Evolution of Ideas Leading to Dynamical Seasonal Prediction

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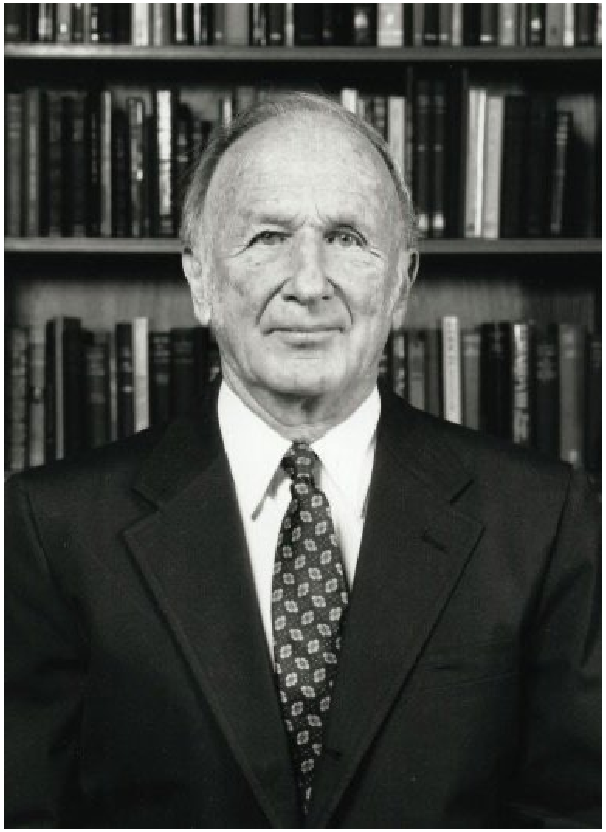
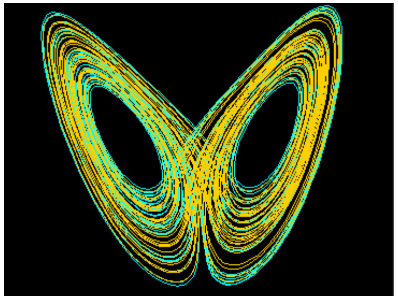
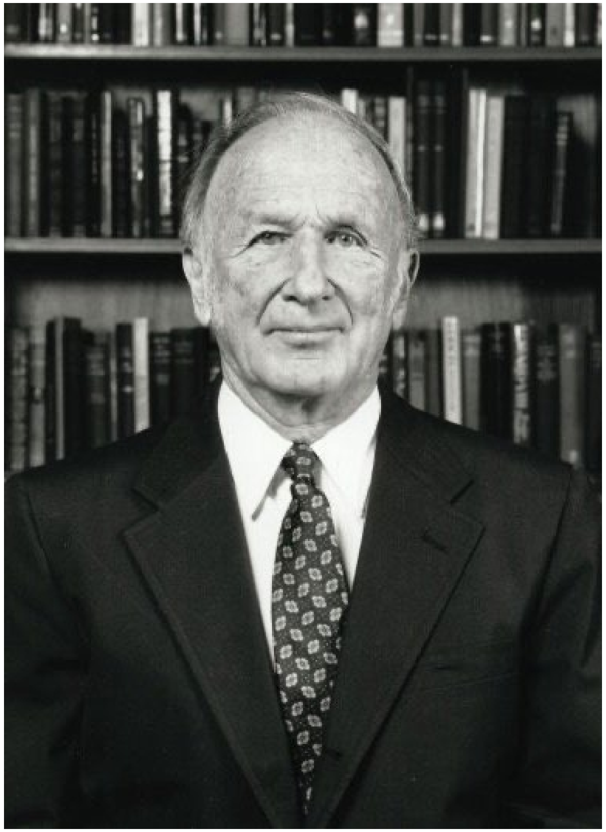
ECMWF, Reading
December 2022

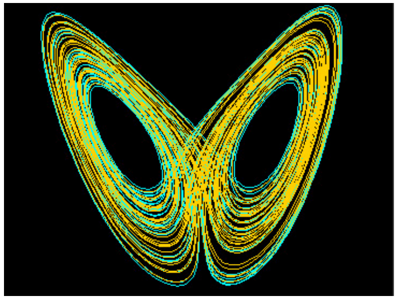


Lorenz (1963)





Lorenz (1963)

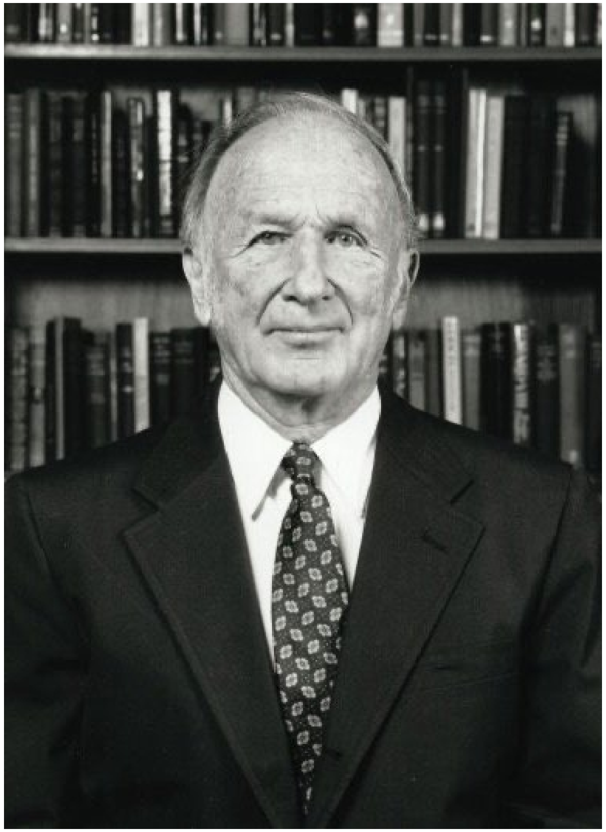


Charney et al (1966)

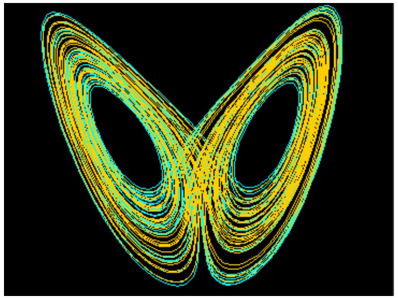
Multi-Model Ensemble:
To Estimate Weather Predictability

3 Models:
Mintz- Arakawa;
Leith; GFDL

BAMS: The Feasibility of a Global
Observation and Analysis Experiment



Lorenz (1963)



Charney et al (1966)

Multi-Model Ensemble:
To Estimate Weather Predictability

3 Models:
Mintz- Arakawa;
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BAMS: The Feasibility of a Global
Observation and Analysis Experiment

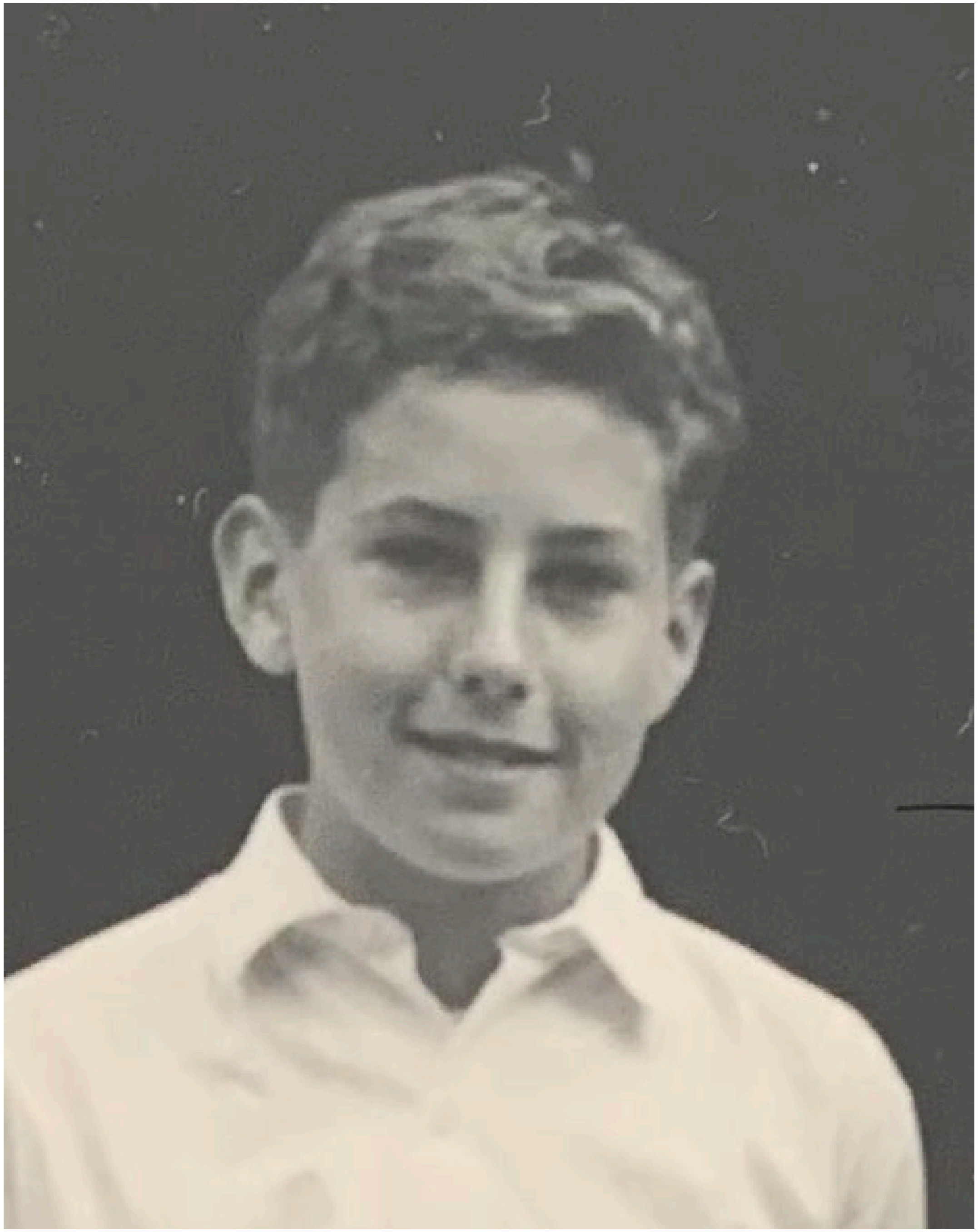
Palmer (ECMWF)

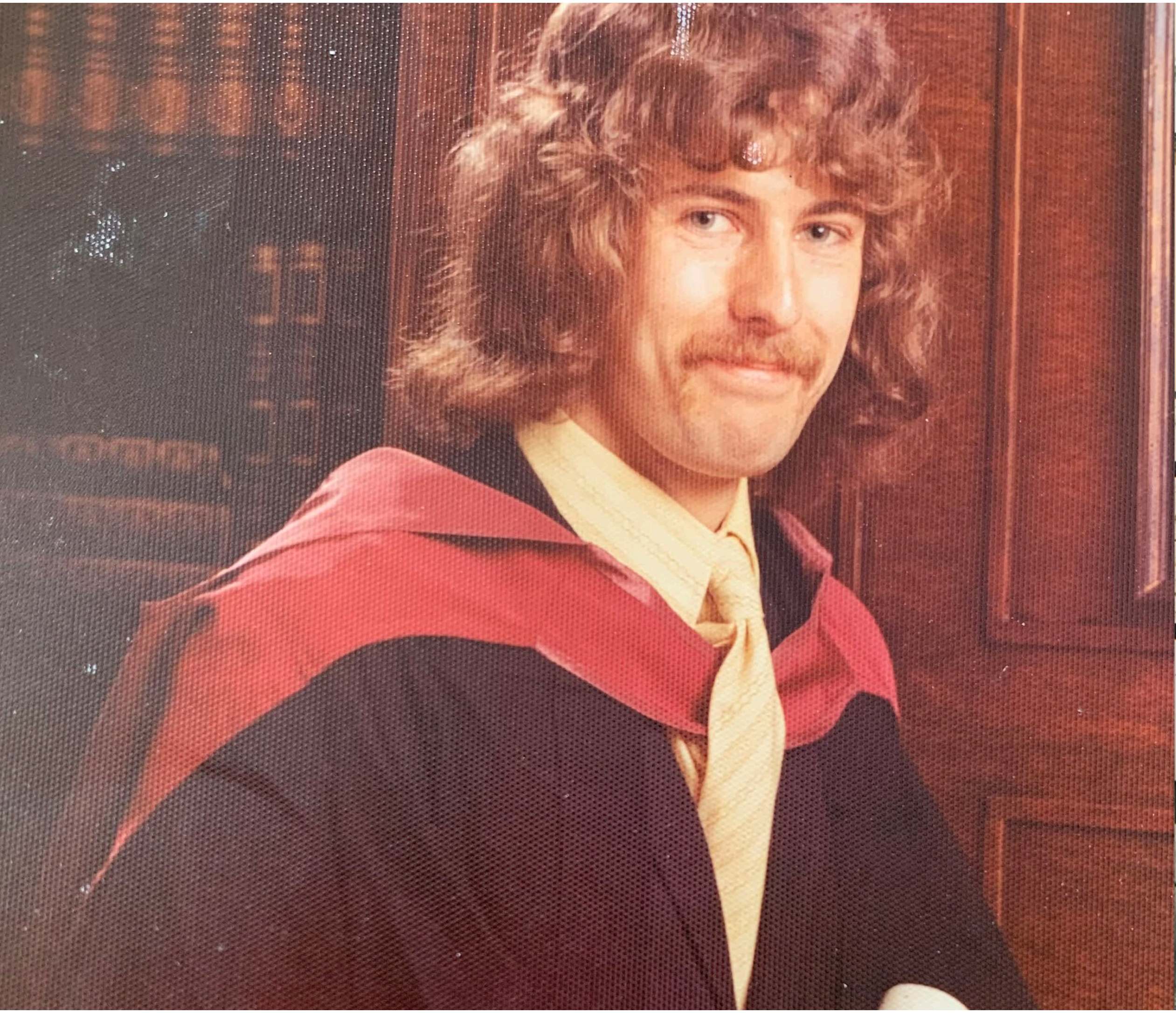
1992: Operational Medium Range Ensemble Forecast

Outline

- Introduction
- Tim’s Early Career
- Selected Papers by Tim and UKMO colleagues
- Billion Butterflies Experiment
- International Programs
  - WCRP/JSC; MONEG; IAP (India)
  - World Modeling Summit; Climate CERN
  - Visiting India and my village

Tim’s Early Career






BALANX

Selected Papers by:
Palmer, Mansfield, Folland, Sun

These papers contributed towards establishing a scientific basis for dynamical seasonal prediction

Palmer and Mansfield (1986, QJRMS pp 613 – 638)

Palmer and Mansfield (1986 QJRMS pp 639 – 660)

Folland, Palmer, and Parker (1986)

Tim Palmer and Sun Zhaobo (1985)

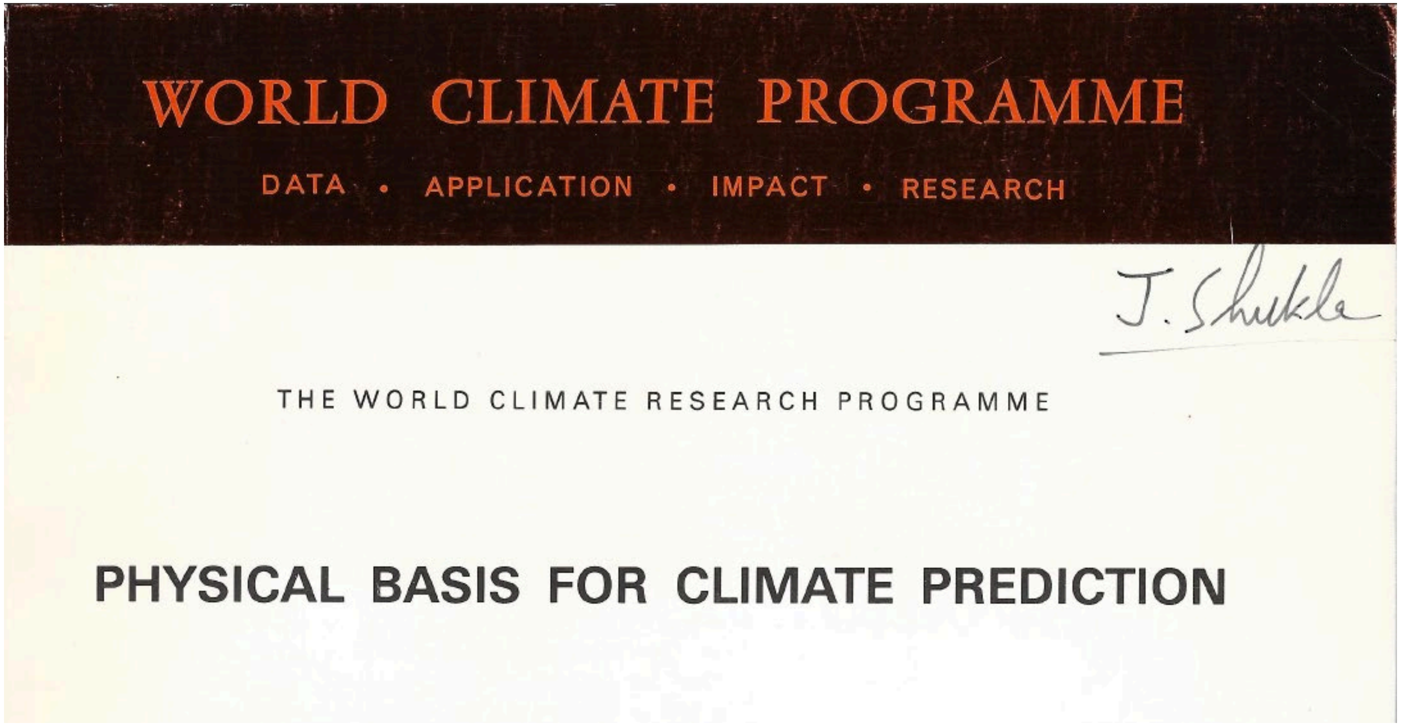
T N Palmer (1994): Chaos and Predictability in Forecasting the Monsoons

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 10 days.*

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

So what are the key ideas that led to dynamical seasonal prediction before ENSO prediction in 1986? (Research at GFDL, UKMO, and COLA)



WORLD CLIMATE PROGRAMME

DATA • APPLICATION • IMPACT • RESEARCH

J. Shukla

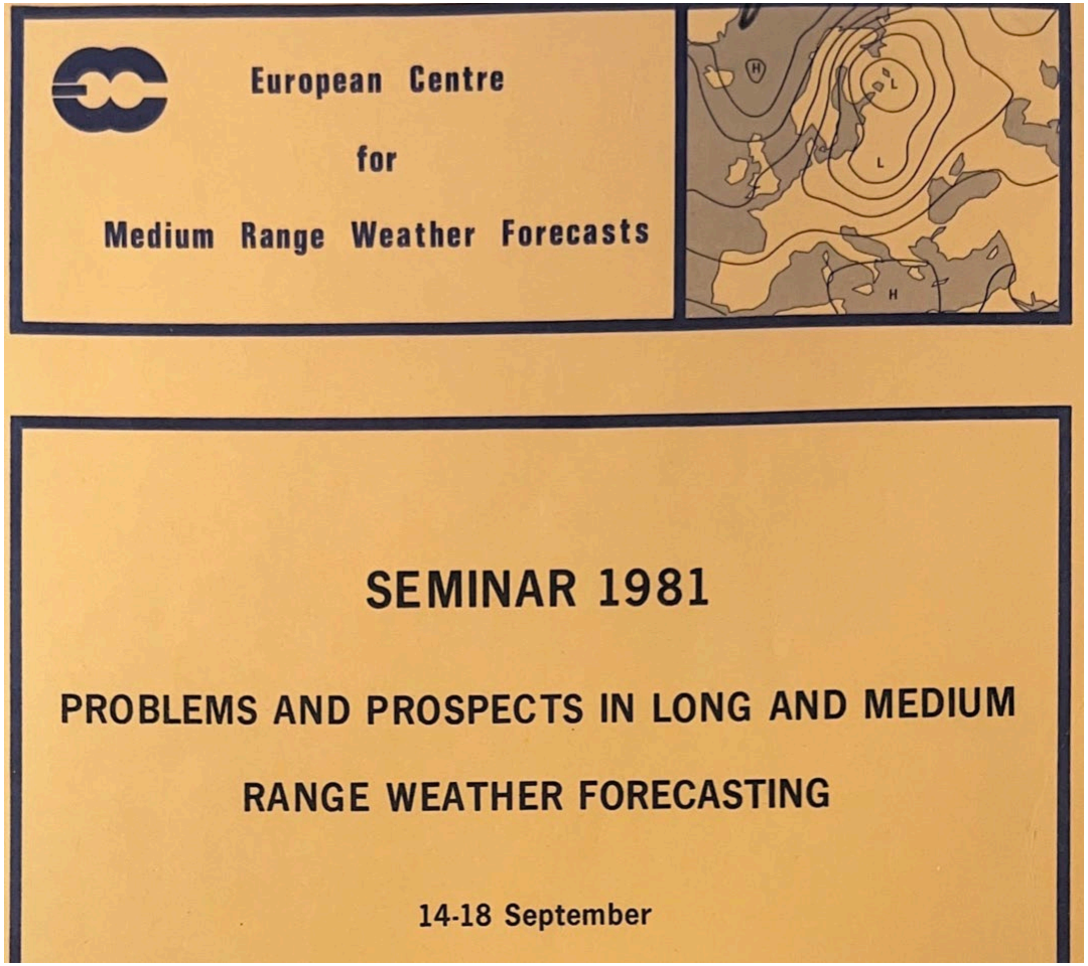
THE WORLD CLIMATE RESEARCH PROGRAMME

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

Authors:
A. Gilchrist,
C. Leith,
E. Lorenz,
R. Madden,
J. Shukla



European Centre
for
Medium Range Weather Forecasts

SEMINAR 1981

PROBLEMS AND PROSPECTS IN LONG AND MEDIUM
RANGE WEATHER FORECASTING

14-18 September

Authors ECMWF:
L. Bengtsson,
G. Cats,
U. Cubasch,
P. Kallberg,
E. Kallen,
A. Simmons,
S. Uppala

Part I: Predictability of Monthly Means
Part II. Influence of the Boundary Forcings

Ensembles to calculate signal to noise ratio as a metric for predictability of seasonal averages

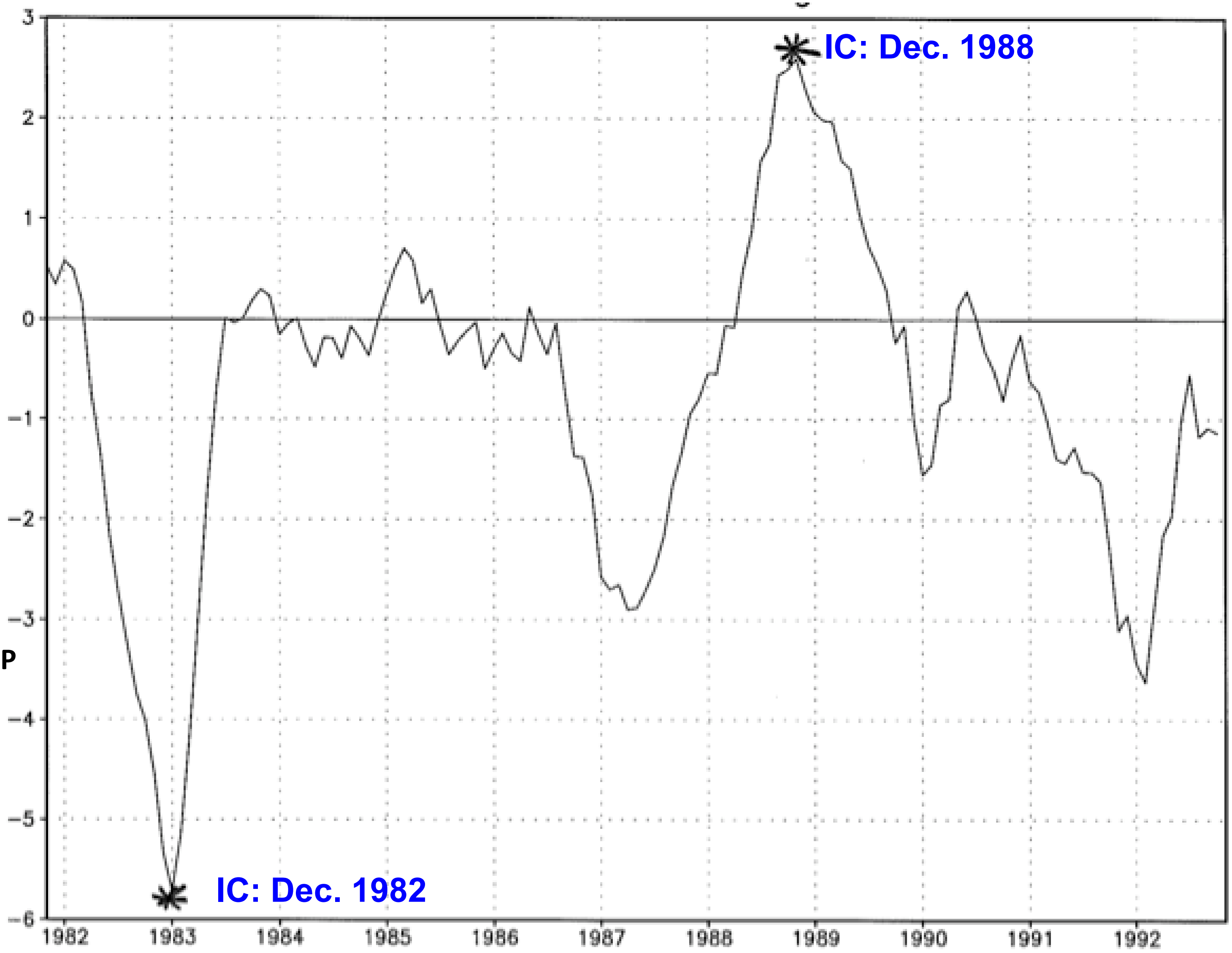
Dynamical Seasonal Prediction: Pre-ENSO 1975 - 1985

- **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**
  - **Signal to noise ratio as a metric for predictability of time averages**
- **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)



IC: Dec. 1988

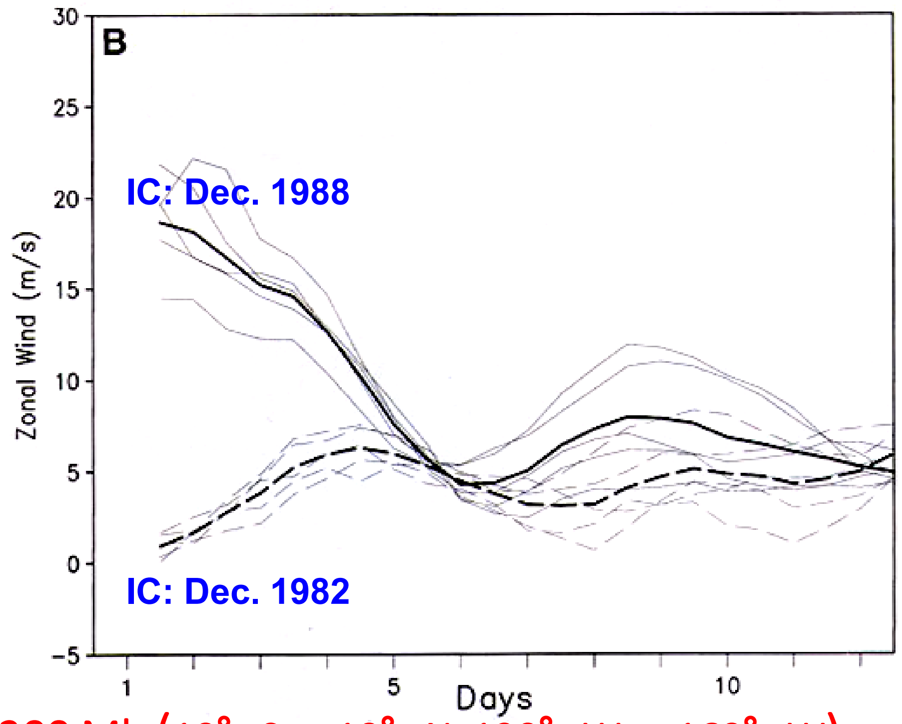
IC: Dec. 1982

SOI = Tahiti – Darwin SLP

Observed 5-month running mean SOI

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)

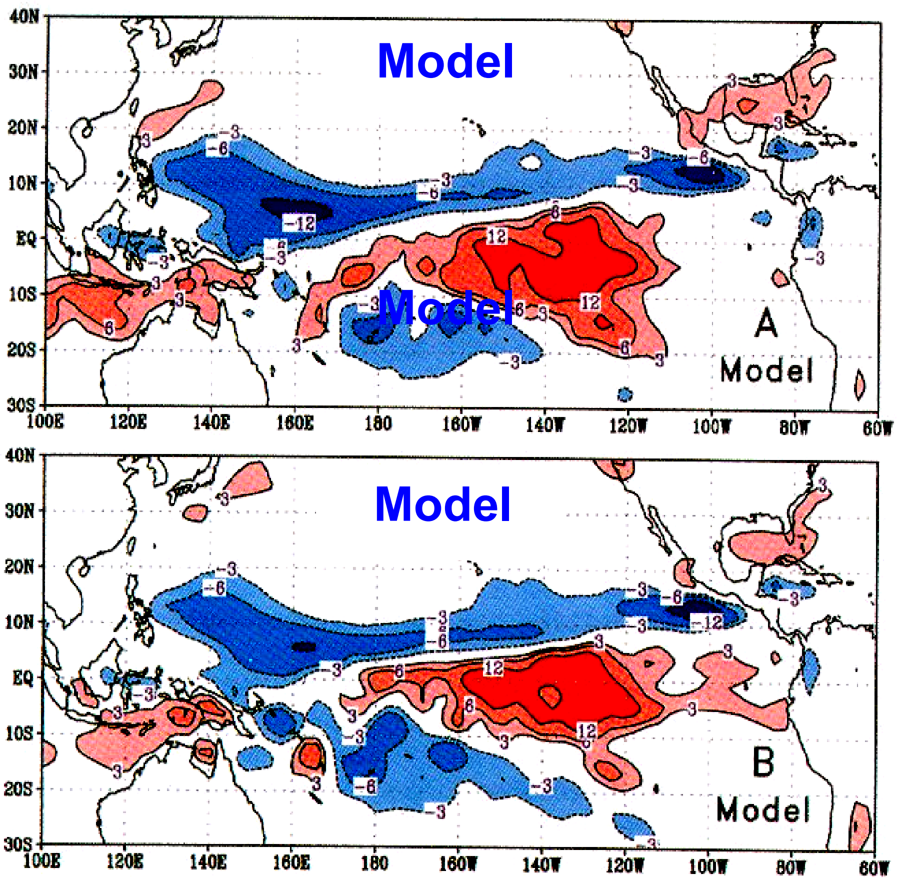
Example of lack of sensitivity to initial conditions of atmosphere

JFM Mean Rainfall Anomalies

Seasonal Mean Rainfall is Not Sensitive to Atmospheric Initial Conditions

IC: Dec. 1988

IC: Dec. 1982

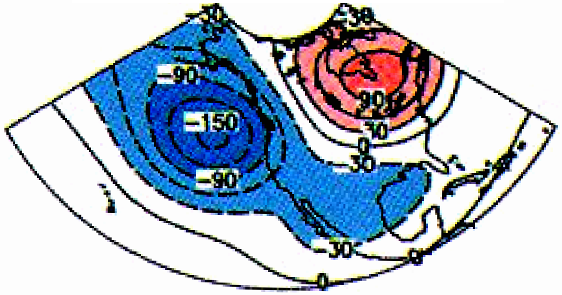


“Predictability in the Midst of Chaos”

JFM Mean Circulation

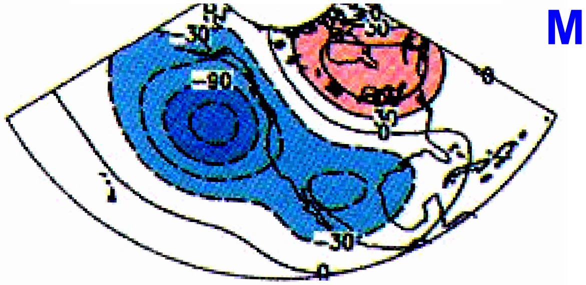
500 hPa ϕ' (meters)

IC: Dec. 1988



Model

IC: Dec. 1982



Model

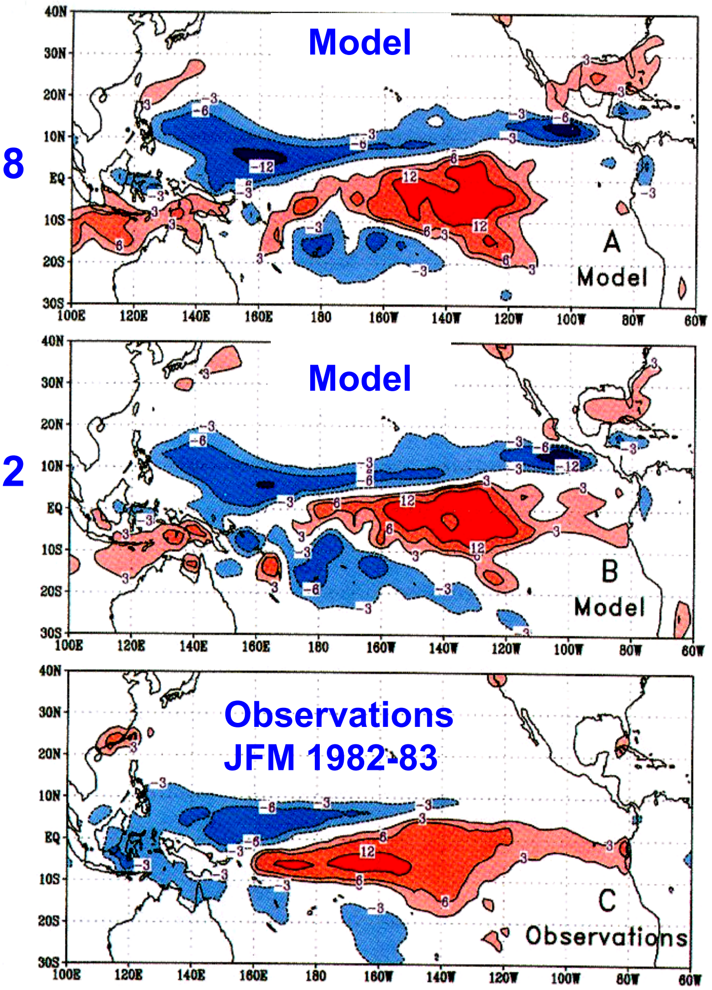
Seasonal Mean Circulation is Not Sensitive to Atmospheric Initial Conditions

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

Both model runs used observed 1982-83 SST

Tropical Pacific rainfall is very strongly determined by the sea surface temperature

JFM Mean Rainfall Anomalies



IC: Dec. 1988

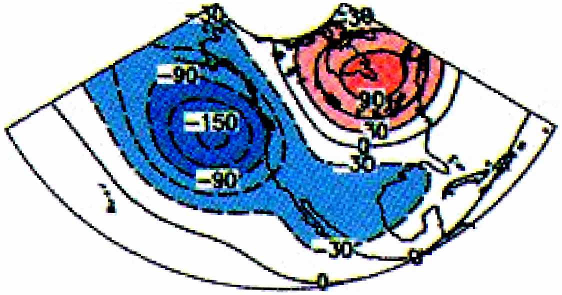
IC: Dec. 1982

“Predictability in the Midst of Chaos”

JFM Mean Circulation

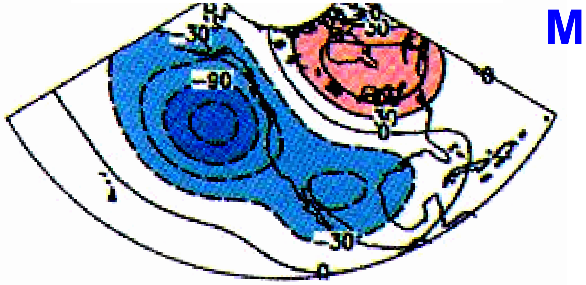
500 hPa ϕ′ (meters)

IC: Dec. 1988



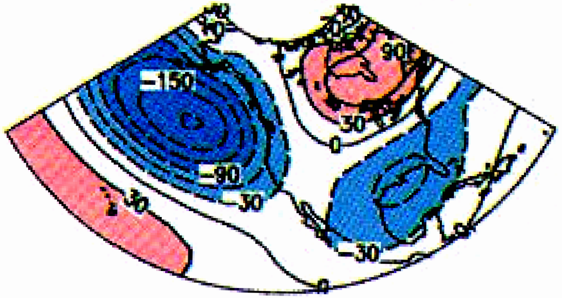
Model

IC: Dec. 1982



Model

Observed JFM 1983



Seasonal Mean Circulation is Not Sensitive to Atmospheric Initial Conditions

When tropical forcing is very strong, it can enhance even the predictability of extratropical seasonal mean circulation, which, in the absence of anomalous SST, has no predictability beyond weather.

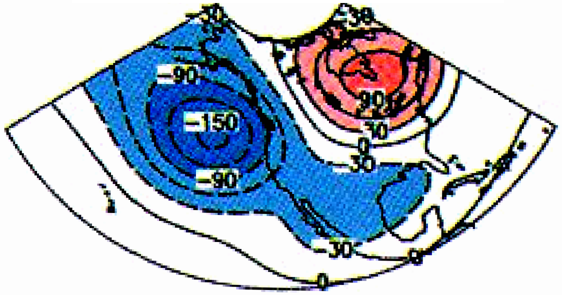
Both model runs used observed 1982-83 SST

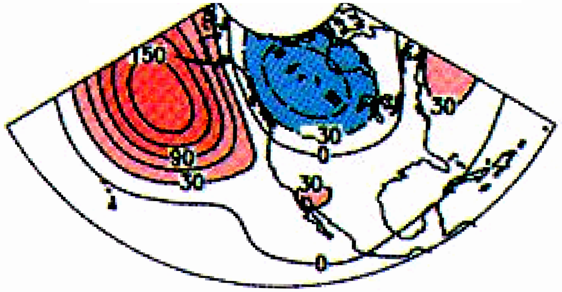
When tropical forcing is very strong, it can enhance even the predictability of extratropical seasonal mean circulation, which, in the absence of anomalous SST, has no predictability beyond weather.

Observed SST JFM 83

Observed SST JFM 89

IC: Dec. 1988



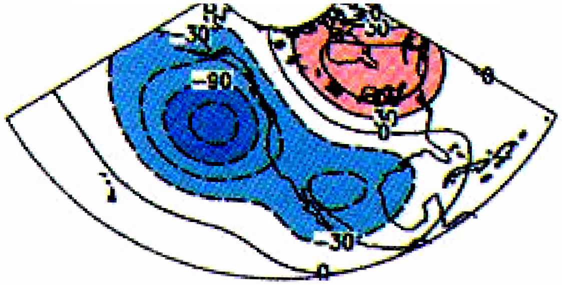


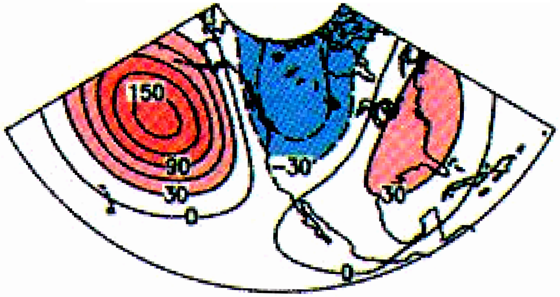
IC: Dec. 1988

Observed SST JFM 83

Observed SST JFM 89

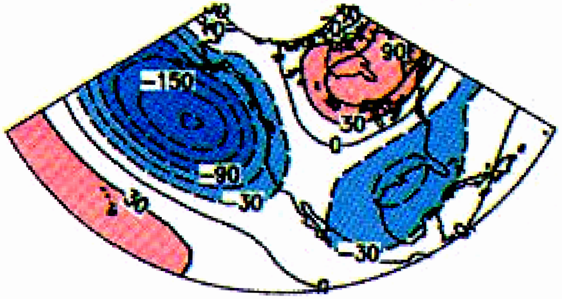
IC: Dec. 1982



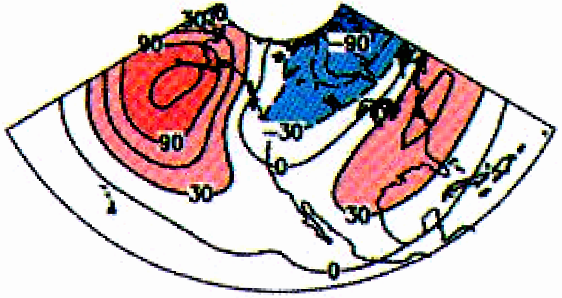


IC: Dec. 1982

C. Observed JFM 1983



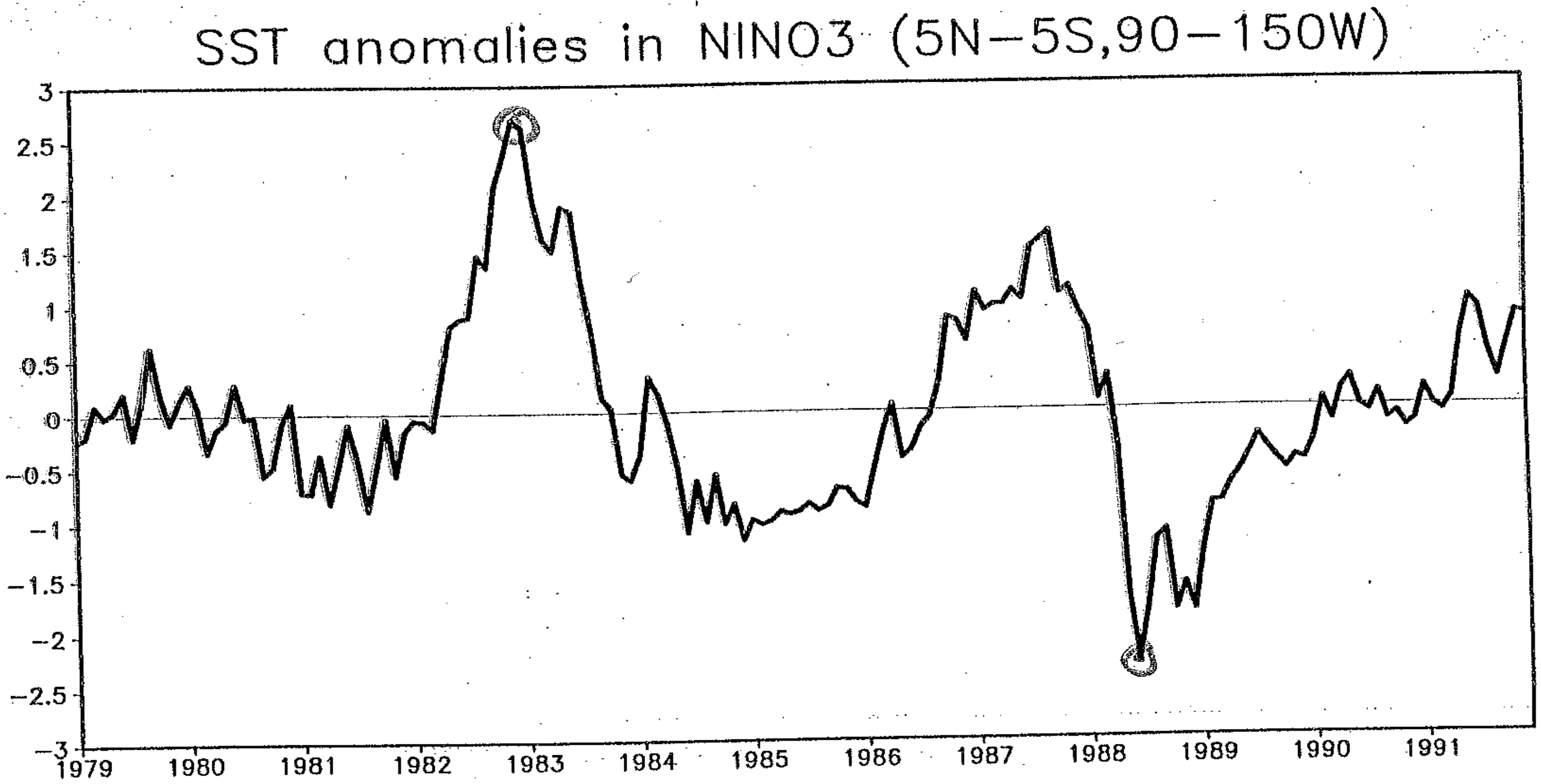
F. Observed JFM 1989



Observed ϕ′ (meters)

Billion Butterflies Experiment (Ocean)

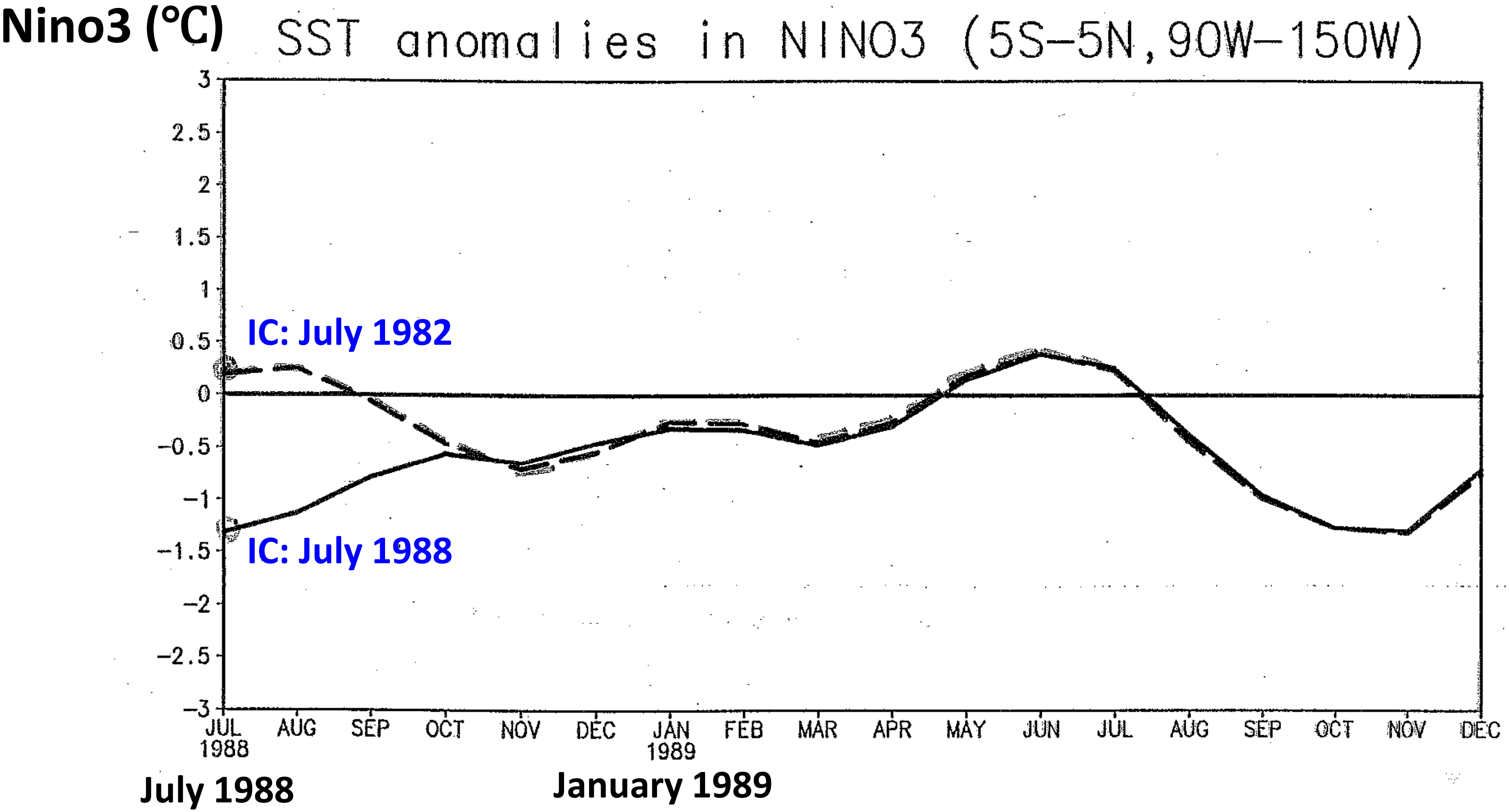
SST Anomalies in Nino3 were very different in 1982 – 83 and 1988 - 89



1982-83 **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.



Example of lack of sensitivity to initial conditions of ocean state

Summary of Billion Butterflies Experiment Results

1. The atmosphere is so strongly forced by the underlying ocean that in spite of very large differences in the initial atmospheric conditions, the simulated atmospheric circulation converges when forced by the same SST forcing.

2. The ocean is so strongly forced by the overlying atmosphere that in spite of very large differences in the initial upper-ocean conditions, the simulated SST converges when forced by the same atmospheric forcing

3. *(When tropical forcing is very strong, it can enhance even the predictability of extratropical seasonal mean circulation*)

Note: This does not guarantee predictability of the coupled ocean-atmosphere system

SST-forced Atmospheric Circulation Anomalies

δ(SST) → **δ**(Q) → **δ**(Circulation)

Large-scale persistent anomalies in SST, create a deep and persistent heat source anomaly (SST) which in turn force atmospheric circulation anomalies

- **δ(SST) → δ(Q) depends upon:**
  - Magnitude and sign of **δ**SST (Palmer, Mansfield, Folland, Sun)
  - Magnitude of mean SST (Palmer, Mansfield, Folland, Sun)
  - Large-scale circulation
    - **δ** SST over regions of large-scale ascent or descent
    - warm **δ**SST over very warm water or very cold water

- **δ(Q) → δ(Circulation) depends upon:**
  - Magnitude and structure of **δ**(Q)
  - Location of **δ**(Q) w.r.t. circulation
  - Structure of Flow
  - **Forced rossby waves**
  - **Tropics: Hadley, Walker, Monsoon circulations**
  - **Extratropics: quasi-stationary waves, instabilities**

Summary of Scientific Ideas and Results in
Selected Papers by: *Palmer, Mansfield, Folland, Sun*

Palmer and Mansfield (1986, QJRMS pp 613 – 638)

Response of El Nino significantly different with and without envelop orography; SST forced response depends on mean state

Palmer and Mansfield (1986 QJRMS pp 639 – 660)

Response of a smaller SST in western pacific can be larger than a larger SST in eastern pacific

(δ(SST) → δ(Q) depends upon: T, δT, and location of δT wrt large scale flow)

Folland, Palmer, and Parker (1986)

The Sahel drought in the 1970s and 1980s was likely caused by global-scale decadal SST anomalies.

Tim Palmer and Sun Zhaobo (1985)

A mid-latitude SST anomaly in the NW Atlantic can have a significant and substantial downstream response

T N Palmer (1994): Chaos and Predictability in Forecasting the Monsoons

Introduction of fixed normalized forcing in Lorenz model shows that monsoon has a chaotic component

ENSO can change the frequencies of active and break cycles during the Asian summer monsoon season

Palmer, T. N., & Mansfield, D. A. (1986). A study of wintertime circulation anomalies during past El Niño events using a high resolution general circulation model. I: Influence of model climatology. Quarterly Journal of the Royal Meteorological Society, 112(473), 613-638 (P&M1) and 639-660 (P&M2)

- **P&M1:** response over US (and downstream) to an Rasmusson Carpenter ENSO SST anomaly depends critically on the parametrization of sub-grid orography. Here we used envelope orography as a way to reduce the westerly bias in the model. I subsequently worked on orographic gravity wave drag as an alternative way of parametrizing sub-grid orography.

- **P&M1:** Top ENSO response in UKMO model with envelope orography (pre gravity wave drag days). Middle ENSO response in model with mean orography.

- **P&M1:** Notice how different the responses are over the US.

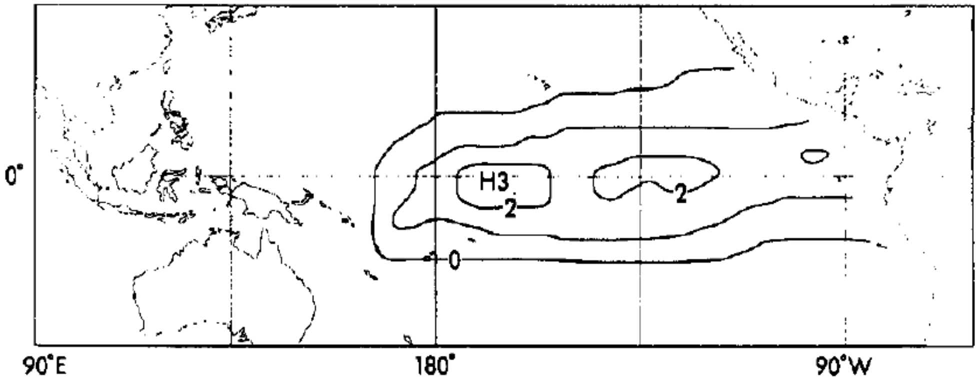
- **P&M2:** Showing how the response to a weak SST anomaly in the western Pacific can be as large as a much larger SST anomaly in the eastern Pacific (639-660)

- ***$\delta(\mathrm{SST}) \rightarrow \delta(Q)$ depends upon: T, δT, and location of δT wrt large scale flow***

- **Predictability of seasonal variations will depend on the fidelity of the model in simulating the mean circulation**

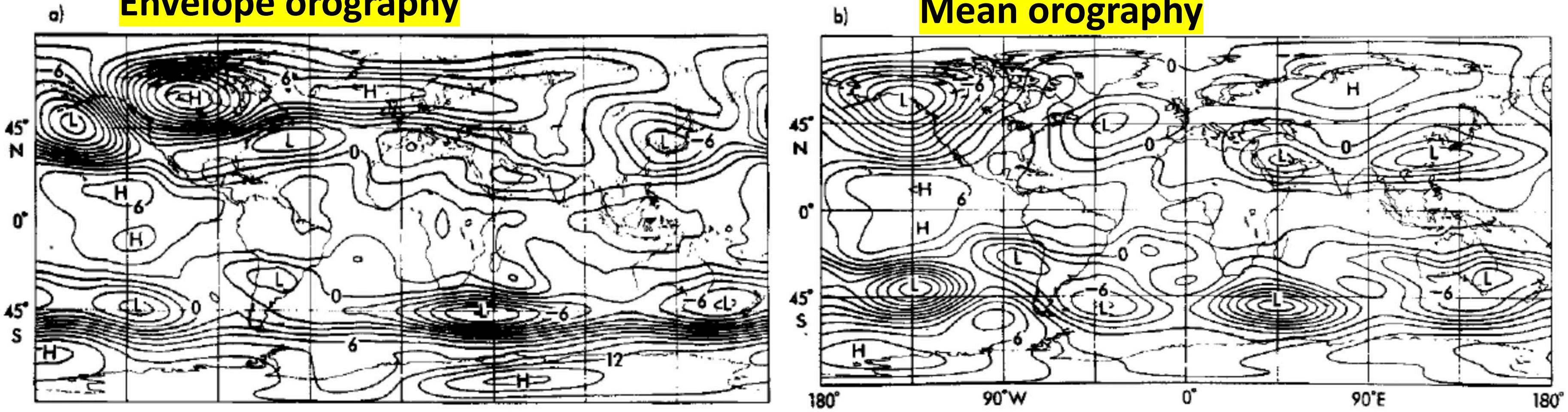
Palmer and Mansfield (1986, QJRMS pp 613 – 638)

ENSO response in UKMO model with mean and envelope orography (pre gravity wave drag days). (Note large difference in response over the US)



Rasmussen and Carpenter
Composite ENSO SST anomaly (x2)

250 mb geopotential height anomalies (contour interval 2 dam)



Envelope orography

Mean orography

Palmer, T. N., & Mansfield, D. A. (1986). A study of wintertime circulation anomalies during past El Niño events using a high resolution general circulation model. I: Influence of model climatology. Quarterly Journal of the Royal Meteorological Society, 112(473), 613-638. doi:10.1002/qj.49711247304

Palmer and Mansfield (1986 QJRMS pp 639 – 660)

The response to a **weak** SST anomaly in the **western Pacific** can be as large as a much **larger** SST anomaly in the **eastern Pacific**

654 T. N. PALMER and D. A. MANSFIELD

SSTA

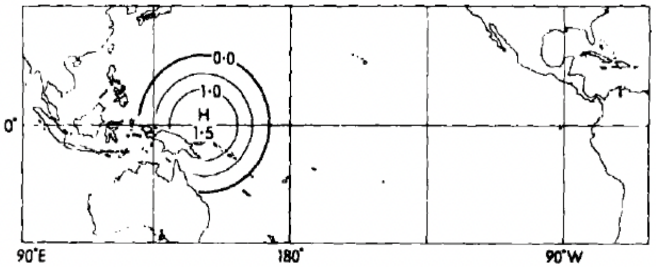
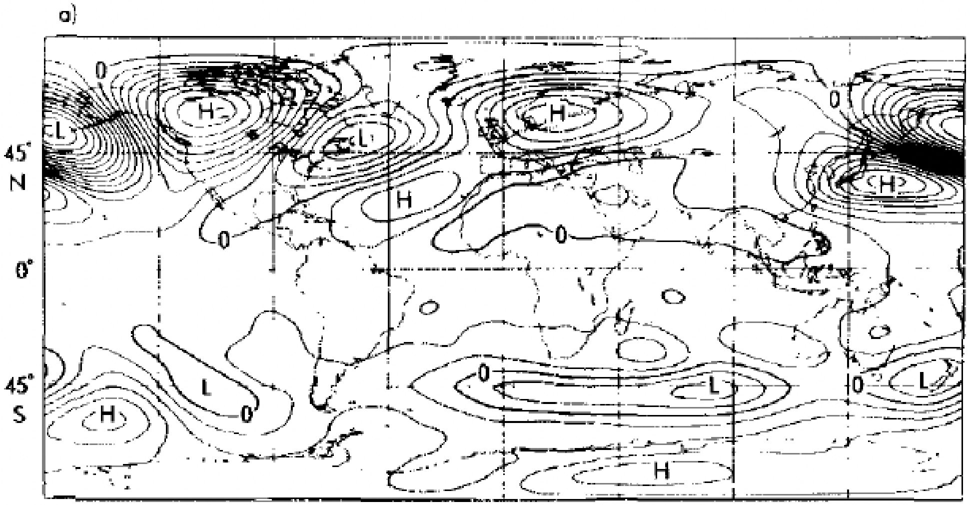
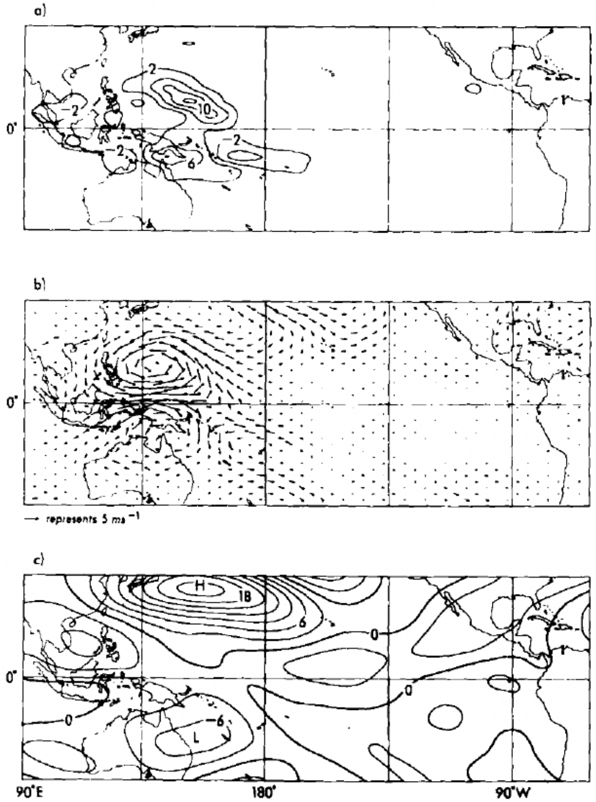


Figure 15. West Pacific sea surface temperature anomaly used in WP_e. Contour interval 0·5 K. Area as in Fig. 6.



250 mb streamfunction anomaly



Rainfall anomaly

850 mb wind anomaly

Figure 16. (a) Rainfall anomaly, (b) 850 mb wind anomaly and (c) 250 mb streamfunction anomaly for WP_e. (a) Contour interval 4 mm d^{-1}, first contour at ±2 mm d^{-1}; (b) arrow below bottom left-hand corner relates wind speed to arrow length; (c) contour interval 2×10^6 m^{2}s^{-1}. Area as in Fig. 6.

Folland, C. K., Palmer, T. N., & Parker, D. E. (1986). Sahel rainfall and worldwide sea temperatures, 1901-85. Nature, 320(6063), 602-607. doi:10.1038/320602a0

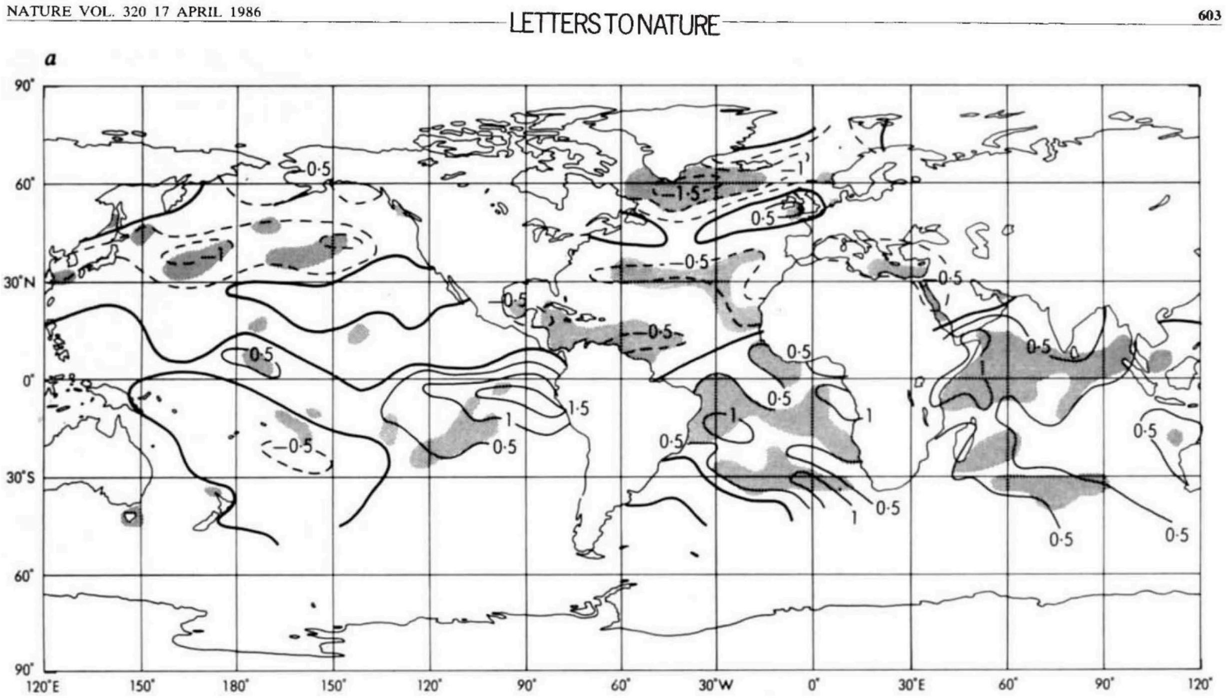
- Showing decadal timescale SST anomalies associated with the Sahel drought, and the response of the UKMO model to these SST anomalies. This rather undermined the Charney hypothesis that the drought was caused by overgrazing, though overgrazing may have exacerbated the drought

- The Sahel drought in the 1970s and 1980s was likely caused by global-scale decadal SST anomalies. The companion paper showed that each ocean basin contributed to the Sahel drought

Folland, Palmer, and Parker (1986)

GCM experiments with prescribed SST anomaly

SST of dry Sahel (1972 – 73, 82 – 84) minus SST of wet Sahel (1950, 1952 – 54, 1958)



NATURE VOL. 320 17 APRIL 1986 LETTERS TO NATURE 603

Contour interval 0.5 °C

Fig,2 a, SST, July to September: average of (1972-73,1982-84) (Sahel dry) minus average of (1950, 1952-54, 1958) (Sahel wet). Contours every 0.5°C. Shaded areas are different from zero at the 90% level of significance according to a t-test

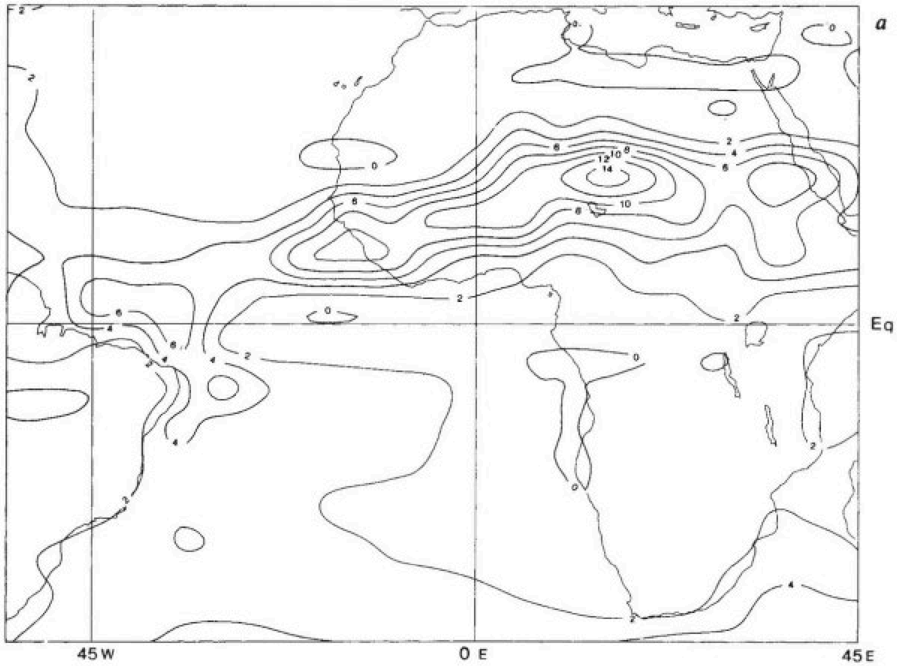
Sahel rainfall and worldwide sea temperatures, Nature, 1901-85 C. K. Folland, T. N. Palmer & D. E. Parker

Folland, Palmer, and Parker (1986)

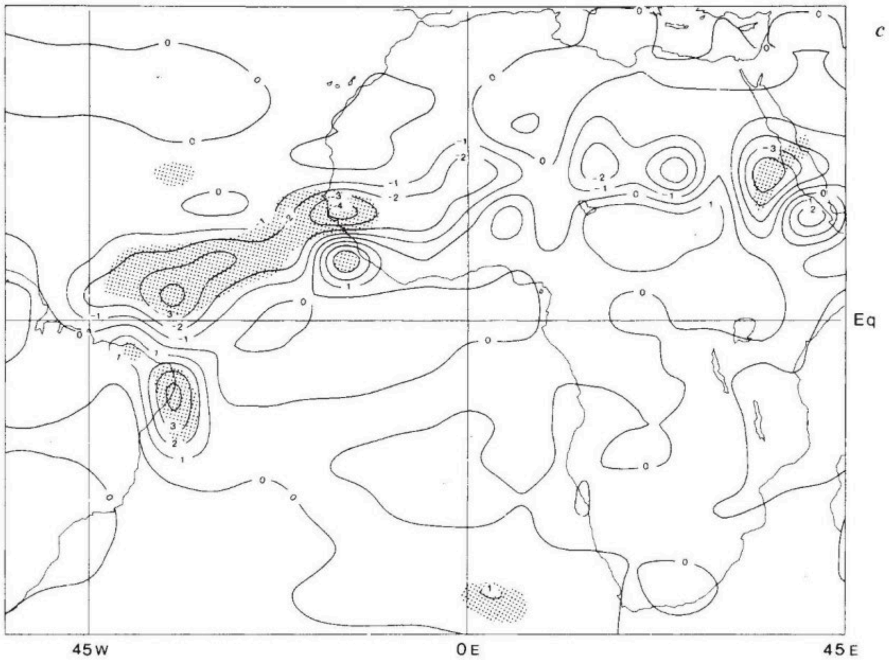
GCM experiments with SST of dry Sahel (1972 – 73, 82 – 84) minus SST of wet Sahel (1950, 1952 – 54, 1958)

The Sahel drought in the 1970s and 1980s was likely caused by global-scale decadal SST anomalies. The companion paper (Palmer 1986) showed that each ocean basin contributed to the Sahel drought.

Mean rainfall for control run (mm/day)



Anomaly minus control run (mm/day)



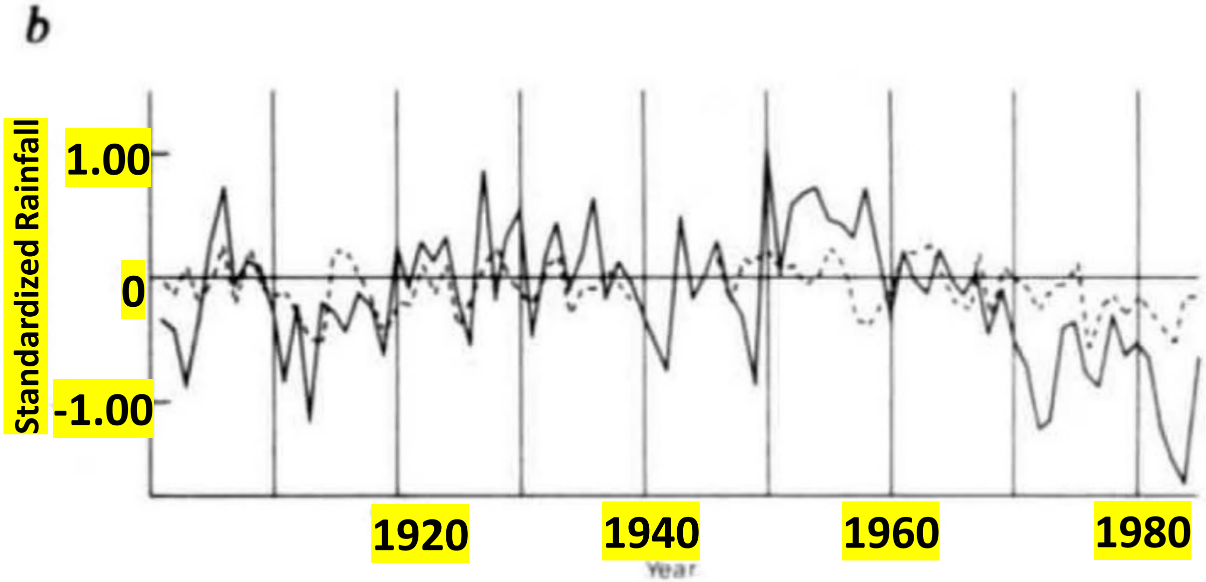
Sahel rainfall and worldwide sea temperatures, Nature, 1901-85 C. K. Folland, T. N. Palmer & D. E. Parker

Folland, Palmer, and Parker (1986)

Note the decadal timescale SST and rainfall anomalies associated with the Sahel drought

Observed (--) and simulated (- -) Sahel rainfall by UKMO Model with Prescribed SST Anomalies for 1901-1985

SST anomaly: SST of dry Sahel (1972 – 73, 82 – 84) minus SST of wet Sahel (1950, 1952 – 54, 1958)



Similarity of observed and simulated rainfall variability undermined the Charney hypothesis that the drought was caused by overgrazing, though overgrazing may have exacerbated the drought.

(In a later paper, Palmer showed the contributions of each ocean basin)

Sahel rainfall and worldwide sea temperatures, Nature, 1901-85 C. K. Folland, T. N. Palmer & D. E. Parker

A modelling and observational study of the relationship between sea surface temperature in the North-West Atlantic and the atmospheric general circulation T. N. Palmer, Sun Zhaobo Q.J.Roy. Met. Soc. https://doi.org/10.1002/qj.49711147003

- **Showing how a mid-latitude SST anomaly in the NW Atlantic can have a significant and substantial downstream response.**

Tim Palmer and Sun Zhaobo (1985)

Numerical experiments with positive and negative SSTA added to climatological SST; inspired by Ratcliffe and Murray (1970) observational study of relationship between SSTA over North-West Atlantic and surface pressure over Atlantic and Europe

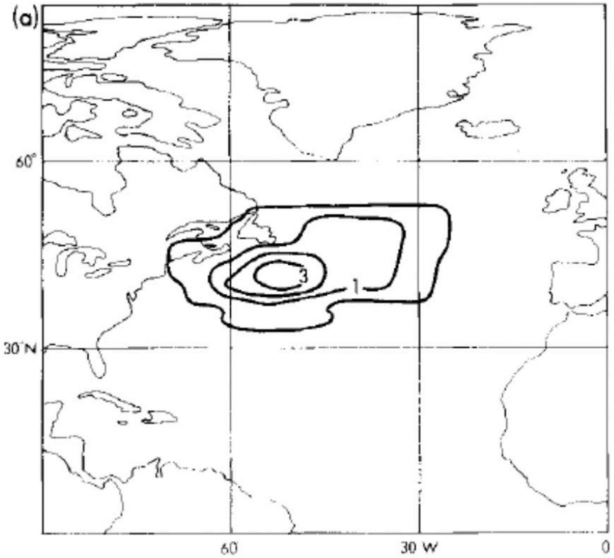


Figure 1. (a) Full s.s.t. anomaly (K) used for the model integrations; (b) s.s.t. with this anomaly added to climatological values (°C); (c) s.s.t. with this anomaly subtracted from climatological values (°C).

Based on GCM experiments, observational study, simple two-layer model, and ocean mixed layer model, the paper showed that both momentum and thermal forcing by anomalous baroclinic wave activity can produce downstream response

The numerical experiments confirmed that a mid-latitude SST anomaly in the NW Atlantic can have a significant and substantial downstream response.

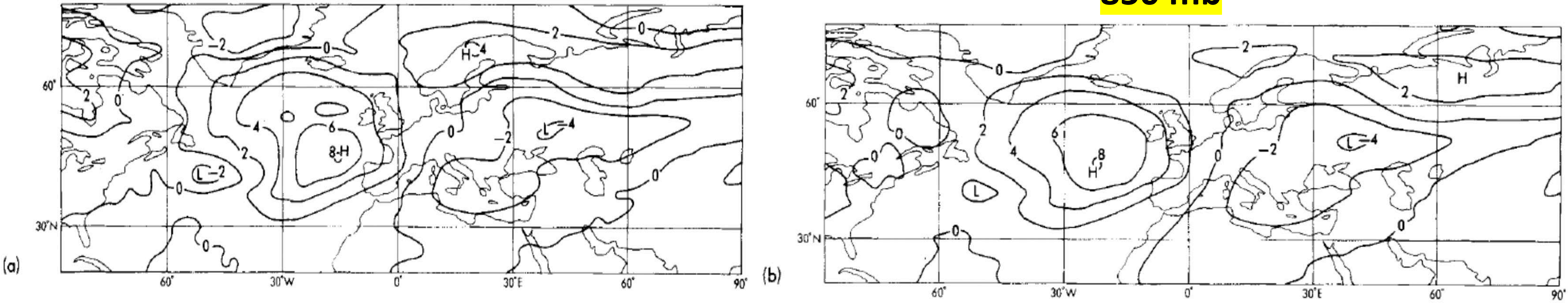
A modelling and observational study of the relationship between sea surface temperature in the North-West Atlantic and the atmospheric general circulation T. N. Palmer, Sun Zhaobo Q.J.Roy. Met. Soc. https://doi.org/10.1002/qj.49711147003

Palmer and Sun Zhaobo (1985)

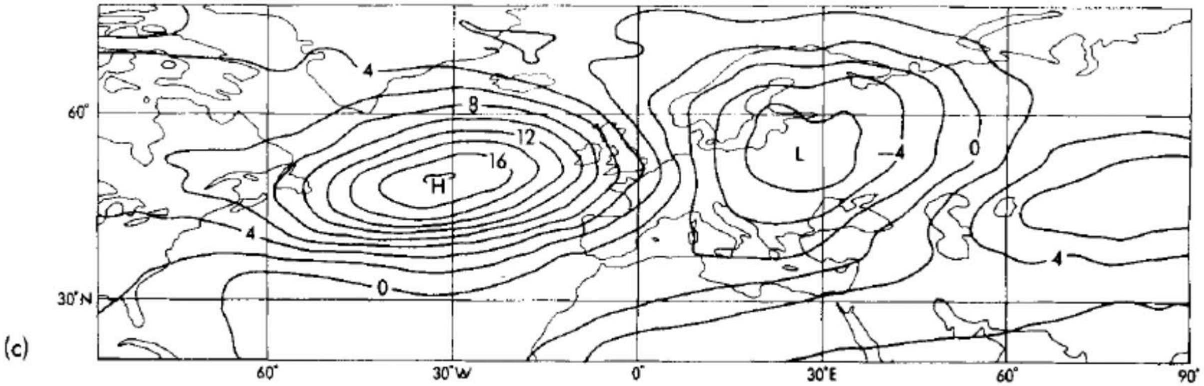
Geopotential height difference (dam), averaged over the four pairs of integrations

1000 mb

850 mb



250 mb



A modelling and observational study of the relationship between sea surface temperature in the North-West Atlantic and the atmospheric general circulation T. N. Palmer, Sun Zhaobo Q.J.Roy. Met. Soc. https://doi.org/10.1002/qj.49711147003

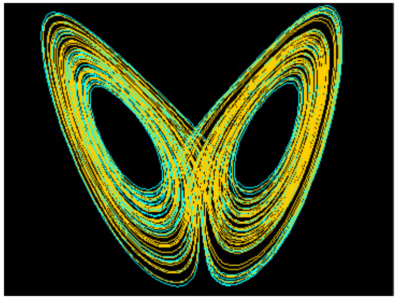
Palmer (1994): Chaos and Predictability in Forecasting the Monsoons, Proceedings of the National Academy of Sciences, 60, pp 57-66

- To study prediction of the second kind some fixed normalized “forcing” into the Lorenz equation was introduced. It showed that the monsoon has a chaotic component.

Lorenz Model

It is one of the simplest forced dissipative nonlinear systems.

X, Y, Z: Dynamical variables; r: Forcing; σ, b: Dissipation



Lorenz (1963)

$$\frac{dX}{dt} = -\sigma X + \sigma Y$$

$$\frac{dY}{dt} = -XZ + rX - Y$$

$$\frac{dZ}{dt} = XY - bZ$$

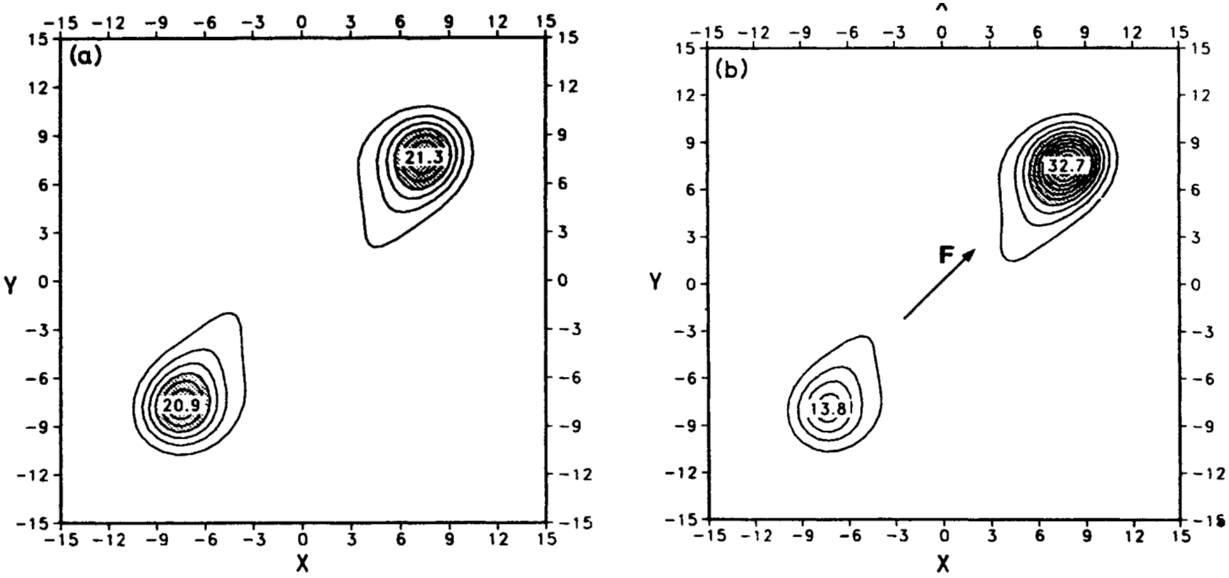
Palmer (1994)

$$\frac{dX}{dt} = -\sigma X + \sigma Y + \alpha F_x$$

$$\frac{dY}{dt} = -XZ + rX - Y + \alpha F_y$$

$$\frac{dZ}{dt} = XY - bZ + \alpha F_z$$

PDF of the Lorenz model, low-pass filtered to remove oscillations around a regime centroid



Unforced Model

Constant Forcing in the X-Y plane

Note: PDF is symmetric for no forcing; and asymmetric with forcing

Current Status of Dynamical Seasonal Prediction

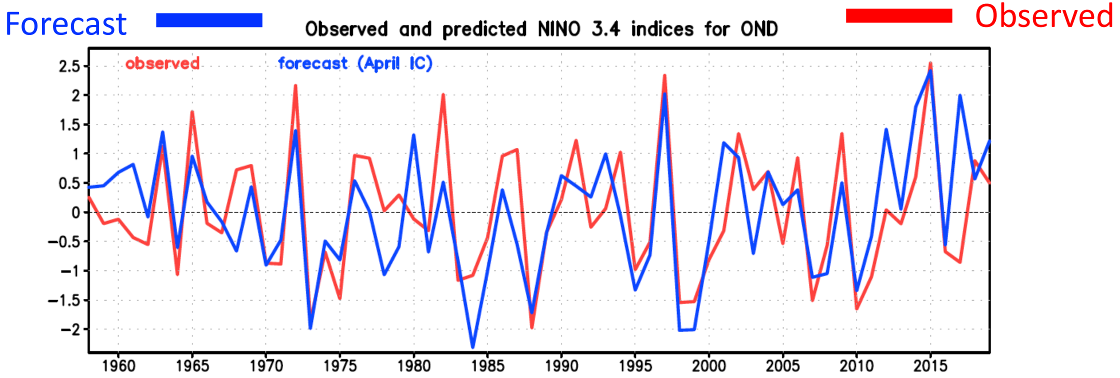
- In spite of large biases *(as large as the ENSO signal)*, the coupled ocean atmosphere models have shown significant skill in Nino 3.4 hindcasts. However, the skill of predicting remote responses is highly variable.

- The skill of Nino 3.4 predictions is systematically decreasing during the past 10 to 15 years

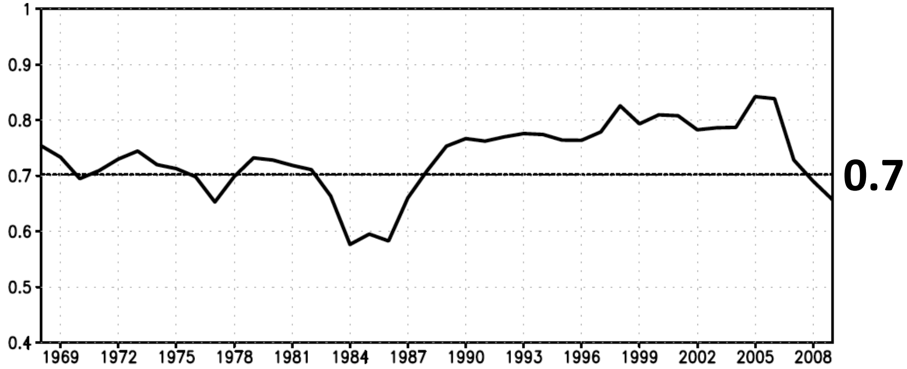
- Is it climate modeler's good luck that the evolution of the systematic model errors does not interact with ENSO signal? WHY?

Reforecasting Nino 3.4 in the Past 62 Years (1958-2019): CFSv2

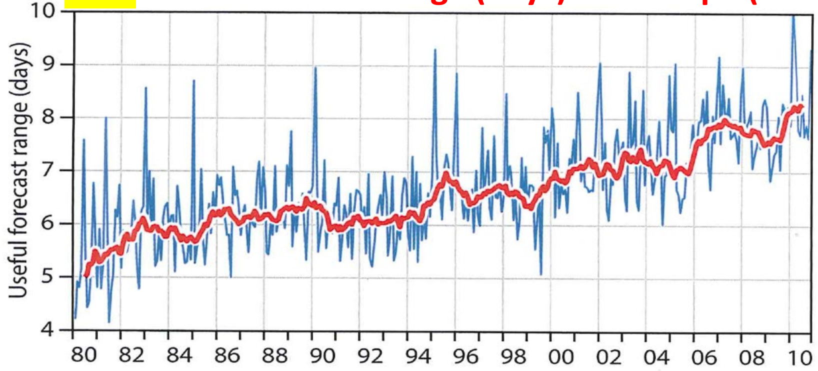
Obs. and Forecast Winter (OND) Tropical SST (Nino 3.4) (April IC)



21 year running mean ACC (0.7 - 0.8)



ECMWF: MRF useful forecast range (days) for Europe (1980 – 2010)



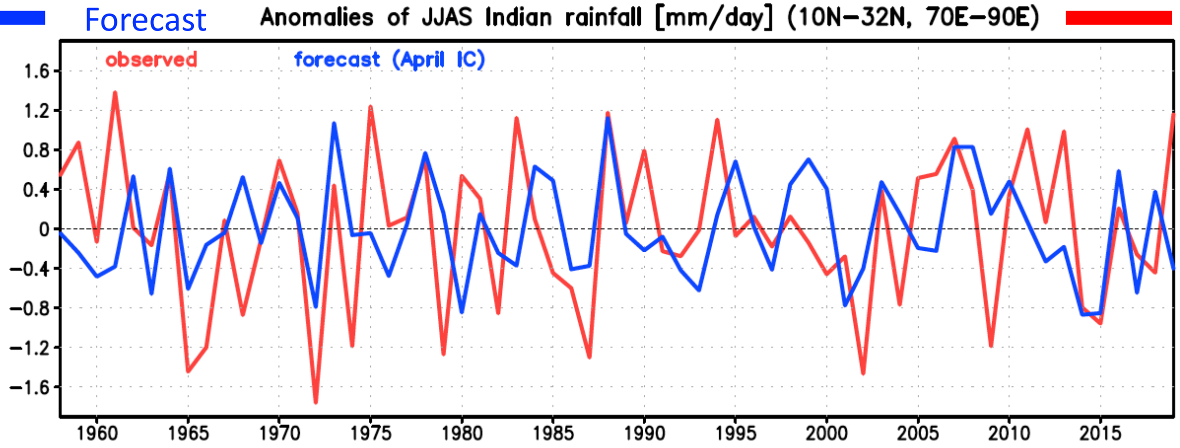
Obs. and Forecast JJAS Precip. Anom., India (10-32N, 70-90E)

🟦 Forecast

🟥 Observed

Prior to 1979

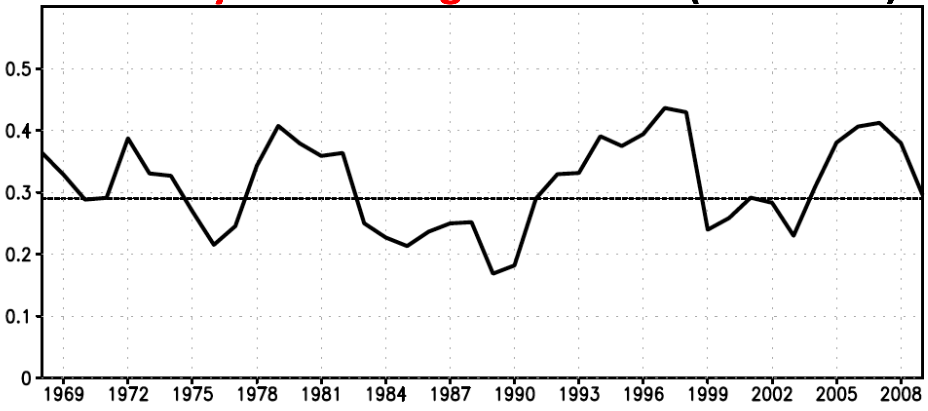
Obs. mean : 7.12 mm/d.
Fcst. mean : 4.60 mm/d.



After 1979

Obs. mean : 6.96 mm/d.
Fcst. mean : 4.67 mm/d.

21 year running mean ACC (0.25 - 0.4)

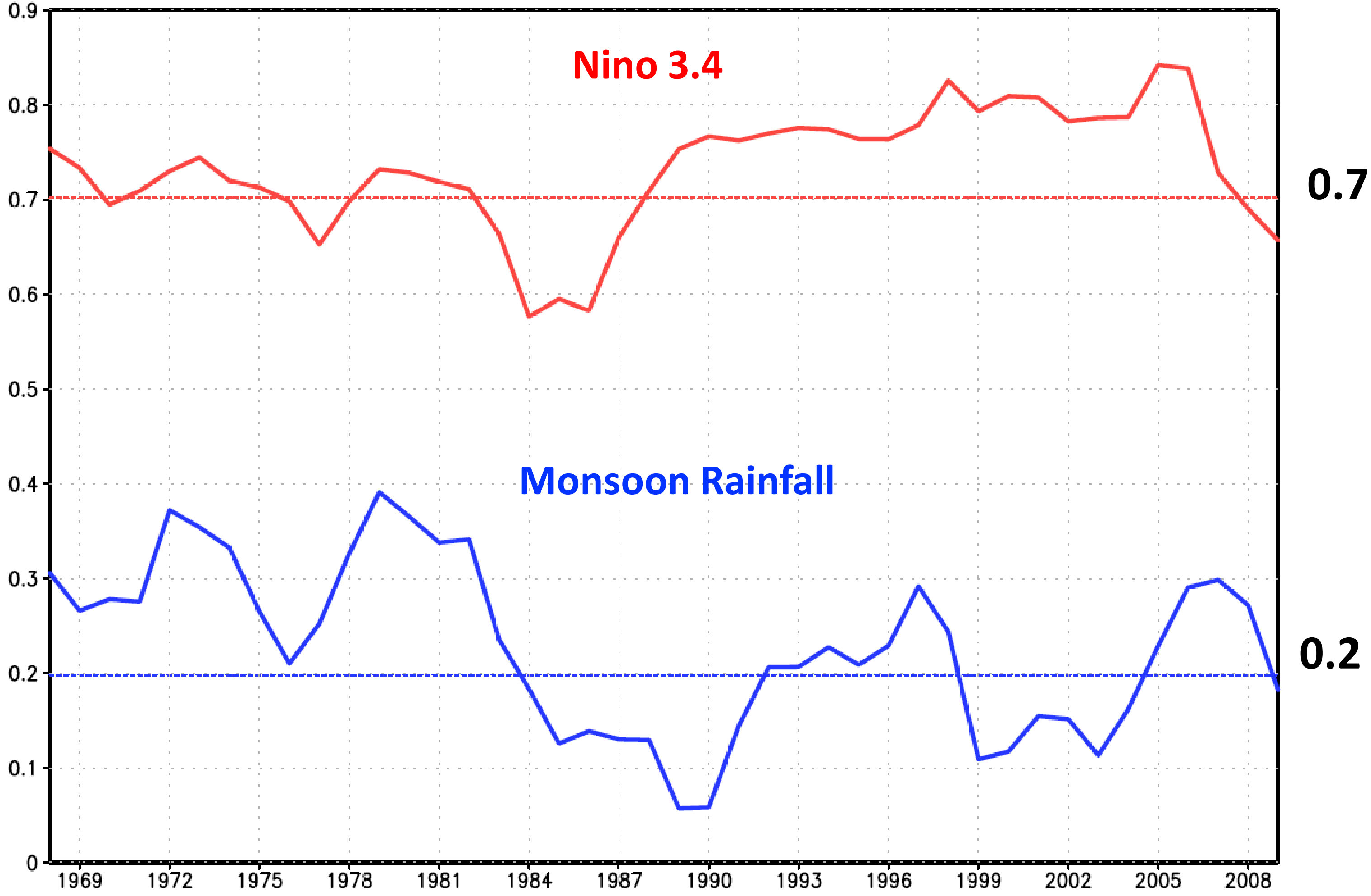


ACC=0.29 for 62 years

x-axis label indicates a center year of 21-yr time window

22 Year Running Mean ACC for Nino 3.4 and Indian Monsoon Rainfall

(1958 – 2019, CFSv2)



Outline

- Introduction
- Tim's Early Career
- Selected Papers by Tim and UKMO colleagues
- Billion Butterflies Experiment
- International Programs
  - WCRP/JSC; MONEG; IAP (India)
  - World Modeling Summit; Climate CERN
  - Visiting India and my village

World Modeling Summit at ECMWF (6-9 May 2008)

Nearly 150 participants from all modeling centers of the world

They say they want a revolution *(Nature, May 2008)*

Climate scientists call for major new modelling facility.

Climatologists have called for massive investment in computer and research resources to help revolutionize modelling capabilities. The eventual aim is to provide probabilistic climate predictions that are as

weather forecasts.

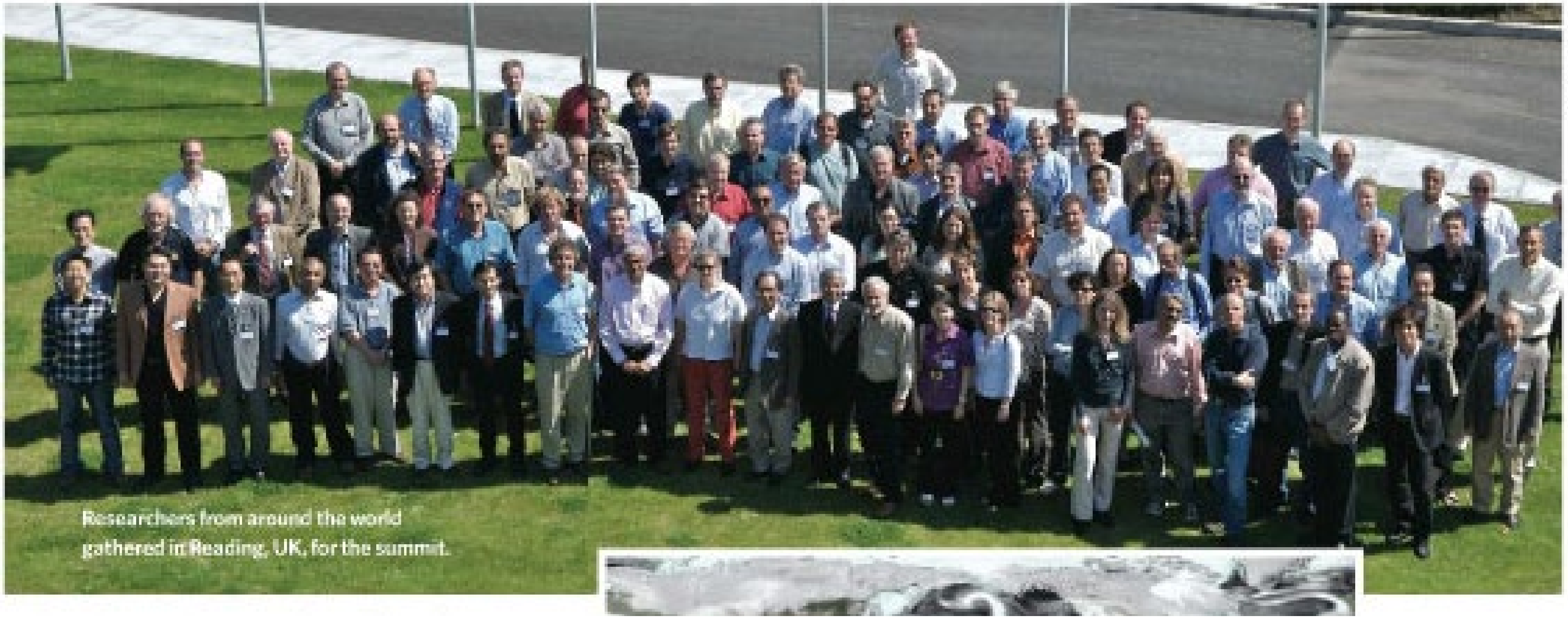
At the end of a four-day
at the European Centre
Weather Forecasts in Rea
made the case for a clima
on the scale of the Huma
key component of this s
cost something up to, o
lars, would be a world cli

— to speeds in the hundreds of petaflops — would allow modellers to study simulations at the kilometre scale, enabling better predictions on the activity of hurricanes and, eventually,

Shukla, J., R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, T.N. Palmer, and J. Slingo,

2009: Revolution in climate Prediction is Both Necessary and Possible: A Declaration at the World Modelling Summit for Climate Prediction (BAMS)

2010: Towards a New Generation of World Climate Research and Computing Facilities. (BAMS)



Researchers from around the world gathered in Reading, UK, for the summit.

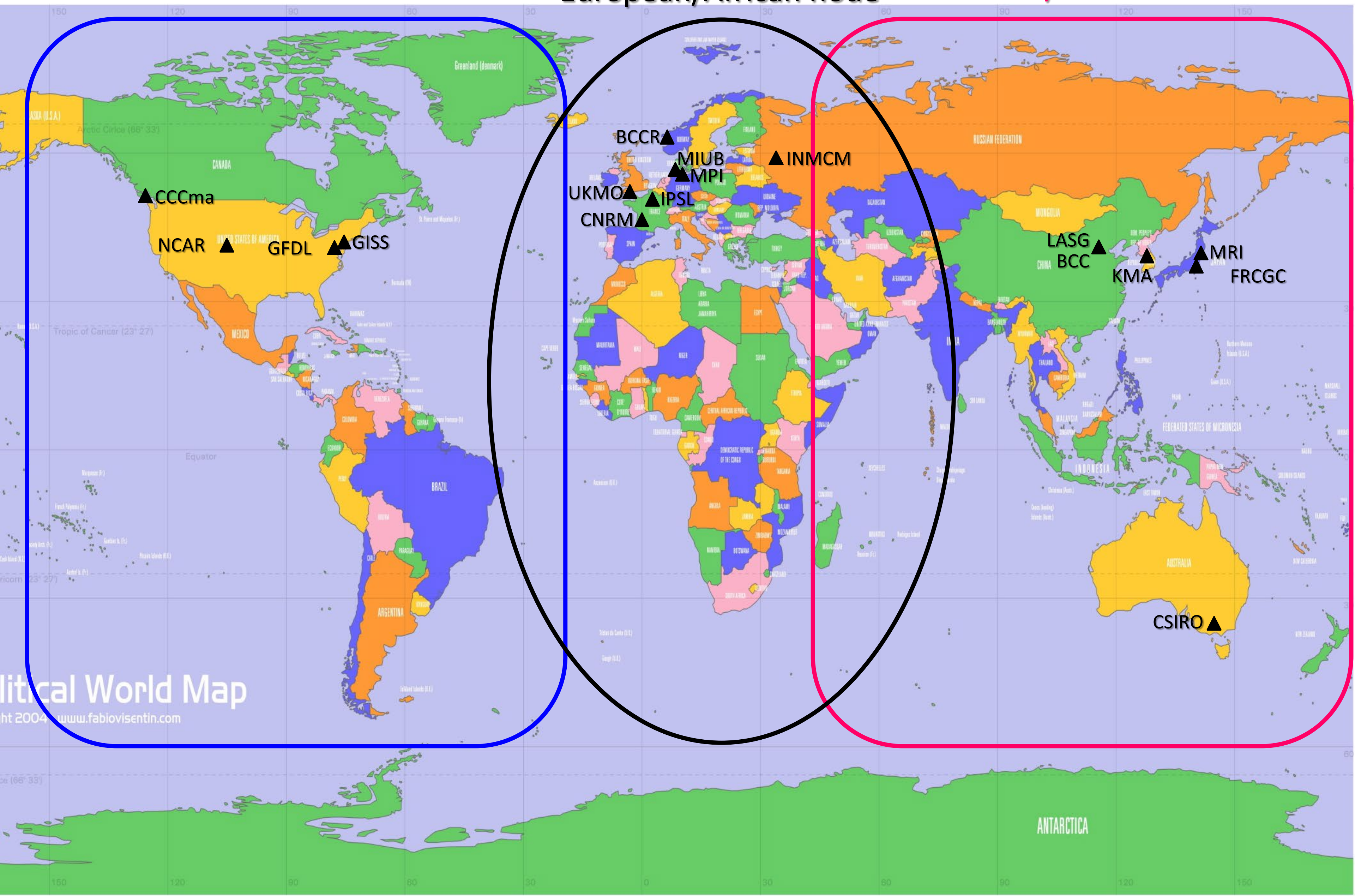
Center of Ocean-Land-
Atmosphere studies

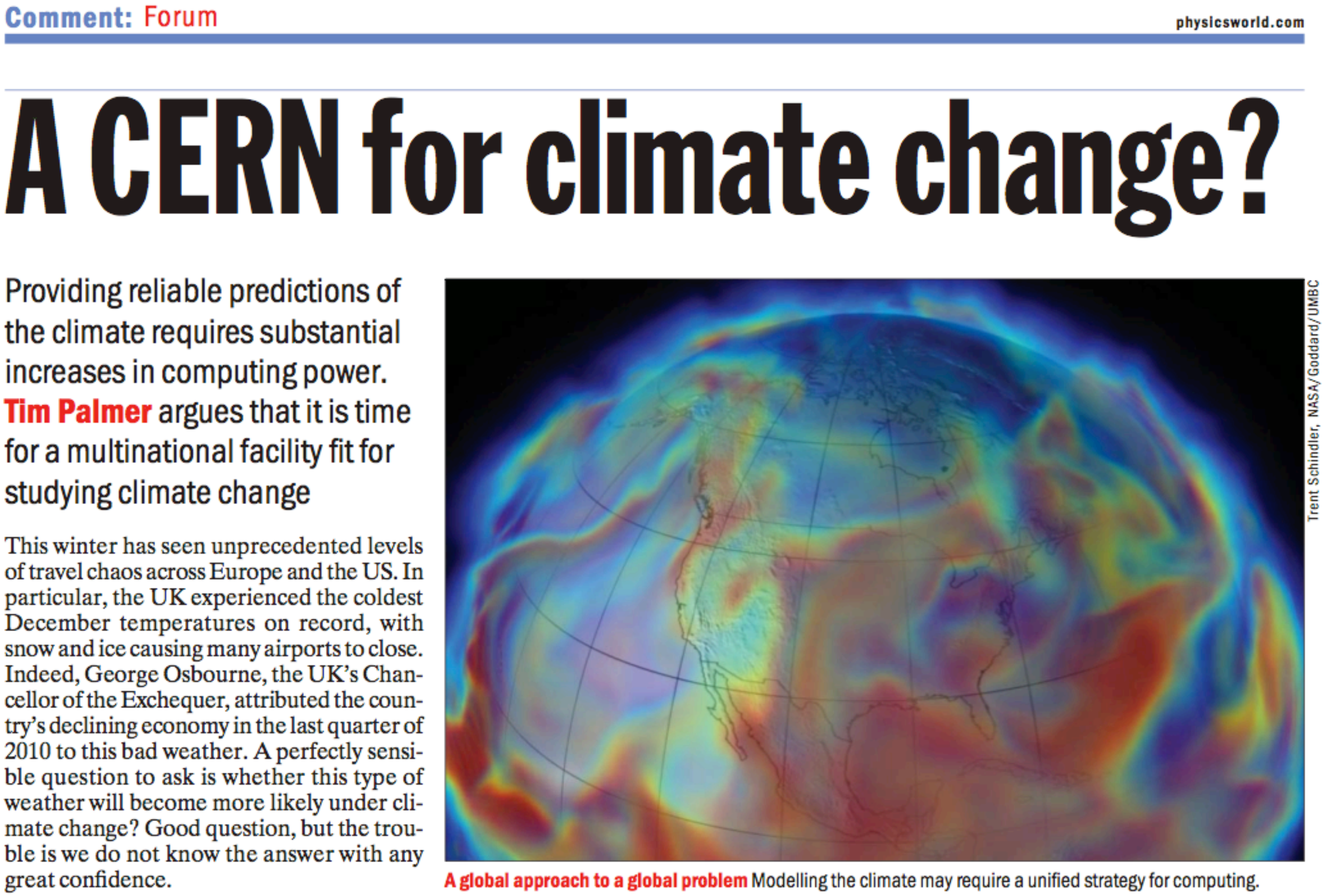
Hypothetical Scientific/Political Domains of Climate Modeling Facilities

American node

European/African node

Asian/Australian node





Comment: Forum

physicsworld.com

A CERN for climate change?

Providing reliable predictions of the climate requires substantial increases in computing power. **Tim Palmer** argues that it is time for a multinational facility fit for studying climate change

This winter has seen unprecedented levels of travel chaos across Europe and the US. In particular, the UK experienced the coldest December temperatures on record, with snow and ice causing many airports to close. Indeed, George Osbourne, the UK's Chancellor of the Exchequer, attributed the country's declining economy in the last quarter of 2010 to this bad weather. A perfectly sensible question to ask is whether this type of weather will become more likely under climate change? Good question, but the trouble is we do not know the answer with any great confidence.

A global approach to a global problem Modelling the climate may require a unified strategy for computing.

Trent Schindler, NASA/Goddard/UMBC

In Physics World by Tim Palmer

Tim’s Visit to India


WEL COME

Four Rossby Medal Winners go to an Indian Temple:

What did God say?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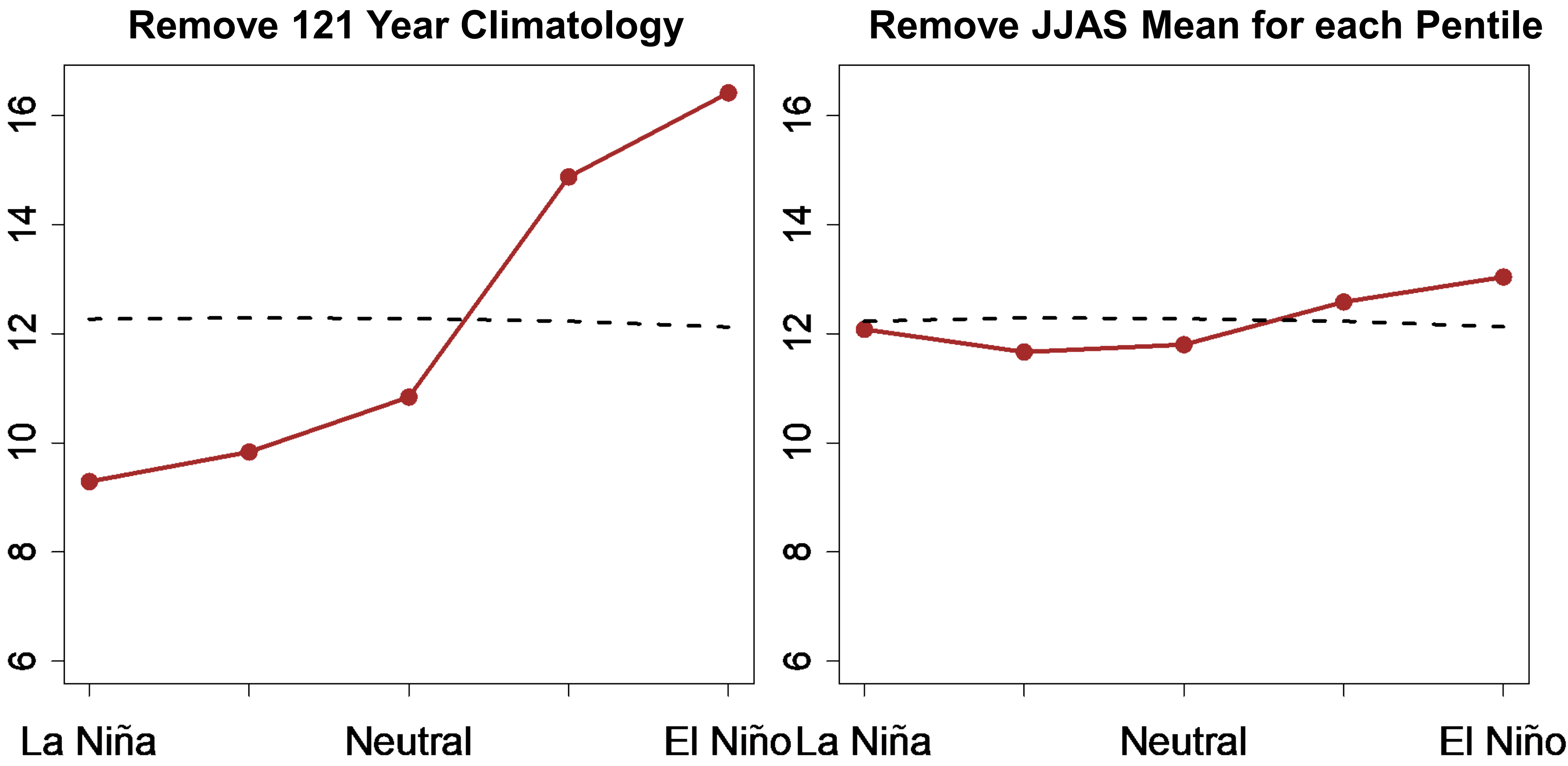
THANK YOU!

ANY QUESTIONS?

Average Break day Count (JJAS)

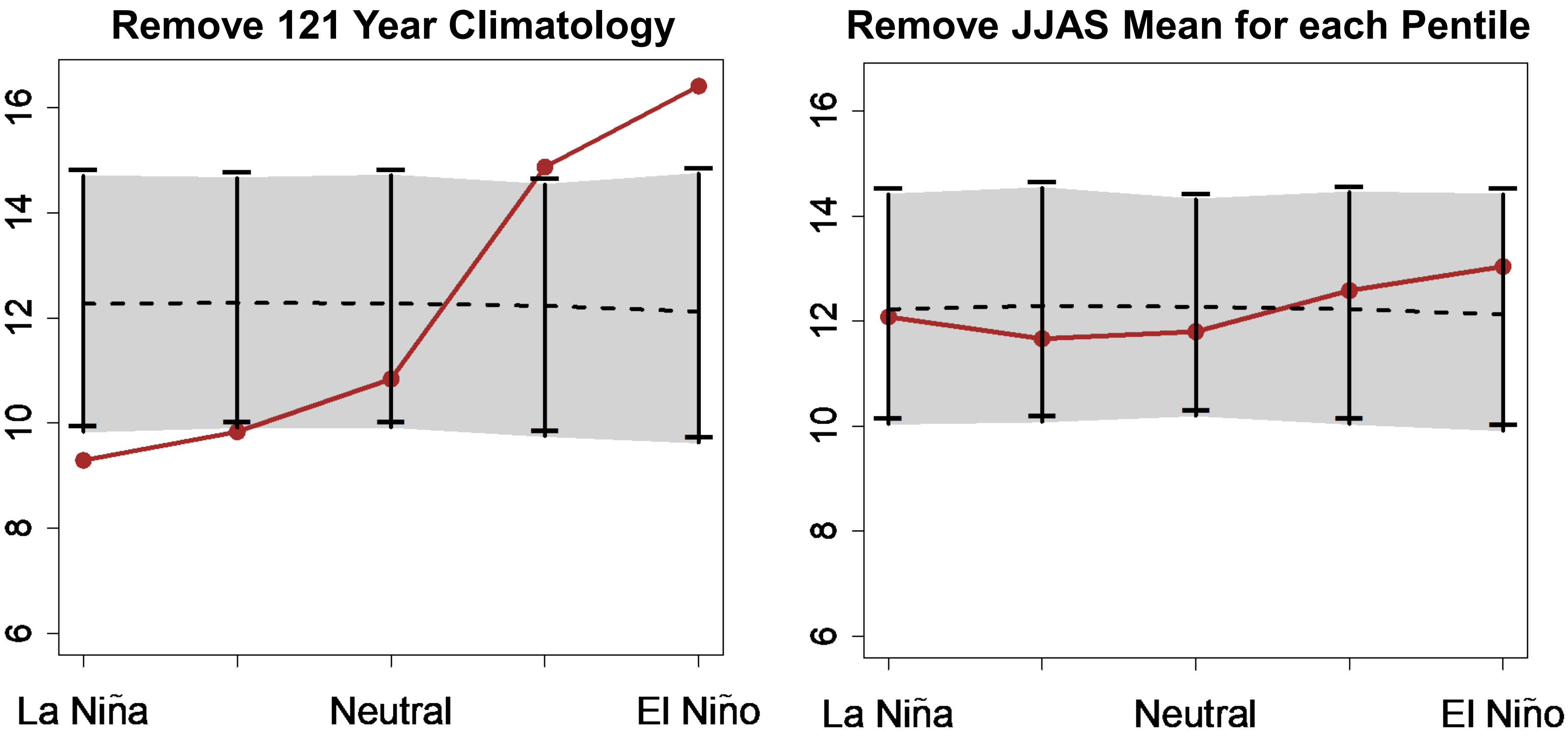
If seasonal mean rainfall is removed, there is no difference in the break day counts during El Nino and La Nina



(Monsoon Core Zone Average)

Average Break day Count (JJAS)

If seasonal mean rainfall is removed, there is no difference in the break day counts during El Nino and La Nina

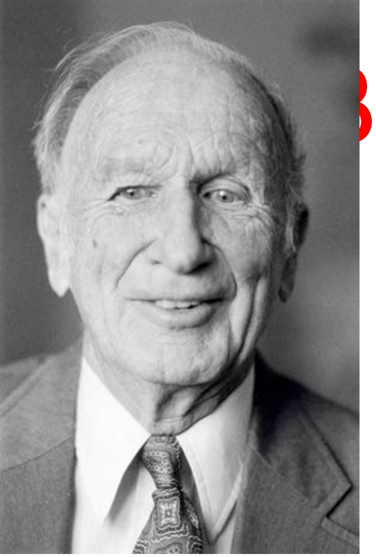


Remove 121 Year Climatology

Remove JJAS Mean for each Pentile

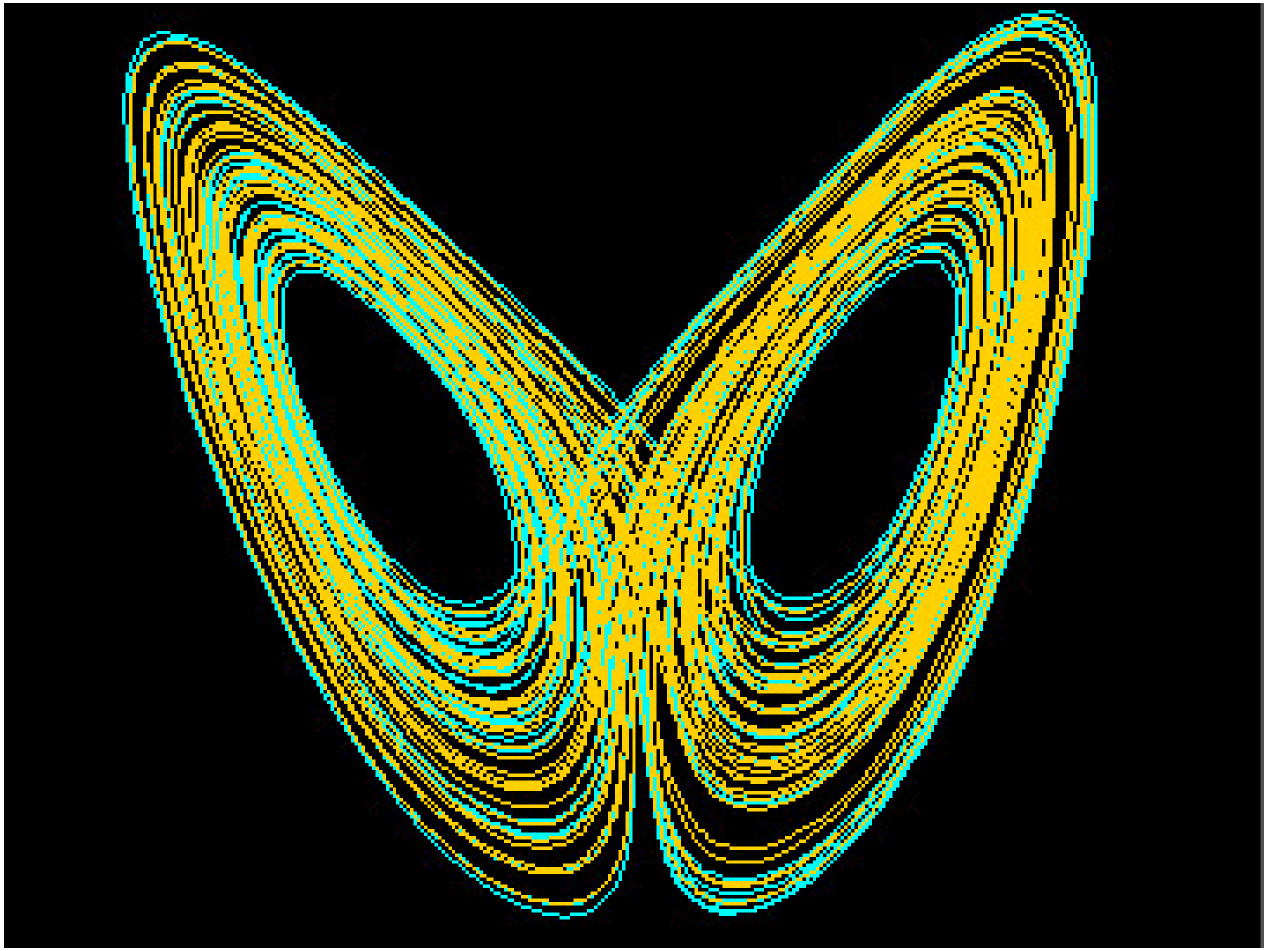
Bootstrapping (1,000 times), 90% confidence

(Monsoon Core Zone Average)

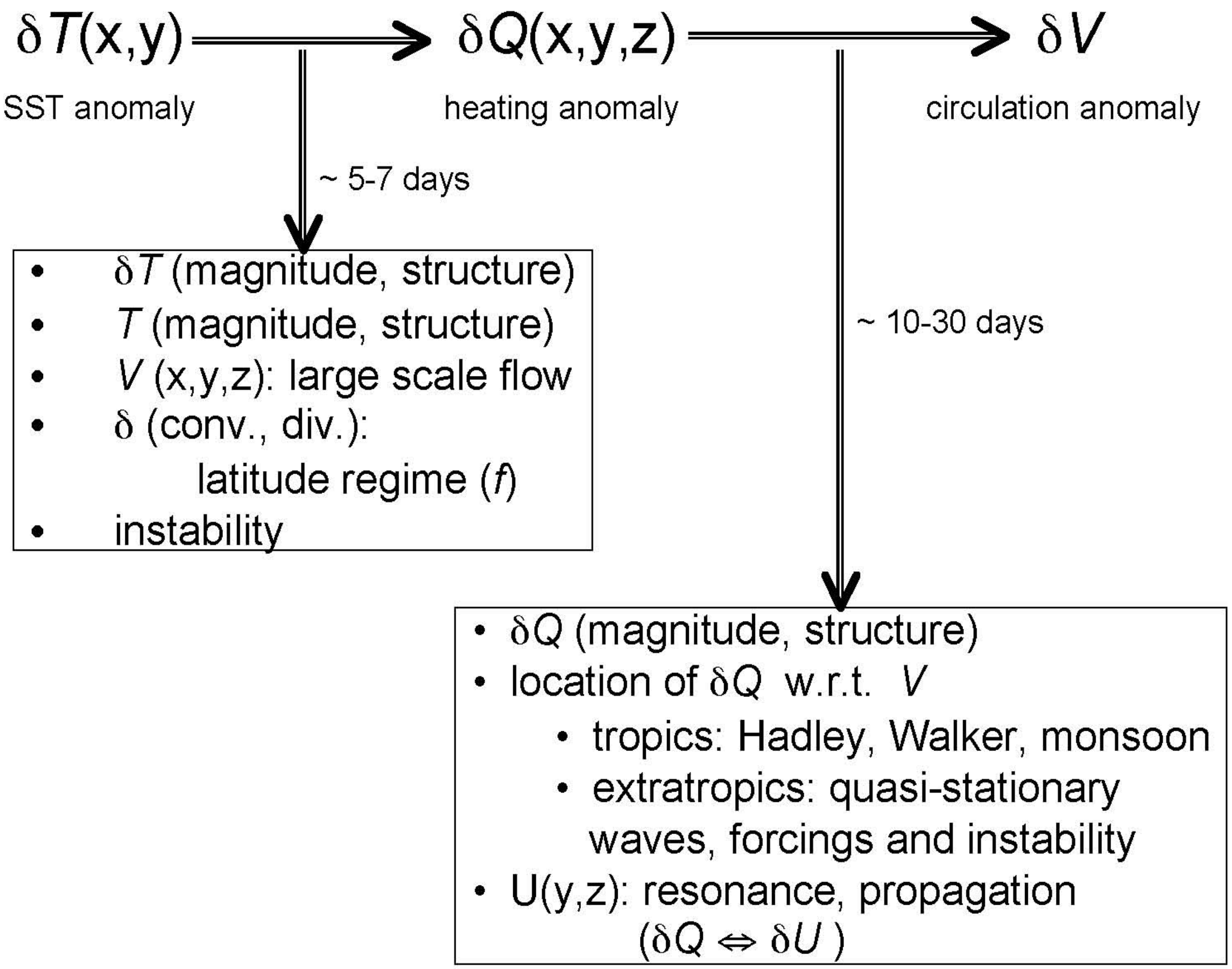


Butterfly Effect

Chaos: Sensitive Dependence on Initial Conditions



Effects of SST Anomaly



$\delta T(x,y) \rightarrow \delta Q(x,y,z) \rightarrow \delta V$

SST anomaly

heating anomaly

circulation anomaly

~ 5-7 days

- δT (magnitude, structure)
- T (magnitude, structure)
- V (x,y,z): large scale flow
- δ (conv., div.):
  latitude regime (f)
- instability

~ 10-30 days

- δQ (magnitude, structure)
- location of δQ w.r.t. V
  - tropics: Hadley, Walker, monsoon
  - extratropics: quasi-stationary waves, forcings and instability
- U(y,z): resonance, propagation
  ($\delta Q \Leftrightarrow \delta U$)

1. $\delta Q \Rightarrow \delta$(Hadley) $\Rightarrow \delta U \Rightarrow \delta$ (extratrop. stat. waves)
2. Forced Rossby waves
3. Normal modes

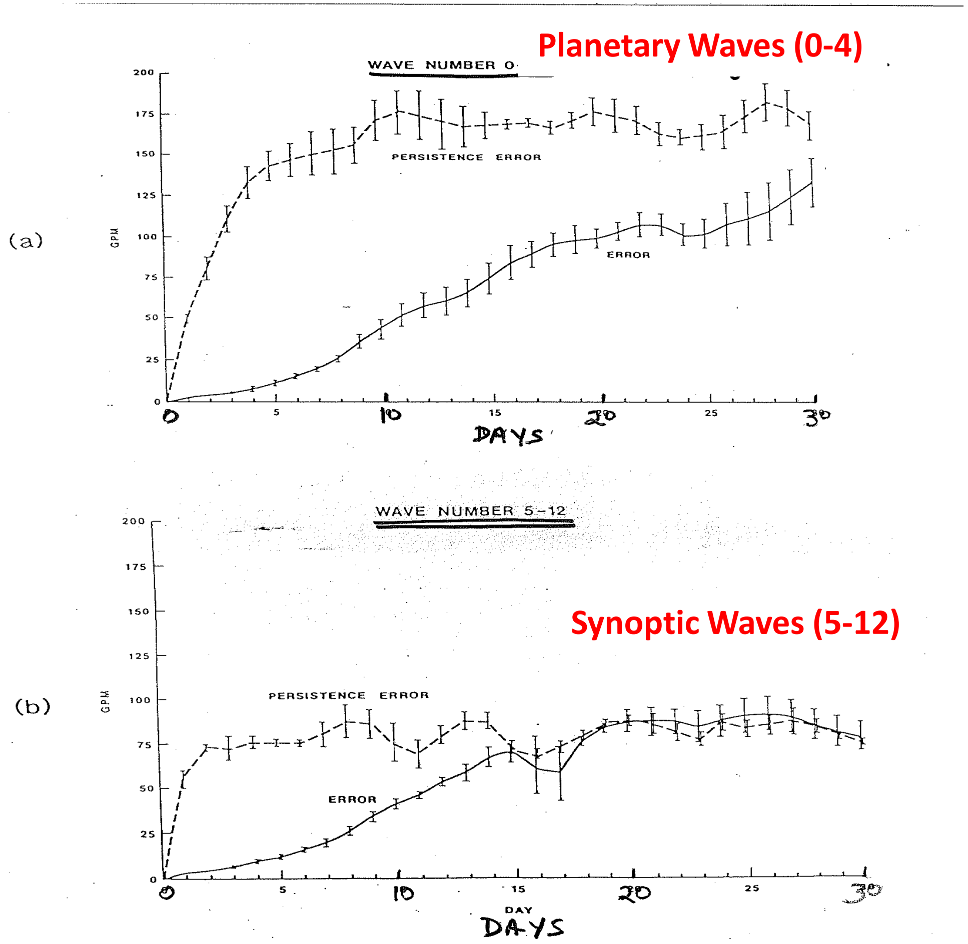
Dynamical Predictability: Beyond Weather

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



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

Bohua Huang[1], Chul-Su Shin[1], J. Shukla[1], Lawrence Marx[1], Magdalena A. Balmaseda[2], Subhadeep Halder[1], Paul Dirmeyer[1], James L. Kinter III[1] (2017, J of Climate)

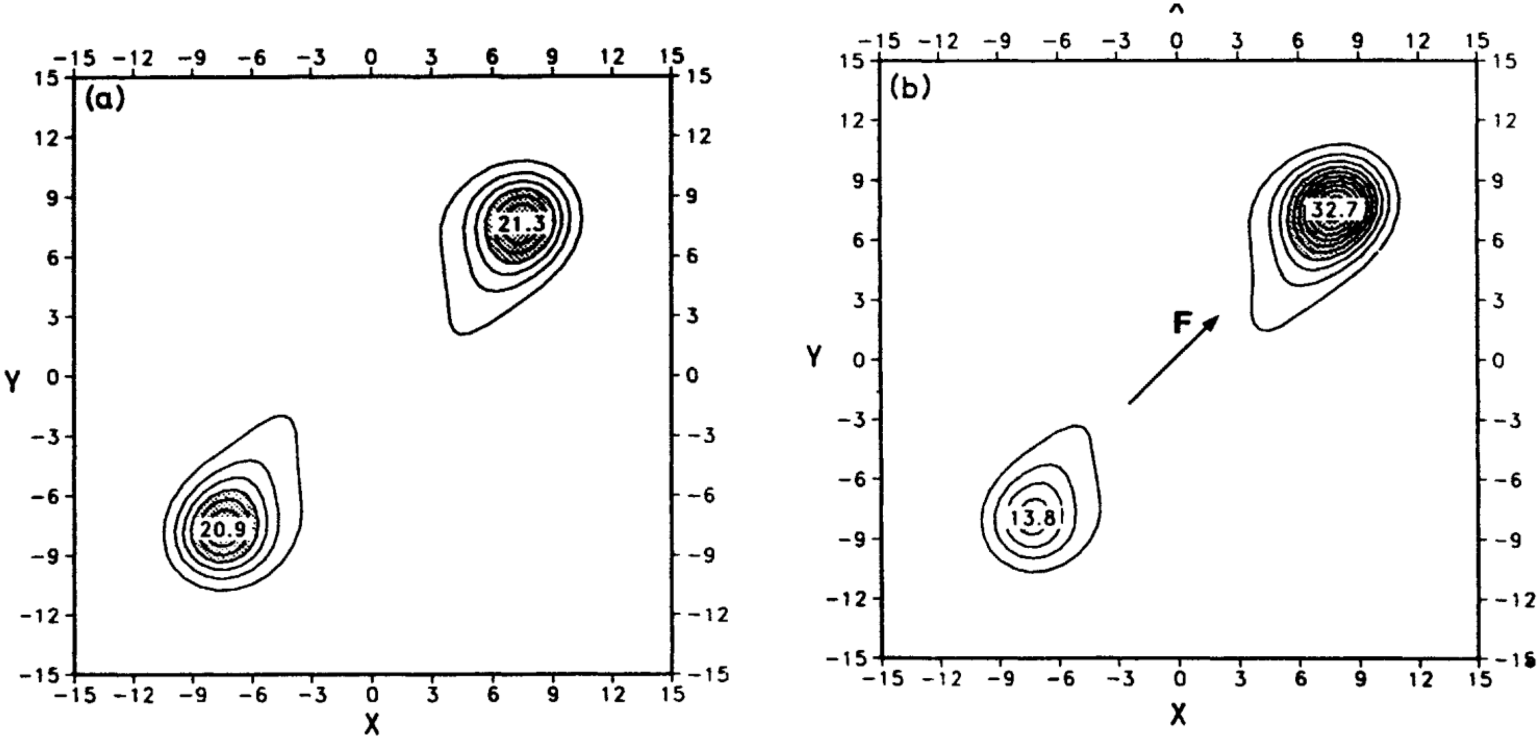
Initial Conditions (ICs)	**1958-1978**	**1979-2019**	
Atmosphere	**ERA-40**	**CFSR**	**4 members** (The first 4 days of each month)
Land	**NASA GLDAS2**		
Sea Ice	**CFSR** (January 1, 1979, April 1, 1979, July 1, 1979, October 1, 1980)		
Ocean	**ORA-S4**		**5 members***

* Perturbed through ocean data assimilation.

20 total ensemble members

Case study: ENSO/Monsoon of 1972-73, and 1997-98

Fig 2 Probability density function of the Lorenz model, low-pass filtered to remove oscillations around a regime centroid. *a*) from the unforced model. *b*) with a constant forcing in the X-Y plane pointing between the regimes.



Chaos and Predictability in Forecasting the Monsoons T N Palmer (1994)

Showing how a mid-latitude SST anomaly in the NW Atlantic can have a significant and substantial downstream response.

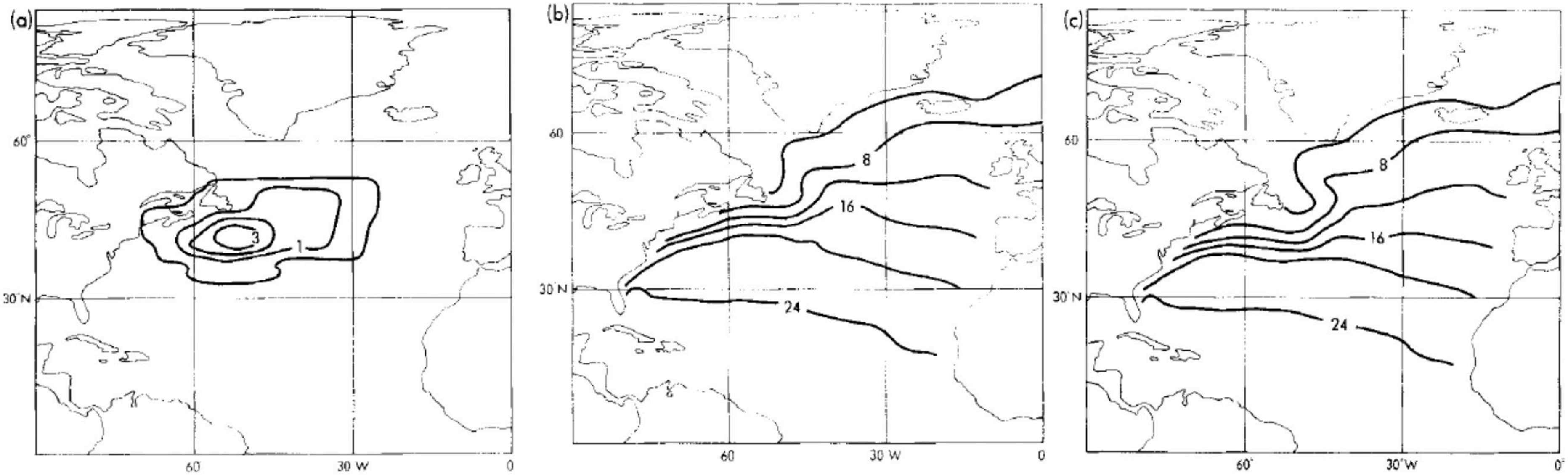
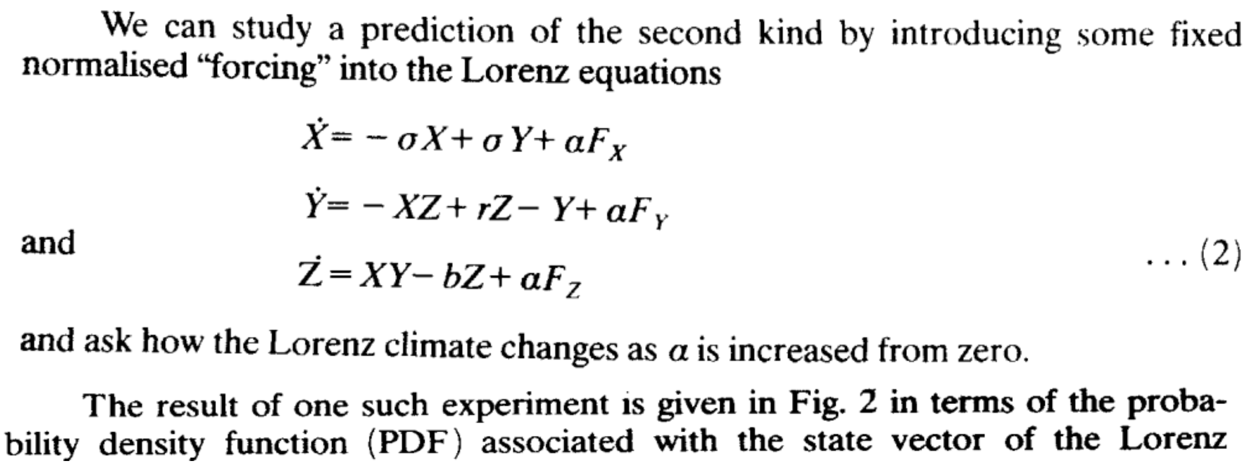


Figure 1. (a) Full s.s.t. anomaly (K) used for the model integrations; (b) s.s.t. with this anomaly added to climatological values (°C); (c) s.s.t. with this anomaly subtracted from climatological values (°C).

A modelling and observational study of the relationship between sea surface temperature in the North-West Atlantic and the atmospheric general circulation T. N. Palmer, Sun Zhaobo Q.J.Roy. Met. Soc. https://doi.org/10.1002/qj.49711147003

Chaos and Predictability in Forecasting the Monsoons T N Palmer (1994)



We can study a prediction of the second kind by introducing some fixed normalised "forcing" into the Lorenz equations

$$\dot{X} = -\sigma X + \sigma Y + \alpha F_X$$

$$\dot{Y} = -XZ + rZ - Y + \alpha F_Y$$

and

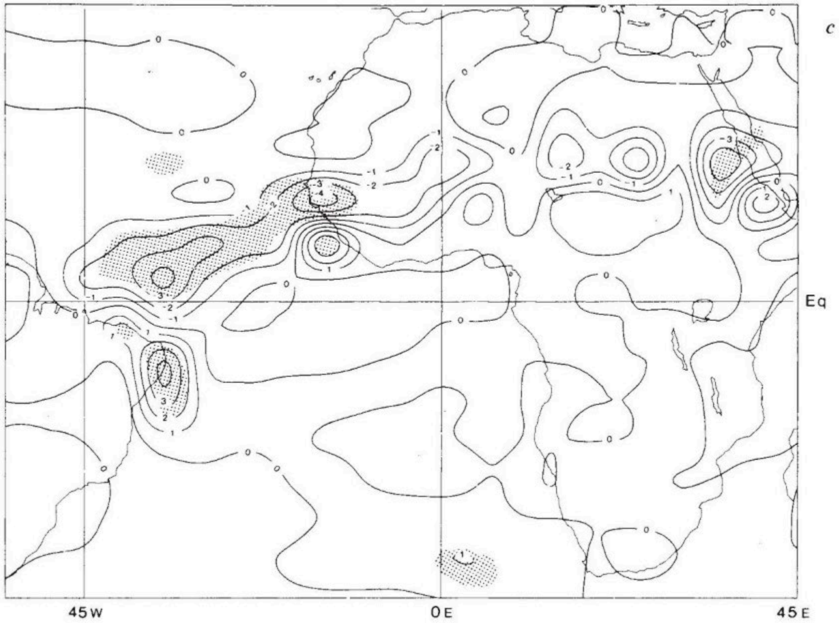
$$\dot{Z} = XY - bZ + \alpha F_Z \qquad \ldots (2)$$

and ask how the Lorenz climate changes as α is increased from zero.

The result of one such experiment is given in Fig. 2 in terms of the probability density function (PDF) associated with the state vector of the Lorenz

Folland et al. The Sahel drought in the 1970s and 1980s was likely caused by global-scale decadal SST anomalies. The companion paper (Palmer 1986) showed that each ocean basin contributed to the Sahel drought.

c, l80-Day mean rainfall (millimetres per day); anomaly integration minus control. d, 180- Day mean 950-mbar steady moisture flux; anomaly integration minus control. The scale of the arrows shown in panel d is 5 times that in b.



Sahel rainfall and worldwide sea temperatures, Nature, 1901-85 C. K. Folland, T. N. Palmer & D. E. Parker