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; this Appendix is followed by the abstracts of the 24 papers published or submitted by TNT since the beginning of 2005.

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.

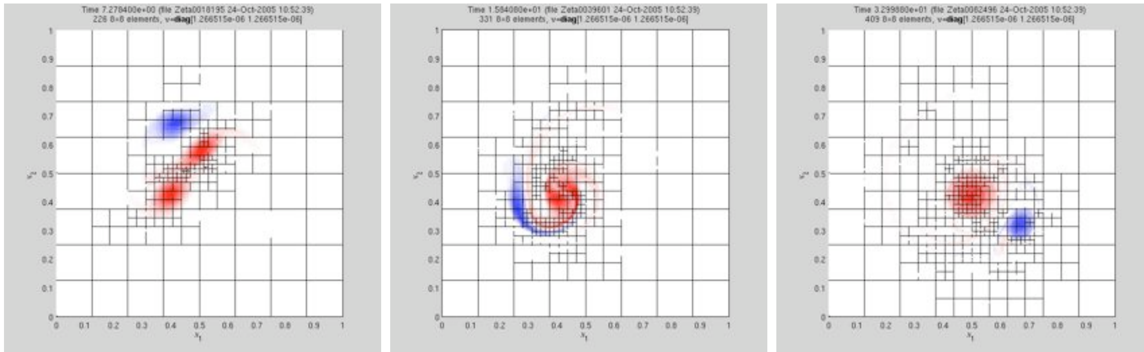

Figure 1: Vorticity snapshots from a simulation of a three-vortex interaction with $R_e = 2 \times 10^4$, using GASpAR (a Navier-Stokes adaptive spectral-element solver) with $3 + 1$ levels of adaption.

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.

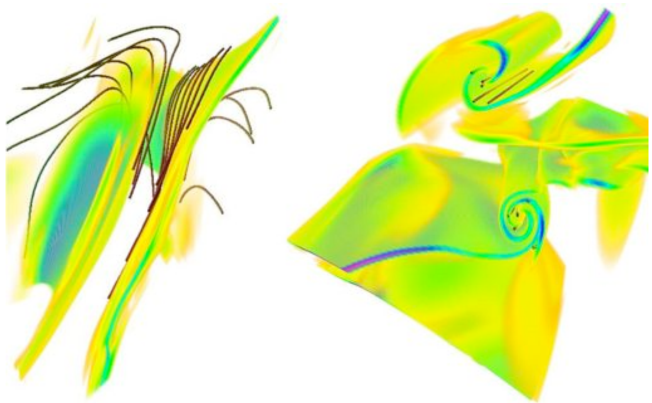

Figure 2: Zoom on current sheets using VAPOR[8]; ABC (Beltrami) flow with superimposed random noise in a free decay MHD run performed at **NCAR** on a grid of $\mathbf{1536}^3$ points, with magnetic field lines (in brown) in their vicinity. Observe Kelvin-Helmotz roll-up parallel to magnetic field lines.

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.

References

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A GTP Workshops in the last three years

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

  Organizers: Andy Majda (Courant Institute) and Joe Tribbia (CGD/NCAR).

  ($\sim$ 35% 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 (University of California at Los Angeles).

- *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 (MMM); Rich Rotunno (MMM); Don Lenschow (MMM); Evgeni Fedorovich (O. U.); 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); Mitchell Montcrieff (MMM); Leo Donner (NOAA); Wojtek Grabowski (MMM).

B GTP Visitors in the last three years

B.1 Seminars

- Harm Jonker Delft university of Technology, Netherlands, August 9, 2006 The Formation of Mesoscale Fluctuations by Boundary Layer Convection

- Harm Jonker Delft university of Technology, Netherlands, August 11, 2006 Laboratory experiments on entrainment in a convective boundary layer

- 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, February 10 2006: 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.