Fractal Fluctuations and Climate Cycles in Atmospheric Flows

Fractal Fluctuations and Climate Cycles in Atmospheric Flows:

Order in Chaos

Edited by

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To:
My brothers Daniel Muthusamy and Gabriel Muthusamy

CONTENTS

PREFACE

Current concepts in meteorological theory and limitations are as follows. The non-equilibrium system of atmospheric flows is modeled with assumption of local thermodynamic equilibrium; molecular motion of atmospheric component gases is implicitly embodied in the gas constant. Non-equilibrium systems can be studied numerically, but despite decades of research, it is still very difficult to define the analytical functions from which to compute their statistics and have an intuition for how these systems behave. Realistic mathematical modeling for simulation and prediction of atmospheric flows requires alternative theoretical concepts and analytical or error-free numerical computational techniques and therefore comes under the field of 'General Systems research' as explained in the following.

Space-time power law scaling and non-local connections exhibited by atmospheric flows have also been documented in other non-equilibrium dynamical systems, e.g. financial markets, neural network of brain, genetic networks, internet, road traffic, and flocking behavior of some animals and birds. Such universal behavior has been the subject of intensive study in recent years as 'complex systems' under the subject headings self-organized criticality, nonlinear dynamics and chaos, network theory, pattern formation, information theory, and cybernetics (communication, control, and adaptation). A complex system is a system composed of many interacting parts, such that the collective behavior or "emergent" behaviors of those parts together is more than the sum of their individual behaviors. Weather and climate are emergent properties of the complex adaptive system of atmospheric flows. Complex systems in different fields of study exhibit similar characteristics and therefore belong to the field of 'General Systems'. The terms 'general systems' and 'general systems research (or general systems theory)' are due to Ludwig von Bertalanffy (1968). According to Bertalanffy, general systems research is a discipline whose subject matter is "the formulation and derivation of those principles which are valid for 'systems' in general".

Skyttner (2006) quotes basic ideas of general systems theory formulated by Fredrich Hegel (1770-1831) as follows:

i. The whole is more than the sum of the parts
ii. The whole defines the nature of the parts
iii. The parts cannot be understood by studying the whole
iv. The parts are dynamically interrelated or interdependent

In cybernetics, a system is maintained in dynamic equilibrium by means of communication and control between the constituent parts and also between the system and its environment.

This book is based on the author's research papers published during her tenure in the Indian Institute of Tropical Meteorology from 1966 to 1999.

Dynamical systems such as fluid flows, heart beat patterns, spread of infectious diseases, etc., exhibit self-similar, i.e., a zig-zag pattern of successive increases followed by decreases of all scales identified as fractal fluctuations. Fractal fluctuations signify non-local connections, i.e., long-range correlations in space and time manifested as inverse power-law form f^{α} for the power spectra. Extensive studies by Lovejoy and Schertzer (2012) and Bunde *et al*. (2013) have identified conclusively the self-similar fractal nature of fluctuations in meteorological parameters.

The Gaussian probability distribution used widely for analysis and description of large data sets underestimates the probabilities of occurrence of extreme events such as stock market crashes, earthquakes, heavy rainfall, etc. The assumptions underlying the normal distribution, such as fixed mean, standard deviation, and independence of data, are not valid for real world fractal data sets exhibiting a scale-free power-law distribution with fat tails (Selvam, 2009).

The study of power laws spans many disciplines, including physics, biology, engineering, computer science, the earth sciences, economics, political science, sociology, and statistics (Clauset *et al*., 2009; Kaniadakis, 2009).

The observed scale invariance or long-range space-time correlations imply inherent 'persistence' or 'memory' in the space-time fluctuation patterns and are identified as signatures of self-organized criticality (Bak *et al*., 1988) intrinsic to dynamical systems in nature.

The author has developed a general systems theory based on classical statistical physics for fractal fluctuations which predicts the following. (i) The fractal fluctuations signify an underlying eddy continuum, the larger eddies being the integrated mean of enclosed smaller-scale fluctuations. (ii)

The probability distribution of eddy amplitudes and the variance (square of eddy amplitude) spectrum of fractal fluctuations follow the universal Boltzmann inverse power law expressed as a function of the golden mean. (iii) Fractal fluctuations are signatures of quantum-like chaos since the additive amplitudes of eddies when squared represent probability densities analogous to the sub-atomic dynamics of quantum systems such as the photon or electron. (iv) The model predicted distribution is very close to statistical normal distribution for moderate events within two standard deviations from the mean but exhibits a fat long tail that is associated with hazardous extreme events.

The model concepts are independent of the exact details, such as the chemical, physical, physiological, etc. properties of the dynamical systems and therefore provide a general systems theory [Peacocke, 1989, Klir, 1992, Allegrini *et al*., 2004, Jean, 1994] applicable for all dynamical systems in nature.

The general systems theory model's prediction of universal inverse power law form for fractal fluctuations is shown to be followed by 10 different climatological data sets in the following ten chapters of this book.

Chapter 1 Signatures of a Universal Spectrum for Atmospheric Interannual Variability in Some Disparate Climatic Regimes

Chapter 2 Universal Spectrum for Short Period (days) Variability in Atmospheric Total Ozone

Chapter 3 Universal Inverse Power Law Distribution for Indian Region Rainfall

Chapter 4 Universal Inverse Power Law Distribution for Fractal Fluctuations in Dynamical Systems: Applications for Predictability of Inter - annual Variability of Indian and USA Region Rainfall

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Chapter 10 Identification of Self-Organized Criticality in Atmospheric Low Frequency Variability

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Abstracts

Chapter 1: Signatures of a Universal Spectrum for Atmospheric Interannual Variability in Some Disparate Climatic Regimes

Atmospheric flows exhibit long-range spatiotemporal correlations manifested as the fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations on all space-time scales ranging from turbulence (centimeters-seconds) to climate

(kilometers-years). Long-range spatiotemporal correlations are ubiquitous to dynamical systems in nature and are identified as signatures of self-organized criticality. Standard models in meteorological theory cannot explain satisfactorily the observed self-organized criticality in atmospheric flows. Mathematical models for simulation and prediction of atmospheric flows are nonlinear and do not possess analytical solutions. Finite precision computer realizations of nonlinear models give unrealistic solutions because of deterministic chaos, a direct consequence of round-off error growth in iterative numerical computations. Recent studies show that round-off error doubles on an average for each iteration of iterative computations. Round-off error propagates to the main stream computation and gives unrealistic solutions in numerical weather prediction (NWP) and climate models which incorporate thousands of iterative computations in long-term numerical integration schemes. An alternative non-deterministic cell dynamical system model for atmospheric flows described in this paper predicts the observed self-organized criticality as intrinsic to quantum-like mechanics governing flow dynamics. The model provides universal quantification for self-organized criticality in terms of the statistical normal distribution. Model predictions are in agreement with a majority of observed spectra of time series of several standard climatological data sets representative of disparate climatic regimes. Universal spectrum for natural climate variability rules out linear trends. Man-made greenhouse gas related atmospheric warming will result in intensification of natural climate variability, seen immediately in high frequency fluctuations such as QBO and ENSO and even shorter timescales. Model concepts and results of analyses are discussed with reference to possible prediction of climate change.

Chapter 2: Universal spectrum for short period (days) variability in atmospheric total ozone

Atmospheric total columnar ozone exhibits nonlinear variability on all time scales from days to years (WMO, 1985; Gao and Stanford, 1990; Prata, 1990). The quantification of the nonlinear variability, in particular, long-term trends in atmospheric total ozone, is an area of intensive research since the identification in recent years of the major spring-time Antarctic ozone hole and the general decreasing trend in stratospheric ozone throughout the high latitudes (Bojkov *et al*., 1990; Callis *et al*., 1991). In this paper, a recently developed cell dynamical system model for atmospheric flows (Selvam, 1990; Selvalm *et al*., 1992; Selvam 1993; Selvam and Radhamani, 1994; Selvam and Joshi, 1994) is summarized. The model predicts quantum-like mechanics for atmospheric flows extending up to the stratosphere and above (Sikka *et al*., 1988). The model predictions are in agreement with continuous periodogram analyses of sets of twenty to twenty five daily or up to 6-days means of atmospheric columnar total ozone content at five different locations.

The power spectra of atmospheric columnar total ozone follow the inverse power law form of the statistical normal distribution. Inverse power law form for the power spectra of temporal fluctuations is ubiquitous to real world dynamical systems and is a temporal signature of self-organized criticality (Bak *et al*., 1988) or deterministic chaos (Selvam, 1990) and implies long-range temporal correlations. Universal quantification for self-organized criticality in the temporal fluctuations of atmospheric columnar total ozone content implies predictability of the total pattern of fluctuations. Further, trends in atmospheric total ozone may also be predictable.

Chapter 3: Universal Inverse Power Law Distribution for Indian Region Rainfall

Space-time fluctuations of meteorological parameters exhibit self-similar fractal fluctuations. Fractal space-time fluctuations are generic to dynamical systems in nature such as fluid flows, spread of diseases, heart beat pattern, etc. A general systems theory developed by the author predicts universal inverse power law form incorporating the golden mean for the fractal fluctuations. The model-predicted distribution is in close agreement with observed fractal fluctuations of all size scales in the monthly total Indian region rainfall for the 141-year period 1871 to 2011.

Dynamical systems such as fluid flows, heart beat patterns, spread of infectious diseases, etc., exhibit self-similar, i.e., a zig-zag pattern of successive increases followed by decreases of all scales identified as fractal fluctuations. Fractal fluctuations signify non-local connections, i.e., long-range correlations in space and time. Lovejoy and Schertzer (2012) have done pioneering work during the last 30 years to identify conclusively the self-similar fractal nature of fluctuations in meteorological parameters. The Gaussian probability distribution used widely for analysis and description of large data sets underestimates the probabilities of occurrence of extreme events such as stock market crashes, earthquakes, heavy rainfall, etc. The assumptions underlying the normal distribution such as fixed mean, standard deviation, and independence of data, are not valid for real world fractal data sets exhibiting a scale-free power law distribution with fat tails (Selvam, 2009). There is now an urgent need to incorporate newly identified fractal concepts in standard meteorological theory for realistic simulation and prediction of atmospheric flows. The author has developed a general systems theory model (Selvam, 2012a, b; Selvam, 2013) for fractal fluctuations in dynamical systems. The model predicts universal inverse power law form incorporating the golden mean ($\tau \approx 1.618$) for the probability distribution of amplitudes of fractal fluctuations. The model predictions are in agreement with monthly total rainfall over the Indian region for the 141-year period 1871-2011.

Chapter 4: Universal Inverse Power law distribution for Fractal Fluctuations in Dynamical Systems: Applications for Predictability of Inter - annual Variability of Indian and USA Region Rainfall

Dynamical systems in nature exhibit self-similar fractal space-time fluctuations on all scales indicating long-range correlations and therefore the statistical normal distribution with implicit assumption of independence, fixed mean, and standard deviation cannot be used for description and quantification of fractal data sets. The author has developed a general systems theory based on classical statistical physics for fractal fluctuations which predicts the following. (i) The fractal fluctuations signify an underlying eddy continuum, the larger eddies being the integrated mean of enclosed smaller-scale fluctuations. (ii) The probability distribution of eddy amplitudes and the variance (square of eddy amplitude) spectrum of fractal fluctuations follow the universal Boltzmann inverse power law expressed as a function of the golden mean. (iii) Fractal fluctuations are signatures of quantum-like chaos since the additive amplitudes of eddies when squared represent probability densities analogous to the sub-atomic dynamics of quantum systems such as the photon or electron. (iv) The model-predicted distribution is very close to statistical normal distribution for moderate events within two standard deviations from the mean but exhibits a fat long tail that is associated with hazardous extreme events. Continuous periodogram power spectral analyses of available GHCN annual total rainfall time series for the period 1900 to 2008 for Indian and USA stations show that the power spectra and the corresponding probability distributions follow model predicted universal inverse power law form, signifying an eddy continuum structure underlying the observed inter-annual variability of rainfall. Global warming related atmospheric energy input will result in intensification of fluctuations of all scales and can be seen immediately in high frequency (short-term) fluctuations such as devastating floods/droughts resulting from excess/deficit annual, quasi-biennial, and other shorter period (years) rainfall cycles.

Atmospheric flows exhibit self-similar fractal fluctuations on all space-time scales ranging from turbulence scale of a few millimeters-seconds to planetary scale of thousands of kilometers-years. Fractal space-time fluctuations are ubiquitous to dynamical systems in nature such as fluid flows, population growth, stock market indices, heart beat patterns, etc. (Mandelbrot, 1975). The power (variance) spectra of fractal fluctuations follow inverse power law, also called $1/f$ noise, in the form f^{α} where f is the frequency and α the exponent and imply long-range space-time correlations since the variance (intensity of fluctuations) is a function of frequency f alone for the frequency range for which α is a constant. The study of power laws spans many disciplines, including physics, biology, engineering, computer science, the earth sciences, economics, political science, sociology, and statistics (Clauset *et al*., 2009; Kaniadakis, 2009). The observed scale invariance or long-range space-time correlations imply inherent 'persistence' or 'memory' in the space-time fluctuation patterns and are identified as signatures of self-organized criticality (Bak *et al*., 1988) intrinsic to dynamical systems in nature.

Lovejoy and Schertzer (2010) have given an exhaustive account of the observed scale invariant characteristics of atmospheric flows and emphasize the urgent need to incorporate the observed inverse power law scaling concepts in atmospheric sciences as summarized in the following. In spite of the unprecedented quantity and quality of meteorological data and numerical models, there is still no consensus about the atmosphere's elementary statistical properties as functions of scale in either time or in space. At present, the null hypotheses are classical so that they assume there are no long range statistical dependencies and that the probabilities are thin-tailed (i.e. exponential). However, we have seen that cascades involve long range dependencies and (typically) have fat tailed (algebraic) distributions in which extreme events occur much more frequently and can persist for much longer than classical theory would allow.

The question of which statistical model best describes internal climate variability on inter-annual and longer time scales is essential to the ability to predict such variables and detect periodicities and trends in them. For over 30 years the dominant model for background climate variability has been the autoregressive model of the first order (AR1). However, recent research has shown that some aspects of climate variability are best described by a "long memory" or "power-law" model. Such a model fits a temporal spectrum to a single power-law function, which thereby accumulates more power at lower frequencies than an AR1 fit. Power-law behavior has been observed in globally and hemi-spherically averaged surface air temperature (Bloomfield 1992; Gil-Alana 2005), station surface air temperature (Pelletier, 1997), geopotential height at 500 hPa (Tsonis *et al*., 1999), temperature paleoclimate proxies (Pelletier, 1997; Huybers and Curry, 2006), and many other studies (Vyushin and Kushner, 2009).

A general systems theory originally developed for atmospheric flows by Selvam (1990, 2005, 2007, 2009, 2010) predicts the observed self-organized criticality as a direct consequence of quantum-like chaos exhibited by fractal fluctuations generic to dynamical systems in nature. The model further predicts that the distribution of fractal fluctuations and the power spectrum (of fractal fluctuations) follow the same inverse power law which is a function of the golden mean τ ($\approx$ 1.618). Model predictions are in agreement with continuous periodogram power spectral analyses of annual rainfall time series for Indian and USA region stations obtained from The Global Historical Climatology Network (GHCN-Monthly) of the National Oceanic and Atmospheric Administration's National Climate Data Center data base for the period 1900 to 2008. The chapter is organized as follows. The general systems theory for self-similar fractal fluctuations is summarized in Section 2 and the application of classical statistical physics principles in general systems theory for the derivation of Boltzmann probability distribution for fractal fluctuations is discussed in Section 3. Details of data sets used for the study are given in Section 4. Analysis techniques and results are described in Section 5. Discussions of results and conclusions from the study are presented in Section 6.

Chapter 5: Universal Spectrum for Interannual Variability of Rainfall over India and Scotland: Implication for Prediction

Atmospheric flows exhibit fluctuations of all scales (space-time) ranging from turbulence (millimeters-seconds) to climate (thousands of kilometers-years). The apparently random fluctuations, however, exhibit long-range spatio-temporal correlations manifested as the self-similar fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations documented and discussed in detail by Lovejoy and his group [Tessier, Lovejoy and Schertzer, 1993; Tessier, *et al*., 1996]. Long-range spatiotemporal correlations are ubiquitous to dynamical systems in nature and are recently identified as signatures of self-organized criticality [Bak, Tang and Wiesenfeld, 1988]. Traditional meteorological theory cannot explain satisfactorily the observed self-organized criticality in atmospheric flows [Tessier, Lovejoy and Schertzer, 1993; Tessier *et al*., 1996]. This paper gives a summary of an alternative non-deterministic cell dynamical systems model for atmospheric flows

[Mary Selvam, 1990] which predicts the observed self-organized criticality as intrinsic to the quantum-like mechanics governing flow dynamics.

Annual rainfall data for India for the 169 years period (1826-1994) [Singh and Sontakke, 1996] and for Scotland for the 236 years period (1757-1992) [*Scottish rainfall series obtained from Dr. Miranda Foster, University of Dundee, Geography Department, Dundee, DD14HN, UK] were used for the study as two representative samples for disparate climatic regimes, namely, tropics (India) and higher latitudes (Scotland).

The two disparate climatic regimes, namely India and Scotland, exhibit the model predicted universal spectrum for interannual variability of rainfall. Universal spectrum for interannual variability rules out linear trends. Atmospheric warming related to man-made green house gases will result in intensification of fluctuation of all scales identifiable immediately in high frequency fluctuations such as QBO, ENSO, and even shorter periodicities. There have been recent reports of such intensification of extreme weather events [Houghton *et al*., 1996]. Interannual variability of rainfall over India and Scotland exhibit model predicted dominant peak periodicities (Eq. 1). Also, T_{50} is less than 5 years for both regions. Therefore, short-term dominant periodicities such as QBO and ENSO may be used for prediction purposes.

Chapter 6: Signatures of a Universal Spectrum for Atmospheric Interannual Variability in Coads Surface Pressure Time Series.

Annual and seasonal mean global surface pressure time series for the 25 years 1964-1988 obtained from the Comprehensive Ocean Atmosphere Data Set (COADS) were subjected to quasi-continuous periodogram spectral analysis. Periodogram estimates are summarized in the following: (i) the atmospheric interannual variability exhibits a broadband (eddy continuum) structure; (ii) the spectra follow the universal inverse power-law form of the statistical normal distribution; (ii) periodicities up to 5 years contribute to as much as 50 per cent of the total variance; (v) the high- and low-frequency El Nino-Southern Oscillation (ENSO) cycles of respective periodicities 3-4 years and 4-8 years and interdecadal oscillations are present in all the data sets.

The inverse power-law form for power spectra is ubiquitous to real-world dynamical systems and is identified as a signature of self-organized criticality or deterministic chaos. The above results are consistent with a recently developed cell dynamical system model for atmospheric flows, which predicts self-organized criticality as intrinsic to quantum-like mechanics governing atmospheric flow dynamics. Identification of self-organized criticality in annual and seasonal mean surface pressure fluctuations and its unique quantification implies predictability of the total pattern of fluctuations. A universal spectrum for interannual variability rules out linear trends in atmospheric surface pressure patterns.

The interannual variability of atmospheric flows as recorded in meteorological parameters such as wind speed, temperature, and pressure at the Earth's surface and in the atmospheric column extending up to the stratosphere have been investigated extensively, and major quasi-periodic oscillations such as the QBO (quasi-biennial oscillation) and the 3-7 years ENSO (El Nino-Southern Oscillation) cycle have been identified (Lamb, 1972; Philander, 1990; Burroughs, 1992; Chao and Philander, 1993). Such dominant cycles are, however, superimposed on an appreciable 'background noise' contributed by a continuum of eddies of all scales within the time- and space-scales investigated (Lorenz, 1990; Tsonis and Elsner, 1990; Barnett, 1991). It is important, therefore, to quantify the total pattern of fluctuations of atmospheric flows for predictability studies. Standard deterministic models for atmospheric flows based on Newtonian continuum dynamics are subject to deterministic chaos and cannot give realistic simulation and prediction of atmospheric flows (Mary Selvam, 1990; Mary Selvam *et al*., 1992). Mary Selvam (1993a) has shown that round-off error doubles, on average, for each step of finite precision iterative computations. Round-off error will enter the mainstream computation and give unrealistic solutions in numerical weather prediction and in climate models that incorporate thousands of iterative computations in long-term numerical integration schemes. Realistic simulation therefore requires alternative non-deterministic models that can predict the observed non-linear variability of atmospheric flows. Long-range spatio-temporal correlations are intrinsic to atmospheric flows and are manifested as the self-similar fractal geometry to the global cloud cover pattern and the inverse power-law form for atmospheric eddy energy spectrum documented by Lovejoy and Schertzer (1986) and Tessier *et al*. (1993). Geophysical phenomena, in general, exhibit inverse power-law form for power spectra (Agnew, 1992), indicating self-similar (fractal) fluctuations in time. Traditional meteorological theory cannot explain satisfactorily the observed self-similar space-time structure of atmospheric flows (Tessier *et al*., 1993). Such long-range non-local connections are ubiquitous to real-world dynamical systems and are now identified as the signatures of self-organized criticality (Bak *et al*., 1988). The physics of self-organized criticality is not yet identified. In this paper a cell dynamical system model for atmospheric flows (Mary Selvam, 1990;

Mary Selvam *et al*., 1992; Mary Selvam, 1993b; Selvam and Radhamani, 1994; Selvam and Joshi, 1995) is summarized. The model predicts self-organized criticality as intrinsic to quanturn-like mechanics governing atmospheric flows, and as a natural consequence leads to the result that the atmospheric eddy energy spectrum represents the statistical normal distribution. The model predictions are in agreement with continuous periodogram analyses of 25 years (1964-1988) annual and seasonal mean oceanic surface pressure (COADS, 1985) for (i) 26 grid-points representative of diverse global climatic regimes and (ii) all available grid-points in the Northern and Southern Hemispheres for one representative season, September to November. Such unique quantification for the inverse power-law form of the atmospheric eddy energy spectrum implies predictability of the total pattern of atmospheric fluctuations.

A brief introduction to the concept of 'fractals' is given first, followed by the application of cell dynamical model concepts for the prediction of inter-annual variability of atmospheric flows.

Chapter 7: Fractal Nature of TOGA Surface Pressure Time Series

The variability of temporal (or spatial) fluctuations of any variable X is represented in conventional statistical theory by the relative dispersion RD equal to the standard deviation S divided by the mean X_m. The RD_n decreases with increase in time resolution n and for uncorrelated fluctuations dealt with in traditional statistics, is given as

$$RD_n = \frac{RD_{n0}}{\sqrt{n/n_0}} \qquad (1)$$

where n_0 is the smallest time resolution available. However, it is now established that temporal (or spatial) fluctuations of dynamical systems exhibit self-similarity or long-range correlations and therefore Eq. (1) is not valid. In this paper, it is shown that resolution dependent variance is described by the fractal dimension D.

Chapter 8: Universal Spectrum for Interannual Variability in COADS Global Air and Sea-Surface Temperatures

Continuous periodogram spectral analyses of 28 years (1961-1988) of seasonal (September-November) mean COADS global surface (air and sea) temperature time-series show that the power spectra follow the universal inverse power law form of the statistical normal distribution. An inverse power-law form for power spectra of temporal fluctuations implies long-range temporal correlation and is a signature of self-organized criticality. Universal quantification for self-organized criticality presented in this paper is consistent with a recently developed cell dynamical system model for atmospheric flows, which predicts such non-local connections as intrinsic to quantum-like mechanics governing flow dynamics. The universal spectrum for inter-annual variability rules out linear secular trends in global surface (air and sea) temperatures. Surface (air and sea) temperatures exhibit inter-annual variability at all time-scales up to the length of record investigated. Major quasi-periodic oscillations, such as the QBO (Quasi-biennial Oscillation) and the 2-7 year ENS0 (El Nino-Southern Oscillation) cycle, have been identified in surface temperature records (Ghil and Vautard, 1991; Elsner and Tsonis, 1991) and in proxy climate data (Cole *et al*., 1993). Such quasi-periodic cycles characterizing atmospheric flows are, however, superimposed on an appreciable 'background noise' formed by a continuum of eddies (Lorenz, 1990; Tsonis and Elsner, 1990). It is therefore important to identify the physics of multiple-scale interactions (Barnett, 1991) and to quantify the total pattern of fluctuations of atmospheric flows for predictability studies. Deterministic chaos in computer realizations of traditional non-linear mathematical models of atmospheric flows imposes a limit on realistic simulation of flow dynamics and prediction. Selvam (1993b) has shown that round-off errors in finite precision numerical computations approximately double for every iteration. Such round-off errors enter the mainstream computation and give unrealistic solutions in long-term numerical integration schemes, such as that used in numerical weather prediction and climate models which incorporate several thousands of iterative computations.

In this paper, recently developed non-deterministic cell-dynamical-system-model (Mary Selvam, 1990, 1993a; Mary Selvam *et al*., 1992) concepts are applied to show that the temporal (years) fluctuations of surface (air and sea) temperatures self-organize to form a universal spectrum. Such a concept rules out linear secular trends in surface temperatures.

Chapter 9: Universal Spectrum for Intraseasonal Variability in TOGA Temperature Time Series

Continuous periodogram spectral analyses of 2-day mean upper air TOGA temperature time series at all available standard levels (from 1000 hPa to 250 hPa) for the 92-day period June to August 1988 for the latitude band 50°N to 50°S give the following results. (1) A majority of the spectra follow the universal inverse power law form of the statistical normal distribution with the percentage contribution to total variance representing the percentage probability corresponding to normalized standard deviation equal to (log $L/\log T_{50}$) -1 where L is the period in days and T_{50} the period up to which the cumulative percentage contribution to total variance is equal to 50. (2) Dominant periodicities occur in wavebands, the band-width increasing with period length. (3) There is a continuous smooth rotation of the phase angle with increase in period within a waveband and from one waveband to the next indicating a continuous spiral-like structure for atmospheric flows. Atmospheric flow frequency broadband oscillations of periodicities up to 40 days are seen in all the spectra and are shown to be intrinsic to atmospheric flows. Universal spectrum for atmospheric intra-seasonal variability implies predictability of the total pattern of fluctuations. The above results are consistent with a cell dynamical system model for atmospheric flows.

The cooperative existence of fluctuations ranging in size-duration from a few millimeters-seconds (turbulence scale) to thousands of kilometers-years (planetary scale) result in the observed long-range spatiotemporal correlations, namely, fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations documented by Lovejoy and Schertzer (1986) and Tessier *et al.* (1993). Long-range spatiotemporal correlations are ubiquitous in real world dynamical systems and are recently identified as signatures of self-organized criticality (Bak, Tang, and Wiesenfeld 1988). The physics of self-organized criticality is not yet identified. It is important to quantify the total pattern of fluctuations in atmospheric flows for predictability studies. Traditional numerical weather prediction models based on Newtonian continuum dynamics are nonlinear and require numerical solutions. Finite precision computer realizations of such nonlinear models are sensitively dependent on initial conditions, now identified as deterministic chaos (Gleick, 1987) resulting in unrealistic solutions. The physics of deterministic chaos is not yet identified. Mary Selvam (1993a) has shown that round-off error approximately doubles on average for each step of finite precision numerical iteration. Such round-off error doubling results in unrealistic solutions for numerical weather prediction and climate models which incorporate long-term numerical integration schemes with thousands of such iterations. Realistic modeling of atmospheric flows therefore requires alternative concepts for fluid flows and robust computational techniques which do not require round-off error prone calculus-based long-term numerical integration schemes. 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 and Radhamani 1994, 1995; Selvam *et al*., 1994, 1995, 1996; Selvam and Joshi, 1995) is summarized. The model predicts the observed self-organized criticality, i.e., long-range spatiotemporal correlations as intrinsic to quantum-like mechanics governing atmospheric flow dynamics. Further, the model concepts show that the temporal fluctuations self-organize to form power spectra with universal inverse power law form of the statistical normal distribution. Representative power spectra of upper air TOGA (Tropical Ocean Global Atmosphere) global 1000 hPa to 250 hPa 00 GMT 2-day mean temperature for the 92-day period June to August 1988 are consistent with model predictions. Atmospheric low frequency variability documented by Madden and Julian (1994) is shown to be intrinsic to atmospheric flows powered by the diurnal cycle of solar heating.

A brief introduction to the concept of 'fractals' is first given, followed by the application of cell dynamical system model concepts for prediction of intra seasonal variability of atmospheric flows.

Chapter 10: Identification of Self-Organized Criticality in Atmospheric Low Frequency Variability

Atmospheric flows exhibit long-range spatiotemporal correlations manifested as self-similar fractal geometry to the global cloud cover pattern concomitant with inverse power law form f^{B} where f is the frequency B the exponent for the power spectrum of the fractal fluctuations. Such non-local connections are ubiquitous to dynamical systems in nature and are identified as signatures of *self-organized criticality*. Standard models in meteorological theory cannot explain satisfactorily the observed *self-organized criticality* in atmospheric flows. A recently developed cell dynamical model for atmospheric flows predicts the observed *self-organized criticality* as a direct consequence of quantum-like mechanics governing flow dynamics. The model predictions are in agreement with continuous periodogram power spectral analyses of two-day mean TOGA temperature time-series. The application of model concepts for prediction of atmospheric low frequency variability is discussed. The cooperative existence of fluctuations ranging in size-duration from a few millimeters-seconds (turbulence scale) to thousands of kilometers-years (planetary scale) result in the observed long-range spatiotemporal correlations, namely, fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations documented by Lovejoy and his group (Tessier, Lovejoy, and Schertzer, 1993). Long-range spatiotemporal correlations are ubiquitous to real world dynamical systems and are recently identified as signatures of *self-organized criticality* (Bak, Tang, and

Wiesenfeld, 1988). The physics of *self-organized criticality* is not yet identified. It is important to quantify the total pattern of fluctuations in atmospheric flows for predictability studies. Traditional numerical weather prediction models based on Newtonian continuum dynamics are nonlinear and require numerical solutions. Finite precision computer realizations of such nonlinear models are sensitively dependent on initial conditions, now identified as *deterministic chaos* (Gleick, 1987) resulting in unrealistic solutions. Mary Selvam (1993) has shown that round-off error approximately doubles on an average for each step of finite precision numerical iteration. Such round-off error doubling results in unrealistic solutions for numerical weather prediction and climate models which incorporate long-term numerical integration schemes with thousands of such iterations. Realistic modeling of atmospheric flows therefore requires alternative concepts for fluid flows and robust computational techniques which do not require round-off error-prone calculus-based long-term numerical integration schemes. In this paper, a recently developed non-deterministic cell dynamical system model for atmospheric flows (Mary Selvam, 1990; Mary Selvam, Pethkar and Kulkarni, 1992; Selvam and Joshi, 1995; Selvam, Pethkar, Kulkarni and Vijayakumar, 1996) is summarized. The model predicts the observed *self-organized criticality*, i.e., long-range spatiotemporal correlations as intrinsic to quantum-like mechanics governing atmospheric flow dynamics.

Further, the model concepts show that the temporal fluctuations self-organize to form power spectra with universal inverse power law form of the statistical normal distribution. Power spectra of global upper air TOGA (Tropical Ocean Global Atmosphere) temperature data are consistent with model predictions. Atmospheric low frequency variability documented by Madden and Julian (1994) is shown to be intrinsic to atmospheric flows powered by the diurnal cycle of solar heating.

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CHAPTER 1

SIGNATURES OF A UNIVERSAL SPECTRUM FOR ATMOSPHERIC INTER-ANNUAL VARIABILITY IN SOME DISPARATE CLIMATIC REGIMES

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Abstract

Atmospheric flows exhibit long-range spatiotemporal correlations manifested as the fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations on all space-time scales ranging from turbulence (centimeters-seconds) to climate (kilometers-years). Long-range spatiotemporal correlations are ubiquitous to dynamical systems in nature and are identified as signatures of self-organized criticality. Standard models in meteorological theory cannot explain satisfactorily the observed self-organized criticality in atmospheric flows. Mathematical models for simulation and prediction of atmospheric flows are nonlinear and do not possess analytical solutions. Finite precision computer realizations of nonlinear models give unrealistic solutions because of deterministic chaos, a direct consequence of round-off error growth in iterative numerical computations. Recent studies show that round-off error doubles on an average for each iteration of iterative computations. Round-off error propagates to the main stream computation and gives unrealistic solutions in numerical weather prediction (NWP) and climate models which incorporate thousands of iterative computations in long-term numerical integration schemes. An alternative non-deterministic cell dynamical system model for atmospheric flows described in this paper predicts the observed self-organized criticality as intrinsic to quantum-like mechanics governing flow dynamics. The model provides universal quantification for self-organized criticality in terms of the statistical normal distribution. Model predictions are in agreement with a majority of observed spectra of time series of several standard climatological data sets representative of disparate climatic regimes. Universal spectrum for natural climate variability rules out linear secular trends. Man-made greenhouse gas related atmospheric warming will result in intensification of natural climate variability, seen immediately in high frequency fluctuations such as QBO and ENSO and even shorter timescales. Model concepts and results of analyses are discussed with reference to possible prediction of climate change.

1.1. Introduction

Atmospheric flows exhibit irregular (chaotic) space-time fluctuations on all scales ranging from climate (kilometers-years) to turbulence (millimeters-seconds) and are a representative example of turbulent fluid flows. Dynamical systems in nature, i.e., systems that change with time, such as fluid flows, heartbeat patterns, spread of infectious diseases, etc., exhibit nonlinear (unpredictable) fluctuations. Conventional mathematical and statistical theories deal only with linear systems and the exact quantification and description of nonlinear fluctuations was not possible till the identification in the 1970s by Mandelbrot (1977, 1983), of the universal symmetry of self-similarity, i.e. fractal geometry underlying the seemingly irregular fluctuations in space and time (Schroeder, 1991; Stanley, 1995). The study of self-similar space-time fluctuations generic to dynamical systems, now (since 1980s) belongs to the newly emerging multidisciplinary science of nonlinear dynamics and chaos (Gleick, 1987).

Self-similar fluctuations in space and time imply long-range spatio-temporal correlations and are recently identified as signatures of self-organized criticality (Bak *et al*., 1988). Self-organized criticality in atmospheric flows is manifested as the fractal geometry to the global cloud cover pattern concomitant with inverse power law form for power spectra of temporal fluctuations documented and discussed in detail by Lovejoy and his group (Lovejoy, 1982; Lovejoy and Schertzer, 1986a, b; Schertzer and Lovejoy, 1991, 1994; Tessier *et al*., 1993, 1996 and all the references therein). Standard meteorological theory cannot explain satisfactorily the observed self-organized criticality in atmospheric flows (Tessier *et al*., 1993, 1996). Also, traditional mathematical models for simulation and description of irregular fluctuations in general, and atmospheric flows in particular are nonlinear and finite precision computer solutions, are unrealistic (chaotic) because of deterministic chaos (Gleick, 1987). In this paper, an alternative nondeterministic cell dynamical system model for atmospheric flows developed by the first author (Mary Selvam, 1990) is summarized. The model predicts the observed self-organized criticality as intrinsic to quantum-like mechanics governing flow dynamics. The model concepts enable universal quantification for the observed nonlinear variability in terms of the statistical normal distribution. The model predictions are in agreement with several standard long-term climatological data sets for meteorological parameters. The implications of model concepts for long-term climate change prediction are discussed.

The paper is organized as follows: Section 1.2 gives a detailed summary of general concepts in the newly emerging science of nonlinear dynamics and chaos and applications for quantifying the observed atmospheric flow patterns. Limitations of current concepts in standard meteorological theory and deterministic chaos in model solutions are discussed in Section 1.3. An alternative nondeterministic cell dynamical system model for atmospheric flows is summarized in Section 1.4. Details of climatological data sets used and analyses techniques are presented in Section 1.5. Section 1.6 contains results and discussions. Possible applications of model concepts for prediction of climate variability and climate change are given in Section 1.7. Conclusions regarding validity of model concepts and predictions are given in Section 1.8.

1.2. Nonlinear Dynamics and Chaos: A Multidisciplinary Science

The new science of nonlinear dynamics and chaos (Gleick, 1987) deals with unified concepts for fundamental aspects intrinsic to the complex (nonlinear) and apparently random (chaotic) space-time structures found in nature. The scientific community at large will derive immense benefit in terms of new insights and powerful analytical techniques in this multi-disciplinary approach to quantify basic similarities in form and function in disparate contexts ranging from the microscopic to the macroscopic scale.

The apparently random, noisy, or irregular space-time signals (patterns) of a dynamical system, however, exhibit qualitative similarity in pattern geometry on all scales and are therefore correlated. In general, the spatiotemporal evolution of dynamical systems trace a zigzag (jagged) pattern of alternating increase and decrease, associated with bifurcation or branching on all scales of space and time, generating wrinkled or folded surfaces in three dimensions. Representative examples for time series of some meteorological parameters used in the present study are shown in

Figure 1.1. Physical, chemical, biological, and other dynamical systems exhibit similar universal irregular space-time fluctuations. A fascinating aspect of patterns in nature is that many of them have a universal character (Dennin *et al*., 1996).

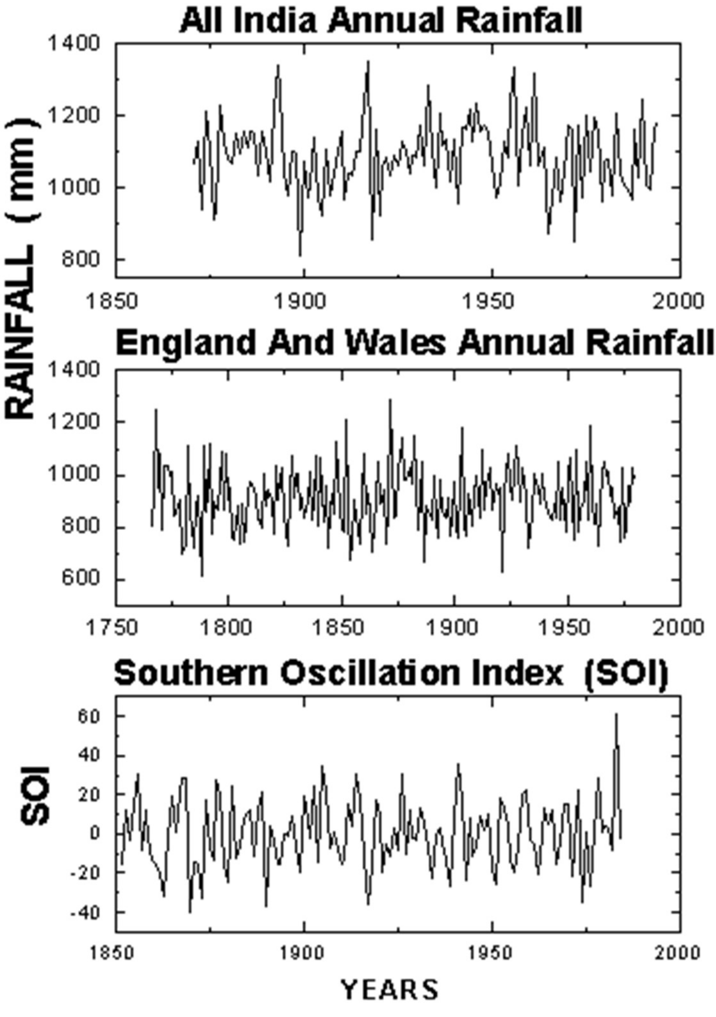

Figure 1.1: Time series data of some of the meteorological parameters used in the present study are shown as representative examples for irregular (zigzag) fluctuations generic to dynamical systems in nature.