ISSN 0252-1075
Research Report No. RR-074

Contributions from
Indian Institute of Tropical Meteorology

SIGNATURES OF A UNIVERSAL SPECTRUM FOR ATMOSPHERIC GRAVITY WAVES IN SOUTHERN OSCILLATION INDEX TIME SERIES

by

A.M.SELVAM,
M.K.KULKARNI,
J.S.PETHKAR
and
R.VIJAYAKUMAR

PUNE - 411 008
INDIA

DECEMBER 1997

CONTENTS

Signatures of a Universal Spectrum for Atmospheric Gravity Waves in Southern Oscillation Index Time Series

A.M.Selvam, M.K.Kulkarni, J.S.Pethkar and R.Vijayakumar

Indian Institute of Tropical Meteorology, Pune 411 008, India

Abstract

Continuous periodogram analyses of seasonal mean Southern Oscillation Index (SOI) time series for various sets of 133, 100, 50 and 25 years available for the interval 1852-1984 show that the power spectra follow the universal and unique inverse power law form of the statistical normal distribution. Inverse power law form for the power spectra of temporal fluctuations implies long-range temporal correlations and is a signature of self-organized criticality in SOI. The above results are in agreement with a recently developed cell dynamical system model for atmospheric flows which predicts the observed self-organized criticality as intrinsic to quantum-like mechanics governing atmospheric flow dynamics. Universal spectrum for interannual variability rules out linear trends in SOI.

Keywords: Southern Oscillation Index, Self-organized Criticality, Universal Spectrum for interannual variability, Climate Change Prediction

1. Introduction

The Southern Oscillation (SO) refers to the marked out-of-phase relationship between pressure over the Indonesian-Australian region and pressure over the southeast Pacific and is closely associated with planetary scale circulation anomalies (Philander 1990, Chao and Philander 1991, Yasunari 1991, Drasdowsky and Williams 1991). Power spectral analyses reveal that the Southern Oscillation incorporates dominant quasi-periodicities such as the Quasi-Biennial Oscillation (QBO) and the 3-7 years El Nino cycle embbed in a broadband continuum of eddies (Bhalme and Jadhav 1984; Philander 1990; Burroughs, 1992). Since SO refers to surface pressure perturbations, the fluctuations in SO when resolved as an eddy continuum may be attributed to atmospheric gravity (buoyancy) waves. The future evolution pattern of global atmospheric flow structure as recorded in the Southern Oscillation is determined by these dominant cycles in combination with the background 'noise', namely the broadband continuum which contributes appreciably to the total variance. The physics of the symbiotic (cooperative) existence of the dominant cycles with the background continuum is not yet identified and therefore total predictability of atmospheric flow pattern is not possible (Lorenz 1990, Tsonis and Elsner, 1990). It is therefore important to identify and quantify the physics underlying the multiple scale, i.e. broadband continuum structure of global atmospheric flows as recorded in the Southern Oscillation for predictability studies (Cai and Mak 199O, Barnett 1991). Atmospheric flows exhibit long-range spatiotemporal correlations manifested as the self-similar fractal geometry to the global cloud cover pattern and the inverse power law form for the atmospheric eddy energy spectrum documented by Lovejoy and Schertzer (1986) and Tessier et. al. (1993). Such long-range spatiotemporal correlations are ubiquitous to real world dynamical systems and are now identified as signatures of self-organized criticality (Bak, Tang and Wiesenfeld 1988;Bak and Chen 1989). The physics of self-organized criticality is not yet identified. In this paper a recently developed non-deterministic cell dynamical system model for atmospheric flows (Mary Selvam 1990,1993a,b,1996; Mary Selvam et al 1992;Selvam 1994;Selvam et al. 1994,1995,1996; Selvam and Radhamani, 1994,1995; Selvam and Joshi 1995) is summarized. The model predicts the following (1) The observed long-range spatiotemporal correlations in atmospheric flows are intrinsic to quantum-like mechanical laws governing atmospheric flow dynamics. (2) Atmospheric flow structure consists of a nested continuum of vortex roll circulations with two-way ordered energy feedback between the larger and smaller scales. (3) Atmospheric eddy energy spectrum follows the universal inverse power law form of the statistical normal distribution.(4) Atmospheric eddy continuum has embedded in it dominant wavebands whose peak periodicities are functions of the golden mean. Continuous periodogram analyses of seasonal mean Southern Oscillation Index (SOI) (Wright 1989) for various sets of 133 100, 50 and 25 years available in the interval 1852-1984 indicate that the power spectra follow the universal and unique characteristics of the statistical normal distribution in agreement with model predictions. The important result of the present study is the unique quantification for the power spectra of the temporal fluctuations of SOI in terms of the statistical normal distribution implying predictability of the total pattern of fluctuations.Universal spectrum for temporal fluctuations of SOI rules out linear trends.Energy input into the atmospheric eddy continuum due to global warming(man made) will result in propagation of energy to all scales resulting in intensification of fluctuations,noticeable immediately in high frequency fluctuations such as the QBO and EL NINO.

2. Multifractal Structure of Space-Time Fluctuations

Nonlinear dynamical systems in nature such as atmospheric flows exhibit complex spatial patterns, e.g., cloud geometry, that lack a characteristic (single) length scale concomitant with temporal fluctuations that lack a single time scale. The mathematical concept of 'fractals' introduced by Mandelbrot (1977) provides powerful tools for describing and quantifying the universal symmetry of self-similarity (Schroeder 1991) underlying the seemingly irregular complex geometrical shapes and temporal fluctuations.

2.1 Fractal Geometry

Objects in nature are selfsimilar fractals, i.e. the internal small-scale structure resembles the whole object in shape. The fractal dimension **D** of such a self-similar object is given as

$$\mathbf{D} = \frac{\mathbf{d \ln M}}{\mathbf{d \ln R}}$$

where **M** is the mass contained within a distance **R** from a point in the extended object. A graph of **M** versus **R** on logarithmic scale will give a straight line of negative slope **D**, i.e., the graph exhibits inverse power law form indicating long-range spatial correlations. Constant value for fractal dimension **D** indicates logarithmic stretching over the length scale **R**. Objects in nature exhibit multifractal structure, i.e. the fractal dimension **D** varies with length scale **R** range. The region of constant fractal dimension **D** is associated with scale invariance, namely, the large and small scale structures are related to each other by only the scale ratio independent of the details of nature of growth.

2.2 Fractals in Time

Spatially extended fractal objects in nature support fluctuations of dynamical processes on all time scales. The power spectra of such broadband fluctuations exhibit inverse power-law of form $1/f^{\alpha}$ where f is the frequency and α the exponent. In general, α decreases with f and approaches 1 for low frequencies. Such spectra, described as $1/f$ or $1/f$-like spectra of temporal fluctuations are ubiquitous to dynamical systems in nature (West and Shlesinger 1989;West 1990) and has been the subject of extensive investigation during the last 30-40 years. The frequency range over which α is constant therefore exhibits self-similarity or scale invariance in temporal fluctuations, i.e., the fluctuations are fractals in time. The intensity or variance of longer and shorter period fluctuations are mutually related by a scale factor alone independent of the nature of dynamical processes. The fluctuations exhibit long-range temporal correlations. Also, temporal fluctuations exhibit multifractal structure since α varies for different ranges of frequency f. $1/f$ power-law would seem natural and white nose (flat distribution) would be the subject of involved investigation. (West and Shlesinger 1989).

2.3 Self-Organized Criticality : Space-Time Fractals

Till very recently (1988), fractal geometry to the spatial pattern and fractal fluctuations in time of dynamical processes of the same extended dynamical system were treated as two disparate multidisciplinary fields of research (Bak and Chen 1989). The long-range spatiotemporal correlations underlying spatial and temporal power-law behavior of dynamical systems was identified as a unified manifestation of self-organized criticality in 1988 (Bak et al., 1988; Stanley, 1995).

The unifying concept of self-organized criticality underlying fractals, self-similar scaling, broadband frequency spectra and inverse power-law distribution offer new and powerful means of describing certain basic aspects of spatial form and dynamical processes in a dynamical system. The systems in which self-organized criticality is observed range from the physical to the biological to the social. The physical mechanism underlying the observed self-organized criticality is not yet identified. However, the long-range spatial and temporal correlations underlying dynamical evolution implies predictability in space and time of the pattern of evolution of the dynamical system , for example , atmospheric flows.

3. Cell Dynamical System Model for Atmospheric Flows

In summary, the model (Mary Selvam, 1990; Mary Selvam et al., 1992; Mary Selvam, 1993b) is based on Townsend's (Townsend, 1956) concept that large eddies can be visualized as envelopes of enclosed turbulent eddies in turbulent shear flows. The root mean square (r.m.s.) circulation speed **W** of large eddy of radius **R** is the integrated mean of the r.m.s. circulation speeds $\mathbf{w_*}$ of enclosed turbulent eddies of radius **r** and is given as

$$\mathbf{W}^2 = \frac{2}{\pi}\frac{\mathbf{r}}{\mathbf{R}}\mathbf{w_*}^2 \tag{1}$$

The eddy length scale ratio **r/R** is equal to the phase angle $\mathbf{d\theta}$ between the eddies. Therefore the phase angle is directly proportional to the variance i.e.,

$$\mathbf{W}^2 \propto \mathbf{d\theta} \tag{2}$$

(2) Since large eddy is the integrated mean of enclosed turbulent eddies, the energy (kinetic) of large eddies follow normal distribution characteristics according to the *Central Limit Theorem* in *Statistics*(Mood and Graybill 1963). The square of the eddy amplitude, namely, the variance, therefore, represents the probability of occurrence. The above result that the additive amplitudes of eddies, when squared, represent the probability density is observed in the subatomic dynamics of quantum systems such as the electron or photon(Maddox 1988). Atmospheric flows, therefore follow quantum-like mechanical laws.

The model also predicts the logarithmic wind profile relationship for atmospheric flows. The overall envelope of the large eddy traces a logarithmic spiral with the quasiperiodic Penrose tiling pattern for the internal structure. Atmospheric circulation structure therefore consists of a nested continuum of vortex roll circulations (vortices within vortices) with a two-way ordered energy flow between the larger and smaller scales. Such a concept is in agreement with the observed long-range spatiotemporal correlations in atmospheric flow pattern. Conventional power spectrum analysis of such logarithmic spiral circulation structure will reveal a continuum of eddies with progressive increase in phase. The conventional power spectrum plotted as the percentage contribution to total variance versus the logarithm of frequency (period) will now represent the eddy probability density versus the standard deviations of the eddy fluctuations since the logarithm of the eddy wavelength represents the standard deviation, i.e., the root mean square (r.m.s.) value of eddy fluctuations. This follows from the concept of logarithmic wind profile and also that the r.m.s. value of eddy fluctuations at each stage form the mean level for the next stage of eddy growth. The r.m.s. value of eddy fluctuations can be represented in terms of statistical normal distribution as follows. A normalized standard deviation t=0 corresponds to cumulative percentage probability density equal to 50 for the mean value of the distribution. Since the logarithm of the wavelength represents the r.m.s. value of eddy fluctuations, the normalized standard deviation t is defined for the eddy energy spectrum as

$$\mathbf{t = (\log L / \log T_{50}) - 1} \tag{3}$$

where **L** is the period in days and T_{50} is the period up to which the cumulative percentage contribution to total variance is equal to 50 and **t** = 0. Further, log $\mathbf{T_{50}}$ also represents the mean value for the r.m.s. eddy fluctuations and is consistent with the concept of the mean level represented by r.m.s. eddy fluctuation. Power spectral analysis will also show that the eddy continuum has embedded dominant wavebands, the bandwidth increasing with period length. The dominant peak periodicities $\mathbf{P_n}$ are given as

$$\mathbf{P_n = \tau^n (2+\tau) T} \tag{4}$$

where τ is the golden mean equal to $(1+\sqrt{5})/2 = 1.618$, **T** is the primary perturbation time period equal to the annual (summer to winter) cycle of solar heating in the present study and **n** is an integer ranging from negative to positive values including zero. In the following section it is shown that continuous periodogram analyses of SOI exhibit the signature of model predicted quantumlike mechanics or self-organized criticality i.e., the power spectra follow the universal inverse power law form of the statistical normal distribution.

4. Data and Analysis

The mean Southern Oscillation Index (SOI) for the four seasons, December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON) for the period 1852 to 1984 (Wright 1989) were used for continuous periodogram analyses (Jenkinson 1977) for the following sets of time series data periods. (1) One set of 133- years (1852- 1984). (2) One set of 100-years (1852-1951). (3) Two sets of 50-years each (1852-1901, 1935-1984). (4) Six sets of 25-years each (1852-1876, 1877-1901, 1902-1926, 1927-1951, 1952-1976, 1960-1984). The broadband power spectrum of the SOI time series can be computed accurately by the elementary but very powerful method of analysis developed by Jenkinson (1977) which provides a quasi-continuous form of the classical periodogram allowing systematic allocation of the total variance and degrees of freedom of the data series to logarithmically spaced elements of the frequency range (0.5 to 0). The periodogram is constructed for a fixed set of 10000 (m) periodicities which increase geometrically as $L_m = 2\exp(Cm)$ where C= .001 and m= 0, 1, 2....m. The data series Y_t for the N data points was used. The periodogram estimates the set of $A_m \cos(2\pi\nu_m S - \phi_m)$ where A_m, ν_m and ϕ_m denote respectively the amplitude, frequency and phase angle for the m^{th} periodicity and S the time in years. The cumulative percentage contribution to total variance was computed starting from the high frequency side of the spectrum. The period T_{50} up to which 50% contribution to total variance occurs is taken as reference and the normalized standard deviation **t** values are computed as (Equation.3)

$$\mathbf{t = (\log L_m / \log T_{50}) - 1}$$

The cumulative percentage contribution to total variance is plotted versus the **t** values in Figure1 for 133, 100, and 50 years and in Figure 2 for the six sets of 25-years time series data for the four seasons DJF, MAM, JJA and SON. The cumulative normal probability density distributions corresponding to the normalized standard deviation **t** values are also shown in Figures 1-2. It is seen that the atmospheric eddy energy spectrum plotted in this manner closely follows the statistical normal distribution. The short horizontal lines in the lower part of Figures 1-2 indicate the lower limit above which the fit is good at 95% confidence level for the chi- square test (Spiegel 1961). Tables 1-2 give the following results of the periodogram analyses corresponding to Figures 1-2 for the different sets of time series considered in this study. (1) Mean and standard deviation of the data series. (2) The atmospheric eddies of periodicities up to T_{50}, T_{75} and T_{90} which contribute respectively to 50, 75 and 90 percent of the total variance. (3) The periodicities contributing maximum normalized variance in wavebands with normalised variance equal to or exceeding 1. Almost all of the SOI data series used are found to exhibit normal distribution characteristics except for a few marked by asterisks in Tables 1-2.

5. Discussion and Conclusion

From Figures 1-2 it is seen that the spectra of temporal (years) fluctuations of Southern Oscillation Index follow the universal and unique inverse power law form of the statistical normal distribution such that the square of the eddy amplitude represents the eddy probability density corresponding to the normalized standard deviation **t** equal to $[(\log L_m / \log T_{50})-1]$ where L_m is the period in days and T_{50} refers to the period up to which the cumulative percentage contribution to total variance is equal to 50. Inverse power law form for the power spectra of temporal fluctuations is a signature of self-organized criticality in the nonlinear variability of Southern Oscillation Index. The unique quantification for self-organized criticality in terms of the statistical normal distribution presented in this paper implies predictability of the total pattern of fluctuations in the SOI over a period of time ranging from 133-years to 25-years in the present study. It may therefore be possible to predict future trends in SOI. Universal spectrum for interannual variability rules out linear secular trends in SOI.

The peak periodicities in the wave-bands with normalized variance equal to or more than 1 (Tables 1-2) correspond closely to the time periods equal to $\mathbf{T\,(2+\tau) = 3.6T}$, $\mathbf{T\tau(2+\tau)=5.8T}$, $\mathbf{T\tau^2(2+\tau)=9.5T}$, $\mathbf{T\tau^3(2+\tau) = 15.3.T}$, $\mathbf{T\tau^4\,(2+\tau) = 24.8T}$ where **T**, the primary perturbation time period is the annual cycle of solar heating. The quasibiennial oscillation ($\approx$ 2 years) which is present in all the data sets analysed may correspond to the period $\mathbf{T(\,2/\tau+1) = 2.2T}$ of the small scale circulation internal to the primary circulation according to the concept of the eddy continuum energy structure (Equation 1). The dominant periodicities in the Southern Oscillation Index time series may therefore be expressed as functions of the golden mean(τ).

Further, short term periodicities in SOI ranging up to 5-years contribute to as much as 50% of the total variance. Future SOI values may therefore be determined by dominant short term periodicities such as the QBO and ENSO in atmospheric flows. In summary, the atmospheric eddy energy spectrum follows the inverse power law form of the statistical normal distribution and implies long-range temporal correlations which is a signature of self-organized criticality in atmospheric flows.

Universal spectrum for interannual variability rules out linear trends in SOI, and therefore, in global weather patterns. Enhanced energy input to the atmospheric eddy continuum due to man-made greenhouse gas induced atmospheric warming will result in propagation of energy to all scales and intensification of weather systems of all scales. Such climate change may be seen immediately as intensification of high frequency fluctuations such as QBO, ENSO and shorter periodicities. The above model predictions are consistent with the following studies. Agee (1991) finds an increase in frequency of cyclone and anticyclone events for the Northern Hemisphere during periods of warming and a decrease during periods of cooling as determined from NASA temperature for this century. Recent increases have been found in the intensity of the winter atmospheric circulation over the extratropical Pacific and Atlantic. These findings are reflected in an analyses of the climate of 1980s (Houghton et al., 1992,1995).

6. Acknowledgement : The author is grateful to Dr. A.S.R. Murty for his keen interest and encouragement during the course of the study. Thanks are due to Mr. M.I.R. Tinmaker for typing the manuscript.

7. References

Agee, E.M., 1991, Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over the northern hemisphere, *J. Climate*, **4**, 263-267

Bak, P., Tang, C. and Wiesenfeld, K.,1988, Self-organized criticality, *Phys. Rev.* **A 38**, 364-374.

Bak, P. and Chen, K.,1989, The Physics of fractals, *Physica D* **38**, 5-12.

Barnett, T.P., 1991, The interaction of multiple time scales in the tropical climate system, *J.Climate* **4**, 269-285.

Bhalme,H.N., and Jadhav,S.K. 1984, The southern oscillation and its relation to the monsoon rainfall.*J.Climate* **4**,509-520.

Burroughs, W.J., 1992, *Weather cycles : real or imaginary ?* Cambridge University Press, Cambridge, U.K., pp. 197.

Cai, M. and Mak M., 1990, Symbiotic relation between planetary and synoptic scale waves, *J.Atmos.Sci.* **47(24)**, 2953-2968.

Chao, Yi and Philander S.G., 1991, On the structure of the southern oscillation and evaluation of coupled ocean- atmosphere models", *TOGA notes* **3**, 1-8.

COADS,1985,*Comprehensive Ocean Atmosphere Data Set* Release 1. NOAA-ERL, Boulder, Co.

Drosdowsky, W. and Williams M, 1991, The southern oscillation in the Australian region, Part I: Anomalies at the extremes of the oscillation. *J.Climate* **4(6)**, 619-638.

Houghton,J.T.,Callander,B.A.,and Varney,S.K. 1992. *Climate Change 1992 : The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

Houghton,J.T.,Meira Filho,L.G.,Callander,B.A.,Harris,N.,Kattenberg,A. and Maskell,K. 1996. *Climate Change 1995 , Intergovernmental Panel on Climate Change* , Cambridge University Press, Cambridge.

Jenkinson, A.F.,1977, *A powerful elementary method of spectral analysis for use with monthly, seasonal or annual meteorological time series.* (U.K. Meteorol. Office) Met. O 13 Branch Memorandum No. 57, 1-23.

Lorenz, E.N., 1990, Can Chaos and intransitivity lead to interannual variability?, *Tellus* **42A**, 378-389.

Lovejoy, S., and Schertzer, D.1986, Scale invariance, symmetries, fractals and stochastic simulations of atmospheric phenomena, *Bull.Amer.Meteorol.Soc.*, **67**,21-32.

Maddox, J., 1988,Licence to slang Copenhagen? *Nature* **332**, 581.

Mandelbrot,1977, B.B. *Fractals : Form, Chance and Dimension*, W.H. Freeman,San Francisco,365 pp,.

Mary Selvam, A.,1990, Deterministic chaos, fractals and quantumlike mechanics in atmospheric flows, *Can.J.Phys.*, **68**, 831-841.

Mary Selvam, A., Pethkar, J.S. and Kulkarni, M.K.,1992, Signatures of a universal spectrum for atmospheric interannual variability in rainfall time series over the Indian region, *Int'l.J.Climatol.*, **12**, 137-152.

Mary Selvam, A.,1993a, Universal quantification for deterministic chaos in dynamical systems, *Appl.Math.Modelling* **17**, 642-649.

Mary Selvam, A.,1993b, A universal spectrum for atmospheric interannual variability of monsoon rainfall over India, *Adv.Atmos.Sci.*, **10(2)**, 221-226.

Mary Selvam, A.,1997, Quasicrystalline pattern formation in fluid substrates and phyllotaxis.In *Symmetry in Plants,* Barabe, D., and Jean, R.V. (Eds). No. 4, World Scientific Series in Mathematical Biology and Medicine, World Scientific, Singapore.

Mood, A.M., and Graybill F.A., 1963, *Introduction to the theory of statistics.* McGraw-Hill, New York.

Philander, S.G., 1990,*El Nino, La Nina and the Southern Oscillation* Academic Press, NY International Geophysical Series 46, pp.291.

Schroeder,1991, M. *Fractals, chaos and power laws.* W.H. Freeman, San Francisco, 417 pp.

Selvam, A.M., and Radhamani, M.,1994, Signatures of a universal spectrum for nonlinear variability in daily columnar total ozone content, *Adv.Atmos.Sci.* **11(3)**, 335-342.

Selvam, A.M., Joshi, R.R., and Vijayakumar, R.,1994, Self-organized criticality in COADS emperature time series : implications for climate prediction. *Proc. Air and Waste Management Association,* Int'l. Speciality Conf., Global Climate Change, April 5-8, 1994, Phoenix, Arizona, Air and Waste Management Association, Pittsburgh, USA, 196-205, 1994.

Selvam, A.M.,1994, The physics of deterministic chaos : implications for global climate model predictions, *Proc. Air and Waste Management Association,* Int'l. Speciality Conf., Global Climate Change, April 5-8, 1994, Phoenix, Arizona, Air and Waste Management Association, Pittsburgh, USA, 412-417, 1994.

Selvam, A.M., and Joshi, R.R.,1995, Universal spectrum for interannual variability in COADS global air and sea-surface temperatures, *Int'l.J.Climatol.* **15**, 613-623.

Selvam, A.M., Pethkar, J.S., and Kulkarni, M.K.,1995, Some unique characteristics of atmospheric interannual variability in rainfall time series over India and the United Kingdom, *Adv.Atmos.Sci.* **12(3),** 377-385.

Selvam, A.M. and Radhamani, M., Universal spectrum for short period (days) variability in atmospheric total ozone, *Mausam* **46(3),** 297-303.

Selvam, A.M., Pethkar, J.S., Kulkarni, M.K., and Vijayakumar, R.,1996, Signatures of a universal spectrum for atmospheric interannual variability in COADS surface pressure time series, *Int'l. J. Climatol.,* **16**, 393-404.

Spiegel, M.R.,1961, *Statistics.* McGraw-Hill Book Co., NY, 359 pp.

Stanley, H.E.,1995 ,Power laws and universality, *Nature* **378**, 554.

Tessier, Y., Lovejoy, S., and Schertzer, D.,1993, Universal multifractals: theory and observations for rain and clouds, *J.Appl.Meteor.*, **32(2)**, 223-250.

Townsend, A.A.,1956, *The structure of turbulent shear flow*, Cambridge University Press, Cambridge.

Tsonis, A.A. and Elsner J.B., 1990, Multiple attractors, fractal basins and long-term climate dynamics, Beitr. Phys. Atmosph. 63 (3,4), 171-176.

Wright, P.B., 1989, Homogenized long-period southern oscillation. indices, Int'l. J.Climatol 9(1), 33-54.

Yasunari, T., 1991, Monsoon and ENSO: A coupled ocean/land/atmosphere system, *TOGA notes* **2**, 9-12.

West , B.J. and Shlesinger, M.F.1989. On the ubiquity of 1/f noise. *Int'l. J. Mod. Phys. B*, **3(6)**, 795 - 819.

West, B.J.1990. Physiology in fractal dimension.*Ann.Biomed.Eng.*, ,**18** , 135-149.

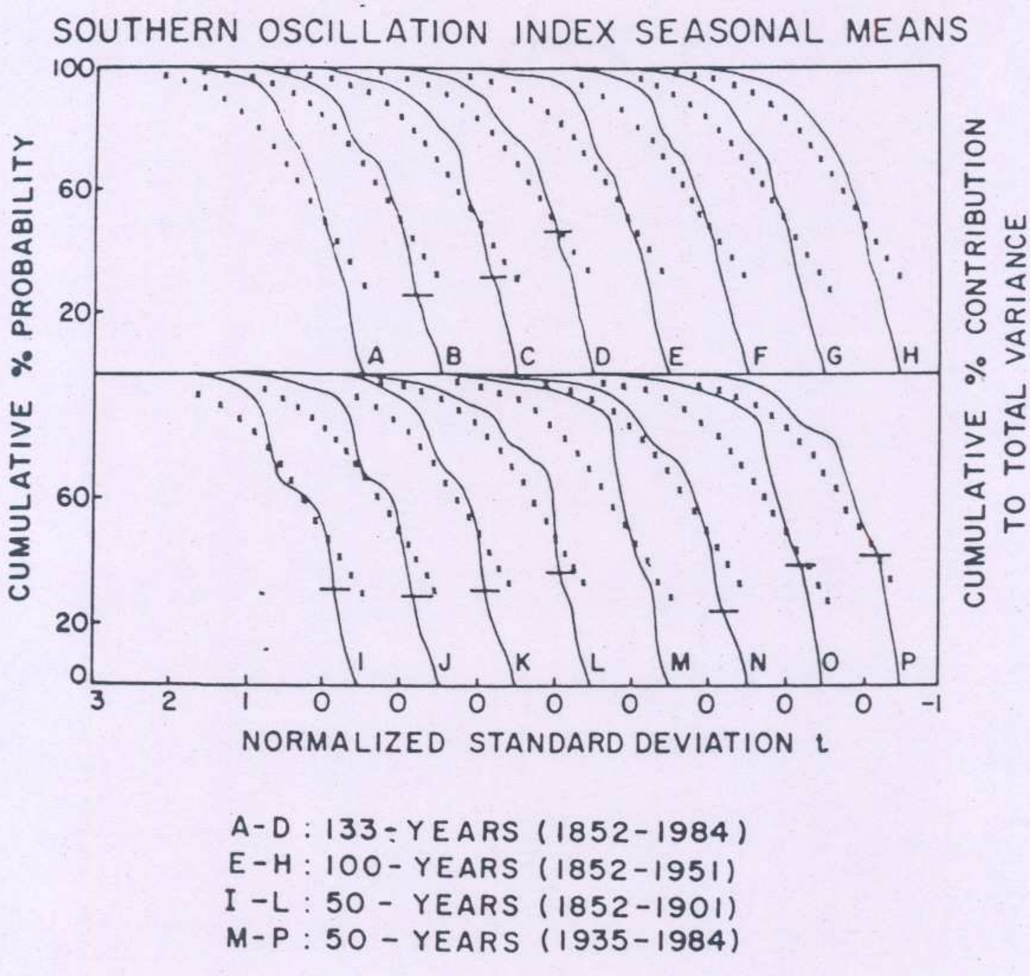
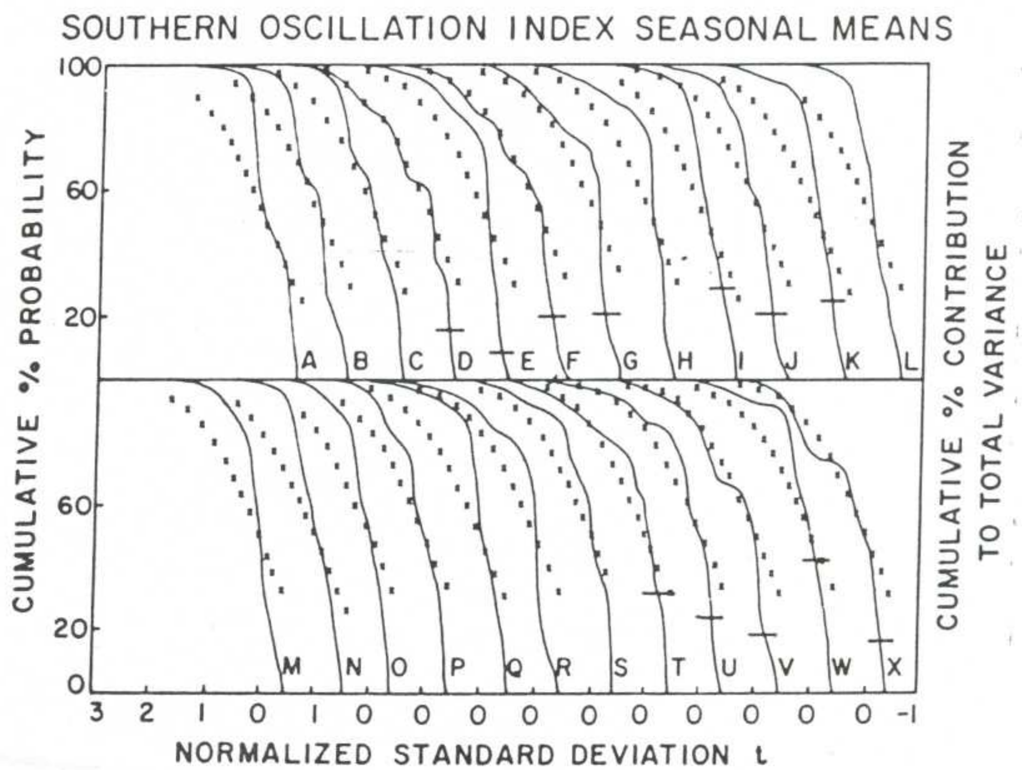


Figure 1 : Power spectra of seasonal (DJF, MAM, JJA & SON) mean Southern Oscillation Index time series for 100 years, 133 years & two sets of 50 years.



A-D : 25-YEARS (1852-1876) M-P : 25-YEARS (1927-1951)
E-H : 25-YEARS (1877-1901) Q-T : 25-YEARS (1952-1976)
I-L : 25-YEARS (1902-1926) U-X : 25-YEARS (1960-1984)

Figure 2 : Same as Fig.1 for 6 sets of 25 years