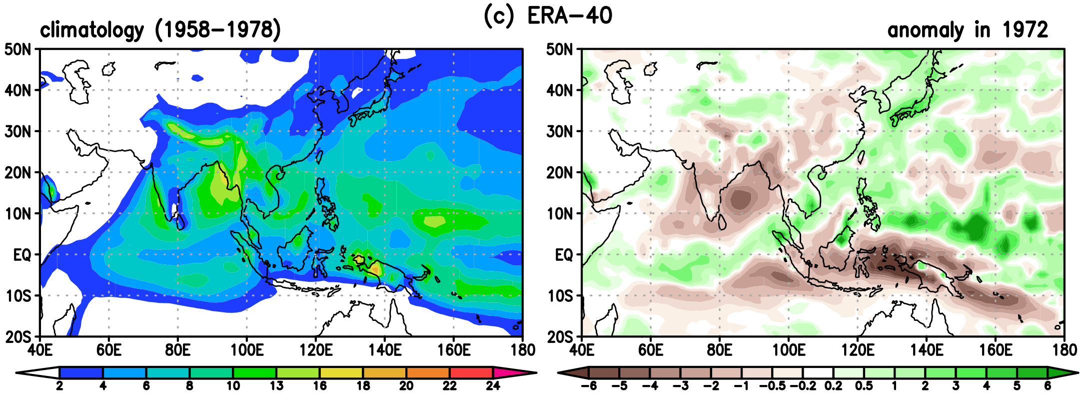


(b) GPCC



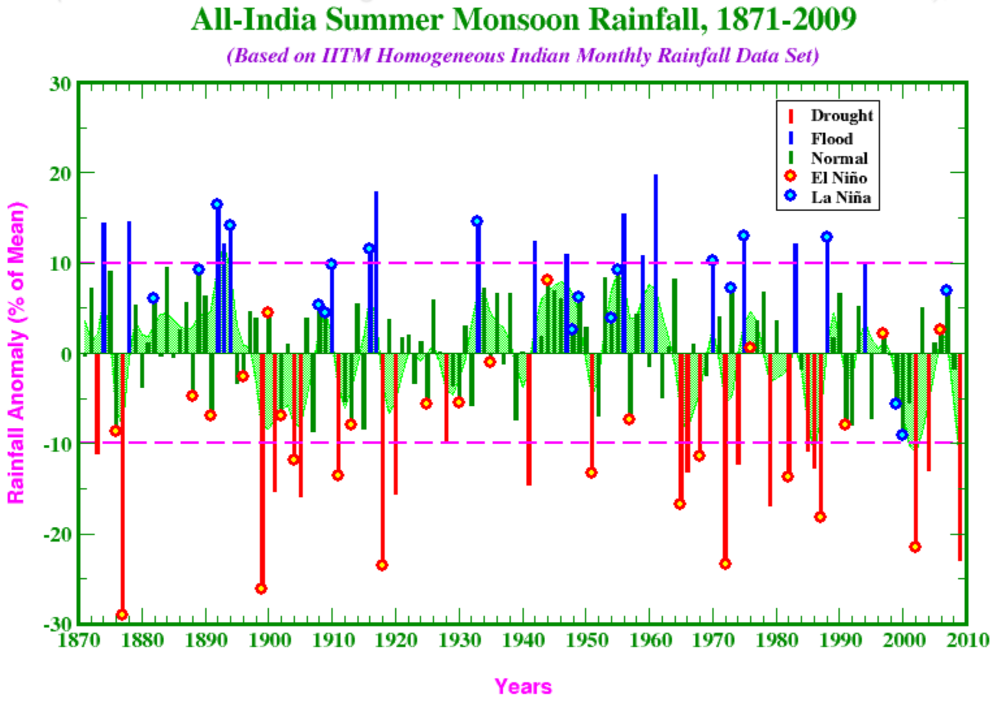
Observed JJAS mean rainfall [mm/day]

(c) ERA–40



All-India Summer Monsoon Rainfall (1871-2009)

(based on IITM homogeneous Indian Monsoon Rainfall dataset)



This figure shows the time series evolution of AISMR anomalies, expressed as percent departures from its long-term mean.

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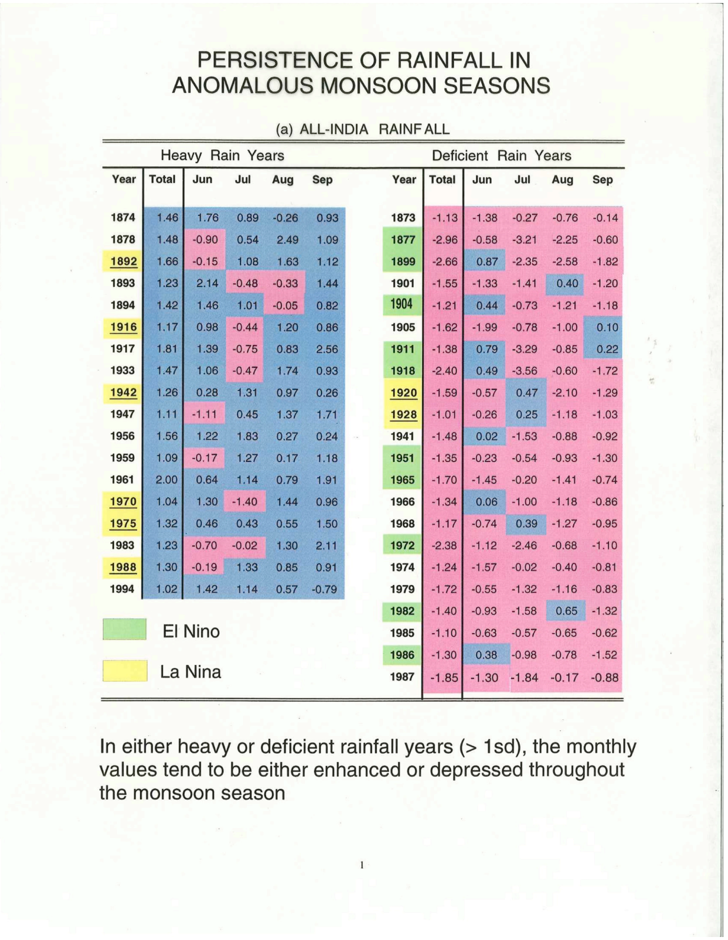


PERSISTENCE OF RAINFALL IN ANOMALOUS MONSOON SEASONS

(a) ALL-INDIA RAINFALL

Heavy Rain Years

Year	Total	Jun	Jul	Aug	Sep
1874	1.46	1.76	0.89	-0.26	0.93
1878	1.48	-0.90	0.54	2.49	1.09
🟨 1892	1.66	-0.15	1.08	1.63	1.12
1893	1.23	2.14	-0.48	-0.33	1.44
1894	1.42	1.46	1.01	-0.05	0.82
🟨 1916	1.17	0.98	-0.44	1.20	0.86
1917	1.81	1.39	-0.75	0.83	2.56
1933	1.47	1.06	-0.47	1.74	0.93
🟨 1942	1.26	0.28	1.31	0.97	0.26
1947	1.11	-1.11	0.45	1.37	1.71
1956	1.56	1.22	1.83	0.27	0.24
1959	1.09	-0.17	1.27	0.17	1.18
1961	2.00	0.64	1.14	0.79	1.91
🟨 1970	1.04	1.30	-1.40	1.44	0.96
🟨 1975	1.32	0.46	0.43	0.55	1.50
1983	1.23	-0.70	-0.02	1.30	2.11
🟨 1988	1.30	-0.19	1.33	0.85	0.91
1994	1.02	1.42	1.14	0.57	-0.79

Deficient Rain Years

Year	Total	Jun	Jul	Aug	Sep
1873	-1.13	-1.38	-0.27	-0.76	-0.14
🟩 1877	-2.96	-0.58	-3.21	-2.25	-0.60
🟩 1899	-2.66	0.87	-2.35	-2.58	-1.82
1901	-1.55	-1.33	-1.41	0.40	-1.20
🟩 1904	-1.21	0.44	-0.73	-1.21	-1.18
1905	-1.62	-1.99	-0.78	-1.00	0.10
🟩 1911	-1.38	0.79	-3.29	-0.85	0.22
🟩 1918	-2.40	0.49	-3.56	-0.60	-1.72
🟨 1920	-1.59	-0.57	0.47	-2.10	-1.29
🟨 1928	-1.01	-0.26	0.25	-1.18	-1.03
1941	-1.48	0.02	-1.53	-0.88	-0.92
🟩 1951	-1.35	-0.23	-0.54	-0.93	-1.30
🟩 1965	-1.70	-1.45	-0.20	-1.41	-0.74
1966	-1.34	0.06	-1.00	-1.18	-0.86
1968	-1.17	-0.74	0.39	-1.27	-0.95
🟩 1972	-2.38	-1.12	-2.46	-0.68	-1.10
1974	-1.24	-1.57	-0.02	-0.40	-0.81
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

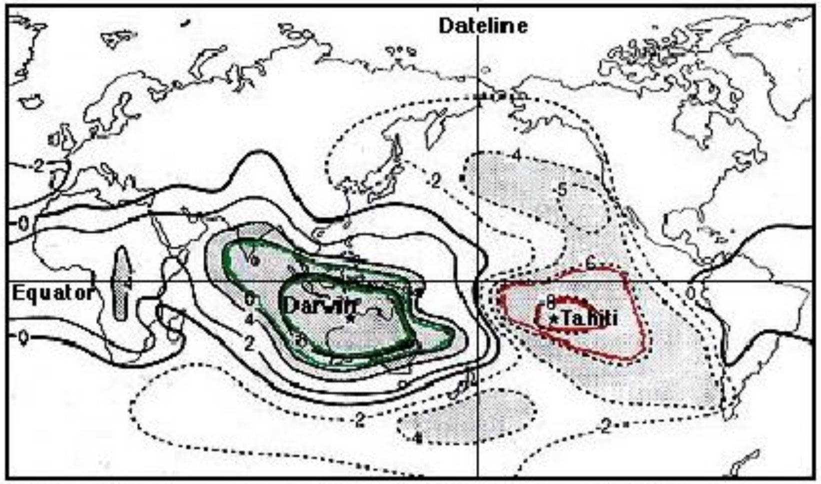
🟨 La Nina

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

Sir Gilbert Walker
1920s

Discovering the Southern Oscillation

SOI: Tahiti and Darwin as "centers of action",
mslp correlations between two locations



Tahiti and Darwin are at opposite ends of the Southern Oscillation's seesaw, and so the difference in pressure between them is used to measure the Southern Oscillation. The numbers represent a statistical measure called the correlation coefficient. The figure shows that the pressure variation at Tahiti is as closely related to Darwin as are locations near to Darwin, but with the opposite sign (i.e., if the Pressure is high at Darwin, it is low at Tahiti and vice versa). (After Rasmusson, 1984.)

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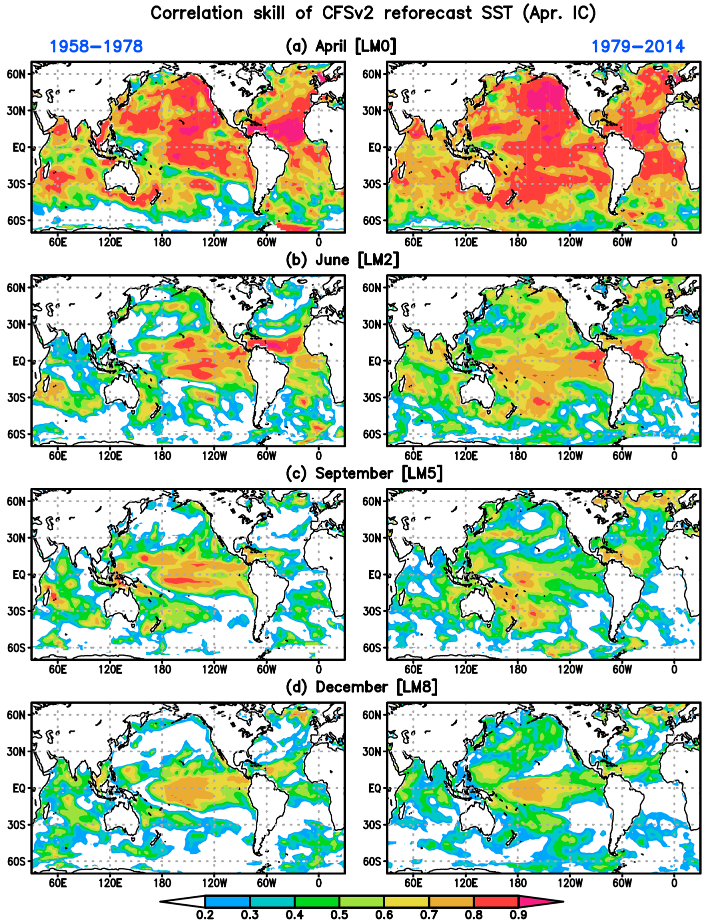
April IC

1958-1978

1979-2014



Quick decrease of skill in extra-tropics

Verified against ERSSTv3

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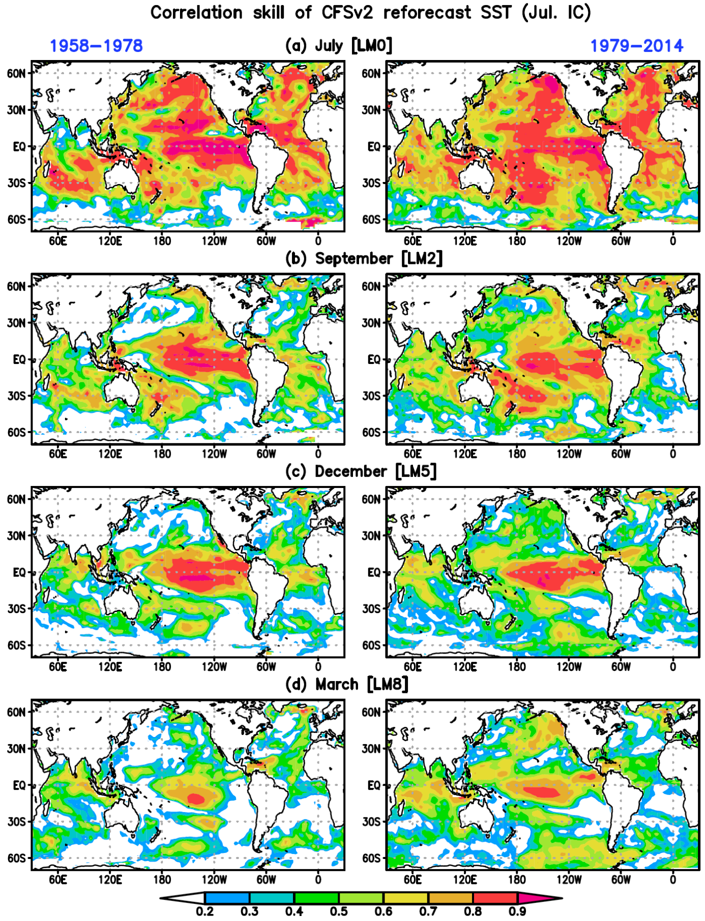
July IC

1958-1978

1979-2014



Verified against ERSSTv3

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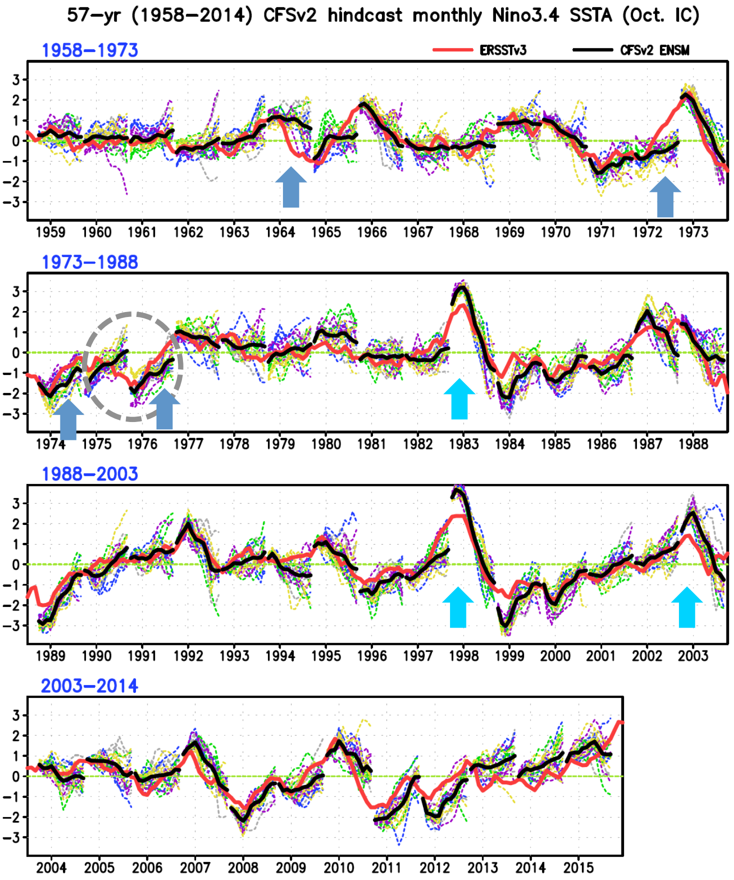
Oct. IC


57–yr (1958–2014) CFSv2 hindcast monthly Nino3.4 SSTA (Oct. IC)

ERSSTv3

CFSv2 ENSM

larger ensemble spread

Missed the cold event in 1975

Overshoot in El Nino peaks becomes more apparent

Model events persist longer in 1958-1978

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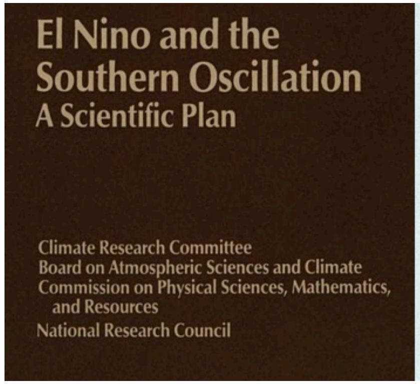
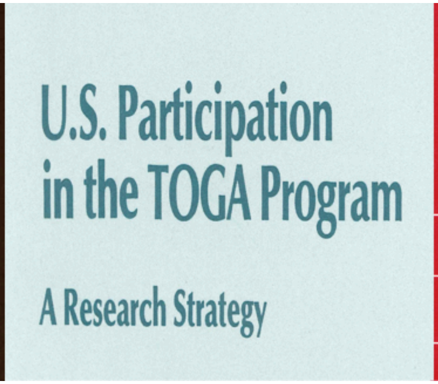


El Nino and the Southern Oscillation
A Scientific Plan

Climate Research Committee
Board on Atmospheric Sciences and Climate
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

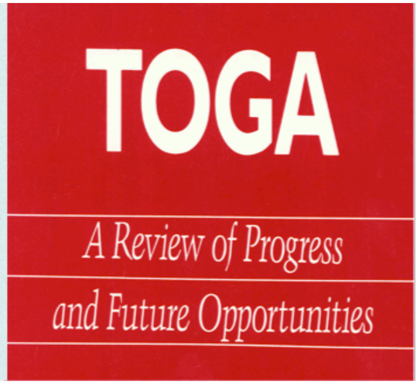
1983



U.S. Participation in the TOGA Program

A Research Strategy

1986

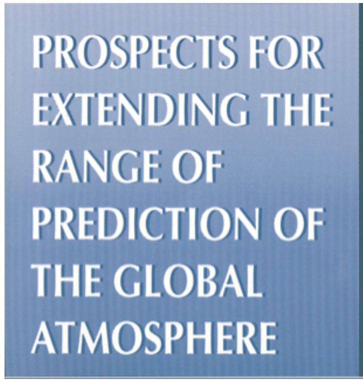


TOGA

A Review of Progress and Future Opportunities

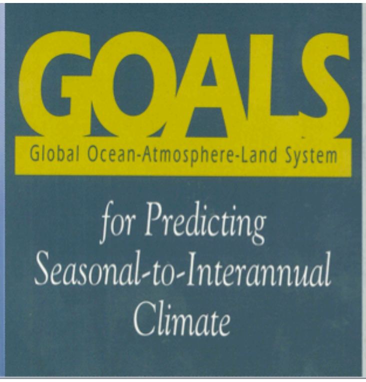
1990

1991



PROSPECTS FOR EXTENDING THE RANGE OF PREDICTION OF THE GLOBAL ATMOSPHERE

1994

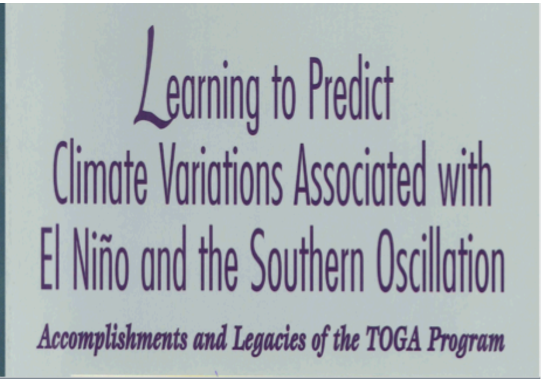


GOALS

Global Ocean-Atmosphere-Land System

for Predicting Seasonal-to-Interannual Climate

1996



Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation

Accomplishments and Legacies of the TOGA Program

Statement

In spite of a million fold increase in the computing power, and enhanced ocean observations since TOGA, there has not been any significant sustained improvement in the prediction of short-term regional climate variability by climate models.

In Spite of Large Biases in Simulated SST, Predictions of SST Anomalies Have Some Skill

In Some Cases

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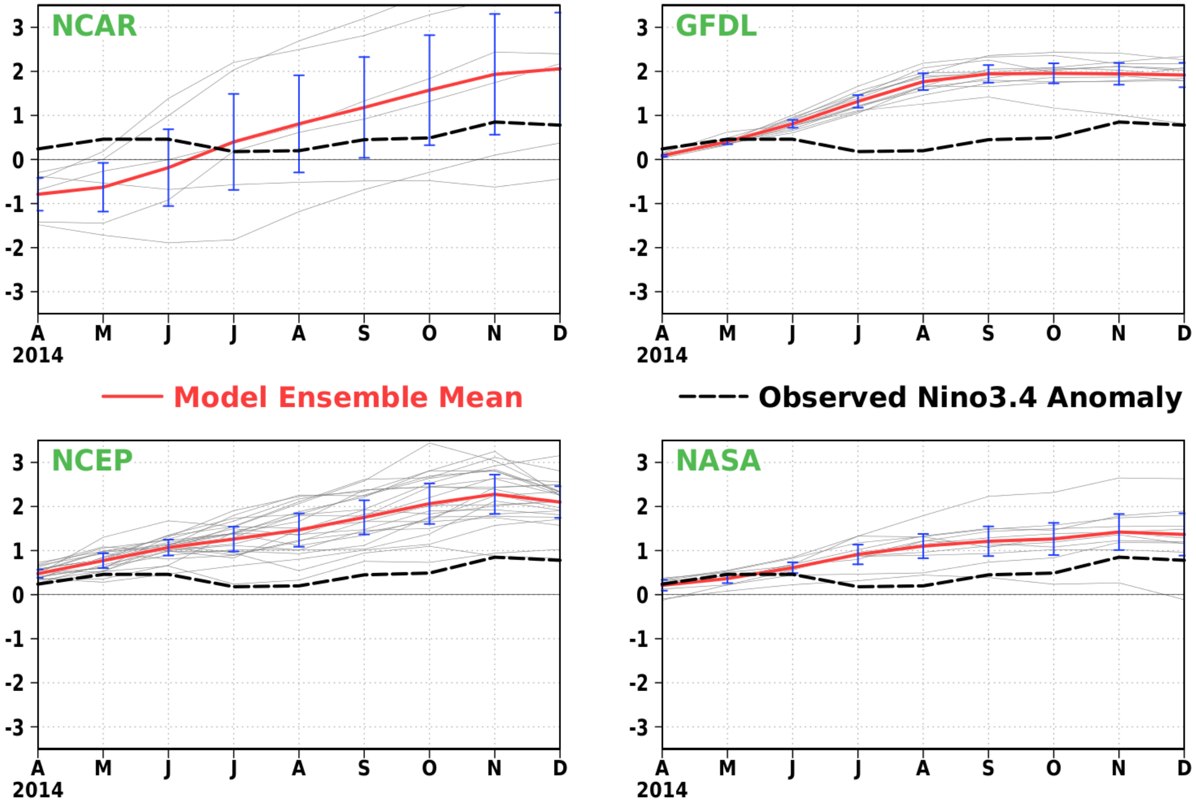
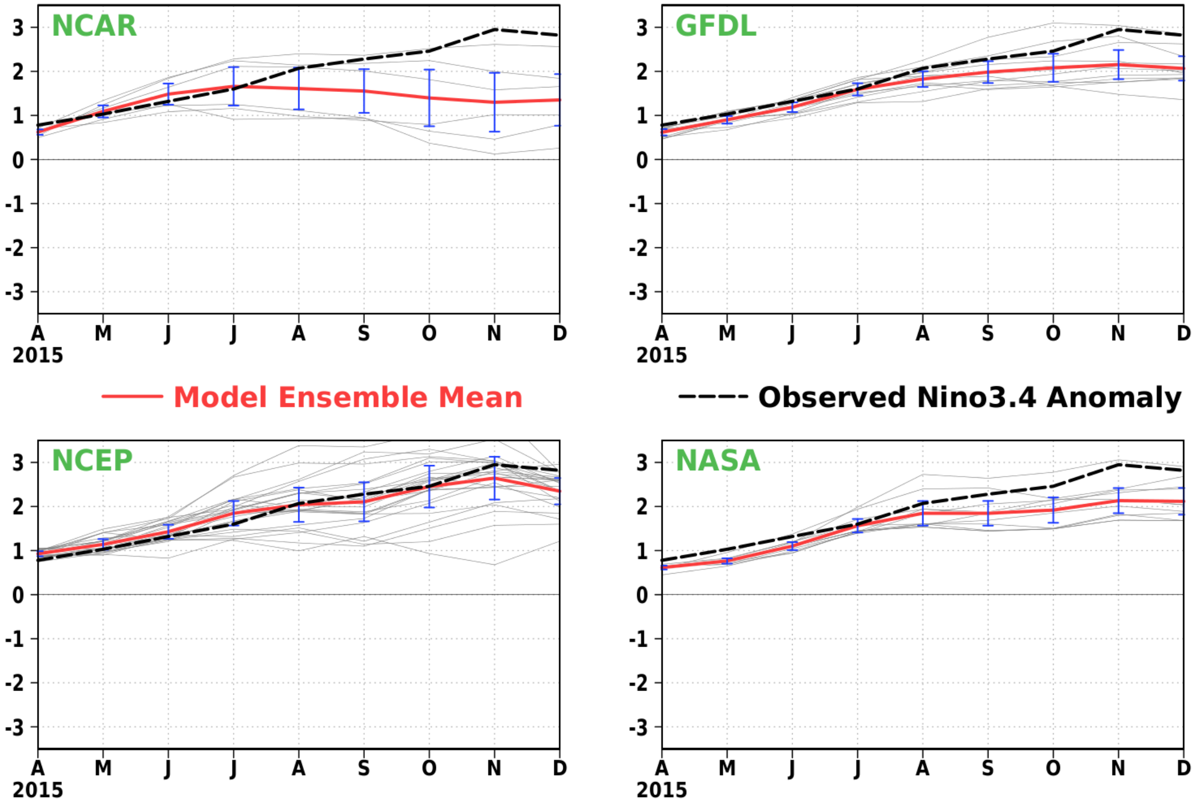
Forecasts of Nino3.4 from April 2014 IC

(Model Bias Removed)



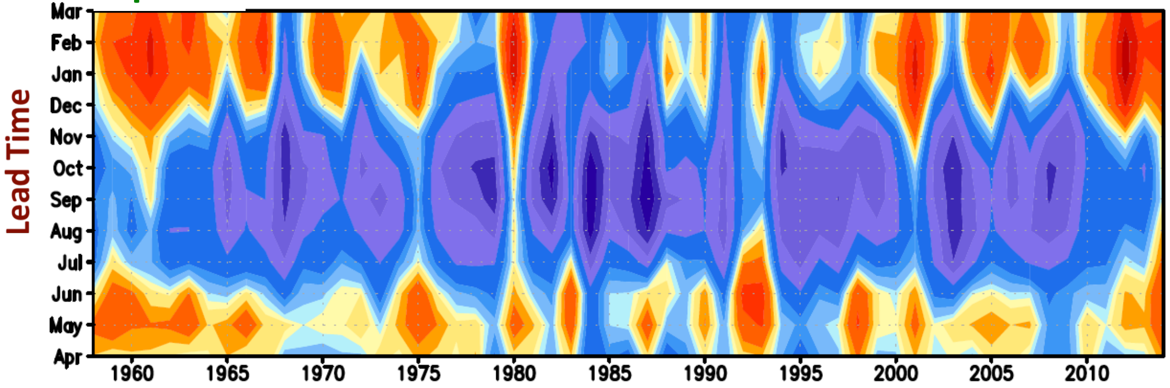
Forecasts of Nino3.4 from April 2015 IC

(Model Bias Removed)

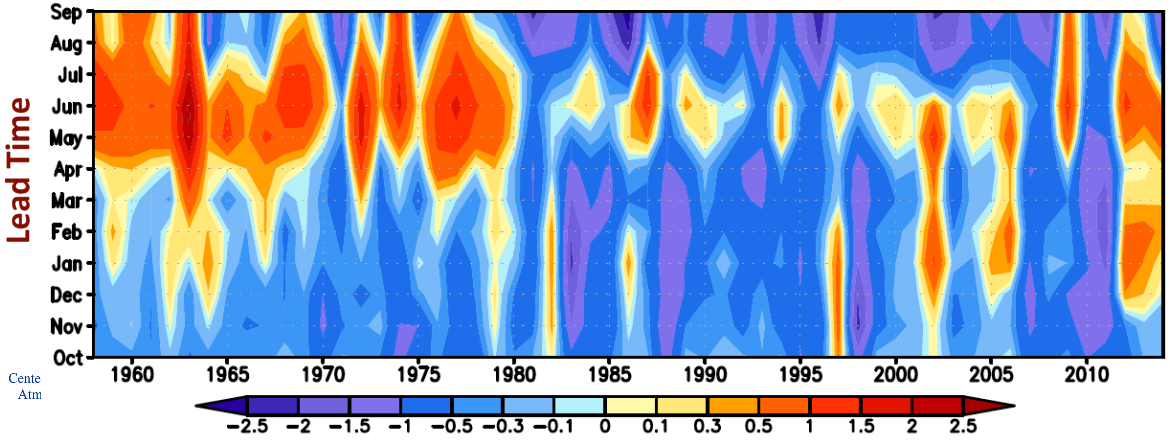


Monthly SST Bias of CFSv2 hindcast over Nino3.4 region

April IC



October IC



Introduction

- **Scientific Basis for Dynamical Seasonal Prediction:**
  - **Atmospheric spectra is red (k^{-3})** (Paradox: NWP vs. DSP)
    - Low-frequency planetary waves have the largest variance and largest contribution to time averages, and higher predictability
  - Surface boundary conditions (SST, SW, snow, etc.) produce predictable forced-response: ***Predictability in the Midst of Chaos***
  - In spite of large biases, climate models are realistic enough to predict anomalies (sometimes!) – ENSO forced monsoon rainfall anomalies
  - High predictability but low prediction skill
- **Challenges:**
  - Climate models have **"large"** biases and forced **response is not independent** of model bias
  - Model predictability depends on **model fidelity**
  - Improving model fidelity and enhancing predictive understanding requires **long-term, large, and stable** human and computational **resources**

Assumptions (Myths?) about Climate Simulation and Prediction

The Past:

1. Model response to external forcings (CO2, SST, etc.) does not depend on the model bias (model bias is subtracted out: forced run minus control run)
2. All models are equally good (model democracy)

The Present

1. Model predictability depends on model fidelity
2. Towards a hypothetical perfect model
3. Estimate predictability using models of highest fidelity

Myth: Widely held but false belief (Oxford dictionary)

Climate Model Fidelity and Predictability

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

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

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

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

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.

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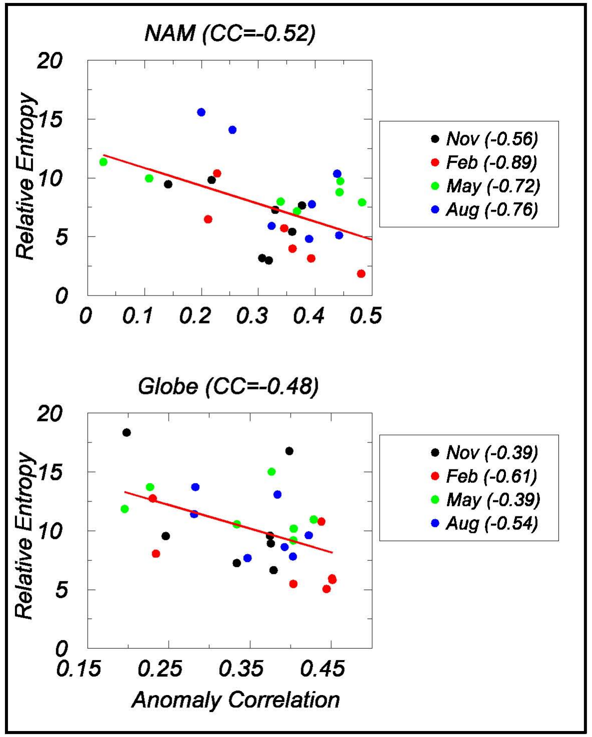
Fidelity vs. Skill



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

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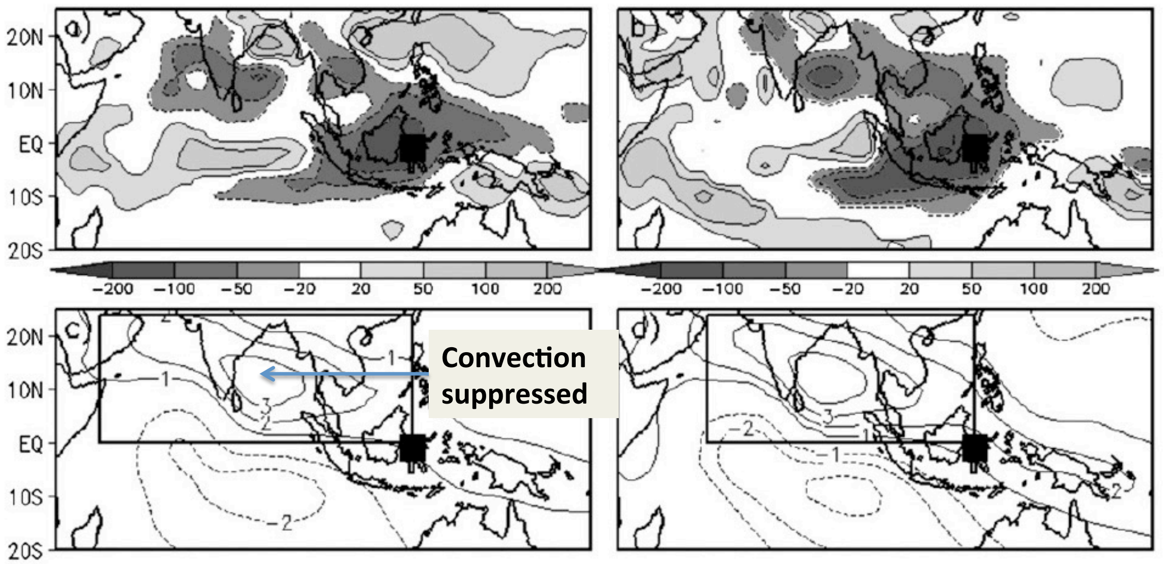
AGCM ONLY

AGCM + Slab Ocean Model



Convection suppressed

Experiments from Jang and Straus with added cooling at 120°E.

Top Row: Vertically Integrated Diabatic Heating (W/m^2)

Bottom Row: 850 hPa Streamfunction (units of 10^6 m^2/s)

Jang, Y. and D. M. Straus, 2013: Tropical Stationary Wave Response to ENSO: Diabatic Heating Influences on the Indian Summer Monsoon. J. Atmos. Sci., 30, 193-222.