Evolution of Ideas Leading to Dynamical Seasonal Prediction

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History of Dynamical Seasonal Prediction

- **Numerical Weather Prediction: 1904 – Present**
- **Dynamical Seasonal Prediction (Pre-ENSO): 1975 – 1985**
- **ENSO Prediction: 1986 - present**

History of Dynamical Seasonal Prediction

Numerical Weather Prediction

- V. Bjerknes (1904); Richardson (1922); Rossby (1939); Charney, Fjortoft, Von Neumann (1949):

  Weather forecasting by solving system of equations representing "laws according to one state of atmosphere develops from another"

- Worldwide operational NWP using primitive equations

- Lorenz: Chaos, Butterfly Effect, Limits to Weather Prediction

First Successful NWP (Charney, Fjortoft, Von Neumann, Tellus, 1949)

By solving nondivergent barotropic vorticity equation on ENIAC computer

Left to right: Harry Wexler, **John von Neumann**, M. H. Frankel, Jerome Namias, John Freeman, Ragnar Fjortoft, Francis Reichelderfer and **Jule Charney** **(Institute for Advanced Study, Princeton, 1950)**

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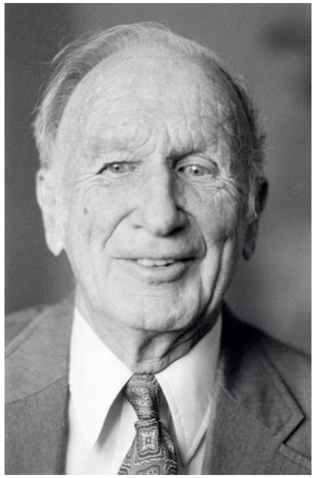
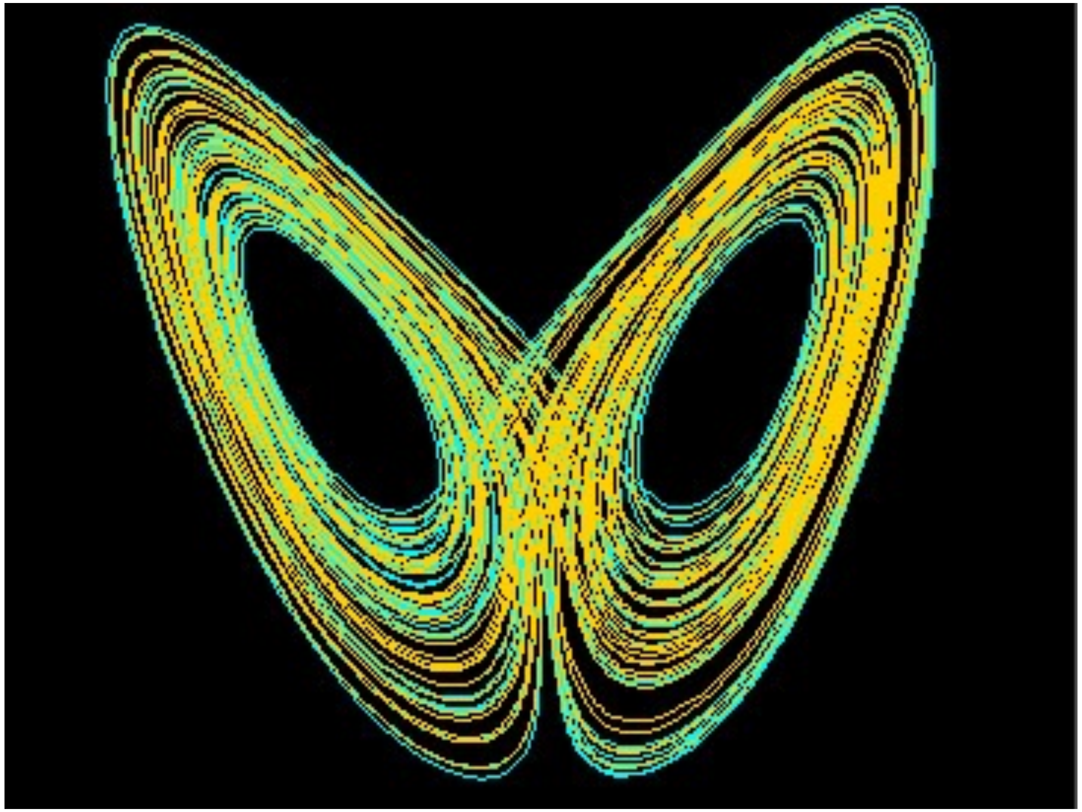


The Butterfly Effect

Chaos: Sensitive Dependence on Initial Conditions



"Our results --- indicate that prediction of sufficiently distant future is impossible by any method---"
Lorenz, 1963

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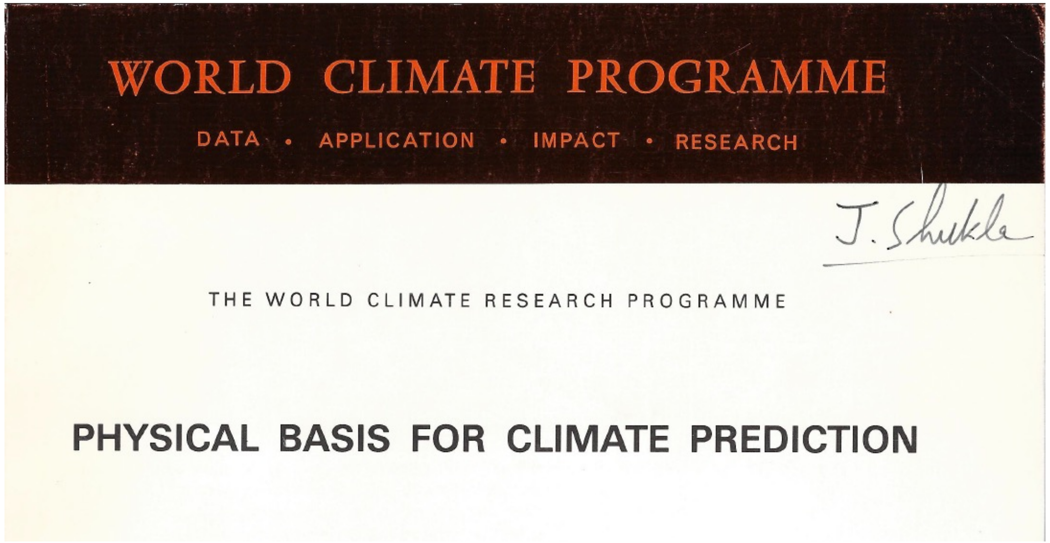

WORLD CLIMATE PROGRAMME

DATA • APPLICATION • IMPACT • RESEARCH

J. Shukla

THE WORLD CLIMATE RESEARCH PROGRAMME

PHYSICAL BASIS FOR CLIMATE PREDICTION

Leningrad, 13 – 17 September 1982

In 1981, WCRP will not accept Climate Prediction as the title of the conference in Leningrad.

But WCRP was willing to accept the title of Physical Basis for Climate Prediction

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Evolution of Ideas Leading to Dynamical Seasonal Prediction

During the 1970s, the "butterfly effect" or "chaos" was the dominant theme of predictability research and *there was deep skepticism about predictions beyond 1 -2 weeks;*

So what are the key ideas that led to dynamical seasonal prediction before ENSO?

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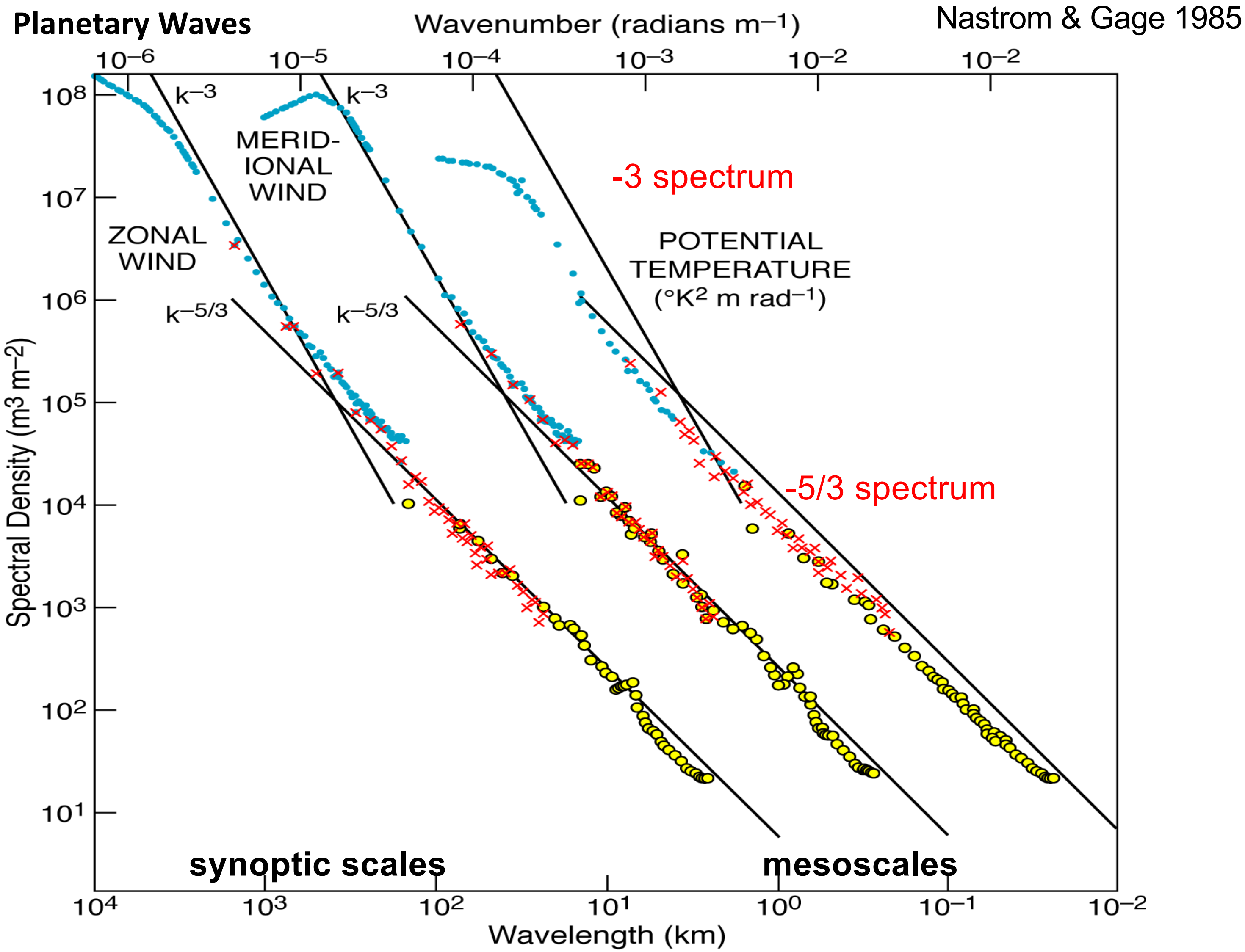
Dynamical Seasonal Prediction: Pre-ENSO 1975 - 1985

- **Dynamical Predictability (IC)**
  - Large scale, low frequency waves have the largest energy (k -3)
  - Long waves have higher predictability
  - Low frequency planetary waves have the largest fraction of variance
- **Boundary Forced Predictability (BC)**

The "Knife's Edge" – The Observed Spectrum

(Planetary waves also have largest variance)



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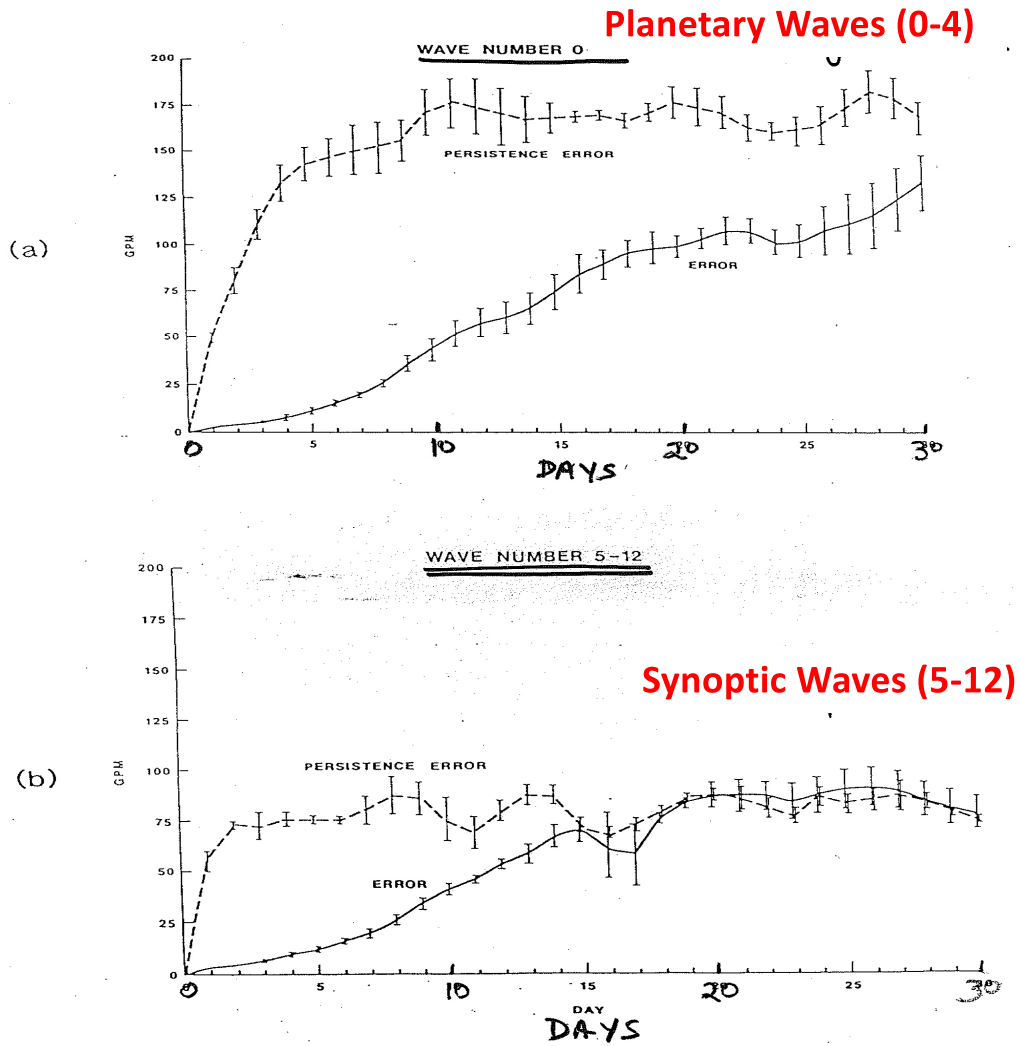
Dynamical Predictability: Beyond Weather

Predictability of Planetary Waves and Synoptic Waves

Longer Predictability for Planetary Waves

Low Frequency Long Waves dominate the seasonal mean, also have the largest variance

Predictability of synoptic waves is less than 2 weeks



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Dynamical Seasonal Prediction: Pre-ENSO 1975 - 1985

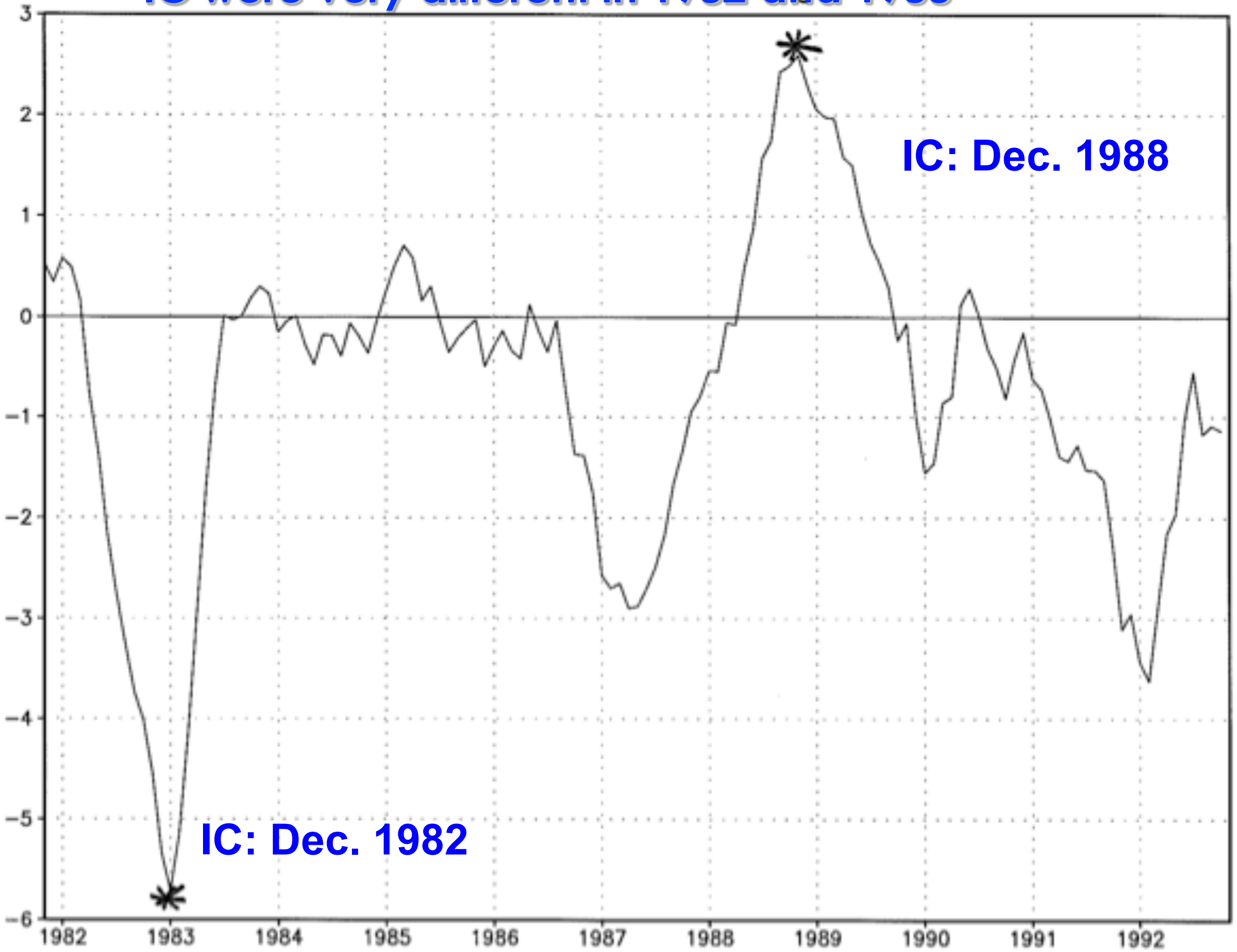
- Dynamical Predictability (IC)
  - Large scale, low frequency waves have the largest energy (k -3)
  - Long waves have higher predictability
  - Low frequency planetary waves have the largest fraction of variance
- Boundary Forced Predictability (BC): Billion Butterflies Experiment
  - Tropical atmosphere (ocean) is so strongly forced by SST (atmosphere) that billion butterflies cannot make the simulations sensitive to initial conditions (exception to the butterfly effect)

Billion Butterflies Experiment (Atmosphere)

IC were very different in 1982 and 1988

Southern Oscillation Index (SOI)

SOI =
Tahiti – Darwin SLP



Observed 5-month running mean SOI

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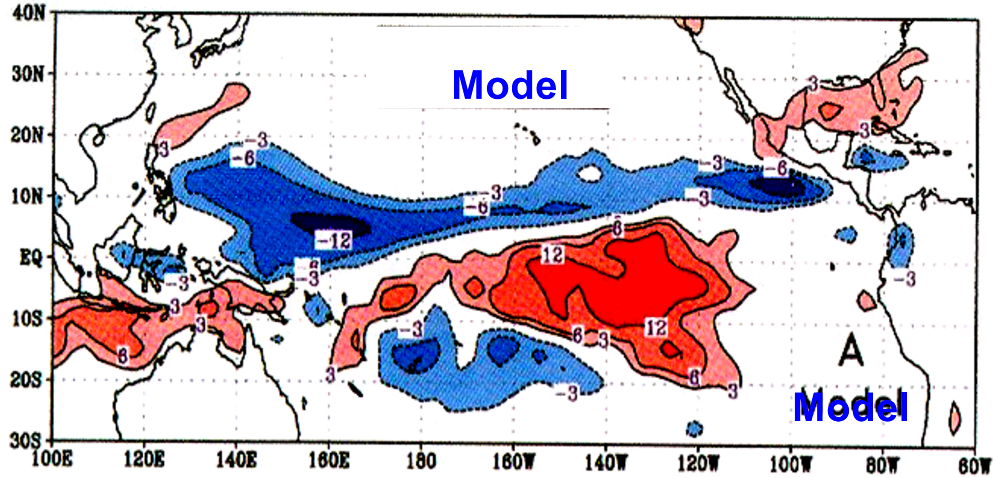
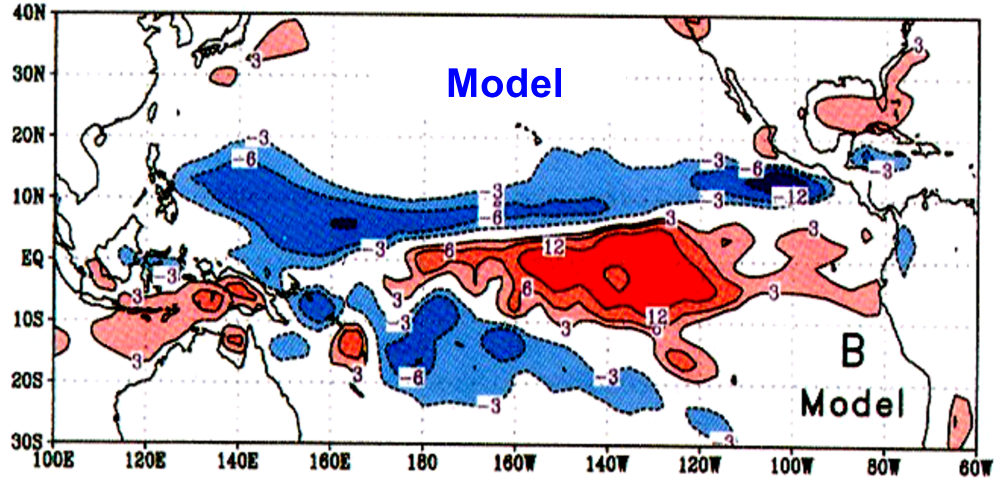
Seasonal Mean Rainfall is **Not** Sensitive to Atmospheric Initial Conditions

JFM Mean Rainfall Anomalies



IC: Dec. 1988



IC: Dec. 1982

"Predictability in the Midst of Chaos"

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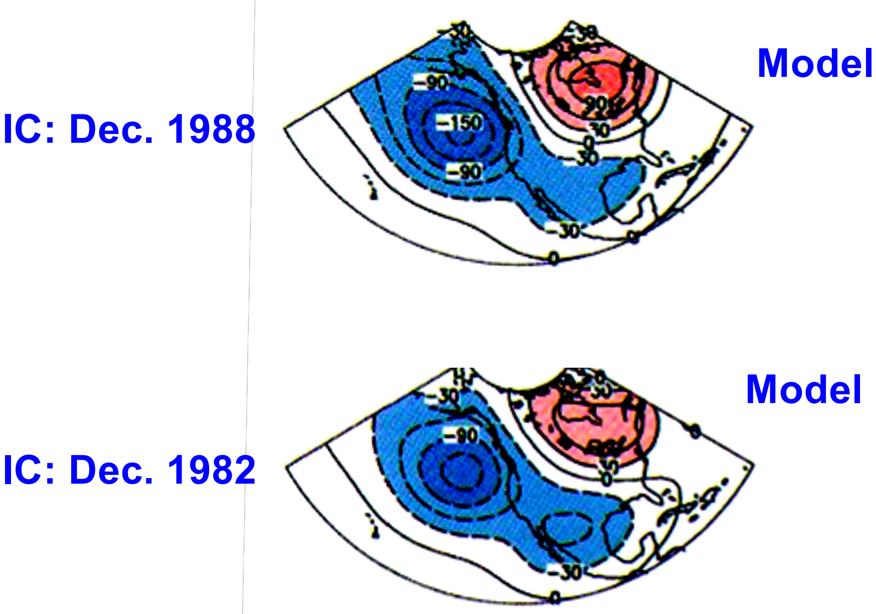
JFM Mean Circulation

500 hPa ϕ' (meters)



Seasonal Mean Circulation is Not Sensitive to Atmospheric Initial Conditions

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Simulations from very different atmospheric initial conditions of Dec 1982 and Dec 1988 converged because both used the same SST of 1982 - 83

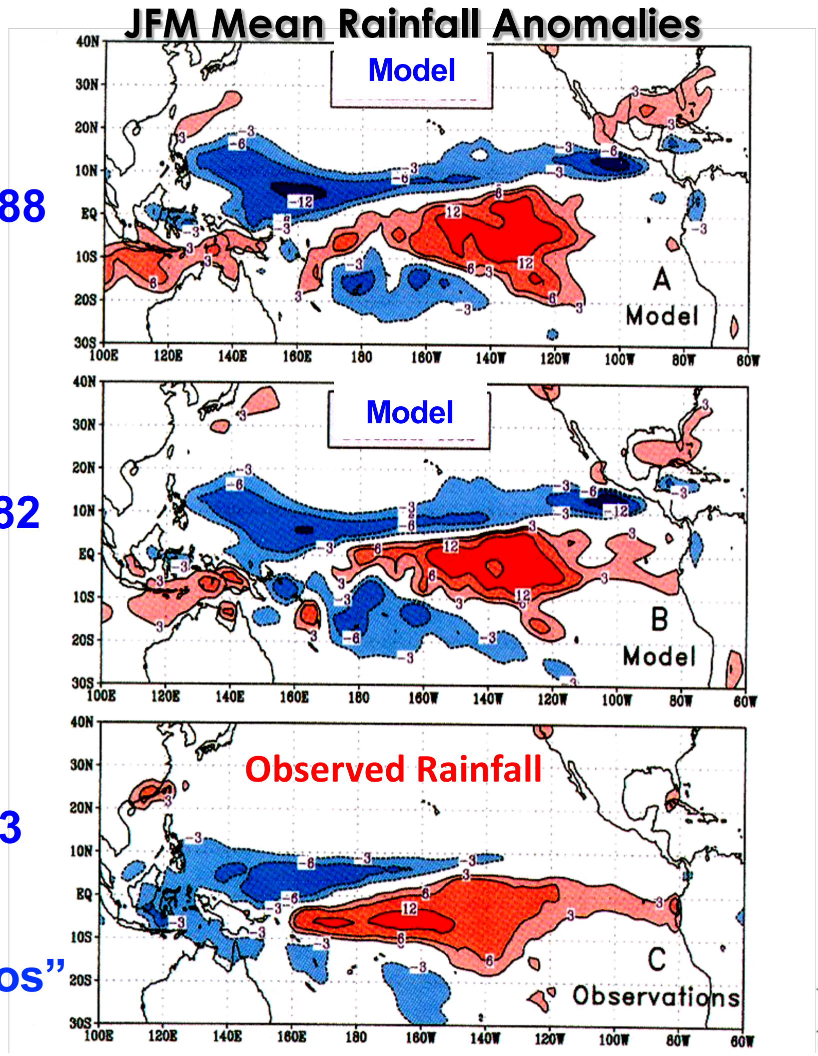
For Strong SST Anomaly of 1982-83, Seasonal Mean Rainfall is Not Sensitive to Atmospheric Initial Conditions

Tropical Pacific rainfall is very strongly determined by the sea surface temperature and not by IC

Model
IC: Dec. 1988

Model
IC: Dec. 1982

Observed
JFM 1982-83



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"Predictability in the Midst of Chaos"

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JFM Mean Circulation

500 hPa ϕ' (meters)

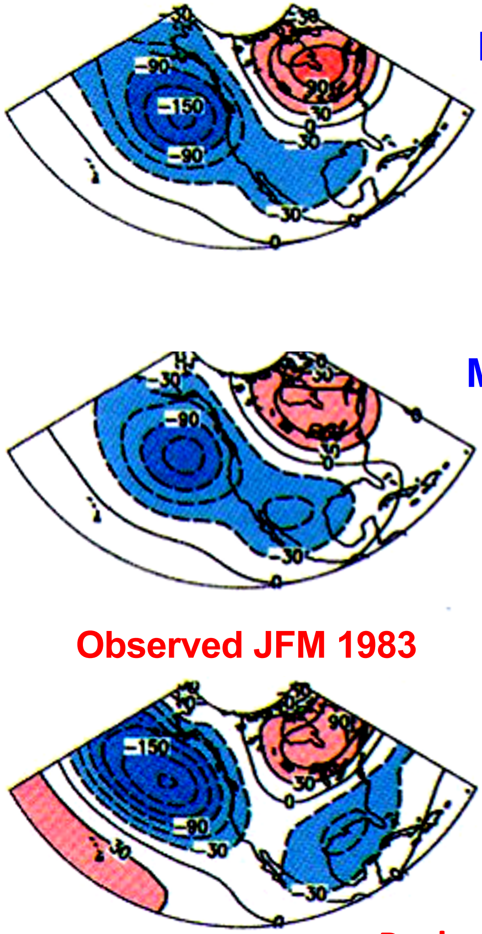
IC: Dec. 1988

Model

IC: Dec. 1982

Model

Observed JFM 1983



Seasonal Mean Circulation also converged because when tropical forcing was quite strong, circulation was also not sensitive to IC

an exception to the Butterfly Effect

Both model runs used observed 1982-83 SST

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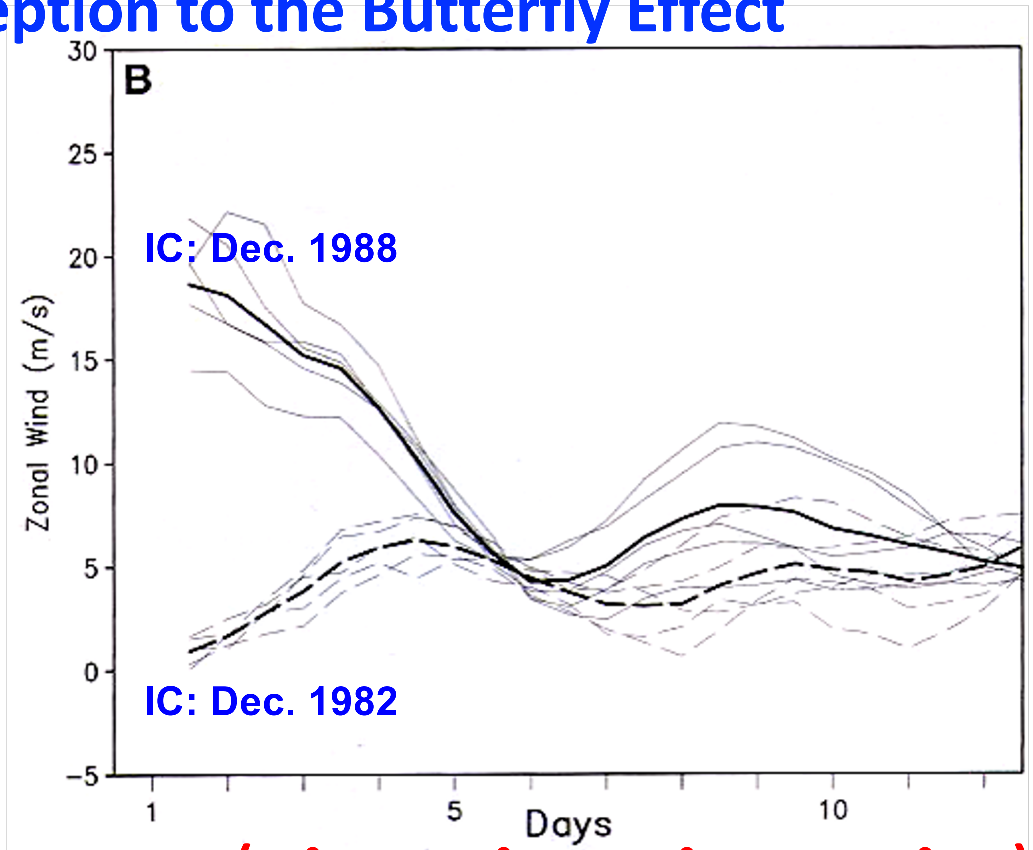
The Tropical Atmosphere is so strongly forced by SST that it is insensitive to initial conditions of the atmosphere – an exception to the Butterfly Effect

In spite of very large differences in the atmospheric IC for 1982 and 1988, tropical zonal wind for the two simulations converged within about 10 days



Zonal Wind (m/s) at 200 Mb (10° S to 10° N, 120° W to 160° W)

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Example of lack of sensitivity to initial conditions of atmosphere

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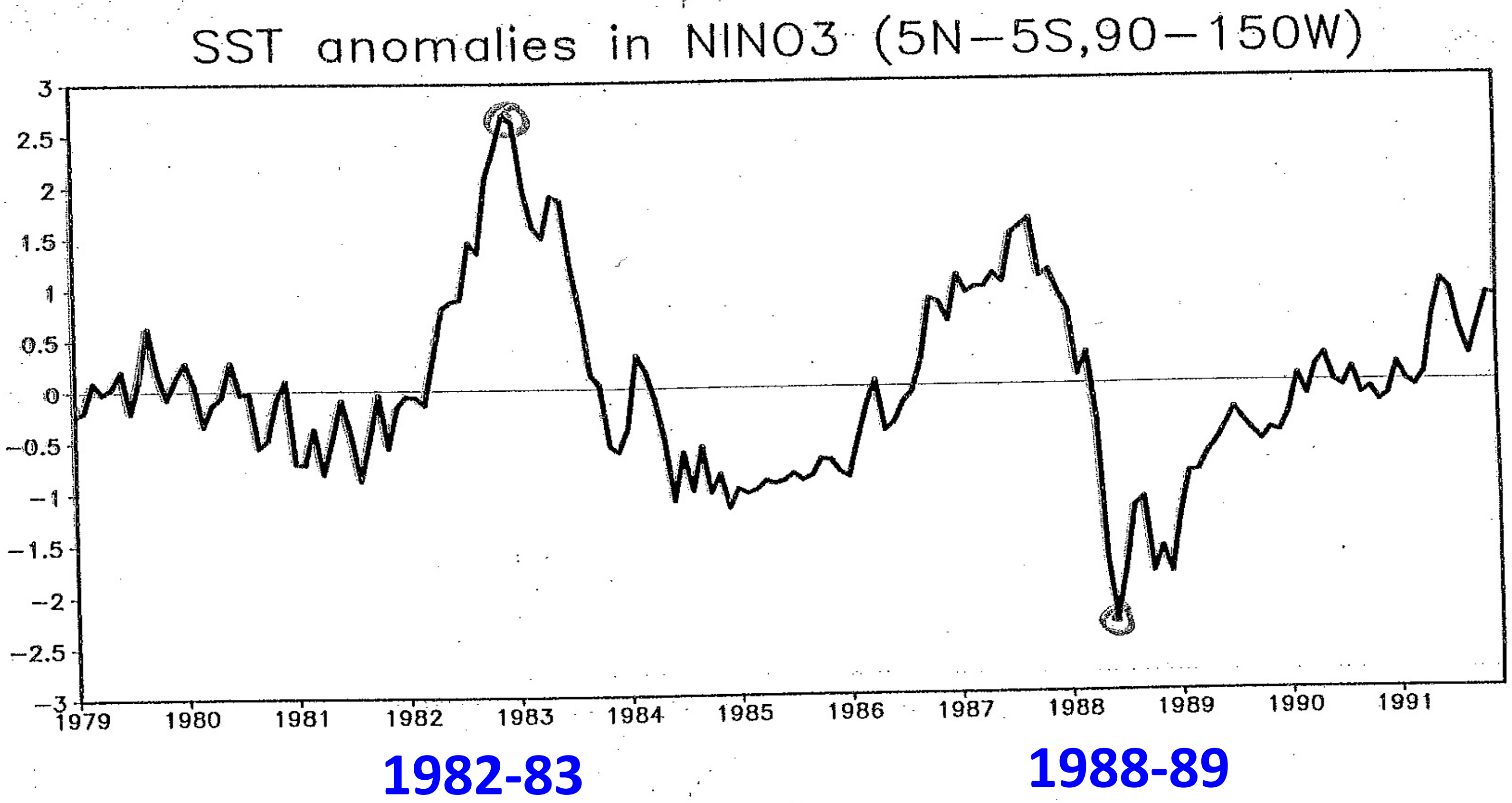
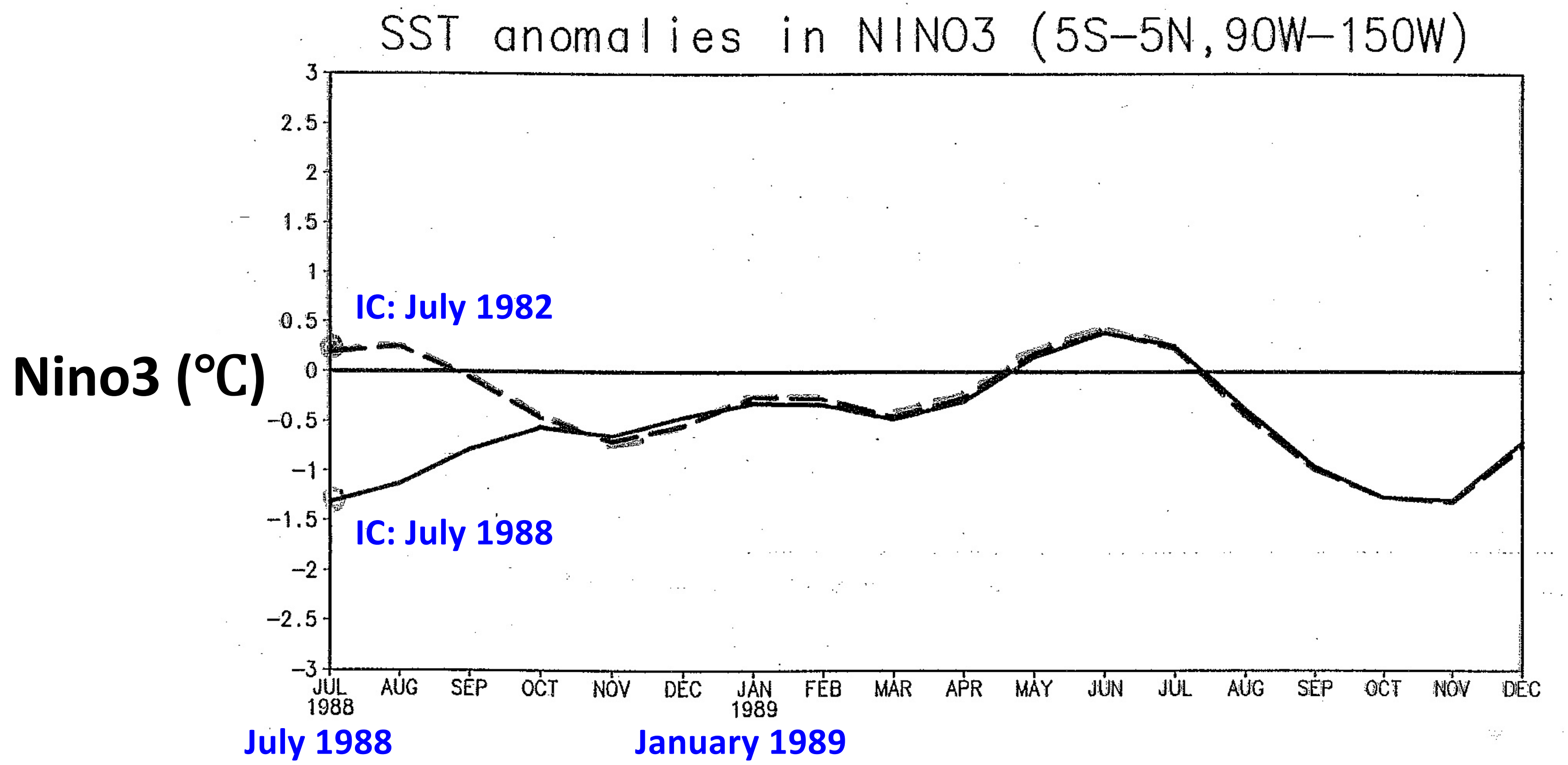
Billion Butterflies Experiment (Ocean)

SST Anomalies in Nino3 were very different in 1982 – 83 and 1988 - 89



Nino 3: (5N-5S, 90-150W)

When ocean was forced by two very different atmospheric forcings for 1982-83 and 1988-89 (IC: July 1), it took about 3-4 months for the tropical SST (Nino3) anomalies to converge.



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Example of lack of sensitivity to initial conditions of ocean state

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Dynamical Seasonal Prediction

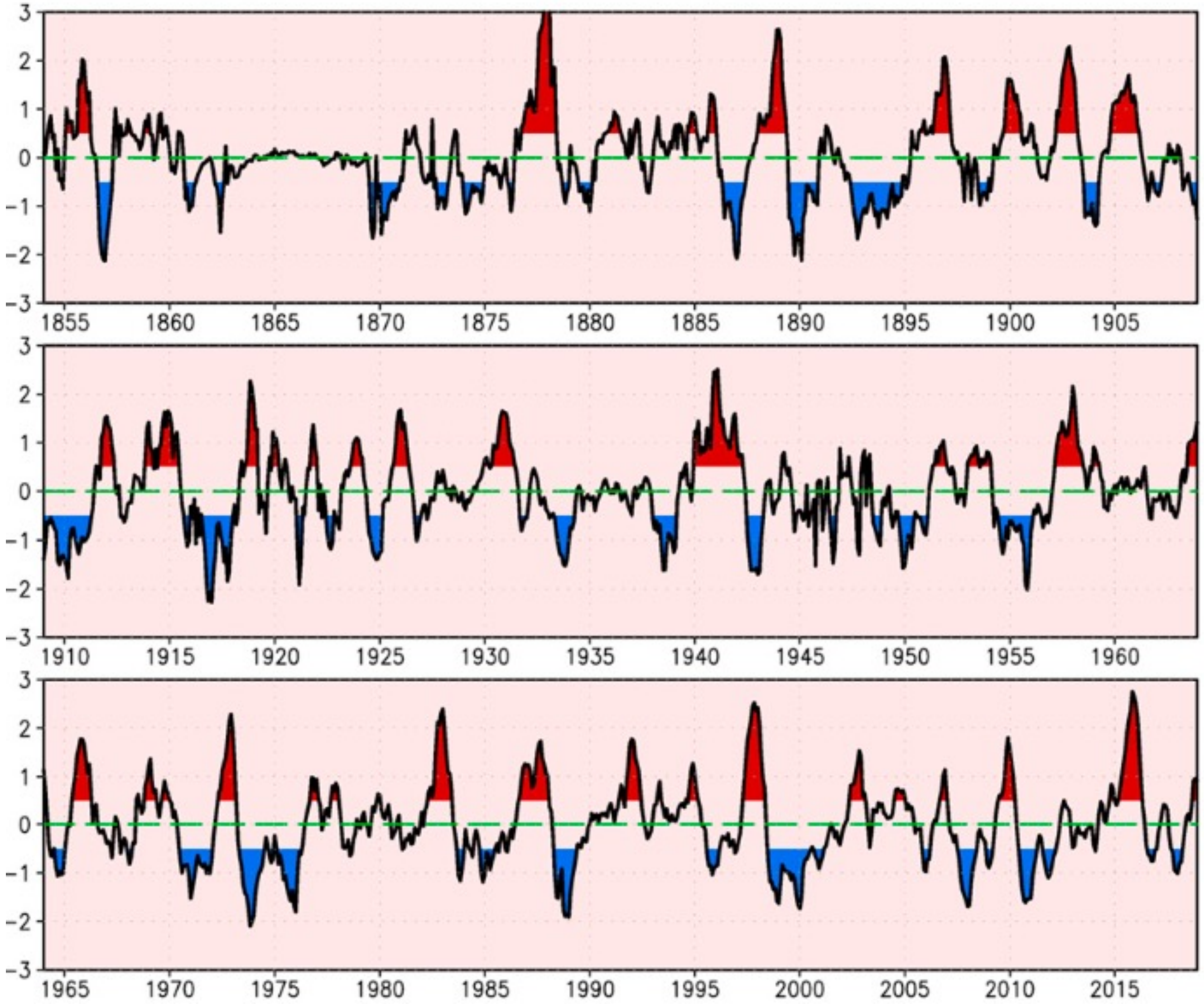
- Demonstration that the influence of boundary forcings (SST, Soil Wetness, Vegetation, Snow, etc.) is significantly larger than the uncertainty due to chaos and the butterfly effect established the scientific basis for dynamical prediction of seasonal mean circulation and rainfall

- Routine dynamical seasonal prediction using coupled ocean – atmosphere models became possible after 1986.

(Cane, Zebiak, Dolan; Nature, 1986; Experimental Forecasts of El Nino)

Nino 3.4
1854-2018

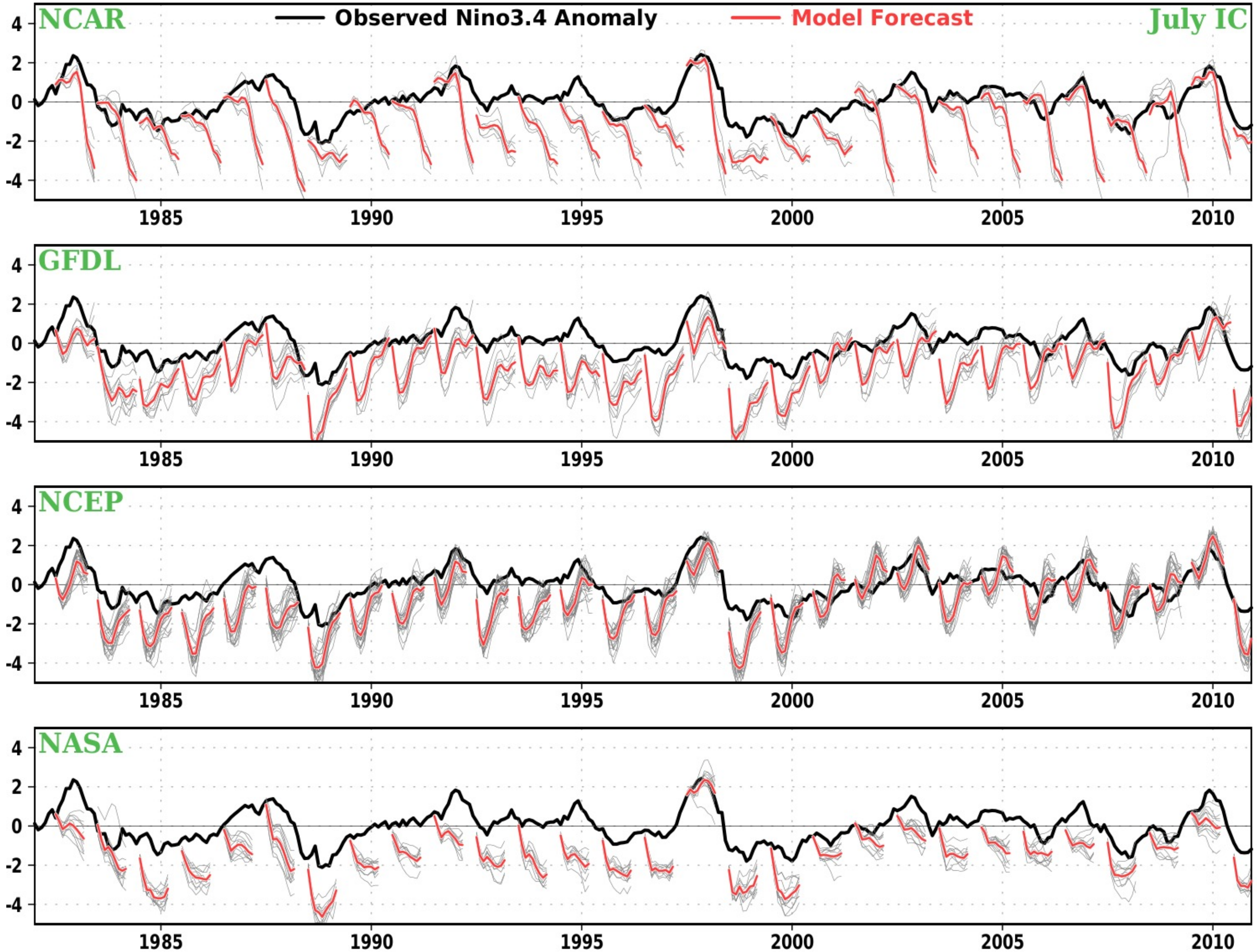
Red: $\geq \mathbf{0.5}$°C
Blue: $\leq \mathbf{0.5}$°C



Hu et al., (2020)

Forecast of Nino 3.4 by four US climate models (IC: July 1)

All "best" models have huge systematic error in forecasting tropical SST.



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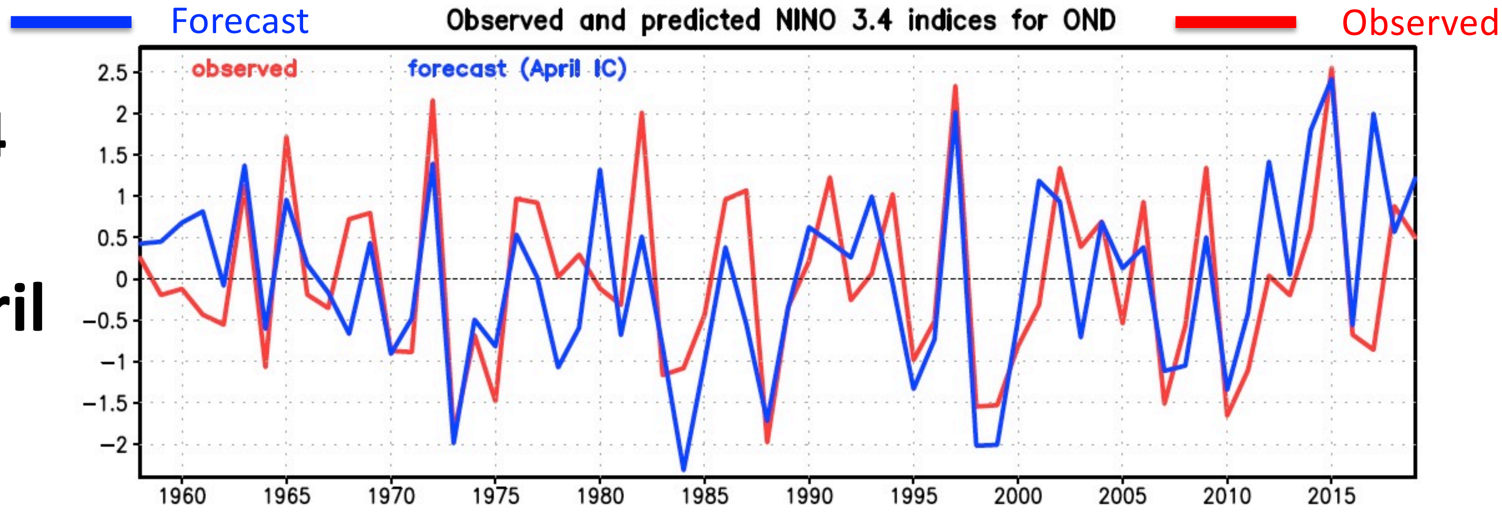
Current Status of Dynamical Seasonal Prediction

- **In spite of large biases *(as large as the ENSO signal)*, the coupled ocean atmosphere models have shown significant skill in Nino 3.4 hindcasts.**

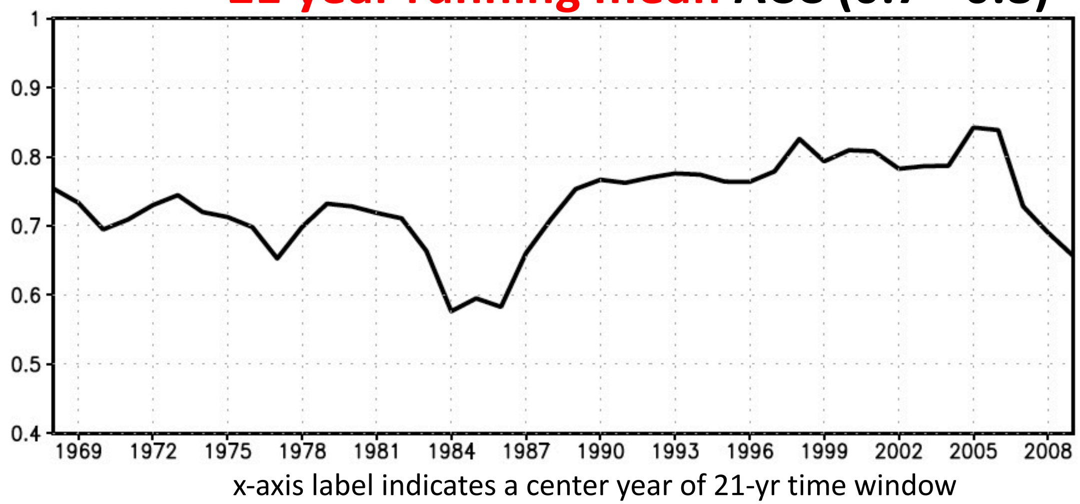
Reforecasting the ENSO Events in the Past 62 Years (1958-2019)

Nino 3.4 (OND)
IC: 1 April



ACC:
21 year running mean

21 year running mean ACC (0.7 - 0.8)



Note: no significant improvement in skill with enhanced ocean observations

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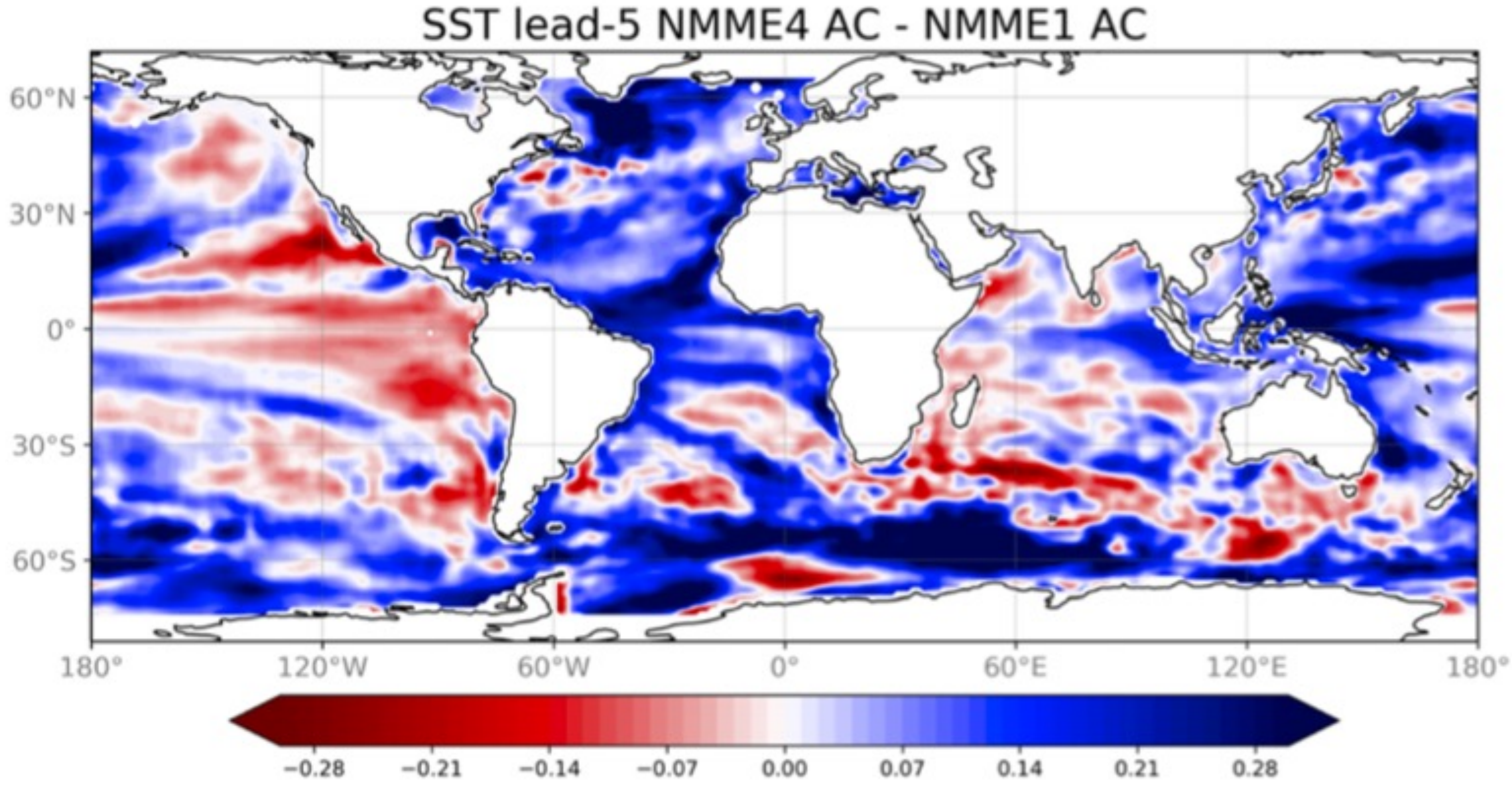
US NMME hindcasts for 1982-2010

The difference between the skill (ACC) of 5-month lead SST hindcast for US models of 2019-20 minus the US models of 2010-11

Skill of SST forecast in the Eastern Pacific has decreased for the most recent US models



Becker, Kirtman, Pegion (2020)

Current Status of Dynamical Seasonal Prediction

- In spite of large biases *(as large as the ENSO signal)*, the coupled ocean atmosphere models have shown significant skill in Nino 3.4 hindcasts.

- **However, the skill of seasonal predictions based on ENSO teleconnections sometimes work marvelously, and sometimes fail miserably**

- **Reforecasting 1972-73 & 1997-98 ENSO and Monsoon**

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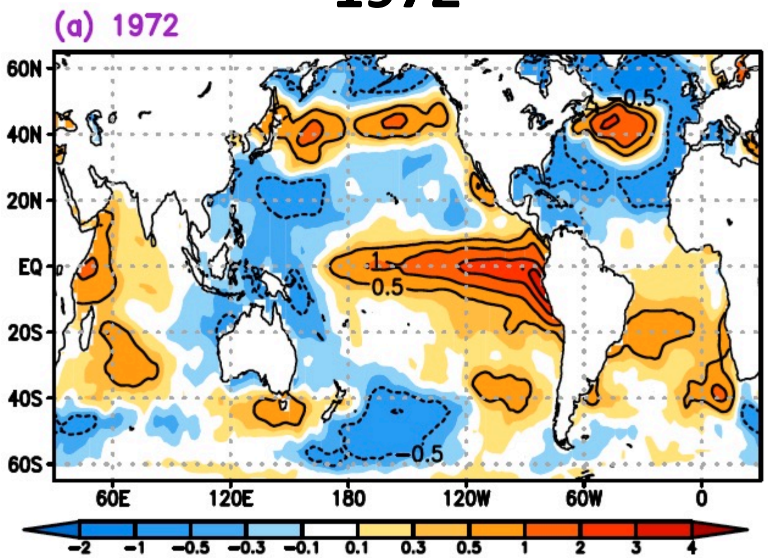
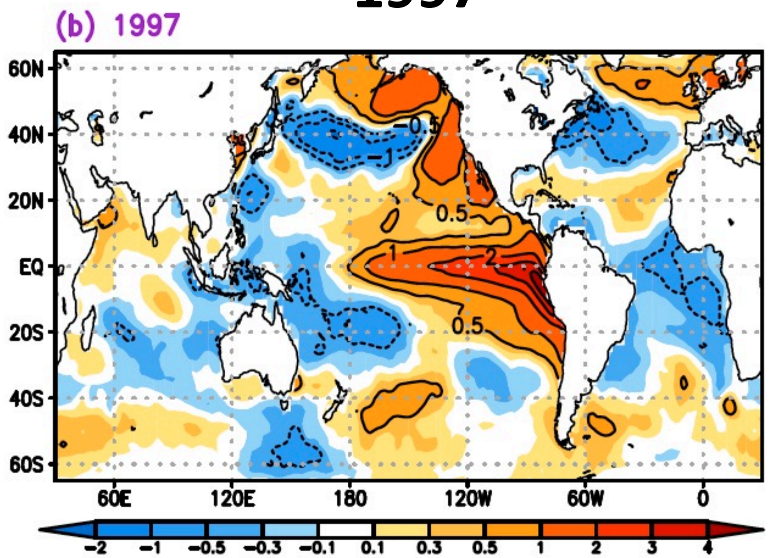
Observed JJAS SST Anomaly

1972



1997



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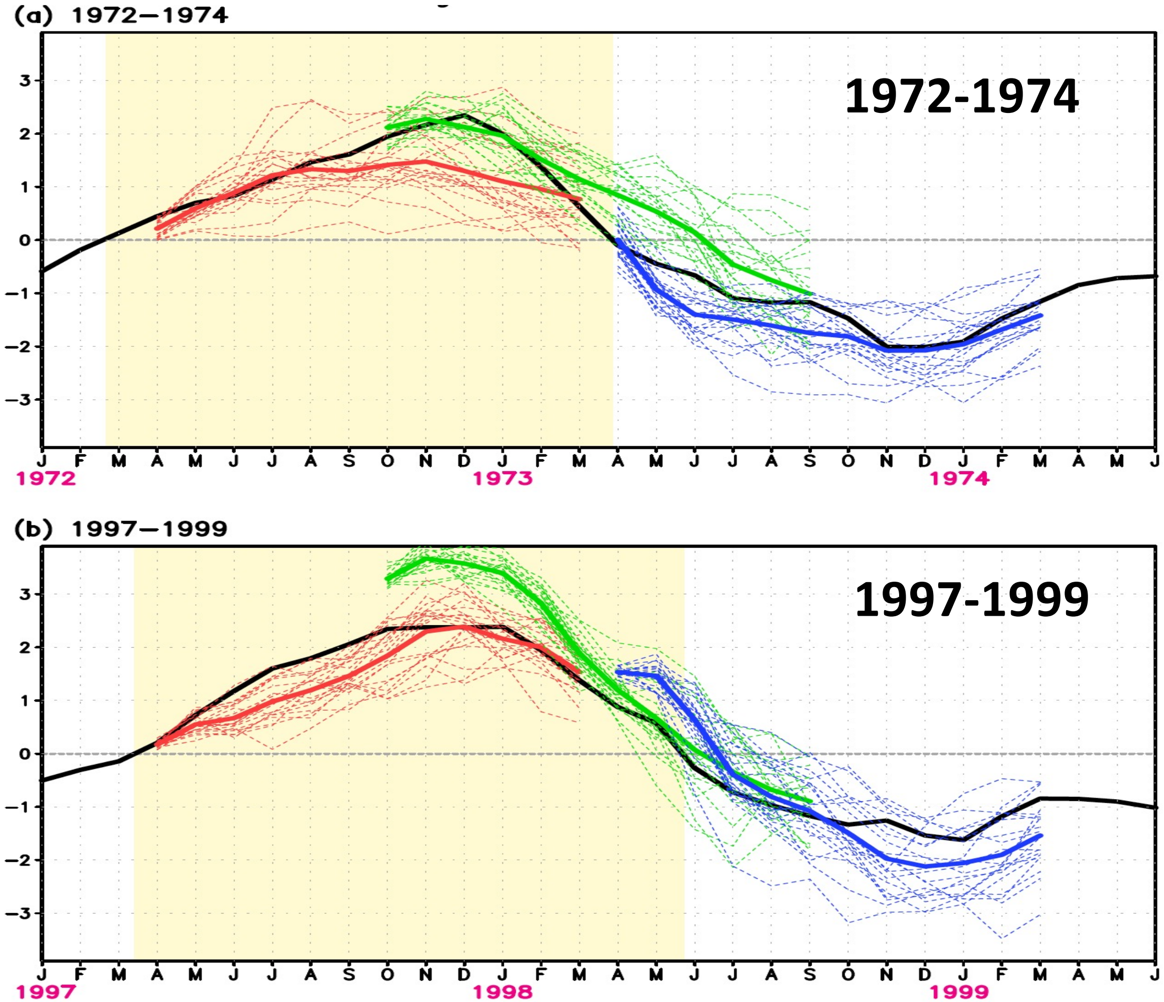
Observed and Forecast SST Anomalies for April and October IC



Prediction of both events by Model (CFSV2) was remarkably good

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Huang et al. (2017)

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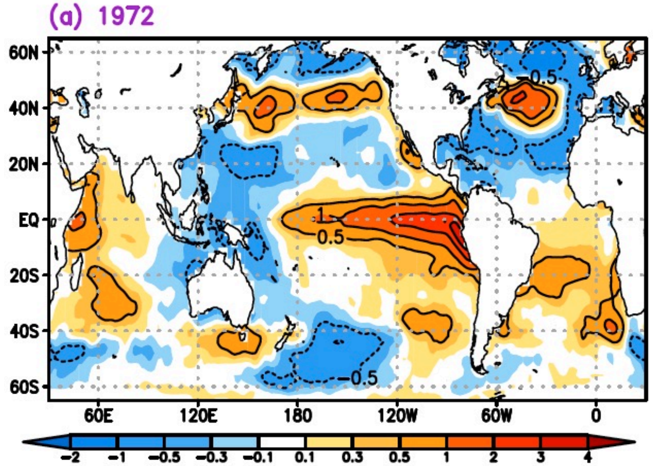
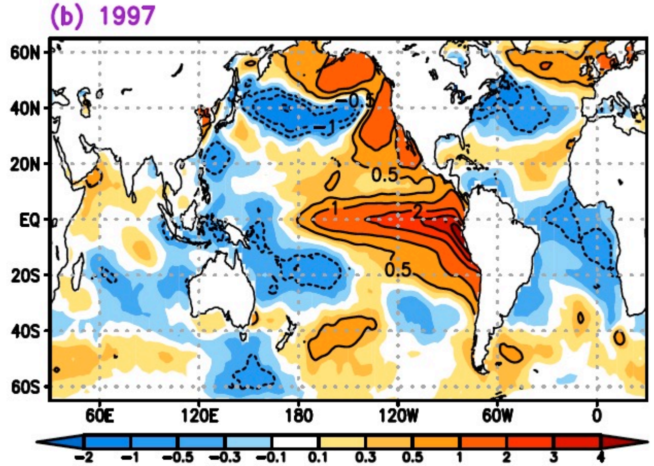
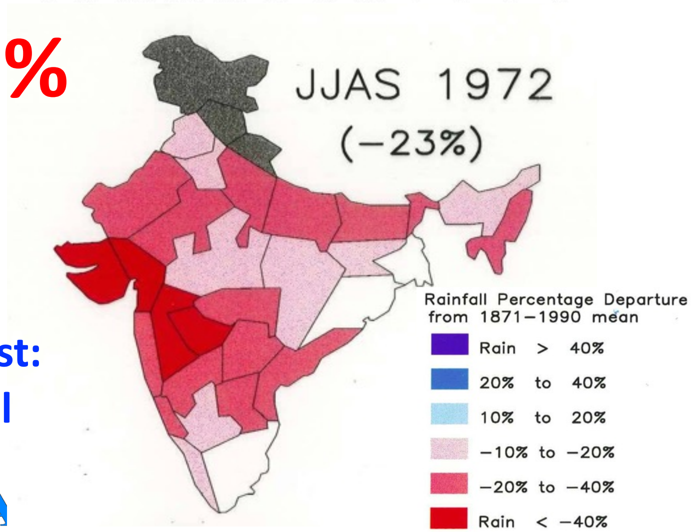
ENSO & ISMR (obs) for JJAS 1972 and 1997

1972 | **1997**



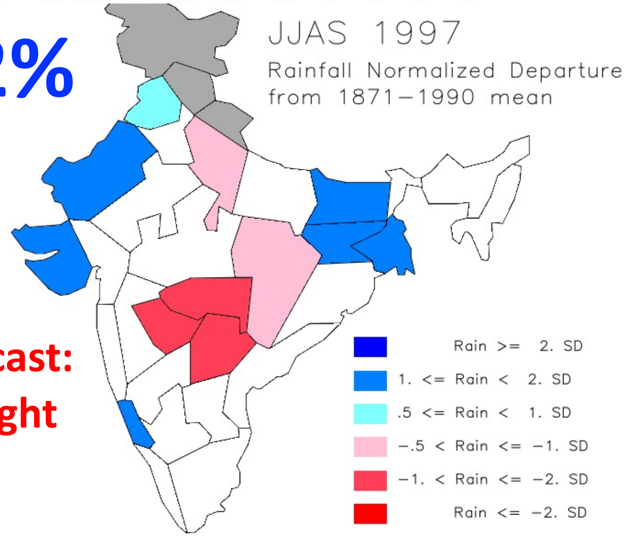


- 23%



IMD Forecast: Normal

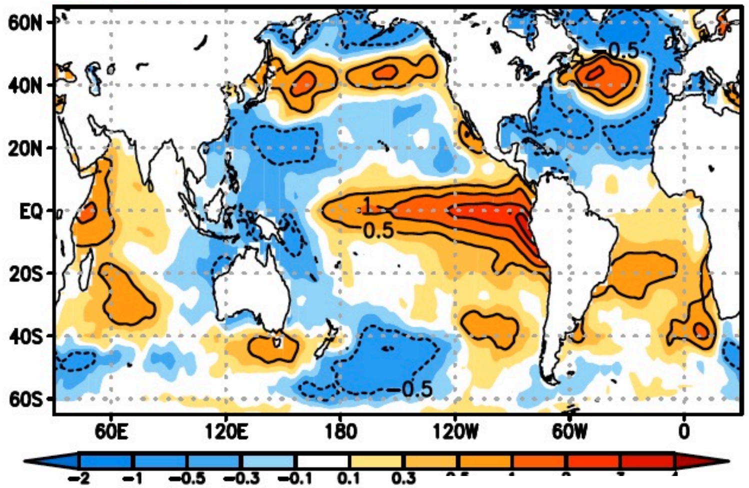
+ 2%

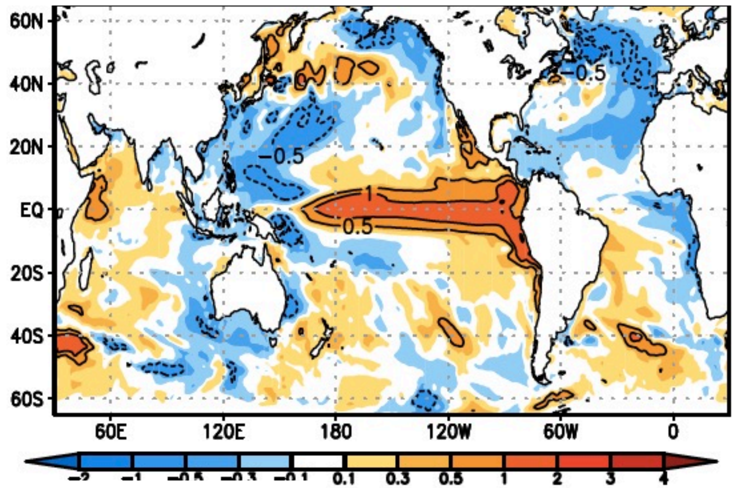


IMD Forecast: Drought

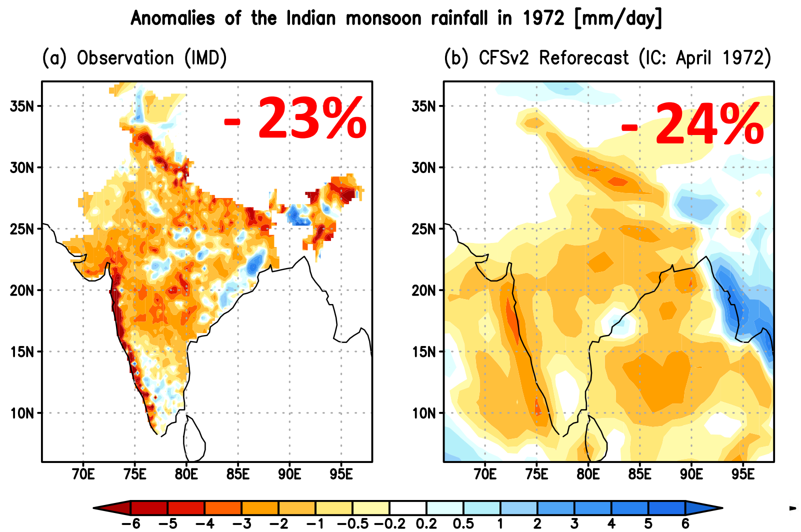
Obs. and Forecast SST Anomalies for JJA (April IC) 1972

Observed SSTA **SST (JJA)** **Forecast SSTA**





Observed Precip. (JJAS)



Forecast Precip. (JJAS)

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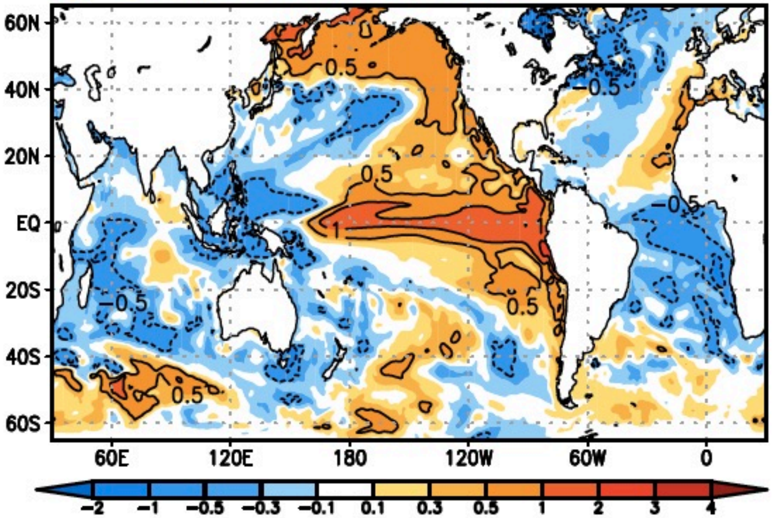
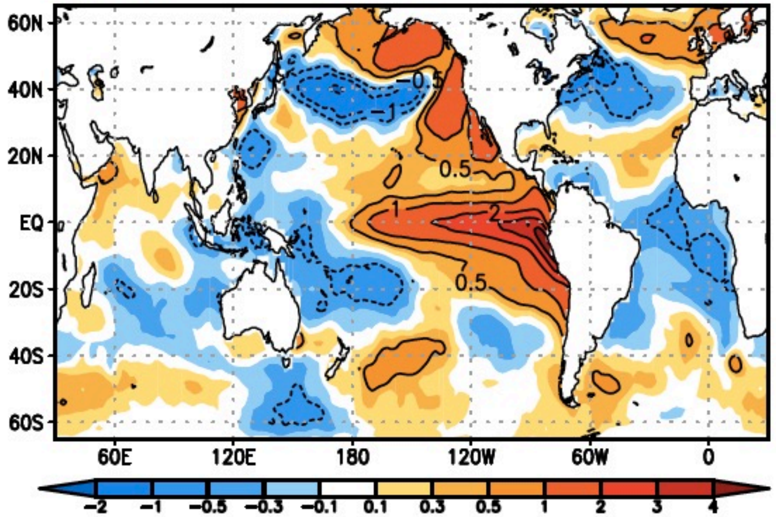
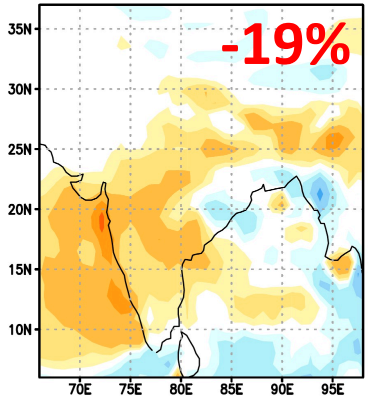
Obs. and Forecast SST Anomalies for JJA (April IC) 1997

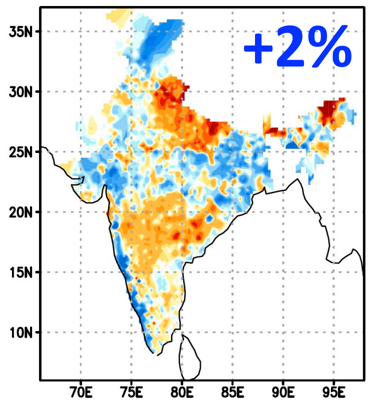
Forecast SST **SST (JJA)** **Observed SST**



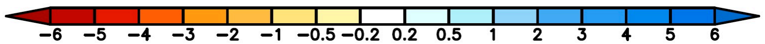


Forecast Precip. (JJAS)





Observed Precip. (JJAS)



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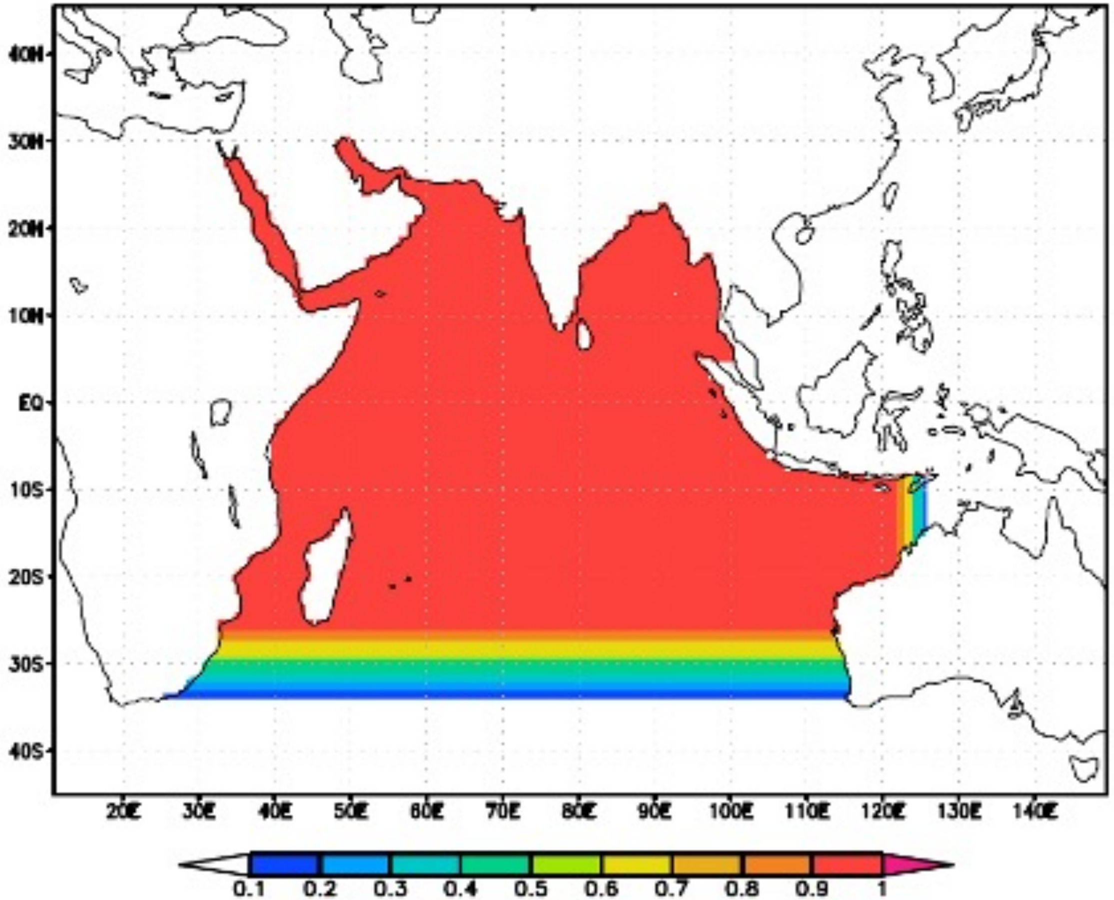
Area of the prescribed SST over the Indian Ocean

(Ocean Model Grids)



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Nudging area is indicated by green to red color in the southern and eastern boundary.

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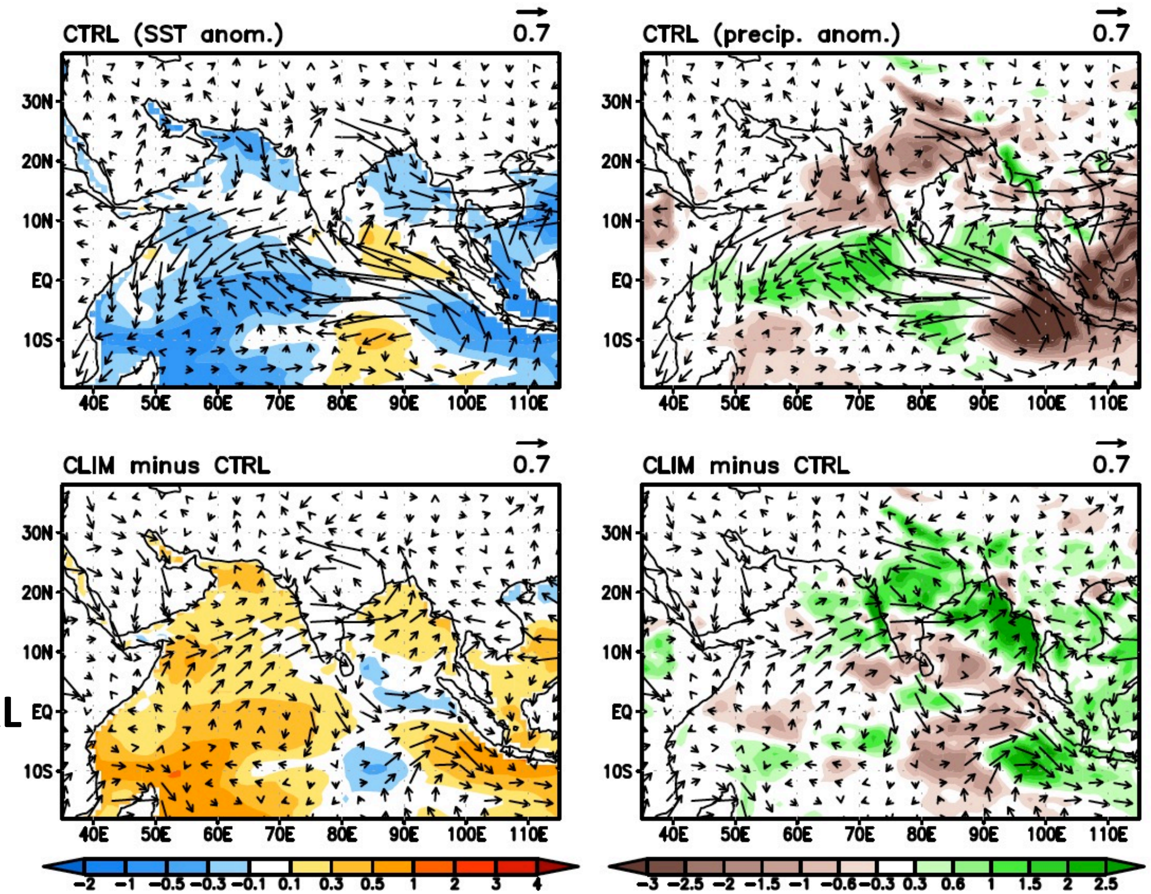
Replacing the Erroneous Cold SST by Climatological SST over the Indian Ocean Correctly Enhanced Rainfall Over India

1997

CTRL

JJAS anomalies of SST (shaded) and wind at 850hPa (vectors)

CLIM SST minus CTRL



JJAS anomalies of Precip. (shaded) and wind at 850hPa (vectors)

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Prescribed Climatological SST over the Indian Ocean

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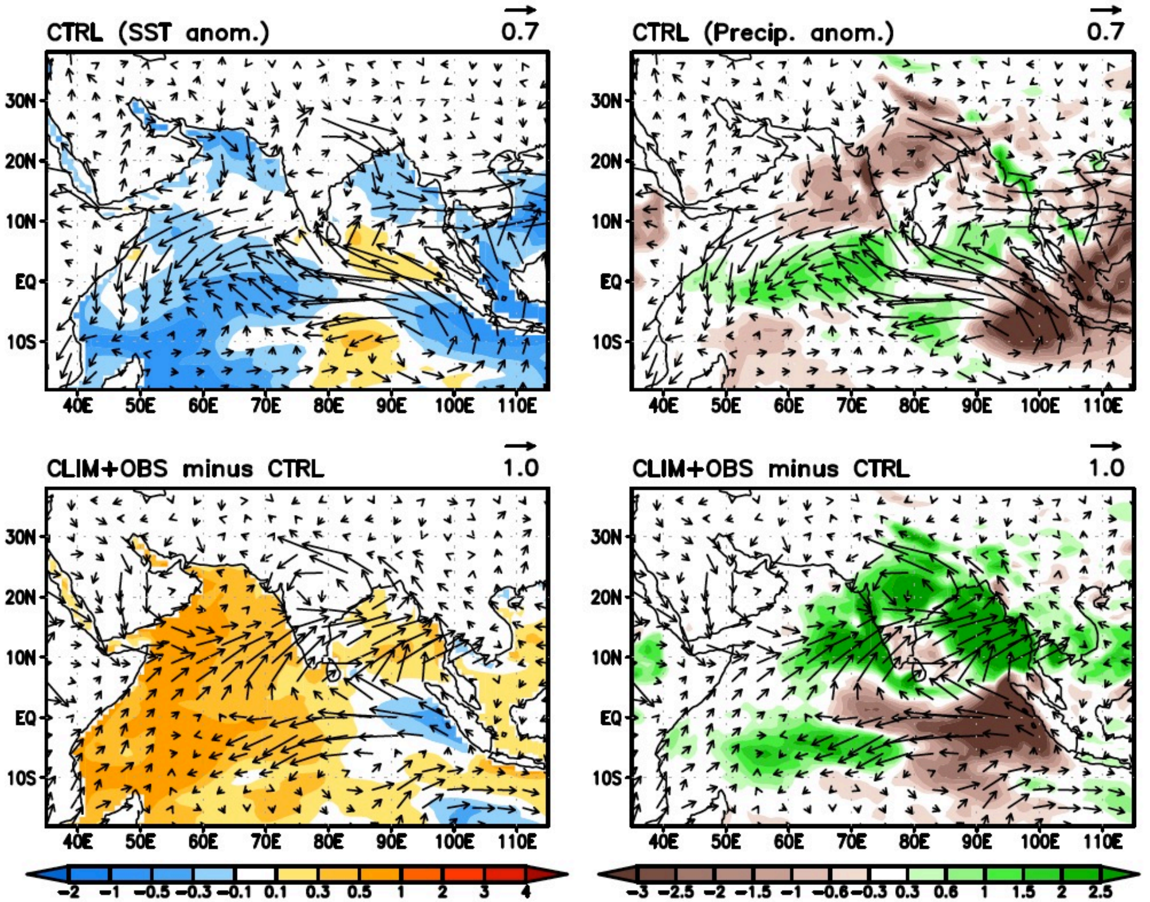
Replacing the Erroneous Cold SST by Observed SST over the Indian Ocean Further Enhanced Rainfall Over India

1997

JJAS anomalies of SST (shaded) and wind at 850hPa (vectors)

CLIM+OBS SST anomalies minus CTRL



JJAS anomalies of Precip. (shaded) and wind at 850hPa (vectors)

Prescribed Observed SST over the Indian Ocean

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Summary

- 40 years ago, a skillful Dynamical Seasonal Prediction (DSP) using coupled models was not conceivable; DSP has achieved a level of skill that is considered useful for a number of societal applications.
- Skill of forecasting tropical SST has not improved in 20 years, it appears that it has gotten worse

Discussion

- **In spite of improved ocean observations during the recent decades (1979-2014), ENSO prediction skill is comparable between 1958-78 and 1979-2014, or perhaps worse, why? Is it because:**

  - the current models and assimilation systems are unable to take full advantage of enhanced ocean observations?

  - climate models have large biases?

  - secular changes in mean climate?

- **Why frequently remote response is entirely incorrect although Nino 3.4 forecast is reasonably good**

- **Is it climate modeler's good luck that evolution of model error does not interact with ENSO signal**

THANK YOU!

ANY QUESTIONS?

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