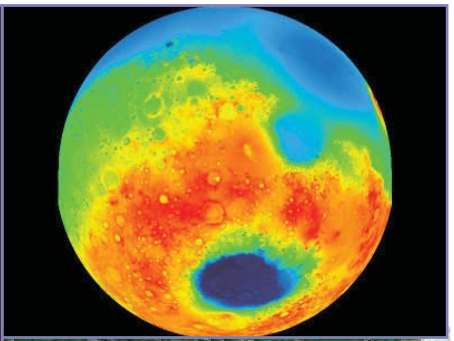
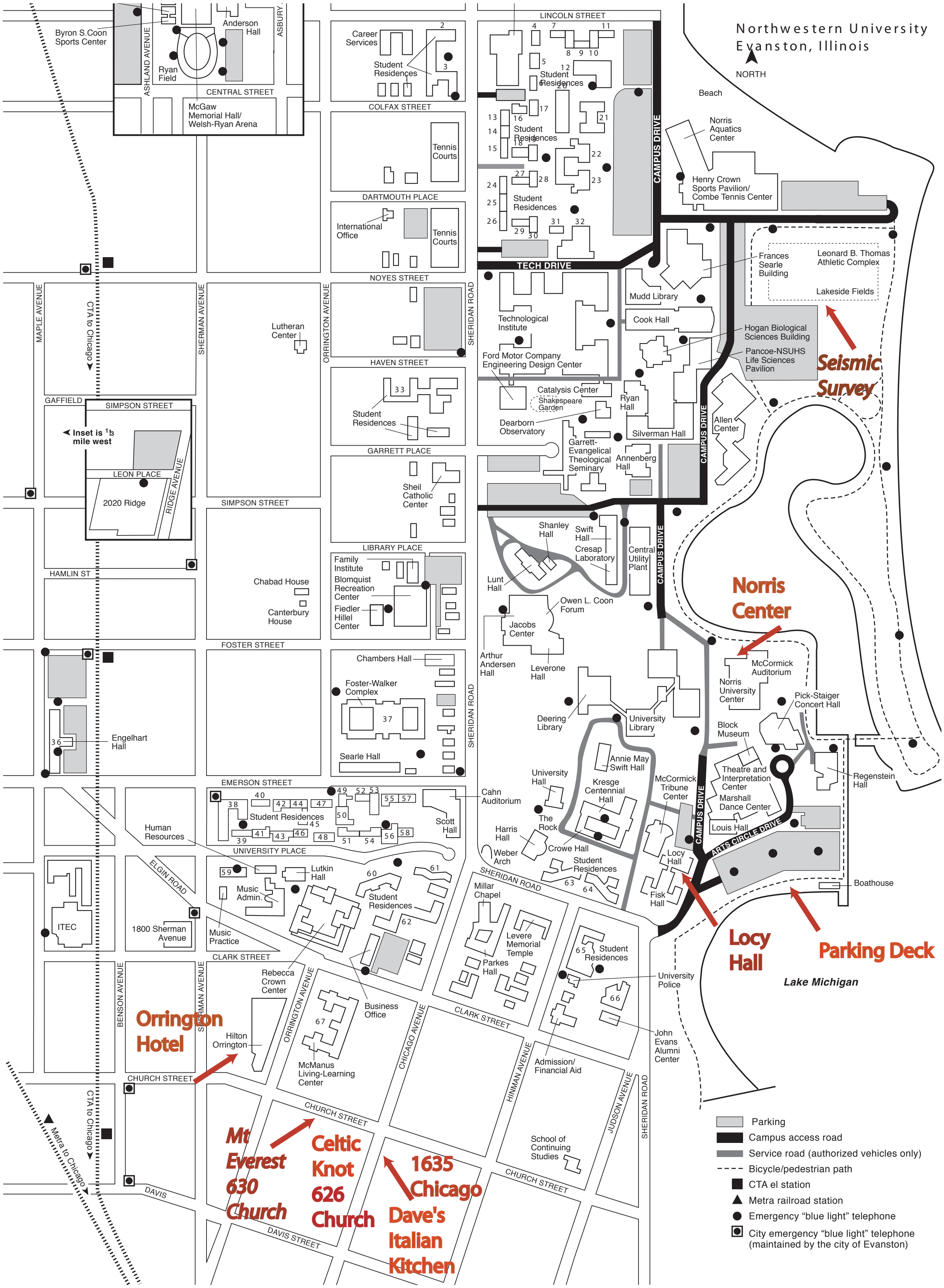
Workshop on Mathematics in the Geosciences

Northwestern University
October 3-6, 2011

Sponsored by the National
Science Foundation

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Evanston, Illinois
NORTH
Beach
Lake Michigan
Seismic Survey
Norris Center
Locy Hall
Parking Deck
Orrington Hotel
Mt Everest 630 Church
Celtic Knot 626 Church
1635 Chicago Dave's Italian Kitchen
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ASHLAND AVENUE
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RIDGE AVENUE
BENSON AVENUE
ELGIN ROAD
CHICAGO AVENUE
HINMAN AVENUE
JUDSON AVENUE
CTA to Chicago
Metra to Chicago
Byron S.Coon Sports Center
Anderson Hall
Ryan Field
McGaw Memorial Hall/ Welsh-Ryan Arena
Career Services
Student Residences
Tennis Courts
International Office
Lutheran Center
Inset is 1⁄3 mile west
2020 Ridge
Chabad House
Canterbury House
Engelhart Hall
Human Resources
ITEC
1800 Sherman Avenue
Music Admin.
Music Practice
Lutkin Hall
Rebecca Crown Center
Hilton Orrington
McManus Living-Learning Center
Business Office
Sheil Catholic Center
Family Institute
Blomquist Recreation Center
Fiedler Hillel Center
Chambers Hall
Foster-Walker Complex
Searle Hall
Scott Hall
Cahn Auditorium
Technological Institute
Ford Motor Company Engineering Design Center
Catalysis Center
Shakespeare Garden
Dearborn Observatory
Garrett-Evangelical Theological Seminary
Ryan Hall
Annenberg Hall
Silverman Hall
Mudd Library
Cook Hall
Frances Searle Building
Hogan Biological Sciences Building
Pancoe-NSUHS Life Sciences Pavilion
Allen Center
Leonard B. Thomas Athletic Complex
Lakeside Fields
Norris Aquatics Center
Henry Crown Sports Pavilion/ Combe Tennis Center
Shanley Hall
Swift Hall
Cresap Laboratory
Central Utility Plant
Lunt Hall
Owen L. Coon Forum
Jacobs Center
Arthur Andersen Hall
Leverone Hall
Deering Library
University Library
McCormick Auditorium
Norris University Center
Pick-Staiger Concert Hall
Block Museum
Regenstein Hall
Annie May Swift Hall
University Hall
Kresge Centennial Hall
McCormick Tribune Center
Theatre and Interpretation Center
Marshall Dance Center
Louis Hall
Harris Hall
The Rock
Crowe Hall
Weber Arch
Locy Hall
Fisk Hall
Boathouse
Millar Chapel
Levere Memorial Temple
Parkes Hall
University Police
John Evans Alumni Center
Admission/ Financial Aid
School of Continuing Studies
Parking
Campus access road
Service road (authorized vehicles only)
Bicycle/pedestrian path
CTA el station
Metra railroad station
Emergency “blue light” telephone
City emergency “blue light” telephone (maintained by the city of Evanston)

MOTIVATION

Over the past two decades the earth sciences have acquired a wealth of new and high quality data from new and greatly improved observing systems. Because this volume of data poses a major challenge for traditional analysis methods, only a fraction of their potential has yet been exploited. Similarly, results of many advanced numerical simulations of earth processes are only partially analyzed. Hence neither the data nor the modeling are being used to their full potential, leaving crucial questions unresolved. This situation arises in a wide range of areas including natural hazards, earthquake and volcano dynamics, earth structure and geodynamics, climate and weather, and planetary science.

Making progress in part calls for the application of mathematical methods not currently used, which requires a deeper and long-term dialogue and interaction between the mathematical and geoscience communities. This workshop, part of such ongoing efforts, seeks to help earth scientists and mathematicians identify and explore jointly crucial unsolved problems amenable to mathematical approaches not currently used. This seems feasible if both groups develop a long-term relationship giving each reasonable sophistication with the other's language, problems, and techniques. To set the stage, the workshop will illustrate some areas in which collaborative efforts are likely to yield significant advances.

These can broadly be viewed as including questions such as:

- Characterizing the earth system from observations: What data are needed? What analysis methods need to be improved?

- Understanding earth system dynamics: How well do models simulate the physical system? How well do the numerical implementations of these models perform?

- Predicting earth system evolution: how well can we predict processes and hazards?

Thank you for joining us in this effort.

The workshop organizing committee:

Seth Stein, Northwestern University, Chair (earth sciences)
David A. Yuen, University of Minnesota (earth sciences)
Ridgway Scott, University of Chicago (mathematics)
Maarten V. De Hoop, Purdue University (mathematics and earth sciences)
Jared Wunsch, Northwestern (mathematics)
Michael Stein, University of Chicago (statistics)
Peter Constantin, University of Chicago (mathematics)
Raymond Pierrehumbert, University of Chicago (earth sciences)
John Schotland, University of Michigan (mathematics and physics)
Mary Silber, Northwestern (applied mathematics)

AGENDA

Monday, Oct. 3

Norris University Center, Rm. 202: Northwestern Room
1999 Campus Drive, Evanston, IL 60208

Moderator: Dave Yuen, University of Minnesota

1:00 p.m.: **Frederik Simons,** Princeton University
Promoting sparsity and localization in geophysical inverse problems

1:40 p.m.: **Maarten de Hoop**, Purdue University
Imaging Earth's deep interior -- multi-scale techniques

2:40 p.m.: **John Schotland**, University of Michigan
Wave propagation in random media

3:20 p.m.: **Blake McShane**, Northwestern University
Statistics of millennial temperature reconstructions

4:20 p.m.: **Seth Stein**, Northwestern University
Predicting earthquakes and earthquake hazards: why so little success?

5:00 p.m.: **Grady Wright**, Boise State University
Radial basis functions for computational geosciences

6:30 p.m.: Dinner and cash bar, Celtic Knot, 626 Church St., Evanston, IL 60201

Tuesday, Oct. 4

Norris University Center, Rm. 205B: Louis South Room
1999 Campus Drive, Evanston, IL 60208

8:30 a.m. Continental Breakfast

Moderator: Omar Ghattas, University of Texas

9:00 a.m.: Introduction and goals of the meeting

9:30 a.m.: **Kerry Emanuel**, MIT
Using applied mathematics to assess hurricane risk

10 a.m.: Questions and comments

10:10 a.m.: Coffee Break

10:40 a.m.: **Clint Dawson**, University of Texas
Hurricane forecasting and hindcasting: Katrina and other hurricanes
11:10 a.m.: Questions and comments

11:20 a.m.: Moderator summary and group discussion

12 p.m.: Lunch

Tuesday, Oct. 4 **Afternoon Moderator: Don Estep, Colorado State University**

1:30 p.m.: **Dave Jackson**, UCLA
Earth science and mathematics: what gets lost in translation

2 p.m.: Questions and comments

2:10 p.m.: **Andrew Majda**, NYU
I*mproving complex models through stochastic parameterization and information theory*

2:40 p.m.: Questions and comments

2:50 p.m.: Coffee Break

3:20 p.m.: **Montserrat Fuentes**, North Carolina State University
Nonparametric Bayesian spatial modeling framework for hurricane surface wind fields data

3:50 p.m.: Questions and comments

4 p.m.: **Mian Liu**, University of Missouri
Multiscale faulting and fault interaction within continents: challenges for numerical modeling

4:30 p.m.: Questions and comments

4:40 p.m.: Moderator summary and group discussion

5:15 p.m.: Discussion: *Future opportunities for mathematics and statistics in the geosciences*
(Moderators: Michael Stein and Maarten de Hoop)

6:30 p.m.: Dinner and cash bar, Dave's Italian Kitchen, 1635 Chicago Ave., Evanston

Wednesday, Oct. 5

Norris University Center, Rm. 205B: Louis South Room
1999 Campus Drive, Evanston, IL 60208

8:30 a.m. Continental Breakfast

Moderator: Stephane Jaffard, Université Paris-Est Créteil Val de Marne

9:00 a.m.: **Richard Peltier**, University of Toronto
Ice-earth-ocean interactions: the mathematics and mechanics of global sea level history

9:30 a.m.: Questions and comments

9:40 a.m.: **Gregory Beylkin**, University of Colorado
On methods of seismic imaging

10:10 a.m.: Questions and comments

10:20 a.m.: Coffee Break

10:50 a.m.: **George Papanicolaou**, Stanford University
Large deviations and uncertainty quantification for mean field models and conservation laws

11:20 a.m.: Questions and comments

11:30 a.m.: Moderator summary and group discussion

12:15 p.m.: Lunch

Afternoon Moderator: Geoff Vallis, Princeton University

1:30 p.m. **Michael Ghil**, UCLA
Toward a mathematical theory of climate sensitivity:complexity, nonlinearity and stochasticity

2 p.m.: Questions and comments

2:10 p.m.: **Bruce Buffett**, University of California – Berkeley
Numerical models of planetary dynamos: challenges and opportunities

2:40 p.m.: Questions and comments

2:50 p.m.: Moderator summary and group discussion

3:10 p.m.: Coffee break & seismic imaging experiment on lakefill

4:15 p.m.: *Discussion of a possible institute or other collaborative structure*
(Moderators: Jared Wunsch and Dave Yuen)

6:30 p.m.: Dinner and cash bar, Mount Everest, 630 Church St., Evanston, IL 60201

Thursday, Oct. 6

Norris University Center, Rm. 205B: Louis South Room
1999 Campus Drive, Evanston, IL 60208

8:30 a.m. Continental Breakfast

<u>Moderator: Maarten de Hoop, Purdue University</u>

9:00 a.m.: **Jay Melosh**, Purdue University
Numerical simulations: How else can you experiment with colliding planets?

9:30 p.m.: Questions and comments

9:40 a.m.: Closing remarks

10:00 a.m.: White Paper planning

ABSTRACTS

Monday, Oct 3
1:00 p.m.

Frederik Simons, Princeton University
Dept. of Geosciences

Promoting sparsity and localization in geophysical inverse problems

Sometimes we don't have enough information, sometimes we have too much and need to choose; sometimes our data present a highly incomplete picture of the truth, and sometimes there is so much redundancy and overdeterminacy that we need to cull it down somehow. In this tutorial I will discuss several ways by which novel mathematical tools have shed much light on problems of this nature. I will talk about the problem of reconstructing global sea level from sparse, uncertain, scattered indicators of local sea level (the solution derived from Monte-Carlo techniques in a Bayesian framework). I will introduce the design of flexible parameterizations to render inverse problems in geodesy and geomagnetics sparse (a solution given by linear combinations of spherical harmonics called Slepian functions). Lastly, I will discuss the nascence of sparsity-promoting algorithms in global seismology (under a new design that ports fastCartesian wavelet transforms onto the sphere and combines least-squares data fitting with the minimization of l-1 norms). For each of these subtopics I will briefly highlight the key mathematical innovations and discuss the often widespread implications of the results.

2:40 p.m.

John Schotland, University of Michigan, Department of Mathematics

Waves and imaging in random media

I will review wave propagation in inhomogeneous media in various asymptotic regimes including: (i) geometrical optics of high-frequency waves (ii) homogenization of low-frequency waves in random media (iii) radiative transport and diffusion theory for high-frequency waves in low-frequency random media. Applications to inverse problems in imaging will be considered.

3:20 p.m.

Blake McShane, Northwestern University
Kellogg School of Management, Department of Marketing

The Reliability of Millennial Multi-proxy Temperature Reconstructions

Predicting historic temperatures based on tree rings, ice cores, and other natural proxies is a difficult endeavor. The relationship between proxies and temperature is weak and the number of proxies is far larger than the number of target data points. Furthermore, the data contain complex spatial and temporal dependence structures which are not easily captured with simple models.

In this paper, we assess the reliability of such reconstructions, focusing on obtaining properly-calibrated standard errors for the reconstruction. When our reconstruction is compared to those from the climate science literature, we find the reconstructions are similar but ours has much wider standard errors, reflecting the weak signal and large uncertainty encountered in this setting.
We evaluate the calibration of our uncertainty intervals with respect to simulated data from GCMs, a mainstay technique in the climate science literature, and find that our wide intervals are calibrated. We then subject the simulated data to a battery of tests in order to assess its similarity with real temperature and proxy data.

4:20 p.m. **Seth Stein**, Northwestern University
Department of Earth and Planetary Sciences

Predicting earthquakes and earthquake hazards: why so little success?

Charles Richter's observation that "only fools and charlatans predict earthquakes," reflects that fact that despite more than 100 years of effort, seismologists remain unable to do so. Meaningful prediction involves specifying the location, time, and size of an earthquake before it occurs, to greater precision than expected purely by chance from the known statistics of earthquakes in an area. To date, highly touted and expensive programs in the U.S. and elsewhere have failed. Two approaches have been used. In one, the known rate of motion accumulating across a fault and the amount of slip in past earthquakes is used to infer when the next earthquake will occur. Unfortunately, the intervals between earthquakes are so variable that the predictions are accurate to no better than a hundred years. The second approach is to identify observable changes in the earth that precede earthquakes. Various precursors have been suggested, and may have been real in certain cases, but none have proved to be a general feature preceding all earthquakes, or to stand out convincingly from the normal variability of the earth's behavior. Thus it is unclear whether earthquake prediction is possible. In one hypothesis, all earthquakes start off as tiny earthquakes, which happen frequently, but only a few cascade via random failure into large earthquakes. If there is nothing special about those tiny earthquakes that happen to grow into large ones, the interval between large earthquakes is highly variable and no observable precursors should precede them. This hypothesis draws on ideas from nonlinear dynamics or chaos theory, in which small perturbations can grow to have unpredictable large consequences. Thus earthquakes would be analogous to the meteorological idea in which the flap of a butterfly's wings in Brazil might set off a tornado in Texas, or in general that minuscule disturbances do not affect the overall frequency of storms but can modify when they occur. The frustrations of this search have led to the observation that "it is difficult to predict earthquakes, especially before they happen."

As a result, seismologists have largely abandoned efforts to predict earthquakes on time scales less than a few years, and turned to trying to make longer-term forecasts. The challenge is illustrated by the 2011 Tohoku earthquake. This was another striking example - after the 2008 Wenchuan and 2010 Haiti earthquakes - of highly destructive earthquakes that occurred in areas predicted by earthquake hazard maps to have significantly lower hazard than nearby supposedly high-risk areas which have been essentially quiescent. Given the limited seismic record available and limited understanding of earthquake mechanics, hazard maps have to depend heavily on poorly constrained parameters and the mapmakers' preconceptions. However, because these preconceptions are often incorrect, hazard maps often fail.

5 p.m. **Grady B. Wright,** Boise State University, Department of Mathematics

Radial Basis Functions for Computational Geosciences

Current community models in the geosciences employ a variety of numerical methods, including finite-difference, finite-volume, finite element, spectral element, and spectral/pseudospectral methods. All have specialized strengths but also serious weaknesses. The first three methods are generally considered low-order and can involve high algorithmic complexity (as in triangular elements on unstructured meshes). Global spectral/pseudospectral methods do not practically allow for local mesh refinement and often involve cumbersome algebra.

Radial basis functions have the advantage of being spectrally accurate for arbitrary node layouts in multi-dimensions with exceptional algorithmic simplicity, and naturally permit local node refinement. We discuss three recent and non-trivial applications of radial basis functions to geosciences, including vortex roll-ups modeling idealized cyclogenesis, unsteady nonlinear flows posed by the shallow water equations, and 3D mantle convection in the earth's interior.

Tuesday, Oct. 4 **Kerry Emanuel**, MIT
9:30 a.m. Department of Earth, Atmospheric, and Planetary Sciences

Using applied mathematics to assess hurricane risk

More than half of all the damage done by hurricanes in the United States since 1870, normalized for changing population, wealth and currency value, was done by only 8 storms. This illustrates the raw fact that history is too short to use by itself to assess hurricane risk. In this lecture, I will discuss how physics and applied mathematics can be used to create large synthetic hurricane event sets driven by large-scale climate data as represented by re-analysis data sets or global climate models. These hurricane event sets are also coupled to storm surge models to create surge events as well. The creation of these synthetic hurricane and surge event sets is entirely independent of historical hurricane data, but such data is used to rigorously evaluate the quality of the synthetic event sets. These sets are large enough to evaluate storms representing return periods of 1,000 years or so, and extreme value theory can then be used to estimate even rarer events. Besides being useful for evaluating hurricane and surge risk in familiar hurricane-prone regions, the method can be used to focus on "Black Swan" events: hurricanes that are not present in any historical data set but which the laws of physics show are possible; these include such events as powerful hurricanes in the Persian Gulf. When applied to global climate models run under increasing greenhouse gas emission scenarios, the method predicts how hurricane activity around the world might respond to anthropogenic climate change.

Tuesday, Oct. 4
10:40 a.m.

Clint Dawson, University of Texas
Department of Aerospace Engineering and Engineering Mechanics

Hurricane forecasting and hindcasting: Katrina and other hurricanes

Natural (and man-made) disasters have wreaked havoc on the earth, and seem to be increasing in magnitude and scope. Mathematical and computational modeling of these events has improved dramatically in recent years due to better understanding of the physics, improved numerics and vast increases in computational power. Much of this work has been funded either wholly or in part by the National Science Foundation. Yet many open questions still remain. In this talk, we will focus primarily on extreme events in the coastal ocean, namely hurricanes and oil spills, however the general technology that we will discuss is common to other geoscience problems.

We will describe the development of the Advanced Circulation (ADCIRC) modeling system, which is a joint project among several universities, and discuss how this modeling system has been applied to hurricane storm surge modeling for recent hurricanes in the Gulf of Mexico, and to the Deepwater Horizon Oil Spill.

1:30 p.m.

David D. Jackson, UCLA, Department of Earth and Space Sciences

Earth Science and Mathematics: what gets lost in translation

Earth scientists, mathematicians, and scientists make a great team for solving important problems. However, we each speak different languages. We resemble nerve cells separated by synapses through which information is passed imperfectly. Crucial information may be lost in translation, or important assumptions unstated or obscured. Garbled communications are especially problematical in earth sciences because many problems do not allow controlled experiments nor follow simple, known physical laws. We have just one earth, mostly inaccessible. It's old, and we are young. I'll discuss examples, mostly from seismology, in which great mathematical and statistical work gave the right answers to the wrong problems. I'll offer excuses. I'll also suggest questions to ask before beginning a collaboration. Here is one interesting and important question: does the probability of a large earthquake increase or decreases in response to a previous big one? The classical elastic rebound theory, used in calculating insurance rates, says it must decrease, and many observations apparently agree. However, there are many papers showing the opposite. How can such a fundamental question be debated after a century of very good earthquake observations? Hint: it's in the synapses.

Tuesday, Oct. 4
2:10 p.m.

Andrew J. Majda, NYU
Department of Mathematics and Climate, Atmosphere, Ocean Science

Improving Complex Models through Stochastic Parameterization and Information Theory

In many situations in contemporary science and engineering involving complex systems, the analysis and prediction of phenomena often occur through complex dynamical equations that have significant model errors compared with the true signal in nature. Clearly, it is important to improve the perfect model's capabilities to recover crucial features of the natural system and also to accurately model the sensitivities in the natural system to change in external of internal parameters. These efforts are hampered by the fact that the actual dynamics of the natural system are unknown. Important examples with major societal impact involve the Earth's climate and climate change where climate sensitivities are studied through a suite of imperfect comprehensive (AOS) computer models; other examples occur in neural science, material science, and environmental engineering. This lecture surveys three different uses of stochastic parameterization and/or information theory developed by the speaker and collaborators to improve model fidelity and predictive skill for complex systems with model error: 1) Improving tropical convective parameterization through the stochastic multi-cloud model; 2) Improving model fidelity and long-range forecasting skill through empirical information theory and stochastic parameterization; 3) Judicious model errors in filtering/data assimilation of turbulent dynamical systems through suitable stochastic parameterization extended Kalman filters (SPEKF) in order to avoid curse dimension and curse of ensemble size. All papers available at Majda NYU faculty website: http://www.math.nyu.edu/faculty/majda/publicationrevised.html

3:20 p.m.

Montserrat Fuentes, North Carolina State University, Department of Statistics

A nonparametric Bayesian spatial modeling framework for hurricane surface wind fields

Storm surge is the onshore rush of sea water caused by the high winds and to a lesser extent the low pressure associated with a hurricane.
Storm surge can compound the effects of inland flooding caused by rainfall, leading to loss of property and loss of life for residents of coastal areas. Numerical ocean models are essential for creating nowcast estimates as well as forecasts for coastal areas that are likely to be impacted by the storm surge. These models are driven primarily by the surface wind forcings. Currently, gridded wind fields used to spin up and force ocean models are specified by deterministic formulas that provide an idealized form of the wind profile based on the central pressure and location of the storm center. While these equations incorporate important physical knowledge about the structure of hurricane surface wind fields they cannot always capture the asymmetric and dynamic nature of a hurricane. A new Bayesian multivariate spatial statistical modeling framework is introduced to improve the estimation of the wind field inputs. A nonparametric spatial model is developed and applied to explain the spatial variability in the wind vectors (u and v as well as the

cross-dependency between these two components. This Bayesian framework allows for estimation of the parameters of the multivariate spatial model and the physically based wind model while accounting for potential additive and multiplicative bias in the observed wind data from buoys, ships, aircraft and satellite data. We find that this multivariate spatial model consistently improves parameter estimation and prediction for surface wind data for case studies of Hurricane Charley (2004) and Ivan (2004) when compared to the original physical model.

*In collaboration with Kristen Foley (Stat., NCSU) and the Coastal
Fluid Dynamics Laboratory headed by Dr. Lian Xie at North Carolina State University.

Tuesday, Oct. 4
4 p.m.

Mian Liu, University of Missouri, Department of Geological Sciences

Multiscale faulting and fault interaction within continents: Challenges for numerical modeling

Large faults play a key role in geodynamics and earthquakes. Whereas the Earth's deep interior deforms by slow plastic creeping, the earth's upper crust deforms mainly by repeated rupturing on faults, resulting in earthquakes. Numerical studies of faulting processes have been challenging, because computational models of crustal deformation are usually based on continuum mechanics. Further challenges arise from the multi-timescale nature of faulting and the associated multiphysics. Multi-timescale faulting is difficult to simulate in a single numerical model, and observational constraints often reflect different timescales and involve different sub-disciplines in geology and geophysics. Consequently, fault studies are currently split into two categories: short-term faulting focused on fault rupture processes and earthquake cycles (seconds to hundreds of years), and long-term faulting related to crustal evolution in geological timescales (millions of years). Researchers of faults are accordingly divided into two separate communities with limited interaction with each other, although it is well understood that faulting at different timescales are intrinsically linked. Another challenge is the mechanical coupling and interaction between fault zones. This is especially important in mid-continents where tectonic loading is accommodated by a complex system of interacting faults. Such fault interaction controls the spatiotemporal occurrence of large earthquakes in continental interiors, but its mechanics remains poorly understood. In this talk I will highlight some of the major challenges that face numerical modeling of faults and review recent progresses. I will show some preliminary results of linking short-term rupture processes with long-term fault evolution, and show how numerical simulations of fault interaction may help us to better understand the spatiotemporal patterns of large earthquakes in mid-continents.

Wednesday, Oct. 5
9 a.m.

Richard Peltier, University of Toronto
Department of Physics

Ice-Earth-Ocean Interactions:
The Mathematics and Mechanics of Global Sea Level History

Modern space-geodetic measurements of the time dependence of the gravitational field, of the three dimensional motions of Earth's crust, and of "absolute" sea level change are enabling new insights into the global climate system. A detailed gravitationally self-consistent viscoelastic field theory has been developed to enable optimal use to be made of the measurements being provided by these space-based platforms. The centre piece of this theory is an integral "Sea: Level Equation", an equation of Fredholm type the solution of which predicts how the water produced by the melting of land ice must be distributed over the global ocean basins in order to ensure that on long timescales the surface of the oceans remains a gravitational equipotential. Using this theoretical structure, together with appropriate Quaternary geological constraints, it has proven possible to disentangle ancient ice-age influence from that due to modern greenhouse gas induced global warming. A biproduct is new knowledge of the physical properties of Earth's deep interior and a heightened understanding of the importance of the solid Earth in surface climate processes.

9:40 a.m.

Gregory Beylkin, University of Colorado, Department of Applied Mathematics

On Methods of Seismic Imaging

By emphasizing an ill-posed problem of wave field extrapolation from space-like surfaces, we consider advantages, disadvantages and limitations of several methods of seismic imaging. We then turn to a mathematical formulation of wave field extrapolation that allows us to suppress only the evanescent waves responsible for ill-posedness of the problem. Finally, we briefly discuss a possible approach to the inverse problem by combining accurate wave field extrapolation with velocity analysis.

1:30 p.m.

Michael Ghil, UCLA, Department of Atmospheric and Oceanic Sciences

Toward a Mathematical Theory of Climate Sensitivity: Complexity, Nonlinearity and Stochasticity

The first attempts at estimating climate sensitivity assumed a climate system in equilibrium. More recently, the IPCC focused on estimates of climate evolution over the coming century; these estimates still differ by several degrees.

We investigate here the mathematical causes of climate sensitivity, by applying random dynamical systems theory.

This theory allows one to study the random attractors of nonlinear, stochastically perturbed systems, as well as the time-dependent invariant measures supported by these attractors.

Results are presented for several simple climate models, from the classical Lorenz (1963) model to El Nino-Southern Oscillation models. Their attractors support random Sinai-Ruelle-Bowen measures with nice physical properties. The response of these measures to changes in poorly known model parameters is studied and implications for climate predictability are discussed.

Wednesday, Oct. 5
2:10 p.m.

Bruce Buffett, University of California, Berkeley
Department of Earth & Planetary Science

Numerical Models of Planetary Dynamos: Challenges and Opportunities

Planetary magnetic fields are sustained by fluid motion in an electrically conducting region of the interior. Our understanding of how this process works in detail is still crude, but rapid advances have been made in the past ten years with the advent numerical dynamo models. These models have been remarkably successful in producing self-sustaining magnetic fields with convectively driven flows. Many of these calculations predict realistic dipole fields that spontaneously reverse. Even the non-dipole part of the predicted field exhibits similarities with the field observed on Earth. However, the success of these models has been surprising because the calculations are based on artificially high fluid viscosities. Such high viscosities have the intended numerical effect of suppressing turbulence, but the unintended consequence of altering fundamental aspects of the dynamics. A major challenge for making improvements lies in dealing with the problem of turbulence. This small-scale flow interacts with both the temperature and magnetic fields to produce new and interesting effects that have no counterpart in conventional turbulence. In addition, the turbulent fluxes are liable to be strongly anisotropic due to the influences of rotation and a large-scale magnetic field. Ongoing efforts to develop better treatments of turbulence in the dynamo problem hold the promise profound new insights into the origin of planetary magnetic field.

Thursday, Oct. 6
9:00 a.m.

H. J. Melosh, Purdue University, Department of Earth and Atmospheric Sciences

"Experimenting" with Planetary Collisions

The Earth, Moon and other planets were born in violence. Models of planetary accretion have evolved from gentle accumulation of tiny "planetesimals" to the realization that the final stages of planetary growth were accomplished by high-speed collisions between bodies of comparable scale. Research on planetary origins thus requires knowledge of what happens when planets smash together at speeds comparable to their orbital velocities. But the touchstone of scientific knowledge is experiment. How can we make progress in this subject without actually smashing up a few planets? The answer to this conundrum, as with many other deep questions in Earth science, is computer simulation solidly grounded in small-scale experiments. Numerical simulations allow us to leap the scale barrier that separates tiny samples in the laboratory from objects of planetary dimensions. But they only work if the physics of the processes we are extrapolating is correct and complete. The output of computer models must thus agree with both laboratory observations and with full-scale observational data. This confrontation tells us whether we have left out some essential process that might have been lost in the gap between scales. Such comparison is what separates scientific research using models from mere video games. Research on planets thus requires a constant dialog between laboratory scale experiments and planetary observations. The language of this dialog is mathematical simulation.