IP1

Earth System Stability and Mass Extinctions

The five great mass extinctions of the geologic past are each associated with significant perturbations of Earths carbon cycle. But many past environmental events are not associated with mass extinction. What makes them different? Previous analyses have usually focused on aspects of ancient environments associated with specific events. Here we study all events. By transforming geochemical signals to physical variables, we find that mass extinctions are associated with rates of environmental change that exceed a limit imposed by mass conservation in a normal carbon cycle. We identify this limit with marginal stability of the Earth system. We conclude with brief remarks on the relevance of these findings to modern environmental change and a potential sixth extinction.

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IP2

The Problem of Translating Climate Change into Impacts

The talk reviews the analytical, conceptual, and empirical problems of translating projections of future climate change into assessments of impacts that are meaningful for policy-makers, whether their focus is mitigation or adaptation policy. The most profound challenge is the mismatch between the spatial and temporal scales used for modeling climate change and the scales at which impacts occur and economic data are collected. Overcoming this challenge will require innovations in computational and modeling practices. Another profound challenge is how to incorporate uncertainty about models, about the occurrence of physical events and about human behavior in a meaningful way into impact assessments: how should one think of uncertainty, and to what extent should one attempt to account for it? It turns out that, for next four or five decades, the vast majority of the economic and social impacts of climate change are likely to be associated with local extreme events; the third issue addressed is how to deal with these in an assessment of climate impacts.

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IP3

Public Lecture - Assessing Risks to Global Food Systems: Mathematicians, Food System Experts and Insurance

Current estimates that the world's food production will have to double by 2050 to feed the growing world population depend on a number of assumptions about technology, infrastructure, dietary demand, conflict and population that may not hold. At the same time, the global food system is impacted by, and impacts, climate change, political instability, and environmental degradation, to name only a few key dynamics. Various powerful stakeholders are interested in developing improved methods to reflect risk and uncertainty that originate in, or amplify through, our global food systems. The speaker will report on work, commissioned by Lloyd's of London, to characterize potential business risks that reside in the global food system, and the wider implications and opportunities defined by current data and analytical gaps. Food system experts, decision-makers, mathematicians and statisticians have collaborated to generate results and recommendations that are relevant and understandable for all. Intensifying demand for probabilistic reflections of these risks and threats for humanitarian concerns and capital define important opportunities for new collaborations.

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IP4

Feedbacks Between Soil Engineers and Vegetation can Increase Ecosystem Robustness

Regular self-organized spatial patterning in plants, mussels, corals, and other sessile organisms is globally widespread and thought to play a key role in mediating important ecosystem functions such as productivity, resilience and robustness in the face of perturbations. Therefore, understanding the mechanisms underlying such patterns is paramount. Self-organized spatial vegetation patterning has been described using models of scale-dependent feedback between plants and water on homogeneous substrates. As rainfall decreases, these models yield a characteristic sequence of patterns with increasingly sparse vegetation, followed by sudden collapse to desert. Thus, the succession of patterns may act as early warning indicators for such catastrophic shifts. In many arid ecosystems, however, termiteengineering imparts substrate heterogeneity by altering soil properties and plant growth. I will use models and data to show (i) how termite nests self-organize in regular, overdispersed patterns and (ii) how termite self-organization and induced soil heterogeneity interact with scale-dependent plant-water feedbacks to produce vegetation patterns at different spatial grains and enhance the robustness (resilience) of the ecosystem in the face of climate change.

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IP5

Smarter Planet 2.0

The Smarter Planet initiative began as an effort to take advantage of increasingly instrumented and interconnected systems for more efficient and sustainable use of resources. Since then, significant gains have been made towards these goals, but considerable challenges remain. This presentation will explore progress to date in applying Big Data and analytic tools to improved operation of infrastructure systems and resource allocation with a focus on water and energy. Examples of improved predictive models, combining physics models with machine learning and optimization approaches to make better decisions and improve sustainability will be covered

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CP1

Risk Analysis and Spatio-Temporal Modeling of

Wildfires in Belgium

Motivated by the unpreparedness of the Belgian intervention services in fighting the wildfires that consumed thousands of hectares of vulnerable vegetation in 2011, and whose frequency is expected to increase in the future, we compiled the first national wildfire risk map using historical fire event data and environmental data. This way, the available resources can be distributed more efficiently. To aid fire suppression, a spatially explicit wildfire model was adapted to the Belgian scale.

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CP1

Optimal Regulations for Effectiveness of Carbon Market

Since the Intergovernmental Panel in Climate Change (IPCC) in 1988, scientists agreed on the role of human activities on the climate change, and consequently on our lives. Therefore, measures in the governmental and intergovernmental level had been taken to curb the increase carbon dioxide as the main source of global warming. Enforcing these measures have an adverse effect on the global economy. Therefore, they have to be chosen very carefully. One of the most attractive approaches to reduce emission of carbon dioxide is emission-trading scheme; so-called cap-and-trade. We model the cap-and-trade by mathematical tools from optimal control to obtain some qualitative results on how a regulator can adjust the parameters of the cap-and-trade (e.g. penalty, availability of information, free allowance) to reduce the level of production of the company or creates incentive for the company to switch to a clean energy source.

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CP1

Mentoring Undergraduates In Measuring Vegetation Dynamics in the Horn of Africa

Aerial imagery showing striped vegetation patterns in the Horn of Africa dates to the 1940s. These and other observations distributed over many decades make it possible to measure aspects of vegetation dynamics on multi-decadal timescales. Such measurements may inform the modeling of vegetation dynamics. We describe the mechanics of our remote collaboration to mentor summer undergraduate students, the training benefits for more junior members of the research team, and the results of our measurement efforts.

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CP1

Large Ecosystems in Transition: Interactions and Feedbacks

We consider a multispecies population model surviving on distributed resources and studied the dynamics of the system under the influence of climate change. The basic model is demanded as Lotka-Volterra type and modelling the plankton ecosystem and the effect of climate is incorporated into the model by considering the effect of environmental temperature on the system dynamics. We prove a general assertion on attractor existence for this model. In case of a positive climate feedback loop, we observe catastrophic bifurcations related to the extinction of all species.

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CP1

The Role of Spatial Structure and Landscape Heterogeneity in Driving Metapopulation Dynamics

Stochastic phenomena are likely to drive local extinctions in metapopulations—populations of disjoint habitat “patches” connected by dispersal—with small patches. Here we use a simulation model designed to evaluate the significance of random fluctuations and the role of spatial structure in driving population dynamics. Our model is formulated as a stochastic process on a finite, spatially explicit array of patches. Probability of successful dispersal is modeled as a function of distance between patches. We apply it to the best-known mammalian metapopulation in North America: the American pika (*Ochotona princeps*) population living on the ore dumps in the ghost mining town of Bodie, California. This population has been of conservation concern as the southern half of the metapopulation went recently. The model was parameterized with demographic and spatial data from the Bodie metapopulation, which has been studied nearly continuously for six decades. Our model is able to describe many of the population dynamics (e.g. mean abundance and patch occupancy) of the Bodie population. In addition, we found spatial structure and landscape heterogeneity are both necessary, and sufficient, to correctly predict the collapse of the southern half of the Bodie metapopulation. This type of model is flexible enough to be applied to many different systems with different spatial structures, dispersal strate-

gies, or different life histories in general.

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CP2

Robust Spatial Optimization for the Invasive Species/Plants Management

Rapid diffusion of non-indigenous species has significant impact on environmental threats and global biodiversity loss. The problem of invasive species management concerns modeling the pattern of spread of the invasive, estimation of control costs, spatial design of the control effort, and accounting for uncertainties in model parameters. We are developing a spatial-optimization model to select sites for efficiently controlling invaders to minimize their ecological damage, as well as to minimize the costs given limited financial resources.

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CP2

On the Boundary Dependent Vortex Invariants in Magneto-Hydrodynamics

Long ago it was stated that quantum vortices in super liquid helium can be studied either as open lines with their ends terminating on free surfaces of walls of the container or as closed curves. Nowadays the closed vortices are treated as topological objects equivalent to circles or membranes. The existence of structures such as knotted and linked vertex lines in the turbulent phase is almost obvious and has forced researchers to develop new mathematical tools for their detailed investigation. The classical helicity theorem describes in a unique way, both the super fluid equations and the related helicity invariants, which are, in the conservative case, very important for studying the topological structure of vortices. In the report we demonstrate a new version [Anatoliy K. Prykarpatsky and Denis Blackmore. New vortex invariants in magneto-hydrodynamics and a related helicity theorem. Chaotic Modeling and Simulation, 2013, 1: 239-245] of the Helicity theorem, based on differential-geometric methods applied to the description of the collective motion in the incompressible super fluid. We propose a new unified proof and give a magneto- hydrodynamic generalization of this theorem for the case of an incompressible superfluid. As a by-product, we construct a sequence of nontrivial helicity type conservation laws, playing a crucial role in studying the stability problem of a super fluid under suitable boundary conditions.

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CP2

The Effect of a Density Interface on Turbulence in a Stably Stratified Two-Layer Fluid

A density interface in the atmosphere and ocean tends to suppress turbulence, mixing, and vertical diffusion. To better understand the effect of a density interface on turbulence in a stably stratified two-layer fluid, integrals are derived for the Eulerian frequency spectra of the horizontal velocity (ψ_{11}) and vertical velocity (ψ_{33}) for both infinite and arbitrary Ri, respectively. The distribution curves of both (ψ_{11}) and (ψ_{33}) are obtained by numerical integration. For infinite Ri, at large dimensionless frequency (ω^*) and the different distance from the density interface (z^*), their distribution curves are converged to the same line, suggesting the negligible effect of the density interface on turbulence at large z^*. As z^* increases, the presence of the density interface results in the reduction of (ψ_{11}) and amplification of (ψ_{33}). However, their distribution curves are eventually coincided. For infinite Ri, at small ω^* and different z^*, the peak and convergence points of the distribution curves of both (ψ_{11}) and (ψ_{33}) are found to vary with z^*. Those of ψ_{33} are greater than of ψ_{11} For a given Ri, with increasing z^*, $\psi_{ii}(\omega^*, z^*)(i = 1, 3)$ is rapidly converging to the same line $\psi_{ii}(\omega^*, 1)$, suggesting the negligible effect of the density interface on turbulence. At arbitrary z^*, the curves of $(\psi_{11})(\omega^*, z^*)$ are converged to the same line. When $z^* > 0$, the distribution curves of $(\psi_{33})(\omega^*, z^*)$ are converged to one line, however, at $z^* = 0$, they are converged to another line, suggesting the discontinuity of the Eulerian frequency spectrum of the vertical velocity above and below the density interface. The dimensionless maximum resonant frequency (ω_r^*) increases with increasing Ri, but the frequency range of the linear internal waves decreases. For a given $Ri, \psi_{33}(\omega^*, 0)$ is greater than (ψ_{33}) $(\omega^*, z^* > 0)$ and then reverses before their convergence as ω^* increases. At sufficiently large ω^*, the distribution curves of (ψ_{11}) and (ψ_{33}) satisfy the -5/3 power law for arbitrary Ri and z^*.

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CP2

G-Type Wave in a Viscoelastic Layer Over a Fibre Reinforced Half Space

This paper inspects the possibility of G-type wave propagation along the plane surface at the interface of two different non homogeneous fibre reinforced and viscoelastic media. In the proposed work, viscoelastic media and non homogeneous fibre reinforced media are supposed to be upper and lower half space respectively. Dispersion equation and condition for maximum energy flow near the surface are obtained in closed form applying mechanism of infinite determinant and Laplace transform. The dispersion equation accord with the classical Love type wave. It is examined that the group velocity is less than the shear wave velocity in the upper mantle. The consequences of reinforcement and non homogeneity parameter on phase and group velocity have been accentuated through graphs.

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CP2

Design of Random Rough Interfaces for Optimal Light Absorption in Thin Film Solar Cells

Reducing a solar cell's thickness improves both its quality and material cost, but limits its absorptive capacity. To ensure strong and broadband light trapping, the interface between the transparent conductive oxide and absorptive layers is usually randomly roughened. We present and analyze an efficient numerical algorithm for determining the optimal random rough interface that maximizes the radiance within the absorptive layer.

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CP3

Toward Improved Ocean-Atmosphere Coupling Algorithms

The interactions between atmosphere and ocean play a major role in many geophysical phenomena, covering a wide range of temporal scales (e.g. diurnal cycle, tropical cyclones, global climate). Therefore the numerical simulation of such phenomena require coupled atmospheric and oceanic models, which properly represent the behavior of the boundary layers encompassing the air-sea interface and their two-way interactions. However deficiencies appear in current ocean-atmosphere coupled models, both in the formulation of the physical parameterizations and in the algorithmic approach used for the coupling. Parameterizations used for representing the oceanic and atmospheric boundary layers and for computing the air-sea fluxes are generally developed independently, without any guarantee regarding the well-posedness of the overall coupled problem. Moreover usual coupling algorithms exhibit synchrony issues. In this talk, we address these problems from the point of view of domain decomposition methods. We show that present coupling methods used for ocean-atmosphere coupled models can be written in the formalism of Schwarz iterative algorithms, and correspond to methods that are not pushed to convergence, which may lead to imperfect coupling. We discuss the objective of achieving a mathematically and physically consistent ocean-atmosphere coupling, and we show that using improved coupling algorithms (like Schwarz methods) can impact the coupled model solution quite significantly.

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CP3

Automatic Generation of Cvt-Based Multi-Dimensional Mesh

A coupling of various media is essential for a first principle physics-based watershed model. Such an integrated model poses several computational challenges since it requires a generation of millions of finite elements and nodes. In this work, we propose a coupled 1D/2D centroidal Voronoi tessellation (CVT)-based system, which is automatically generated as the solution of a constrained optimization problem. The preliminary results illustrate certain benefits in terms of both accuracy and speed.

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CP3

Invisible H2O: Tracking the Water We Cannot See

In order to better predict the timing and intensity of floods, we must have a strong understanding of the methods by which precipitation is translated into streamflow. When using mathematical hydrologic models to represent the transmission of precipitation to streamflow, the most easily observed values often represent the outputs of said models, while the observable inputs tend to contain significant uncertainty. Because of this, the ability to work with a hydrologic model in reverse chronological order (the 'backwards direction') of the water cycle is a useful technique which can result in more accurate models. In this talk, we will present a model for water flow through a hillslope. We will then apply this model under dry conditions, and use observed streamflow time series to infer the pattern of evaporation which has forced the aforementioned streamflow to occur.

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CP3

Unbiased Factor for the Entropy Estimator in Information Theory: A New Suggested Estimation and Application to Rainfall Network

Information theory is one of different branches of probability theory, which has extensive potential applications to the communication system. Shannon (1948) has introduced the entropy to measure the amount of information and uncertainty. In this paper, we try to review different entropies and made a comparison between them by applying them on the rain fall data from two distinguished regions on the world which have totally different climatic conditions, and then indicate which region would have a maximum uncertainty to the climatic conditions. Moreover, we will suggest a new estimator of entropy in describing its properties as well as applications. Our new estimator is in fact an unbiased factor of the Shannons entropy estimator. In this study we use the hazard rate to find a new estimator of entropy. The new estimator is more applicable in engineering, biological sciences, information theory and life sciences. Our finding could lead to a more significant and potentially applicable approach due to the fact that generally we dont have the parametric value of the probability distribution and we use the estimated values for the analysis. The quantitative model in our paper can be very helpful for the weather forecasting with more high accuracy. We wish the general outcome of this paper would contribute to resolution for the planetary problem such as climate change and global warming effects which are always with high uncertainty issue.

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CP3

A High Accuracy Surface Modeling Method and Its Applications in Climate Change Research

In this talk, we will give a new mathematical method for climate variables simulation.Based on the fundamental theorem of surfaces, a surface is uniquely defined by the first and the second fundamental coefficients, which represents the macro and micro information of it, respectively. A method for high accuracy surface modeling (HASM) is thus developed based on this theory. HASM can be conducted either as an interpolator with high accuracy or as a data fusion method. The method has been widely used in earth science and climate change.

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CP4

A Partial Differential Equation Model for Fire Resource Allocation

Interactions between humans and wildland fire generate complex management problems with ecological and social dimensions. One pressing subset thereof seeks to optimize allocation of nationally-pooled, expert fire professionals to meet seasonal demand for suppression and preparedness work. This study explores archived national requests (2011-2015) from the Resource Ordering Status System (ROSS), which tabulates fire resources (helicopters, fire engines, etc) and their mobilization to incidents. When the ROSS-managed supply pool depletes, decision-makers face increased potential for unmet demand, which compounds management risks. We treat the scarce limit of allocation by exploring national efficiency and local request priority in a partial differential heat equation (PDE) model:

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \left(a(\vec{x}, t) \vec{\nabla} u \right) = f(\vec{x}, t),$$

where u counts resources, $a(\vec{x}, t)$ captures resource mobility, and $f(\vec{x}, t)$ describes demand. Current fire activity and short-term workload predictions are parameterized as initial and boundary conditions. We establish feasibility and utility of such a model by estimating mobility fields $a(\vec{x}, t)$ using a finite difference inverse approximation and performing a scenario-based study of human-drawn decision-making borders such as the broad Geographic Area Coordination Center (GACC) and fine Predictive Service Area (PSAs) as finite elements.

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CP4

Empirical evaluated SDE modelling for dimensionality-reduced systems and its predictability estimates

This paper develops and validates a method of empirical modelling for a dimensionality-reduced system of a nonlinear dynamical system based on the framework of the stochastic differential equation (SDE). Following the mathematical theorem corresponding to some inverse problem of the probability theory, we derive empirically evaluating formulae for the drift vector and the diffusion matrix of the SDE. Focusing on a low-dimensional dynamical system of the Lorenz system, we empirically reconstruct an SDE that approximates the original time-series on the projected 2-dimensional plane. To assess the availability of the obtained SDE, we compare the ensemble variance of solutions generated by the numerical SDE to that of the trajectories of the projected orbit of the time-series. The results have good agreements in the distribution of values of the ensemble variance and show the predictive ability of the SDE modelling. This framework can be applied to empirical estimate of ensemble spread of an operational climate forecast system. Applying the present methodology to dimensionality-reduced climate reanalysis datasets, we can evaluate a magnitude of error growth, corresponding to the ensemble spread, as diffusion of solution paths of the estimated SDE in the low-dimensional phase space. The present study gives theoretical fundamentals of the predictability estimates for the ensemble forecasts.

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CP4

Bayesian Inference for Expensive Simulators

I explore applications of likelihood-free Monte Carlo methods to computationally expensive simulators. My work considers potential benefits of using variations of Approximate Bayesian Computation (ABC) algorithms in Agent Based Models (ABMs). The novel algorithms such as ABC SMC are very promising: the simulators may be faster and more accurate than the standard rejection sampling approach. I will present these methods in comparison to standard Monte Carlo simulations as well as an example of their usage on particular ecological model considering energy budgets of earthworms.

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CP4

Energy-Optimal Control of Temperature for Wine Fermentation

In the literature, many models based on ordinary differential equations already exist to describe the process of wine fermentation. However, the dynamics due to yeast cell growth play an important role in this fermentation process. That is why we take a closer look at the mass structure of yeast cells by introducing a nonlinear partial integro-differential equation for the population balance of yeast and ordinary integro-differential equations for the other substrates such as sugar, nitrogen, oxygen and the product, i.e. ethanol.
The derived model is solved numerically using a finite volume scheme for the discretization of the mass domain and a (semi-)implicit temporal discretization scheme for the resulting system of time dependent ordinary differential equations.
Moreover, in the process of making wine a high potential for the conservation of energy exists. Therefore we take a closer look at energy-optimal control of the cooling process during wine fermentation. Thereby the dynamic process is represented by the system of integro-differential equations considering also the mass structure of yeast cells where the reaction behavior is modeled based on a novel model including a death phase for yeast and the influence of oxygen on the process.
All in all, the conservation of energy in the process of making wine, realized by the control strategy presented in this talk, helps towards the sustainability of planet earth.

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CP4

Generalizing the Modified Buckley-Leverett Equation with TCAT Capillary Pressure

The Buckley-Leverett partial differential equation has long been used to model two phase flow in porous media. One application is contaminant flow in groundwater, where the contaminant and water are the two fluid phases flowing through a porous medium of compacted sand, for example. In recent years, the PDE has been modified to include a rate-dependent capillary pressure constitutive equation. Known as dynamic capillary pressure, this constitutive equation describes the difference between pressures at the interface of the two fluid phases with an equilibrium pressure and a time-dependent term involving saturation of the water phase. More recently, thermodynamically constrained averaging theory (TCAT) has generalized the capillary pressure equation by including additional dependence on fluid properties. In this talk, we describe the changes in the Buckley-Leverett PDE that result from incorporating TCAT capillary pressure. Traveling wave analysis of the updated model uncovers both classical and nonclassical solution structures of the associated Riemann problem, when the initial condition of the PDE represents a jump discontinuity between the two fluids. Remarkably, and unlike the case of dynamic capillary pressure with quadratic relative permeability functions, nonclassical solutions involving an undercompressive shock now exist when the initial condition involves pure water upstream and pure pollutant downstream.

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CP4

A Reaction-Diffusion Model of Tropical Vegetation and the Effect of Deforestation

There is concern that tipping points might be reached in rainforest ecosystems that could provide feedbacks to climate change. Such concerns partly derive from increasing evidence that Amazonian vegetation represents a bistable ecosystem that can exist in both forest and savanna states. Between these states, abrupt transitions are possible due to hydrological or fire-related feedbacks. A bimodal distribution of tropical tree cover at intermediate precipitation levels has been reported as evidence of fire-induced bistability. We have shown before with analysis of remote-sensed data that bimodality is almost absent in human unaffected areas, whereas it is substantially enhanced in regions close to human-managed zones. These patterns are confirmed in our reaction-diffusion model, which produces a sharp front separating forests and savannas spatially. The location of the front occurs at the Maxwell point, which is a function of water deficit, soil texture and human impact. We simplify a system of partial differential equations for several cover types to arrive at a single reaction-diffusion equation of forest cover that captures the essence of the dynamics and further derive a potential energy functional that allows us to obtain an expression for the Maxwell point. We apply the model to the Amazonian region, Africa and Southeast Asia and further show the possible effect of hydrological feedbacks on the dynamics.

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MS1

Inferring Changing Subglacial Hydrologic Conditions from Ice Sheet Surface Speed

Recent improvements in basal friction laws and subglacial hydrology models provide a path to a physically-based representation of these processes in ice sheet models, yet these models are difficult to calibrate and validate as observations to do so are few and poorly constrain the primary model state variables. Here we compare the output of a subglacial hydrologic model with basal traction inverted from ice surface speed on the Greenland Ice Sheet.

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MS1

Ice Sheet Initialization Through Large Scale PDE-constrained Optimization

Initialization of ice sheets is essential for modeling ice sheets dynamics. The initial state should be consistent with ice flow models and in good agreement with observed fields (e.g. surface velocity and temperature) and climate forcings (e.g. surface mass balance). We present a steady, adjoint-based PDE-constrained optimization capability to estimate fields like basal friction, thickness and temperature, we demonstrate it with large scale simulations and discuss the results.

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MS1

Bayesian Inversion for Ice Sheet Models

Modeling the dynamics of polar ice sheets is critical for projections of future sea level rise. Yet, there remain large uncertainties in the basal boundary conditions employed within ice sheet models, which rely on the incompressible Stokes equations with shear thinning rheology to describe the behavior of ice sheets. We address the problem of quantifying uncertainties in the inference of basal boundary conditions for large-scale ice sheet inverse problems within the framework of Bayesian inference.

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MS1

The Albany/felix First Order Stokes Finite Element Ice Sheet Dynamical Core Built Using Trilinos Software Components: Performance, Next-Generation Capabilities and Validation

This talk describes the Albany/FELIX First-Order Stokes finite element ice sheet code developed using Trilinos libraries, and its coupling to land ice dycores (CISM, MPAS) for dynamic simulations. We will discuss the algorithms that make the solver scalable, fast and robust. We will discuss the solvers next-generation capabilities: performance-portability, model calibration, UQ. We will show results of a recent validation study that simulates the period 1991-2013 with realistic climate forcing, performed using the CISM-Albany dycore.

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MS2

Multiple Scales in Storm Surge Modeling

Coastal hazards are a growing problem worldwide due to not only the current and projected sea-level rise but also due to increasing populations and economic dependence on coastal areas. Today, coastal hazards related to strong storms are one of the most frequently recurring and wide spread hazards to coastal communities today. In particular storm surge, the rise of the sea surface in response to wind and pressure forcing from these storms, can have a devastating effect on the coastline. Furthermore, with the addition of climate change related effects, the ability to predict these events quickly and accurately is critical to the protection and sustainability of these coastal areas. Computational approaches to this problem must be able to handle its multi-scale nature while remaining computationally tractable and physically relevant. In this talk, I will outline some of the approaches we are developing to address several of these shortcomings and address the multi-scale issues inherent in the problem. These approaches include adaptive mesh refinement, better wind-driven wave physics, cut-cell discretizations, and more accurate model equations such as the two-layer shallow water equations. Combining these new approaches promises to address some of the problems in current state-of-the-art models while continuing to decrease the computational overhead needed to calculate a forecast or climate scenario.

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MS2

A High-order Discontinuous Galerkin Solution of the Shallow Water Equations with Wetting and Drying and Adaptive Artificial Diffusion

To mitigate the destructing effect of a tsunami, coastal communities around the world are considering moving inland and build relatively large scattered hills by the shore. In this talk, we give some insight of our findings on the effect of these hills on tsunami waves as they reach the shore. Our analysis is based on the numerical solution of the viscous shallow water equations via high order discontinuous finite elements (DG) with fully implicit time integration. To remove the Gibbs oscillations that affect the solution in the proximity of sharp wave fronts (e.g. bores), a dynamically adaptive, residual-based artificial diffusion is applied. The wetting and drying approach, based on the use of an infinitely thin water layer in the dry regions plus a flux limiter, shows to be particularly well suited for high order elements. Preliminary, first results indicate that large hills are a viable solution to remove/deviate energy from the flow, as long as the geometrical configuration of a group of hills is properly designed. Certainly, the fact that erosion of the hill foundations is not catastrophic, they represent a viable alternative to the concrete walls that are often used today but that, as recently seen in Japan, may fall down and add to the destructive power of the moving water.

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MS2

Connecting Earthquake and Tsunami Warnings: The Role of Observations and Simulations

Local tsunami warning requires rapid assessment and communication of the tsunami hazard for communities immediately adjacent to a large earthquake. Here, the warning times are typically of minutes to tens of minutes. Local warning remains a challenging problem with very few systems worldwide capable of issuing such alerts. I will show how the advent of real-time GPS to monitor crustal deformation and strong shaking during large events as well as new ocean-based sensor networks are contributing to warning techniques. I will discuss prototype local warning systems based on these observations, which are growing alongside traditional earthquake early warning systems, and are quickly closing the gap in local tsunami warning. I will touch upon a fundamental outstanding problem. How does one test and assess the performance on these systems, designed from the ground up to respond to very large events, when these large events are rare? I will argue that simulation plays here a fundamental role and that one must rely on techniques that combine physics-based methods with stochastic approaches in order to produce a reliable ensemble of test events to exercise and assess the performance of real-time systems.

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MS2

Challenges in the Simulation of Natural Disasters – with Application to Tsunami-Inundation Modelling

Natural disasters typically arise from complex processes in the earth system and affect vulnerable areas with lasting impact to economy and society. The involved processes are often of global scale, such as hurricanes or earthquakes. However, the damage they cause can heavily depend on local features. In a tsunami resulting from an undersea earthquake, for example, the local topography and the urban structure near the coast can be important factors for the resulting damage. In the first part of the talk we will introduce the modelling and simulation of natural disasters. This involves the deterministic modelling of the natural processes and of their local impact to vulnerable areas. The scales involved are analyzed and the arising numerical challenges are discussed. We will outline some solution strategies from the literature. The simulation of such severe events will be exemplified in case of tsunami modelling in the second part of this talk. In this framework a dynamically adaptive numerical model is presented to solve the shallow water equations. It is based on a Runge-Kutta Discontinuous Galerkin discretization and robustly treats inundation events at the coast. The impact in the modelling of the earthquake source and other factors on the extent of the damage is discussed.

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MS3

Modeling the Role of Education in Preventing An Outbreak of the Ebola Virus Disease

In light of the Ebola outbreak in 2014, we worked on an Ebola model during our South Africa Mathematical Sciences Association Masmau program in 2014 and 2015. Our model partitions the population into those who take precautions against contracting the disease and those who do not. We consider new infections arising in both hospital settings as well as in the community, and include transmission from dead bodies and the environment. Our goal is to illustrate role of education in limiting a potential future Ebola outbreaks in Sudan using data and modeling. We considered implications of a new strain with respect to different death rates and recovery rates.

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MS3

Preemptive Intervention on Networks Informed by Demographic Covariates of Cholera Risk

The risk of disease outbreaks on networks is important when considering where preemptive intervention strategies should be focused. The problem is intensified when considering the uncertainty within a network. We investigate questions of vaccination distribution on heterogenous community networks given uncertainty about patch transmissibility. We consider the problem of reducing the risk of outbreak while minimizing the associated intervention costs. Two optimization problems are introduced, both incorporating the basic reproduction number as a measure for an outbreak. Our methods are then applied to a case study of the 2010-11 cholera outbreak in Cameroon to answer questions of whether demographic covariates are good predictors for cholera risk and, along with network structure, whether they inform where to prioritize vaccination.

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MS3

A Canine Distemper Outbreak Modeled in An Animal Shelter

Canine distemper virus is a highly contagious virus that can cause outbreaks, especially in crowded conditions such as in an animal shelter, in which a large number of susceptible dogs are brought together. Introduction of this virus into a shelter can have devastating effects, with the potential to result in shelter canine depopulation. Motivated by recent outbreaks in the United States, a mathematical model was constructed to find relevant factors that could assist in preventing or reducing outbreaks. We derived a system of ordinary differential equations that models the spread of this virus through S-E-I-R classes as well as a vaccinated and two different infectious classes. Using available data, our model was adapted to represent a local Knoxville shelter. The effect of vaccination on disease spread was investigated.

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MS3

Immune Response to Infection by Leishmania: A Mathematical Model

Leishmaniasis is a disease caused by the Leishmania parasites. The injection of the parasites into the host occurs when a sand fly, which is the vector, bites the skin of the host. The parasites, which are obligate, take advantage of the immune system response and invade both the classically activated macrophages (M1) and the alternatively activated macrophages (M2). In this paper, we develop a mathematical model to explain the evolution of the disease. Simulations of the model show that, M2 macrophages steadily increase and M1 macrophages steadily decrease, while M1 + M2 reach a steady state which is approximately the same as at healthy state of the host. Furthermore, the ratio of Leishmania parasites to macrophages depends homogeneously on their ratio at the time of the initial infection, in agreement with in vitro experimental data. The model is used to simulate treatment by existing or potential new drugs, and to compare the efficacy of different schedules of drug delivery.

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MS4

Evaluation of Coastal Protection Systems for Hurricane Storm Surge

Many coastal regions around the world are prone to flooding caused by tropical and extratropical storms. In response to these events, government agencies and local entities are studying potential mitigation systems to protect future generations from storm surge and the impacts of combined surge, sea level rise and/or subsidence. These studies rely on a number of tools, including accurate and efficient forward models of coastal flooding, and probabilistic methods for generating suites of synthetic hurricanes which are based on prior information. We will discuss a particular study focused on the Houston-Galveston region of the Texas coast. In this study the Advanced Circulation (ADCIRC) model, combined with the Simulating Waves Nearshore (SWAN) model, has been used as the forward model for simulating storm surge. This coupled model has been validated for many prior historical storms and serves as an excellent tool for risk assessment. A suite of synthetic storms has been generated for the Texas coast using the Joint Probability Method with Optimal Sampling (JPM-OS). This suite is supplemented with historical storms. We will focus on a recent study of the efficacy of a proposed storm mitigation system in the Houston-Galveston region, called the Houston Galveston Area Protection System or HGAPS.

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MS4

Analysis and Modeling of Tropical Cyclone Climatology

A main challenge to assessing the tropical cyclone (TC) risk is the limitation of TC records. Thus Monte Carlo (MC) method is often applied to generate synthetic TC catalogues to support risk analysis. We aim to develop a climate-variant TC climatology model that can be used to generate large numbers of synthetic TCs (characterized by their track, intensity, and size) under various observed or projected climate conditions. We will present the modeling results for the TC intensity component.

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MS4

Performing and Communicating Probabilistic Tsunami Hazard Assessment

Probabilistic Tsunami Hazard Assessment (PTHA) is typically performed by first defining a set of potential earthquakes, with associated annual probabilities, and then running a tsunami model on each potential source and combining the results into hazard maps for a particular community of interest. Recent work on this topic will be discussed, including use of a Karhunen-Loève expansion to specify a probability distribution of possible events, efficient sampling techniques for this high-dimensional space, and issues that arise in designing hazard maps that also effectively communicate the epistemic uncertainty arising from lack of knowledge of the true distribution of potential earthquakes.

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MS4

Process Complexity and Uncertainty in Coastal Hydrodynamics Hazards Modeling

Flood hazards along coasts is affected by the geometry, topography, and bathymetry of the coast, friction, tides, wave set up, winds, atmospheric pressure, and riverine discharge driven "still water levels", wind waves, infragravity waves, and tsunamis. While some of the processes such as tides are deterministically and quite accurately forced, other forcing functions such as winds and tsunami generation at the source are much less certain. In addition, dissipation mechanisms in portions of many geometrically complex domains are often not sufficiently well quantified. In this paper, we look at a Bering-Chukchi Sea model as well as a South China Sea model in which dissipative mechanisms through island strings and over deep ocean ridges with strong baroclinicity appear to be significant. Tidal complexity in these regions in very high with many amphidromic points appearing which easily shift as dissipation varies. The sensitivity on tidal and storm forcing is explored. In addition, air-sea interaction with ice is poorly quantified in arctic regions. Drag law variability on measured responses is explored for summer ice free conditions and for strong winter storms with varying ice coverages.

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MS5

Multi-Model Cross Pollination in Time: Address

Model Inadequacy Via Data Assimilation

Multi-model ensembles have become popular tools to account for uncertainties due to model inadequacy in weather and climate simulation-based predictions. The current multi-model forecasts focus on combining single model ensemble forecasts by means of statistical post-processing. Assuming each model is developed independently, each is likely to contain different dynamical strengths and weaknesses. Using statistical post-processing, such dynamical information is only carried by the simulations under a single model ensemble: no advantage is taken to influence simulations under the other models. A novel methodology, named Multi-model Cross Pollination in Time, is proposed for multi-model ensemble scheme to take advantage of instances where some models produce systematically more accurate forecast of some components of the model-state via integrating the dynamical information regarding the future from each individual model operationally. The proposed approach generates model states in time via applying data assimilation (DA) scheme(s) to yield truly multimodel trajectories. It is demonstrated to outperform traditional statistical post-processing in Lorenz96 flow. The aim of this talk is to introduce a framework that uses nonlinear DA to improve multi-model probability forecasts (not to argue for any one particular DA scheme). Thus the basis for a more general approach to reduce the impact of model error which could be deployed in future operational forecasting is suggested.

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MS5

Data Assimilation for the 3D Planetary Geostrophic Model Using Temperature Measurements

Analyzing the validity and success of a data assimilation algorithm when some state variable observations are not available is an important problem meteorology and engineering. In this talk, we will present an improved continuous data assimilation (downscaling) algorithm for the 3D Planetary Geostrophic model that *requires observations of temperature only.* This supports an earlier conjecture of Charney that complete temperature history of the atmosphere for certain simple atmospheric models, will determine other state variables.

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MS5

Sequential Implicit Sampling Methods for Bayesian Inverse Problems

The solution to the inverse problems, under the Bayesian framework, is given by a posterior probability density. For large scale problems, sampling the posterior can be an extremely challenging task. Markov Chain Monte Carlo (MCMC) provides a general way for sampling but it can be computationally expensive. Gaussian type methods, such as the Ensemble Kalman Filter (EnKF), make Gaussian assumptions even for the possible non-Gaussian posterior, which may lead to inaccuracy. In this talk, the implicit sampling method and the newly proposed sequential implicit sampling method are investigated for the inverse problem involving time-dependent partial differential equations (PDEs). The sequential implicit sampling method combines the idea of the EnKF and implicit sampling and it is particularly suitable for time-dependent problems. Moreover, the new method is capable of reducing the computational cost in the optimization, which is a necessary and the most expensive step in the implicit sampling method. The sequential implicit sampling method has been tested on a seismic wave inversion. The numerical experiments show its efficiency by comparing it with the MCMC and some Gaussian approximation methods.

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MS5

Overview and Bifurcation Phenomena in a Predator-Prey Based Cloud Dynamics Model

In this talk we present an overview of the talks in Part I and Part II of this minisymposium. Time permitting we will present some recent work on bifurcation analysis of a predator-prey based delay differential equation model of cloud dynamics. The models considered are extensions of a model proposed by Koren & Feingold PNAS 2011. Of particular interest are the existence of subcritical and supercritical Hopf bifurcations as well as secondary bifurcations and the relationship of these bifurcations to cloud dynamics processes.

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MS6

Simulation and Analysis of the Predator-Prey Dynamics of Dinoflagellates

This study analyzes the predator-prey dynamics of dinoflagellates and uses numerical simulations to validate theoretical and experimental studies. Several mathematical models of increasing complexity are presented to describe these predator-prey interactions. The simple model mechanics are derived from analogies to chemical kinetics, while biological observations and intuition are utilized to enhance the model and account for predatory inefficiencies. One of the specific aims of this study was to investigate how the predatory dinoflagellate Karlodinium veneficum uses toxins to immobilize its prey and increase its feeding

rate. Numerical simulations of predator-prey interactions matched the experimentally observed predatory behavior of K. veneficum and reinforce the notion that predatory dinoflagellates can utilize toxins to increase their feeding rate.

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MS6

Survival Games: Planktonic Diversity Examined Through Non-Cooperative Game Theory

Abstract not available.

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MS6

Biophysical Interactions of Plankton with Environments: From Individual Locomotion to Population Dynamics

Abstract not available.

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MS6

Effect of Light on the Growth of Non-nitrogen-fixing and Nitrogen-fixing Phytoplankton in an Aquatic System

Abstract not available.

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MS7

Reduced Basis Method in PDEs and Optimization

When reduced basis (RB) or another projection based technique is used to generate reduced order models, the number of equations and unknowns is typically reduced dramatically. However, for nonlinear or parametrically varying problems, the cost of evaluating the reduced order models still depends on the size of the full order model and is still expensive. We demonstrate how a combination of RB and empirical interpolation method leads to reduced order models that typically can be evaluated at a cost that only depends on the size of the reduced order model. We will apply the idea to a nonlinear parameter dependent advection diffusion equation discretized using finite element method and finally present another application for a shape optimization problem.

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MS7

Improved Passive Microwave Retrievals of Precipitation from Space Using Sparse Approximation

This presentation discusses a new passive microwave retrieval algorithm, the shrunken locally linear embedding algorithm for retrieval of precipitation (ShARP), which relies on a sparsity promoting regularization technique and makes use of two joint dictionaries of coincident rainfall profiles and their corresponding upwelling spectral brightness temperatures. A sequential detectionestimation strategy is adopted, which assumes that similar rainfall intensity values and their spectral radiances live close to some sufficiently smooth manifolds with analogous local geometry. The detection step employs a nearest neighbor classification rule, whereas the estimation scheme is equipped with a constrained shrinkage estimator to ensure the stability of retrieval and some physical consistency. The algorithm is examined using coincident observations of the radar and the passive microwave imager on board the TRMM satellite. We focus on a radiometrically complex region (covering the Tibetan highlands, Himalayas, GangesBrahmaputraMeghna River basins) that is unique in terms of land surface radiation regime and precipitation type. Promising results are presented using ShARP over snow covered surfaces and near coastlines, in comparison with the land rainfall retrievals of the standard TRMM 2A12 product. ShARP can significantly reduce the rainfall overestimation due to the background snow contamination and markedly improve detection and retrieval of rainfall in the vicinity of coastlines.

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MS7

Lagrange Multiplier Methods and the Problem of Estimating the Ocean Circulation from Sparse Observations and Models

Understanding the global full-depth ocean circulation, attributing its evolution and changes through time, inferring its role in the global climate system, and quantifying related uncertainties are hampered by sparse and heterogeneous observations, an inherently turbulent fluid, imperfect models, and uncertain forcing functions. Viewed as a very large-scale estimation or optimal control problem, the goal is to find an optimal state and parameter estimate through fitting a state-of-the art circulation model to all available observations while fulfilling underlying conservation laws and equations of motion. To do so we formulate a variational problem in which a weighted squared model-data misfit function is augmented by the model equations via Lagrange Multiplier Method. Minimization of this Lagrangian is achieved through adequate variation of elements of the very high-dimensional uncertainty or control space (consisting initial and boundary conditions as well as model parameter fields) as informed by the adjoint model. As practiced by the "Estimating the Circulation and Climate of the Ocean" (ECCO) consortium, the optimal state and parameter estimates so obtained provide valuable in-

formation for ocean and climate science. The adjoint model which propagates the Lagrange multipliers, i.e. misfit function sensitivities to the controls back in time is obtained via algorithmic differentiation.

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MS7

Land Surface Data Assimilation

Information about land surface water, energy and carbon conditions is of critical importance to real-world applications such as agriculture, hydrology, weather, and environmental preservation. While observational networks are improving, the only practical way to observe on large scales is via satellites. Remote sensing can make spatially comprehensive measurements of various components of the terrestrial system, but it cannot provide information on the entire system. Land surface process models may be used to predict temporal and spatial terrestrial dynamics, but these predictions are often poor, due to model initialization, parameter and forcing, and physics errors. Therefore, an attractive prospect is to combine the strengths of land surface models and observations to provide a superior terrestrial state estimate. Data Assimilation combines observations into a dynamical model, using the models equations to provide time continuity and coupling between the estimated fields. Land surface data assimilation aims to utilize both our land surface process knowledge, as embodied in a land surface model, and information that can be gained from observations. Both model predictions and observations contain different kinds of information, that when used together, provide an accuracy level that cannot be obtained individually. Model biases can be mitigated using a complementary calibration and parameterization process.

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MS8

Carbon Cycle Data Assimilation: What Have We Learned, and Where Are We Going?

A prerequisite for improving our understanding of carbon-climate feedbacks is accurate and precise knowledge of carbon fluxes in the major carbon pools and reservoirs, their spatial and temporal distribution over land and ocean, and the mechanisms controlling them. In this talk, I will present an overview of the evolving use of data assimilation (DA) frameworks for estimating carbon fluxes at a variety of spatiotemporal scales. Such frameworks are now being routinely used to mine information from CO_2-dedicated remote-sensing missions, such as JAXAs Greenhouse gases Observing SATellite IBUKI (GOSAT), NASAs Orbiting Carbon Observatory-2 (OCO-2), etc. I will also highlight more recent applications of DA within carbon cycle science, for example, either for estimating atmospheric CO_2 concentrations or for estimating parameters within biogeochemical models. I will conclude with an outlook for the role of DA in carbon cycle science, including opportunities for assessing the benefit of new and planned CO_2 observing systems, or for integrating carbon cycle DA within fully coupled Earth System models.

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MS8

Accounting for Forcing Uncertainty in Oceanographic and Estuarine Data Assimilation

Temperature is a critical factor in understanding and predicting physical and biological processes in the coastal ocean where they vary considerably in time and space. Data assimilation of satellite data has the potential improve temperature estimates and thus biological forecasts, but there are several challenges. While data assimilation is often framed in terms of chaotic growth of initial condition errors in the atmosphere, errors in the coastal ocean system are driven more by forcing. In addition, there are questions about using surface information to make subsurface corrections. I will discuss some of the challenges with coastal ocean assimilation and share results from comparison experiments between 4DVAR and LETKF in the Chesapeake Bay. Both methods have been implemented on NOAAs operational forecast model and are compared for the assimilation of satellite sea surface temperature data.

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MS8

Observing System Simulation Experiments to Assess the Potential Impact of Observing Systems on Global Numerical Weather Prediction

Observing System Simulation Experiment (OSSE) provide a rigorous approach to evaluate the impact of the new (envisioned) observing systems, alternate deployment strategy for the existing systems and new data assimilation (DA) methods and systems, by the assimilation of synthetic observations drawn from a realistic model simulation, called a nature run (NR), into a DA system, and assessing the impact on forecasts. This approach however, in order to be robust and provide reliable metric for the real analysis and forecast system like global Numerical Weather Prediction (NWP), is challenging and consumes large high performance computing resources. This talk will cover the overview, with focus on practice and challenges for the global NWP including observation error characteristics and experimental design. A new approach, Observing System Assessment(OSA) experiments, that complement the OSSE, will be also introduced.

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MS8

An Introduction to Data Assimilation in Earth Systems

Data assimilation is a tool that allows one to incorporate observations about the state of some real world process into a numerical simulation of that state, thereby improving the quality of the estimate. In this presentation I give a broad introduction to data assimilation in the context of earth systems. I discuss numerical weather prediction, for which data assimilation was originally developed, and also the carbon cycle, climate and oceanography. The talk will highlight the scope and practical limitations of the data assimilation problem in each case, discuss the present state of the art, and mention current directions for research.

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MS9

Relevance of Conserved Quantities in Data Assimilation

Data assimilation is broadly used in atmosphere and ocean science to reduce uncertainty and to correct model error by periodically incorporating information from measurements (e.g. satellites) into the mathematical model. Ensemble-based data-assimilation methods propagate multiple solutions to approximate the evolution of the probability distribution function. However, these methods typically destroy any physical laws otherwise preserved by the numerical discretization. In my talk I will address the importance of numerical conservation laws in data assimilation.

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MS9

Reduced Order Gaussian Smoothing for Nonlinear Data Assimilation

We investigate Gaussian filtering for data assimilation in numerical weather prediction (NWP). Data assimilation is the process of combining prior forecasts and observations to produce a system estimate. The prevailing data assimilation method in operational NWP centers is variational data assimilation. This method involves solving a cost function over a time window forming a maximum likelihood estimate. These methods, however, require the use of linearized models which in practice are difficult to produce and maintain. As an alternative we propose Gaussian smoothing for derivative free nonlinear data assimilation. Gaussian filters and their corresponding smoothers use numerical integration to evaluate the recursive Bayesian formulas for optimal filtering under Gaussian assumptions. This numerical integration typically requires many model evaluations making conventional Gaussian filtering/smoothing impractical for use in NWP. We will present a reduced order method for forming a Rauch-Tung-Striebel (RTS) type smoother. To do so we review the Bayesian filtering and smoothing equations and discuss an efficient numerical method for evaluating them.

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MS9

A Nonequilibrium Statistical Theory of Subgrid-Scale Parameterization for Quasi-Geostrophic Turbulence

We propose a statistical-mechanical coarse-graining of two-dimensional, or quasi-geostrophic, turbulence in terms of the means and variances of the low Fourier modes of the vorticity, or potential vorticity. The reduction from the high-dimensional fluid dynamics to a low-dimensional model is achieved by a dynamical optimization procedure. Paths of Gaussian trial probability densities on the microscopic phase space are adopted as the macrostates in the model, and the best-fit macroscopic evolution is defined to be that path which minimizes the time-integrated, mean-squared Liouville residual. The cost functional in this optimization principle has an information-theoretic interpretation, and the variational equations for the optimal path have a generic thermodynamic structure. The closed reduced equations for the resolved low modes contain intrinsic dissipation resulting from their interactions with the thermal bath of unresolved high modes. The precise dissipation operator due to coarse-graining is thus revealed: it is a specific, sub-diffusive, eddy viscosity. This optimal closure is validated quantitatively against direct numerical simulations of ensembles without tuning any closure parameters.

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MS9

Applications of Equilibrium Statistical Mechanics to Geostrophic Turbulence

Geostrophic turbulent flows have the beautiful property to self-organize into large scale coherent structures. This problem involves a huge number of degrees of freedom, which gives a strong incentive for a statistical mechanics approach. After reviewing the equilibrium theory, we will present recent applications of this approach to atmospheric and oceanic turbulence: spontaneous formation of rings and jets, emergence of bottom-trapped flows above topography anomalies and tendency towards barotropization.

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MS10

Coupling Between Ice Sheets Movement and Subglacial Hydrology

When considering the sliding of ice sheets, the interaction between ice and the bedrock can be modeled with a regularized Coulomb friction condition, which involves an additional unknown quantity, namely the effective pressure at the ice-bedrock interface. This quantity can be modeled as the solution of an additional PDE holding along the ice-bedrock interface that models the subglacial hydrology. In this presentation we consider the coupled ice-hydrology problem.

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MS10

Modeling Calving Front Dynamics Using a Level-set Method: Application to Jakobshavn Isbr, West Greenland

Recent observations highlight the influence of the calving front position on tidewater glaciers. Here, we present the theoretical and technical framework for a level-set method (LSM), which is now implemented into the Ice Sheet System Model. The LSM proves to be a robust tool to implicitly represent a dynamically evolving calving front in an Eulerian approach. We apply this method to a 3D thermodynamically coupled model of Jakobshavn Isbr, West Greenland.

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MS10

Topographic Controls of Subglacial Water Flow Under Ice Streams

Satellite laser altimetry reveals short timescale changes in Antarctic ice stream surface elevation that are suggested to be driven by subglacial water transport and storage. Simulations of a two-way coupled model of ice and subglacial water flow, show that basal topography controls the temporal and spatial variability of the subice stream hydraulic system. The orientation and characteristic dimensions of the topographic undulations determine the morphology and timescales of the subice stream drainage system.

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MS10

Modeling Hydraulic Fracture of Glaciers Using Continuum Damage Mechanics

The presence of water-filled crevasses is known to increase the penetration depth of crevasses and this has been hypothesized to play an important role controlling iceberg calving rate. Here, we develop a continuum-damage-based poro-mechanics formulation that enables the simulation of water-filled basal and surface crevasse propagation, where a Maxwell-type viscoelastic constitutive model is used for modelling glacial ice. This study supports the hypothesis that hydraulic fracture is a plausible mechanism for the accelerated breakdown of glaciers.

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MS11

Space-time Information Metrics for Improved Averaging of Multi Scale Non-gaussian Systems with Rare Intermittent Instabilities

Turbulent dynamical systems associated with dissipative PDEs involve both a large dimensional phase space and a large number of positive Lyapunov exponents on the attractor with intermittency on a wide spectrum of spatio-temporal scales. The need to deal with such complex systems is common in applications where practical statistical ensemble prediction and real-time filtering/state estimation require reduced and imperfect forward models. We discuss a class of information metrics which help with tuning averaging techniques, as well as with detecting information barriers to further model improvement. Various averaging/coarse-graining approaches are compared on a class of statistically exactly solvable non-Gaussian test models where a generalised Feynman-Kac formulation reduces the exact behaviour of conditional statistical moments to the solution of inhomogeneous forward Kolmogorov equations modified by linear lower order coupling and source terms.

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MS11

A Stochastic Model for Tropical Rainfall

The largest variations of water vapor and rain fall rates occur in the tropical regions of the globe. Modeling water vapor in these regions is important for predicting rare, large rainfall events. In this talk, I will present a linear stochastic model for the dynamics of water vapor and tropical rain-

fall. Despite its linear formulation, the model reproduces a wide variety of observational statistics from disparate perspectives, including (i) a cloud cluster area distribution with an approximate power law; (ii) a power spectrum of spatiotemporal red noise, as in the background spectrum of tropical convection; and (iii) a suite of statistics that resemble the statistical physics concepts of critical phenomena and phase transitions. Exact analytical solutions are available for many statistics, and numerical realizations can be generated for minimal computational cost and for any desired time step. Given the simple form of the model, the results suggest that tropical convection may behave in a relatively simple, random way. Potential applications of the model include several situations where realistic cloud fields must be generated for minimal cost, such as cloud parameterizations for climate models or radiative transfer models.

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MS11

Variational Homogenization Estimates for the Rheological Properties of Ice and other Geo-materials Materials with Extreme Heterogeneity Contrast

Sea ice and many other geological materials are polycrystalline aggregates of low-symmetry/high-anisotropy single crystals containing voids, cracks and other inclusions. The extreme contrast in the constituent properties of these nonlinear materials makes it challenging to develop rheological models for their macroscopic behavior. In this paper, we present a new variational homogenization method to estimate the macroscopic constitutive response of heterogeneous materials consisting of aggregates of viscoplastic single-crystal grains and other inhomogeneities. The method derives from a stationary variational principle for the macroscopic stress potential of the viscoplastic composite in terms of the corresponding potential of a linear comparison composite, whose viscosities and polarizations are the trial fields in the variational principle. The resulting estimates for the macroscopic response are guaranteed to be exact to second-order in the heterogeneity contrast, and to satisfy known bounds. Applications will be given for porous ice single crystals.

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MS11

Rare Event Extinction and Control in Heterogeneous Networks

We consider epidemic extinction as rare events in finite networks with broad variation in local connectivity. Given random networks with a given degree distribution, we are able to predict the most probable, or optimal, paths to extinction in various configurations, including truncated power-laws. We find that paths for heterogeneous networks follow a limiting form in which infection first decreases in low-degree nodes, which triggers a rapid extinction in high-degree nodes, and finishes with a residual low-degree extinction. The usefulness of our approach is further demonstrated through optimal control strategies that leverage the dependence of finite-size fluctuations on network topology. Interestingly, we find that the optimal control is a mix of treating both high and low-degree nodes based on theoretical predictions, in contrast to methods that ignore dynamical fluctuations. This research is supported by the Office of Naval Research.

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MS12

Changes in the Frequency, Duration, Magnitude and Volume of Flood Events Across the United States Over the Past 70 Years

In the United States, there have a been an increasing number of studies quantifying trends in the annual maximum flood; yet, few studies examine trends in floods that may occur more than once in a given year. This type of flood series is commonly referred to as peaks-over-threshold (POT) series because flood events are defined as any discharge that exceeds a predetermined threshold value and, therefore, one can examine the properties of multiple flood events that may have occurred in the same year. A POT series of flood events for 345 long-term streamgages across the United States having no major hydrologic alteration to streamflow was developed using a multi-threshold, event-based approach using the daily time series. The series of flood events were examined for at-site and regional trends in the peak-day discharge, total volume of discharge for the event, duration of the event, and the frequency of events per year. Results show a complex picture of trends across the United States. Clustering the streamgages in the study according to the trends in the four flood properties revealed regions experiencing similar changes in flood frequency, magnitude, duration and volume. The results of this study show no consistent trends in these flood properties except in a few distinct regions in the United States and these are primarily trends in frequency or duration and not in peak magnitude.

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MS12

Using SVD and CVT to Study Precipitation Patterns in U.S.

Centroidal Voronoi tessellations (CVTs) are a powerful tool traditionally used for optimal mesh generation, quantization of signals, image analysis and model reduction. In this work, we explore the use of this idea in the context of optimal placement of water gauges by coupling it to an SVD-based spatio-temporal analysis of precipitation variability patterns. We present some preliminary results of this study based on the US GLDAS precipitation data over the last several decades and compare them with those obtained by other methods explored in the literature. We use similar techniques to look at the ways of detecting anomalies in the duration and severity of droughts.

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MS12

Advances in Precipitation Error Modeling and Analysis

This study proposes a framework to evaluate and estimate uncertainty estimates associated with high resolution satellite precipitation products. The quantification and inclusion of error estimates in the these products allow inferences about their accuracy and will be especially crucial in unmonitored regions, where satellite retrievals still represent the only available precipitation estimate on which flood forecasting and water resources management can rely. The main goal is to develop a scheme to assign error estimates to satellite precipitation products and mitigate uncertainties associated with predictions that use these products. The PUSH (Precipitation Uncertainty in Satellite Hydrology) model is presented as a possible framework to estimate errors associated with satellite rainfall retrievals. PUSH evaluates several components of the precipitation error, including (i.e., missed precipitation events; false alarms; and hit biases) and provides probability density functions of the errors for fine-resolution precipitation products. This error model has been shown to be successful when applied to the daily products over Oklahoma, using a rain gauge network as reference.

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MS12

Dynamical Data-Driven Assessment of Long-term Flood Hazards in a Changing Environment

Rainfall and soil moisture play key roles in freshwater flooding, and the future of flood hazards will be tied to changes in these variables. Surprisingly little emphasis, however, has been placed on understanding these roles quantitatively, and in particular how variability in rainfall and soil moisture can combine to either enhance or suppress floods. Instead, approaches to flood hazard analysis typically neglect important sources meteorologic and hydrologic variability and can be dependent on the subjectivity of the analyst. Trends in rainfall and flooding due to changes in land use and regional climate place limits on existing techniques. Remote sensing datasets offer high-resolution estimates of environmental variables nearly everywhere on the globe. These data can be used to improve our understanding of the role of rainfall and soil moisture space-time variability in flooding in a variety of settings. I have coupled rainfall remote sensing data with a probabilistic framework known as stochastic storm transposition (SST). SST lengthens the rainfall record by resampling observed storms and to extracts space-time information from the remote sensing data. I have codified the SST approach in RainyDay, a platform for quickly generating large numbers of realistic probabilistic extreme rainfall scenarios. I highlight some of the advantages the SST approach and discuss the implications for understanding the nature of flood risk in a changing environment.

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MS13

Improved Validation of Conceptual Climate Models Using Data Analysis Techniques

Because of their high degree of simplification, output from conceptual climate models often only qualitatively matches empirical records. Moreover, disparate models frequently have comparable correlations with any given observation even when based on substantially different physics. We will show how modern time series analysis techniques, such as Empirical Mode Decomposition, can be used to extract and compare subtler features of the observational records and of the model outputs, thereby improving model validation.

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MS13

Peatlands, Agriculture, and the Carbon Budget: A Conceptual Model for 15kyr Bp to the Present

How long have humans been impacting the climate and to what atmospheric effect? By investigating dynamical rates of carbon transfer one can better understand the predominant forces affecting the carbon budget in the past and anticipate forces in the future. In this talk we explore dynamics of carbon sources and sinks in a conceptual model to obtain a better understanding of the global carbon budget over the past 15,000 years.

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MS13

Palaeoclimate Dynamics Modelled with Delay Equations

The Quaternary period is characterized by oscillations between glacial and interglacial states. External orbital forcing only partly explains this behavior, so it is necessary to study the associated internal processes. Delays in feedback loops have been shown to produce such oscillations in dynamical systems. I will discuss where delays are present in climate feedbacks, how they can be incorporated into conceptual models as delay differential equations (DDEs), and the periodic orbits that can result.

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MS13

Conceptual Models: Understanding Past Climate Through Mathematics

The Budyko energy balance model of climate has been a useful starting point for those in the mathematics community. We highlight recent advances using this model in our study of the glacial-interglacial cycles. This exploration has led to some new results in mathematics as well as clues about Earth's past climate.

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MS14

The Late-Time Behavior of a Bounded, Inviscid Two-Dimensional Flow

Abstract not available.

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MS14

Noise-Induced Transitions Between Meta-Stable Atmospheric Jet Configurations

We consider barotropic flows forced by a random white-in-time Gaussian noise, in particular those governed by the quasi-linear approximation of the 2D barotropic quasi-geostrophic equation in the beta-plane. For suitible parameters this equation allows for meta-stable zonal jet solutions. In the limit of large time-scale separation between the inertial scale and the spin-up time (which is equivalent to the limit of vanishing Ekman-damping), rare transitions between these meta-stable jet configurations are described by a large deviation principle. A numerical evaluation of the minimizer of the associated ratefunction allows statements about the stability and lifetime of atmospheric jets as well as the most likely trajectories leading to creation or destruction of atmospheric jets.

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MS14

Evolution of Clusters at the Ocean Surface in Models and Observations

Floating material has frequently been observed to accumulate in uneven patterns at the ocean surface. We have recently made advances in developing methods for rigorously defining a cluster, quantifying its degree of clustering, and identifying regions prone to clustering within an ocean model. Here we will provide an overview of these results, focusing on the range of "typical" life-cycles exhibited by clusters and comparing the model results with observations from a large drifter deployment.

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MS14

Assimilation of Images for Geophysical Fluids

The observation of the Ea and their dynamicsth provides a huge amount of information under the form of images. We could define the problem of images assimilation : as to couple the information provided by mathematical models with the dynamics of images. We have proposed to use variational methods to achieve this goal. We will have to define several coupled systems:

- On system defining of the flow : it's based on equation of conservation
- An equation of concentration for the contaminant. it's an equation of conservation coupled with the dynamics of the fluid through the advection of the contaminant and also some interactions with the fluid.
- An equation for the dynamics of the images : we will consider level sets to define the images. There are interactions both with the dynamics of the fluid and the concentration of contaminant.

Of course we have to define functional spaces in which these items will live and operators between these spaces. The Variational Analysis will be completed by defining a cost function measuring the discrepancy between observed and computed image. We will minimize it using optimal control and optimization tools. A crucial advantage of this approach is to consider images as a state variable of a global system. Numerical results will be presented with an application to oil spill on the ocean with a complex topology.

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MS15

Increasing the Multiscale/multiphysics Capability of Cam-Se Using Implicit Time Integration and Gpu Accelerators

The recent focus on regional refinement in the Community Atmosphere Model (CAM5) has created a strong need to develop time-stepping methods capable of accelerating throughput on high performance computing for climate dynamics across multiple spatial and temporal scales. This research is focused on developing implicit methods that can be executed at scale on GPU based machines. Efforts to port the scalable spectral element dynamical core to incorporate these developments is presented, including both 2D and 3D benchmark test case results. The current implicit solver and preconditioner implementations utilize

a Fortran interface package within the Trilinos project, third party software that allows fully tested, optimized, and robust code with a suite of parameter options to be included a priori. Merging this coding strategy with GPU libraries will be discussed along with beneficial optimization gains and data structure requirements to evaluate Trilinos binded residual calculations on GPU processors.

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MS15

Exploring the Computational Performance of Implicit Methods for a Large Scale Climate Application

Explicit and implicit Newton-Krylov (NK) time-stepping methods are evaluated for a range of configurations of the shallow water dynamical core of the spectral-element Community Atmosphere Model (CAM) to explore their computational performance. These configurations are designed to explore the attributes of each method under different but relevant model usage scenarios including varied spectral order within an element, static regional refinement, and scaling to the largest relevant problem sizes. These are analyzed for many simulations that in some cases scale to maximum processor counts and in other cases make use of hybrid CPU/GPU nodes within the function evaluation. This analysis is performed within the shallow water dynamical core option of a full climate model code base to enable a wealth of simulations for study, with the aim of informing optimal solver development within the operational hydrostatic core. The limitations and benefits to using implicit versus explicit, with different parameters, are discussed in light of the trade-offs with communication and memory, and inherent efficiency bottlenecks associated with each. Given the performance behavior across the configurations analyzed here, the recommendation for future work using the implicit solvers is conditional based on scale separation and the stiffness of the problem, although with several concrete but substantial steps there is good potential even for these cases.

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MS15

Algebraic Multigrid Solvers for Coupled Linear Systems from Subsurface Flow Models

Multigrid solvers are efficient for solving linear systems that arise from Large-scale geoscience applications. However, applications with multiple physical unknowns pose a challenge for standard multigrid techniques, particularly when the coupling between the unknowns is strong. We present our efforts to develop a multigrid-preconditioned Krylov solver, designed to represent the coupling between the physical variables and account for the underlying physics of the system. We present results on solver performance on applications from subsurface models.

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MS15

Iterative Solution of Coupled Implicit Subsurface and Overland Flow Simulations

Subsurface and overland flow models constitute a significant portion of fresh water resource simulations, and coupling these models can produce insights into efficient management of these renewable resources. However, due to the complex dynamics inherent in the physical models, the numerical formulation of subsurface and overland flow coupling can be challenging to solve. We will discuss an implicit solution approach to the coupled model and overview the formulation and effectiveness of an iterative solution strategy. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC.

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MS16

Forward-Backward Stochastic Differential Equations: Applications to Carbon Emissions Markets

As a response to the risk of climate change, carbon markets are currently being implemented in several regions worldwide. Since 2005, the European Union (EU) has had its own Emissions Trading System (ETS), which today is the largest such market. In September 2015, it was announced that China (whose carbon emissions make up approximately one quarter of the global total) will introduce a national emissions trading scheme in 2017. In this talk, I will consider mathematical models for the pricing of emissions permits. The model considered so far has particular applicability to the trading of European Union Allowances (EUAs) in the EU ETS but could also be used to model other cap-and-trade schemes. The pricing problem that arises fits into the theory of fully coupled forward-backward stochastic differential equations (FBSDEs). In contrast to the classes of FBSDEs considered in most of the literature, these FBSDEs are significant in two ways: the terminal condition of the backward equation is given by a discontinuous function of the terminal value of the forward equation, and the forward dynamics may not be strongly elliptic, not even in the neighbourhood of the singularities of the terminal condition. The main application of such FBSDEs is in the modelling of a (single-period) emissions trading system such as the system in force in the European Union (EU). My work focuses on the class of FBSDEs arising from a multi-period model of such an emissions trading system.

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MS16

Mimetic Discontinuous Galerkin Methods for Simulation of Nonlinear Wave Interactions

We introduce a methodology of discretising bi-Hamiltonian PDEs via discontinuous finite element methods focusing on two wave equations, KdV and Camassa-Holm, as illustrative examples. The resultant methods are of arbitrary order in space and have desirable properties including conservation of the relevant Hamiltonians.

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MS16

Stochastic and Statistical Modelling of Extreme Meteorological Events: Tropical Cyclones

Understanding tropical cyclone genesis and the factors that contribute to it are of great interest to the financial and meteorological industries as well as governmental agencies. Currently in the literature, models only capture the temporal aspect of genesis, that is the frequency whether it be the seasonal variation or the interannual variability. The spatial distribution of genesis is generally only qualitatively assessed and no quantitative measure has been put forward. However, the distribution tropical cyclone genesis is not separable, the spatial patterns are intrinsically linked to the temporal component. In this talk I will define what is meant by genesis and introduce a spatio-temporal model to predict tropical cyclone genesis in the western-North Pacific. I will introduce a flexible method to analyse the spatio-temporal goodness-of-fit of genesis and discuss the role of vorticity and other covariates in modelling tropical cyclone genesis.

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MS16

An Introduction to Multilevel Monte Carlo Methods for Uncertainty Quantification in Earth Science

Monte Carlo sampling is a widely used tool for estimating quantities of interest in physical models that incorporate sources of uncertainty, e.g. arising in modelling parameters, the geometry, initial conditions or external source terms. However, standard Monte Carlo often is too costly when generating an individual sample requires solving the underlying physical dynamics numerically on high resolution. At a given accuracy, multilevel methods can reduce computational costs dramatically compared to standard methods by generating most of the samples needed on low resolution and thereby reducing the statistical error of the estimate. In this presentation, the multilevel Monte Carlo approach will be introduced in the context of differential equations with random coefficients. Several recent extensions of multilevel Monte Carlo are derived, and the current directions for research are discussed in the context of earth science applications.

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MS17

Extraction and Prediction Of Coherent Patterns In Incompressible Flows Through Space-Time Koopman Analysis

We discuss a method for detecting and predicting the evolution of coherent spatiotemporal patterns in incompressible fluid flows. The approach is based on a representation of the Koopman operator governing the evolution of observables in a smooth basis learned from velocity field data through the diffusion maps algorithm. This representation enables the detection of coherent flow patterns through Koopman eigenfunctions and simulation of the evolution of observables and probability densities under the flow map. We present applications in Gaussian vortex flows and chaotic flows generated by Lorenz 96 systems.

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MS17

Jet Stream Variabilities and Weather Extremes: A Linear Response Function Perspective

Blocking events, large planetary waves, and annular modes are variability patterns of midlatitude jets that are known to associate with weather extremes such as heat waves and cold spells. Thus there is much interest in robust projections and skillful predictions of these patterns; however, the progress has been slow, owing to incomplete dynamical understanding of these patterns. We discuss some of the recent developments and challenges about these patterns, and show, as an example, that understanding jet variabilities is difficult even in a highly idealized GCM. We argue that knowing the Linear Response Function (LRF) of GCMs can help with better understanding these variabilities. The LRF L relates the state vector x to its tendency $\dot{x}$ and forcing f via $\dot{x} = Lx + f$. We present a new framework, based on Greens functions, to accurately calculate the LRFs of GCMs of varying degrees of complexity, and discuss/validate the LRF of an idealized GCM calculated using this approach (Hassanzadeh and Kuang 2016 JAS). Then the results of 3 studies using this LRF are discussed: 1) probing causality in the relationship between blocking variability and annular modes (Hassanzadeh and Kuang 2015 GRL), 2) confirming/quantifying the positive eddy feedback in annular mode dynamics (Ma et al 2016 JAS), and 3) showing why the fluctuation-dissipation theorem, commonly used to calculate LRFs, performs poorly for GCMs (Hassanzadeh and Kuang 2016 JAS).

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MS17

Capturing Rare Events with the Heterogeneous Multiscale Method

We discuss heterogeneous multiscale methods (HMM) and their ability to capture fluctuations acting on the slow variables in fast-slow systems. In particular, it is shown via analysis of central limit theorems (CLT) and large deviation principles (LDP) that the standard version of HMM artificially amplifies these fluctuations. A simple modification of HMM, termed parallel HMM, is introduced and is shown to remedy this problem, capturing fluctuations correctly both at the level of the CLT and the LDP.

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MS17

Trajectory Stratification of Markov Processes for Rare Event Simulation

Stratification has long been a cornerstone of experimental design in statistics where, for example in the context of estimating the frequency of some trait in a population, it entails dividing a population into subsets or strata, computing the frequency of that trait within each strata, and then assembling those conditional averages to form an estimate of the trait for the whole population [?, ?]. When the strata are chosen carefully the conditional averages computed within strata can be computed with high accuracy at relatively low cost, leading to a more accurate overall estimate. We describe an extension of this basic philosophy to the estimation of fairly general averages with respect to a Markov process, such as those involving certain severe weather, climate, and geological events.

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MS18

Fluid Mechanics of Pyroclastic Density Currents

Pyroclastic density currents are generated in explosive volcanic eruptions when gas and particle mixtures remain denser than the surrounding atmosphere. These mobile currents have a diversity of flow regimes from energetic granular flows to turbulent suspensions. Due to their hazardous nature, much of our understanding of the internal dynamics of these currents has been explored through mathematical and computational models. This talk discusses the anatomy of these currents and their phenomenology and places these observations in the context of forces driving the currents. All aspects of the current dynamics are influenced by multiphase interactions, and the study of these currents offers insight into a high-energy end-member of multiphase flow. At low concentration, momentum transfer is dominated by particle-gas drag. At higher concentration, particle collisions, friction and gas pore pressure act to redistribute momentum. I will discuss end member theoretical models for dilute and concentrated flow, microscale and large-scale experiments, and then consider insight gained from multiphase simulations of pyroclastic density currents.

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MS18

Assessing Hazard Related to Atmospheric Dispersion of Dense Gas Using High-Resolution Wind Fields: Application to Limnic Eruptions

Numerical simulations of atmospheric dispersion of dense gas require high-resolution evaluation of near-surface wind fields over complex terrains. In particular, dense gas dispersion models (e.g. TWODEE) typically assume either near-surface wind profiles given by the classical Monin-Obukhov similarity theory or heterogeneous wind fields from diagnostic models incorporating local terrain effects. Here we present a novel methodology for hazard assessment based on high-resolution wind field characterization over complex terrains. The methodology couples yearly mesoscale Weather Research Forecast (WRF) model simulations with a microscale Computational Fluid Dynamics (CFD) model based on the Reynolds Averaged Navier-Stokes (RANS) equations adapted to the atmospheric boundary layer. The meso-to-micro coupling considers a statistical downscaling based on transfer functions and allows estimating a statistical set of high-resolution wind fields to drive the shallow waters TWODEE dispersal model. As an example, the methodology is applied to generate probabilistic hazard maps over the lake Nyos area (Cameroon), a tragic example of CO_2 hazard from limnic eruptions resulting from lake overturn.

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MS18

Shallow Flow Models for Natural Hazards Due to Gravity-Driven Mass Movements - Potential and Limitations

Huge efforts have been made towards the development of simulation tools aiming for quantifying the impact of gravity-driven mass movements, e.g. avalanches or landslides. Although these processes are geomorphologically very distinct they share gravitational acceleration as their dominant driving force. This causes a dynamic similarity and leads to longitudinal spreading. Mathematical models for rapid, gravity-driven mass movements exploit this apparent shallowness by formulating the system in terms of depth-averaged quantities giving rise to a first-order hyperbolic mathematical system. It is closed in terms of empirical friction relations tailored to the actual material. Although the gap between model idealization and complexity of reality is huge, these models perform well in certain situations, e.g. for snow avalanches in the Alps. In other situations, their predictive power is still insufficient. We address this fact by investigating the model error due to simplifying model assumptions. During the presentation we will review selected depth-averaged shallow flow theories both for homogeneous, granular material as well as for heterogeneous solid-fluid mixtures. We will summarize their model assumptions and discuss to which extent these are fulfilled. Finally, we will present simulation results for realistic topographies and discuss mechanisms to indicate an assumption breakdown during calculation. This could serve as an access point for future model hybridization.

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MS18

Large-scale Simulation of the 2004 M 9.1 Sumatra Earthquake with SeisSol

Simulations of dynamic earthquake ruptures and the subsequent radiated seismic waves are computationally expensive and require a multi-physics approach in order to solve on-fault frictional failure simultaneously with the seismic wave equation off-fault. Furthermore, simulations of large subduction zone earthquakes require consideration of a wide range of length scales, ranging from the narrow, meter-scale process zone at the rupture front to the vast, thousands of square kilometers of fault surface that slip. We highlight the ability of the peta-scale software package SeisSol, a 2014 Gordon Bell prize finalist, to meet these challenges with a three-dimensional simulation of the 2004 M 9.1 Sumatra-Andaman megathrust earthquake. SeisSol uses an Arbitrary high-order DERivative Discontinuous Galerkin (ADER-DG) scheme on unstructured tetrahedral meshes. Recent optimizations (e.g. in terms of parallel I/O schemes and customized hardware-aware algorithmic optimization) allow it to run efficiently on large HPC architectures. The simulation uses a mesh on the order of 100 million elements.

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MS19

Qualitative Assessment of the Role of Temperature Variations on Malaria Transmission Dynamics

A new mechanistic deterministic model for assessing the impact of temperature variability on malaria transmission dynamics is developed. The effects of sensitivity and uncertainty in estimates of the parameter values reveal that, for temperatures in the range [16-34]^{o}C, the dominant parameters influencing disease dynamics are the mosquito carrying capacity, transmission probability per contact for susceptible mosquitoes, human recruitment rate, mosquito maturation rate, biting rate, transmission probability per contact for susceptible humans, and recovery rate from first-time infections. This study emphasizes the combined use of mosquito-reduction strategy and personal protection against mosquito bite during the periods when the mean monthly temperatures are in the range [16.7, 25]^{o}C. For higher daily mean temperatures in the range [26, 34]^{o}C, mosquito-reduction strategy should be emphasized ahead of personal protection. Numerical simulations of the model reveal that mosquito maturation rate has a minimum sensitivity at $T = 24^o$C and maximum at $T = 30^o$C. The mosquito biting rate has maximum sensitivity at $T = 26^o$C, while the minimum value for the transmission probability per bite for susceptible mosquitoes occurs at $T = 24^o$C. Furthermore, disease burden increases for temperatures between 16^oC and 25^oC and decreases beyond 25^oC. This finding suggests the importance of the role of global warming on future malaria transmission trends.

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MS19

Malaria Incidence and Anopheles Mosquito Density in Irrigated and Adjacent Non-Irrigated Villages of Niono in Mali

In this paper, we extend the mathematical model framework of Dembele et al. (2009), and use it to study malaria disease transmission dynamics and control in irrigated and non-irrigated villages of Niono in Mali. In case studies, we use our "fitted" models to show that in support of the survey studies of Dolo et al., the female mosquito density in irrigated villages of Niono is much higher than that of the adjacent non-irrigated villages. Many parasitological surveys have observed higher incidence of malaria in non-irrigated villages than in adjacent irrigated areas. Our "fitted" models support these observations. That is, there are more malaria cases in non-irrigated areas than the adjacent irrigated villages of Niono. As in Citinis et al., we use the sensitivity analysis on R_0 to study the impact of the model parameters on malaria control in both irrigated and non-irrigated villages of Niono.

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MS19

Influence of Concurrency, Partner Choice, and Viral Suppression on Racial Disparity in the Prevalence of HIV Infected Women

We present a mathematical model of the transmission of HIV through sexual contact in a population stratified by sexual behavior and race/ethnicity. The model also includes the effect of concurrency through the force of infection term, variations in population mixing (partner choice), and non-uniform Highly Active Anti-Retroviral Treatment (HAART) leading to viral suppression. We use this mathematical model to understand the non-uniform spread of HIV in women who were infected through heterosexual contact. Numerical simulations of the reproduction number as a function of concurrency, viral suppression level, and mixing show a reservoir of disease present in both heterosexual and MSM populations. Statistical analysis of parameter values shows that viral suppression level, mixing and progression to AIDS without viral suppression have a strong correlation (either positive or negative) with the number of HIV positive women. Concurrency and assortative mixing are shown to be essential to reproduce infection levels in women, as reported by 2010 data from the Center for Disease Control (CDC).

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MS19

Demographic Allee Effects and Fatal S-I Disease Dynamics

In this talk, we will focus on biodiversity, a major problem for ecosystem resilience. We will use extensions of the susceptible-infected (SI) epidemic model of Hilker et al. to study how population persistence or extinction of a vulnerable species relates to habitat dependent Allee thresholds, fatal disease dynamics, and migration rates in both discrete and continuum sets of compartments. We will analyze the migration-linked models and establish verifiable conditions that guarantee host population persistence (with or without infected individuals) or extinction.

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MS20

Hybrid Upwinding for the Implicit Simulation of Three-Phase Flow in Porous Media

The simulation of underground CO2 storage requires solving the PDEs governing multiphase flow and transport. In the implicit finite-volume method (FIM), large nonlinear systems must be solved at each timestep using Newtons method. We present a new first-order flux approximation, leading to an improved nonlinear convergence rate. It relies on a separate treatment of the viscous, buoyancy, and capillary fluxes to achieve a differentiable numerical flux. The scheme reduces the simulation cost compared to a FIM discretization based on the widely used phase-per-phase upwinding.

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MS20

Addressing Adaptive Mesh Refinement Challenges in Non-Hydrostatic Atmosphere Simulations

We present an adaptive non-hydrostatic dynamical core based on a higher-order finite volume discretization on the cubed sphere. Adaptivity in space uses nested horizontal refinement that is both flux-conservative and higher-order, even as refined regions move. Challenges in algorithm development will be reviewed, including approaches and tools for debugging, validation, and performance comparisons. We show results for DCMIP tests as well as more challenging ones that highlight the benefits of refinement.

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MS20

Bisicles – Adaptive Mesh Refinement for Ice Sheets

The dynamics of ice sheets span a wide range of scales. Correctly resolving the dynamics of localized regions such as grounding lines and ice stream shear margins requires extremely fine (better than 1 km in places) resolution. Modeling an entire continental-scale ice sheet at such resolutions is impractical or impossible with current computational resources. At the same time, such fine resolution is unnecessary over large dynamically quiescent regions, which makes ice sheet modeling an ideal candidate for adaptive mesh refinement (AMR). BISICLES, part of the Community Ice Sheet Model (CISM), is a scalable AMR ice sheet modeling code built on the Chombo framework. With a dynamical core based on the vertically-integrated model of Schoof and Hindmarsh (2010), BISICLES can resolve dynamically important regions at the sub-kilometer scale while using much coarser resolution where appropriate, dynamically adapting the mesh as the ice sheet evolves to follow such phenomena as grounding-line retreat. We present BISICLES Antarctic regional and continental scale results which demonstrate the importance of resolution and the effectiveness of our approach in the study of the Antarctic response to forcing from warm-water incursion from the Southern Ocean.

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MS20

Advances in Nonlinear Solvers For Coupled Systems in Watershed Modeling

Unstructured polytopal meshes capture critical variability of topography and stratigraphy in terrestrial applications. Advanced spatial discretizations, such as the Mimetic Finite Difference and Nonlinear Finite Volume methods, are required to maintain accuracy, but analytic differentiation of the discrete system may lead to an unstable Jacobian. We control preconditioner properties for Jacobian-Free nonlinear solvers by discretizing the analytic Jacobian. The efficacy of this approach is demonstrated for coupled systems of energy and flow in watershed modeling.

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MS21

Algorithms Dedicated to Rare Event Simulations in Turbulent Flows and Climate Dynamics

For some aspects of climate dynamics, rare dynamical events may play a key role. A first class of problems are extreme events that have huge impacts, for instance extreme heat waves. A second class of problems are rare trajectories that suddenly drive the complex dynamical system from one attractor to a completely different one, for instance abrupt climate changes. In the recent past, new theoretical and numerical tools have been developed in the statistical mechanics community, in order to specifically study such rare events. We will present some of these algorithms and the related theoretical aspects. We will also discuss their application to two paradigmatic examples in climate dynamics. First, the disappearance of one of Jupiter's jets during the period 1939-1940 is a simple example of a drastic climate change related to internal variability. We will demonstrate that quasi geostrophic turbulent models show this kind of ultra rare transitions. Using a multilevel splitting algorithm we predict transition rates, transition paths, and sample transitions in a way that can not be achieved using direct numerical simulations. Second, we will study the probability of extreme heat waves over Europe, in a comprehensive climate model. We will demonstrate that the Giardina-Kurchan algorithm, a genealogical algorithm dedicated to compute Donsker–Varadhan large deviations, allows to sample extremely efficiently extreme heat waves.

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MS21

Multilevel Splitting and Steady State Simulation for Extreme Events

Straightforward (or crude) Monte Carlo (MC) simulation is known to be inefficient for rare events. In case of low probability events, the squared relative error on estimates obtained from crude MC is inversely proportional to the number of samples. As a result, an excessively large number of samples may be required to reach a desired accuracy. To improve the efficiency of MC sampling for rare events, various techniques have been developed for applications in e.g. communication networks and reliability analysis. I will discuss a technique called multilevel splitting, in which model sample paths are split into multiple copies each time they cross thresholds (or levels) that lead closer to the rare event set. Central to splitting is the use of a so-called importance function which monitors the approach of the system state to the set of rare events. The choice of the

importance function can affect the estimation of rare event probabilities with splitting. Furthermore, splitting is primarily aimed at transient probabilities, e.g. the probability to reach the rare event set within a fixed time interval. For climate extremes, quantities such as the long-term fraction of time spent in the rare event set are also relevant. For these quantities, an additional step is required, as in steady-state simulation.

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MS21

Predictability of Extremes in Stochastic-Dynamic Climate Models

Extreme events are an important aspect of the climate system and are the first manifestation of global warming. Extremes have a significant impact on society and, thus, being able to predict such events is of utmost importance. In my presentation I will present methods for extreme event prediction and show evidence that extreme events are more predictable the more extreme they are. I will discuss a stochastic point of view on extremes and also derive the tail behavior of the distribution from the normal form of stochastic climate models.

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MS21

Sampling Rare Events in Chaotic Climate Models Through Genealogical Particle Analysis

Rare events are of importance in many branches of science, for example in the form of heat waves or storms in climate dynamics and meteorology or complex reactions in chemistry. Although these events are rare, they can have a large impact. A reliable estimation of their probability is therefore necessary. Recently, a class of rare event simulation algorithms has been introduced that could yield significant increases in performance with respect to brute force estimation of rare event probabilities. In these algorithms an ensemble of simulations is evolved in parallel, while at certain interaction times ensemble members are killed and cloned so as to have better statistics in the region of phase space that is relevant to the rare event of interest. I will discuss issues in implementation and performance gains of the algorithms. I also present results on a first application of a rare event simulation algorithm to a toy model for chaos in the atmosphere, the Lorenz 96 model. I demonstrate that for the estimation of the histogram tail of the energy observable, the algorithm gives a significant error reduction. I will furthermore discuss first results on the application of rare event simulation algorithms to a complex climate model.

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MS22

Robust Forecasts of Volcanic Ash Clouds

The constraints that satellite data and other observations place on the forecasting of volcanic ash clouds have a precise description in terms of uncertainties in wind, ash source, and the position of ash clouds in the atmosphere. Specifically, the maximum constraints satellite data place upon ash transport models are obtained by exploiting the Hessian of the misfit between satellite observations and model predictions.

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MS22

Modeling Debris Flows Given Uncertainty, Sensitivity and Mobility Bifurcation

Debris flows are highly energetic gravity-driven masses, composed of sediment, rock and interstitial fluid, that rush down mountain slopes and potentially devastate communities up to tens of kilometers from their source. Debris flows and related phenomena (lahars, mudslides, mudflows etc.) can begin seemingly spontaneously from shallow landslides when the balance between gravitational driving forces and Coulombic frictional shear resistance is perturbed. The ultimate fate of these failing masses is surprisingly unpredictable, and may involve slumping and stabilization, or the evolution into a highly mobile debris flow. This process is mediated by the evolving pore-fluid pressure, which can impart rheological behaviors similar to a deforming solid ranging to a highly fluidized mass. This process is increasingly well understood and is known to be strongly dependent on, and highly sensitive to, the initial porosity of the sediment mixture as well as a critical state porosity characteristic of the granular composition of the mixture. However, the uncertainties of these initial properties in the field is large compared to the physical sensitivities they generate. I will discuss the resulting difficulties of predicting landslide and debris-flow hazards with mathematical and computational models, when a bifurcation of flow behavior can result from varying initial properties within their known constraints.

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MS22

Simulating Storm Surge in a Future Climate Condition Using Adaptive Mesh Refinement

Storm surge, a type of coastal flooding caused by tropical and extra-tropical cyclones and a main component of extreme sea level change, is a major concern for the world's coastal population centers, especially highlighted by recent major disasters such as Typhoon Haiyan (2013) and Hurricane Sandy (2012). Furthermore, the impacts of climate change on storm frequency, intensity, and trajectory makes storm surge an important uncertainty in hazard planning.

Numerical simulation of storm surge can be highly demanding due to large computational domains and the need for fine resolution along coastlines, but a recent approach incorporates adaptive mesh refinement to reduce computational cost, allowing for dynamic local refinement to track features of interest while less active regions can be coarsely resolved. We model the storm surge in the Typhoon Haiyan scenario using GeoClaw, a finite volume solver for the nonlinear shallow water equations with adaptive mesh refinement and robust Riemann solvers for wet/dry cells, together with elevation data and atmospheric forcing terms. We further consider climate changes for the North Pacific Ocean based on an ensemble of CMIP5 projections and downscaling experiments to estimate future changes in storm track and intensity distributions. We compute the storm surge based on these projections and compare changes in surge severity for Haiyan-like super storms in present and future climate scenarios.

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MS22

Probabilistic Assessment for Volcanic Hazards Using Model Ensembles and Large Data

This paper presents a comprehensive approach to assessing the hazard threat to a locale due to a large volcanic avalanche. The methodology combines:

- mathematical modeling of volcanic mass flows;
- field data of avalanche frequency, volume and runout;
- large-scale and accurate numerical simulations of flow events;
- use of statistical methods to minimize computational costs, and to capture unlikely events;
- calculation of the probability of a catastrophic flow event over the next T years at a location of interest;
- innovative computational methodology (”big data” methods) to implement these methods.

The field data and numerical simulations used here are subject to uncertainty from many sources, uncertainties that must be properly accounted for in assessing the hazard. The methodology presented here will be demonstrated with data from the Soufrière Hills Volcano on the island of Montserrat, where there is a relatively complete record of volcanic mass flows from the past 15 years. This methodology can be transferred to other volcanic sites with similar characteristics and where sparse historical data has prevented such high quality analysis. More generally, the core of this methodology is widely applicable and can be used for other hazard scenarios, such as floods or ash plumes.

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MS23

Improving Model Throughput by Parallel-Splitting Atmospheric Physics and Dynamics

If fluid dynamics and atmospheric physics parameterizations were computed in parallel, they could be calculated simultaneously on separate cores of a supercomputer. This would greatly increase model throughput for high-resolution simulations. Additionally, because atmospheric physics is embarrassingly parallel, more sophisticated physics parameterizations could be used without slowing simulations down by simply increasing the number of cores used. The downside to this approach is that it increases time-truncation error. In this presentation, we demonstrate that parallel splitting the ACME model and using a smaller timestep for physics results in faster, more accurate solutions.

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MS23

Implicit-Explicit Time Integration Methods for Nonhydrostatic Atmospheric Models

The Accelerated Climate Model for Energy (ACME) is developing a non-hydrostatic atmospheric dynamical core to enable accurate modeling at resolutions beyond the hydrostatic limit. A key component in computational efficiency at high resolution is the development of time integration methods that can accurately step over the stiff modes that are irrelevant to climate modeling (acoustic waves). To this end we investigate the performance of a number of Implicit-Explicit (IMEX) Runge-Kutta schemes in the Tempest non-hydrostatic atmospheric model. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-687104

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MS23

Efficient, Large Time Step, Multi-Moment Methods for Time-Explicit Climate Simulations

Multi-moment methods (e.g., Galerkin) require less work for similar accuracy than single-moment methods (e.g., Finite-Volume) because they require N^D times fewer reconstructions per time step (N is order of accuracy, and D is spatial dimensionality). Also, Spectral Element (SE) methods have very well-bounded bases, meaning higher-order accuracy adds real value to the solution even for discontinuous data. However, Galerkin time steps scale as N^{-2}, often making very high-order accuracy untenable in practice. This talk discusses the development of new multi-moment methods with much larger time steps and well-bounded basis functions. Many existing multi-moment methods have bases that are too oscillatory at high-order. The new methods presented here perform more efficiently than existing Galerkin methods, are well-bounded, and retain minimal parallel communication.

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MS23

Tempest: Tools for Addressing the Needs of Next-Generation Climate Models

Tempest is a comprehensive simulation-to-science infrastructure that tackles the needs of next-generation, high-resolution, data intensive climate modeling activities. This project incorporates three key components: TempestDynamics, a global modeling framework for experimental numerical methods and high-performance computing; TempestRemap, a toolset for arbitrary-order conservative and consistent remapping between unstructured grids; and TempestExtremes, a suite of detection and characterization tools for identifying weather extremes in large climate datasets. In this presentation, the latest advances with the implementation of this framework will be discussed, and a number of projects now utilizing these tools will be featured.

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MS24

A Well-balanced Operator Splitting Based Stochastic Galerkin Method for the Saint-Venant System with Uncertainty

We introduce an operating splitting based stochastic Galerkin method for the Saint-Venant system of shallow water equations with random inputs. The method uses a generalized polynomial chaos approximation in the stochastic Galerkin framework (referred to as the gPC-SG method). It is well-known that such approximations for nonlinear hyperbolic systems do not necessarily yield globally hyperbolic systems: their Jacobians may contain complex eigenvalues and thus trigger instabilities and ill-posedness. We overcome this difficulty by implementing a splitting strategy. The main idea is to split the underlying system into a linear hyperbolic system and a nonlinear degenerated hyperbolic system, which can be successively solved as scalar conservation laws with variable coefficients and source terms. The gPC-SG method, when applied to each of these subsystems, results in globally hyperbolic systems. We then utilize the second-order semi-discrete central-upwind scheme based well- balanced scheme in order to exactly preserve the lake at rest steady states. This is a very important feature of the proposed method since the lack of balance between the flux and source terms may cause large artificial waves to emerge in the case the method is used on a coarse grid, while using sufficiently fine mesh may be impractical. The performance of the designed gPC-SG method will be illustrated on a number of numerical examples.

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MS24

Parameter Identification and Bias Correction in Data Assimilation

Various implementations of the Kalman filter have been used successfully for model state estimation and numerical weather prediction. Open questions include methods for handling model error and estimation of model parameters. The latter issue is particularly relevant in systems biology contexts (such as the response of biological systems to changing parameters). I will illustrate a couple of approaches using a simple ODE model and an application to numerical weather prediction.

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MS24

A Discrete-time Approach to Data-Driven Stochastic Model Reduction

In computational climate modeling, typically one can only observe large-scale processes, and it is useful to model the effect of unresolved, small scales on the large scales. We introduce a discrete-time stochastic model reduction method, based on discrete observations of the large-scales processes. The method is able to capture long-term statistics, as well as to make short-term predictions, for chaotic systems such as the two-layer Lorenz 96 system and the Kuramoto-Sivashinsky PDE.

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MS24

A Method for Computing Rate-Induced Tipping Points Based on Lyapunov Exponent Theory

Tipping is a rapid and irreversible change in the state of a system caused by a small change in an input or parameter. In systems with time-varying inputs, tipping can be induced by a small shift in the rate of change of an input. In this talk we discuss a method for computing the critical rate of change at which tipping occurs using techniques that have proven useful in the approximation of Lyapunov exponents. We apply this method to compute the critical rate of global warming in the compost-bomb instability.

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PP1

A Numerical Study of Biofilm Growth in a Microgravity Environment

Understanding the effects of spaceflight on biofilms is important for manned space missions. We examine the case of biofilm tissue submerged in a nutrient solution. Finite Element simulations are performed to model the effects of microgravity on biofilm growth. Results in microgravity are presented for various values of the governing parameters and are compared to 1g simulations and experimental results found in the literature.

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PP1

Lagrangian Transport in a Dynamic Stratified Quadrupole Ocean Model

Lagrangian transport theory has been developed in idealized flows and more recently applied to realistic ocean general circulation models. These studies have provided important insight into ocean transport, yet little is known about the underlying dynamical mechanisms particularly regarding vertical motion and vertical shear. Here we report on transport mechanisms in a fully three-dimensional, time-dependent dynamically balanced quadrupole. The analysis is based on an exact solution to the linearized Euler equations with rotation and stratification.

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PP1

Validation of Oceanic Transport Markov Models

In recent years, empirical transit matrices based on drifter buoy data have become increasingly popular tools for making long-term predictions of oceanic transport phenomena. Applications include the transport of biomass and the formation of ocean garbage patches. In this work, we investigate the statistical validation of such models by analyzing the assumption of Markovianity, the effect of seasonality, and the relation between length and time scales.

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PP1

Undergraduate Sustainability Experiences in Mathematics (Use Math)

Solid quantitative reasoning skills (logic, mathematics, and statistics) are at the core of understanding and interpreting many environmental sustainability concepts and are required for making sustainability-related decisions. The goal of the NSF-funded Undergraduate Sustainability Experiences in Mathematics (USE Math) project is to develop and disseminate activities appropriate for use in introductory level mathematics courses that engage students in authentic experiences within the context of sustainability. In this session, we will share a number of USE Math projects and provide examples showing ways in which various collections of USE Math materials have been used in classrooms.

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PP1

A Bond-Topology Approach to Ice As Solar Panel Material

Recent experiments by the author suggest that there may be viable conditions for power production in cold-weather locations from solar panels made out of water ice. The most promising model uses a three-layer panel, with a partially melted layer of ice plus acid (or base) sandwiched between two layers of water ice. The energetics of the material are explored based on both structure and chemical composition.

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PP1

Simulation of Coastal Inundation Using Adaptive Mesh Refinement and Novel Bottom Friction Parametrization

Storm surge, a type of coastal flooding caused by intense storms and a main component of extreme sea level change, is a concern for many population centers especially highlighted by recent major disasters such as Typhoon Haiyan (2013) and Hurricane Sandy (2012). Numerical simulation can be highly demanding due to large computational domains and the need for fine resolution along coastlines. Mesh refinement is one way to reduce computational cost, and in particular adaptive mesh refinement allows for dynamic local refinement to track features of interest while less active regions can be coarsely resolved. Furthermore, highly detailed topography is becoming widely available but may be too fine for direct use in a simulation, so one might wish to upscale the effect of bottom roughness to coarser grids. However, the calibration is likely to be gridsize dependent which poses a challenge to an adaptive mesh refinement approach. We explore a novel bottom friction parametrization which is robust to gridsize. We apply it to a simulation of storm surge in the Typhoon Haiyan scenario using GeoClaw, a finite volume solver for the nonlinear shallow water equations with adaptive mesh refinement and robust Riemann solvers for wet/dry cells, along with atmospheric forcing terms.

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PP1

Heuristic and Eulerian Interface Capturing Approaches for Shallow Water Type Flows

Determining the wet-dry boundary and avoiding the related spurious thin-layer problem when solving the depth-averaged shallow-water (SW) equations (or similar granular flow models) remains an outstanding challenge, though it has been the focus of much research effort. In this paper, we introduce the use of level set and phase field based methods to address this issue and related problems. We also propose new heuristic methods to address this problem. We implemented all of these methods in TITAN2D, which is a parallel adaptive mesh refinement toolkit designed for numerical simulation of granular flows. Results of the methods for flow over a simple inclined plane and Colima volcano are used to illustrate the methods. For the inclined plane, we compared the results with experimental data and for Colima volcano they are compared to field data. Our approaches successfully captured the interface of the flow and solved the accuracy and stability problems related to the thin layer problem in SW numerical solution. The comparison of results shows that although all of the methods can be used to address this problem, each of them has its own advantages/disadvantages and methods have to be chosen carefully for each problem.

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PP1

A Minimalistic Model for Phytoplankton Blooms

In this work, we develop a minimalistic (i.e., a single ordinary differential equation) model for describing phytoplankton blooms. Our model is motivated by analysis of chlorophyll satellite data. This analysis suggests that phytoplankton concentrations change in proportion to the relative, rather than the absolute, change in division rate, because of predator-prey interactions. We test this suggested mechanism with a model and compare our model predictions to data for primary production and chlorophyll concentration.

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PP1

An Optimal Multirate Method for Climate Applications

Climate modeling involves multiscale problems as well as multirate problems with locally coupled time-scales [Keyes et al., *Multiphysics simulations: Challenges and Opportunities*, 2013]. We have developed novel multirate methods with a multirate structure that is appropriate in a wide range of climate applications. These new methods extend recent work in both the climate science and applied mathematics communities. Notable influences include the Recursive Flux-Splitting Multirate methods [Schlegel et al., *Numerical solution of multiscale problems in atmospheric modeling*, 2012] and the generalized-structure additively partitioned Runge Kutta family of methods [Sandu et al., *A Generalized-Structure Approach to Additive Runge–Kutta Methods*, 2015]. These methods have an improved order of accuracy over similar existing methods, in addition to other desirable properties. These improvements will be demonstrated in numerical tests on problems of relevance to climate applications.

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PP1

Cross-Scale Feedback Interaction in a Reaction-Diffusion Model of Tropical Vegetation

There is concern that tipping points might be reached in rainforest ecosystems that could provide feedbacks to climate change. Such concerns partly derive from increasing evidence that Amazonian vegetation represents a bistable ecosystem that can exist in both forest and savanna states. Between these states, abrupt transitions are possible due to regional hydrological and local fire-related feedbacks. We made a reaction-diffusion model that incorporates the bistability on local and regional scale and explore the effect of their interaction on the bifurcation diagrams.

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