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IP1

Assessing and Anticipating Arctic Risks: Advanced Modeling of Permafrost Erosion and Infrastructure Stability

Accelerating Arctic coastal erosion rates and changes in the Arctic environment have put critical infrastructure and native communities at risk. Although the Arctic is warming at a rate of 4x the global average, current tools for quantifying permafrost erosion fail to explain the episodic, storm-driven erosion events occurring in the region. After overviewing the unique characteristics of the Arctic permafrost erosion process and summarizing the current state-of-the-art in permafrost modeling, I will introduce our innovative thermo-mechanics-based permafrost model, known as the ACE (Arctic Coastal Erosion) model, which features: (1) failure mode predictions based on constitutive (vs. empirical) relationships; (2) the ability to predict failure from any allowable deformation; (3) the ability to simulate erosion events through dynamic element removal; (4) the incorporation of realistic oceanic and atmospheric boundary conditions; and (5) calibration using experimental data involving both Alaskan permafrost cores and synthetic permafrost samples. I will show results for a realistic calibration study demonstrating ACEs ability to reproduce erosion behavior observed during a summer 2018 field campaign at Drew Point, Alaska. I will additionally describe some recent extensions of ACE in which the model is used to study the impacts of Arctic warming on Arctic critical infrastructure, focusing on a specific exemplar involving a runway in Paulatuk, Canada.

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IP2

Beyond the Bonanza: AI as a Science Discovery Engine

Artificial Intelligence promises to transform how we understand complex systems like the Earth. From predicting ocean currents to identifying patterns too subtle for traditional analysis, the potential is vast. However, rigorous validation to avoid false positives remains a key concern. I have two goals: to highlight where AI can yield transformative insights for climate science, and to show how we can build the trust and transparency needed to distinguish genuine discoveries from convenient illusions. Specifically, using examples from ocean and atmosphere dynamics, we will use unsupervised learning to uncover governing equations, identify dominant processes, and reveal new circulation patterns. These physically interpretable structures then serve as a semantic foundation, grounding model predictions in known science and enabling us to verify their fidelity. We will demonstrate this with a complex tipping-point system from the North Atlantic Ocean, showing that supervised learning can determine physical relationships to make its predictions, and thus be applied well beyond the data it was trained on.

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IP3

Earthquakes, Tsunamis, and Supercomputers

Earthquakes and earthquake-triggered tsunamis arise from nonlinear dynamics on fault systems that span orders of magnitude in space and time. Although earthquakes cannot be predicted deterministically, physics-based models can illuminate how rupture evolves, how seismic waves generate damaging ground motion, and how seafloor deformation produces tsunamis. I will discuss how large-scale simulations, inverse methods, and dense observations are reshaping earthquake science toward real-time and probabilistic hazard analysis. Recent multi-fault and supershear ruptures expose the limits of statistical descriptions and the need for models that encode mechanics, geometry, friction, and uncertainty. Supercomputing enables high-fidelity hero runs of earthquake rupture, wave propagation, and tsunami generation, but such models remain too costly for routine ensemble evaluation, early warning, or physics-based hazard assessment. Reduced-order models, Bayesian inference, and data assimilation retain key dynamics while enabling rapid exploration of scenarios. I will highlight work toward earthquake and tsunami digital twins, including our 2025 ACM Gordon Bell Prize paper on real-time Bayesian inference for tsunami early warning in Cascadia. Together, these efforts show how mathematics, computation, and Earth observations can turn large-scale physics-based models into actionable tools for understanding and anticipating natural hazards.

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SP1

SIAG/Mathematics of Planet Earth Early Career Prize Lecture - Theory and Scaling in AI for Multiscale Dynamics

In this talk, we develop a unified theoretical and computational framework for AI-based autoregressive models for multi-scale chaotic systems such as weather, climate, and ocean dynamics grounded in recent advances in scientific machine learning. We examine the persistent instability of neural weather and climate models through the lens of dynamical systems theory, showing how spectral bias in deep architectures, specifically the preferential learning of large-scale low-frequency modes, leads to systematic misrepresentation of small-scale physics and drives error amplification in long-horizon rollouts. Building on this foundation, we present a theoretical analysis of stability for autoregressive neural operators using Jacobian spectral properties and edge of stability regimes, establishing conditions under which learned dynamics remain bounded and physically consistent over extended forecasts. We then connect these results to emerging neural scaling laws for scientific machine learning, demonstrating how model capacity, data resolution, and training horizon jointly control generalization across regimes, including out of distribution rare events, e.g., gray swan extremes. Finally, we highlight recent progress in constructing stable, physically consistent climate emulators that integrate these principles to enable long term prediction, uncertainty quantification, and data driven discovery, thereby outlining a path toward reliable AI models for the physical sciences.

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SP2

SIAG/Mathematics of Planet Earth Prize Lecture - New Mathematics and Statistical Physics for Cli-

mate Extremes: Theory, Algorithms, and Applications

Climate change is poised to profoundly transform our society, making mitigation and adaptation an urgent priority. Mathematicians have a crucial role to play in addressing these challenges, by developing new theoretical frameworks and algorithms capable of understanding and modelling physical phenomena that lie beyond the reach of existing tools. The study of unprecedented events in climate dynamics is a paradigmatic example where mathematics has made a decisive difference, drawing on large deviation theory, rare event simulations, and machine learning for stochastic processes. The death toll from climate-related disasters is dominated by a handful of extreme weather catastrophes events for which no historical data exists and for which realistic models are too costly to simulate and poorly anchored to observations. To address this severe scientific challenge, I have developed three complementary approaches: i) rare event simulations that efficiently generate model trajectories for unseen events and accurately estimate their probabilities; ii) dynamical emulators leveraging machine learning to simulate Earth atmosphere dynamics thousands of times faster than physical models; iii) Bayesian generalised extreme value statistics combining observational data and model outputs to estimate probabilities of rare events in future climates. I will present these approaches and illustrate their application to extreme heat waves and to the supplydemand balance in electrical systems.

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JP1

Joint Plenary Speaker with 2026 SIAM Annual Meeting: Grid to Grid: A Vision for Coupling Earth Systems Models to Energy Networks

Producing accurate, actionable Earth system forecasts that include information relevant about impacts upon the water cycle, energy infrastructure, and other related and interconnected targets is as important as ever. However, the Earth and its component system models are complex, multiscale, and interconnected, especially at the regional and local spatial and time scales where smart coupling to equally complex and multimodal Energy models is needed. This talk presents a vision and strategy to apply more powerful and flexible models to diagnose and predict a diverse suite of impactful events. This is especially important as we welcome learning-based models in Earth and energy system prediction. The community requires coordinated and specialized interactions of model and experimental output that are designed to be used by multiple infrastructure model types, spatial and time scales, data structures and volumes, software, security protocols, and scientific cultures. This talk presents considerations in planning, executing, and optimizing multidomain coupling, workflows and communication strategies along with several illustrative examples. The role of verification and validation to quantify the effects of algorithmic and statistical choices in improving and coupling models is also discussed. The expansion of best practices, community benchmarks, key stakeholder needs will enable multifaceted, actionable, and flexible forecasts that will save lives, mitigate damage, and lead us to a more prosperous future.

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CP1

Mathematical Modeling of Complex Systems with Applications to Fisheries

This study aims to deepen the understanding and optimize fishing activity in Morocco by holistically integrating biological and economic aspects. On the biological front, we examine the rivalry between three marine species: Sardine, Mackerel, and Tuna, and the need to preserve the balance of their biomass [1]. On the economic side, we focus on maximizing fishermens profits. We develop a biological equilibrium model for fishermen operating in the Atlantic region, where the three species coexist. These competing species exhibit their natural growth represented by logistic curves. We propose a mathematical model that takes into account the density and competition between species to explain population dynamics. Integrating human intervention adds a realistic dimension to our modeling. Fishermen specifically target all three species, thereby influencing population dynamics based on their fishing activities. This approach allows us to explore the effects of human-nature interaction on the biological equilibrium of sardine equilibrium of sardine, mackerel, and tuna populations.

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CP1

A Meta-Analysis of Lake Model Validation

The scientific literature contains a well-known gap concerning the lack of industry standards in mathematical verification of lake models. To address this gap, we present a systematic review on how a lakes physical properties, its model calibration, and its model sensitivity/uncertainty analysis influence the statistical validation of their simulations. To determine the primary drivers of lake model accuracy, we performed K-means clustering and random forest algorithms on a dataset containing lake metadata and reported statistical errors, with optimized hyperparameters to cement the validity of our inferences. The findings provide critical insights for limnologists on the recommended methodology of model verification, leading to more well-informed lake management decisions.

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CP1

Lagrangian Coherent Structures and Network Approaches on Interannual Time Scales in the Subpolar North Atlantic

The Atlantic meridional overturning circulation (AMOC) plays a critical role in regulating Earths climate by transporting heat and nutrients throughout the Atlantic Ocean. The AMOC consists of a northward-flowing surface branch of warm, saline Atlantic waters that cool as they move into subpolar regions. There, the cooling increases the water density, causing it to sink to depth in a process known as deep convection, which subsequently drives the southward branch of the AMOC in the deep ocean. Climate models suggest that increasing greenhouse gas concentrations over the past century have weakened circulation, altering AMOC variability. Subpolar regions such as the Labrador Sea, Irminger Sea, and Nordic Seas, are where deep convection influences AMOC variability. AMOC variability is an important topic because changes in circulation have direct consequences for weather patterns. The aim of the project is to first develop a computationally efficient framework that combines Lagrangian Coherent Structures and graph-theoretic measures on interannual scales to diagnose the flow of surface water and how it impacts deep convection within the subpolar regions. Once that has been established, the project will include how freshwater melt from Greenland reorganizes surface transport connectivity across subpolar regions on the interannual timescales, and how these changes influence deep convection within the AMOC.

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CP1

Time-Causal Point Processes for Probabilistic Seismic Hazard Prioritization

Short-term earthquake readiness can be formulated as a mathematical ranking problem: given an event history observed up to time t, estimate fixed-window exceedance probabilities and prioritize regions under limited operational budgets. I present a time-causal stochastic point-process framework for seismic hazard prioritization that combines an ETAS triggering intensity with learned interaction terms derived from waveform-enriched event histories. Using California as a testbed, approximately 340 TB of continuous waveforms from 2008 to 2023 were distilled into phase picks, relocations, enriched catalogs, and compact waveform-derived sequence marks. For each query time t, the model estimates the probability of at least one target event within a future space-time window, while chronological splits and causal masking ensure that only pre-t information is used. Under identical filters and evaluation rules, waveform enrichment improved AUC from 0.733 to 0.790 and increased Top-5 regional capture from 26.7% to 31.9%. This work connects stochastic modeling, time-causal evaluation, and Earth-system hazard prioritization, offering a mathematical pathway from large-scale seismic observations to auditable decision-support indicators.

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CP1

Heterogeneous Domain Decomposition Approach for Coupled Soil-Snow Model.

We present a heterogeneous domain decomposition approach for solving nonlinear heat conduction in a fully coupled snow-soil model in Arctic environments. The snow and soil are considered as two distinct physical domains, each described by a nonlinear heat equation with material properties that depend on temperature. The two subdomains are coupled across their interface by ensuring the continuity of temperature and the conservation of heat flux. The coupled system is solved iteratively, where the snow and soil subproblems are solved simultaneously, updating the interface conditions until convergence is achieved. Thisapproach allows us to solve each subdomain independently, maintaining the system fully coupled. Our analyses and simulations, based on the iterative domain decomposition approach, contribute to understanding the response of Arctic soil to weather conditions and help assess the reliability of the coupled model.

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CP1

Verification of a Data Driven Hurricane Model Through Computational Storm Surge Modeling

Computational, physics-based models are instrumental in understanding evolving coastal flood risk caused by hurricane storm surges, as various scenarios that have not been observed can be simulated. In previous work, we coupled the Weather Research and Forecasting (WRF) Model to the ADvanced CIRCulation (ADCIRC) storm surge model to deterministically assess the impact of long-term atmospheric variability on hurricane storm surges [Camelo et al., 2020]. Probabilistic analyses facilitate uncertainty quantification and more comprehensive risk assessment, however the computational costs of physics-based models such as WRF and ADCIRC are prohibitive to these approaches. Data-driven methods are promising solutions, and a WRF emulator has recently been developed to efficiently simulate hurricanes. In this work, the WRF emulator is verified using ADCIRC storm surge simulations, a foundational step in producing computationally efficient coastal flood risk analyses.

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CP2

Error Calculations for a Coupled Water Flow Model in Porous Media

A time-dependent flow model coupled to heat transport is considered. We present the error analysis for the coupled system, which is more complex than the well known error calculations for the individual PDEs. We focus on treating the error accumulation that arises and describing how the error for the system can be estimated. We provide numerical solutions and show convergence results.

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CP2

Lagrangian Coherence and Dispersion During a Loop Current Eddy Formation

The ocean dynamics of the Gulf of Mexico are dominated by the strong Loop Current, flowing in through the Yucatan Strait, looping north of Cuba, and exiting through the Straits of Florida. In the transition from an extended state, with the jet reaching far north, and a retracted state, with the jet hugging Cuba, large eddies may be spun off. These eddies change the connectivity of the Gulf and transport water masses westward. Traditionally, the 17-cm sea surface height contour has been used as an indicator for eddy detachment. However, in recent years, Lagrangian indicators have become more popular, as they are more closely tied to the dynamics. Here, we report on the evolution of Lagrangian metrics for both coherence and relative dispersion during such an eddy formation event, as derived from a regional ocean model. Metrics include the well-established finite-time Lyapunov exponent and Lagrangian average vorticity deviation, as well as the newer rigidity deficit, which measures the polar distance of a flow map from a rigid transformation.

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CP2

Recasting Transitional Gas Flow Modeling as a Data-Driven Closure Problem

Growing interest in expanding satellite operations into the rarefied upper atmosphere, where the Knudsen number (mean free path over characteristic length) exceeds approximately 0.01, motivates continuum models that retain NavierStokesFourier (NSF) computational efficiency while incorporating essential kinetic effects. In the transitional regime (Kn between 0.01 and 1), NSF loses validity yet fully kinetic solvers like Direct Simulation Monte Carlo (DSMC) are prohibitively expensive for large-scale simulations. We recast this breakdown of NSF as a closure problem analogous to subgrid-scale (SGS) stress modeling. In classical SGS modeling, filtering the governing equations leaves unresolved terms representing subgrid physics. These are traditionally modeled (e.g., Smagorinsky-type approaches) or, more recently, learned from filtered data using machine learning. We introduce NSF++, which treats higher-order kinetic corrections to the constitutive relations as unknown closure terms. These corrections represent averaged particle-scale effects learned from high-fidelity DSMC data, adapting data-driven SGS closure ideas to rarefied gas dynamics. This talk presents the NSF++ kinetic-informed continuum modeling framework alongside classical SGS closure ideas using a one-dimensional test case to illustrate the analogy. Rather than presenting a trained model, we establish the theoretical framework and demonstrate the feasibility of data-driven constitutive corrections.

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CP2

A Leading-Order Effect of Wave-Induced Mean Flow on Instabilities in Sheared Currents

Stokes drift is the wave-driven contribution to the average velocity experienced by fluid parcels and is typically smaller than the background current in magnitude, so its dynamical influence is often assumed negligible. Yet many fluid instabilities rely on the velocity experienced by parcels and are shear-controlled. In this context, the effects of Stokes drift need not be negligible, as its shear can match or exceed the background shear. We show that Stokes drift can indeed give rise to leading-order effects on baroclinic and symmetric instabilities. These instabilities correspond to two limiting cases of the unstable eigenmodes of the Eady problem: baroclinic instability energizes eddies, while symmetric instability drives mixing and turbulence in fronts. We recast the problem in generalized Lagrangian mean (GLM) variables, develop a double-asymptotic analysis, and extend it with numerical solutions of the corresponding primitive-equation eigenvalue problem. This reveals the emergence of a distinct Stokes-driftinduced instability branch, which is not strictly additive on the background instability. Additionally, oblique Stokes drift breaks directional degeneracy, enabling orientation selection and excitation of symmetric instability even when the mean flow alone would not support it. Taken together, these results show that wave-driven drift can substantially shift instability thresholds and growth rates, with implications for wave-aware stability-based parameterizations.

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CP3

Astrophysical Shocks: Jupiter, Earth and Saturn

The dusty plasma comprises charged dust particles, ions, electrons, etc. They are prevalent outside of Earth as well. In this work, we aim to study the plasma environment outside of Jupiter. Specifically, we aim to study the shock waves that form when the solar wind interacts with Jupiter's magnetosphere. We also draw comparisons from shock waves in Earths and Saturns magnetospheres. The methodology comprises Lie groups and self-similarity analysis. The research problem is defined using a collisionless multi-fluid plasma system, which is represented by partial differential equations (PDEs) and converted into ordinary differential equations (ODEs) using self-similarity transformations. The results highlight the dynamics of the flow variables, which help us understand the behavior of shocks in dusty plasma around Jupiter. The research concludes that due to the dominance of the thermal effect, the extraterrestrial shock follows an exponential path and decays with no steep fronts. Additionally, we are applying physics-informed neural networks on this model to validate and compare the findings.

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CP3

International Perspectives on Earth and Environmental Observation Through Digital Technologies: Critical Infrastructure Required for Communication

Earth and Environmental Observations are vital component for implementing the 2030 Agenda for Sustainable Development, declared by the United Nations. Social Media, Digital Technologies are essential for achieving Sustainable Development Goals. Artificial Intelligence, Machine Learning, Big Data Analysis for earth observation are essential for creating the communication system required for imparting Earth and Environmental Education. This presentation discusses the Critical Information infrastructure required for creating and managing the communication networks for the modules on Earth and Environmental observation. It focuses on various efforts undertaken by various countries to create information and communication systems for Earth and Environmental observation. Critical knowledge and information are required for earth observation. It signifies that High level of dependency of global communities is reliant on information and communication systems required for earth observation. This study suggests that empowering communities is crucial for helping citizens and responders alike understand how modern digital technologies and critical information infrastructure can be used to assess and respond to various needs through Earth, Environmental, atmosphere and ocean observation. The presentation also discusses joint efforts and initiatives on International perspectives on Earth and Environmental observation using Digital Technologies, Data sceince and ICTs.

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CP3

Rapid Neural Simulation of Earthquake-Induced Mudslides for Arbitrary Basin Topologies

Rapid prediction of earthquake-induced mudslide and debris-flow evolution is critical for hazard assessment. However, physics-based numerical solvers for shallow-flow models are often too computationally expensive for large-scale or real-time use. In this work, we trained a U-Net to learn earthquake-induced shallow-flow dynamics over heterogeneous terrain, enabling the model to serve as a fast and accurate surrogate solver. To generate training data for our U-Net, we created a finite-volume Kurganov-Tadmor solver to simulate earthquake-induced mudslides based on four inputs: basin elevation, basin slope, earthquake forcing amplitude, and initial free surface state. The solver then outputted the free-surface evolution for eleven future time-steps. After stacking, each simulation produced an input-output data point of shape (1,512,4) and (1,512,11), respectively. To train the U-Net, we used a composite loss that combines point-wise accuracy, gradient matching, weak mass conservation, and a small adversarial refinement term. After training, our U-Net predicted mudslide evolution with good fidelity, capturing global mass redistribution and sharp advancing fronts. With an inference time of only 0.046 second, our U-Net is 3400 times faster than our Kurganov-Tadmor solver. Our proposed framework enables fast, terrain-aware prediction and provides a scalable foundation for future extension to two-dimensional, Earth-observation-driven hazard modeling.

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CP3

Enabling Accurate Validation of PDE-Based Traffic Models from Imperfect Vehicle Trajectory Data

Vehicular transportation has a significant impact on Planet Earth, hence the advancement of mathematical traffic models that reproduce real traffic behavior accurately is critical. Vehicle trajectory datasets, like the I-24 MOTION dataset, play a critical role for both microscopic and macroscopic traffic models. Unfortunately, such data sets often suffer from missing data, measurement noise, and incomplete structural information. These limitations make it challenging to construct reliable macroscopic traffic quantities and lane specific information, relevant for a variety of traffic models. In this talk, we present systematic mathematical methodologies for reconstructing accurate and consistent macroscopic traffic flow quantities from trajectory data, even if those incur the aforementioned imperfections. We then leverage these reconstructed fields to conduct a data-driven validation of families of first and second order hyperbolic conservation law models for traffic flow, with a particular focus on critical traffic features like wave formation and propagation associated with traffic instabilities. The results provide insight into what structure of traffic models are best-suited for capturing real-world non-equilibrium traffic dynamics.

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MS1

Listening for Deep Ocean Warming with Autonomous Floats

Accurately tracking ocean warming, which accounts for over 90% of anthropogenic warming, remains limited by the sparse coverage of current observing systemswith some 4000 Argo floats, there is insufficient resolution in time and space to separate the large anomalies due to mesoscale eddies from the comparatively smaller climate signal. In this presentation, we use earthquake-generated sound waves to complement Argo point measurements. Since the propagation speed of sound is sensitive to temperature fluctuations, by measuring the relative arrival time of these waves across a network of hydrophone-equipped floats, we obtain nonlocal information about the ocean temperature field. Then, exploiting the spatiotemporal correlation structure of the temperature field, we can jointly invert Argo and acoustic arrival-time measurements, obtaining probabilistic estimates of ocean temperature. We demonstrate the method on a magnitude 5.0 earthquake captured by hydrophone-equipped floats from the MERMAID program. We then show how a broader inclusion of hydrophones in the observing system could substantially enhance our ability to estimate ocean temperatures, providing a clearer picture of the oceans role in climate change.

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MS1

Probing Forced Responses and Causality in Data-Driven Climate Emulators: Conceptual Limitations and the Role of Reduced-Order Models

Developing data-driven models of multiscale systems that capture both stationary statistics and responses to external perturbations is a central challenge in climate science. Current neural emulators aim to resolve the atmosphereocean system in its full complexity but often struggle to reproduce forced responses, limiting their use in causal studies such as Greens function experiments. In this talk, I argue that the ability of emulators to reproduce perturbed statistics depends critically on (i) appropriate coarse-grained representations and (ii) careful parameterization of unresolved processes. These insights highlight reduced-order models, tailored to specific goals and scales, as valid alternatives to general-purpose emulators. I then present a reduced-order neural emulator for the joint variability of large-scale surface temperature and radiative fluxes. By prioritizing optimal coarse-grained variables, the model accurately captures stationary statistics and recovers the system's response to external perturbations. Throughout, I propose linear response theory (LRT) as a rigorous framework for evaluating neural models beyond mean-state statistics, probing causal mechanisms, and guiding model design. Finally, I present a new proposal to constrain neural emulators to respect a given causal structure, highlighting how such constraints improve the representation of responses to weak and strong forcings, even when trained on unperturbed data alone.

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MS1

Data-Driven Reduced-Order Modeling for a Double Gyre Ocean Model Using Operator Inference

Numerical ocean models are powerful tools for simulating ocean circulation, but their high computational cost can be limiting. This poses a major challenge for tasks that require many forward model evaluations. To address this, we develop reduced-order models (ROMs) as efficient surrogates that can be used to analyze ocean response to a range of atmospheric forcing conditions. Our approach is data-driven and leverages the Operator Inference framework to learn low-dimensional dynamical systems from high-fidelity simulation data. Operator Inference combines data-driven learning and physics-based modeling by learning the reduced operators that minimize the misfit between projected state snapshots and reduced dynamics. While the method has shown success in systems with low-dimensional parameter spaces and relatively simple forcing functions, ocean models present notable challenges; they often exhibit slow eigenvalue decay in proper orthogonal decomposition and are driven by complex, spatially and temporally varying forcings that are major drivers of ocean circulation. We apply this methodology to a double-gyre ocean subject to time-varying wind and buoyancy forcing in a fully three-dimensional spatial domain. Results show that the learned ROM achieves low prediction error and substantial computational speedup, demonstrating the potential of Operator Inference for enabling fast and reliable ocean simulations that can be used for climate predictions under a range of forcing scenarios.

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MS1

Ice Floes as Lagrangian-like Sensors: Observability and Contrastive Learning for Ocean Flow Inference

There are limited under-ice eddy-resolving observations in the Arctic Ocean, impeding our ability to understand and quantify polar ocean dynamics and its response to a changing climate. Sea-ice floe translation and rotation are driven in part by wind and ocean currents, making floe motion a potentially informative but indirect measurement of the under-ice eddy field. Here, we compare the problem of inferring ocean flow characteristics from standard Lagrangian trajectories with the analogous problem of inference from ice floe motion. We first characterize the difficulty of this inverse problem, using formalism from nonlinear observability theory to quantify how floe size and number affect the information available about changes in the ocean state. We then compare these theoretical measures of inference difficulty with the performance of a CLIP-style multimodal contrastive learning model trained to associate ice-floe observations with surface ocean flow characteristics. This framework allows us to ask how much ice floe information is needed to recover flow characteristics typically inferred from Lagrangian observations, and how confidence in this inference depends on floe properties.

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Noise-Induced Tipping in a Conceptual Model of Arctic Sea Ice Dynamics

One impact of global climate change is the retreat of Arctic sea ice, which, if carbon emissions continue to rise unchecked, could disappear in the near future. In 2009, Eisenman and Wettlaufer introduced an extension of the classic ice-albedo feedback model that was first introduced by Budyko in 1969. Specifically, they introduced a seasonally varying model of the Arctic sea-ice-ocean-atmosphere system that accounts for the thermodynamics of the sea ice, the ocean mixed layer, and atmospheric heat transport. In this talk, we present an analysis of this system when the effect of greenhouse gases is modeled by weak additive Gaussian noise. Using a combination of tools from asymptotic analysis, large deviations, and pathwise analysis of stochastic differential equations, we study the most probable transition paths as well as expected tipping times between metastable states. The benefit of such an approach is that it allows for sharp estimates of the expected tipping time in terms of the physical parameters in the small noise limit. The aim of this analysis is to shed light on the mechanisms governing a potential transition to a perennially ice-free Arctic, potentially contributing valuable insights for climate prediction and policy.

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MS2

An Energy-Focused Model for Permafrost

As permafrost thaw increasingly impacts high-latitude soil and infrastructure, there is a need for modern treatment of conceptual permafrost thaw models. In this talk, we extend the analysis of a novel conceptual model for heat conduction in frozen soil, formulated as a single-column PDE for energy density with explicit phase transitions, which was introduced by Snchez Muiz in 2025. We explore the parameter dependence of permafrost characteristics such as time to thaw and the evolution of the temperature profile. We further compare model output to two contemporary models of permafrost thaw, an intermediate-complexity model and a temperature-based model, as well as data from borehole sites made available with each model.

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MS2

Identifying a Cusp Bifurcation in a Thermohaline Ocean Circulation Model

The Atlantic Meridional Overturning Circulation (AMOC) can be analyzed using low-order box models to understand tipping points. Historically, studies focus on freshwater hosing as the primary bifurcation parameter, treating the temperature gradient as a fixed restoring target. However, the erosion of the equator-to-pole temperature contrast due to polar amplification suggests that thermal forcing should be treated as a dynamic control parameter. In this study, we use Cessis reduced box model to map the global bifurcation structure of the thermohaline circulation. We relax the assumption of a fixed thermal background and analyze the systems behavior under joint thermal and haline forcing. We prove the existence of a cusp bifurcation, identifying the specific geometry of pitchfork and saddle-node bifurcations that bound the stable regime. This geometric characterization reveals that thermal erosion acts as a distinct mechanism for destabilization, capable of driving the system across critical thresholds even in the absence of anomalous freshwater forcing.

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MS3

Modeling Anomalous Diffusion and Transport in Sea Ice Dynamics

We develop a discrete element model of sea ice dynamics to quantitatively explain observations of anomalous transport in the southern Beaufort Sea [1] and elsewhere. Toward modeling large-scale evolution of the sea ice concentration field, we then connect floe-scale transport to classical and fractional advection-diffusion equations. In the classical case, we show that the effective diffusivity of simulated ice floes lies within theoretical bounds originally computed for neutral tracer models.

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MS3

Data-Conditioned PINNs for Inverse Modeling of Sea Ice Concentration

Polar sea ice is a thin but influential component of the earth system, reflecting coupled thermodynamics and elastic viscoplastic mechanics across many spatial scales. In this talk, I investigate an inverse problem for the dynamics of sea ice concentration modeled by a forced advection-diffusion equation, applying a data-conditioned physics-informed neural network (PINN) to determine effective coefficient fields for the polar regions. In contrast to standard coordinate-based PINNs, this model incorporates local observational context directly through learned convolutional features built from NOAA/NSIDC passive-microwave concentration data. The method reconstructs observed concentration fields accurately with small mean absolute error, but thus far fails to yield physically meaningful parameterizations of the sea ice concentration equation, resulting from the ill-posedness of the problem. These results demonstrate that data-conditioned PINNs may be a promising architecture for data-rich problems but emphasize the need to constrain the problem to determine meaningful parameterization. Physically or empirically motivating these constraints remains a chief area of investigation for the polar inverse modeling and forecasting problems and will serve to enable the application of data-conditioned PINNs to this domain.

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MS3

Bounds on the Complex Viscoelasticity for Surface Waves on Ice-covered Seas

Oceanic wave propagation through Earth's sea ice covers is a critical component of accurate ice and climate modeling. Continuum models of the polar ocean surface layer are characterized rheologically by the effective complex viscoelasticity of the composite of ice floes and sea water. Here we present the first rigorous theory of this parameter, and distill its dependence on mixture geometry into the spectral properties of a self-adjoint operator analogous to the Hamiltonian in quantum physics. Bounds for the complex viscoelasticity are obtained from the sea ice concentration and the contrast between the elastic and viscous properties of the ice and water/slush constituents. We find that several published wave attenuation datasets in both laboratory and field settings fall well within the bounds for specific contrast values of the ice/ocean composite.

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MS4

Agents4GEOS: AI Agents Enabling GNN Surrogate Construction for Geological CO2 Storage

Graph neural networks are natural surrogate models for simulations on unstructured meshes, as they directly encode irregular grid connectivity. GEOS, an open-source reservoir simulator with native unstructured-mesh support, is therefore ideally suited to generate the large, physically consistent datasets that GNN training requires. In practice, however, the complexity of configuring GEOS input files remains a major barrier, particularly for new users. We introduce Agents4GEOS, an AI-agent framework that exposes 48 domain-aware tools through the Model Context Protocol, enabling natural-language-driven simulation setup, mesh inspection, fluid property computation, and post-processing. Human-curated agent skills further allow automated evaluation of simulation outputs and guided troubleshooting. Our roadmap extends these agents toward an end-to-end pipeline encompassing dataset generation, GNN architecture and hyperparameter selection, GPU-cluster training management, and uncertainty quantification significantly reducing the expertise required to build reliable surrogates for many-query applications.

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MS5

Is it Rainier in Durham or Seattle?: Climate Explorations Using Computation

This talk presents two climate modeling modules developed for introductory undergraduate mathematics courses, requiring no calculus or programming background. The first module, included in *Climate Applications for the College Mathematics Classroom*, leads students to the question: How might legislation impact renewable energy production? Students work with publicly available data on wind, hydropower, nuclear, biofuel production, and energy consumption. They fit linear, quadratic, exponential, and logarithmic models, and use models to make projections. In the second module, students use a variety of statistical tools to answer the central question, Is it rainier in Durham or Seattle? Driven by suggested practices in the GAIMME report, students must decide how to distill this question into a math problem, making assumptions, defining variables, and defending their choices. Students gain exposure to statistical tools like mean, median, outliers, and box-and-whisker plots. We will discuss practical implementation and student reactions to both modules.

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MS5

Calculus-Free Climate Mathematics

Freshman Seminars at the University of Minnesota have no prerequisites other than a high school diploma and admission to the University. Luckily, Minnesota high schools teach the use of spreadsheets. This talk will describe the author's experience teaching a freshman seminar with the title, "Mathematical Climate Models." The goal was to lead the students toward thinking quantitatively about climate processes and toward analyzing data available on the Internet.

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MS5

Unpacking Earth's Changing Temperature with College Algebra

We present two climate-themed sets of exercises for College Algebra students. In a classic energy balance computation, quartic polynomial equations yield an estimate of Earths average temperature and reveal the effect of greenhouse gas concentrations on this temperature. In the second set of exercises, students predict committed warming by coupling measurements of Earth's current energy imbalance with models of incoming and outgoing radiation.

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MS5

Climate-Based Modules for Teaching Introductory Statistics

This talk presents climate-based modules designed for an Introductory Statistics course. Using real climate datasetssuch as temperature records and CO2 levelsstudents learn core statistical ideas in a meaningful context. The modules focus on measures of center (mean and median), measures of dispersion (range and standard deviation), basic visualization, and simple regression. By analyzing real data about climate trends, students build statistical intuition while strengthening their ability to interpret variability, compare distributions, and think critically about quantitative claims.

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MS6

Producing Weather Counterfactuals by Bogusing a Weather Foundation Model for Tropical Cyclone Prediction

We present ongoing research using weather foundation models to generate tropical cyclone counterfactuals for experimental design and causal discovery to better understand the underlying causes of extreme events in the Earth's atmosphere. Predicting atmospheric extreme events is critical for preparation and damage mitigation. Accurate prediction of extreme events is challenging because they are the result of multiple conditions converging through complex spatiotemporal structures. Each natural event is unique, so research is often conducted with Earth system models (ESMs) to simulate different conditions and causal factors. However, ESMs are computationally expensive, significantly limiting counterfactual studies. The Aurora Earth system foundation model enables the rapid generation of significantly more counterfactual studies of tropical cyclone formation compared to fully-coupled Earth system models. Rapid counterfactual generation enables more rigorous causal investigations, with methods such as randomized controlled trials and active causal discovery of the drivers of cyclone formation and intensification. In contrast to typical post-hoc causal discovery of non-interventional data, active causal discovery iteratively intervenes on the system to produce a more robust causal graph. In this talk, we will present preliminary results of generating targeted interventions to model inputs in the Aurora model for causal analysis of tropical cyclone drivers. New methods for more rigorous counterfactual analysis of extreme events can help identify their causes, improving prediction accuracy and enhancing preparedness for these destructive natural forces.

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MS6

Data-Driven Dynamics of Subpolar Gyre Tipping and Its Physical Implications

The North Atlantic subpolar gyre exhibits marked interannual variability and may be approaching a tipping point, raising concerns about its predictability in a warming climate. Climate model simulations suggest that the gyre can transition irreversibly from a regime of deep convection and strong circulation to one with weak convection and diminished currents. Such a collapse would substantially cool the North Atlantic and could hasten the slowdown of the Atlantic Meridional Overturning Circulation (AMOC). Here, we use CESM2 preindustrial control simulations to perform a data-driven analysis of the Labrador Sea subpolar gyre within a low-dimensional manifold defined by a small set of physically interpretable variables. First, we estimate the committor functionquantifying the probability that a given state will evolve toward the strong-convection regime before reaching the weak-convection regimeusing these variables as predictors. Second, we construct an effective low-dimensional dynamical model that captures the essential physics and provides a framework for evaluating climate model behavior. This reduced-order approach offers a tractable tool for probing the mechanisms of subpolar gyre tipping and for assessing the risks of deep-convection collapse under climate change.

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MS6

An Integrated Framework for the Identification of Compound Extreme Climate Events and Impact Assessment

The frequent occurrence of extreme hydroclimate events has significant impacts on ecosystems and socio-economic systems. However, intercomparisons of extreme events are often hampered by inconsistent definitions and a lack of standardized thresholds across event types. Here, we introduce the Optimal Path Threshold (OPT) method, a dynamic programming–based approach that adaptively determines optimal thresholds for defining extreme events at specific severity levels. We apply OPT to compound hot–dry–windy (CHDW) events, which are driven by simultaneous anomalies in multiple meteorological variables and can produce impacts far more severe than those associated with extremes in a single factor. Although compound extremes are known to influence agriculture, ecosystems, and economies, a comprehensive quantitative understanding of their interaction effects, temporal evolution, regional heterogeneity, and specific impacts on crop yields remains limited, particularly in key agricultural regions such as the U.S. Corn Belt. Using a region-adaptive compound-event identification framework, we systematically identify daily CHDW events across all U.S. counties over the past 45 years. We find that nearly two-thirds of U.S. counties experienced more than a 50% increase in CHDW days. For the first time, we also identify an emerging and strong negative effect of CHDW events —especially those occurring in June — on maize and soybean yields across the Corn Belt, with the largest impacts centered on the Iowa–Illinois region.

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MS7

Survival of a Species with a Moving Habitat

We investigate rate-induced tipping in a model of a moving habitat due to environmental change. We study a scalar reaction-diffusion equation with a non-autonomous reaction term representing a spatially localized, single-species, favorable habitat zone moving from one asymptotic location to another. The movement is characterized by the displacement d and the rate parameter r, which quantifies the time scale on which it occurs. Our main result identifies a critical displacement d^* and, for $d > d^*$, demonstrates the existence of a critical rate $r^*(d)$ above which the system undergoes rate-induced tipping: for $r > r^*$ an initially thriving habitat population becomes extinct due to the rapid habitat change.

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MS7

Excitability in a Soil Carbon Model: Tipping Points, Canards, and the Blow-Up Method

One of the many concerns arising from global warming is the acceleration of peat decomposition, potentially leading to a massive increase in the release of carbon into the atmosphere. We consider a peatland soil model by Luke and Cox (2010) that can be represented as a 3D slow-fast system. The fast variable is the temperature of the soil, while the slow variable measures the soil carbon content. A third variable forces the system by gradually raising the air temperature at a rate γ. Surprisingly, a spike (excitable response) occurs in the soil temperature once a certain threshold (tipping point) is passed by the ramp parameter γ. Using geometric singular perturbation theory, canard theory, and the blow-up method, we investigate this critical value γ_c and its dependence on different parameters. By approximating the stable manifold of a folded saddle, good numerical estimates for γ_c are obtained.

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MS8

Computational Topology and Uncertainty Quantification for Homogenization in Sea Ice

This talk features undergraduate research in mathematics at the University of Utah, and is given by Natasha Smith and Clara Platt, both first year undergraduates. In the first part bySmith, topological data analysis is used to characterize the geometric and connectivity properties of melt pond networks on Arcticsea ice. By looking at the relationship between fractal dimension and area fraction, scaling laws that mirror those found in three-dimensional brine inclusions are detected, suggesting a common geometric framework across scales. Using skeletonization to compute the Euler characteristic curve, we further quantify topological phase changes and provide insight into melt pond evolution. In the second part, Platt will consider uncertainty quantification for Stieltjes integral representations in homogenization for composites. Classical formulations assume fixed input parameters, such as volume fraction of the brine inclusions, yet in practice these parameters are often uncertain due to microstructural variability. We'll discuss how this parameter uncertainty propagates through the Stieltjes framework to bounds on effective properties of composites, and how variability in other microstructural parameters in matrix-particle composites leads to uncertainty in the spectrum in the integral representation and thus the homogenized behavior.

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MS8

Integral Equation Formulations for Flexural and Electromagnetic Wavesin Sea Ice

Electromagnetic and flexural waves arise frequently in the study of sea ice and ice shelves. Understanding their propagation in sea ice is crucial for measuring its microstructure and scattering properties. For electromagnetic waves, sea ice is modeled as a two-phase complex composite consisting of brine inclusions and pure ice. In this talk, we will briefly review the Stieltjes-transform representation of polarizability and demonstrate its connections to the classical boundary-integral operators in potential theory. Based on this observation, we will introduce a fast, accurate method via the integral equation method to compute the measure that encodes the geometric information of the inclusions associated with the Stieltjes-transform. For flexural waves, sea ice is modeled as an elastic thin plate and mathematically corresponds to a fourth-order PDE with clamped, free, and supported-plate boundary conditions. Here, we focus on the free-plate boundary condition and illustrate a novel integral representation that reduces the problem to a second-kind integral equation.

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MS9

Memory-Based Flow Map Learning for Subsurface Digital Twins under Hidden Uncertainty

Accurate prediction of decision-relevant quantities of interest (QoIs) in subsurface systems remains challenging because the governing dynamics are high-dimensional, nonlinear, and strongly affected by uncertain geological properties that are rarely observable in practice. In many practical settings, however, the main objective is not to reconstruct the full system state, but to forecast a few low-dimensional QoIs, such as production responses, pressure signals, leakage indicators, or plume migration metrics. This work investigates how memory-based flow map learning (FML) can be leveraged for this purpose in subsurface systems with hidden uncertainty. Our study builds on the existing memory-based FML framework, which is motivated by the Mori-Zwanzig perspective for partially observed dynamical systems. Since QoIs are projections of an unresolved full-order system, their dynamics are generally non-Markovian: future values depend not only on the current QoI, but also on unresolved states and uncertain subsurface parameters. To address this challenge, we adapt memory-based FML to construct a parameter-hidden surrogate model for QoI evolution. In this formulation, the influence of hidden geological heterogeneity is represented through a finite history window of past QoI observations, with control histories incorporated when external forcing is present. This yields a targeted digital-twin framework for predicting future QoIs directly from observable histories, without explicitly identifying the underlying uncertain parameters. We demonstrate the approach on heterogeneous subsurface flow problems in a two-dimensional quarter five-spot setting, where the hidden parameters are heterogeneous permeability fields and the QoI is the production response. Training data are generated from ensembles of high-fidelity simulations across many geological realizations, while the learned surrogate uses only QoI trajectories and prescribed operating histories. Numerical results show that this adaptation of memory-based FML accurately reproduces QoI dynamics over long rollout horizons under both fixed and time-varying operating conditions, with strong agreement with full-order simulation data.

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MS10

Teaching Students to Apply Bifurcations with Earth Energy Balance Models

Bifurcations are a challenging topic for undergraduates, both in introductory differential equations courses and in more advanced mathematical modeling classes. Students must first grasp what a bifurcation represents conceptually, and even then often struggle to interpret bifurcation diagrams and connect them to the behavior of real physical, biological, or ecological systems. In this talk, I describe an inquiry-based lesson developed for a senior-level Mathematical Modeling course in which students use bifurcation diagrams to interpret the predictions of an Earth energy balance model. By situating bifurcations in the context of climate tipping points, students develop a deeper conceptual understanding of bifurcation behavior and greater facility in interpreting bifurcation diagrams. In particular, students are challenged to use these diagrams to tell a coherent story about the possible evolutionary pathways of Earths climate system. I will also discuss several unexpected difficulties students encountered during the lesson and the instructional strategies I used to address them. The talk will highlight transferable approaches for helping students connect bifurcation theory to applied models in climate and other Earth system contexts.

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MS10

Integrating Climate-Focused Projects into Calcu-

lus Courses

In this talk, I will share my experience integrating climate focused projects into calculus courses, particularly Calculus I and Calculus III, as alternatives to traditional final exams. Instead of taking a cumulative exam, students worked in groups on applied projects based on climate topics. These projects required students to use core calculus concepts to analyze and solve application problems (some involving real data and others based on theoretical models) and to interpret their results in meaningful environmental contexts. I will discuss the structure of the projects, assessment methods, and student learning outcomes, as well as the opportunities and challenges of this approach. This experience illustrates how climate related themes can be thoughtfully integrated into calculus courses while maintaining mathematical rigor.

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MS10

Exploring Energy Balance Models from Multiple Perspectives

Energy balance provides a mathematical framework that can be explored from a variety of perspectives. At its core, the concept equates incoming solar radiation, adjusted for surface albedo, with outgoing longwave radiation governed by the StefanBoltzmann law. Incorporating time dependence, greenhouse gas effects, and spatial variability transforms a basic algebraic expression into differential equation models of increasing complexity. These range from low-dimensional conceptual models to large-scale Earth System Models comprising thousands of coupled equations. While mathematically intricate and challenging to analyze, such models remain central to understanding and simulating the Earths climate system. This talk examines how to explore energy balance across multiple mathematical levels, from simple algebraic formulations to more complex systems of differential equations.

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MS10

Carbon and Compute: Mathematical Stories of Acceleration

We present a module designed to engage undergraduate students in the mathematical modeling of climate change using atmospheric carbon dioxide emission data. Suited for introductory courses ranging from quantitative reasoning to college algebra, this module utilizes datasets from the NASA Goddard Institute for Space Studies and the NOAA Mauna Loa Observatory. Students analyze the historical trend of CO_2 mixing ratios, combining ice core estimates with direct observational data from 1850 to the present. The core activity guides students through calculating average rates of change via secant lines and employing regression techniques to fit various function types including linear, polynomial, exponential. By evaluating the coefficient of determination, R^2, students assess the model goodness-of-fit and select the most appropriate functions to project future emission scenarios up to the year 2100. These projections are contextualized within the framework of the IPCCs 6th Assessment Report, specifically regarding the 1.5^oC and 2.0^oC warming targets. The module also incorporates a critical examination of modern energy demands, asking students to investigate how the rising electricity consumption of data centers for AI training and inference impacts global emission trajectories. The activity concludes with a reflection on model uncertainty and data literacy, bridging the gap between abstract mathematical concepts and urgent planetary challenges.

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MS11

Differentiable Atmospheric Dynamics on Unstructured Grids Using the Pysces Jax Port of the Homme Dynamical Core

Atmospheric General Circulation Models (AGCMs) combine a large-scale fluid solver called a dynamical core with physics based parameterizations of small-scale processes like precipitation. End-to-end AI emulators of AGCMs still struggle with the long-term stability necessary for climate simulation. Recent work such as the NeuralGCM project has shown that combining differentiable versions of physics-based dynamical cores with AI-models for subgrid processes can increase model stability. This requires rewriting the dynamical core in Python using the automatic differentiation capabilities of the JAX library. However, there is not yet a Python-based differentiable dynamical core with support for variable-resolution modeling, which would allow physics+AI models to selectively increase the resolution over climatologically important regions of the globe. This work introduces the Python Spectral Element Dynamical Cores (pysces), which is a Python+JAX port of the NCAR CAM-SE and DOE HOMME dynamical cores. Our model includes the numerical techniques that were developed to allow CAM-SE and HOMME to be used for variable resolution Earth System Model simulations at resolutions ranging from 120km grid spacing to 3km grid spacings. We will discuss the capabilities of our model, including GPU parallelism (including multi-node capabilities), support for non-hydrostatic dynamics, and outline some hybrid AI-physics GCM architectures that are possible with our element-based modeling approach.

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MS11

Enabling AI Components in the Energy Exascale Earth System Model

Artificial Intelligence (AI) and Machine Learning (ML) are rapidly transforming Earth system modeling by offering data-driven pathways to complement traditional physics-based predictions. To harness these advances, the Energy Exascale Earth System Model (E3SM) project has launched a pilot study to develop and release AI-enabled emulators alongside standard physics-based components, targeting an eventual AI-enabled E3SMv4 due in early 2028. In this presentation, we outline the architecture and current progress of a robust software framework designed to integrate these emulators directly into the E3SM codebase and workflow. We discuss the ongoing development of this hybrid workflow, emphasizing the incorporation of physics constraints for stability and conservation, and present preliminary evaluation of E3SM emulators designed to complement E3SM physics counterparts.

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MS11

Learning Data-Informed Parameterizations for Deep Convection in Earth System Modeling

Earth system models rely on parameterizations to represent physical processes that occur at scales too fine to be explicitly resolved. Deep convection is one of the most consequential of these processes. The ZhangMcFarlane (ZM) scheme represents convection through ensemble-averaged moist updrafts and downdrafts within a vertical column, triggered when convective available potential energy (CAPE) is positive. A key quantity in this framework is the updraft base mass flux, M_b, which is determined using a prescribed CAPE consumption timescale. Model behavior, however, is highly sensitive to this parameter, and the scheme does not generalize robustly across model resolutions. We hypothesize that M_b is a functional of the local atmospheric state. We therefore develop a machine learning framework to infer M_b directly from high-resolution large-eddy simulations that explicitly resolve convective dynamics without relying on a deep convection parameterization. Training data are drawn from diverse regimes including tropical cyclones, marine convection, and continental convection. We demonstrate that the learned closure captures regime dependence and reduces sensitivity to resolution. Time permitting, we show preliminary results from an Earth system model in which the traditional ZM formulation is augmented with the learned M_b, evaluated at operational scales.

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MS12

Quantifying the Contribution of the Vertical "Gray zone" to Land Surface Flux Errors in the Energy Exascale Earth System Model

Simulation errors from Earth system model (ESM) parameterizations can come from formulation deficiencies and/or discretization inaccuracies. So far, the gray zone has referred to a horizontal grid size range where sub-grid processes are partially resolved explicitly rather than completely parameterized. In the Energy Exascale Earth System Model (E3SM), the bottommost atmosphere layer thickness is 20 m. This puts this layer well within the canopies of certain land cover types like tropical rain forests producing a vertical gray zone problem for land surface fluxes. Our goal is to assess whether this has a strong impact on atmosphere-land coupling in E3SM. We evaluate the effect of atmosphere layer thickness using three different E3SM Land Model (ELM) simulations driven by atmospheric conditions where ELM is coupled to the atmosphere model. The simulations differ by which of the three bottommost layers is providing atmospheric forcings. Fluxes from forcings from the default bottommost layer do not necessarily agree with tower observations, suggesting that the vertical gray zone does impact land-atmosphere coupling in E3SM, but other problems may be contributing to these biases also. We will further explore how much of these biases are derived from missing physical considerations or a lack of well-posedness of the problem. Distinguishing between the various biases is a necessary first step towards improved land-atmosphere coupling in E3SM and other similar ESMs.

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MS12

A Multirate Integration Framework Applied to Solid-Solid and Fluid-Fluid Interaction Models

We discuss a framework for multirate integration of multi-component systems with coupling across interfaces. The problem is to derive algorithms that support different time step sizes for each component. In the context of multirate coupling, there can be problems with accuracy, stability, or preservation of properties such as system invariants. The proposed framework provides a way to derive algorithms with the desired properties. The multirate coupling is based on recent work that treats the subdomain integrators as piecewise polynomial in time using the mathematics of discontinuous-Galerkin-in-time methods. These piecewise representations are then mapped into a smooth coupling space that spans some predefined interval of time called a *coupling window*. Two example applications are discussed: solid-solid interaction and a two-layer air-sea proxy using rotating thermal shallow water equations. We show how to apply the framework and customize the multirate coupling for each application. Numerical examples illustrate the accuracy, stability and preservation of a system invariant with different time step sizes for each component.

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MS12

Well-Posedness of Surface-Atmosphere Turbulent

Flux Parameterizations

In the absence of adequate vertical resolution, Earth system models rely on turbulent flux parameterizations to resolve transfers of energy, mass, and momentum at the surface-atmosphere interface. These parameterizations consist of systems of nonlinear equations which are approximated using iterative methods such as a fixed point iteration. However, in practice little consideration has been given to whether the equations underlying the turbulent flux parameterizations are well-posed — that is, whether a unique solution exists. We demonstrate that under certain meteorological conditions, the underlying equations associated with some commonly used turbulent flux parameterizations have no solution or have more than one solution. These issues have implications for the convergence of iterative methods used to solve the underlying equations as well as accuracy of the model output. In this scenario, we present regularization techniques to ensure existence and uniqueness of the computed turbulent fluxes and discuss overall model impacts.

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MS12

From MCT to MOAB: Tradeoffs in E3SM Coupler Design, Numerics, and Performance

In the Energy Exascale Earth System Model (E3SM), the coupler provides critical infrastructure to orchestrate the exchange of fluxes and state variables across the atmosphere, ocean, sea ice, land, and river component models. It primarily handles coupled field remaps between components, enforcement of model consistency through area normalizations, and scalable data transfers on massively parallel systems independent of the underlying PE layout. To address escalating demands for ultra-high-resolution simulations, E3SM is transitioning from the lightweight Model Coupling Toolkit (MCT) to the Mesh-Oriented datABase (MOAB), a fully parallel, topology-aware interface that delivers identical scientific outcomes with better scalability and adaptability. Developed as a hybrid "Franken-coupler" blending MCT and MOAB elements, the new E3SM coupler has achieved bit-for-bit (BfB) reproducibility through meticulous optimizations, including the use of file-based mapping weights, consistent accumulation orders, and adjusted compiler flags. Rigorous validation confirms BfB equivalence with MCT across diverse configurations, paving the path for the MOAB coupler for seamless adoption as E3SM's default coupler moving forward. This transition introduces tradeoffs: MOAB's explicit mesh topology and low-memory representations enable online remapping as an option, flexible repartitioning (geometric or graph-based) for improved data layout, and nonlinear filters to recover conservation and monotonicity in fields, thereby boosting both performance and numerics in high-resolution, multi-component couplings. We present E3SM timing comparisons between the MCT and MOAB coupler initialization and runtime operations, providing insight into the overheads if any, of using richer data structures as opposed to MCT couplers simplicity. We will also discuss numerical experiments quantifying stability and accuracy through control of the coupler rendezvous steps that determine the frequency of field exchange between components.

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MS13

Modeling Biological Drivers of Sea Ice Permeability

Algae living in the brine inclusions of polar sea ice produce a protective gelatinous coating of extracellular polymeric substances (EPS), which helps them survive in their harsh sea-ice habitat. One consequence of EPS production may be a reduction in nutrient availability, as EPS alters the ice microstructure, reducing permeability and the flux of nutrient-rich seawater into the ice. Here, we identify and analyze a novel biophysical feedback loop in which algae modify their environment through EPS production, thereby affecting nutrient availability and subsequent algal growth. To quantify the physical component of this feedback, we develop a microstructure fluid-transport model that represents sea ice as a connected network of brine inclusions, idealized as a heterogeneous pipe lattice with EPS-dependent permeability. We extend network models of interconnected brine channels by incorporating EPS transport, deposition, and clogging that dynamically reduce local cross-sectional area and hydraulic connectivity. Using pressure-driven flow solved on the network, we characterize how EPS accumulation restricts fluid exchange and nutrient delivery into the ice, providing a mechanistic basis for the EPS-permeability-nutrient feedback underlying algal bloom dynamics.

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MS13

Modeling EPS Transport and Fluid Flow in Sea Ice Brine Inclusions

Extracellular polymeric substances (EPS) produced by algal cells play an important role in sea ice ecosystems. In this project, we investigate how EPS-mediated reductions in permeability affect nutrient availability for algae. Previous studies show that pennate diatoms and other microorganisms adjust EPS production and composition in response to environmental stressors such as nutrient limitation, salinity, and low temperatures. EPS production may create competing effects on nutrient uptake: low EPS levels can lead to nutrient washout, while high EPS may form a dense matrix that restricts nutrient transport. This suggests a possible non-monotonic relationship between EPS concentration and nutrient uptake. Using a computational optimization framework, we explore whether an intermediate EPS secretion level maximizes nutrient availability for algal cells.

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MS13

Using Transition Path Theory to Study State Transitions in a Model of the Stratospheric Polar Vortex

The stratospheric polar vortex, an intense circulation of low-pressure and cold air over the winter pole, is critical in driving unusual surface weather patterns, including extreme cold air outbreaks and flooding. Understanding this phenomenon and forecasting the scale and timing of disruptions to the vortex remains a significant scientific challenge with real-world consequences in weather pattern predictions. My research focuses on leveraging stochastic differential equations and transition path theory to investigate the dynamics of variability within stochastic models of the polar vortex. I am applying a rare events algorithm to a three-dimensional minimal contour model, where separate basins of attraction represent strong and weak vortex states. Using this algorithm, I aim to characterize and analyze the transitions between these basins that are indicative of vortex disruptions. This will provide insight into where and why such transitions occur, and how we can better predict them. This approach can significantly improve our ability to forecast vortex disruptions and predict their magnitude and impact. Ultimately, my research seeks to study the transitions between vortex states during extreme vortex disruptions. My research seeks to bridge this gap, offering new mathematical tools and insights for understanding and predicting extreme events in climate systems.

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MS13

Data-Integrated Earth System Modeling Via Neural Ordinary Differential Equations: Temperature Reconstruction

Understanding past climate conditions from proxy data requires accurately linking these indirect observations to underlying climate variables. Statistical methods such as Expectation Maximization-based approaches can approximate these relationships but often lack physical constraints. In contrast, Earth System Models (ESMs) provide physically grounded simulations typically without incorporating observations. Hybrid models address this gap by combining datadriven methods with physical principles, improving efficiency over traditional General Circulation Models. We develop a hybrid Neural Ordinary Differential Equation (Neural ODE) framework, evaluating its performance on high-frequency ODEs and a nonlinear PDE. Using these insights, we integrate proxy data with a simplified ESM in the form of a carbon box model, applying data-driven corrections within the Neural ODE. This approach leverages both machine learning and physics-based modeling to better approximate relationships between proxy records and climate variables. Our results show the model has the ability to forecast temperature anomalies up to 15 years ahead using proxy data. We conclude by outlining possible improvements to further enhance predictive performance.

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MS14

Spatiotemporal Modeling of Power Outages with Weather Drivers

Power grid outages are becoming increasingly frequent, largely driven by the rising intensity and variability of weather events like hurricanes and storms. Yet, few studies have systematically examined the relationship between weather variables and outage dynamics at fine spatial and temporal scales. We develop a spatiotemporal probabilistic model that incorporates key weather drivers to characterize outage occurrence and duration. In addition, we integrate county-level demographic information, vegetation and land-use characteristics, and service-territory features to capture structural and environmental factors that influence grid vulnerability. This framework provides a comprehensive, data-driven understanding of outage behavior and supports improved planning for grid resilience.

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MS14

Modeling Spatio-Temporal Extremes Via Conditional Variational Autoencoders

Extreme weather events are widely studied in fields such as agriculture, ecology, and meteorology. The spatio-temporal co-occurrence of extreme events can strengthen or weaken under changing climate conditions. In this paper, we propose a novel approach to model spatio-temporal extremes by integrating climate indices via a conditional variational autoencoder (cXVAE). A convolutional neural network is embedded in the decoder to convolve climatological indices with the spatial dependence within the latent space, thereby allowing the decoder to be dependent on the climate variables. There are three main contributions here. First, we demonstrate through extensive simulations that the cXVAE accurately emulates spatial fields and recovers spatially and temporally varying extremal dependence with very low computational cost. Second, we provide a scalable approach to detecting condition-driven shifts and whether the dependence structure is invariant to the conditioning variable. Third, when dependence is found to be condition-sensitive, the cXVAE supports counterfactual experiments allowing intervention on the climate covariate and propagating the associated change to quantify differences in joint tail risk, co-occurrence ranges, and return metrics. To demonstrate the practical utility of the model in real data, we apply our method to analyze the Fire Weather Index over eastern Australia from 2014 to 2024 conditioned on the El Niño/Southern Oscillation (ENSO) index.

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MS15

Stochastic Process Models of Multilevel Selection in Evolutionary Game Theory

Multilevel selectionwhere natural selection acts simultaneously at individual and group levelsoften pushes in opposing directions: individuals are tempted to cheat while groups benefit from cooperation. Such antagonistic pressures are ubiquitous across taxa and scales (e.g., microbial public-goods production and mating strategies), motivating general formalisms that expose the common structural features driving these systems. Building on this context, two-strategy models have been extensively analyzed. For finite populations, net birthdeath processesbirths governed by rates and deaths triggered probabilistically by birthsare frequently employed; Shi, Shi, and Luo introduced a ball-and-urn representation coupling individual- and group-level events under constant birth rates. Subsequent work incorporates altruistic punishment and reward into multilevel models, allowing cooperators to incur costs to sanction defectors or to reward cooperators within the same hierarchy. We extend this mechanism by embedding evolutionary game-theoretic interactions at both levels and analyze a three-strategy system comprising cooperators, defectors, and punishers who sanction defectors (and may reward cooperators). We derive the corresponding PDE limit and perform stochastic simulations to investigate how sanctioning/reward parameters and the underlying game payoffs shape the long-run maintenance of cooperation in hierarchically structured populations.

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MS15

Pattern Formation in a Model with Nonlocal Facilitation and Competition

Spatially periodic patterns are observed in a multitude of applications, including semi-arid vegetation, mussel beds, during multicellular development, and in reactions of chemical species. Importantly, the existence and stability of these patterns can have profound consequences for the system. For example, the arrangement into spatial patterns has been shown to be a productive strategy that can delay the extinction of vegetation and other populations experiencing harsh conditions. A core ingredient necessary for patterns to arise is the existence of processes that promote activation and inhibition over multiple spatial scales. The formation and persistence of patterns have traditionally been studied in nonlinear reaction diffusion equations, and more recently in models with nonlocal interactions as well. The addition of nonlocal terms introduces additional spatial scales into the model and therefore has interesting implications for pattern formation. In this talk, we will apply analytical and numerical ideas to determine characteristics of pattern onset and the behavior of patterns far from onset in a nonlocal reaction diffusion model that contains competition and facilitation terms. Of particular interest is how the choice of competition and facilitation kernels contributes to differences in pattern formation and persistence.

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MS15

When Cooperation Induces Inequality

Many traditional models of evolutionary dynamics start with the following premise: cooperation is good, so how can it be promoted? Implicit in this premise is an idea that groups of cooperators are better off than groups of defectors. While the latter is true in classical social dilemmas, which take place in small groups (e.g., in a two-person prisoner's dilemma), it can fail to hold in populations, especially when realistic resource constraints are taken into account. In this talk, I will discuss game-theoretic models of social dilemmas in populations and argue that a common formulation of "take a two-player game and put it in a population" can yield unrealistic findings. In particular, heterogeneity in the population structure can lead to a tradeoff between the cooperative behaviors that evolve most easily and those inducing substantial inequality.

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MS15

Pattern Formation in Agent-Based and PDE Models for Evolutionary Games with Payoff-Driven Motion

Spatial structure can play an important role in the evolution of cooperative behavior and the achievement of collective success of a population. In this paper, we explore the role of random and directed motion on spatial pattern formation and the payoff achieved by populations in both stochastic and deterministic models of spatial populations who engage in social interactions following a hawk-dove game. For the case of purely diffusive motion, both a stochastic spatial model and a partial differential equation model show that Turing patterns can emerge when hawks have a greater movement rate than doves, and in both models hawks and doves see an increase in population size and average payoff as hawk mobility increases. For the case of the payoff-driven motion, the stochastic model shows an overall decrease in population size and average payoff, but the PDE model displays more subtle behavior in this setting and will depend on the relative diffusivities of the two strategies. The PDE model also displays a biologically infeasible short-wave instability in the case of payoff-driven motion and equal diffusivities, indicating that we need to be careful about the mathematical properties of PDE models with payoff-driven directed motion and indicating potential use for nonlocal PDE models for spatial patterns in evolutionary games with directed motion.

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MS16

Rigorous Uncertainty Quantification of Probabilistic AI Weather Forecasts with Conformal Prediction

Probabilistic weather forecasting is undergoing rapid transformation with artificial intelligence (AI)-based models. In traditional numerical weather prediction, computing power limits how many ensemble members approximate the unknown statistical distribution of future states. AI-based models facilitate larger ensembles with higher skill and, ideally, better uncertainty quantification. These state-of-the-art models produce forecasts that are often considered well-calibrated, especially when trained with probabilistic considerations in mind. However, we show that the statistical coverage of such models can struggle, especially on rare extreme events. We turn to conformal prediction, a class of statistical methods that mathematically guarantees coverage under no distributional assumptions, unlike previous post-processing techniques. We apply online conformal inference to the forecasts of three leading global weather models, GenCast, NeuralGCM, and AIFS-ENS, ensuring calibrated uncertainty at no expense to other probabilistic metrics. This post-processing method can be applied to any forecasting model.

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MS16

High-resolution Severe Weather Prediction with Differentiable Atmosphere-ocean Modeling Software

Weather forecasting is being disrupted by machine learning (ML). The shocking success and rapid proliferation of ML weather prediction begs the question: will ML models completely displace traditional physics-based models for numerical weather prediction? In this talk, we argue that future models must utilize the best of both physics-based and ML-based atmosphere models requiring fast, differentiable atmosphere models written in modern programming languages. This is required as conventional models cannot handle the complexity of driving physics to achieve more accurate, timely predictions. To this end, we present new, differentiable, GPU-first, Julia-based software for weather research and forecasting named Breeze.jl. We argue that Breezes differentiability enables the blending of well-established physics (such as advection and diffusion) with ML techniques and with missing physical processes, providing a fundamental advantage over purely data-driven models. We discuss how Breeze.jl is instantly installable, easy to use, and very fast, all necessary features of a next-generation operational system. Breeze.jl is based on Oceananigans.jl, popular ocean modeling software, which enables seamless coupling of atmosphere and ocean components via the Earth system modeling framework, NumericalEarth.jl. We demonstrate Breezes performance on common atmospheric benchmark cases and give examples of how differentiability enables hybrid physics-ML model development, learnable subcomponents, and variational data assimilation.

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MS16

Toward Data-Integrated Atmospheric Simulation: Adjoint Infrastructure for a Hybrid Hommexx Dynamical Core

The HommeXX dynamical core solves the non-hydrostatic equations of motion for the atmosphere in the U.S. Dept. of Energy Exascale Earth System Model (E3SM). It is a massively parallel global atmosphere model capable of very high resolution simulations that leverage the computational power of exascale computing resources. In this talk we discuss new efforts to compute and provide gradient information from HommeXX using scalable automatic differentiation software and PDE adjoint methods. These efforts will enable sensitivity analysis of the simulated Earth system in E3SM and support hybrid, or data-integrated, methods that combine forward simulation via HommeXX with machine learning workflows aimed at learning new sub-grid parameterizations from observational data using neural networks.

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MS16

A Machine-Learned Corrective Model for 3D Cloud Radiative Effects in 1D Radiative Transfer Codes

Recent breakthroughs in Earth system models (ESMs) have enabled global climate simulations with ultra-high horizontal resolution. These resolutions allow the explicit capture of deep convective motions and clouds. However, at these same resolutions, the approximations which underpin radiative transfer codes used in ESMs begin to break down. Radiative transfer presents a unique opportunity to leverage AI in Earth system modeling. Although approaches to solving the unsimplified radiative transfer equation online in ESMs are prohibitively expensive, they may be used offline to generate high-quality data to train machine-learned emulators. We develop a machine-learned operator to emulate three-dimensional effects in the one-dimensional radiative transfer codes currently used in ESMs. We demonstrate the operator in offline examples that highlight its corrective capabilities and computational efficiency.

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MS17

Circadian Rhythms of Spiders

Experimental data from multiple nocturnal spider species reveals distinct circadian patterns with varied propensities for entrainment across species. To explain these differences, we augment a standard Goodwin model by incorporating both a light entrainment pathway and a locomotor gating mechanism. Our robust modeling framework introduces possibilities for circadian adaptation that preserve the underlying clock architecture.

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MS17

Curvature and Confinement: Resilience of Vegetation on Undulating Sloped Terrain

Vegetation in arid environments must overcome scarcity of resources, primarily of water, to survive. Yet we find vegetation in very arid environments all over the world. Early phenomenological models by Klausmeier (Klausmeier, Science (1999)) demonstrated that vegetation on sloped terrain is able to survive in arid conditions by breaking up into densely vegetated stripes along the elevation contours of the slope. Bare soil regions between the stripes collect water which flows downhill before being caught and captured by the vegetation stripe immediately following. The formation of vegetation patterns can then be seen as a mechanism for developing resilience against aridity. While there are multiple models of this type in use today, they are typically studied on idealized 1-dimensional slopes. In this talk, I will present new results on the formation of patterns on 2-dimensional undulating slopes in a phenomenological model similar to Klausmeiers. We investigate links between the topography and the selected patterns, and how the formation of patterns affect the resilience of vegetation as water becomes more scarce. This is a joint work with Punit Gandhi and Mary Silber.

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MS17

Quantifying Transient Reactivity in Two-Dimensional Linear Systems

There is an inherent interplay between disturbance and transient dynamics in resilience questions. *Reactivity* refers to the phenomenon of a linear system of ODEs "reacting to and amplifying a disturbance. This is especially important when a disturbance is magnified to undesirable levels, which can happen even when there is a globally attracting equilibrium. In this talk we introduce a new framework for analyzing reactivity in two-dimensional linear systems. While the eigenstructure of the system captures the long-term dynamics, we use the new framework to define an orthostructure, dual to the eigenstructure, that captures transient reactivity dynamics of the system. By interweaving the eigen- and ortho-structures, we are able to exactly quantify the maximum disturbance amplification possible.

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MS19

Relaxation for Spatio-Temporal Risk Hazard Estimation from Historical Data

Utilizing historical data to understand hazards to power grids is crucial for disaster management and resource allocation, but it can be difficult to account for spatio-temporal effects within historical point observations. We present an approach that utilizes such data to create a detailed spatio-temporal mapping of fire, flood, and power outage risks in Texas from 2014-2022, defining fire and flood events at the county level as hours within the 90th quantile of observed PM2.5 and precipitation, and corresponding outage events as hours in which 20% of households were affected. We organize this data into a Markov Random Field-like network structure, connecting each county to its neighbors for spatial effects then layering these networks temporally, connecting each county at time i to itself at times $i+1$ and $i-1$. We then fill this three dimensional structure with binary event flags for each risk class (fire, flood, and outage) at the county-hour level and employ Jacobi relaxation on the resultant binary event matrices to produce temporal risk likelihood maps from known localized events. By directly including spatial and temporal effects within the risk estimates this methodology allows for more globally accurate probability field estimates, enabling future work in detailed compound risk evaluation. *SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.*

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MS19

Multivariate Approaches for Estimating Compound Event Risk

The increasing threat of multiple hazards in close temporal and/or spatial proximity to critical infrastructure puts significant strain on multiple operations, including power delivery and disaster response. However, it is common to evaluate extreme events in isolation, which can lead to underestimates of risk. In this talk, we discuss an effort to advance techniques for quantifying the risk and potential impacts of compound extreme events (i.e., multiple hazards occurring in close temporal and/or spatial proximity). Through an exemplar of the electric grid in California, we will present an initial probabilistic framework to evaluate risk of co-occurring and consecutive hazards. This work will improve our understanding of compound hazards and help inform more effective risk management strategies for critical infrastructure. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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MS19

Hazard Informed Capacity Expansion Planning

Power outages often co-occur during natural hazard events such as hurricanes or periods of extreme temperatures. As these events become more frequent and severe, electric grid planners must develop capacity expansion plans that enhance resilience and reliability. In this talk, we present a two-stage formulation that identifies the most likely component outages based on historical customer outage data. By integrating hazard-related risks into the capacity expansion problem, we evaluate various adaptation strategies to support grid expansion. This work provides valuable insights for decision-makers seeking to strengthen the electric grid against the increasing risks posed by natural hazards.

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MS19

Stochastic Modeling of Tropical Cyclone Wind Fields from Track Data

Tropical cyclones (TCs) pose significant risk to infrastructure and human safety, and their frequency and intensity are expected to increase in the future. Quantifying this risk to coastal and inland regions due to TCs is a challenge, partly due to limited historical data and their extreme nature, which challenges typical modeling assumptions. We introduce a new stochastic model of TC wind fields based on a small number of physical variables commonly found in storm track databases. The model consists of a physically motivated mean model and an expansion of the residual field into a wavelet frame. We demonstrate the approach on a dataset consisting of runs of the Weather Research and Forecasting Model for storms impacting the area of Houston, Texas.

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MS20

Red-DiffEq: Regularization by Denoising Diffusion Models for Solving Inverse Pde Problems with Application to Full Waveform Inversion

Partial differential equation (PDE)-governed inverse problems are fundamental across various scientific and engineering applications; yet they face significant challenges due to nonlinearity, ill-posedness, and sensitivity to noise. Here, we introduce a new computational framework, RED-DiffEq, by integrating physics-driven inversion and data-driven learning. RED-DiffEq leverages pretrained diffusion models as a regularization mechanism for PDE-governed inverse problems. We apply RED-DiffEq to solve the full waveform inversion problem in geophysics, a challenging seismic imaging technique that seeks to reconstruct high-resolution subsurface velocity models from seismic measurement data. Our method shows enhanced accuracy and robustness compared to conventional methods. Additionally, it exhibits strong generalization ability to more complex velocity models that the diffusion model is not trained on. Our framework can also be directly applied to diverse PDE-governed inverse problems.

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MS22

Sea Ice State Initialization in Coupled Forecasting Systems: Approaches and Challenges for Global and Regional Applications

Reducing initial state error is fundamental to improving forecasts in operational prediction systems. Data assimilation (DA) provides the best estimate of the current state and has demonstrated substantial success in atmospheric and ocean forecasting. However, applying DA to sea ice presents additional challenges. A primary limitation is the scarcity and uncertainty of near-real-time sea ice observations, particularly for thickness and snow depth. Further challenges include the strong nonlinearity of sea ice physics, tight coupling with the ocean and atmosphere, and poorly constrained background and observation error statistics.

This presentation employs two simplified sea ice initialization approaches, sequential relaxation and direct insertion, in both regional and global coupled systems to assess forecast sensitivity to assimilated ice variables, seasonal dependence, and selected sea ice model parameters. Case studies include a global UFS forecasting configuration using the CICEv6 sea ice model and a regional coupled forecasting system using the SIS2 sea ice model. The methodology for ingesting sea ice variables into the models is described. Results highlight the seasonal and regional importance of specific sea ice state variables for forecast skill, including in the Southern Ocean, and discuss the impacts of limited sea ice and snow observations.

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MS22

Lagrangian Data Assimilation for Sea Ice: State Estimation, Uncertainty, and Eddy Diagnostics

Lagrangian observations of ice floes provide valuable insight into the coupled dynamics of sea ice, the ocean, and the atmosphere in the marginal ice zone. In this talk, we demonstrate how Lagrangian data assimilation combined with an effective stochastic model can significantly improve state estimation of both ice and ocean variables. We first develop an efficient and statistically accurate nonlinear dynamical interpolation framework to recover missing floe observations. The method successfully reconstructs floe locations, curvatures, angular displacements, and their strongly non-Gaussian uncertainty in the Beaufort Sea, while also estimating floe thickness and the unobserved underlying ocean field with quantified uncertainty. Building on the estimated ocean field, we then introduce a mathematical framework for eddy identification using Lagrangian observations. This framework elucidates how uncertainty interacts with nonlinear eddy diagnostics and how assimilating additional observations reduces uncertainty. Finally, we show that the same framework enables a statistical analysis of floe collisions.

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MS22

When Satellite Observations Might Mislead: Passive Microwave Sic Biases and Their Impact on Sea Ice Forecasting

Passive microwave (PM) sea ice concentration (SIC) products form the backbone of polar sea ice forecasting and data assimilation. Yet PM sensors do not observe SIC directly; they measure top of atmosphere brightness temperatures that are inverted through empirical algorithms assuming linear mixing between ice and open water endmembers. These assumptions are not strictly satisfied in the marginal ice zone and during melt, where surface state, ice type, and atmospheric influence modify the radiometric signal. Here we evaluate PM SIC biases through systematic comparison with contemporaneous C band Synthetic Aperture Radar (SAR) observations, which resolve sea ice structure and concentration at finer spatial scales. We show that PM retrievals exhibit systematic underestimation in non compact ice regimes, leading to artificially broad marginal ice zones and regionally coherent errors. These biases are not random noise but structured algorithmic artifacts that can propagate into data assimilation systems and influence forecast skill. Our results highlight the need to explicitly diagnose observation related uncertainties in operational sea ice forecasting and motivate forward modeling approaches that bridge brightness temperatures, sea ice physics, and prediction systems.

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MS22

Practical Data Assimilation at the Limits: Constraining Sea Ice Variables in a Multi-Category Sea Ice Model

Data assimilation methods are widely wielded in geophysical applications, many of which involve complex dynamical models and a relative paucity of real-world observations. Sea ice, which is an important component of global climate models, highlights many common challenges of assimilating Earth system observations. In addition to being underobserved, sea ice is a non-Gaussian system, particularly when discretized on a model grid. Popular sea-ice models further discretize sea ice into categorized thickness distributions, altering the relationship between sea-ice quantities that can be observed and those that are unobserved but underpin model dynamics and thermodynamics. Each of these discretizations presents challenges for Gaussian ensemble filtering methods that can lead to analysis inaccuracies. We will review recent advances in non-Gaussian ensemble filtering for geophysical applications developed in response to these sea-ice challenges, and present ongoing efforts to ensure consistency when updating both observed and unobserved sea ice variables.

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MS23

Bridging Idealized and Operational Models in Earth Systems

In this talk, we present an explainable AI approach that bridges idealized and operational Earth system models across the model hierarchy. The method leverages a reconfigured latent data assimilation strategy designed to make effective use of the sparse, process-focused output of idealized models. The resulting bridging model retains the spatial resolution and variable richness of operational models, while achieving targeted global improvements informed by idealized representations of key processes. Importantly, the explainable structure of the AI provides physical insight into the source of these corrections, moving beyond black-box bias adjustment toward a transparent and computationally efficient framework that supports uncertainty quantification and physics-assisted digital twins. We demonstrate the approach by correcting systematic biases in CMIP6 simulations of El Nio spatiotemporal patterns using statistically accurate idealized models. The results highlight the value of advancing idealized model development and strengthening communication across Earth system modeling communities.

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MS23

Continuous Data Assimilation with Learned Surrogate Dynamics

Continuous data assimilation concerns estimating the state of a dynamical system from partial measurements. In many applications, the dynamics governing the state evolution are either incompletely known or too expensive to simulate at the desired resolution, leading to model error. Motivated by this challenge and the increasing use of machine learning surrogates in data assimilation, this talk presents a unified theoretical framework for nudging algorithms that employ learned surrogate models of the dynamics. To that end, we first establish general conditions on the dynamics and measurements under which nudging with the true dynamics model achieves accurate tracking, both in the noise-free setting and under noisy measurements. We then show that nudging algorithms that employ surrogate models retain exponential convergence up to an explicit error floor that quantifies the effects of surrogate approximation error and measurement noise. Finally, we analyze surrogate models constructed by learning either the vector field defining the dynamics or its solution map over a short time interval. Our results quantify the amount of training data required to guarantee accuracy for nudging algorithms based on these learned surrogate models. Numerical experiments illustrate and support the theory.

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PP1

Identifying the Universal Domain Size Required for An Accurate Description of Porous Media

Three-dimensional porous media imaging datasets pose significant computational challenges due to their enormous size, often comprising billions of voxels. This work identifies the smallest length scale at which porous media can be analyzed while still yielding reliable structural information such as permeability. Using topological data analysis (TDA), and building on preliminary evidence of topological homogeneity in a trial experimental dataset, we extended the investigation to synthetic data we generated as well as to additional, more extensive experimental datasets. We tested whether an effective "law of large numbers" holdswhereby subsamples of smaller domain sizes remain reliably representative of the full domain. Extracting characteristic length scales through multiple independent methods, including chord-length analysis and Fourier transforms, we find that a single dimensionless parameter governs the required length scale across diverse datasets. This near-universality provides a well-justified basis for selecting representative domain sizes, substantially reducing computational cost while preserving the fidelity of topological characterizations. This work was supported by NSF Grants DMS-2201627 and DMR-2410985 and ACS PRF 69100-ND.

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PP1

Delayed Loss of Stability for the Lorenz '96 System and Extensions

In 1996, Edward Lorenz introduced a dynamical system that describes very simple "weather' on a cartoon planet: a scalar quantity evolves on a circular array of N sites, undergoing forcing, dissipation, and nonlinear advection. Lorenz proposed this system as a test bed for numerical weather prediction. This is an nonlinear N-dimensional dynamical system with a single bifurcation parameter (forcing strength). The system has spatially constant equilibrium states that are stable for small forcing. These equilibria lose stability in a Hopf bifurcation as the forcing increases, resulting in stable time-periodic wave patterns that move around the circle. We study the behavior of this system as it undergoes dynamic bifurcation, i.e. when the forcing strength slowly increases beyond the bifurcation point. It turns out that the loss os stability is always delayed: As the forcing increases, solutions track the moving equilibria long after these have lost stability and then suddenly transition to approach large amplitude time-periodic solutions. We discuss this delay phenomenon for general time-dependent forcing.Our approachrelieson the special structure of the Lorenz '96 system. It will also be explored whether similar results can be extended to more general systems with slowly moving bifurcation parameters.

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PP1

Quantifying the Influence of Fault Geometry on Earthquake Dynamic Rupture Via Model Order Reduction

Natural fault geometries are complex and influence how earthquakes rupture, but are often ill-constrained at depth. Quantifying the sensitivity of numerical models of earthquake dynamic rupture (DR) to geometric variation is challenging due to the effort required for mesh generation and the computational cost of high-fidelity simulations. We use reduced-order models (surrogate models) to investigate the influence of fault geometry on simulated earthquake rupture on the Southern San Andreas fault (SSAF). The SSAF poses a significant hazard to several major metropolitan areas in Southern California. Despite being one of the best-studied faults in the world, its geometry at depth is still poorly known and remains a subject of debate. Using a technique called mesh morphing, we take a single reference mesh and deform, or morph, the mesh to represent a different fault geometry by updating the vertex coordinates. Since mesh connectivity is preserved, we can use output from DR simulations to build highly efficient, data-driven reduced-order models (ROMs) that approximate displacement, velocity and fault slip as a function of geometry. Using the ROMs, we explore the uncertainty range of fault dip angles and fault curvature to quantify their effect on simulated SSAF ruptures. By robustly characterizing these relationships, we illustrate the influence of fault geometry on rupture dynamics and assess the implications of uncertain fault geometry for potential SSAF earthquakes.

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PP1

Near-Bottom Circulation in the San Pedro Basin from Mooring Observations and the Mitgcm

From the 1930s to the 1970s, industrial and military waste, including Dichlorodiphenyltrichloroethane (DDT), was disposed of off the coast of Southern California. Of the 14 dispersal sites identified by SCCWRP's 1973 report, research efforts have focused on Dumpsite 2 in the San Pedro Basin. This study interprets velocity, temperature, and oxygen data collected at 892m depth from a mooring deployed at Dumpsite 2 from September 2024 to March 2025, with emphasis on near-bottom currents as they can remobilize sediment and carry pollutants. It also assesses the validity of the MIT General Circulation Model (MITgcm) against in situ observations. Current velocities are dominated by tides, but changes in low-pass filtered currents are coherent with temperature and oxygen. Variance ellipses of model-generated and mooring-observed currents show greater variability in the observations, though both display similar orientation. Spectral analysis reveals high Power Spectral Density (PSD) at low frequencies, pronounced peaks near the inertial period, diurnal and semidiurnal tides, and low PSD at very high frequencies. Temperature and oxygen fluctuations are anticorrelated. The sudden onset of dips in temperature coinciding with spikes in oxygen in November 2024 suggests a basin flushing event. Past studies suggest flushing occurs over timescales of days to weeks and roughly every other year, but these new observations suggest that flushing is more rapid than previously thought.

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PP1

Quantum Machine Learning Seismic Imaging

Quantum computing can improve seismic imaging by using quantum machine learning (QML), Synthetic/generative AI to more accurately and efficiently process seismic data, leading to better subsurface images for targeting seismic fault detection.. This is especially promising for challenging tasks like seismic fault detection and velocity model inversion, where quantum computing can outperform classical methods by handling complex data and large datasets with greater speed and accuracy. Quantum seismic imaging is an emerging field that uses quantum principles and computing to improve seismic data processing and analysis for subsurface imaging. It involves applying quantum computing techniques like quantum annealing and quantum machine learning to complex seismic problems, leading to higher accuracy and resolution in areas like fault detection and seismic inversion compared to traditional methods. Quantum Wavelet Transform(QWT)- seismic imaging Quantum Computing-wavelets have emerged as a powerful tool for analyzing and processing signals with varying frequencies and resolutions.Wavelets decompose signals into localized, transient components. This localization property makes wavelets particularly well-suited for analyzing signals with non-stationary signal seismic data. QWT can analyze multiple signals simultaneously, the inherent parallelism of quantum computing-parallelism promises significant speedup in processing large datasets and complex signals.

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