A NONLINEAR DYNAMICAL PERSPECTIVE ON THE PREDICTABILITY AND PREDICTION OF THE INDIAN SUMMER MONSOON RAINFALL

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Motivation

- Timely and correct prediction: highly desirable and has a great socio-economic impact

- Predictability is limited mainly due to (i) modeling error and (ii) initial condition error (chaos).

- To address and understand them using conventional modeling studies (GCMs) involving millions of degrees of freedom is difficult (and in some cases even nearly impossible).

- Tools of nonlinear dynamical system theory may come as handy for:
    - quantifying predictability
    - suggesting improvements in prediction capability
    - constructing prediction models

- Low-order atmosphere-ocean models: provide necessary insight to understand complex meteorological processes.

Outline

- Prediction rules for the two-regime models

- Development of empirical prediction models for long-range forecasting of Indian Summer Monsoon Rainfall (and Indian Ocean Dipole)

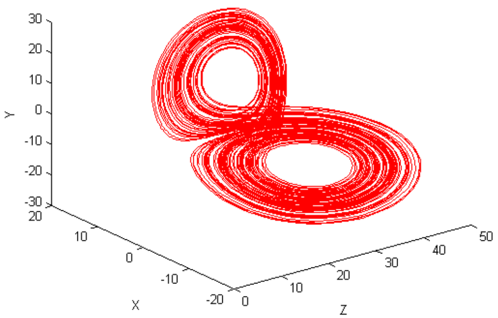
- Frequency of active/break spells during El Nino and La Nina events

- Nonlinear Time Series Analysis: Quantifying the limit of predictability

TWO-REGIME MODELS/PROCESSES:
MOMENTOUS DISCOVERY

❖ **We discovered** *Prediction Rules for Regime Changes and Duration in New Regime for the Lorenz and other Two Regime Models*

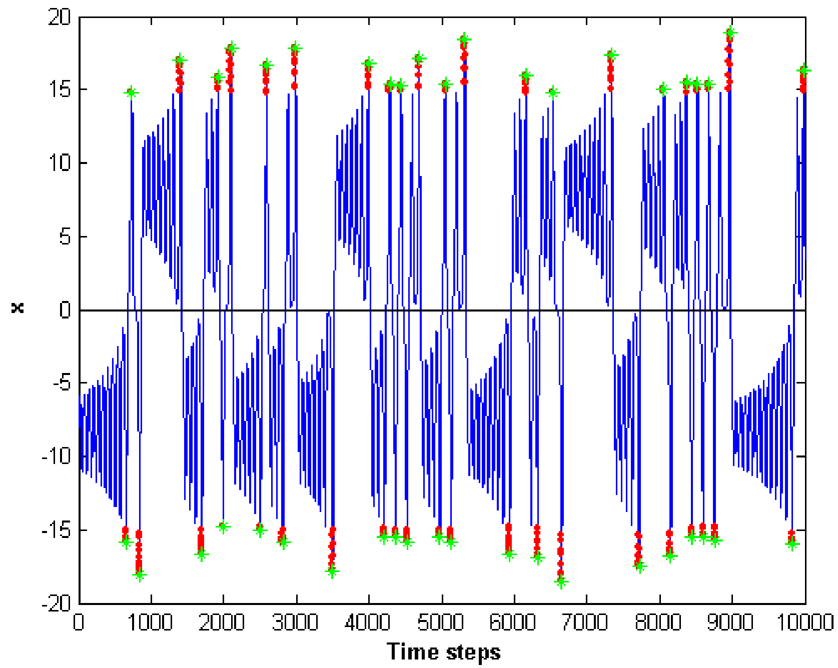
$$\frac{dx}{dt} = -ax + ay$$
$$\frac{dy}{dt} = -xz + rx - y$$
$$\frac{dz}{dt} = xy - bz$$

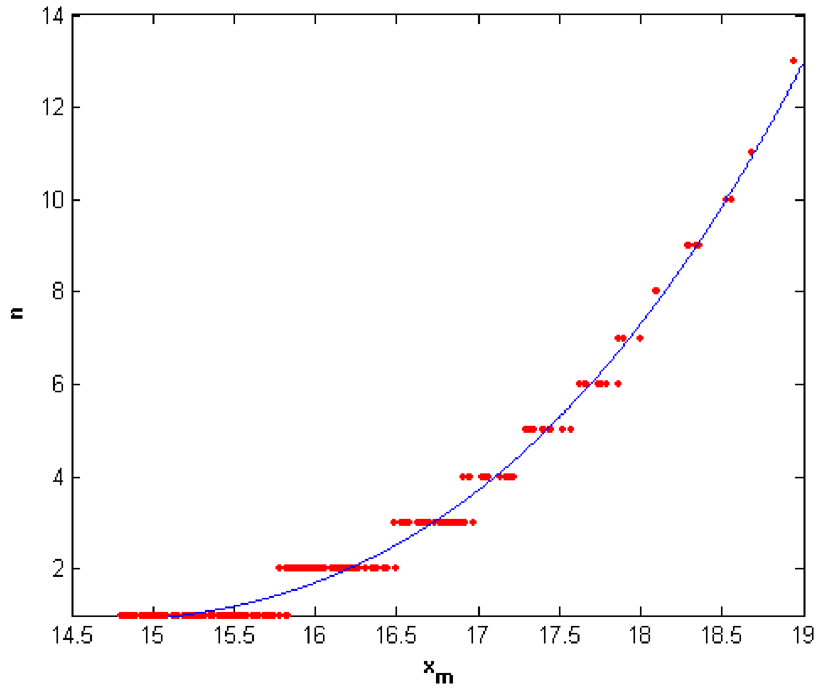


➢ ***Rule 1: When |x(t)| is greater than a critical value (x_c ~ 14.8) the current regime will end after it completes the current orbit.***

➢ ***Rule 2: The length n of the new regime increases monotonically with the maximum value x_m of |x(t)| in the previous regime.***

Yadav, Dwivedi and Mittal, J. Atmos. Sci., 62, 2316-2321, 2005





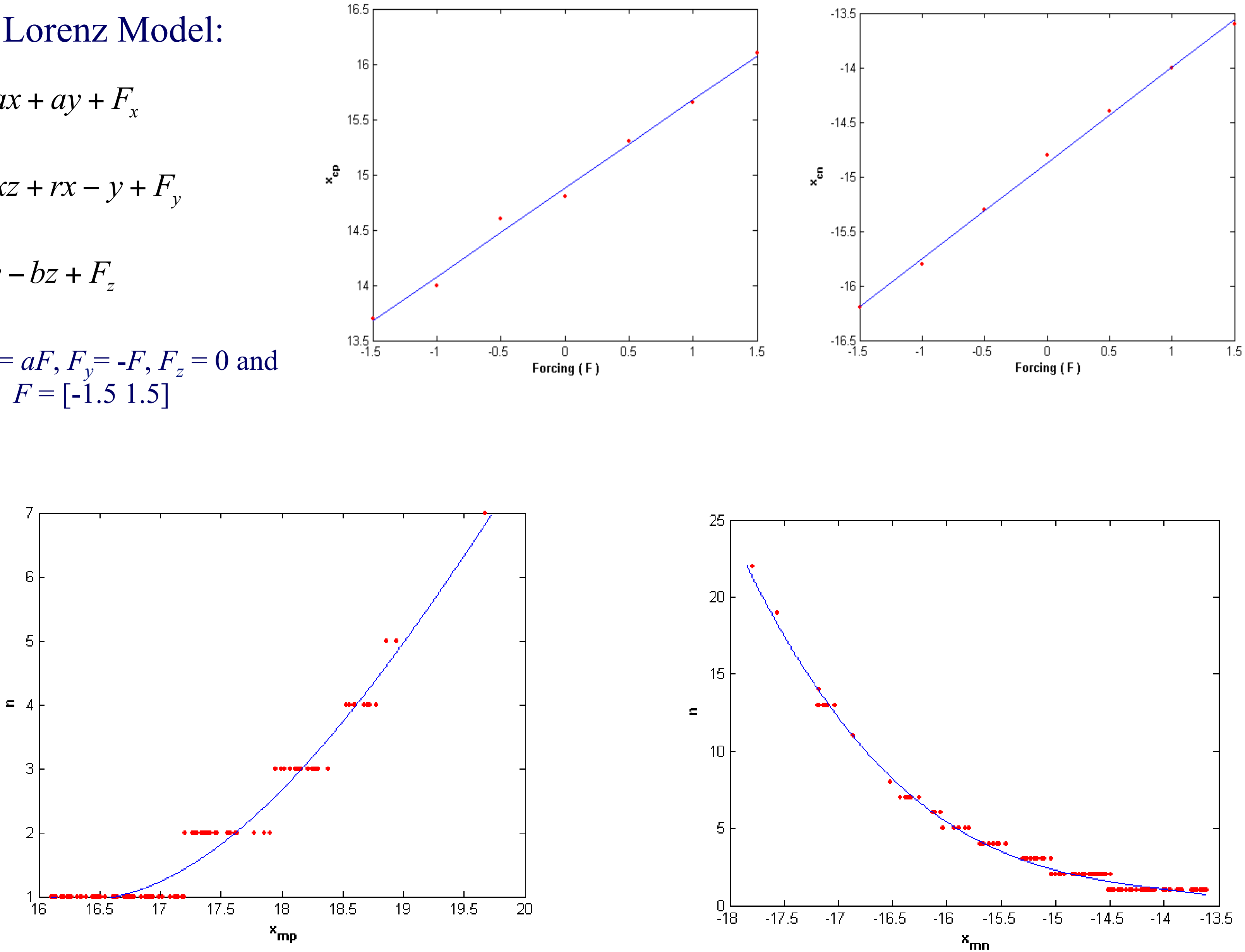
Forced Lorenz Model:

$$\frac{dx}{dt} = -ax + ay + F_x$$

$$\frac{dy}{dt} = -xz + rx - y + F_y$$

$$\frac{dz}{dt} = xy - bz + F_z$$

with $F_x = aF$, $F_y = -F$, $F_z = 0$ and $F = [-1.5\ 1.5]$



Yadav, Dwivedi and Mittal, J. Atmos. Sci., 62, 2316-2321, 2005

Obs / Fcst	Yes	No	Total
Yes	266	0	266
No	01	386	387
Total	267	386	653

Contingency table for rule 1

Lorenz Model

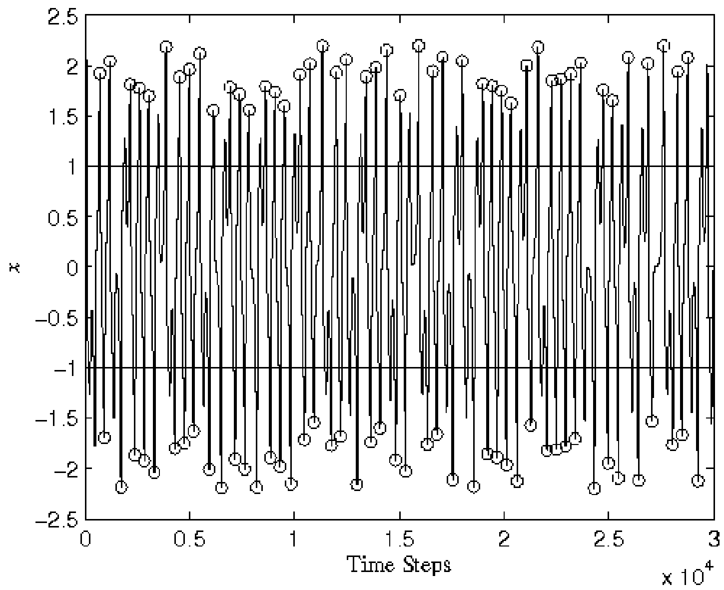
Obs / Fcst	Yes	No	Total
Yes	255	0	255
No	01	409	410
Total	256	409	665

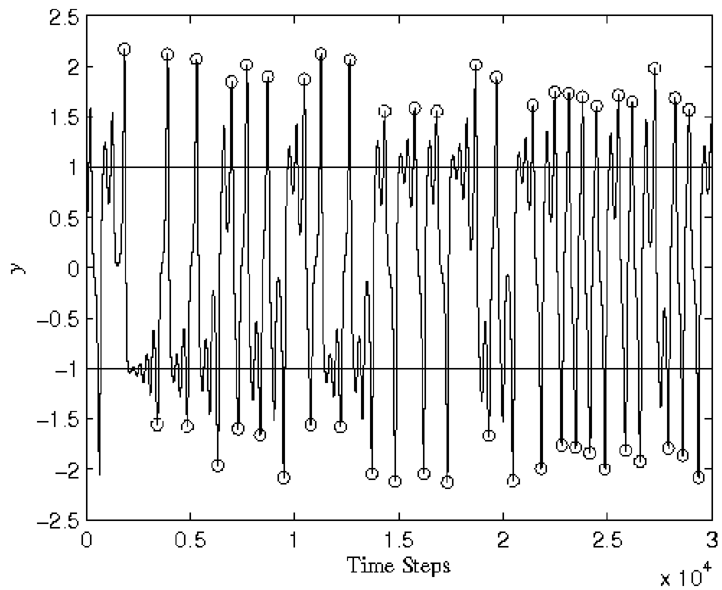
Contingency table for rule 1

Forced Lorenz Model with F =1.5

Generic Prediction Rules: Applies to large class of two-regime models/processes

ACT





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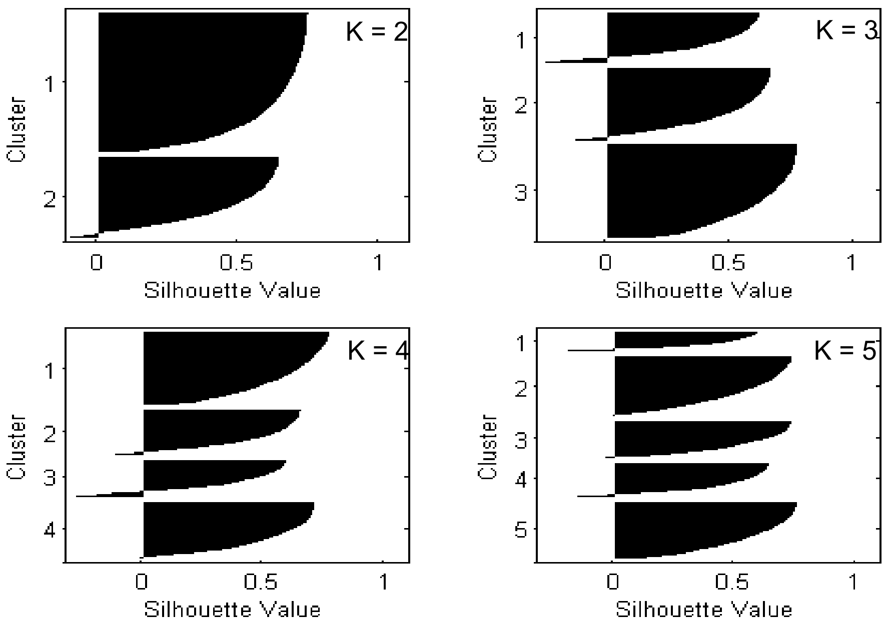
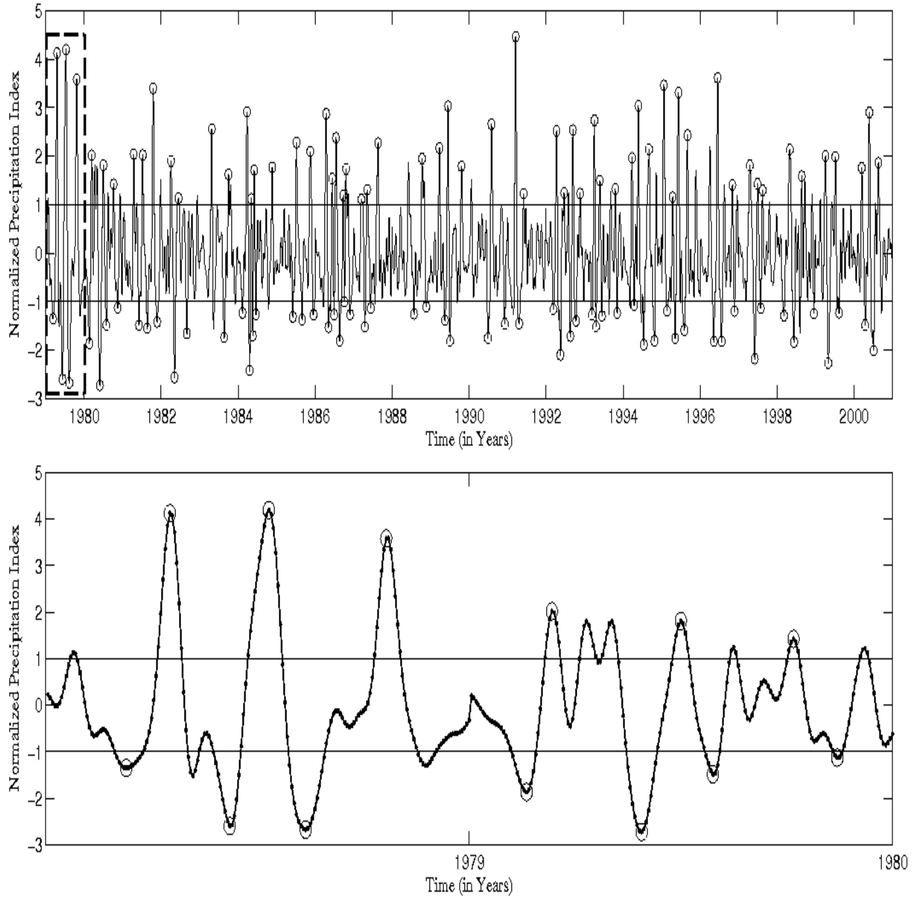


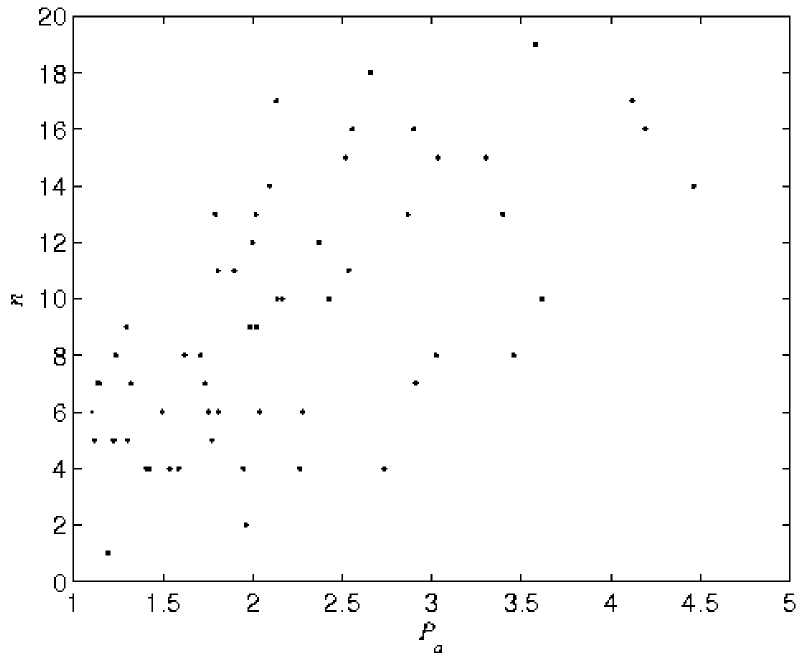
K-mean clustering of the ISO data

❖ **These prediction rules are generic in nature: applicable to even real time processes such as ISO and IOD**

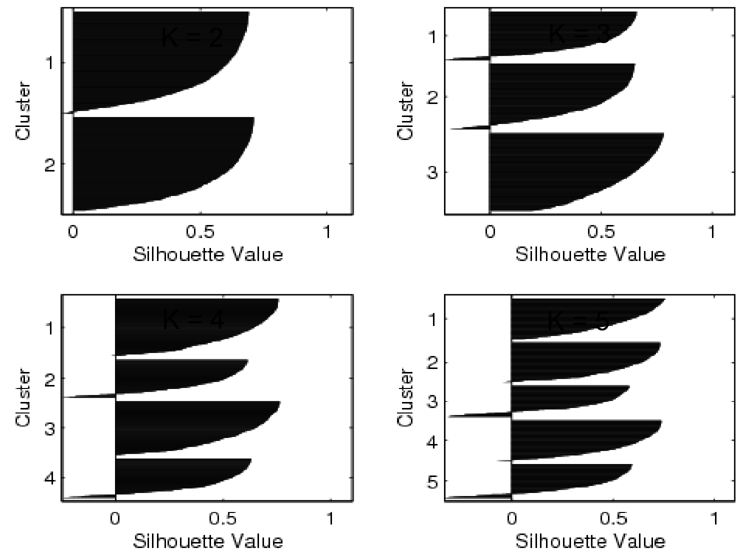
Dwivedi and Mittal, Pure and Applied Geophysics, 169, 755-761, 2012



10-90 day filtered ISO data
[70-90 E, 15-25N]



DMI



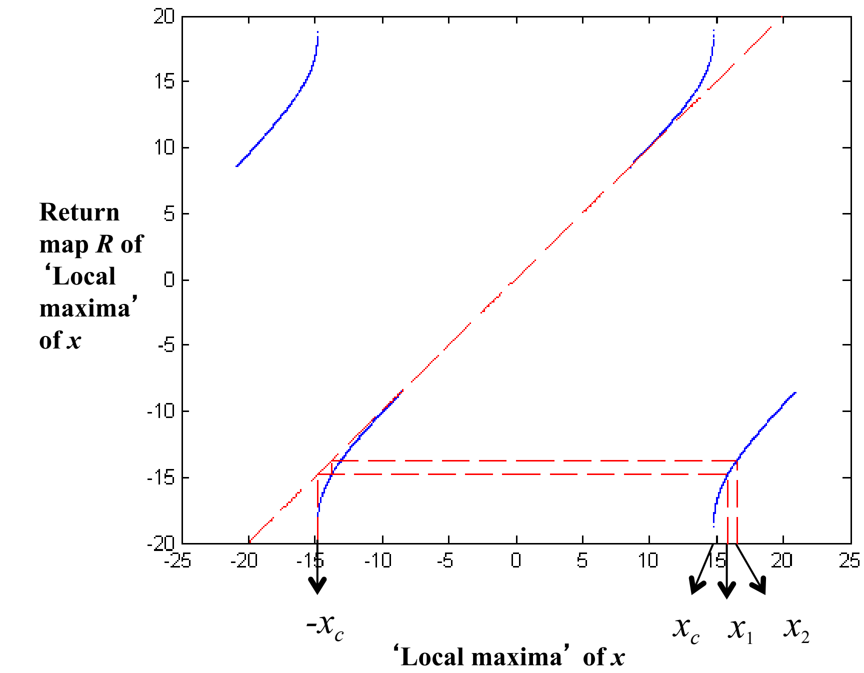
Dwivedi and Mittal, Pure and Applied Geophysics, 169, 755-761, 2012

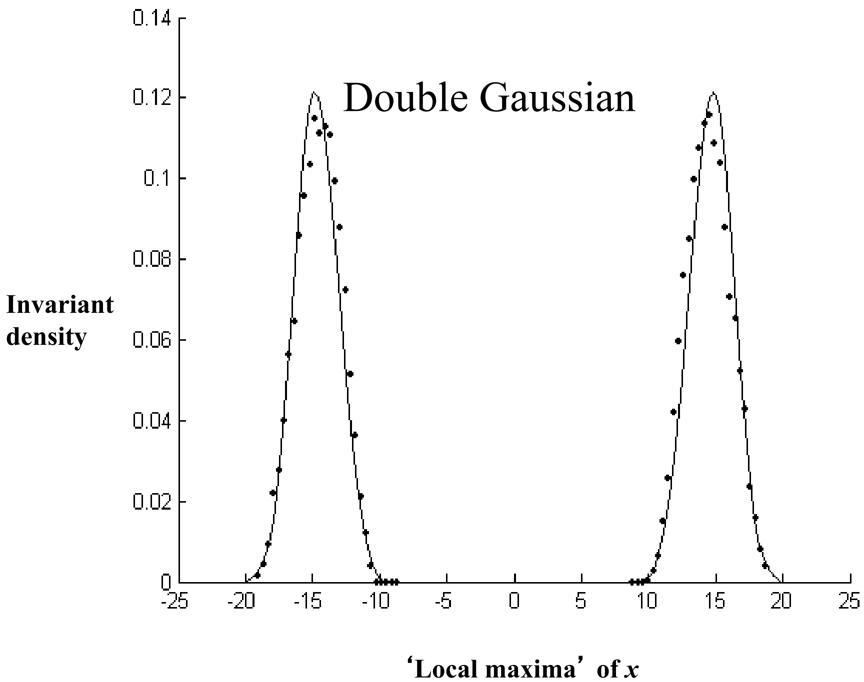
Probability distribution for Number of Cycles Between Successive Regime Transitions for the Lorenz Model

- Return map for the maximum value of the variable *x* of the Lorenz model with the help of an invariant manifold technique.

- Return map is used to derive the regime transition rules.

- The probability of different regime lengths is estimated for the Lorenz model and forced Lorenz model.





Mittal, Dwivedi and Yadav, Physica D, 233, 14-20, 2007

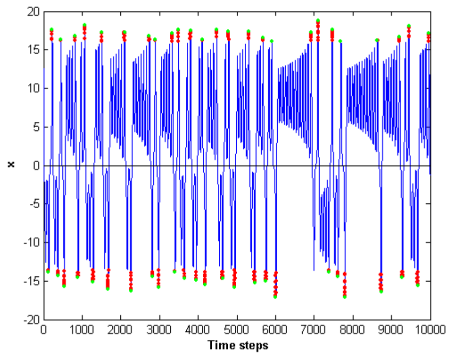
❖ Forced Lorenz Model: introduced by Palmer to explore the effect of eastern pacific SST on JJAS mean monsoon rainfall)

$$\frac{dx}{dt} = -ax + ay + F_x$$

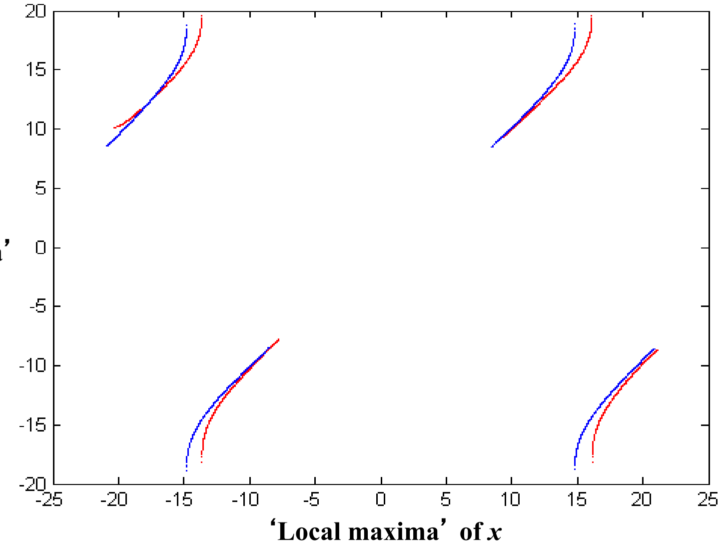
$$\frac{dy}{dt} = -xz + rx - y + F_y$$

$$\frac{dz}{dt} = xy - bz + F_z$$

with $F_x = aF$, $F_y = -F$, $F_z = 0$ and $F = [-1.5\ 1.5]$

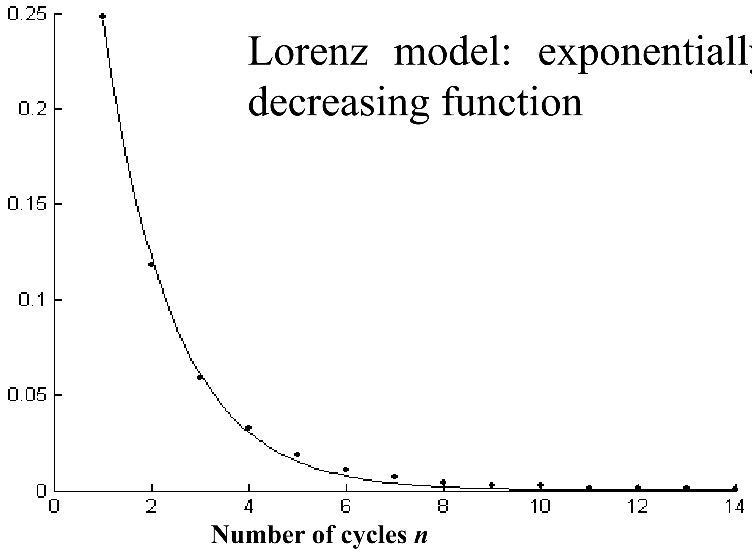


Return map of 'Local maxima' of *x*



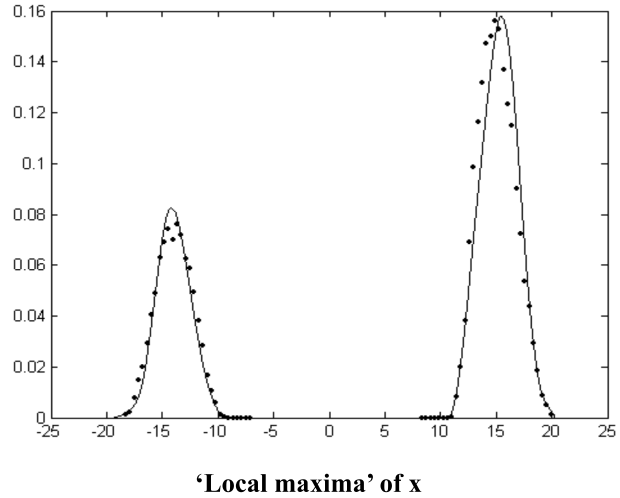
❖ Probability distribution for residency time in a regime

Probability



Lorenz model: exponentially decreasing function

Invariant density



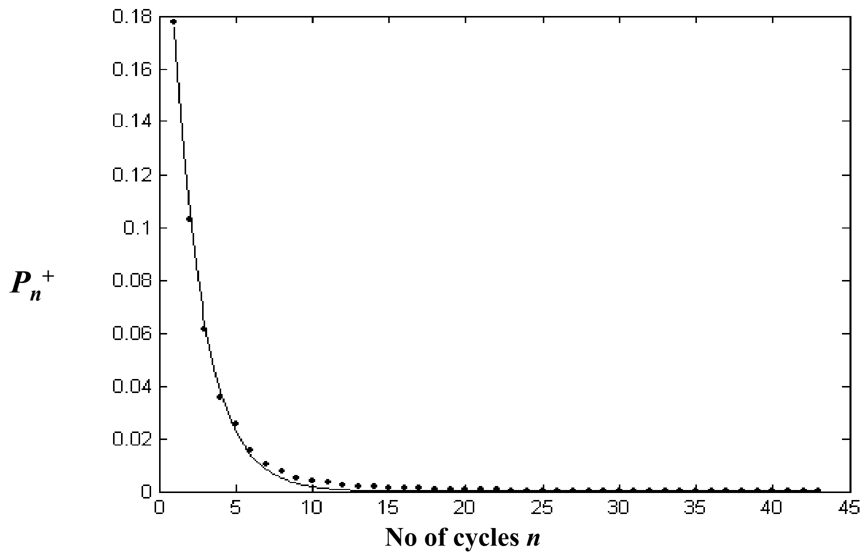
Mittal, Dwivedi and Yadav, Physica D, 233, 14-20, 2007

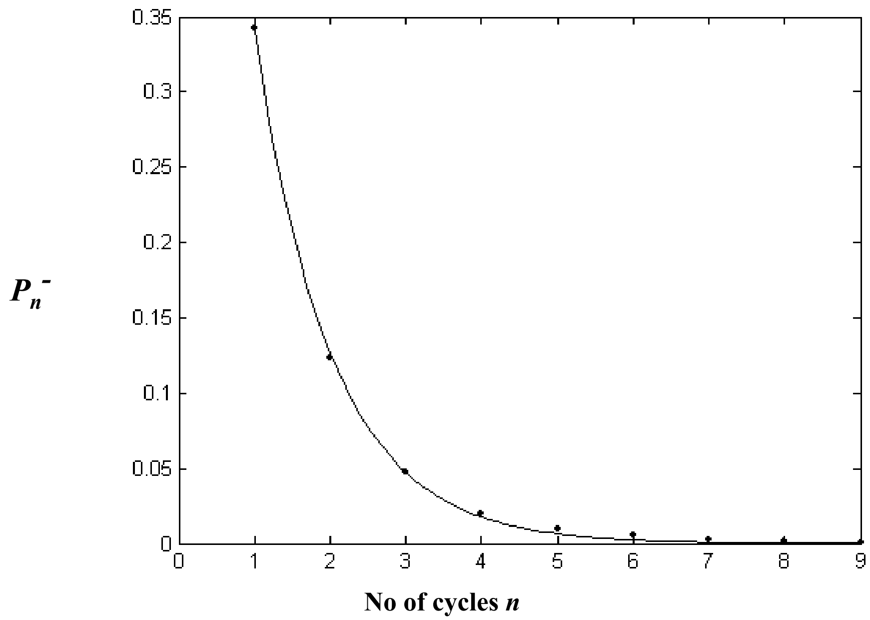
Effect of (+ve) Forcing:

- probabilities of duration in positive and negative regimes are no longer equal. What can we learn? Interpretation??

Hypothesis:

- generally: negative correlation between El Nino index and Indian Seasonal Mean Rainfall.
- shift of focus from seasonal mean rainfall to the statistics of lengths of active and weak spells.
- La Nina year: the probabilities of longer active spells should increase whereas those of shorter active spells should decrease.
- the probabilities of shorter break spells increase whereas those of longer break spells decrease.
- El Nino years: opposite

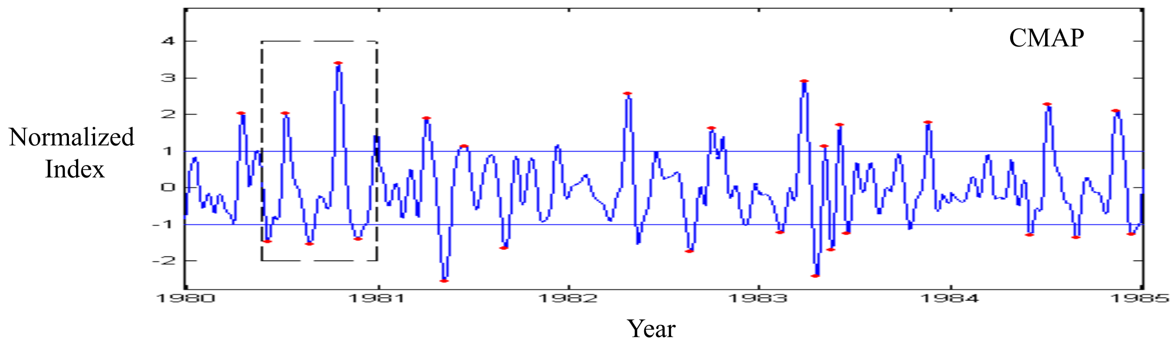




Mittal, Dwivedi and Yadav, Physica D, 233, 14-20, 2007

Extended Range Prediction of ISO Breaks

ISO indices were generated using CMAP and IMD gridded rainfall data, OLR data, and U850hPa data

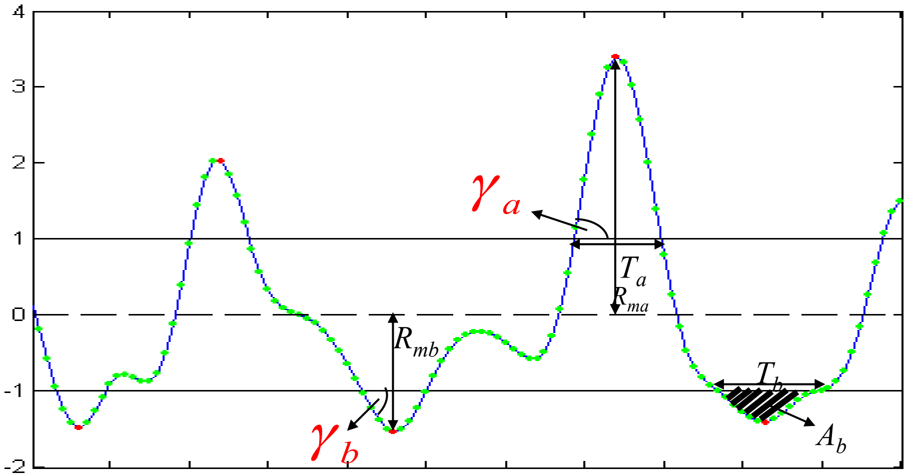


May-Oct area averaged 10-90 day filtered normalized rainfall anomaly

- the peak anomaly in an active regime can be used as a predictor for the duration of the subsequent break spell

- average growth rate around the threshold to an active condition can be used as a predictor of the peak anomaly in the active spell

- average growth around the threshold to an active condition can give useful prediction of the duration of the following break, on an average, about 23 days (38 days) in advance of its commencement (end).



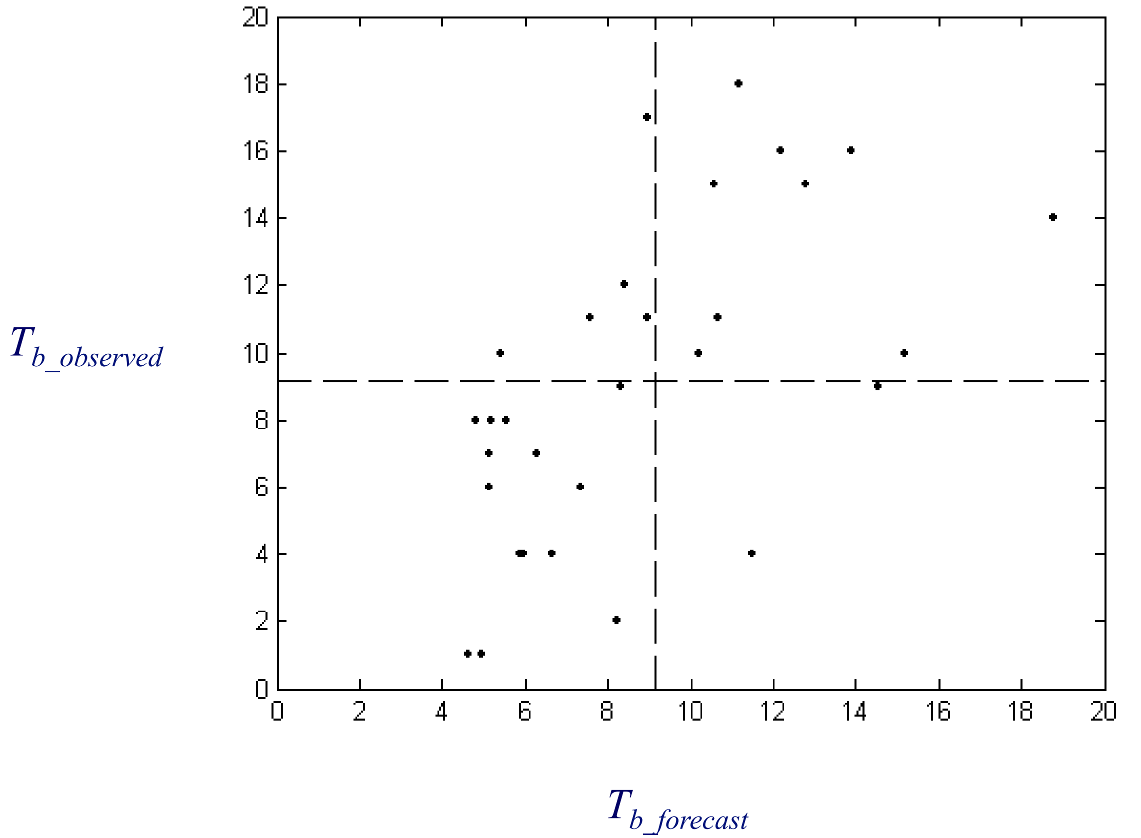
active (break) conditions: normalized anomaly values > (<) 1 (-1)

Dwivedi, Mittal, and Goswami, Geophys. Res. Lett., 33, 2006

half the length of the data set is used to construct the simple forecast model; the fidelity of this forecast model is verified on the other half of the data set

Empirical Rule for Extended Range Prediction of Duration of Indian Summer Monsoon Breaks

Out of the 14 (16) observed events above (below) average, 9 (14) are correctly predicted by R_{ma}



Forecast Strategy:

Average growth rate of the anomaly around the threshold +1 (-1) of active (break) phase	⇨	Peak anomaly in active (break) spell R_{ma} (R_{mb})	⇨	Duration of break (active) spell T_b (T_a)

Stochastic forced Lorenz model:

$$dx/dt = -ax + ay + aF$$

$$dy/dt = -xz + rx - y - F$$

$$dz/dt = xy - bz$$

Here $F = -1 + e(t)$, where e is an independent random number chosen at each time step, from the range [-0.1, 0.1].

x: Rainfall anomaly per unit time interval

- similar results (on carrying out the same analysis)

- seems to be reasonable in representing the basic dynamical character of the monsoon ISO

- may be useful in deriving insight regarding the underlying physical processes responsible for regime transitions of the monsoon ISO

Dwivedi et al, GRL, 33, 2006

Physical Mechanism

- Recalling that ISOs result from a convective-radiative-dynamical feedback, the relationship between R_{ma} and T_b is indicative of such an underlying mechanism.

- Higher the intensity of the active condition, larger is the rainout level (drying) and stabilization of the atmosphere.

- The radiative and moistening processes would take that much longer to recharge for triggering a new active episode, thereby causing longer breaks.

Dwivedi et al, GRL, 33, 2006

Forecasting the duration of active and break spells in intrinsic mode functions (IMFs) of Indian monsoon intraseasonal oscillations (ISOs)

❖ The ISO has a complex nature with the coexistence of various types of propagating low frequency modes with their respective characteristic time scales (10-20 days, MJO mode, 40-60 days etc).

❖ Whether it is possible to predict the duration of active/break spells of different ISO modes at different time scales? : **never attempted before**

❖ Several indices (ISMR, OLR, U850) of the observed Indian summer monsoon ISO are decomposed into their respective IMFs using the EMD technique

❖ EMD is an empirical and adaptive method that can isolate physically meaningful modes from a set of raw data.

❖ Especially useful for nonlinear, non-stationary time series, for which the commonly used methods may give rise to frequencies, which have no physical significance.

Dwivedi and Mittal, Geophys. Res. Lett., 34, L16827, 2007

IMFs:

Properties:

i) Instantaneous frequencies lying in a narrow band.

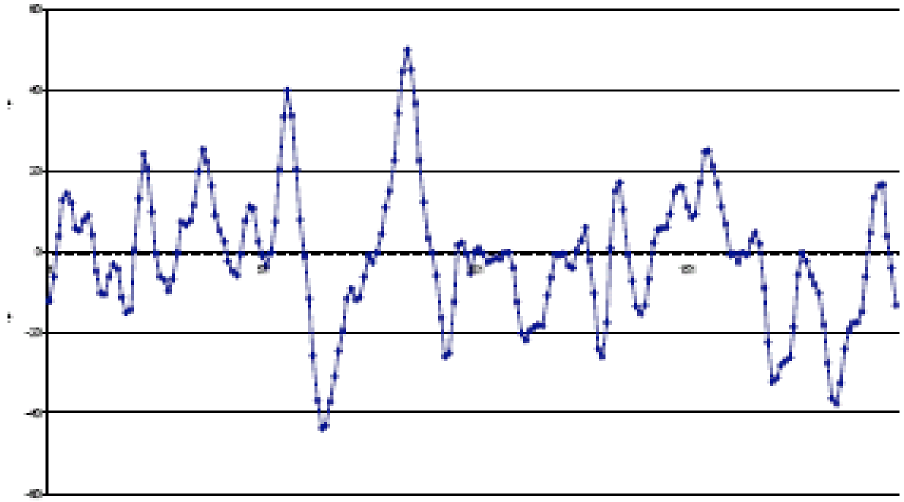
ii) The amplitude and frequency vary slowly with time.

iii) The local extrema and zeros alternate, zero mean value and nearly orthogonal to each other.

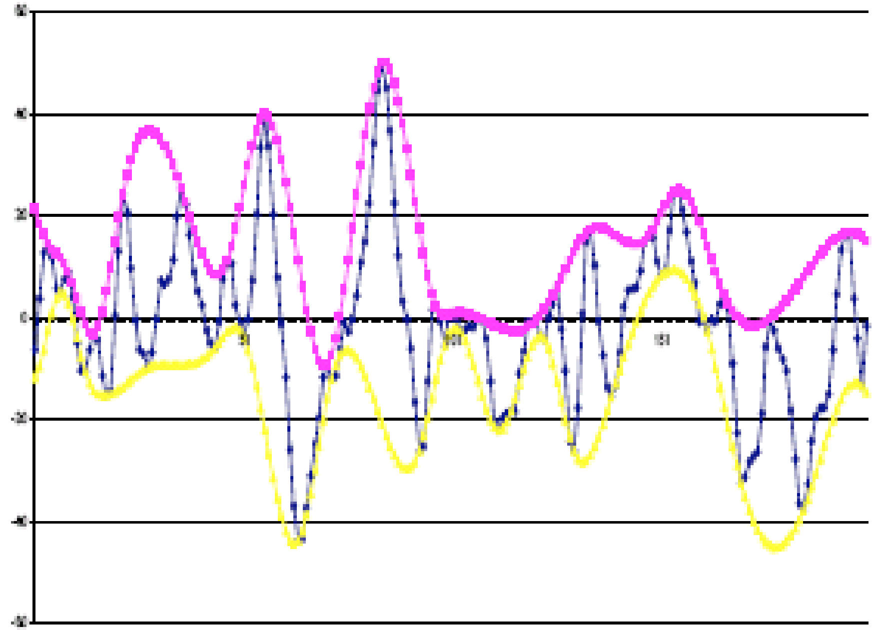
iv) End effects are negligible.

EMD Methodology

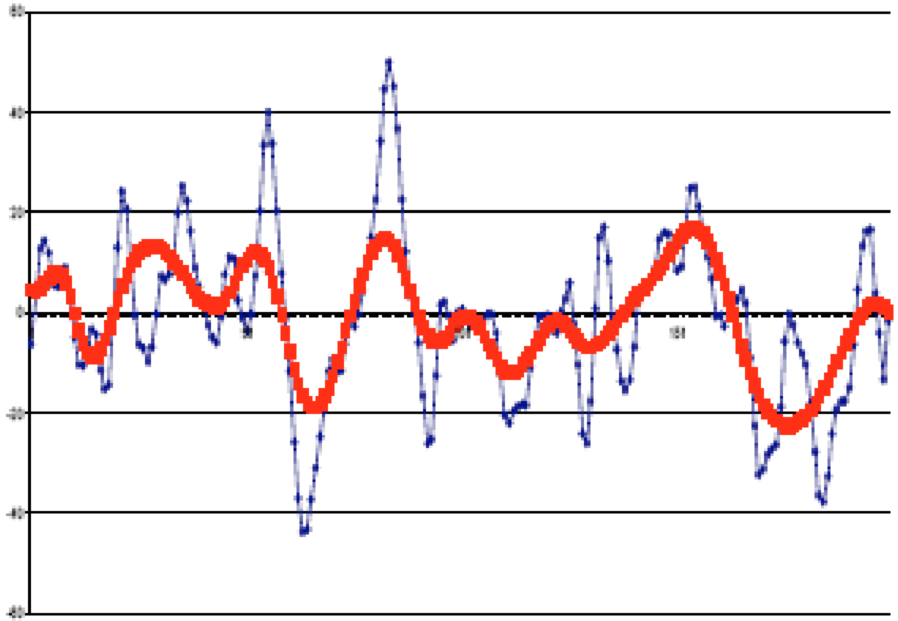
- **Initial data: A time series**



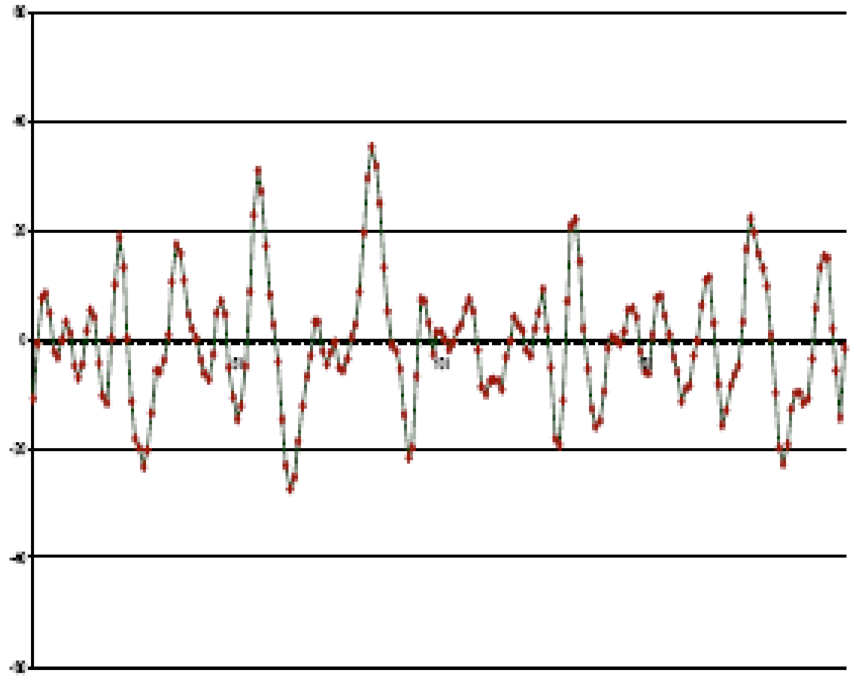
- **Identify maxima and fit a cubic spline through these. Then identify minima, and fit another cubic spline through these**



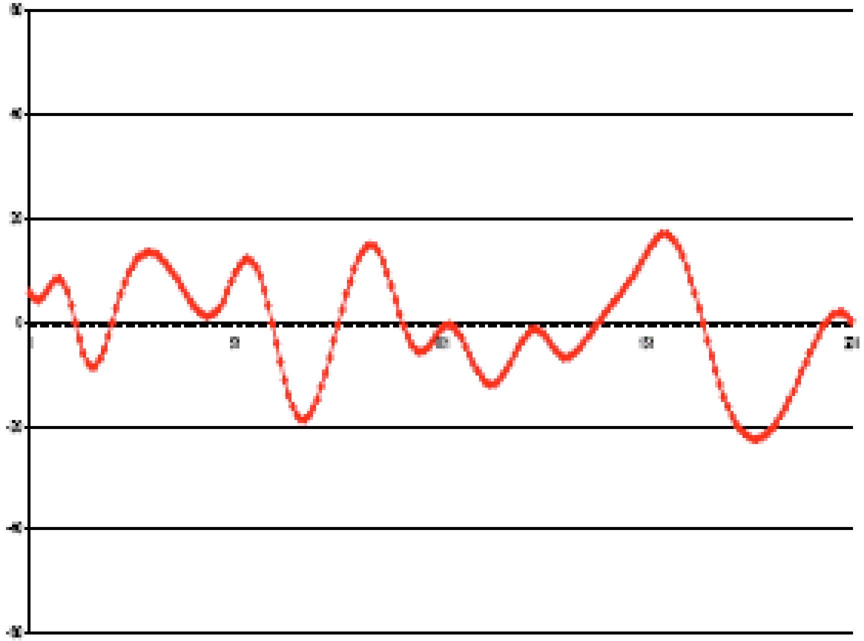
- **Take the mean of the two splines.**

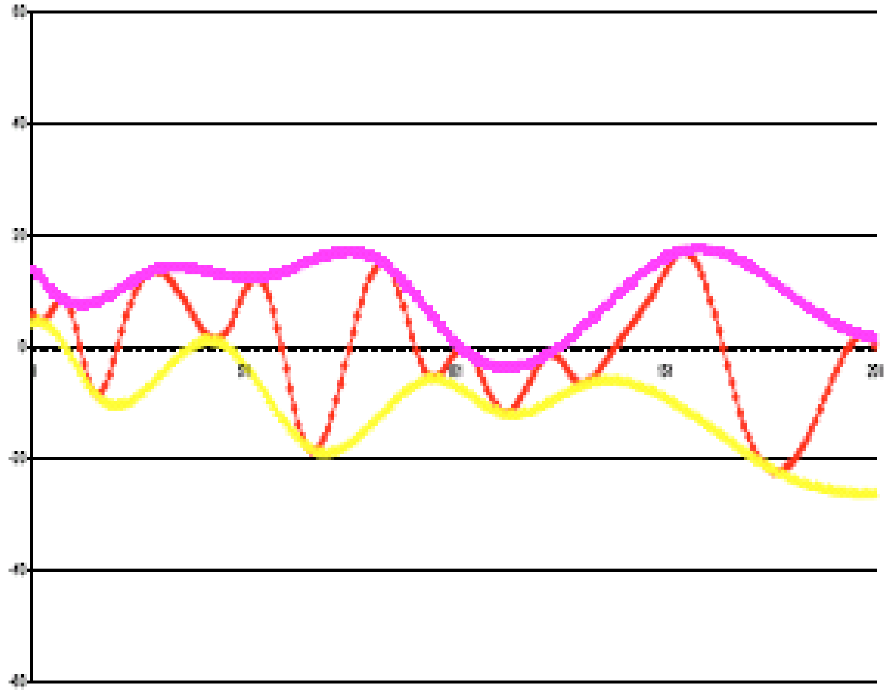


- **Subtract the mean from the initial data to create the first EMD mode.**



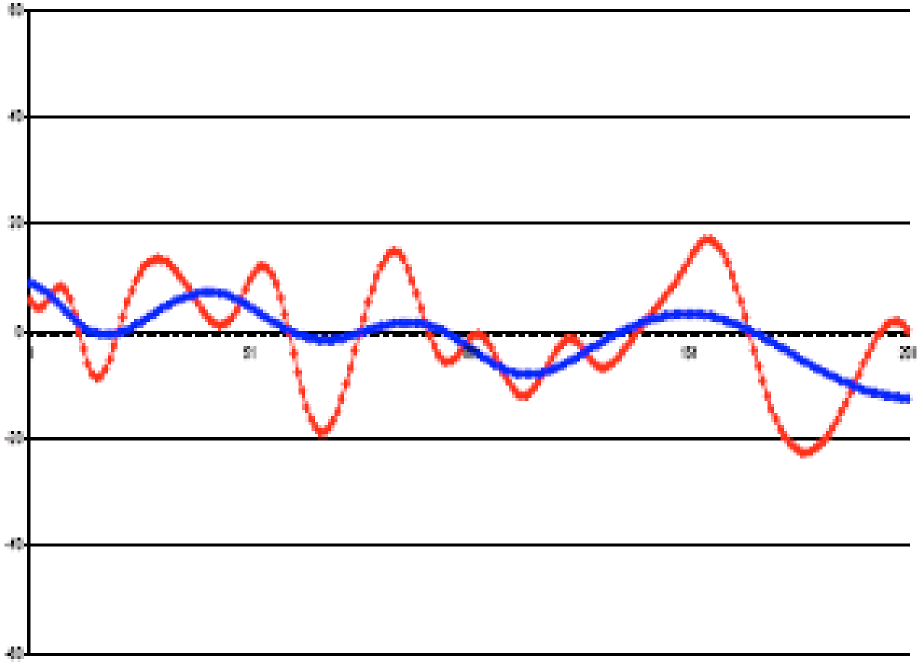
- **The mean is then recycled as the data for the next calculation.**





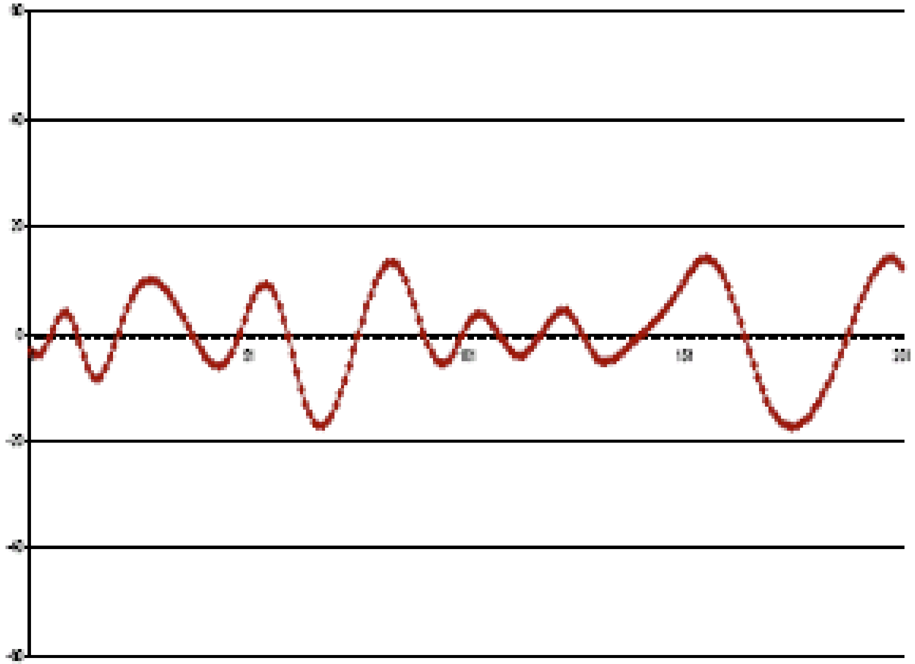
- **Identify maxima and fit a cubic spline through these. Then identify minima, and fit another cubic spline through these.**

• **Take the mean of the two splines.**

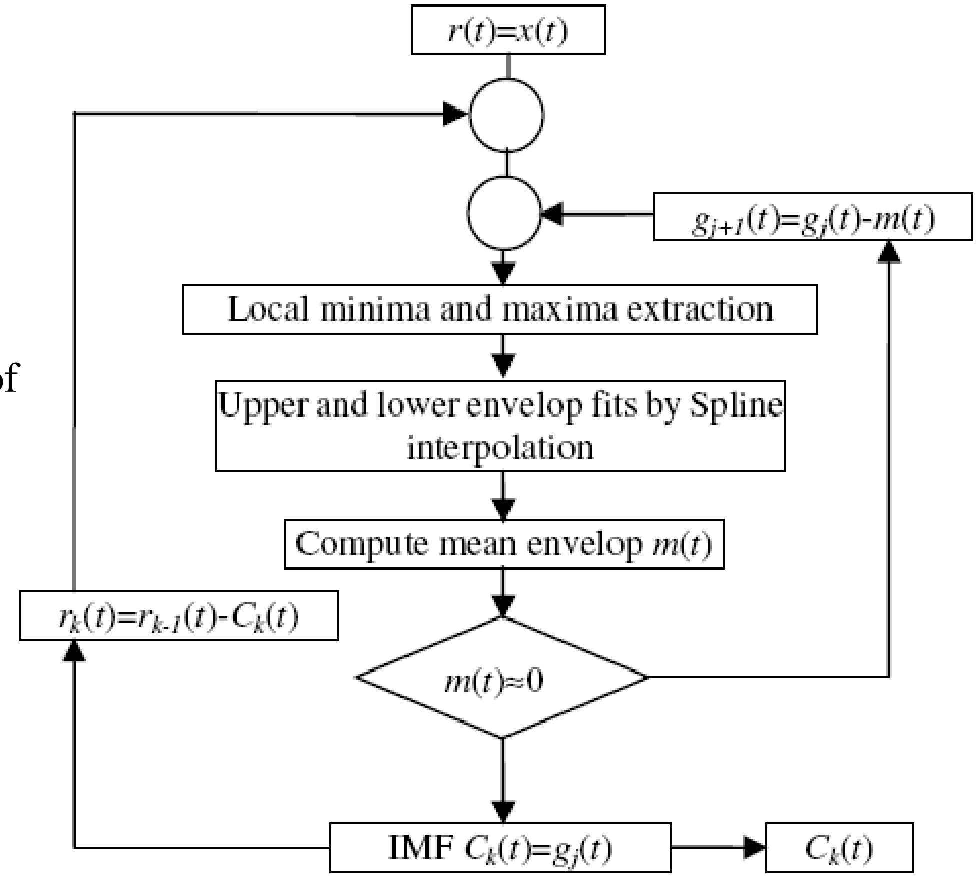


• **Subtract this mean from the initial data to create the second EMD mode.**

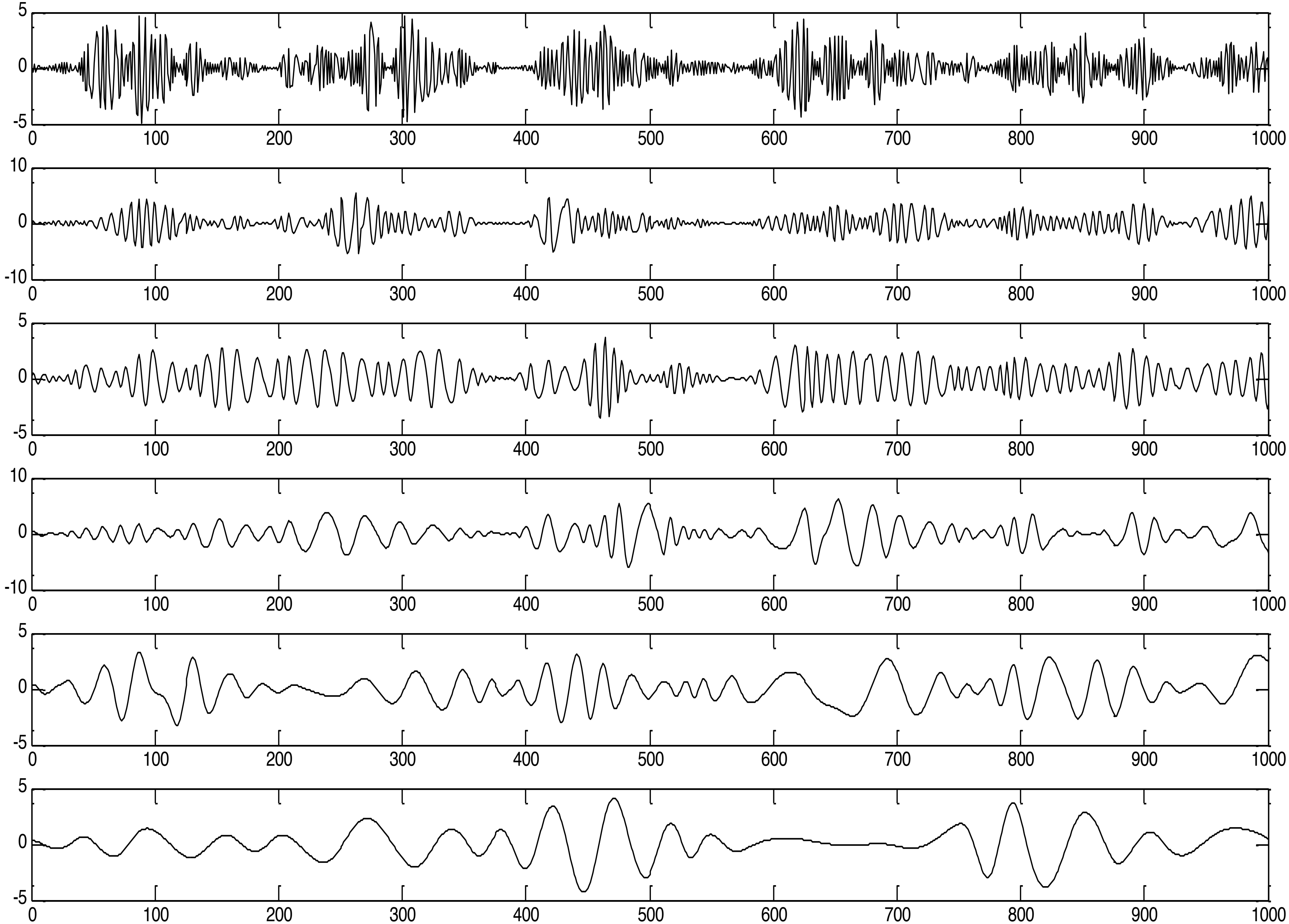
• **The mean is then recycled as the data for the next calculation.**



Decomposition of the signal $x(t)$ into a set of IMF components



Dataset	IMF											
	1		2		3		4		5		6	
	τ (days)	FEV	τ (days)	FEV	τ (days)	FEV	τ (days)	FEV	τ (days)	FEV	τ (days)	FEV
Gridded Rainfall	3.3 ± 1.4	0.13	5.8 ± 2.2	0.12	9.8 ± 3.4	0.13	17.0 ± 6.4	0.21	30.6 ± 13.0	0.18	56.7 ± 18.9	0.13
OLR	3.7 ± 1.4	0.11	7.6 ± 2.7	0.14	16.1 ± 5.6	0.18	30.9 ± 10.2	0.23	51.1 ± 14.3	0.15	96.9 ± 28.6	0.09
U850	3.6 ± 1.5	0.06	7.9 ± 2.9	0.12	16.0 ± 5.8	0.28	33.1 ± 10.8	0.30	69.6 ± 23.5	0.19	145.9 ± 31.4	0.05



IMFs of ISO

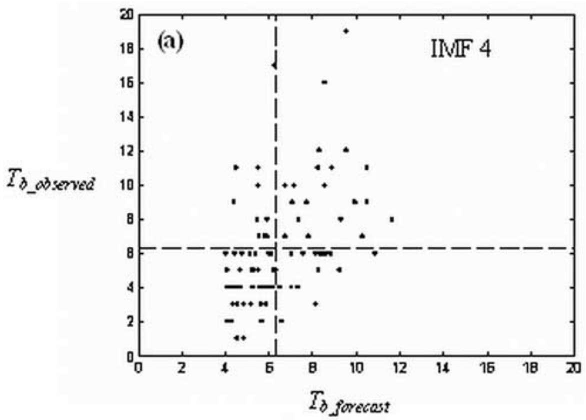
Variable 1	Variable 2	IMFs of gridded station rainfall					
		1	2	3	4	5	6
Number of pairs		470	372	240	116	66	39
R_{ma}	T_b	0.40[a]	0.56[a]	0.57[a]	0.55[a]	0.30[b]	0.25
R_{mb}	T_a	0.30[a]	0.47[a]	0.52[a]	0.50[a]	0.40[a]	0.33[b]
γ_a	R_{ma}	NA	NA	0.25[a]	0.48[a]	0.43[a]	0.57[a]
γ_b	R_{mb}	NA	NA	0.57[a]	0.58[a]	0.37[a]	0.53[a]
R_{ma}	T_a	0.32[a]	0.51[a]	0.57[a]	0.60[a]	0.57[a]	0.28[b]
R_{mb}	T_b	0.43[a]	0.56[a]	0.69[a]	0.68[a]	0.50[a]	0.32[b]

- First 30 years (1954-1983) : model development and estimation of correlation between prospective predictors and T_b (T_a)
- Last 20 years (1984-2003) : verification (fidelity) of forecast model

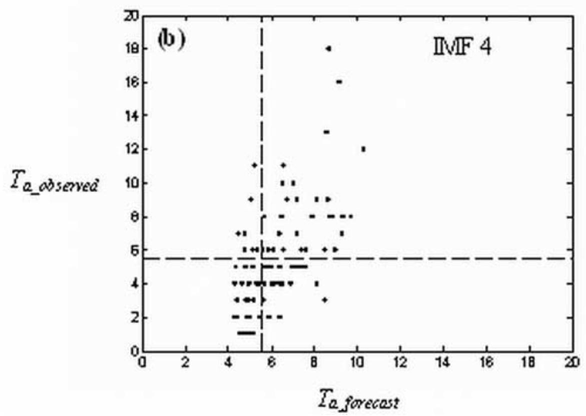
❑ Important and Useful: Prediction of duration of break (active) spell using observed growth rate in active (break) regime through peak anomaly in that regime.

❑ Correlation reduces significantly: however advantage in terms of a greater lead-time for prediction of break/active spells

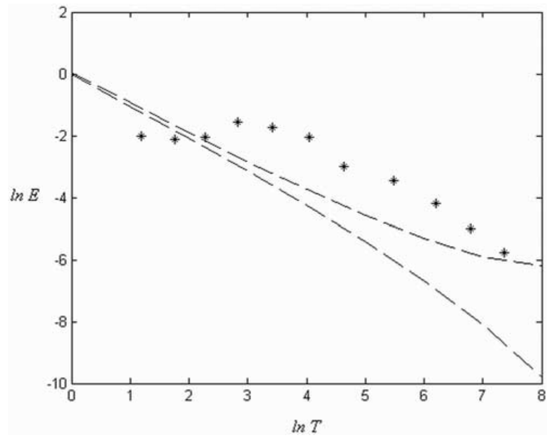
❖ For each ISO index, for most of the dominant IMFs, the peak in the active (break) regime may be used as a predictor for the duration of the subsequent break (active) regime : led to construction of forecast model



- For IMF 4, out of the 32 (57) observed break events above (below) average, 22 (41) are correctly predicted by peak anomaly in active regime



- Similarly, out of the 39 (50) observed active events above (below) average, 32 (30) are correctly predicted by peak anomaly in break regime



Statistical Significance Test (White noise) to distinguish between the IMFs that are spurious from those that carry physically significant information

Dwivedi and Mittal, Geophys. Res. Lett., 34, L16827, 2007

<u>Potential forecasting strategy:</u>

Use the average growth rate around the threshold as an early predictor followed by the peak anomaly as a more reliable predictor.

Forecasting the peak anomalies of dominant intrinsic modes of Indian Ocean Dipole (IOD)

Objectives:

- To decompose the time series representative of the IOD into its IMFs, and to identify dominant modes of the IOD.

- To develop a simple yet robust extended range prediction rule for forecasting the climatologically important peak SST anomalies of IOD regimes for each dominant intrinsic mode.

Strategy:

- IOD is considered as an approximate two-regime phenomenon with the SST anomalies oscillating between positive and negative IOD regimes

- Index of IOD : DMI : anomalous SST gradient between the western equatorial Indian Ocean (50E-70E, 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E, 10S-0N)

- Dominant modes of IOD are obtained using EMD technique

Dwivedi, Deep Sea Res. I, 70, 73-82, 2012

Forecasting the Indian summer monsoon intraseasonal oscillations using genetic algorithm and neural network

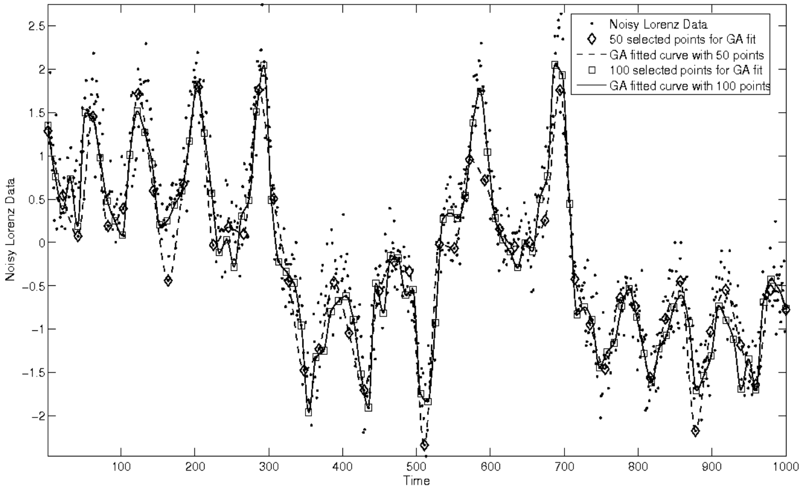
❖ applicability of Genetic Algorithm (GA) is demonstrated for nonlinear curve fitting of the inherently chaotic and noisy Lorenz time series and the ISO data.

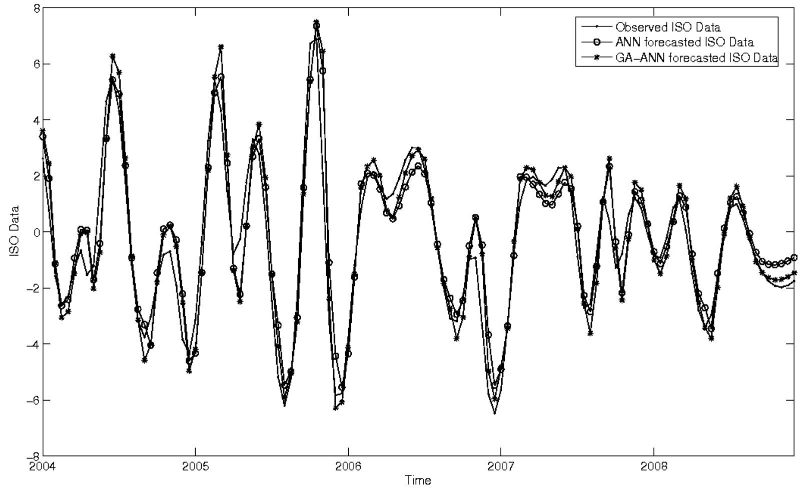
❖ a robust method is developed for the very long-range prediction of the ISO using a feed-forward time delay backpropagation Artificial Neural Network (ANN).

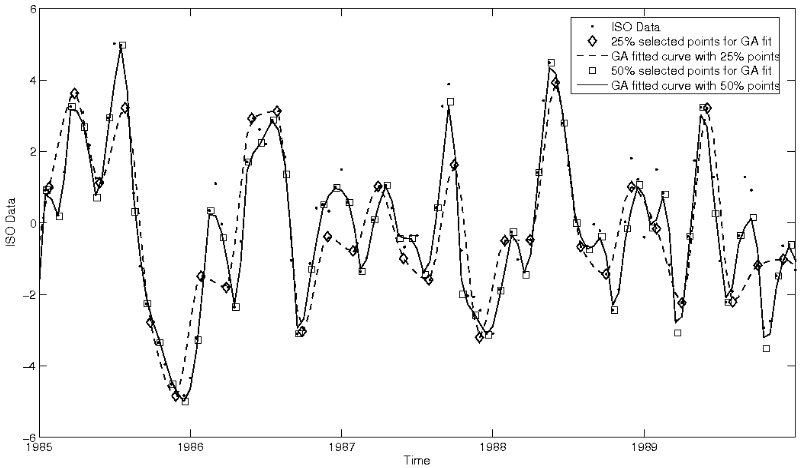
❖ using an iterative one-step-ahead prediction strategy, five years (120 pentads) of advanced prediction is made for the ISO data with good forecast skill.

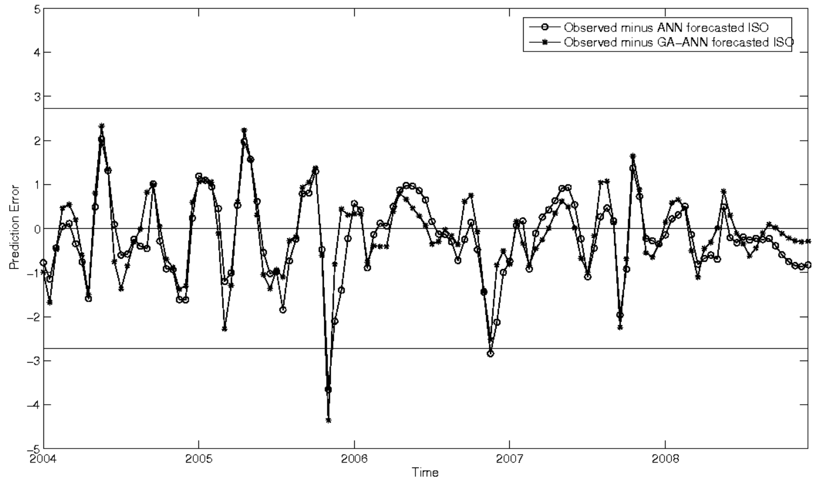
❖ hybrid GA-ANN model may be used as an early forecast model followed by ANN only model as a more reliable model.

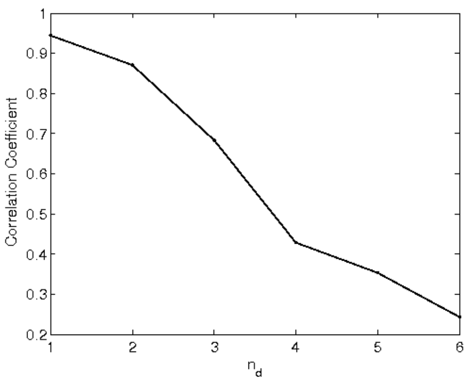
Dwivedi and Pandey, Geophys. Res. Lett., 38, L15801, 2011











- 1979-2008 (30 yrs JJAS CMAP pendad values over monsoon trough area): EMD is used: 20-105 days intraseasonal component
- 25 yrs for creating the network; 5 yrs for prediction

Dwivedi and Pandey, Geophys. Res. Lett., 38, L15801, 2011

DURATION OF ACTIVE AND BREAK SPELLS OF THE INDIAN SUMMER MONSOON RAINFALL DURING EL NIÑO AND LA NIÑA

- **The knowledge about the number and duration of active and break spells during a particular monsoon season is highly desirable in the Indian context.**

- **The ISMR variability is greatly influenced by the El Niño and La Niña events.**

- **Computing the negative (positive) correlation between the seasonal mean ISMR and El Niño (La Niña) is quite common in this context.**

- **This information is neither sufficient nor very useful for the agricultural planning and water resource management.**

- **Moreover, a considerable weakening in the correlation between the ISMR and El Niño has also been observed in the recent decades.**

- **Several weak and strong monsoon years occurred in the past which were not associated with El Niño and La Niña events, respectively.**

Proposal

- **instead of looking at the correlation between the seasonal mean ISMR and ENSO events, the emphasis should be towards estimating the influence of the El Niño and La Niña events on the frequency (occurrence) of intraseasonal active and break spells of the ISMR.**

El Niño and La Niña years during 1901-2004

- ✧ An El Niño (La Niña) event is said to occur if 5-month running means of sea surface temperature (SST) anomalies in the Niño 3.4 region [5°N-5°S, 120°W-170°W] exceed 0.4°C (– 0.4°C) for 6 months or more.

- ✧ A total of 26 El Niño years and 23 La Niña years identified using the abovementioned definition during 1901-2004.

El Niño years	1902, 1905, 1911, 1914, 1918, 1923, 1925, 1930, 1939, 1940, 1941, 1951, 1953, 1957, 1963, 1965, 1968, 1972, 1976, 1982, 1986, 1991, 1994, 1997, 2002, 2004
La Niña years	1903, 1909, 1910, 1916, 1924, 1933, 1938, 1942, 1949, 1950, 1954, 1955, 1956, 1963, 1964, 1970, 1973, 1975, 1984, 1988, 1995, 1998, 1999

Active and Break Spells of ISMR

- Rainfall Dataset: $1^o x 1^o$ daily gridded raingauge data analyzed into regular grid boxes over the Indian subcontinent for 104 years (1901-2004).

- A time series representative of the ISMR is obtained by area averaging the daily gridded rainfall anomaly of 104 years over the monsoon trough area 68.5 E - 90.5 E, 15.5 N - 29.5 N for the Jun-Sep (JJAS) season of each year.

- Break Spells : period during which the rainfall anomaly normalized by its standard deviation is less than -1.0, consecutively for three days or more.

- Active Spells: periods during which the rainfall anomaly normalized by its standard deviation is more than +1.0, consecutively for three days or more.

- Number of break spells during:
  - El Niño years: 66
  - La Niña years: 34
  - Normal years: 122

Methodology:

- Number of break spells of each duration (i.e. of 3 days, 4 days, 5 days, etc.) is divided by the total number of break spells to obtain probability (normalized value) corresponding to that break spell length.

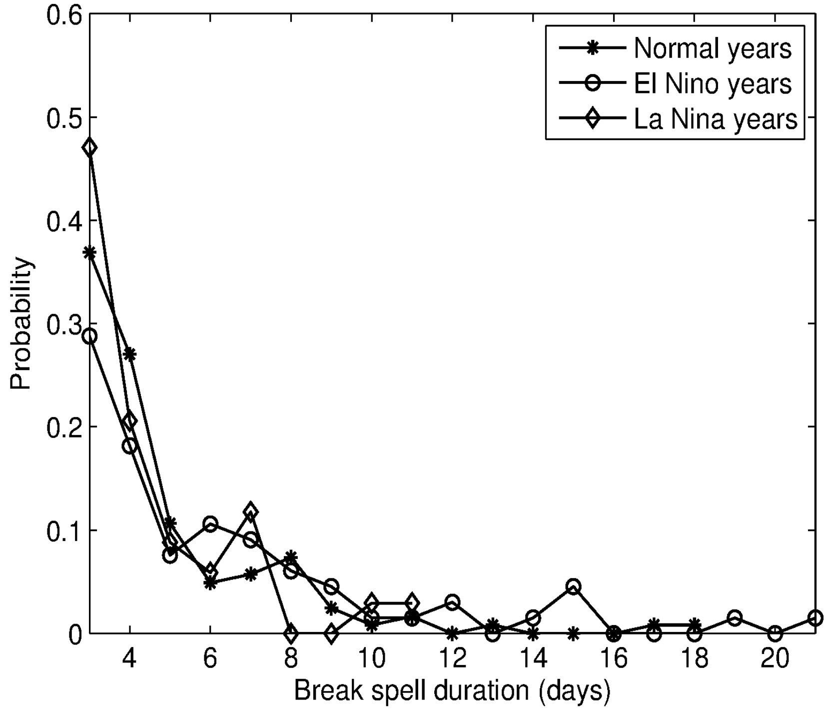
- Break spells are classified into two categories, namely, short break spells and long break spells.

- Break spell duration of 3-7 days: Short break spells

- Break spell duration greater than 7 days: long break spells

Probability (in % age) of break spell duration

Category	Normal years	El Niño years	La Niña years
Short break spells (3-7 days)	87	74	90
Long break spells (>7 days)	13	26	10



- These probabilities reveal interesting facts.
- During the El Niño years, the probability of shorter break spells decreases whereas the probability of longer breaks increases.
- On the other hand, during the La Niña events, the probability of longer breaks decreases whereas that of shorter breaks increases.

- A similar analysis is made for the active spells duration.

- A total of 51, 67, and 140 active spells are observed during El Niño years, La Niña years, and normal years, respectively.

- The duration of break spells is on an average longer than active spells (for example, longest break spell is of 21 days as compared to longest active spell of 11 days).

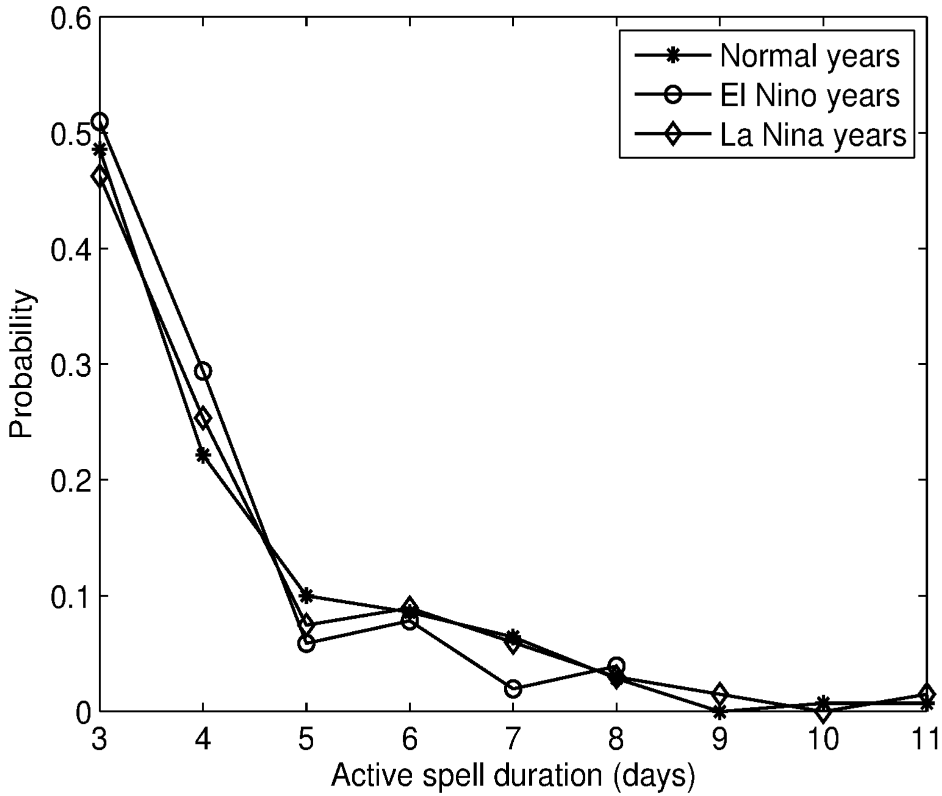
- Breaks tend to have a longer life-span than active spells: while, almost 80% of the active spells last 3-4 days, only 40% of the break spells are of such short duration.

- Active spells with duration of 3-4 days: short active spells

- Active spells with duration greater than 4 days: long active spells

Probability (in %age) of active spell duration

Category	Normal years	El Niño years	La Niña years
Short active spells (3-4 days)	73	81	68
Long active spells (>4 days)	27	19	32



- During the El Niño years, the shorter active spells become more frequent whereas longer active spells become less frequent.

- On the other hand, the frequency of longer active spells increases whereas that of shorter active spells decreases during the La Niña events.

- To put the results in perspective, a similar probability analysis is made for strong and weak monsoon years.
- Strong monsoon years: AISMR > 1 standard deviation above the mean
- Weak monsoon years: AISMR < 1 standard deviation below the mean

Strong and Weak Monsoon years during 1901-2004

Strong Monsoon years	1910, 1916, 1917, 1933, 1942, 1947, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994
Weak Monsoon years	1901, 1904, 1905, 1911, 1918, 1920, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004

Probabilities during Strong and Weak Monsoon years

- Strong monsoon years: probability of short break spells increases
- Weak monsoon years: probability of long break spells increases
- Probability values are also close to their respective values during La Nina and El Nino events, respectively, as expected.

Category	Normal years	El Niño years	La Niña years	Strong Monsoon years	Weak Monsoon years	Weak but No El Nino years
Short break spells (3-7 days)	87	74	90	89	75	86
Long break spells (>7 days)	13	26	10	11	25	14

Separating out and demonstrating the influence of the El Nino on the ISMR

Weak but No El Nino years: Break spell duration during those weak monsoon years, which were not forced by the El Nino events

Category	Normal years	El Niño years	La Niña years	Strong Monsoon years	Weak Monsoon years	Weak but No El Nino years
Short break spells (3-7 days)	87	74	90	89	75	86
Long break spells (>7 days)	13	26	10	11	25	14

It is interesting to note that these probabilities are nearly the same as during the normal years thus confirming the role of the El Nino in causing longer breaks.

- Strong monsoon years: probability of long active spells increases
- Weak monsoon years: probability of short active spells increases
- The probabilities during these years are also close to their respective values during La Nina and El Nino events, respectively, as expected.
- *'Strong but No La Nina years': strong monsoon years which were not forced by the La Nina events: the probabilities are same as during the normal years thus illustrating the impact of the La Nina events in causing longer active spells.*

Category	Normal years	El Niño years	La Niña years	Strong Monsoon years	Weak Monsoon years	Strong but No La Nina years
Short active spells (3-4 days)	73	81	68	62	75	73
Long active spells (>4 days)	27	19	32	38	25	27

Physical Mechanism !!!!

- Our results are in conformity with the modeling study performed by Prasanna and Annamalai (2012) where they estimated moisture and moist energy budgets to explain extended monsoon breaks

- Dry advection is the principal moist process to initiate extended breaks

- The net radiative flux due to cloud-radiation interaction plays an important role in maintaining extended breaks, the duration of which is further amplified during the El Nino events

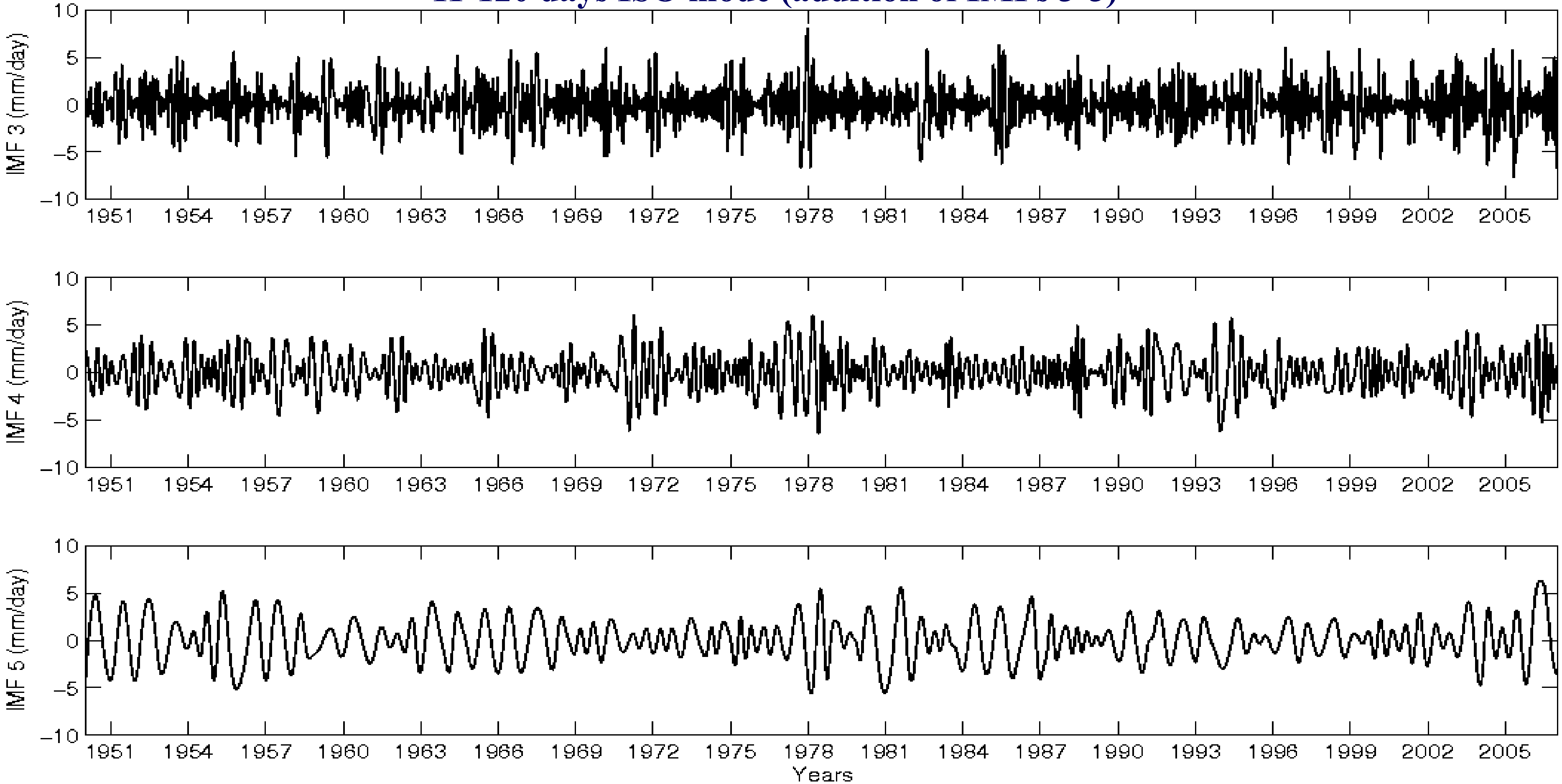
Advantage:

- The information about the frequency of active (break) spells may become potentially useful for agricultural planning and preparedness during a particular summer monsoon season considering the fact that it has now become possible to predict El Niño and La Niña events 4-6 months in advance to a good accuracy.

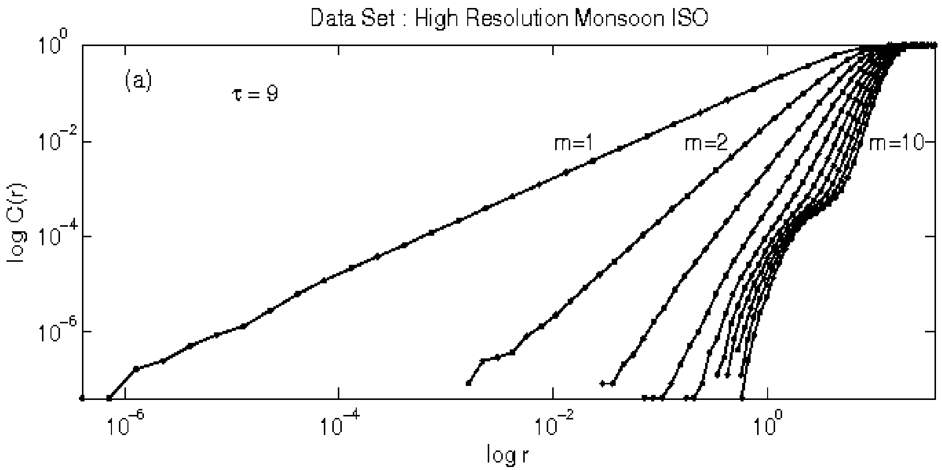
Quantifying predictability of Indian summer monsoon intraseasonal oscillations using nonlinear time series analysis

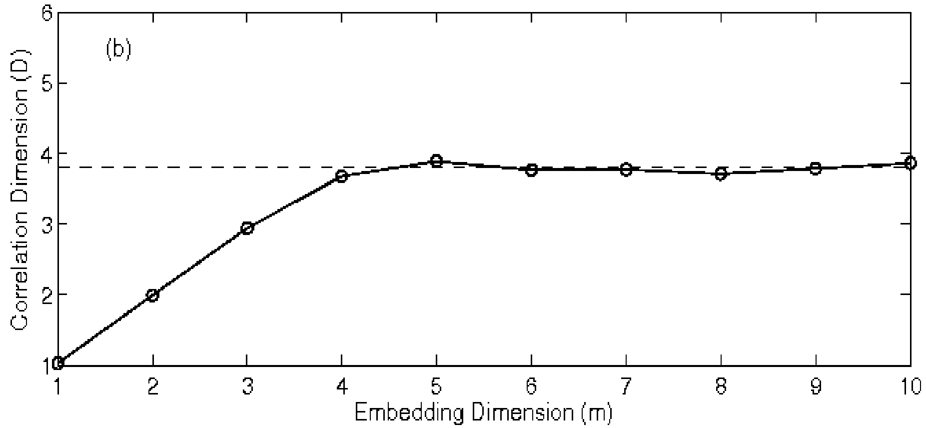
The chaotic time series analysis is used to estimate the predictability of the Indian summer monsoon ISOs. An index of the ISO is constructed using the daily gridded high-resolution (0.25 x 0.25) Indian summer monsoon rainfall dataset during 1951–2007.

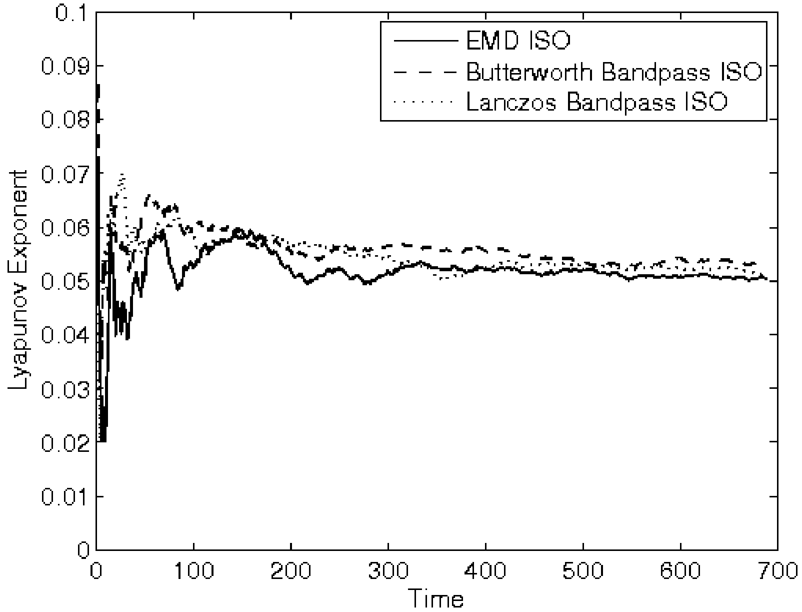
11-120 days ISO mode (addition of IMFs 3-5)

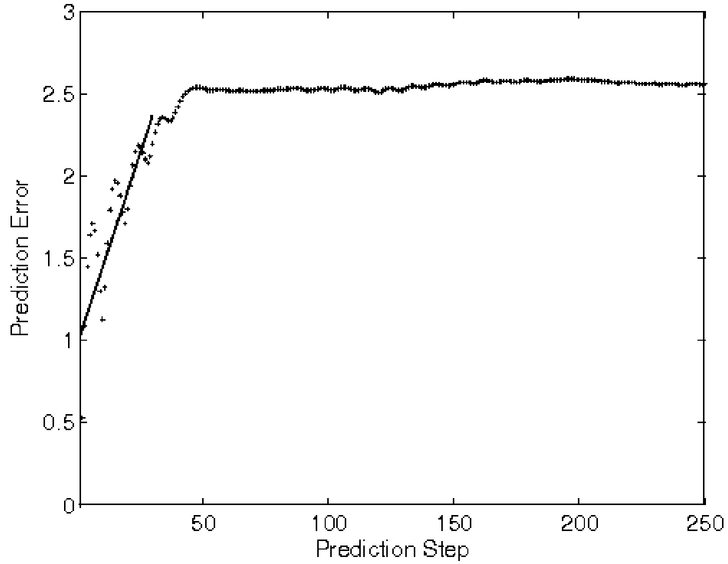


Dwivedi, Meteorologische Zeitschrift, 21, 413-419, 2012









❖ A low-dimensional chaotic attractor for the monsoon ISO is identified. A minimum of 4 variables and a maximum of 5 variables should be able to simulate the ISO.

❖ The largest Lyapunov exponent of the ISO index time series is 0.05. The limit of predictability of the monsoon ISO is nearly 3 weeks.

Dwivedi, Meteorologische Zeitschrift, 21, 413-419, 2012

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THANK YOU FOR YOUR PATIENCE