NG71A MCC: 120 Sunday 0830h

Scaling and the Fluid Earth: Chaos and Multifractals in the Atmosphere, Oceans, Hydrology, and Climate I

(joint with A, B, H, OS, SA, SH, SM, T, PP, MR)

Presiding: **D Schertzer,** Laboratoire de Modelisation en Mecanique**; S Lovejoy,** McGill University

NG71A-01 0830h INVITED

On the Relationship Between Large-Scale Properties and Small-Scale Statistics in Turbulence

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One of the basic assumptions in statistical theories of fully developed turbulence (in particular far from walls or boundaries) is that, at large enough Reynolds numbers, three-dimensional effects involved in the processes of energy transfer result in the existence of a range of scales for which statistical properties become independent from the large-scale production process. These properties are then universal (i.e. they do not depend on the large-scale flow specific features nor on the Reynolds number value), and tend to satisfy isotropy over a range of scales (for which the expression local isotropy is commonly used).

However, it is now obvious that, for moderate Reynolds numbers, the isotropic relations between second-order and third-order moments for temperature (Yaglom's equation) or velocity increments (Kolmogorov's equation) are not respected, reflecting a non-negligible correlation between the scales responsible for the injection, the transfer and the dissipation of turbulent energy. For grid turbulence, the dominant large-scale phenomenon is the non-stationarity (or, in an experimental context, the streamwise non-homogeneity) of statistical moments resulting from the decay of energy downstream of the grid. The objective of our work has been to quantify the influence of this non-homogeneity on various properties associated with the inertial and dissipative ranges of scales. In particular, a new term must be added to Yaglom's and Kolmogorov's equations to account for the decay of second-order moments and thus explain the observed departure of the inertial range from the '4/3rds' and '4/5ths' laws. The new equations admit equilibrium similarity solutions for fixed initial conditions. Low Reynolds number grid turbulence measurements satisfy these solutions approximately; this is very important when calculating the third-order structure function reliably for any fixed set of initial conditions. One inference from our work is that the reported non-universal inertial-range properties are most often a result of the large-scale influence - linked to the initial conditions - rather than an indication of strong departure from isotropy. Our most recent results suggest that R_λ needs to reach 10^6 before a two-decade inertial range is established, so that even geophysical 'inertial-range' data may be influenced by large-scale properties.

NG71A-02 0845h INVITED

Strongly stratified turbulence: An explanation to the energy spectra of the stratosphere.

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Kinetic and potential wave number energy spectra of the stratosphere have been the object of debate for several decades. To explain the underlying physics of these spectra, is an important task for atmospheric physics as well as theoretical fluid dynamics.

Many observational studies have shown that the horizontal energy spectra in the mesoscale range, *i.e.* wave lengths of $\sim$ 1-1000 km, follow a $k_h^{-5/3}$-dependence, just as hydrodynamic turbulence. Here, k_h is the horizontal wave number. Other studies have given evidence that the vertical wave number energy spectra follow a k_v^{-3}-dependence in the range of wave lengths of $\sim$ 100-1000 m.

The horizontal $k_h^{-5/3}$-spectra have commonly been explained by assuming that nonlinear advective forces are dominating the dynamics, and by further assuming that such forces give rise to an inverse cascade of energy, just as in two-dimensional turbulence. An inverse cascade means that energy is travelling from small scales to large scales, as opposed to a forward cascade which is found in three-dimensional turbulence.

The vertical k_v^{-3}-spectra have commonly been explained by assuming that linear buoyancy forces are dominating and that the motion can be described as a large system of linear waves. The waves interact weakly by one onother and become saturated, which mean that they are just on the limit to breake. The spectrum is, according to this mode of explanation, determined by the parameter controlling the stability of the waves, which is the Brunt-Väisälä frequency N.

In this contribution, it is argued that the horizontal $k_h^{-5/3}$-spectrum and the vertical k_v^{-3}-spectrum arise from one and the same motion, described by the Boussinesq equations. It is assumed that nonlinear inertial forces and buoynace forces are equally strong at each scale. The balance between these forces results in a very special type of motion, called strongly stratified turbulence. In this kind of motion there is a forward cascade of kinetic as well as potential energy, *i.e.* large structures of motion transfer their energy to small structures of motion. The cascade is highly anisotropic, which means that highly elongated large structures of motion transfer their energy to small and less elongated structures of motion, according to a special scale relation:

$$r_h = \frac{N^3}{\epsilon} r_v^3 , \qquad (1)$$

where r_h is a horizontal scale of motion, r_v the corresponding vertical scale and ϵ is the rate at which energy is transferred in the cascade.

A vast experimental material processed from the MOZAIC data base of aircraft records of wind and temperature, is presented to support the theory, as well as several large numerical simulations of the Boussinesq equations.

NG71A-03 0900h INVITED

The Law of Mass Action in the Arctic Lower Stratospheric Polar Vortex January March 2000: ClO Scaling and the Calculation of Ozone Loss Rates in a Turbulent Fractal Medium

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We consider the effects of power-law scaling in the 1999-2000 Arctic lower stratospheric vortex from the point of view of the law of mass action and its application to the chemical kinetics of ozone loss embedded in a turbulent, macroscopic, fractal medium. The ER-2 observations of ClO obey power law scaling; the exponent varies with time in a manner shown to be consistent with the scaling of NOy and O3, via the influences of polar stratospheric clouds and actinic solar radiation. While the microscopic rate coefficient for ClO 3-body recombination to the dimer applies as measured to three-dimensional volumes in which the sole transport mechanism is molecular diffusion, this cannot be true in the 2.56-dimensional space in which macroscopically fluctuating ClO reacts in the lower stratosphere. We show that the rate of loss of ozone via the ClO dimer mechanism is proportional to $[ClO]^{2.18}$ in late January/early February, and to $[ClO]^{2.55}$ in March.

NG71A-04 0915h INVITED

Evidence That a Complex Atmosphere Shown by High Resolution Lidar Imagery can be Represented by a Stratified Mulitfractal Field

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The complex nature of the atmosphere becomes very apparent when looking at high-resolution lidar (laser radar) imagery. Recent field studies have provided an opportunity to look at the turbulent nature of the atmosphere using two different lidar techniques. RASCAL (Rapid Acquisition SCanning Aerosol Lidar) imagery from industrial stack plumes and AERIAL (AERosol Imaging Airborne Lidar) imagery from a simultaneous upward/downward airborne lidar system show the dynamic nature of the aerosol particulate over very different space and time scales. Since the lidar technique employed is sensitive to the concentration of aerosol particles, the data can be used to investigate passive scalar advection. Both conventional numerical (GCM) modelling and conventional turbulence approaches have difficulty in modeling and predicting the transport and dispersion of such highly variable and stratified aerosol concentrations.

We have chosen to exploit a different approach by constructing a stratified cascade model of pollutant transport and dispersion that include the observed extreme variability. The differential stratification is particularly significant since it is defined by a 23/9 (=2.55) dimensional elliptical space rather than the conventional (isotropic) three or two dimensionsional ones. In this space, the concentration is multifractal so that increasingly rare, high concentration pollution "pockets" are on increasingly sparse (lower dimensional) fractal sets.

We have tested this new theory using state-of-the-art lidar data with outstanding success. Applications are expected to include improved understanding of fundamental weather dynamics and hence improved weather and climate modelling as well as improved techniques for estimating the rates of industrial and natural emissions. These new techniques potentially include routine source monitoring from aerial or satellite imagery.

NG71A-05 0930h INVITED

FRACTIONAL KINETICS AND DYNAMICS OF ANOMALOUS TRANSPORT OF PASSIVE PARTICLES

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We discuss the dynamics of anomalous transport of passive particles . We formulate general principles that lead to the appearance of sticky trajectories and superdiffusive processes. The later are shown as being of Levy-type.

The particle (chaotic) dynamics are defined with the help of space-time fractional kinetics. At least, two critical exponents are required to define the kinetic equation. They characterize the fractional properties of space-time behavior of trajectories. These critical exponent are obtained with the help of renormalization group approach and microscopic evaluations of sticky domains properties.

Various complex systems can be considered and be theoretically controled. We illustrate these theoretical developments with the help of the example of passive particles dynamics in a system of point vortices.

NG71A-06 0945h

Expoliting Local Low Dimensionality of the Atmospheric Dynamics for Efficient Ensemble Kalman Filtering

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Recent studies (Patil 2001) have shown that, when the Earth's surface is divided up into local regions of moderate size, vectors of the forecastuncertainties in such regions tend to lie in a subspace of much lower dimensionthan that of the full atmospheric state vector. We show how this finding can be exploited to formulate a potentially accurate and efficient data assimilation technique (Ott 2002). The basic idea is that, since the expected forecast errors lie in a locally low dimensional subspace, the analysis resulting from the data assimilation should also lie in this subspace. This implies that operations only on relatively low dimensional matrices are required. The data assimilation analysis is done locally in a manner allowing massively parallel computation to be exploited. The local analyses are then used to construct global states for advancement to the next forecast time. Numerical tests of successful implementations of the method on model systems show its potential advantages.

References:
D.J. Patil, et al. *Phys. Rev. Lett.* **86**, 5878 (2001).
E. Ott, et al., arXiv:physics/0203058.

URL: http://arxiv.org/pdf/physics/020305

NG71A-07 1020h INVITED

Nonlinearity, Uncertainty, Dynamics and Stochastics in the Geosciences

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It has been clear that it is indispensable to take nonlinearity into account, in order to better understand complex systems like the geosystem. There is a growing recognition of a role for the inclusion of stochastic terms in the modeling of complex and multi-scale phenomena in the geosciences.

During the last decade, significant progress has been made towards building a comprehensive theory of random dynamical systems, while the applications of these random dynamics ideas and techniques to other areas have not yet been fully explored. The core questions in the modeling, analysis, simulation and prediction of geophysical phenomena under uncertainty include: exploring appropriate ways to take stochastic effects into account; understanding the impact of randomness on the evolution of the geosystem; and designing efficient numerical algorithms to simulate nonlinear and random phenomena.

I will present recent work on nonlinear and stochastic dynamical systems methods, such as effective approximation, ergodicity principle, averaging principle, nonautonomous perturbations, and determining functionals, for geophysical fluid dynamics.

NG71A-08 1035h INVITED

Introduction to a Lagrangian-averaged Turbulence Closure Model

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This talk is not specifically about chaos or fractal structure, although it does refer to nonlinear dynamical systems that possess global attractors whose fractal, or Hausdorf, dimension is finite. Specifically, I shall speak about a new turbulence closure model that is based on Lagrangian averages (following the fluid parcels). I shall review how well this model describes the mean effects of fluctuations in turbulent flows by comparing its predictions with experimental data and numerical simulations. Mathematically, the turbulence model has a global attractor whose fractal, or Hausdorf, dimension has a finite upper bound, proportional to Reynolds to the 3/2 power. So the model is rigorously computable as a finite degree-of-freedom dynamical system. I shall also discuss how the model affects the Kolmogorov scaling laws for turbulence at small scales and large scales. Finally, I shall discuss the potential advantages of Lagrangian averaging for modeling GFD turbulence.

NG71A-09 1050h INVITED

On The Design of Ensemble Climate Experiments: A Simulation of climateprediction.net

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Obtaining meaningful long-term forecasts for nonlinear systems under transient forcing using imperfect models is nontrivial. We consider the issue of resource allocation in ensemble climate model experiments which aim to quantify the effects of uncertainty in initial condition, parameter values, parameterisations, model class and so on. A deployable approach to informed selection of the 'next' ensemble member is illustrated in a simple nonlinear system (see L.A. Smith, (2002) What Might We Learn from Climate Forecasts? *Proc. National Acad. Sci.* **4**, 99, 2487–2492). Interpretation of the results of such experiments, and their implementation within the climate*prediction*.net project are discussed.

URL: http://www.maths.ox.ac.uk/~lenny

NG71A-10 1105h

Multifractality and Universal Laws of the Extremes, beyond Frechet and Gumbel.

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The Gumbel law has been frequently considered as the universal law for the extremes, i.e. the probability distribution of the minimal value or maximal value observed on a given period. This consideration was based on a mathematical theorem that requires two hypotheses to be satisfied: (i) exponential fall-off of the probability distribution of the component of the series (ii) a short range correlation between these components. Unfortunately, both hypotheses are in general not satisfied by a (stochastic) multifractal field.

In order to clarify this issue, we investigated the multifractal and extreme behaviours of various series of 10 years of tipping bucket measurements, estimated time resolution of the order of 5 minutes (Meteo-France PRECIP data base,). We got universal exponent estimates in good agreement with those obtained in other studies. As expected in the framework of stochastic multifractals, we also found a power-law tail for the pdf, not an exponential one. If correlations between components will be only short range, then the corresponding universal law will be Frechet, rather than Gumbel.

We do find that Frechet law fits quite better the empirically observed extremes than Gumbel law. However, we empirically note a slight overestimation of the extreme events by the former. An equivalent of the Frechet's law for components with a scaling dependence is presumably needed to get a better fit

NG71A-11 1120h INVITED

From Boundary Layer Turbulence to Hydrologic Response: Recent Results on Scaling, Nonlinearity, and Predictability and Their Implications

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Deepening our understanding of the space-time variability of atmospheric/hydrologic processes and their interactions over a range of scales has important implications for improving model parameterizations and increasing the accuracy of predictive models. At the same time, the inherent nonlinear and chaotic character of some of these processes imposes limits on their predictability, and therefore provides upper bounds on the expected prediction accuracy from numerical models. This paper will address questions of scaling, nonlinearity and predictability in processes active at two major interfaces of the hydrologic system: the land-atmosphere interface, and the land-water interface. Specifically, recent findings and their practical implications will be presented on: (a) multiscale interactions in turbulent boundary layers and implications for boundary condition formulations; (b) predictability assessment of turbulent velocities in a boundary layer as a function of scale; and (c) nonlinear dynamics of basin hydrologic response as a function of spatio-temporally varying forcing and basin geomorphological organization.

NG71A-12 1135h INVITED

Scaling, a key issue of the Prediction in Ungaged Basins (PUB)

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PUB (Prediction in Ungaged Basins) is a scientific initiative launched by the IAHS to provide hydrological data in ungaged or information poor basins. PUB is a scientific endeavor to assemble, promote and capacity build the science and technology to predict and estimate the hydrological phenomena without depending on calibration data. The hydrological phenomena to be predicted and estimated include precipitation, land surface processes, stream flow, groundwater flow, snow and ice, sediments and water quality.

The collection of Hydrological data remains a fundamental task, but PUB requires new and significant advances in:

- Better understanding of currently the observed variability over a wide range and space scales of rainfall and runoff processes (within and between catchments), including extremes (at time scales ranging from diurnal to inter-annual and even inter-decadal, and space scales ranging between 0.1 to 15,000 sq. km.).
- Development and use of advanced mathematical techniques for the characterization of space-time variability at multiple scales: fractal structures and multifractal fields, nonlinear dynamics.
- Derivation and validation of new balance equations at various scales and in particular at the basin scale,
- Development of measurement techniques, as well as new data processing methodologies, especially for remote sensing, to measure and estimate over a wider range of scales quantities, which are fundamental to the development and validation of these new theories and the remote monitoring of state variables such as saturated areas and groundwater levels.
- Improve our understanding of the interactions between runoff processes, and the chemical and biological processes, at all time and space scales, which is crucial for water quality predictions (salinity, sediments, nutrients, heavy metals etc.) at the basin scale.
- Development and advancing of the emerging focus on holistic thinking, ecohydrology, Gaia theory etc. that will enable more parsimonious descriptions of climate-soil-vegetation-topography interactions.

As for an illustration, we will discuss some recent multifractal analysis of the rainfall-runoff process.

NG72A MCC: Hall C Sunday 1330h

Scaling and the Fluid Earth: Chaos and Multifractals in the Atmosphere, Oceans, Hydrology, and Climate II Posters *(joint with A, B, H, OS, SA, SH, SM, T, PP, MR)*

Presiding: **D Schertzer,** Laboratoire de Modelisation en Mecanique**; S Lovejoy,** McGill University

NG72A-0908 1330h INVITED POSTER

Rain is Earthquakes in the Sky

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