National Center for Atmospheric Research
Institute for Mathematics Applied to Geosciences
Geophysical Statistics Project

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September 26, 2006

TO: IMAGe Advisory Board
RE: Written materials for visit.

Thank you for agreeing to serve on the Institute for Mathematics Applied to the Geosciences (IMAGe) advisory board. To give you some background for the presentations and discussions during your visit, we are sending some written materials ahead of time. We have tried to limit the amount of potential reading, and so there are several small sections on different aspects of the institute. This memo gives a short introduction to IMAGe, taken from last year's annual report and then gives a list of the other materials along with this letter.

When people ask "What is the purpose of the new math institute at NCAR?" our short reply is "It's about tools and models." An acknowledged hallmark of mathematical science is that the same mathematical and statistical methods and models can be used to solve problems in very different contexts. NCAR has a long history of supporting innovative models and developing new algorithms and methods. Moreover, NCAR's focus on grand challenges facing the geosciences also provides a rich source of new applications for mathematics. IMAGe takes advantange of this confluence of tools and problems and accelerates the transfer of new mathematical techiniques to geoscience problems. It also serves as a portal for the mathematical sciences community to NCAR. IMAGe was started in the Fall of 2004 by combining three established groups at NCAR involving statistics, turbulence, and data assimilation.

Each of these groups has ties to many parts of NCAR and the university community, and these are expected to grow. One common thread among the IMAGe sections is the development of open source software to transfer mathematical tools and models to a wide group of scientists. Perhaps the single most visible feature of IMAGe is a year-long program, the Theme-of-the-Year (TOY) that tackles particular problems in the geosciences or in a mathematical field through a series of focused workshops and a visitor program. Included with this note are:

- Charge to the board
- NCAR and IMAGe organizational charts.
- Description of the past Theme-of-the-Year and the plans for the current theme.
- Summary of a recent IMAGe retreat.
- Descriptions of the IMAGe sections.

- IMAGe Charter which was used a planning document for creating this part of NCAR
- A brochure that is a shortened version of the NCAR strategic plan.

To save on length we have omitted recent advisory reports but these will be posted on the web page. There will also be copies available during your visit.

Thanks again for helping us determine the future for IMAGe!

Sincerely Yours,

Douglas W. Nychka
Director and Senior Scientist

Charge to IMAGe Advisory Board.
Board visit 3-4 October, 2006

The IMAGe board is a external advisory group that will report to Doug Nychka, the IMAGe Director and Al Kellie, the Director of the Computational and Information Systems Laboratory. The board will provide a valuable external perspective on IMAGe and in general is encouraged to

a) suggest ways that IMAGe can interact with the broader mathematical sciences communities.

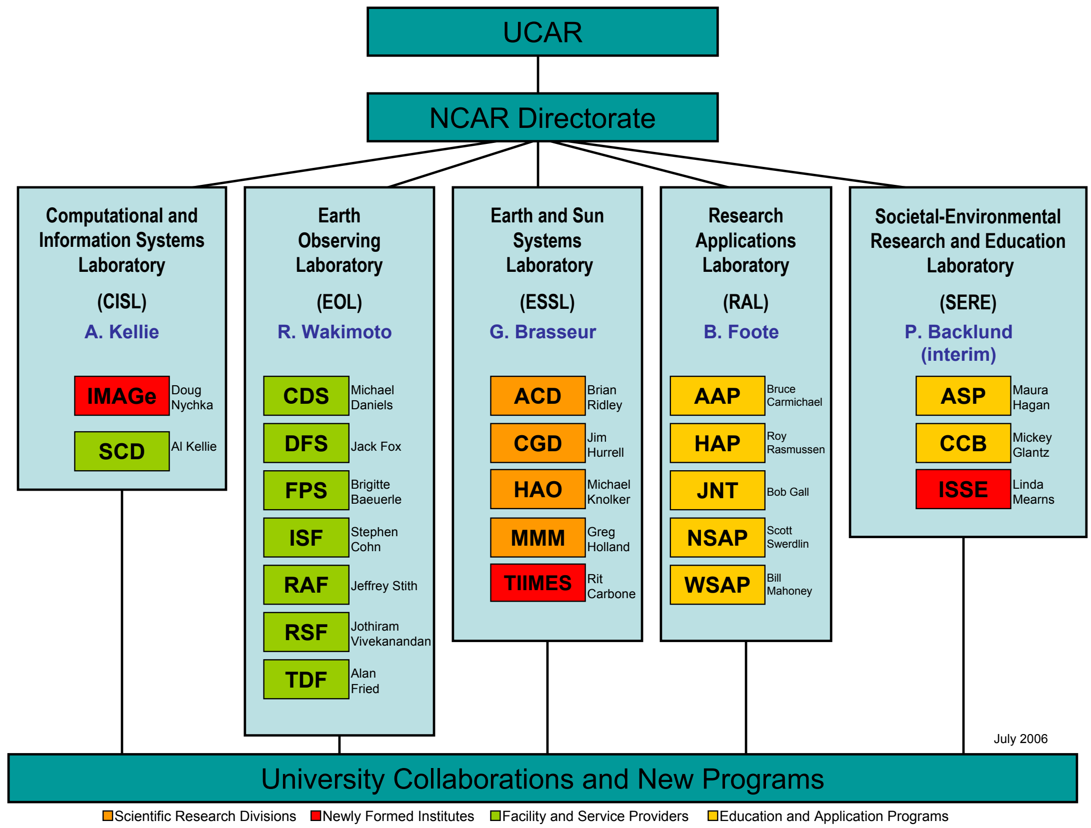
b) identify areas or problems in the geosciences that have the potential to benefit from mathematical and statistical methods and where IMAGe can facilitate collaboration.

The following specific areas have been identified where the board's advice is needed.

1. What are the strengths of IMAGe?
2. What are principles to balance IMAGe activities among outreach, theme-of-the-year, fundemental research and service to other NCAR science programs?
3. What are good topics in mathematics that support the NCAR science plan? What topics are suitable for a theme-of-the year and what areas are better pursued as collaborative research?
4. How can IMAGe enhance its credibility among the mathematics community?
5. What should be the priorities for IMAGe growth?

The products from the board visit are a short oral report at the end of the visit to the IMAGe staff and a written report sent within a few weeks after the visit. The board should not feel limited by the specific topics listed above and if they are encouraged to address other areas that are relevant to the mission and goals of IMAGe. Panel can also provide informal comments to Doug Nychka that they feel need not be included in the report.

Organizational chart for NCAR



Organizational chart for IMAGe (Summer 2006)

IMPORTANT NOTE: Given below is an organizational chart accurate to August 2006. Some of the post doctoral scientists are now placed in other positions outside NCAR. Also, several new applied mathematicians from the CISL numerics group have been added to IMAGe.

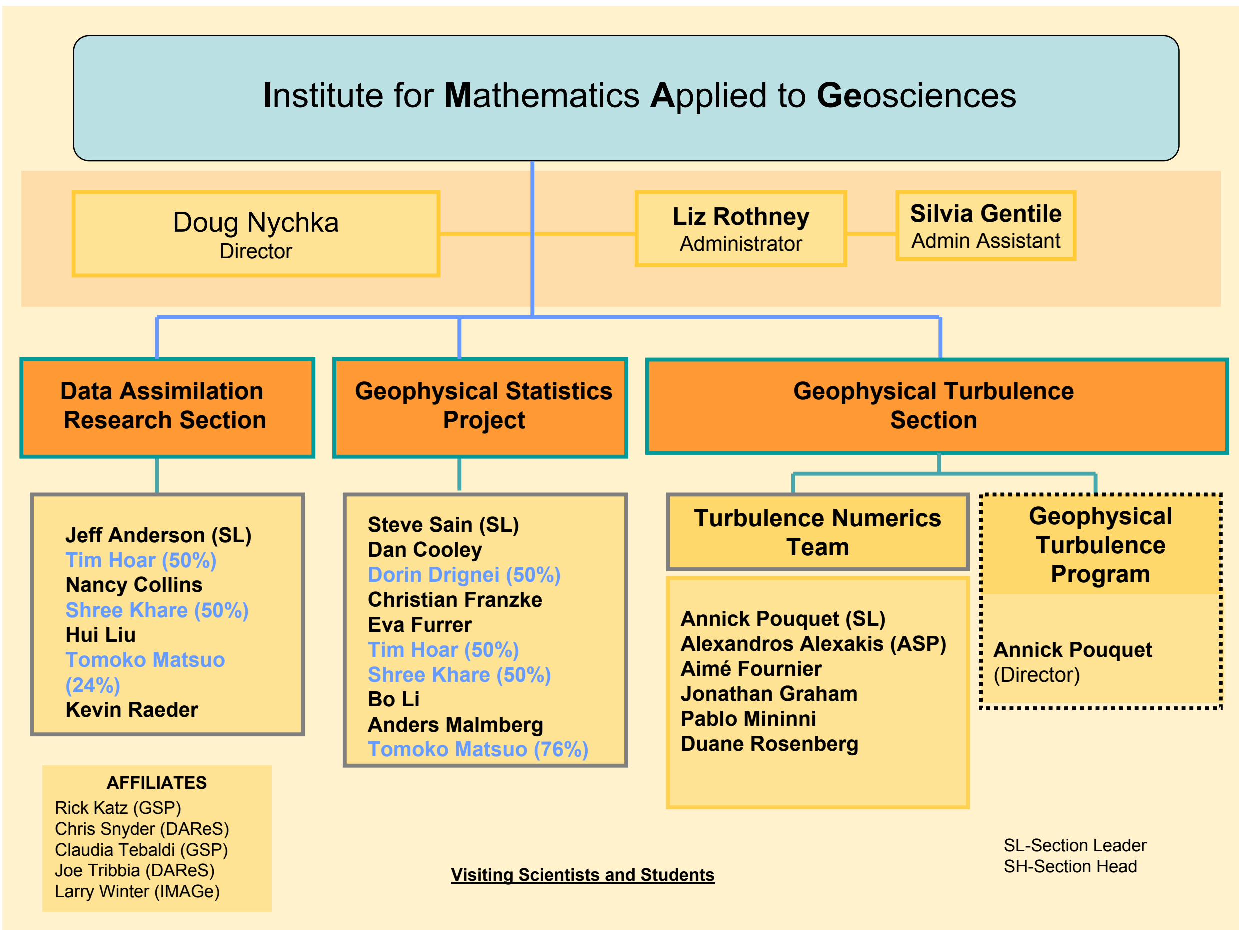


IMAGe Theme-of-the-Year

A central activity in IMAGe is the Theme-of-the-Year (TOY), an annual focus on a particular area of the geosciences or applied mathematics that has an impact on NCAR's scientific mission.

IMAGe TOY FY2006: Emerging Mathematical Strategies for Multi-Scale and Stochastic Modeling of the Atmosphere and Climate

In FY2006[1], the first full TOY sponsored by IMAGe consisted of four workshops held at NCAR in a series that blended tutorial lectures with presentations of recent research. A grand challenge in modeling the Earth system is understanding how geophysical processes interact across many different scales. Many important processes occur at scales that are too fine for the broad-scale grids of climate models to resolve. However, subgrid processes such as convection and cloud formation have significant impacts on the circulation of the atmosphere. Resolving the interactions between scales will lead to improved understanding of climate and improved weather forecasting. Besides supporting the Earth system modeling component of NCAR's science this acitivity was also intended to build intellectual bridges between two distinct communities. This TOY was co-directed by Andrew Majda, Morse Professor of Arts and Sciences, Courant Institute of Mathematical Sciences, NYU, and Joseph Tribbia, Senior Scientist, Cimate and Global Dynamics Division, NCAR. Securing an external, eminent faculty member in applied mathematics was an important component in this TOY.

The workshop series was spread over the academic calendar with the topics:

I Multi-scale Interactions in the Tropics to Midlatitudes: Mathematical Theory, Observations and Numerical Models

II Multi-Scale Interactions in a GCM Grid Box: Mathematical Theory, Numerics, and Parameterization

III Stochastic and Statistical Parameterization of Unresolved Features in the Atmosphere and Upper Ocean

IV Multi-Scale Processes for Low Frequency Variability, Climate, and Climate Change Response

[1]FY= Fiscal Year 1-Oct- 30-Sep

The FY2006 TOY involved over 100 different researchers and students. Consistent with the TOY goals, the participants had a broad background, from graduate students to faculty and from atmospheric scientists to applied mathematicians and statisticians. Each five-day workshop included three days of tutorials and two days of technical presentations, with plenty of time for discussion and interaction. The workshops were successful in establishing a two-way communication between the university mathematics community and the scientific community at NCAR, focusing on specific areas of research that will benefit from intense collaboration. Another benefit was to expose Ph.D. students, post docs, and junior faculty in applied mathematics and statistics to the scientific issues and principles in modeling the atmosphere. Based on this activity, IMAGe was successful in recruiting a young researcher at the Courant Institute, NYU, Christian Franzke, to complete a year of his postdoctoral fellowship at NCAR.

IMAGe TOY FY2007: Statistics for Numerical Models

Numerical models are vital to simulate geophysical, chemical and ecological processes and to understand the relationship among components in the Earth system. As models have become larger and more complex, their construction, validation and analysis are no longer amenable to simple approaches and statistical summaries. Statistical science in the past 20 years has advanced to handle the interpretation of complicated multivariate, spatial and temporal data sets and it is well suited to tackle the massive outputs from numerical experiments that are now the norm in the geosciences. This theme is undertaken with the goal of matching cutting edge statistical methods to the needs of geophysical model development and to make statisticial scientists aware of the particular scientific issues and research in the geophysical modeling community.

The TOY is pursued in partnership with the Statistical and Applied Mathematical Sciences Institute (SAMSI), located in Research Triangle Park, NC and the Mathematical Sciences Research Instititute (MSRI), Berkeley, CA. Both SAMSI and MSRI are NSF mathematics institutes with an international stature in the mathematics community. The main acitivites will be a series of three workshops and a summer school, all held at NCAR, that dovetail with SAMSI activities on its programs on random matrices and on computer models and with the MSRI summer school program. IMAGe participation will be valuable in representing a suite of geophysical models within the SAMSI program. Derek Bingham, a faculty member at Simon Fraser University, British Columbia, CA, and an expert in the design of computer model experiments will serve as TOY co-director and will visit NCAR through the year with an extended stay in May. Montse Fuentes, a faculty member at North Carolina State University and a SAMSI Fellow, will be the main liason with the SAMSI programs.

The main planned activities are:

I Some outstanding challenges in geophysical modeling and a catalog of statistical tools. 13-14 November 2006.

II Application of random matrices theory and methods. 12-15 Feb 2007

III Statistical methods for complex numerical models in the goesciences. 21-24 MAY 2007

IV Tracking carbon sources: A summer school on models and methods. JUN 2007

The first workshop is intended as a scoping and brainstorming meeting where four NCAR modeling groups will interact with a large group of statisticians interested in the design and analysis of computer experiments. The NCAR geophysical models/groups[2] are

1) Upper atmosphere model (TIEGCM) (HAO: Maura Hagan, Ray Roble, Art Richmond)
2) Single column boundary layer model (RAL/MMM: Josh Hacker)
3) Two dimensional turbulence in Navier Stokes flows (IMAGe: Annick Pouquet)
4) Land component of the NCAR climate model (CGD: Gordon Bonin; U Kansas: Johannes Feddema)

The intent is that concrete problems will be identified that will help structure the statistical working group activity at SAMSI. For each modeling group a statistical researcher will serve as a liason to guide collaboration among the modeling group and the statistical working groups.

Workshops II and III will be more traditional conferences but will include a blend of tutorial and research talks. In each workshop, ample time will be reserved for discussion and also for presentations on progress on the specific modeling project initiated in the first workshop.

The summer school will be in partnership with and focuses on the mathematical tools such as inverse methods and data assimilation to estimate the surface sources of carbon dioxides. The determination of sources of carbon in the Earth's atmosphere is an important area of biogeochemistry and crucial in quantifying human emissions of greenhouse gases. The summer school will build off of the successful model that was held JUL 2006 at MSRI and will feature morning tutorial lectures with reinforcing

[2] HAO= High Altitude Observatory, RAL= Research Applications Laboratory, MMM= Meso- and microscale meteorology, CGD= Climate and Global Dynamics

afternoon computational exercises and projects. The Data Assimilation Research Testbed (DART) will be used as a software framework for the mathematical and statistical methods.

Besides these large and formal gatherings the TOY will also support visits of students and faculty between SAMSI and NCAR and also the coordination of working groups at SAMSI with parallel groups in IMAGe. SAMSI and IMAGe will also share support of a postdoc in statistics, Cari Kaufman.

Report on IMAGe retreat August 28, 2006

The Institute of Mathematics Applied to Geosciences (IMAGe) held a retreat for NCAR scientists and staff on August 28, 2006 at the Community House in Chautuaqua, Boulder, CO. The retreat had several goals:

- Bring forward ideas for Theme-of-the-Year topics and process, and for the expansion of IMAGe to better represent applied mathematics.
- Provide a forum for IMAGe and NCAR researchers to outline goals for IMAGe and also to voice concerns.
- Allow the participants to become better acquainted with all the groups in the Institute.

There were approximately 50 participants comprising the staff in IMAGe, members of the CISL/SCD computational sciences section and a wide sampling of NCAR staff that have connections to applied mathematics and/or the science programs pursued by IMAGe. The timing of this retreat was chosen to provide an internal, NCAR perspective on IMAGe that would be useful for the IMAGe advisory board visit on October 3-4, 2006.

An overview of the retreat discussion

IMAGe identity The participants raised issues of the identity of IMAGe in several modes. Emerging from the reports was the description of IMAGe as engaged in *transformative mathematics* —mathematical methods and models that can advance or shape a scientific field in new ways. The introduction of spectral methods into early generation climate models is a historical example of how mathematical ideas could transform a scientific field, in that case making the numerical approximations of the numerical models substantially more accurate. There was wide recognition, however, that while its multi-disciplinarity was a great strength, IMAGe lacked sufficient specific representation in applied mathematics. A strong sentiment was that the mathematical scientists in other groups in CISL should be transferred and made part of IMAGe. Also, IMAGe should build on its ability to engage in high-performance computing. Finally, although IMAGe staff identified strongly with their home sections, identifying as a member of the Institute as a whole was not widespread. It was felt IMAGe needs to acquire new Scientist-I positions, but organizationally would benefit from consolidation and interlinking of its groups before seeking to expand.

IMAGe collaboration and outreach The retreat generated several topics for the Theme-of-the-Year that resonate with the NCAR science plan. These are:

- Stochastic dynamics and modeling
- Capability computing
- Seamless prediction of geophysical processes across scales.
- Mathematics of closure-scheme formulation and evaluation
- Nested regional-climate modeling
- Astrophysical and planetary dynamos
- Transitions between 2D and 3D turbulence
- Solution of nonlinear partial differential equations

In general the participants felt that mathematics has an important role in supporting the NCAR science program. There was some diversity of opinion, however, in how to pursue effective collaborations across the institution and the balance of IMAGe efforts among research, outreach and thematic activities and service. Besides developing and becoming part of a network of mathematics groups with a geoscience focus, the participants also suggested the value of consolidating and reinforcing activities among the Front Range university mathematics departments.

Feedback to NCAR leadership The retreat was very successful in bringing together a diverse group of NCAR staff and much of the discussion also served to make the participants aware of the scope of IMAGe activity. The retreat was attended by the NCAR Deputy Director (Larry Winter), Director of CISL (Al Kellie), Deputy Director of ESSL (Annick Pouquet) and SCD Deputy Director (Rich Loft) and was very helpful in informing the NCAR leadership how IMAGe is viewed by its members and other NCAR staff.

Data Assimilation Research Section

The Data Assimilation Research Section (DAReS)[3] of IMAGe performs fundamental research on ensemble data assimilation methodologies for application across a wide range of geophysical problems. Data assimilation refers to the methods for combining observations with a numerical model to provide better estimates of the state of a physical system. DAReS develops and maintains the Data Assimilation Research Testbed (DART), a software facility for doing ensemble data assimilation. Using DART as a common framework, DAReS also provides support to a growing community of NCAR, university, and government laboratory collaborators who are interested in applying ensemble data assimilation methods. In addition, DAReS pursues basic research on algorithms for data assimilation with a view to finding common solutions that have relevance for many different physical systems and different types of observations.

Fundamental data assimilation research focuses on advancing ensemble methods to make them more powerful and generic, capable of being effectively applied to many problems as nearly 'black-box' algorithms. Updating the system state with observations can be viewed as a Bayesian statistics problem where the uncertainty in the system is a probability distribution. Ensemble methods approximate this distribution with a sample of states and have been shown to have comparable accuracy to other approaches such as variational methods. Moreover ensemble methods are easy to implement even for complex geophysical models. Examples of recent advances that are now available in the DART framework are:

- hierarchical Bayesian filters that automatically and dynamically correct for ensemble sampling error;
- hierarchical Bayesian adaptive error correction methods that automatically detect and ameliorate the effects of model error;
- ensemble smoothers that use data from both the past and the future to produce high-quality 'reanalyses'.

One advantage of DART is that once a method has been implemented it is available to all of the numerical models that DART supports. These range from simple tutorial models of dynamical systems to the current and state-of-the-art NCAR weather (WRF) and atmosphere models (CAM).

[3]DAReS is lead by Jeff Anderson, S3 and includes Kevin Raeder, AS3, Tim Hoar, AS3 (50%), Hui Liu, PS, Nancy Collins, SE4, David Dowell, S1,(50%), Joe Tribbia, S4 (17%), Chris Snyder, S4 (17%), Doug Nychka, S4 (17%). S= Scientist, AS= Associate Scientist, PS= Project Scientist, SE= Software Engineer.

The DART user community includes members from many NCAR divisions, more than a dozen universities, and several government labs. Within NCAR, DART has been particularly successful in rapidly adding data assimilation to established community models and incorporating new types of observations. Some examples are:

- Climate and Global Dynamics Division: using DART/CAM to validate and improve climate models,
- Meso- and Microscale Meteorology Division: using DART/WRF to assimilate radar observations for convective-scale and hurricane prediction research,
- Atmospheric Chemistry Division: using DART/CAM to assimilate observations of CO,
- UCAR COSMIC program: using DART/WRF to assimilate GPS radio occultation observations
- Research Applications Laboratory: using DART/WRF to study boundary layer assimilation and modeling,
- High Altitude Observatory: exploring the feasibility of space weather applications.

University groups are using both DART/WRF and DART/CAM and several researchers have incorporated their own models including hydrological models, small-scale tracer transport models, and ocean/atmosphere GCMs. Researchers at DOE/LLNL and NOAA/NSSL are also using DART products or software in their research. DAReS provides support for all these activities and uses feedback from users to develop more powerful and generic assimilation tools. DART has also been used to support graduate-level data assimilation classes at several universities.

Some DAReS projects

The DART facility is comparable in quality to operational variational systems as demonstrated by Figure 1 which shows results from the NCEP operational system and a DART/CAM assimilation system for January 2003. The DART system used all conventional observations but no radiances with a T85/L26 version of CAM. Comparisons are shown for the observation space errors of 6-hour forecasts for temperature over the tropics and the Northern Hemisphere, along with analysis errors. The CAM forecasts are better almost everywhere for temperature.

Figure 2 demonstrates the capabilities of DART to facilitate the evaluation of new observing systems. The figure compares analysis errors for temperature and moisture over North America for January 2003 using the WRF/DART assimilation system. In one set of experiments, the vast majority of radiosondes are assimilated. In the second set, radiosondes plus available GPS Radio Occultation profiles are assimilated. In both sets, radiosonde profiles within 200km and +/- 3 hours of a GPS profile are withheld and used for verification. The results show that assimilating GPS profiles improves the analysis relative to the withheld radiosondes throughout most of the troposphere. The ease of adding new observation operators to DART made this the first result of this kind for GPS RO observations.

Figure 1 Errors in 6-hour temperature forecasts

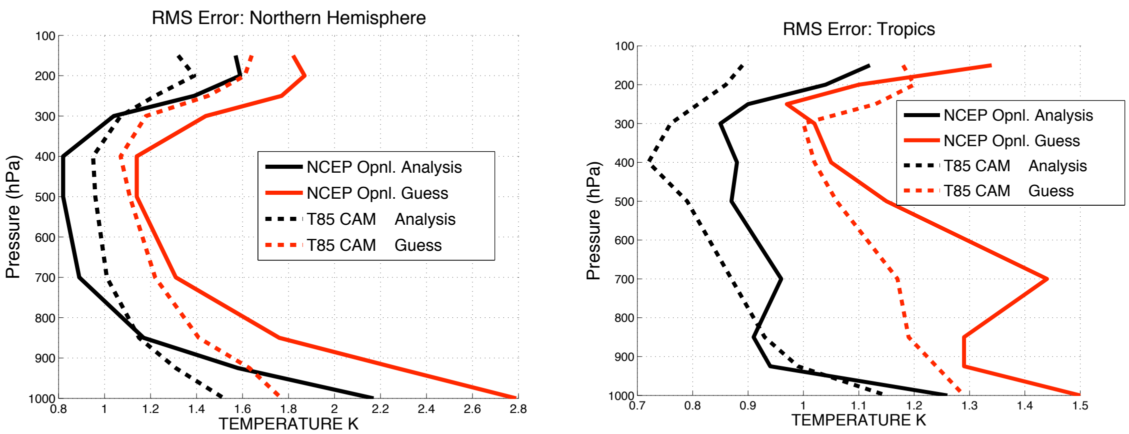
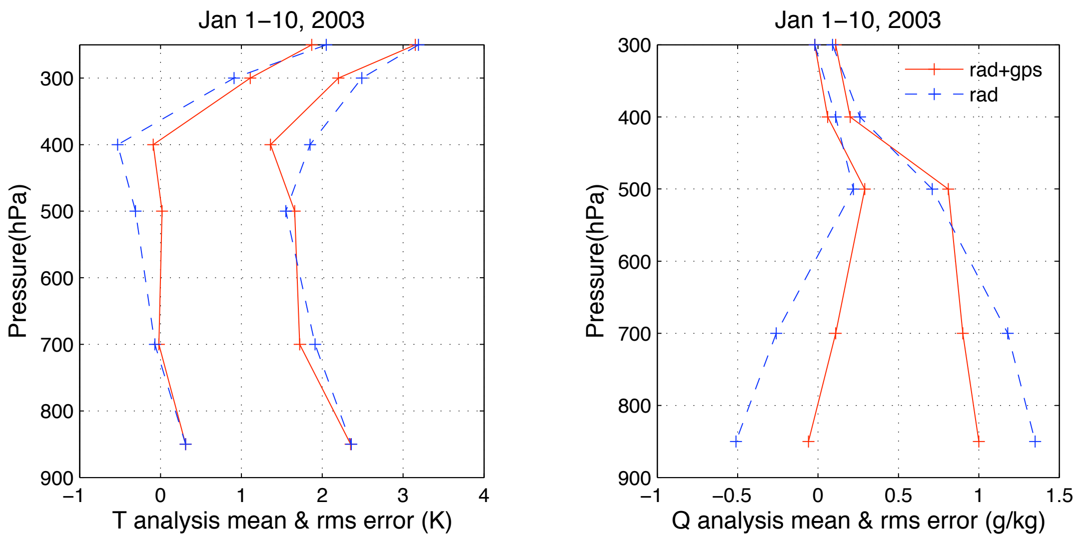


Figure 2 Analysis errors for temperature and moisture using GPS observations



Future plans

DAReS plans to continue expanding the DART facility by adding new algorithms and by exploring new applications. Planned algorithmic enhancements include:

1. Release of a highly parallel version that scales well on at least 100 processors.
2. Spread restoration algorithms that predict and significantly reduce the systematic loss of ensemble variance that can occur in the presence of dense observations.
3. An enhanced ability to perform model parameter estimation.

Planned new applications include:

1. Applying ensemble filters and smoothers for tracer concentration, source and sink estimation. Partners include NCAR/ACD, University of Chicago, for small scale urban applications, and possibly Duke University, for global scale carbon applications. DAReS will cohost a summer workshop on carbon data assimilation that will focus on ensemble methods for source estimation and is part of the IMAGe TOY.

2. Operational mesoscale analysis/prediction system using WRF/DART in conjunction with NOAA/NSSL. Goal is to prototype a system at high resolution using conventional data, doppler radar, GPS, and other data sources.

3. Prediction of tropical storms using GPS and all other available observations. This project will use WRF/DART configured in tropical bands to study impact of ensemble assimilation on tropical storm genesis and track forecasts.

Geophysical Statistics Project

Established at the National Center for Atmospheric Research (NCAR) over a decade ago, the Geophysical Statistics Project (GSP)[4] has been a leader in training and research emphasizing the synergy between the geosciences and the statistical sciences. This synergy is at the heart of the mission of GSP at NCAR:

> The Geophysical Statistics Project pursues the innovative application and development of statistical methodology to address problems faced in the Earth sciences. A complementary activity is to generalize specific problems in the geophysical sciences to broadly based statistical research.

The unique position of GSP within NCAR's scientific activities has provided a fertile research environment, with researchers affiliated with GSP authoring or co-authoring over a hundred publications in highly-regarded statistics and geoscience journals, two published books (with a third currently underway), and a number of software packages including the `fields` and `extRemes` packages for the R statistical computing environment. GSP maintains a post-doctoral training program with between four and six visiting scientist positions each with two-year terms. In addition, GSP has been active in supporting graduate student research with thesis-in-residence and student visitor programs, as well as an active visitor program for both junior and senior statistics faculty. The goal of these programs is to foster collaboration between the students, the post-docs, the permanent and visiting statistical staff, and the NCAR scientists. Finally, an external advisory panel consisting of both statistical and geophysical scientists meets yearly and aids in the guidance of the project.

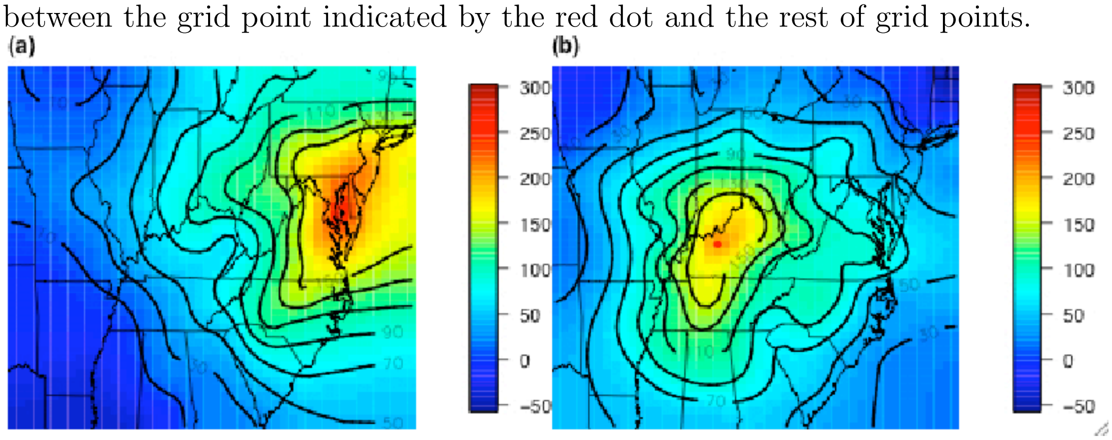
Some Current Research

The research activities of GSP have included substantive statistical contributions in spatial and spatial-temporal statistics, hierarchical modeling, extreme value theory and application, the design and analysis of computer experiments, data assimilation, data mining, and statistical computing. Geophysical applications include weather forecasting, weather generators, downscaling, weather and climate model parameterization, analysis of climate model output, carbon transport, extreme precipitation, turbulence and tracking vortices and storms, among others. To give some of the flavor of the research, three recent and ongoing projects are briefly outlined.

[4]The permanent staff of GSP includes Stephan Sain, a newly appointed project leader, Doug Nychka, Scientist 4 (33%), Rick Katz Scientist 4 (20%), Claudia Tebaldi, Project Scientist 2 (20 %) and Tim Hoar, Associate Scientist 3 (50%). Currently GSP is supporting five post docs: Anders Malmberg, Cari Kaufman (50%) Christian Franzke, Dan Cooley (20%) and Bo Li.)

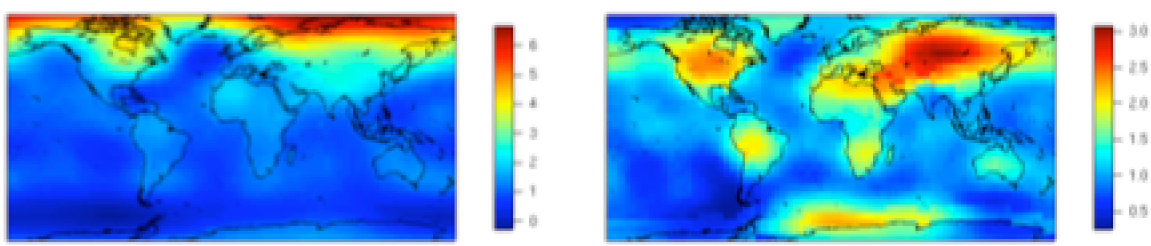
Hierarchal models for estimating atmospheric carbon monoxide from observations and retrievals. Carbon Monoxide (CO) is an indicator of air quality and is an important gas for studying climate change. In addition, CO is one of the few atmospheric species that can be remotely sensed from space. The Measurement of Pollution in the Troposphere (MOPITT) instrument, on the polar-orbiting Terra satellite, provides estimates of CO concentrations at seven different levels throughout the lowermost portion of the atmosphere. Anders Malmberg, a current GSP post-doctoral researcher, is involved in modeling the transport and chemical transformation of CO using MOPITT retrievals of CO. The statistical approach will be useful for creating concentration fields from irregularly spaced statellite observations and also will facilitate combining observations from different instruments. The methodology incorporates a hierarchical structure where the first layer includes a model for the data while the process layer models the true concentration with a spatial-temporal model. Estimating the true CO mixing ratio and its dynamics will, in the end, allow us to make predictions of CO for the entire spatial domain for the entire timeframe of interest, as well as specifying the uncertainties of those predictions.

Nonstationary covariance models for geophysical fields Monitoring air quality in the U.S. is accomplished through a network of monitoring stations that are pooled to produce regional inferences for pollution. Complicating such an analysis, daily surface ozone is well known to have nonstationary covariance over large regions and so standard geostatistics based on assumptions of stationarity are not appropriate. This environmental context motivates the work of GSP post-doctoral researcher Tomoko Matsuo in adapting wavelet bases as models for nonstationary fields. The appropriate wavelet combinations are chosen by determining the significant correlations among the wavelet coefficients. This can be justified from theory and has the practical benefit that the statistical computations can still be done efficiently. The figure below displays profiles for a nonstationary covariance function estimated for surface ozone in the Eastern U.S. Each of the four panels in the figure displays the covariance surface between the grid point indicated by the red dot and the rest of grid points.



The nonstationarity is clear as the shape of the contours changes from location to location. For example, panel (a) exhibits an elongated correlation pattern along the urban coastal area while panel (b) demonstrates a rather isotropic (i.e. radially symmetric) pattern in the midwest.

Statistical inference from climate model experiments Research on the analysis of climate model output has been and will continue to be a core activity within GSP. Dorin Drignei, a recently graduated GSP post-doctoral researcher now at Oakland University in Rochester, MI, has been involved in a project focused on obtaining estimates of climate model parameters based on observational data. Mikyoung Jun, another recently graduated post-doctoral researcher now at Texas A&M University, has been examining model biases in 20 global climate models used with the Intergovernmental Panel on Climate Change (IPCC). Reinhard Furrer, a former post-doctoral researcher now at the the Colorado School of Mines, and Stephan Sain have been involved in combining global climate model output to produce improved estimates of climate change. The basic approach has focused on a hierarchical structure that includes a spatial statistics model for the projections of climate change from each of a suite of models. The goal is to estimate what is common among the different model experiments taking into account the uncertainty due to internal variability and systematic biases among models. The figure below is based on a study combining 9 global climate models and shows the DJF and JJA temperature change (degree Celsius) that occurs with at least 80% probability in 70 years with a 1% annual CO_2 increase. These results have been used by the NCAR modeling group lead by Warren Washington and Gerald Meehl to summarize the uncertainties among climate model experiments.



Besides collaboration with the NCAR modeling groups, Stephan Sain and Doug Nychka are among the principals in the North American Regional Climate Change Assessment Program (NARCCAP)[5] This is an ambitious program designed to use global climate models to drive regional climate models in order to study sources of uncertainty and the impact of the downscaling as well as to derive improved projections of climate change.

[5]NARCCAP is an international program that will serve the climate scenario needs of both the United States and Canada. NSF, DOE, NOAA, and OURANOS are providing inititial funding for the program.

Future Plans

Historically GSP has been focused on the post-doctoral training of statisticians. The plans for the future shift from this single activity and branch out into research opportunities for undergraduate and graduate students and more deliberate collaborative research across NCAR.

In addition to the traditional post-doctoral training program, expanding the training mission will include:

- Summer programs aimed at quantitatively-minded undergraduates from statistics, mathematics, and the sciences and focusing on applied and computational statistics and applications in the geosciences.
- Additional emphasis on graduate student training, through a summer visitor program, student/advisor visits and also providing opportunities for the direction of statistics PhD students from the local,Front Range universities (Department of Statistics, Colorado State University; Department of Applied Mathematics, University of Colorado; Department of Mathematics, Colorado School of Mines.)

The GSP post-doctoral training program has received continuous external funding from the Division of Mathematical Sciences (DMS) at the National Science Foundation (NSF) since its inception in 1993. Despite the numerous successes of GSP and its clear support at NCAR, in the current funding climate it is unlikely to secure a renewal of a single large 'center' through the NSF Probability and Statistics Program. This does not preclude support through a number of smaller targeted grants.

Many of the projects that have fueled the post-doctoral training program have involved collaborative efforts between GSP and the science divisions at NCAR. It is exactly these collaborations that will be leveraged when considered more targeted grants to support the program. NARCCAP is an excellent example of just such a collaboration.

Finally, GSP can strengthen its role within NCAR by expanding to include a service orientated initiative that includes a consulting center modeled after those that exist within a number of university statistics and biostatistics departments. Services would include a type of walk-in or appointment based program where GSP staff can aid NCAR researchers with statistical or data analysis questions. In addition, the consulting center could serve the NCAR community by including statistical or data analysis support on external grant proposals.

THE GEOPHYSICAL TURBULENCE PROGRAM AND THE TURBULENCE NUMERICS TEAM

Annick Pouquet, September 22, 2006

1 Introduction

The Geophysical Turbulence Program (GTP) and the Turbulence Numerics Team (TNT) are both housed in IMAGe. GTP has been in existence almost since the origin of NCAR and has presently more than forty members across divisions and laboratories, with a small but growing university component, and TNT is a more recent emanation from GTP following the NCAR reorganization[1].

2 The Geophysical Turbulence Program

The scientific leaders of NCAR recognized early on that in order to understand the dynamics of the atmosphere and oceans, the sun and solar-terrestrial interactions, investigating relevant turbulent processes at a fundamental level would be essential. Reactive flows, aerosols and turbulent mixing, cloud physics and convection, turbulent interfaces and anisotropies, quasi-geostrophic or stratified flows, the dynamics of passive vs. active scalars and that of magnetized plasmas are topics of current interest, together with code and model developments e.g., Large Eddy Simulations (LES) and its variants such as super-parametrization (with a newly-created NSF center at CSU).

In this context, GTP provides channels for interaction and information-sharing among NCAR and other scientists engaged in fundamental and applied geophysical turbulence research at NCAR and in the broader community, including (in today's parlance) outreach activities. GTP organizes yearly one or two workshops on varied themes, has a few long-term visitors (from one week to, rarely, one year) and holds monthly seminars. Visitors and workshops are chosen in an open yearly meeting[2]. The scientific topics covered this year, in collaboration with NCAR staff, range from wind-wave interactions, intermittency and modeling of turbulent flows, fast dynamos, convection and entrainment in the Planetary Boundary Layer using LES, the effect of air turbulence on rain development on warm clouds or stochastic effects on cloud droplet formation and distribution. GTP has also enjoyed a much-needed special allocation of computer resources from the Directorate at NCAR since, in the reorganization of NCAR, its past allocation disappeared from view. This should be remedied in the next round of redistribution of such resources, to occur soon.

If the budget of NSF doubles in the next ten years, a healthy growth of GTP is desirable; an experimental connection comes to mind, in view of several recent progress achieved recently, such as the resolving of turbulent structures with lidars and radars through the atmospheric boundary layer down to the scales of a few meters. Such a budget enhancement would serve many other purposes.

[1] The staff in TNT is composed of Aimé Fournier (Project Scientist), Ed Lee (Graduate Student in Applied Mathematics at Columbia University), Pablo Mininni (Senior Post-Doc, on an NSF-CMG grant), Jonathan Pietarila Graham (Graduate Student in Applied Mathematics at CU; on an NSF-CMG grant), Annick Pouquet (Section head, 50% of the time and Senior Scientist; the other 50% is spent as Deputy Director of the Earth and Sun System Laboratory, on indirect funds), and Duane Rosenberg (Software Engineer). Alex Alexakis (ASP Post-doc until August 31st (2006) and presently at Nice Observatory) and Jai Sukhatme (ASP Post-doc until January 15th (2006) and presently at Madison) have recently left the team. Furthermore, a few graduate students have participated to tool developments with paid summer stipends, in particular in the VAPOR group headed by John Clyne (SCD).

[2] One can consult the list of the 6 GTP Workshops, the 42 seminars and the 12 other Visitors with their affiliations for the last three years in the Appendix. Another Appendix with the abstracts of the 24 papers published or submitted by TNT since the beginning of 2005 is available upon request.

A GTP post-doctoral fellow would support better connections to the atmospheric community at large, and so would a one-year early-career scientist position. Another example is the need to extend the Visitor Program in novel ways, with some follow-up from year to year, perhaps organized around specific themes or priorities. Yet another possibility would be to have an internal visitor program where NCAR staff could work with TNT in using, and further extending, tools and concepts developed in TNT. These issues will be discussed at our annual meeting and at a retreat to be organized in the next 18 months. It would also be desirable to mentor graduate students from various programs (around the Math Centers and elsewhere) on some of the tools that are being developed both within GTP and TNT. An increase in the permanent staff of GTP/TNT will likely be needed in order to achieve these tasks, e.g. with a Scientist 1 and software engineer hires.

3 The Turbulence Numerics Team

Progress in the understanding of turbulent flows is somewhat limited, except in the experimental and observational domains. Following Moore's law of doubling of computing power every 18 months, doubling the grid resolution in three dimensions occurs every six years, so direct numerical simulations (DNS) of turbulence advance slowly in Reynolds number (R_e). This, and the fact that turbulent behavior may be dominated by intermittent structures, are the driving forces behind one of the main objectives of the team, i.e. *to develop adaptive mesh refinement codes for the community*. Combining such codes, in a quasi-DNS way (see Section 5, note (4)), with different kinds of modeling, where hopefully the behavior of the flow at a given R_e (in contrast to the limit of large R_e) can be approached, represent our main directions of research.

In this context, the work in TNT is organized around two main themes. In a nutshell, we develop both tools and models that enhance our capability to investigate turbulence, and we apply these tools and models to specific projects. The applications cover two broad areas: (1) we pursue our investigations of homogeneous and isotropic turbulence at the highest possible Reynolds numbers and/or incorporating new phenomena (specifically this year, rotation); and (2) we begin exploring turbulent flows with boundaries at moderate R_e. The software development pertains to the NCAR priority concerning highly scalable numerical tools for geophysical flows, in particular in the context of the *Data Center project at NCAR and the Petascale Computing Initiative at NSF* (for which a run at $R_\lambda \sim R_e^{1/2} \sim 4000$ is part of the requirements, a challenge that the team will want to tackle).

The *forte* of the team may be in the *investigation of the dynamics of turbulent flows, in particular when coupled to magnetic fields*, with applications to the generation of such fields (the dynamo problem, e.g., in the context of the Earth and the Sun), and to solar-terrestrial interactions in the Solar Wind, both issues being NCAR priorities as well. It is also in the dialectic approach of considering different flows and contrasting their properties, in the hope of learning from both what is universal and what is specific to a given configuration in a parameter space that is large. The challenge is to pursue this approach incorporating realistic conditions that pertain to the many facets of geophysical turbulence, as *per* the agenda of NCAR. We deal more with fundamental geophysics than applied mathematics, but one driving force of our research is indeed to give the applied mathematics community the most accurate data at the highest possible R_e. In so doing, it relates e.g. to the Clay Institute challenge for the 21st century, of the existence (or not) of a Navier-Stokes singularity, a problem that can be extended to MHD with important applications as for example the heating of the solar corona and the production of Coronal Mass Ejections.

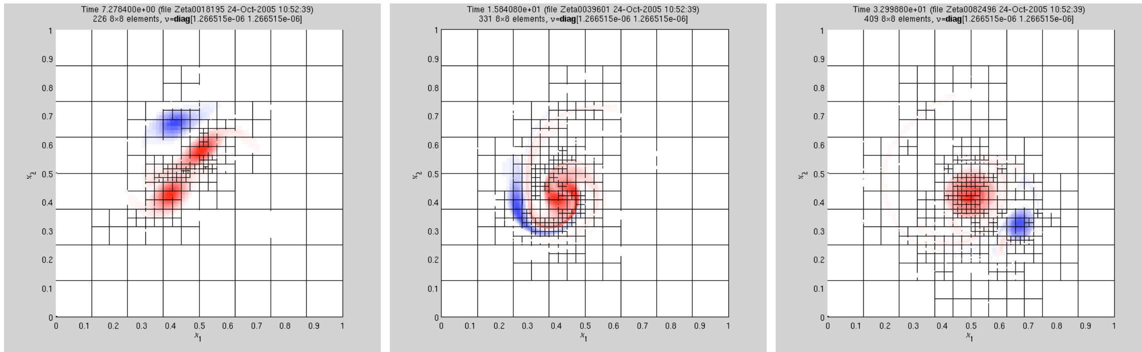


Figure 1: Vorticity snapshots from a simulation of a three-vortex interaction with $R_e = 2 \times 10^4$, using GASpAR (a Navier-Stokes adaptive spectral-element solver) with $3 + 1$ levels of adaption.

We now briefly review the main focus areas of TNT, with emphasis on present developments.

4 What tools for studying Geophysical Turbulence?

- Adaptive Mesh Refinement (AMR) using spectral elements. The Geophysical and Astrophysical Spectral element Adaptive Refinement code (GASpAR), developed *ab initio* in collaboration with P. Fisher (Chicago), has been tested on the Burgers and Navier-Stokes equations in the two-dimensional incompressible case for inhomogeneous Dirichlet and periodic boundary conditions (see Fig. 1). It will be extended to coupling to a magnetic field in the MHD approximation relevant to large-scale dynamics of non-relativistic fluids. Collaborations with A. St-Cyr (SCD) on decreasing the number of iterations in the Krylov pressure solver, and with C-S. Ng and A. Bhattacharjee (New Hampshire) on coronal heating, are under way. Turbulent boundary layers, as for the atmosphere, are an obvious next step, together with going compressible and to three dimensions, but the priority remains to make this type of code more efficient CPU-wise, with the help of the applied mathematics community. In a different (pseudo-spectral) context, a 1D moving grid algorithm with spectral accuracy is being developed, in collaboration with P. Swarztrauber (SCD) and S. Galtier (Orsay).

- Scalability of pseudo-spectral codes. Existing codes have to be adapted to computers with tens of thousands of processors. For example, our present decomposition in slices, tested presently up to 10^3 processors and optimal for a number of processors comparable to the number of (linear) grid points, may well have to be modified into a pencil approach. *Availibility of access to such machines becomes an essential requirement in order to progress steadily.*

- Spherical geometry and realistic boundaries, [3]. The turbulence regime in homogeneous and isotropic flows on the one hand, and boundary layers in the laminar regime on the other hand, are a staple of fluid dynamics research. However, the behavior of complex turbulent flows in the presence of boundaries when a multiplicity of scales are interacting nonlinearly is not well known. We plan to investigate these regimes in the next few years, including as well the interactions of eddies and waves arising for example from the incorporation of rotation and

[3] in collaboration with D. Montgomery (Dartmouth).

stratification. In this context, a fully spectral code in spherical geometry has been developed this year; it will also serve as a test-bed for the GASpAR AMR code.

- Multi resolution analysis and simulations of turbulent flows. The adaptivity criterion and fast application of operators in simulations of turbulent flows, as well as the computation of statistical diagnostics for these flows, may benefit from using a rigorous multiresolution approach. Multiresolution decomposition and energy spectra[4] are already routinely computed using methods newly developed in TNT for the adaptive grids produced by GASpAR.

5 Modeling turbulent flows

Many models such as Large Eddy Simulations (LES) are being used in communities spanning engineering to geo- and astrophysics. We presently focus on two approaches. The first one can be viewed as a quasi-DNS[5]; the second one should allow for a study of the necessity (or not) to include systematically turbulent transport coefficients, as derived analytically in the context of two-point closures. The incorporation of such approaches implies substantial code development.

- The Lagrangian Averaged Model[6]. This model, developed by Camassa, Holm, Marsden, Titi and others, is being studied in two and three dimensions both for fluids – in MMM in the context of the air-sea interface, playing a role e.g. in controlling tropical cyclone intensity – and in its extension to MHD in TNT. We presently analyze its capacity at capturing nonlocal effects and the ensuing intermittency through the appearance and dynamics of extreme events.

- Two-point spectral closures of turbulence[7] can be employed in new ways to model both upscale and down-scale coupling in turbulent flows, in order to go beyond eddy-viscosity concepts and to adapt to non-Kolmogorovian spectra as they may develop in more complex situations as encountered in geophysical turbulence, for example (but not uniquely) in MHD.

6 Investigating turbulent flows using tools and models

- Addressing turbulence-simulation challenges with dynamic Adaptive Mesh Refinement. What advantages does dynamic AMR offer? With and without non-trivial boundary conditions and/or geometries, background flow, buoyancy, topography, or a free surface? Can effectively higher R_e and other challenging parameter regimes be reached with dynamic AMR at a reasonable cost? These questions will be addressed subsequently in the next few years.

- Degree of non-locality of non-linear transfer for Navier-Stokes and MHD. How does it scale with Reynolds number (a computation on a grid of 2048^3 points is starting at Pittsburgh for the fluid case)? What can we infer from these results for modeling turbulent flows?

- Dynamo at small magnetic Prandtl number P_M and applications to the Sun, the Earth and laboratory experiments[8]. Combining DNS, quasi-DNS and LES, a dynamo has been obtained

[4]For an illustration of multiresolution and energy spectra on the 3-vortex dynamics problem in two space dimensions, see http://www.image.ucar.edu/∼fournier/projects/nugmasse/ and ∼fournier/projects/nug3vort/ respectively.

[5]preserving invariants of the primitive equations, albeit in a different norm ($\mathcal{H}_1$, involving vorticity, instead of $\mathcal{L}_2$).

[6]In collaboration with D. Holm (Imperial and LANL) and D. Montgomery (Dartmouth).

[7]In collaboration with J. Baerenzung, H. Politano and Y. Ponty (Observatoire de Nice).

[8]In collaboration with J-F. Pinton (École Normale Supérieure, Lyon) and the Nice Observatory team.

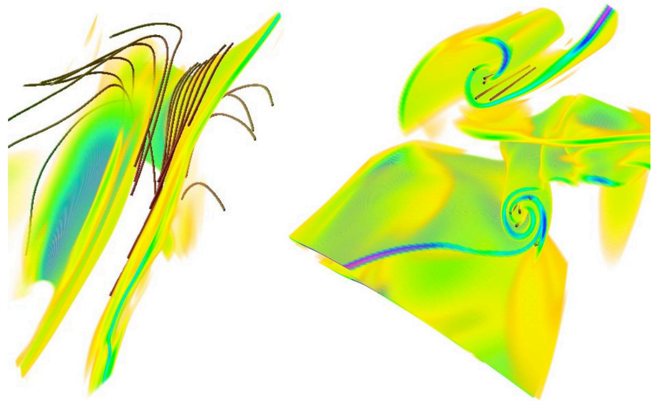


Figure 2: Zoom on current sheets using VAPOR[8]; ABC (Beltrami) flow with superimposed random noise in a free decay MHD run performed at **NCAR** on a grid of $\mathbf{1536}^3$ points, with magnetic field lines (in brown) in their vicinity. Observe Kelvin-Helmotz roll-up parallel to magnetic field lines.

down to $P_M \sim 10^{-3}$ (when previously none was known numerically below $P_M \sim 0.25$). We now focus on understanding the role of interactions between widely separated scales in both the kinematic (linear) and saturated (nonlinear) regimes of the dynamo instability[9].

- Universality in turbulence, or lack thereof? Is there a dynamical role for helicity (velocity-vorticity correlations), and more generally what of the slow return to recovering the symmetries of the primitive equations in the small scales? Do forcing and dissipation play a role as well?

- Kelvin-Helmoltz instability in vorticity and current sheets in MHD. A DNS at high Reynolds number on a grid of 1536^3 points showed for the first time that such an instability develops (see Fig. 2). Many investigations remain to be done to understand the ensuing dynamics.

- The inclusion of rotation: bi-dimensionalization of the flow, and turbulence. Ongoing work!

7 Conclusions

Of course, we want more: more staff, more visitors, substantially more computing power. Code enhancement is very demanding and help in this area is very much needed, given the wide array of tools that the team is developing. Let us keep in mind that, as we approach the petaflop regime in the years to come, multi-scale interactions will emerge from the rather laminar behavior observed today with heavily parameterized physics, chemistry, biology and land processes in general (not to speak of societal, economical and political impacts of climate research). As the kilometer scale is reached in climate codes (and below for weather), better modeling of the nonlinear interactions between scales and fields will be in great demand. GTP and TNT staff pursue their investigations thinking of this plausible and near future scenario, keeping in mind both the commonality of problems because of the underlying multi-scale nonlinear couplings, and the diversity of geophysical applications.

[9]The graphical software needed for analyzing large numerical simulations of turbulent flows is being developed in-house in collaboration with SCD (see in particular VAPOR, http://www.cisl.ucar.edu/hss/dasg/software/vapor).

The following bibliography covers the published, in press or submitted refereed scientific production of the TNT team from 2005 onward. The abstracts of the papers are given in the Appendices that follow, after the list of workshops, seminars and visitors for the last three years.

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A GTP Workshops in the last three years

- *Participation to the 2006 Theme of the Year Workshops on Multi-scale Modeling*

  Organizers: Andy Majda (Courant Institute) and Joe Tribbia (CGD/NCAR). ($\sim 30^{+}$% of the Workshop budget for GTP in 2006).

- *Turbulence and Scalar Transport in Roughness Sublayers; 26-28 September 2006.*

  Organizers: Don Lenschow (MMM); Steven Oncley (EOL); Ned Patton (MMM); Peter Sullivan (MMM); Jielun Sun (MMM); Jeffrey Weil (University of Colorado); Peggy LeMone (MMM); Chin-Hoh Moeng (MMM); Tom Horst (EOL).

- *Modeling Magnetohydrodynamic Turbulence Application to planetary and stellar dynamos; June 27 to 30 2006*

  Organizers: David Montgomery (Dartmouth College) ; Annick Pouquet (NCAR/GTP); Paul Roberts (UCLA).

- *Coherent Structures in Atmosphere and Ocean, July 11 to 14 2005*

  Organizers: Joseph Tribbia (NCAR/CGD) ; Yoshi Kimura (Nagoya University) ; Jean-Marc Chomaz (École Polytechnique/LadHyX).

- *Atmospheric Turbulence and Mesoscale Meteorology, 14-15 June 2004*

  Organizers: Chin-Hoh Moeng, Rich Rotunno & Don Lenschow (M^3); Evgeni Fedorovich & Katharine Kanak (O. U.); Bjorn Stevens (UCLA).

- *The Cumulus Parameterization Problem in the Context of Turbulence Studies; 23-25 February 2004*

  Organizers: Jun-Ichi Yano (Météo France); Joseph Tribbia (CGD); Leo Donner (NOAA); Mitchell Montcrieff; & Wojtek Grabowski (MMM).

B GTP Visitors in the last three years

B.1 Seminars

- Harm Jonker Delft U. of Technology, Netherlands, The Formation of Mesoscale Fluctuations by Boundary Layer Convection (August 9, 2006) and Laboratory experiments on entrainment in a convective boundary layer (August 11, 2006)
- Paul Roberts University of California, Los Angeles, June 26 2006: A Precessionally-Driven Dynamo in a Plane Layer
- Daniel Brito Université Joseph Fourier, Grenoble, June 26 2006: MHD Turbulence in a Rotating Spherical Couette Flow of Sodium with an Imposed Dipolar Magnetic Field
- Nic Brummell and John Clyne June 15 2006
- Chung-Sang Ng University of New Hampshire, May 24 2006 : Anisotropic MHD/EMHD Turbulence
- Michael Waite NCAR ASP/MMM, May 9 2006: Vortical and Wave Motion in Rotating Stratified Turbulence
- Timothy DelSole George Mason University, April 28 2006: Predictability, Information Theory, and Stochastic Models
- Sébastien Galtier Université Paris-Sud, April 7 2006: Wave and Turbulence in the Inner Solar Wind
- John Finnigan CSIRO, 02/10/06: Network Dynamics and Dynamics on Networks: Steps towards modeling human interaction with climate
- Hsiao-ming Hsu NCAR, February 9 2006: Spatial Spectral Structures of Rainfall Patterns Based on NEXRAD Observations
- Robert Krasny University of Michigan, Feb 2 2006: Lagrangian Particle Simulations for Vortex Sheets
- Amitava Bhattacharjee University of New Hampshire, October 28 2005: Recent Developments in Magnetic Reconnection Theory: Applications to Space and Laboratory Plasmas
- Daniel P. Lathrop University of Maryland, October 24 2005: Laboratory Models of Astrophysical and Geophysical Turbulence
- Mark Peterson Los Alamos National Laboratory, June 3 2005
- Keith Julien Department of Applied Mathematics , University of Colorado, May 11 2005: Rotationally Constrained Rayleigh-Bénard Convection
- David Montgomery Dept. of Physics and Astronomy , Dartmouth College, April 28 2005
- Igor Mezic University of California at Santa Barbara, March 7 2005: Two Topics in Coupling Probabilistic and Dynamical Systems Approaches for Complex Systems
- Yukio Kaneda Department of Computational Science and Engineering, Nagoya University, March 7 2005: Turbulence DNS with up to 4096^3 Grid Points
- Donald Estep Colorado State University , January 18 2005: Fast and Reliable Methods for Determining the Evolution of Uncertain Parameters in Differential Equations
- David Montgomery Dartmouth College, November 24 2004: Magnetic and Electrical Scattering of High-Energy Charged Particles
- Darryl D. Holm Mathematics, Imperial College London, November 4 2004: Computational and Computer Science, Los Alamos National Laboratory EPDiff, a nonlinear wave equation with weak solutions

- W. H. Matthaeus Bartol Research Institute, University of Delaware, September 29 2004: Transport, evolution and distribution of MHD turbulence in the heliosphere
- Robert Kerr University of Warwick, UK, September 15 2004: A new mixed non-linear LES
- Rafail Abramov Courant Institute of Mathematical Sciences, New York University, August 25 2004: Statistically relevant conserved quantities for trucated quasigeostrophic flow
- Toshiyuki Gotoh Nagoya Institute of Technology, August 24 2004: Statistics of the transfer flux of the energy and scalar variance in steady turbulence
- Yue-Kin Tsang Physics Department, University of Maryland, July 28 2004: Intermittency and Multifractality in Two-dimensional with Drag
- Dana A. Knoll Theoretical Division, Los Alamos National Laboratory, July 15 2004: System Scale Theory for Fast Magnetic Reconnection
- David Gurarie Department of Mathematics, Case Western Reserve University, July 2 2004: Inviscid 2D turbulence, statistical equilibria and 'vortex solitons'
- Jean-François Pinton Laboratoire de Physique, École Normale Supérieure de Lyon CNRS, four seminars; June 22 2004: Global fluctuations in turbulence and in correlated systems; May 26 2004: Lagrangian statistics in fully developed turbulence; May 7 2004: The dynamo (2): numerical simulation issues; and April 30 2004: The dynamo (1): experimental issues.
- Vladimir Zakharov University of Arizona, April 21 2004: Weak turbulent theory of wind-driven sea
- Misha Stepanov Siberian Branch of the Russian Academy of Sciences, Institute of Automation and Electrometry , April 15 2004: Collision rate of droplets in a turbulent cloud
- John Clyne NCAR/SCD, January 8 2004: Exploiting progressive access for interactive analysis of high resolution CFD simulation data
- Kamran Mohseni University of Colorado, Boulder, Dept. of Aerospace Engineering Sciences, December 11 2003: Numerical Simulations of Turbulent Flows Using the Lagrangian Averaged Navier Stokes-alpha Equations
- Kai Schneider L3M-CNRS and CMI, Université de Provence, Marseille, November 19 2003: Adaptive wavelet methods for modeling and computing turbulent flows
- Marie Farge LMD-CNRS, École Normale Supérieure, Paris, November 19 2003: Extraction of coherent vortices in three-dimensional turbulent flows using orthogonal wavelets
- Alessandra Lanotte CNR, Italy, November 14 2003: The decay of homogeneous anisotropic turbulence
- Oleg V. Vasilyev University of Colorado, Boulder, November 5 2003: Stochastic Coherent Adaptive Large Eddy Simulation (SCALES) Method
- Larry Winter NCAR , October 31 2003: Darcy-Type Groundwater Flows Through Random Domains
- Jai Sukhatme NCAR / GTP, October 24 2003: The Advection-Diffusion of Passive Scalars by Smooth Velocity Fields in Bounded Domains
- W. Kendall Melville Scripps Institution of Oceanography, 21 October 2003: Air-Sea Interaction: The Role of the Surface-Wave Layer

B.2 Other GTP Visitors

- Julien Baerenzung Observatoire de la Côte d'Azur, February 6 2006 to February 28 2006; Host: Annick Pouquet Theme of research: Spectral closure as source of modeling of turbulent flows
- Stephen Belcher University of Reading, UK, March 2004; and April 6 to April 20 2006; Host: P. Sullivan, D. Lenschow (MMM)
- Harm Jonker Delft University, May 27 to August 27 2006; Host: Peter Sullivan
- Robert Kerr University of Warwick, December 11 2005 to January 11 2006; Host: Joe Tribbia
- Szymon Malinowski University of Warsaw, Poland, September 2004; Host: P. Smolarkiewicz (MMM)
- Andreas Muschinski University of Massachusetts-Amherst, June 1 2005 to July 2 2005; Theme of research: BLTG
- Allain Noullez CNRS, France, December 2004; Host: A. Pouquet (GTP) Theme of research: Adaptive Mesh Refinement
- Jean-François Pinton Laboratoire de Physique, École Normale Supérieure de Lyon CNRS, 26 June through 7 July, 2006; Host: Mark Rast (HAO) Theme of research: Lagrangian statistics in turbulent flows
- Hélène Politano, CNRS, France, December 2003 -January 2004; Host: A. Pouquet (GTP) Theme of research: Dynamo at small magnetic Prandtl number
- Yannick Ponty CNRS, France, November 2003; Host: A. Pouquet (GTP) Theme of research: Dynamo at small magnetic Prandtl number
- Bogdan Rosa University of Delaware, July 15 to August 19 2006; Host: Wojtek Grabowski
- Jean Thiebaux Dalhousie University, August 10 2005 to August 12 2005; Host: Joseph Tribbia
- Lian-Ping Wang University of Delaware, July 15 to August 19 2006; Host: Wojtek Grabowski

Note that Darryl Holm (Imperial College and LANL) and David Montgomery (Dartmouth College) were both hosted by the TNT team multiple times on funds from a NSF- CMG grant.

A Charter for the Institute for Mathematics Applied to the Geosciences at the National Center for Atmospheric Research, June 2004

Preamble

This charter describes an Institute at the National Center for Atmospheric Research (NCAR); the Institute for Mathematics Applied to the Geosciences (IMAGe). IMAGe will coordinate the application of mathematics and statistics to the geosciences and will motivate new research in the mathematical sciences based on grand challenge problems from geophysics and related environmental sciences. A primary intent of this charter is to ensure that IMAGe in its initial form and through future expansion will remain focused on vital geosciences research.

This Institute will build upon three existing groups at NCAR: the Data Assimilation Initiative (DAI), the Geophysical Turbulence Program (GTP) and the Geophysical Statistics Project (GSP) and will support and nurture these programs. IMAGe will also provide the structure to broaden the mathematical activity at NCAR through collaborative projects, affiliated scientists, additional IMAGe sections and alliances with other mathematics centers and programs. Accordingly, the implementation of this charter has two parts: the immediate consolidation of DAI, GTP and GSP into a distinct Institute and a more deliberate broadening of IMAGe to fulfill its long-term vision.

1.1 Vision Statement

IMAGe brings mathematical and conceptual tools to bear on fundamental problems in the geosciences and aims to be a center of activity and an integrator for the mathematical and geophysical communities. This is achieved through internal collaborations among NCAR divisions, institutes and UCAR programs and through an external network of mathematics centers, university groups and government laboratories. IMAGe activities will emphasize the grand scientific challenges that are faced in understanding the Earth system and the subsequent enrichment of the mathematical sciences achieved by tackling such problems. Based on this vision, the Institute posits a broad definition of applied mathematics including statistics, probability, scientific computation, algorithm development and machine learning, along with more traditional disciplines based on differential equations and mathematical physics.

1.2 Mission Statement

The Institute for Mathematics Applied to the Geosciences, (IMAGe) exists to foster, enhance, and sustain strong collaborations between the geoscience and mathematical science communities and to become a center of excellence for these communities.

IMAGe will bring together mathematical scientists and geoscientists from the U.S. and abroad to facilitate contacts and to disseminate knowledge through:

- research workshops, tutorials and schools;
- visitor, fellowship, senior under-graduate, graduate and post-doctoral programs;
- long-term focused research activities of joint interest;
- and the creation of innovative focused software that is open source and developed in concert with the geoscience and mathematical science communities.

The Institute supports NCAR and UCAR scientific programs by engaging and coordinating cross-divisional/cross-laboratory grand challenge science from a fundamental and mathematical perspective. It also helps identify the need for, and accelerate the development of advanced mathematical, computational, conceptual and statistical methods within the NCAR/UCAR community, with emphasis on multi-scale phenomena, model/data fusion, stochasticity and uncertainty.

1.3 Provenance

The initial ideas for IMAGe were developed through a sub-committee of the NCAR Realignment Committee chaired initially by Larry Winter (NCAR Directorate) and subsequently by Annick Pouquet (GTP/ASP). The other members were: Jeff Anderson (DAI), Tom Bogdan (HAO), Jim Curry (Applied Mathematics Department, CU), Natasha Flyer (SCD), Doug Nychka (GSP), Piotr Smolarkiewicz (MMM), Steve Thomas (SCD), Joe Tribbia (CGD), and Wes Wilson (RAP).

Based on the work from this subcommittee, IMAGe became part of the NCAR reorganization plan and a committee was formed to create an implementation plan. Implementation committee members were: Barbara Hansford (ASP), Doug Nychka (GSP), Jeffrey Anderson (DAI), Joanne Dunnebecke (RAP), Mark Rast (HAO), Mitchell Moncrieff (MMM), Annick Pouquet (GTP), and Richard Loft (SCD).

2 Organizational Structure

2.1 Institute

IMAGe will be an NCAR Institute and is at the similar organizational level as that of traditional NCAR divisions. An Institute is understood to be a research and education group whose relevance depends on substantive collaboration with more than one NCAR science division or laboratory. Although cross-divisional collaboration and synergy is to be expected throughout NCAR, it is a defining attribute for an Institute. IMAGe is administratively within the Computational and Information Sciences Laboratory (CISL).

2.2 Sections

IMAGe will be composed of sections. The founding sections are DAI, GTP and GSP and the longer term goals of IMAGe include adding other sections. Any decision to augment IMAGe will include consultation with the internal scientific board (Section 4) to ensure relevance to NCAR programs and the external advisory board (Section 4) to assess benefits to external collaborations.

2.3 Institute Members

The Institute will be composed of a variety of members depending on the level of support and affiliation.

- *IMAGe staff:* Permanent members of IMAGe sections.
- *Joint Appointments:* Scientists at NCAR whose support is partially from IMAGe. Typically these would be members contributing directly to IMAGe projects, to Theme activities or with the IMAGe network members. A joint appointment includes the expectation of administrative and facilities support from the Institute but need not be permanent.

- *Affiliates:* Scientists at NCAR who have significant collaborations with IMAGe related projects but who do not receive salary through IMAGe.
- *Institute Fellows:* Researchers outside of NCAR with significant involvement in IMAGe activities. Typically IMAGe will support regular visits of a Fellow to NCAR over a prescribed period, not necessarily in conjunction with Focused Theme (Section 3.3) programs

2.4 External Network

Intrinsic to IMAGe is the formation of a network of mathematical centers and other related research and educational groups that will provide a national and international scope. Initially the network is expected to include:

- Institute for Pure and Applied Mathematics (IPAM), UCLA
- Statistics and Applied Mathematical Sciences Institute (SAMSI), North Carolina
- Center for Atmosphere Ocean Science (CAOS), NYU

Within the network IMAGe will assume a leadership role in maintaining a scientific framework and context for mathematical modeling and analysis methods. IMAGe will engage shorter mathematical programs sponsored by network members as part of longer term scientific collaborations and programs. The Focused Research Themes (Section 3.3) supported by IMAGe will be in coordination with the network members, NCAR laboratories, and UCAR programs.

2.5 Leadership

Director: The Institute will be led by a director on a term appointment with four major roles:

1) to represent IMAGe to the NCAR Directorate and coordinate activities with other NCAR divisions and laboratories,
2) to represent IMAGe to the university and research communities and to be responsible for the maintenance of the Focused Research Theme program,
3) to coordinate a broad scientific agenda and its ensuing budget.
4) to supervise the administrative staff of IMAGe.

Section Leaders: The leaders of IMAGe sections will manage the section's research, programs, and projects, and develop the strategic plans for their sections. The IMAGe section leaders will coordinate these plans within IMAGe, with other groups at NCAR, and with external partners. Section leaders will take responsibility for the IMAGe sections being substantively engaged with the scientific program at NCAR.

Theme Director: The theme director will be responsible for the management and success of the Focused Research Theme. It is anticipated that in most cases this individual will be a distinguished researcher from a UCAR university, a national laboratory or an equivalent international research center. The theme director will be appointed by the NCAR Directorate under advisement by the IMAGe director and the external advisory board.

Steering Committee: An IMAGe steering committee will provide coherence to the activities of the different sections in IMAGe. It will be composed of the heads of each section, the Theme Director and the Director of the Institute. This committee will meet regularly and will set priorities for IMAGe. Responsibility of the steering committee includes Institute planning and organization, personnel decisions, pursuing outside funding, and resource allocation. Although the Director will have primary responsibility for setting the agenda for the steering committee, it is expected that the committee itself will provide substantial guidance and administrative support to the Director.

2.6 Visitor Program

It is expected that the IMAGe will have an active visitor program that is coordinated with the current Focused Research Theme (Section 3.3) and the activities of the Institute's sections. An important component of the visitor program is an IMAGe seminar series that seeks to integrate visitors into the broader activities of the Institute. This will be achieved through regular seminars that are often introductory and tutorial and include participation of all IMAGe sections.

3 Institute Activities

3.1 Role within NCAR

IMAGe will network extensively with research efforts undertaken within the NCAR. Within the Computational and Information Systems Laboratory, IMAGe will complement work in the Computational Science section and in particular, the Numerical Modeling Group. Based on the flexibility and broad application of mathematical and statistical tools it is expected that IMAGe can maintain a collaborative presence in all NCAR laboratories. Such connections will anchor the contributions of IMAGe to geophysical and related problems and will insure that the Institute remains an integral part of NCAR research and outreach. The IMAGe internal scientific board (Section 4) will serve to evaluate and to foster this role.

3.2 Sectional Research

IMAGe will be a balance between research pursued by individual scientists and staff in the IMAGe sections and broad collaboration outside of NCAR. This is based on the principle that for IMAGe to pursue integration of geophysical research and training on a national or international scale, the members must themselves be experts in disciplines related to IMAGe projects. The founding sections already have strong integrative research and service roles within NCAR, and IMAGe must necessarily support these activities. In general, sectional research will be guided by an Institute strategic plan that draws on the NCAR scientific plan, the particular mission and vision for IMAGe, recommendation of the advisory boards for the sections, the IMAGe internal scientific board (see Section 4), and an annual Institute retreat.

3.3 Focused Research Theme

A cornerstone of IMAGe's support of the mathematical science community is the coordination of mathematical and statistical research and education on a challenging area drawn from the geosciences. Ideally, the theme will provoke a synergy between a scientific problem and mathematics: the application of advanced mathematical models and tools will result in substantive advances in an area of the geosciences. In a complementary fashion, the focus on specific geophysical problems will motivate new mathematics and the need for novel mathematical tools. Typically IMAGe will adopt one theme per year and so this program is will also be referred to as the Theme-of-the-Year (TOY). A theme can either be an area drawn from the mathematical sciences with broad application, such as data assimilation, or a scientific topic that may entrain one or more areas of mathematics and statistics. Not all of the theme activities need be located at NCAR and it is expected that most themes will be distributed among one or more members of the external network members. However, themes that have substantial participation by IMAGe will also map onto the broader NCAR scientific and educational plans.

Some broad criteria for theme selection include:

1) Geophysical problems that have broad impact across the Earth System.
2) Scientific applications that have the potential to generate new and perhaps unanticipated mathematical results or suggest the need for new mathematical tools.
3) Themes where some local mathematical expertise is represented in IMAGe either through staff, NCAR affiliates or long-term visitors.
4) Scientific themes that leverage local scientific expertise at NCAR and are aligned with the NCAR strategic science plan.
5) Coincident interest with one or more external research centers or groups.

3.4 Education and Outreach

Beyond the structured activities such as the Focused Research Theme, the IMAGe will have a significant and sustained training and outreach component. Outreach will range from co-developing educational materials with university partners that have wide dissemination to more informal and tutorial events targeted largely to the NCAR community. IMAGe members will be encouraged to visit and, when appropriate, participate in network members programs.

4 Oversight and Reporting

- *Sectional advisory boards:* Due to the uniqueness of the IMAGe sections it is anticipated that each will be prescribed to have its own external scientific advisory board. The reports of these boards will be coordinated into an annual document with the intent of reducing the need for a formal program review by an Institute level panel.
- *IMAGe external board:* The IMAGe external board will be composed of representatives from mathematics centers, government laboratories and other relevant university groups and will focus on Focused Research Theme selection and other external activities. This board is the main entity to coordinate the IMAGe network and will be convened at least once a year. The current theme director is an *ex officio* member of the board. This group will set research themes, coordinate and plan collaboration among the network institutions and will contribute to the final reports for the research themes. Although it is expected that IMAGe members may play a leading role in proposals to the board it is also expected that substantial decision making will derive from the participation of all the board members.
- *Internal scientific board:* An internal advisory panel will be formed drawn largely from NCAR scientists that provide broad representation of the NCAR science divisions and laboratories. This panel should not only track existing IMAGe activities, but also be engaged in planning, selection and maintenance of scientific and educational programs in IMAGe.
- *Policy oversight:* IMAGe will not have a separate policy advisory board but will rely on policy guidance through the board convened for its Laboratory.