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A general systems theory for atmospheric flows and atmospheric aerosol size distribution

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Abstract: Atmospheric flows exhibit selfsimilar fractal spacetime fluctuations manifested as the fractal geometry to global cloud cover pattern and inverse power law form for power spectra of meteorological parameters such as windspeed, temperature, rainfall etc. Inverse power law form for power spectra indicate long-range spacetime correlations or non-local connections and is a signature of selforganised criticality generic to dynamical systems in nature such as river flows, population dynamics, heart beat patterns, etc. The physics of selforganised criticality is not yet identified. The author has developed a general systems theory which predicts the observed selforganised criticality as a signature of quantumlike chaos in dynamical systems. The model predictions are (i) The fractal fluctuations can be resolved into an overall logarithmic spiral trajectory with the quasiperiodic Penrose tiling pattern for the internal structure. (ii) The probability distribution represents the power (variance) spectrum for fractal fluctuations and follows universal inverse power law form incorporating the *golden mean*. Such a result that the additive amplitudes of eddies when squared represent probability distribution is observed in the subatomic dynamics of quantum systems such as the electron or photon. Therefore the irregular or unpredictable fractal fluctuations exhibit quantumlike chaos. (iii) Atmospheric aerosols are held in suspension by the vertical velocity distribution (spectrum). The atmospheric aerosol size spectrum is derived in terms of the universal inverse power law characterizing atmospheric eddy energy spectrum. Model predicted spectrum is in agreement with the following two experimentally determined atmospheric aerosol data sets, (i) SAFARI 2000 CV-580 Aerosol Data, Dry Season 2000 (CARG) (ii) World Data Centre Aerosols data sets for the three stations Ny Ålesund, Pallas and Hohenpeissenberg.
Keywords: Universal atmospheric aerosol size spectrum, SAFARI 2000 aerosol size spectra, World data center aerosol size spectra, Fractal fluctuations in atmospheric flows, Chaos and nonlinear dynamics..

1 Introduction

Information on the size distribution of atmospheric aerosols is important for the understanding of the physical processes relating to the studies in weather, climate, atmospheric electricity, air pollution and aerosol physics. Aerosols affect the radiative balance of the Earth/atmosphere system via the direct effect whereby they scatter and absorb solar and terrestrial radiation, and via the indirect effect whereby they modify the microphysical properties of clouds thereby affecting the radiative properties and lifetime of clouds [1]. At present

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empirical models for the size distribution of atmospheric suspended particulates is used for quantitative estimation of earth-atmosphere radiation budget related to climate warming/cooling trends. The empirical models for different locations at different atmospheric conditions, however, exhibit similarity in shape implying a common universal physical mechanism governing the organization of the shape of the size spectrum.

Atmospheric flows exhibit selfsimilar fractal fluctuations generic to dynamical systems in nature. Self-similarity implies long-range space-time correlations identified as self-organized criticality [2]. The physics of self-organized criticality ubiquitous to dynamical systems in nature and in finite precision computer realizations of non-linear numerical models of dynamical systems is not yet identified. During the past three decades, Lovejoy and his group [3] have done extensive observational and theoretical studies of fractal nature of atmospheric flows and emphasize the urgent need to formulate and incorporate quantitative theoretical concepts of fractals in mainstream classical meteorological theory. The empirical analyses summarized by Lovejoy and Schertzer [3] directly demonstrate the strong scale dependencies of many atmospheric fields, showing that they depend in a power law manner on the space–time scales over which they are measured. In spite of intense efforts over more than 50 years, analytic approaches have been surprisingly ineffective at deducing the statistical properties of turbulence. Conclusions about anthropogenic influences on the atmosphere can only be drawn with respect to the null hypothesis, i.e. one requires a theory of the natural variability, including knowledge of the probabilities of the extremes at various resolutions. 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 observations show 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 [3].

A general systems theory for the observed fractal space-time fluctuations of dynamical systems [4-7] helps formulate a simple model to explain the observed vertical distribution of number concentration and size spectra of atmospheric aerosols. The atmospheric aerosol size spectrum is derived in terms of the universal inverse power law characterizing atmospheric eddy energy spectrum. A universal (scale independent) spectrum is derived for suspended atmospheric particulate size distribution expressed as a function of the golden mean τ ($\approx$ 1.618), the total number concentration and the mean volume radius (or diameter) of the particulate size spectrum. Knowledge of the mean volume radius and total number concentration is sufficient to compute the total particulate size spectrum at any location. The physical basis and the theory relating to the model are discussed in Sec. 2. The model predictions are (i) Fractal fluctuations can be resolved into an overall logarithmic spiral trajectory with the quasiperiodic Penrose tiling pattern for the internal structure. (ii) The probability distribution of fractal space-time fluctuations represents the power (variance) spectrum for fractal fluctuations and follows universal inverse power law form incorporating the *golden mean*. Such a result that the additive amplitudes of eddies when squared represent probability distribution is observed in the subatomic dynamics of quantum systems such as the electron or photon. Therefore the irregular or unpredictable fractal fluctuations exhibit quantumlike chaos. (iii) Atmospheric aerosols are held in suspension by the vertical velocity distribution (spectrum). The normalised atmospheric aerosol size spectrum is derived in terms of the universal inverse power law characterizing atmospheric eddy energy spectrum. Model predicted spectrum is in agreement with the following two experimentally determined atmospheric aerosol data sets, (i) SAFARI 2000 CV-580 Aerosol Data, Dry Season 2000 (CARG) (ii) World Data Centre Aerosols data sets for the three stations Ny Ålesund, Pallas and Hohenpeissenberg.

2 General systems theory for atmospheric aerosol size spectrum

The atmospheric eddies hold in suspension the aerosols and thus the size spectrum of the atmospheric aerosols is dependent on the vertical velocity spectrum of the atmospheric eddies. Atmospheric air flow is turbulent, i.e., consists of irregular fluctuations of all space-time scales characterized by a broadband spectrum of eddies. The suspended aerosols will also exhibit a broadband size spectrum closely related to the atmospheric eddy energy spectrum.

A general systems theory for turbulent fluid flows predicts that the eddy energy spectrum, i.e., the variance (square of eddy amplitude) spectrum is the same as the probability distribution P of the eddy amplitudes, i.e. the vertical velocity W values. Such a result that the additive amplitudes of eddies, when squared, represent the probabilities is exhibited by the subatomic dynamics of quantum systems such as the electron or photon. Therefore the unpredictable or irregular fractal space-time fluctuations generic to dynamical systems in nature, such as atmospheric flows is a signature of quantum-like chaos. The general systems theory for turbulent fluid flows predicts [4-7] that the atmospheric eddy energy spectrum follows inverse power law form incorporating the *golden mean* τ [7] and the normalized deviation t for values of $t \geq 1$ and $t \leq -1$ given as $P = \tau^{-4t}$. Normalised deviation t ranging from -1 to +1 corresponds to the primary eddy growth region. In this region the probability density distribution P is shown to be equal to $P = \tau^{-4k}$ where k is the fractional volume dilution by eddy mixing equal to $k = \sqrt{\frac{\pi}{2z}}$ where z is the eddy length scale ratio ranging from 2 to 10 and the corresponding to t values are equal to 1.1-(z/10).

The normalised height is also represented by z. The model predicted probability density distribution P along with the corresponding statistical normal distribution with probability values plotted on linear and logarithmic scales respectively on the left and right hand sides are shown in Figure 1. The model predicted probability distribution P for fractal space-time fluctuations is very close to the statistical normal distribution for normalized deviation t values less than 2 as seen on the left hand side of Figure 1. The model predicts progressively higher values of probability P for values of t greater than 2 as seen on a logarithmic plot on the right hand side of Figure 1 and may explain the reported *fat tail* for probability distributions of various physical parameters [8].

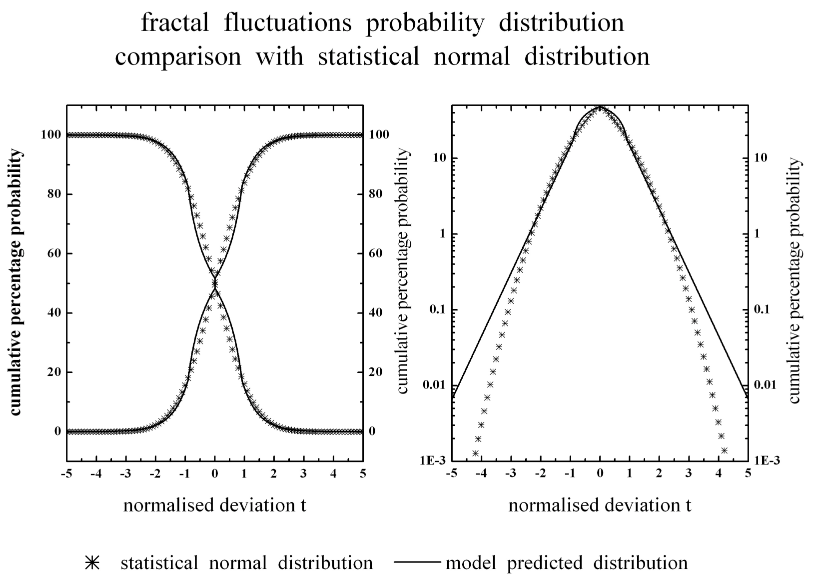

Figure 1. Probability distribution of fractal fluctuations. Comparison of theoretical with statistical normal distribution.

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The normalized aerosol size spectrum is obtained by plotting a graph of normalized aerosol concentration $\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}(\ln r_{\mathrm{n}})} = \frac{3}{2}P\tau^{2t}$ versus the normalized aerosol radius $r_{\mathrm{n}} = r/r_a = \tau^{2t/3}$ where r_a is the mean volume radius, N the total number concentration and dN the number concentration in the size interval dr. The normalized aerosol size spectrum is derived directly from the universal probability density P distribution characteristics of fractal fluctuations and is independent of the normalised height z of measurement and is universal for aerosols in turbulent atmospheric flows. The aerosol size spectrum is computed

starting from the minimum size, the corresponding probability density P refers to the cumulative probability density starting from 1 and is computed as equal to $P = 1 - \tau^{-4t}$. The model predicted universal scale-free aerosol size spectrum is shown in Figure 2.

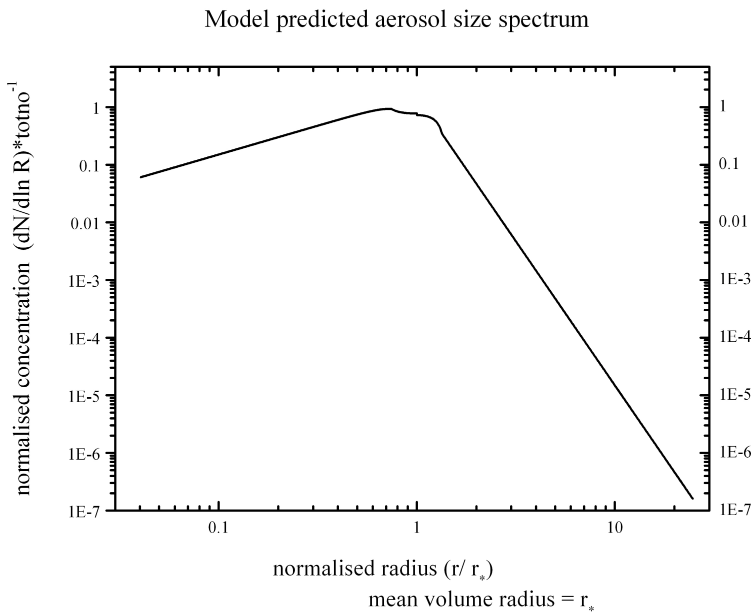

Figure 2. Model predicted aerosol size spectrum

3 Comparison of Observed and Model Predicted Aerosol Size Spectra

The following two data sets were used for comparison of observed with model predicted aerosol size spectrum:
(i) SAFARI 2000 CV-580 Aerosol Data, Dry Season 2000 (CARG). The Cloud and Aerosol Research Group (CARG) of the University of Washington participated in the SAFARI-2000 Dry Season Aircraft campaign with their Convair-580 research aircraft. This campaign covered five countries in southern Africa from August 10 through September 18, 2000. The UW Technical Report for the SAFARI 2000 Project (http://daac.ornl.gov/data/safari2k/atmospheric/CV-580/comp/SAFARI-MASTER.pdf) gives a complete detailed guide to the extensive measurements obtained aboard the UW Convair-580 aircraft in support of SAFARI 2000 [Hobbs PV. SAFARI 2000 CV-580 Aerosol and Cloud Data, Dry Season 2000 (CARG). Data set. Available on-line (http://www.daac.ornl.gov/) from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/710, 2004]. The mean and standard deviation of normalised aerosol size spectrum was computed for

245037 and 189761 individual spectra respectively for *pcasp* and *tsi3320* aerosol measurement instrument systems and shown in Figure 3 along with the model predicted universal normalized aerosol size spectrum.

(ii) Aerosol size distributions for three land stations (Ny Ålesund, Pallas and Hohenpeissenberg) were obtained from World Data Centre for Aerosols (http://wdca.jrc.it/data/parameters/data_size.html) at The Aerosol Size Distribution Data Archive. The annual means (2001 to 2004 for the first two and 2001 to 2005 for the third staion) normalized aerosol size spectra with associated standard deviations were computed for the three stations Ny Ålesund, Pallas and Hohenpeissenberg for each year and shown in Figure 4.

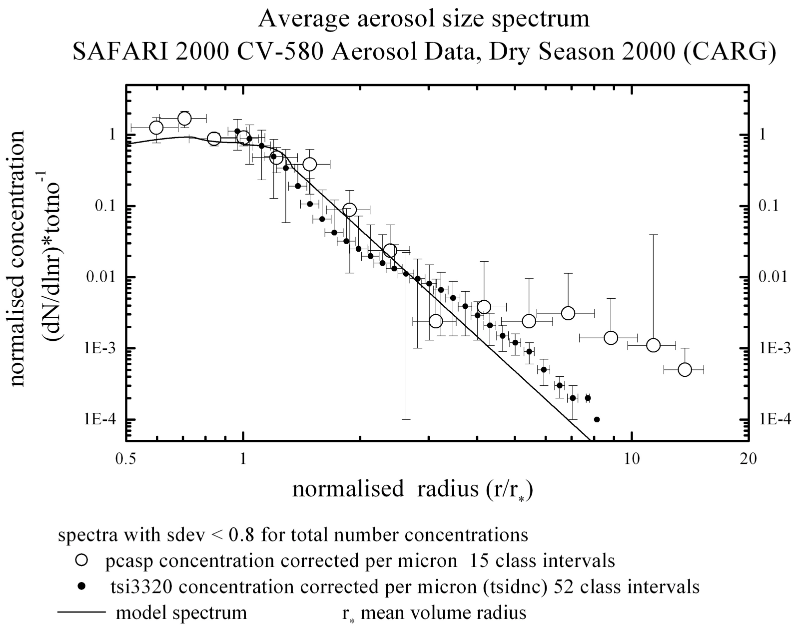

Figure3. Average aerosol size spectrum for SAFARI 2000 CV-580 aerosol size spectra and comparison with model prediction. Error bars indicate one standard deviation on either side of the mean

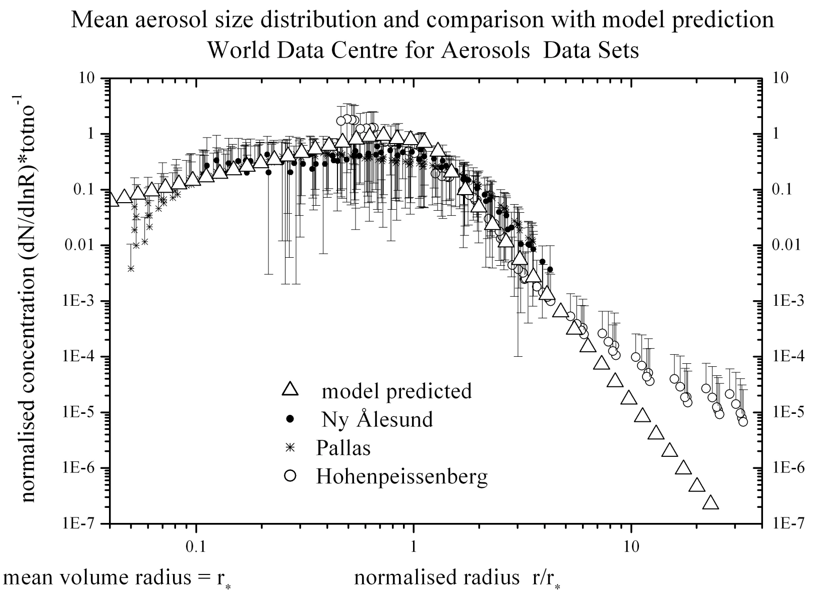

Figure 4. Mean aerosol size spectrum for World data center aerosols data sets and comparison with model prediction. Error bars indicate one standard deviation on either side of the mean

4 Conclusions

There is a close agreement between the model predicted and the observed aerosol size distributions for the two aerosol data sets (SAFARI 2000 and World Data Center) used in the study. SAFARI 2000 aerosol size distributions reported by Haywood *et al*. [1] also show similar shape for the distributions. The physical hypothesis relating to the dynamics of the atmospheric eddy systems proposed in the present paper can be extended to other planetary, solar and stellar atmospheres.

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