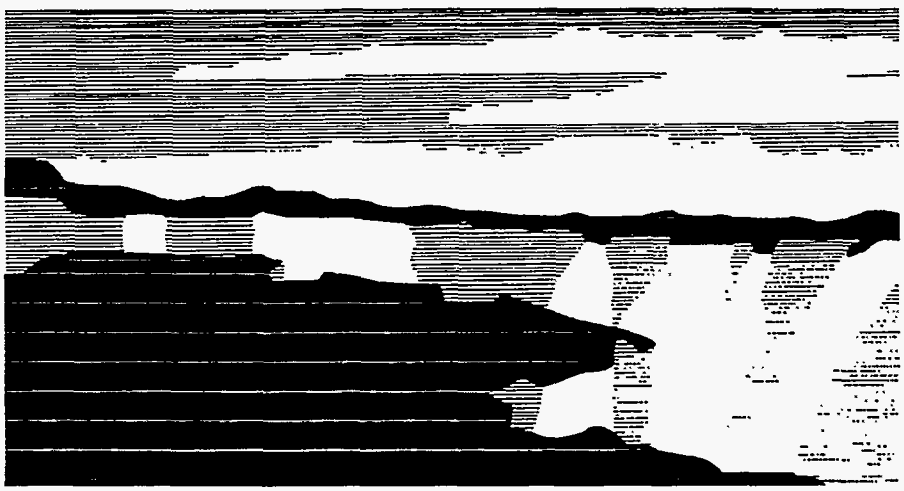
LA-UR-96-3330

Title: **Turbulent Scaling in Fluids**

Author(s): **Robert Ecke, MST-10**
Ning Li, MST-10
Shi-Yi Li, T-13
Yuanming Liu, MST-10

Submitted to: **DOE Office of Scientific and Technical Information (OSTI)**



Los Alamos
NATIONAL LABORATORY

DISCLAIMER

Turbulent Scaling in Fluids

Robert Ecke*, Ning Li, Shiyi Chen, and Yuanming Liu

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The project was a study of turbulence in fluids that are subject to different body forces and to external temperature gradients. Our focus was on the recent theoretical prediction that the Kolomogorov picture of turbulence may need to be modified for turbulent flows driven by buoyancy and subject to body forces such as rotational accelerations. Models arising from this research are important in global climate modeling, in turbulent transport problems, and in the fundamental understanding of fluid turbulence. Experimentally, we use 1) precision measurements of heat transport and local temperature; 2) flow visualization using digitally-enhanced optical shadowgraphs, particle-image velocimetry, thermochromic liquid-crystal imaging, laser-doppler velocimetry, and photochromic dye imaging; and 3) advanced image-processing techniques. Our numerical simulations employ standard spectral and novel lattice Boltzmann algorithms implemented on parallel Connection Machine computers to simulate turbulent fluid flow. In laboratory experiments on incompressible fluids, we measure probability distribution functions and two-point spatial correlations of temperature T and velocity V (both T-T and V-T correlations) and determine scaling relations for global heat transport with Rayleigh number. We also explore the mechanism for turbulence in thermal convection and the stability of the thermal boundary layer.

1. Background and Research Objectives

Fluid dynamics has undergone a revolution in the last 10 years as understanding of nonlinear problems has increased. This derives from a combination of numerical simulations made possible by spectacular advances in computing power, analytical theory, and quantitative experiments. In particular, experiments have progressed to the point where

*Principal investigator, e-mail: ecke@lanl.gov

measurement precision and control of experimental conditions can approach parts per million, and to where simulations of realistic systems have become possible owing to increases in computational power and the introduction of novel algorithms. These new capabilities, in proper combination, can lead to profound advances in fundamental understanding and in applications.

The outstanding unsolved problem in classical physics is fluid turbulence. Recently, this problem has been attacked with renewed vigor, encompassing a wide variety of approaches from dynamical systems methods to massively parallel computer simulations. Concepts from statistical mechanics have played an important role here as well. We have focused on a very exciting recent theoretical prediction that the Kolomogorov picture of turbulence may need to be modified for turbulent flows driven by bouyancy and subject to body forces such as rotational accelerations.

The inertial range of isotropic, homogeneous barotropic turbulence has a particular wave-number spectrum of turbulent energy where $E(k) \sim k^{-5/3}$. Recent numerical simulations of Chen, et al., on the Connection Machine (CM-2) have confirmed this scaling and have revealed a number of important properties about turbulent energy dissipation, about the form of velocity probability distribution functions (PDFs), and about spatially-localized vorticity. Different scalings are possible, however, for turbulence in systems subject to additional body forces such as gravity and heating. Experiments and simulations to test this new scaling hypothesis would be extremely valuable. It can provide a clear picture of the relationship between the energy spectrum and conserved physical quantities.

Models arising from this research will have important implications for global climate models, in turbulent transport problems, and in the fundamental understanding of fluid turbulence. Finally, the current interest in this area, on both a national and international scale, is tremendous. Testable theories have emerged and experiments on temperature PDFs have been done that are at the forefront of research in the physics and fluid dynamics community. Our work on local temperature-velocity measurements coupled with global flow visualization and superb simulation capabilities contributes substantially at that level. This combination of fundamental research at the edge of scientific understanding coupled with the real potential for direct and far-reaching applications is exciting.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The problem of buoyancy-driven fluid turbulence arises in many circumstances in practical applications, from combustion to nuclear weapons testing. Further, the understanding and correct modeling of turbulence in the atmosphere is crucial for the implementation of global climate models used to predict the effects of CO_2 emissions (and other man-made effluents) on earth's climate. Recent experiments and theory suggest that current models of bouyancy-driven turbulence based on the scaling laws of Kolomogorov are incorrect and that they need to be modified to account for correlations between temperature and velocity fluctuations. We have found that this is the case for length scales above the Bolgiano length scale, whereas Kolmogorov scaling is observed for smaller length scales. We use this information to impact hydrodynamic simulations at the Laboratory and on national R&D efforts in turbulence.

Fully-developed convective turbulence experiments provide ideal test systems with which to compare numerical simulations using parallel computation. Our numerical simulations using spectral and lattice-Boltzmann techniques on the CM-2 and CM-5, are highly relevant to other efforts in high performance computing on massively-parallel machines. Our incorporation of rotation with thermally-induced buoyancy provides the simplest model of atmospheric and oceanic circulation and mantle convection and is relevant to modeling global change. We have established important collaborations with Professor Phil Marcus at UC Berkeley and with Dr. Joe Werne at NCAR on the interpretation and significance of our measurements.

3. Scientific Approach and Results

Our approach has been to make precise, quantitative measurements on systems with highly controlled experimental conditions **[1]**. We can control and measure temperatures to about 1 ppm of the absolute temperature (0.001 K) and visualize the flow with modern digitally-enhanced optical shadowgraph and with local temperature and velocity (laser-Doppler velocimetry) measurements. We have been developing several new visualization capabities including thermochromic liquid crystal imaging and photoluminescent dye visualization. We use sophisticated image processing and analysis methods implemented on high-performance workstations.

Our project consisted of experiments designed to study buoyancy-driven turbulence subject to body forces. The fluids used were water and other room-temperature liquids such as acetone, ethanol, and silicone oil with Prandtl numbers between 2 and 100. These systems are capable of temperature control to better than 1 mK and of heat transport measurements with a reproducibility and precision approaching 0.5%. Optical access was from the top and from the side, depending on the visualization technique. For the rotating experiments we designed and built a rotating apparatus capable of speeds up to 2 Hz and with visual access. These speeds were sufficient to induce very strong Coriolis and centrifugal accelerations. Rotation frequencies were controlled to 0.1% in the worst case (i.e. at low rotation speeds).

The main product of these investigations was the development of understanding and expertise in two important areas: the formation and dynamics of turbulent coherent structures and scaling behavior, and spatial correlations in buoyancy-driven turbulent flows. We have made significant progress on this project, building two experiments and obtaining experimental data on thermal plumes, on thermal and velocity boundary layers, and on the scaling of temperature and velocity fluctuations. A number of publications are presently in preparation **[2, 3]** and a follow-up LANL Technical Report will detail full technical progress of this project. Here we present the highlight accomplishments:

- Constructed a 10.5 x 10.5 x 12 in^3 convection cell which can achieve Rayleigh numbers in the range 10^7 to 10^{10} with highly controlled boundary conditions. The top boundary was temperature controlled with an innovative double-layer water cooling plate attached to the aluminum top plate. The bottom boundary was heated uniformly and temperature homogeneity was maintained using a pool boiler technology.
- Measured scaling of temperature and velocity fluctuations using local temperature and velocity measurements over a range in Rayleigh number. Showed isotropy of the turbulence in the central region and found Taylor microscale and Kolmogorov scale for thermal convective turbulence. Demonstrated usefulness of laser Doppler velocimetry in convection studies.
- Demonstrated scaling of temperature and velocity boundary layers which control heat transport. Observed local boundary layer structures using laser sheet visualization.
- Built new rotating convection apparatus with visualization access from the side to study rotating thermal turbulence. Measured heat transport scaling as a function of rotation and heating at fixed Rossby number. Compared temperature probability distribution functions (PDF) with recent theoretical predictions **[4]**. Measured thermal boundary layer thickness to observe interaction of the thermal layer with viscous Ekmann layer.
- Showed, for the first time, correlations between temperature and velocity fluctuations in thermally-convective turbulence. Obtained power spectra and probability distribution functions for temperature and velocity.
- Studied the role of sidewall boundaries on recirculating flows and on heat transport. In rectangular geometries found reversing flows that made measurement of single-point correlations difficult. Using a cylindrical geometry we found locations in the fluid where a steady mean flow existed. This allowed us to use the Taylor hypothesis to translate measurements in time to space and test the scalings of temperature and velocity fluctuations using the recent scaling self-similarity analysis of Benzi et al **[5]**. Using

this "extended self-similarity" we showed for the first time the scalings of velocity fluctuations for thermal convection.

References

[1] L. Ning and R. Ecke, "Thermal Boundary Layer in Convection," Bull. Amer. Phys. Soc., **38**, 2209 (1993); and L. Ning and R. Ecke, "Velocity Fluctuations in Thermal Convection," Bull. Amer. Phys. Soc., **39**, 319 (1994).

[2] Y. Liu, L. Ning, and R.E. Ecke,"Turbulent Scaling in Rotating Rayleigh-Benard Convection," in preparation for Physical Review Letters or Rapid Communications.

[3] L. Ning, Y. Liu, and R.E. Ecke, "Extended Self Similarity in Turbulent Rayleigh-Benard Convection," in preparation for Physical Review E.

[4] K. Julien, S. Legy, J. McWilliams, and J. Werne, "Hard Turbulence in Rotating Rayleigh-Benard Convection: Preliminary Results from Numerical Simulation," submitted to Physical Review Letters.

[5] Benzi et al, "Extended Self-Similarity in Turbulent Flows," Phys. Rev., **E48**, R29 (1993).

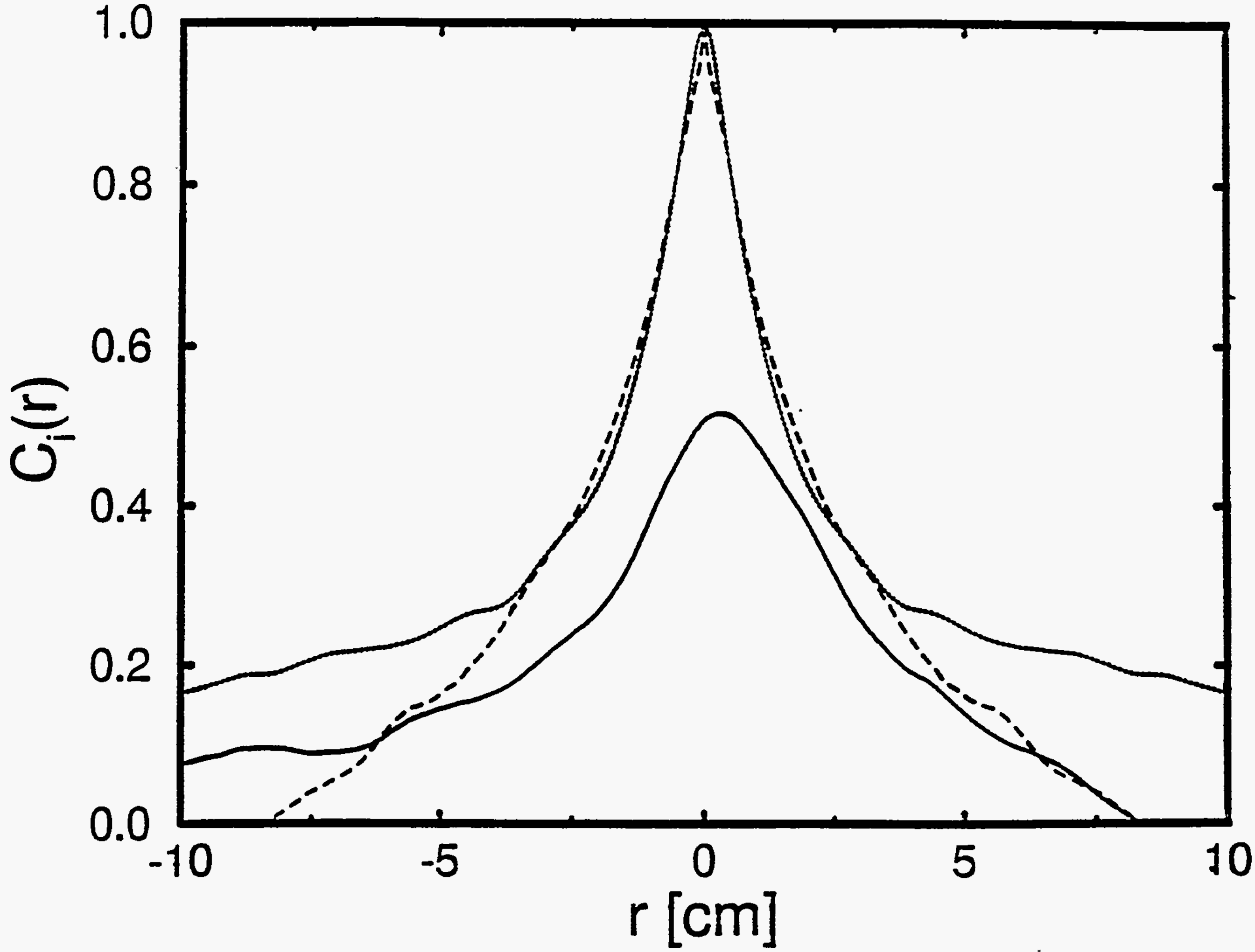


Fig. 1. Correlation functions of temperature (dashed line) and velocity (dotted line) and temperature-velocity (solid line) showing strong correlation between the two fields. This correlation demonstrates that for length scales larger than the Bolgiano length, temperature in convection is not a passive scalar field.

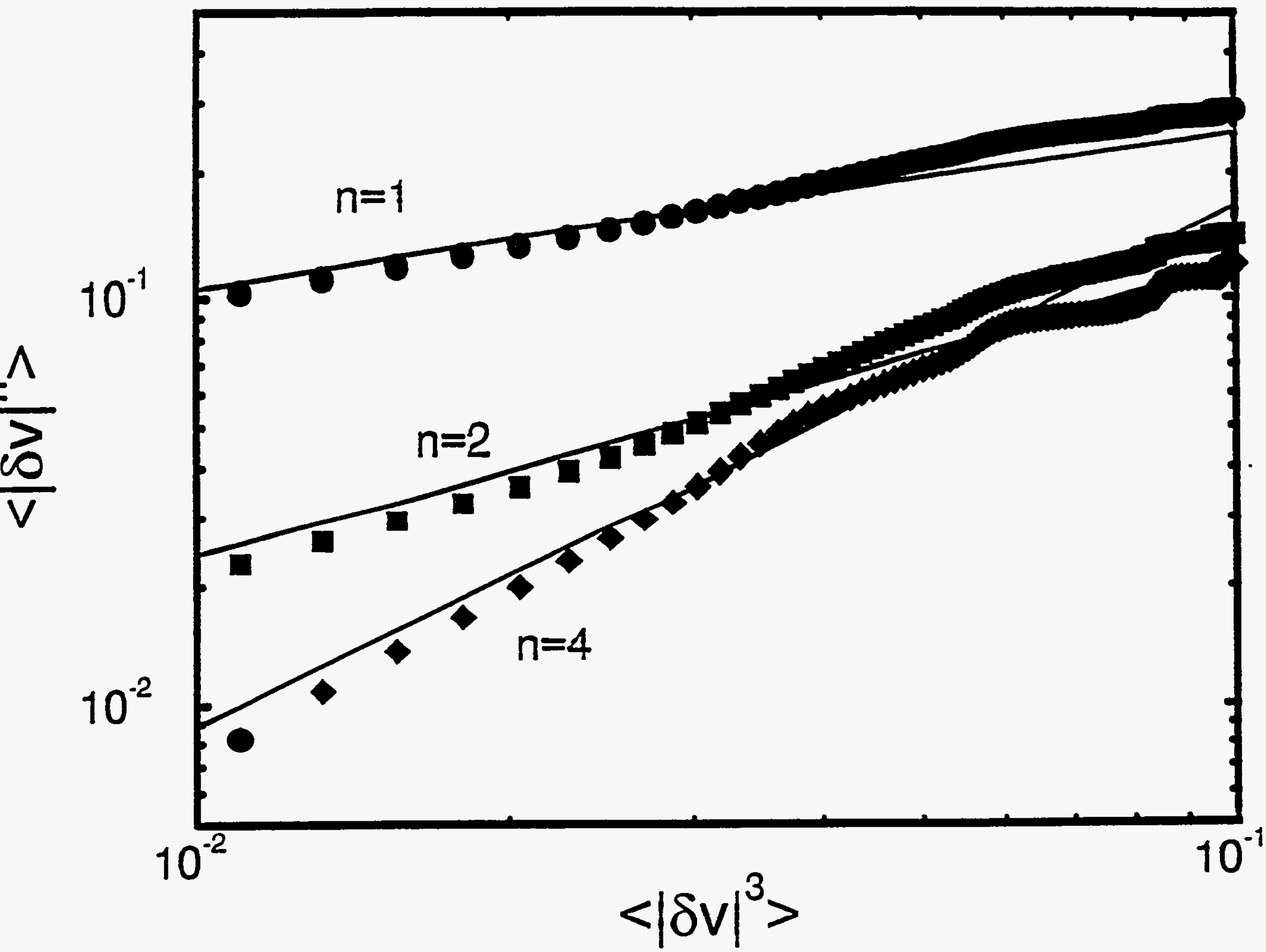


Fig. 2. Single-point velocity correlation functions <|dv|n> vs <|dv|3> showing the property of "Extended Self-Similarity" in thermal convection.