STOCHASTIC and PROBABILISTIC METHODS for ATMOSPHERE, OCEAN and CLIMATE DYNAMICS
CRG Summer School

July 14-18, 2008
University of Victoria

VOLUME ONE

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SUMMER SCHOOL – ABSTRACTS

Adam Monahan (Grant Holder)

An Introduction to Probability and Stochastic Processes for Ocean, Atmosphere, and Climate Dynamics

The notion that "climate is what you expect, but weather is what you get" is fundamentally probabilistic. Atmosphere/ocean/climate variability involves a broad spectrum of processes interacting across different space and time scales. Any given model of these systems typically involves "fast" unresolved processes, the net effect of which on resolved scales must be accounted for. The natural language for investigating these connections between "weather" and "climate" is that of probability and stochastic processes.

These lectures will present an introduction to probability and stochastic processes in the context of ocean, atmosphere, and climate dynamics. Part 1 is an introduction to basic probability. Part 2 presents an introduction to stochastic processes. Part 3 brings all of these ideas together in a cautionary tale about Empirical Orthogonal Functions - a much abused diagnostic tool in atmosphere/ocean/climate science.

Saroja Polavarapu (Grant Holder)

Atmospheric Data assimilation lectures

Atmospheric measurements are critical for assessing the current state of the atmosphere and for predicting its future state. Despite the vast quantity and variety of measurements currently available, observations alone cannot alone define the complete atmospheric state. To fill in the gap, we must use our knowledge of atmospheric physics as encapsulated in numerical models. The process of combining measurements and models is called data assimilation and it has been used to generate numerical weather forecasts for decades. These lectures will provide an overview of atmospheric data assimilation starting with simple scalar problems and progressing to common methods of data assimilation (optimal interpolation, Kalman filtering, variational methods). The main applications of data assimilation that will be discussed are weather and environmental prediction.

Lecture 1:
- General idea
- Numerical weather prediction context
- simple scalar examples
- optimal interpolation

Lecture 2:
- Initialization
- basic estimation theory
- 3D variational assimilation

Lecture 3:
- 4D variational assimilation
- Kalman filtering

Xiaoming Wang (Grant Holder)

Introduction to Statistical Theories for Basic Geophysical Flows

In the first part of the lecture we give a quick review of the classical theory of empirical statistical mechanics and equilibrium statistical mechanics together with their application to the barotropic quasi-geostrophic equations. In the second part of the lecture we consider the damped barotropic quasi-geostrophic model under small scale random bombardments. We show the emergence of large scale coherent structure under appropriate small scale random bombardments. In the third part of the lecture, we focus on dissipative geophysical systems and we investigate the dependence of stationary statistical properties on parameters as well as the issue of accurate time approximation.

Alexandros Sopasakis (Grant Holder)

Monte Carlo. A general overview of methods, theory and practice

Background and theoretical/analytical development of the Monte Carlo method

We give a historical and theoretical background of the Monte Carlo method with easy to follow examples and hands-on numerical simulations. In this first lecture we establish all the foundational and mostly theoretical concepts which lead to the creation of a Markov Chain as well as the method for sampling that Chain. Ideas such as ergodicity, detailed balance and irreducibility are explained.

Numerical simulation practices and common techniques used in modern modeling applications

In this lecture we examine the numerical application of all the theoretical concepts presented in the first lecture of the series. Numerical challenges stemming from real applications provide the backdrop for the need of the Monte Carlo method. This gives a good stepping stone from which to explore the numerical issues associated with a large number of particles interacting. In that respect we overview different types of possible interaction potentials depending on thy physics of each application. The differences between Arrhenius, Metropolis, Glauber and Kawasaki dynamics are outlined while reviewing different types of Monte Carlo updating mechanisms.

A research project perspective: application to traffic flow

In this final lecture of the series we first provide a short overview of some of the most important concepts presented in lectures 1 and 2 while proceeding to explore how all these ideas fit together in a real-life research project in vehicular traffic flow. This step by step presentation develops a stochastic type model for traffic which can predict vehicular behavior on a multi-lane highway. Relevant, real-time, Monte Carlo simulations are presented in order to stimulate key concepts.

Richard Kleeman (Grant Holder)

Irregularity and Predictability of ENSO

Prediction of ENSO is an important economic undertaking as many global industries are influenced by this largest of climatic variations. ENSO is spectrally a broadband phenomena i.e. it is irregular with a peak oscillation frequency around four years. Such irregularity intuitively may limit our ability to predict the effect. In this lecture we review two theories to explain the irregularity and discuss the implications for the upper limits on ENSO predictability.

Information theory and statistical predictability Part I: Basic theory and simple models

Information theory is an attractive theoretical approach to exploring the temporal evolution of uncertainty within many practical dynamical systems. We outline the basic mathematics of information theory and its application to statistical (ensemble) prediction within a dynamical system. To illustrate the value of the theory we consider two very well known simple models, one stochastic, the other chaotic.

Information theory and statistical predictability Part II: Applications

Following on from the first Part we consider application of the theoretical machinery of information theory to two realistic dynamical systems one from climate (ENSO) and the other from atmospheric science (mid latitude atmosphere). Finally we shall discuss the concept of information flow and its potential application to data assimilation i.e. the effective initialization of practical dynamical systems.

Norm McFarlane (Grant Holder)

Parameterization in large-scale atmospheric modelling

The spatial resolution of comprehensive global circulation numerical models (GCMs) used for weather and climate prediction has increased over the past several decades with advances in computing power. However these models have also become increasingly complex and now include a wide range of physical processes that also incur a substantial computational burden. Consequently all modelling groups must deal with the limitations imposed by computational resources in designing and using GCMs. Almost all of the physical processes of importance are non-linear and frequently have their most pronounced spatial and temporal variability on scales that are not resolvable by the GCM. Despite this they interact with resolves processes in ways that lead to significant effects in resolved scales. Representing these effects in GCMs is the problem of parameterization and is now widely understood to be of critical importance in climate modelling and quantitative weather predictions. These lectures will address the problem of parameterization in broad terms to begin with and then illustrate the application in the context of representing the effects of three well known and studied groups of processes, namely moist convection, boundary-layer processes, and gravity-wave drag.

Summer School Posters

Josue Polanco

Hunting False Spectral Peaks detected in Unevenly Paleo(Climate) Time Series with Large Gaps using Lomb-Scargle Periodogram

Paleo(climate) time series are frequently unevenly spaced in time. A way to overcome this problem is to interpolate the unevenly spaced time series, but unfortunately, the interpolation can alter the spectrum (Schulz \& Stattegger 1997; Schulz \& Mudelsee 2002). To avoid the interpolation the Lomb-Scargle periodogram (LS-P) can can be used. One of the problems using LS-P is the (possible) appearance of false spectral peaks, and overall when the Time Series have large gaps (Nian-chuan, et al., 2007). In this work unevenly spaced time series of δ^{18}O stable isotope of belemnites from the Basque-Cantabrian basin (Rosales et al. 2004) has been used to discern possible false spectral peaks following the Nian-chuan et al. (2007) method. In order to compute the LS-P the REDFIT method has been followed faithfully (Schulz and Mudelsee, 2002).

Scott Capps

Sub-gridscale Wind Speed Variability and Climate

Winds at the surface play a key role in climate processes by determining air-sea energy and gas exchanges. These non-linear exchanges can be dominated by the tail of the wind speed distribution in regions and periods of strong wind variability. Hence, surface heat and energy fluxes vary significantly on spatio-temporal scales not resolved by GCMs. We characterize climatological surface wind speed probability density functions (PDFs) estimated from observations and use them to detect GCM biases. We perform climate simulations that account for surface fluxes due to sub-gridscale GCM winds. Climatological wind speed statistics and tropospheric circulation are improved as a result.

Maryam Namazi

Effect of barotropic shear on equatorially trapped Kelvin waves

The equatorial atmosphere harbors a large spectrum of waves that are trapped near and travel along the equator. Kelvin waves, which are observed to play a central role in organized tropical convective systems, are the simplest example. They are characterized by a zero meridional velocity and the meridional pressure gradient which is balanced by the Coriolis force. Here, we investigate the effect of westerly and easterly barotropic shear on the zonal structure and propagation of Kelvin waves. Specially we are interested in the fact that Kelvin waves in nature seem to have a non-zero meridional velocity resulting in North-South converging flow toward the equator. It is suggested here that this effect is possibly due to non-linear interaction with a background barotropic flow.

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CRG Workshop

ABSTRACTS

July 20-23, 2008
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VOLUME TWO

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Graduate & Post-Docs

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WORKSHOP ABSTRACTS

INVITED SPEAKERS

Rafail Abramov (Grant Holder)	**A new algorithm for low frequency climate response** A new FDT-type climate response algorithm, based on the exact linear response formula for chaotic nonlinear forced-dissipative systems, is tested on the T21 model of the barotropic atmosphere. Significant improvement from the classical quasi-Gaussian FDT algorithm is observed for the response of both mean and variance of kinetic energy EOFs at 300 and 500 hPa geopotential height.
Alexandros Sopasakis (Grant Holder)	**A treatment of multi-scale hybrid systems involving deterministic and stochastic approaches, coarse graining and hierarchical closures** We undertake a systematic study which examines hybrid systems consisting of partial differential equations (PDEs) coupled to stochastic lattice models. The coupling of the stochastic model arises as a boundary contribution to the PDE while at the same time the PDE acts on the stochastic model as an external, although local, force via its interaction potential. Specifically the stochastic component includes both spin-exchange (with/out look-ahead) and spin-flip Arrhenius dynamics and we systematically study the system behavior by ranging the parameters responsible for each mechanism. Therefore we can isolate and study effects originating from just one stochastic mechanism or a combination of both. In this manner we explore the hybrid system via a multi-time scale Markov jump process. Through this study, the key question of significant preparation created in the model through the stochastic mechanisms is explored. Kinetic Monte Carlo simulations are undertaken to facilitate the study. Applications of such systems range from chemical catalysis to climate prediction and forecasting.
Grant Branstator, NCAR (Grant Holder)	**Atmospheric Response Operators from the Fluctuation-Dissipation Theorem: Validation and Applications** Based on the fluctuation-dissipation theorem presented by Leith (1975) and broadened by Majda (2005) and Dymnikov and Gritsun (2005), we construct, test and apply three-dimensional operators that estimate the response of the atmosphere to external forcing. The FDT allows one to construct response operators by using only lag-correlations statistics of the undisturbed system; neither knowledge of the governing equations nor observations of its response to external forcing is required. Using tests within an atmospheric general circulation model framework, we find that provided a sufficiently long record of the system’s internal variations is available, remarkably accurate response operators can be produce.

Operators are considered that not only estimate the response of mean state variables but also variances and eddy fluxes of bandpass fields. Special consideration is given to the time-dependent response to time-dependent forcing rather than limiting applications to steady situations, as is usually done. Using these time-dependent operators we study problems of interest for extended range forecasting, including finding efficient means of exciting the midlatitudes from the tropics on weekly timescales and determining the degree to which the Madden-Julian Oscillation may affect the extratropics.

Greg Holloway (Grant Holder)

Entropic forcing from microscales to megascales

Atmospheres, oceans, lakes and most duck ponds express vastly more degrees of freedom than we can ever take into account, theoretically or computationally, within the classical mechanical basis of GFD. However, these fluids are fundamentally forced, dissipative, open systems that are not amenable to equilibrium statistical mechanics. We need a stronger basis that draws upon both classical and statistical mechanics. Using oceanic examples, this talk explores non-equilibrium statistical mechanical representations expressed as entropic forcing terms that are absent from classical GFD. Results allow us to make corrections to the classical GFD that serves as basis for general circulation models.

George Craig (Grant Holder)

Equilibrium and Nonequilibrium Convection in the Atmosphere

Deep moist convection is a major source of variability and uncertainty in numerical weather prediction and climate modeling. It is natural to represent convective variability by a stochastic parameterisation, but there is a key difficulty in that there are two fundamentally different regimes of convective behaviour in its interaction with larger scales of atmospheric motion. On the one hand, convection may be in an equilibrium where the statistical properties are strongly constrained by the large-scale flow. One the other hand an unstable state may build up where convective activity responds sensitively to small-scale triggers. Examples will be presented from ensemble forecasting and data assimilation to illustrate the different behaviour of the two types of convective behaviour. Key properties of equilibrium convection will be reviewed, showing how a stochastic parameterisation can be designed based on physical principles. The presentation will conclude with a look forward towards stochastic parameterisation of triggered convection.

Adam Monahan & John C. Fyfe

How Generic are Dipolar Jet EOFs?

Dipolar structures arise as Empirical Orthogonal Functions (EOFs) of extratropical tropospheric zonal-mean zonal wind in observations, in idealized dynamical models, and in -complex general circulation models. This talk will characterize the conditions under which dipoles emerge as EOFs of a jet of fixed shape f(x) which takes a unique localized extremum

and is smooth but is otherwise arbitrary, characterized by fluctuations in strength, position, and width of arbitrary distribution. It will be shown that the factors which influence the extent to which a dipole-like structure will arise as an EOF are:
(i) the skewness of position fluctuations, (ii) the dependence of position fluctuations on strength and width fluctuations, and (iii) the relative strength of position and width fluctuations. In particular, the leading EOF will be a dipole if jet position fluctuations are not strongly skewed, not strongly dependent on strength and width fluctuations, and sufficiently large relative to strength and width fluctuations. As these conditions are generally satisfied to a good approximation by observed and simulated tropospheric eddy-driven jets, this analysis provides a simple explanation of the ubiquity of dipolar jet EOFs.

Philip Sura (Grant Holder)

On Non-Gaussian SST Variability in the Gulf Stream and other Strong Currents

Since the very early days of physical oceanography the Gulf Stream system plays a central role in the dynamical description of the general circulation of the ocean. The Gulf Stream is a warm western boundary current that transports large amounts of heat northward, and cones-quently is a major part of the global climate system. Therefore, it is important to study and understand the physics behind its temperature fluctuations. Here we will study the physics of non-Guassian SST variability in the Gulf Stream and other strong currents in a recently developed stochastic framework.

Paul Kushner (Grant Holder)

Power-law and long-memory characteristics of the atmospheric general circulation

Recent research has shown that some aspects of climate variability are best described by a “long-memory” or “power-law” model that fits a temporal spectrum to a power law instead of to a classical AR1 "Hasselman" model. We have applied several power-law estimators to global temperature data from reanalysis products to determine and begin to understand the global distribution of power-law exponents. A select-ion of available estimation methods agree well for pure power-law stochastic processes, but are highly non-robust when applied to the ob-served temperature time series. The observational results converge once analysis frequency ranges are made consistent and the lowest frequencies are included, and once several climate signals have been filtered. We have also used general circulation model simulations to at-tribute power-law features of the general circulation to specific forcing processes. Two robust results emerge from the analysis: first, that the tropical circulation features relatively large power-law exponents that connect to the zonal-mean extratropical circulation; and second, that the subtropical lower stratosphere exhibits power-law behavior that is volcanically forced.

Prashant Sardeshmukh (Grant Holder)

Reconciling Non-Gaussian Climate Statistics with Linear Dynamics

Linear stochastically forced models have been found to be competitive with comprehensive nonlinear weather and climate models at representing many features of the observed covariance statistics and at predictions beyond a week. Their success seems at odds with the fact that the observed statistics can be significantly non-Gaussian, which is often attributed to nonlinear dynamics. The stochastic noise in the linear models can be a mixture of state-independent ("additive") and linearly state-dependent ("multiplicative") Gaussian white noises. It is shown here that such mixtures can produce not only symmetric but also skewed non-Gaussian probability distributions if the additive and multiplicative noises are correlated. Such correlations are readily anticipated from first principles. A generic stochastically generated skewed (SGS) distribution can be analytically derived from the Fokker-Planck equation for a single-component system. In addition to skew, all such SGS distributions have power-law tails, and a striking property that the (excess) kurtosis K is always greater than 1.5 times the square of the skew S. Remarkably, this K-S inequality is found to be satisfied by circulation variables even in the observed multi-component climate system. A principle of "Diagonal Dominance" in the multi-component moment equations is introduced to understand this behavior.

Alexey Kaplan (Grant Holder)

Small-scale and short-term variability in the ocean: Use of its statistics for error modeling

Variability in nature exists on all spatial and temporal scales, including those smaller than the resolution of model and observational data sets. Imperfect parameterization of this small-scale and short-term variability in models and its incomplete sampling by observational systems creates model and observational error on the resolved scales of variability. Advent of satellite data sets made it possible to compute directly statistics of variability on scales smaller and shorter than what is traditionally resolved in the global climate data sets of observations or model fields. Such analyses provide additional insights into the nature and balance of error in these data sets. Changes in subgrid variability with the grid size naturally invoke a power-spectral description of the physical field. Applications to the error analysis of sea surface temperature and sea surface height data sets will be shown.

Bill Merryfield (Grant Holder)

Statistical-mechanical forcing of ocean circulation: What can ocean models tell us?

Theory and idealized numerical models offer abundant evidence that unsteady motions over sloping topography tend to produce mean flows in the pseudo-westward direction, i.e. with shallower water to the right of the current vector in the Northern Hemisphere. This can be viewed as resulting from the tendency for eddies to drive fluid systems closer to statistical mechanical equilibrium. Observing this effect in nature is challenging due to the relative sparsity of direct current measurements, as well as competing influences on ocean dynamics such as winds and buoyancy. Another means for assessing its impact on ocean circulation is through ocean models, which provide more complete information as well as the opportunity to represent ocean circulation in both eddying and non-eddying regimes. This talk examines differences between mean flows in eddying and and non-eddying ocean models in the context of the statistical-mechanical forcing problem.

Paul Williams (Grant Holder)

Stochastic physics across a hierarchy of weather and climate models

The only strictly mathematically defensible approach to weather and climate simulation is to run models at resolutions so fine that even the smallest, fastest phenomena are explicitly resolved. Unfortunately, this approach is not computationally feasible at present, nor is it likely to be for decades or centuries to come. Hence, parameterisation of unresolved processes is essential, and will remain so. I will discuss the impacts of stochastic physics schemes in a hierarchy of weather and climate models, from highly truncated low-order conceptual models, through high-resolution grid-point models of balanced flows, to state-of-the-art coupled atmosphere-ocean general circulation models.

Andrew Majda (Grant Holder)

Systematic Strategies for Low Dimensional Stochastic Mode Reduction in Dynamical Systems with Many Degrees of Freedom:

This lecture discusses systematic mathematical strategies for low-dimensional stochastic mode reduction for turbulent large dimensional dynamical systems and their application to modelling low frequency weather dynamics and climate change. A remarkable fact of Northern Hemisphere low frequency variability is that it can be efficiently described by only a few teleconnection patterns that explain most of the total variance. These few teleconnection patterns not only exert a strong influence on regional climate and weather, they are also related to climate change. These properties of teleconnection patterns make them an attractive choice as basis functions for climate models with a highly reduced number of degrees of freedom. The development of such reduced climate models involves the solution of two major issues: 1) how to properly account for the unresolved modes, also known as the closure problem; and 2) how to define a small set of basis functions that optimally represent the dynamics of the major teleconnection patterns. In this lecture examples of stochastic mode reduction are discussed ranging from an explicit solvable pedagogical example with three modes to a prototype atmospheric general circulation model with a thousand degrees of freedom where an effective reduced stochastic model with only ten low frequency modes captures the statistical dynamical behavior. A controversial topic in the recent climate modeling literature is the fashion in which metastable low-frequency regimes in the atmosphere occur despite nearly Gaussian statistics for these planetary waves. Here a simple 57-mode paradigm model for such metastable atmospheric regime behavior is introduced and analyzed through hidden Markov model (HMM) analysis of the time series of suitable low-frequency planetary waves. The analysis of this paradigm model elucidates how statistically significant metastable regime transitions between blocked and zonal statistical states occur despite nearly Gaussian behavior in the associated probability distribution function and without a significant role for the low-order truncated nonlinear dynamics alone; turbulent backscatter onto the three-dimensional subspace of low-frequency modes is responsible for these effects. It also is demonstrated that suitable stochastic mode reduction strategies, which include both augmented cubic nonlinearity and multiplicative noise, are also capable of capturing the metastable low-frequency regime behavior through a single stochastic differential equation compared with the full turbulent chaotic 57-mode model. This feature is attractive for issues such as long-term weather predictability. Research papers regarding most of the research here can be found on Majda's faculty website: http://www.math.nyu.edu/faculty/majda

Cecile Penland (Grant Holder)

MultiLIM: A Work in Progress

It is well known that a complete description of a system can be obtained from time series if that system is described as a multivariate linear process with additive stochastic forcing. The inverse problem is much more difficult if it is a Stratonovich system with multiplicative noise. In this talk, I will discuss progress that has been made to date, including a way to finesse the problem of an arbitrary orthogonal matrix that keeps getting in the way.

GRADUATE & POST-DOCS

Claudie Beaulieu

A Bayesian approach to detect artificial discontinuities in climatic series

Changes in station location, instrumentation, observer, observing procedure or in surrounding of the observing site often result in artificial discontinuities or inhomogeneities in hydrological and climatic data records. Such data inhomogeneities can interfere with the detection of trends and computation of statistics of hydroclimatic variables. Several techniques have been developed for the detection of inhomogeneities in climate series. Most of the classical techniques allow the detection of changes in the climate series with or without reference series (series representing the regional climate that are free of inhomogeneities). The metadata (if available) are also investigated to identify the cause of the inhomogeneities. A Bayesian approach allows the use of multiple sources of evidences to infer the presence, number and positions of the changes. It also provides full probability distributions for the parameters, providing more information than classical techniques do. New Bayesian techniques for the detection of inhomogeneities in climatic series are presented. They allow the detection of a single shift in a linear regression model or multiple shifts in a multiple linear regression model. The ability of the techniques to identify inhomogeneities is validated with applications to precipitation series in the province of Quebec, Canada.

Boris Gershgorin

A Nonlinear Test Model for Filtering Slow-Fast systems

A nonlinear test model for filtering turbulent signals from partial observations of nonlinear slow-fast systems with multiple time scales is developed here. This model is a nonlinear stochastic real triad model with one slow mode, two fast modes, and catalytic nonlinear interaction of the fast modes depending on the slow mode. Despite the nonlinear and non-Gaussian features of the model, exact solution formulas are developed here for the mean and covariance. These formulas are utilized to develop a suite of statistically exact extended Kalman filters for the slow-fast system. Important practical issues such as filter performance with partial observations, which mix the slow and fast modes, model errors through linear filters for the fast modes, and the role of observation frequency and observational noise strength are assessed in unambiguous fashion in the test model by utilizing these exact nonlinear statistics.

Samuel Stechmann

A Stochastic Parameterization for Convective Momentum Transport

Two important challenges for parameterizing convection in general circulation models (GCMs) are (i) increasing the variability of convectively coupled waves and (ii) parameterizing convective momentum transport (CMT) from unresolved convection.
A method is developed and tested here that is aimed at these challenges. The method attempts to capture instances of both downscale CMT (i.e., cumulus friction) and the intermittent occurrence of upscale CMT from organized mesoscale convection. Preliminary tests are shown using this parameterization in a single column model and in a two-dimensional model with a multicloud convection parameterization.

Kirsten Zickfeld

Admissions pathways reducing the risk of dangerous climate change

The ultimate objective of climate change mitigation is to reduce the amount of anthropogenic greenhouse gas (GHG) emissions in order to achieve ``stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, Article 2). This statement raises a number of questions regarding (i) what ``dangerous interference" means, (ii) what GHG concentration level may considered ``safe", and (iii) what emissions pathway should be taken towards stabilization. Here we present a novel approach to coupled climate-carbon cycle modelling which allows one to estimate the probability that any given level of GHG emissions will exceed specified global mean temperature thresholds for ``dangerous anthropogenic interference", taking into consideration uncertainties in climate sensitivity and the carbon cycle response to climate change. Results obtained wit hin this framework can serve as a basis for selecting a GHG emissions level given a global mean temperature target and an overshoot probability that society is willing to accept. For instance, we show that in order to stabilize global mean temperature at 2°C above pre-industrial levels with a probability of 0.33, cumulative CO$_2$-equivalent emissions after 2000 must not exceed a best estimate of about 640~PgC, independent of the path taken to stabilization.

Nedjeljka Zagar

Application of normal mode functions to analysis and forecast fields

This talk will present application of normal mode expansion to various analysis and forecast fields. A special advantage of the applied set of normal modes is that three-dimensional modes are orthogonal which permits the representation of the wind and mass fields simultaneously. This allows energy quantification as a function of a zonal wave number, a meridional mode and a vertical eigenstructure as well as balanced and unbalanced motions. The normal mode analysis is applied to the outputs of the 80-member ensemble of analyses and forecasts using the NCAR's Community Atmosphere Model and the ensemble adjustment Kalman Filter (DART/CAM). Difference between the expansion coefficients for the prior and posterior fields provide information about the scales and motions which are affected by observations and assimilation modeling. For a particular analysis time, information about the ensemble spread in the wave space is provided. For the departure fields, variances of errors in the prior and posterior ensembles are estimated in terms of various modes. Analyzing this information provides understanding about how the assimilation is treating various modes. Of particular interest are large-scale divergent tropical motions, known to be poorly analyzed by traditional analysis methods.

Karim Houchi

Characterization of wind and wind-shear profiles using high-resolution radiosondes

The Atmospheric Dynamics Mission (ADM-Aeolus) is the 2nd Core Earth Explorer mission to be developed within ESA's living planet programme. The Aeolus satellite will carry a Doppler Wind Lidar (DWL) instrument called ALADIN. This will allow a direct measurement of wind globally along the laser beams line-of sight (LOS), in the lowermost 30 km of the atmosphere. Wind vertical profiles will thus be obtained by measuring the Doppler shifted light of the backscattering particles, therefore their motion, at different levels in the atmosphere. The light from aerosol and cloud is collected in a Mie receiver and from molecules in a Rayleigh receiver. However, the vertical resolution of both Mie and Rayleigh channels is limited by the number of adjustable range bins of 24. This motivates an assessment of the most useful vertical distribution of the bins. To do so, global and regional statistics of the horizontal wind and wind shear are needed to characterize the structure of wind in the troposphere and the lower stratosphere, and to investigate possible systematic sampling effects. In view of the global character of Aeolus wind measurements, high resolution radiosondes which offer a wide coverage over the world of the wind observations up to about 35 km are presently the best candidate, and they are used. For reference, the study compares high resolution radiosondes with standard resolution radiosonde data and with analysis fields of the ECMWF model. As such,

- Available high-resolution radiosondes data from many stations over the world (from SPARC, FASTEX projects, UK Met-office UCAR...) are collected and collocated with the Short-Range Forecast (SRF) of the ECMWF model fields, and statistics are performed for both data sets to allow comparison.
- Special attention is paid to the radiosonde Quality Control in view of the differences in the accuracy of the wind-finding systems (Theodolite, Loran-C, GPS...) used for each dataset in order to distinguish the outliers from the representative data.
- Temporal and spatial variability over the climate regions (tropics, mid-latitudes and polar) of the wind and the vertical shear in the horizontal wind at each vertical level is under investigation.

George Djoumna

High-order C1 finite-element interpolating schemes for ocean modelling

The finite-element, semi-implicit, and semi-Lagrangian methods are used on unstructured meshes to solve the nonlinear shallow-water system. Several C1 approximation schemes are developed for an accurate treatment of the advection terms. By tracking the characteristics backward from both the interpolation and quadrature nodes and using C1 interpolating schemes, an accurate treatment of the nonlinear terms and, hence, of Rossby waves is obtained. The performance of our approach in the test problems to simulate slowly propagating Rossby modes illustrate the promise of the proposed approach in ocean modelling Method of Payment

John Harlim

Mathematical strategies for filtering turbulent signals in complex systems

An important emerging scientific issue in many practical problems ranging from climate and weather prediction to biological science involves the real time filtering and prediction through partial observations of noisy turbulent signals for complex dynamical systems with many degrees of freedom as well as the statistical accuracy of various strategies in this context. Our strategies blend classical stability analysis for partial differential equations and their finite difference approximations, suitable versions of Kalman filtering, and stochastic models from turbulence theory to deal with the large model errors in realistic systems.

Nathan Arnold

Spectra of surface ocean variability from observations and models:

Frequency and wavenumber spectra of basic variables in geophysical fluid dynamics have been the subject of many outstanding theoretical works but, until recently, observations have been of relatively limited scope. Most famous theoretical results derive log-log wavenumber spectral slopes of -5/3 or -3 for kinetic energy and a -2 frequency spectral slope for sea surface temperature. Satellite records of surface ocean variability have now reached the length of about two decades and can provide the ultimate test of existing theories as well as material for the derivation of spectral forms from observations. On the other hand, specifically surface variability of the ocean might be more complicated and less uniform than what theories predict because of interaction with the atmosphere, presence of land, etc.

In this work the variability in sea surface height is characterized using fifteen years of altimetric data from the Topex/Poseidon, ERS-1/2, Jason and Envisat missions. Sea surface temperature is analyzed on the basis of AVHRR fields and moorings in the Monterey Bay area. Multi-taper frequency and wavenumber spectra are calculated for sea surface heights from both mono-mission along-track data and merged gridded products. Comparisons are made with frequency spectra from the global tide gauge network to estimate variability at frequencies unsampled by altimetry and to verify energy levels at common frequencies. Geographic regions of common spectral shape are identified, including broad regions of ω^{-2} decay associated with high eddy energy. Maps of variance within specific space-time windows were produced and compared with those from regional ocean model (ROMS) simulations of various resolutions. The immediate practical application of this work is in modeling effective observational error for ocean data assimilation schemes. [In collaboration with A.Kaplan, H.-P.Huang, E.N.Curchitser, C.A.Edwards].

Jahansha Davoudi

Stochastic variability of mass flux in a cloud resolving simulation

The results of the random Poisson theory for cloud coverage proposed recently by Craig and Cohen \cite{1,2,3,4} is tested in a CRM simulation with interactive radiation code and diurnal variability. The predictions of the theory for area averaged mass flux and averaged number of updrafts are in good agreement with the numerical simulation up to $[1,6]$ Km. For altitudes higher that $[6,12]$ Km we show a systematic deviation from the theory is observed .

The regime when the deviations are built up is shown to be correspondent with a large level of fluctuation in the number of up drafts which is reflected by fat tail distributions in the probability distribution of number of updrafts.

Joel Culina (Adam Monahan, Sergey Kravtsov)

Stochastic Parameterisaiton Schemes in a Mathematically Rigorous Framework

Low-dimensional (planetary scale) models of extratropical atmospheric low-frequency variability (LFV) are derived from a nearly 10000 dimensional (planetary and synoptic scale) model through averaging and stochastic representation of the fast processes. The bottom drag parameter is a bifurcation parameter of the unreduced model, controlling the transition to multiple regime behavior, characterized by aperiodic, low-frequency meridional shifts of the jet. At realistic bottom drag, at which there are meridional shifts, the statistics of the mode that best captures the medirional shifts is generated by one-dimensional stochastic differential equations (SDEs). Two primary strategies are applied to achieve this reduciotn to a closed system of slow-evolving models, each strategy based on mathematically rigorous theory in the limit of infinte timescale separation. One strategy is suitable for an explicit stochastic parameterization scheme, as it yields explicitly the co-efficients of the reduced SDE. The other strategy is flexible, as the parameters can be adjusted according ot the desired balance between cost and error tolerance, and it is easily implemented. The reduced models shed light on the physics of LFV, including different interpretations from previous studies of the dynamics of the shifting jet.

SUMMER SCHOOL/WORKSHOP POSTERS

Tsuyoshi Wakamatsu

On the influence of random wind stress errors on the four dimensional, mid-latitude ocean inverse problem

The effects of the parameterized wind stress error covariance function on the a priori error covariance of an ocean general circulation model (OGCM) are examined. These effects are diagnosed by computing the projection of the a priori model state error covariance matrix to sea surface height (SSH). The sensitivities of the a priori error covariance to the wind stress curl error are inferred from the a priori SSH error covariance. They are shown to differ between the subpolar and subtropical gyres due to different contributions from barotropic and baroclinic ocean dynamics. The spatial structure of the SSH error covariance due to the wind stress error indicates that the a priori model state error is determined indirectly by the wind stress curl error. The impact of this sensitivity on the solution of a four dimensional inverse problem is inferred.

Chaim Garfinkel

The Different ENSO Teleconnections & Their Effects on the Stratospheric Polar Vortex

Reanalysis data are used to study the El-Nino Southern Oscillation (ENSO) signal in the troposphere and stratosphere during the late fall to mid-winter period. Warm ENSO events have extratropical tropospheric teleconnections that increase the wave-1, and reduce the wave-2 amplitude, as compared to cold ENSO. The increase in wave-1 overwhelms the decrease in wave-2, so the net effect is a weakened vortex. This odification in tropospheric wave forcing is induced by a deepening of the wintertime Aleutian low via the Pacific-North America Pattern (PNA). Model results are also used to verify that the PNA is the primary mechanism through which ENSO modulates the vortex. During easterly Quasi-Biennial Oscillation (EQBO), warm ENSO does not show a PNA response in the observational record. Consequently, the polar vortex does not show a strong response to the different phases of ENSO under EQBO, nor to the different phases of QBO under WENSO. It is not clear whether the lack of a PNA response to warm ENSO during EQBO is a real physical phenomenon or a feature of the limited data record we have.