



# Center for Scientific Computation And Mathematical Modeling

University of Maryland, College Park

## Tutorial School on Fluid Dynamics: Topics in Turbulence

May 24-28, 2010

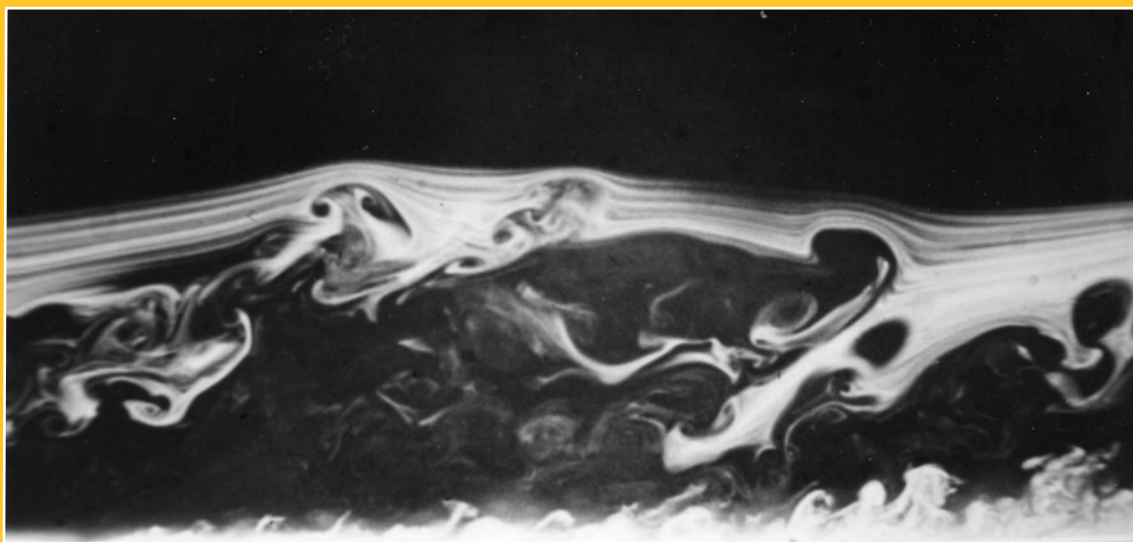


Image courtesy of J.-L. Balint, M. Ayrault and J. M. Wallace

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The Burgers Program for Fluid Dynamics, University of Maryland

The Institute for Physical Science & Technology, University of Maryland

Center for Environmental and Applied Fluid Mechanics, Johns Hopkins University

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Center for Environmental  
& Applied Fluid Mechanics



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College of Computer,  
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Physical Sciences



Center for Scientific Computation And Mathematical Modeling (CSCAMM)

## **Tutorial School on Fluid Dynamics: Topics in Turbulence**



CSIC Building (#406), CSCAMM Seminar Room 4122  
Directions: [www.cscamm.umd.edu/directions](http://www.cscamm.umd.edu/directions)

### **Organizing Committee**

Charles Meneveau  
Rajarshi Roy  
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Eitan Tadmor  
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Department of Mechanical Engineering, Johns Hopkins University  
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CSCAMM

**W**elcome to the Center for Scientific Computation and Mathematical Modeling (CSCAMM). The primary goal of the Center is to foster research activities that highlight novel computational algorithms and mathematical modeling and their interplay with physical, biological and engineering disciplines. To stimulate such activity, CSCAMM sponsors an active visitors program through a series of seminars, lectures and workshops such as the current tutorial school\* on "Fluid Dynamics: Topics in Turbulence".

The turbulent motion of liquids and gases is a ubiquitous phenomenon in nature and engineering. Such motion is fundamental to the formation of planets from interstellar clouds of particulates, to the dynamics of the earth's atmosphere and oceans that determine weather systems, to the mixing of reactants in combustion, to the dispersion of pollutants from smokestacks and storm sewers, and to the health risks caused by diseased arteries, to name but a few examples. Understanding and modeling the physics of turbulent motion is the basis of predicting its effects in these and numerous other examples and controlling it in engineering applications such as the design of air and surface vehicles, efficient engines for propulsion, heat exchangers and stents and heart valves.

This School on Topics in Turbulence is designed primarily for advanced graduate students and post-docs, i.e. participants who have had an introductory course in turbulence and who would find it beneficial to go deeper into the subject. It will focus on recent developments in the understanding of turbulence, its prediction and control using modern experimental and analytical techniques and powerful numerical simulation capabilities. Tutorials on turbulence theory, experimental and simulation methods, turbulent transport in single and two-phase flows and applications of turbulence will be given by senior lecturers. Ample open discussion time will provide opportunities for participants to have a rich exchange of ideas.

On behalf of the organizers, Charles Meneveau, Rajarshi Roy, Katepalli Sreenivasan, James Wallace, and myself, we look forward to your participation in a mutually stimulating and productive environment at CSCAMM.

**Eitan Tadmor**  
Director

*\*Partially supported by The Burgers Program for Fluid Dynamics and the Institute for Physical Science & Technology at the University of Maryland, by the Center for Environmental and Applied Fluid Mechanics at Johns Hopkins University and by the National Science Foundation.*

## Monday, May 24

8:30

**COFFEE**

### **MORNING SESSION**

8:45 - 9:00

**Eitan Tadmor** (CSCAMM)  
**Steve Halperin** (Dean, CMPS)  
**Rajarshi Roy** (IPST)  
Opening Remarks

9:00 - 10:15

**James Wallace** (University of Maryland)  
Refresher Material

10:15 - 10:45

**COFFEE BREAK**

10:45 - 12:00

**Kenneth Kiger** (University of Maryland)  
**James Wallace** (University of Maryland)  
Experimental Methods I

12:00 - 1:30

**LUNCH hosted by CSCAMM**

### **AFTERNOON SESSION**

1:30 - 2:45

**Kenneth Kiger** (University of Maryland)  
Experimental Methods II

2:45 - 3:15

**COFFEE BREAK**

3:15 - 5:30

**Lab Visits and Demonstrations of Experimental Methods**



## Tuesday, May 25

8:30

**COFFEE**

### **MORNING SESSION**

9:00 - 10:15

**Katepalli Sreenivasan** (New York University)  
Turbulence Theory I - Mixing

10:15 - 10:45

**COFFEE BREAK**

10:45 - 12:00

**Gregory Eyink** (Johns Hopkins University)  
Turbulence Theory II – Dissipation

12:00 - 1:30

**LUNCH hosted by CSCAMM**

### **AFTERNOON SESSION**

1:30 - 3:15

**Hands-on Computational Exercises**

3:15 - 3:45

**COFFEE BREAK**

3:45 - 5:30

**Hands-on Computational Exercises**

## Wednesday, May 26

8:30

**COFFEE**

### **MORNING SESSION**

9:00 - 10:15

**Charles Meneveau** (Johns Hopkins University)  
Large Eddy Simulation (LES) Theory

10:15 - 10:45

**COFFEE BREAK**

10:45 - 12:00

**Charles Meneveau** (Johns Hopkins University)  
**Elias Balaras** (University of Maryland)  
LES and Subgrid-scale Models

12:00 - 1:30

**LUNCH hosted by CSCAMM**

### **AFTERNOON SESSION**

1:30 - 2:30

**Peter Bernard** (University of Maryland)  
Vortex Methods and Applications

2:30 - 3:30

**Mohamed Gad-el-Hak** (Virginia Commonwealth University)  
Turbulence Control and Applications

3:30 - 4:00

**COFFEE BREAK**

4:00 - 5:00

**Pino Martin** (University of Maryland)  
Compressible Turbulent Boundary Layers and Applications

5:00 - 5:30

**Open Discussion**

## Thursday, May 27

8:30

**COFFEE**

### **MORNING SESSION**

9:00 - 10:15

**Peter Bernard** (University of Maryland)  
Turbulent Transport in Single-phase Flow

10:15 - 10:45

**COFFEE BREAK**

10:45 - 12:00

**Kenneth Kiger** (University of Maryland)  
**Bin Chen** (Xi'an Jiatong University)  
Turbulent Transport in Multi-phase Flow

12:00 - 1:30

**LUNCH hosted by CSCAMM**

### **AFTERNOON SESSION**

1:30 - 2:30

**Marcelo Chamecki** (Pennsylvania State University)  
LES Applications in Meteorology

2:30 - 3:30

**Kyle Squires** (Arizona State University)  
LES Applications in Aerodynamics

3:30 - 4:00

**COFFEE BREAK**

4:00 - 5:00

**Elias Balaras** (University of Maryland)  
LES Applications in the Cardio-vascular System

### **EVENING ACTIVITY**

5:00 - 6:00

**CLOSING RECEPTION at CSCAMM**

## Friday, May 28

9:00 - 6:00

**Annual Symposium on Environmental and Applied Fluid Mechanics**  
Kay Boardrooms 1107 and 1111 of the Jeong H. Kim Engineering Building

Organized jointly by the Burgers Program for Fluid Dynamics of the University of Maryland and the Center for Environmental and Applied Fluid Mechanics of Johns Hopkins University.

Following a keynote lecture, the first session will be devoted to turbulence with short presentations from Johns Hopkins and Maryland graduate students and Post-docs. Later sessions will cover other areas of fluid dynamics.

Participants of the Turbulence Tutorial School are invited and encouraged to attend.

Monday Morning

## **Refresher Material**

*James Wallace, University of Maryland*

### **Rate equations**

- mean momentum
- turbulent kinetic energy
- Reynolds stress
- dissipation rate
- enstrophy
- scalar concentration

### **Turbulence scales**

- integral
- Taylor
- Kolmogorov

### **Statistical tools with examples of uses to reveal flow physics in various flows**

- correlation functions
- spectra
- probability density functions
- conditional and phase averaging

## **Experimental Methods I**

*Kenneth Kiger, University of Maryland*

*James Wallace, University of Maryland*

### **Why do we perform experiments?**

#### **Hot-wire and hot-film anemometry**

- forced convection cooling
- effective cooling velocity
- multi-sensor probes
- velocity vector and velocity gradient tensor measurements
- Taylor's frozen turbulence hypothesis
- constant-current operation
- constant-temperature operation
- calibration

#### **Laser-Doppler anemometry (LDA)**

- light propagation and interference
- Doppler shift
- instrument configurations
- post-processing

Monday Afternoon

## **Experimental Methods II**

*Kenneth Kiger, University of Maryland*

### **Particle image velocimetry (PIV)**

- PIV basics
- image correlation
- factors influencing the correlation
- practical set-up guidelines
- laser safety and operation
- seed particle selection and generation

Tuesday Morning

## **Turbulence Theory I - Mixing**

*Katepalli Sreenivasan, New York University*

**Examples of mixing problems**

**The mathematical statement: Eulerian and Lagrangian views**

**Models of mixing**

**Computational advances**

**Knowledge of the following aspects in several configurations:**

probability density

spectral scaling in the inertial-convective and viscous-convective regions  
(Kolmogorov-Obukhov-Corrsin-Batchelor- Kraichnan scaling results)

**Richardson's diffusion** (if time permits)

**Thermal convection** (if time permits)

## **Turbulence Theory II – Dissipation**

*Gregory Eyink, Johns Hopkins University*

**Experimental and simulation studies of turbulent energy dissipation**

**Coarse-grained equations and energy-cascade**

**Singularities and dissipation** (Onsager 1949 theorem)

**Two examples:**

Burgers equation (shocks, dissipation and cascade)

Kraichnan scalar model (Richardson diffusion and dissipation)

**Taylor's vortex-stretching picture**

the vortex "autodynamo", vorticity and energy cascade, possible role of vortex reconnection

**Dissipation in wall-bounded flows** (if time permits)

experiments and simulations, vortex dynamics

Wednesday Morning

## **Large Eddy Simulation (LES) Theory**

*Charles Meneveau, Johns Hopkins University*

### **Filtering and projections**

- definitions of subgrid or subfilter stresses and fluxes
- scaling of subgrid scale stresses
- von Karman-Howarth-Kolmogorov equation for filtered turbulence
- subgrid dissipation of kinetic energy and other relevant statistical features of the SGS stress tensor

## **LES and Subgrid-scale Models**

*Charles Meneveau, Johns Hopkins University*  
*Elias Balaras, University of Maryland*

### **Eddy-viscosity and Smagorinsky models**

### **Calibration of coefficient in isotropic turbulence**

### **Germano identity**

### **Dynamic model and applications**

### **Very brief mention of other approaches:**

- similarity, nonlinear, SGS reconstruction approaches, implicit LES, Leray - and LANS regularization

### **Wall modeling in LES**



Wednesday Afternoon

## **Vortex Methods and Applications**

*Peter Bernard, University of Maryland*

**Introduction to vortex methods**

**A vortex filament LES scheme for turbulent flows**

**Gridfree simulation of turbulent jets and shear layers**

**Application of a filament scheme to boundary layers**  
including new insights into vortical structures in transition

**Simulations of complex flows with vortex filaments:**  
applications to automobiles and rotorcraft including particle dispersion

## **Turbulence Control and Applications**

*Mohamed Gad-el-Hak, Virginia Commonwealth University*

**Why is turbulence so difficult to understand?**

**Why is turbulence so difficult to control?**

**Five eras of flow control**

**Emerging technologies:**  
MEMS; soft computing; dynamical systems theory and chaos control

**Wall control; freestream control; and in-between control**

**Passive versus active control**

**Predetermined versus reactive control**

**Vorticity flux at wall and its role in reactive flow control**

**Sensors/actuators needed for reactive flow control on a commercial aircraft:**  
length and frequency scales; energy considerations

**Sensors/actuators needed for reactive flow control on a nuclear submarine**

Wednesday Afternoon

## **Compressible Turbulent Boundary Layers and Applications**

*Pino Martin, University of Maryland*

### **Foundational Research in Hypersonic Boundary Layers:**

- fundamental flow physics of the coupled problem
- development of a numerical capability to enable the study of the coupled problem
- validation of the numerical data, statistics and energetically dominant turbulence structure
- learning from the numerical data
- Mach number, heat transfer, real gas effects
- turbulence structure
- future directions (if time permits)

Thursday Morning

## **Turbulent Transport in Single-phase Flow**

*Peter Bernard, University of Maryland*

### **Simulation vs. Closure Modeling**

### **Reynolds Stress modeling vs. Reynolds Stress Equation modeling**

### **Linear vs. nonlinear eddy viscosity models**

### **Transport physics:**

- analogy with molecular transport
- separation of scales
- Lagrangian transport analysis

### **k-epsilon closure**

### **Near-wall modeling**

### **What to expect from the popular RANS models**

Thursday Morning

## **Turbulent Transport in Multi-phase Flow**

*Kenneth Kiger, University of Maryland*

*Bin Chen, Xi'an Jiatong University*

### **Examples and fundamental challenges**

### **Averaging formalisms and conservation equations**

### **Dilute, dispersed systems**

### **Interphase closure modeling**

one-way coupling models

two-way coupling models

### **Examples of prototypical systems**

shear layers

particle-laden channel flow

### **Numerical methods in multi-phase flow**

interface tracking methods

unstructured domains

case studies

Thursday Afternoon

## **LES Applications in Meteorology**

*Marcelo Chamecki, Pennsylvania State University*

### **The atmospheric boundary layer (ABL)**

### **Wall models and buoyancy effects**

### **Subgrid scale models for ABL flows:**

break-up of scale invariance

effects of buoyancy

### **Technical challenges**

horizontal boundary conditions

surface heterogeneity and vegetated surfaces

complex topography (if time permits)

### **Example of applications:** (if time permits)

flow over forests and crops

dispersion of pollutants and biological particles

cloud dynamics

future directions

Thursday Afternoon

## **LES Applications in Aerodynamics**

*Kyle Squires, Arizona State University*

### **Subgrid-scale models**

length scales in LES vs. length scales in RANS

### **Challenges for whole-domain LES in aerodynamics applications**

resolving the boundary layer at high Reynolds numbers

### **Formulation of hybrid RANS-LES models**

advantages and disadvantages

### **Applications**

## **LES Applications in the Cardio-vascular System**

*Elias Balaras, University of Maryland*

### **Introduction**

### **Methodologies**

solution strategies

an embedded-boundary method with adaptive mesh refinement for LES

grid topology

prolongation and restriction operators

temporal integration scheme

a direct forcing scheme based on moving least squares

fluid-structure interaction and summary of the algorithm

validation and examples

### **Applications**

flows in stenotic arteries

treatment of heart valve disease: design of surgical procedures and implant using LES

## Tutorial Instructor Bios

**Elias Balaras** is an Associate Professor at the Fischell Department of Bioengineering at the University of Maryland. He received his Ph.D. from the Swiss Federal Institute of Technology in Lausanne, Switzerland in 1995. He was formerly a visiting scientist at the National Institute for Standards and Technology and a post-doctoral research associate at the University of Maryland. He has been on the faculty at the University of Maryland since January 2001. Balaras' current research program aims at the development of robust numerical techniques for parallel, large-scale simulations of multiscale, multiphysics problems in physical and biological systems. Emphasis is given to large-eddy and direct numerical simulations, fluid-structure interactions and biological fluid dynamics.

**Peter Bernard** is a Professor in the Department of Mechanical Engineering at the University of Maryland where he has been since 1978. He received a B.E. from the City College of CUNY in 1972 and a M.S. and Ph.D. from the University of California, Berkeley in 1973 and 1977. His research has centered on the Lagrangian analysis of turbulent transport and the role of vortex stretching in the physics of isotropic and homogeneous shear flow turbulence. Most recently he has developed a grid-free vortex filament scheme for large eddy simulation and employed the methodology in the study of the physics of free shear flows and boundary layers.

**Marcelo Chamecki** was born in Curitiba (Brazil), where he received his B.S. degree from Federal de Educação Tecnológica do Paraná in 2000 and a M.Sc. degree from the Universidade Federal do Paraná, Brazil in 2003. He then moved to the U.S. and received M.S. and Ph.D. degrees from Johns Hopkins University in 2006 and 2008. After the completion of his Ph.D., Chamecki joined Pennsylvania State University as an Assistant Professor of Meteorology. Chamecki's research focuses on turbulence in the atmospheric boundary layer and combines field experiments and numerical simulations using large eddy simulation.

**Bin Chen** is a Professor in the State Key Laboratory of Multiphase Flow in Power Engineering at Xi'an Jiaotong University. He received his B.S. and M.S. degrees in 1993 and 1996 at Xi'an Jiaotong University in Cryogenic Engineering, and in 2002 he received his Ph.D. in Thermal Engineering there. He was a Postdoctoral Fellow of Japan Society for the Promotion of Science from 2002 to 2004 at the University of Tokyo. He joined the faculty of Xi'an Jiaotong University in 1996 where he is currently a Professor of Thermal Engineering. Chen does numerical simulation of two-phase flows, in particular with the development of techniques for an interface capturing method in complicated domains. He also conducts investigations of multiphase flow and heat transfer related to Cryogen Spray Cooling in Laser Treatment of skin disease.

**Gregory Eyink** is Professor of Applied Mathematics & Statistics at the Johns Hopkins University, with joint appointments in the departments of Physics & Astronomy, Mathematics, and Mechanical Engineering. He received his Ph.D. in Physics from the Ohio State University in 1987 with a thesis on quantum field theory and theoretical particle physics. After postdoctoral positions in the Université Libre de Bruxelles, Rutgers University, Universität München and Los Alamos National Laboratory, he held faculty positions at the University of Illinois in Urbana-Champaign (1992-94) and the University of Arizona (1994-2001) before joining Johns Hopkins in 2002. His research interests are mathematical physics in general, and specifically fluid mechanics and turbulence, dynamical systems, partial differential equations, nonequilibrium statistical physics, geophysics and climate, and astrophysics.

**Mohamed Gad-el-Hak** received his B.Sc. in Mechanical Engineering from Ain Shams University in 1966 and his Ph.D. in fluid mechanics from the Johns Hopkins University in 1973. Gad-el-Hak has since taught and conducted research at the University of Southern California, University of Virginia, University of Notre Dame, Institut National Polytechnique de Grenoble, Université de Poitiers, Friedrich-Alexander-Universität Erlangen-Nürnberg, Technische Universität München, and Technische Universität Berlin. He is currently the Inez Caudill Eminent Professor of Biomedical Engineering and Chair of Mechanical Engineering at Virginia Commonwealth University in Richmond.

**Kenneth Kiger** is an Associate Professor of Mechanical Engineering at the University of Maryland where he came after receiving his Ph.D. in Engineering Science from the University of California, San Diego in 1995. His diverse research interests are unified by the common theme of utilizing advanced experimental techniques to help understand the detailed physical mechanisms involved in complex flows, with contributions varying from the area of particle-turbulence interaction, the details of the heat transfer mechanisms in nucleate boiling and spray cooling to the complex fluid dynamics of biological systems on problems related to cardiogenesis, transition in pulsatile stenotic flows and entomological fluid dynamics.

**Pino Martin** received her B.S. degree in Aerospace Engineering from Boston University and her Ph.D. in Aerospace Engineering from the University of Minnesota in 1994 and 1999. She held Research Associate positions at the University of Minnesota from 1999-2000 and at the Center for Turbulence Research in Stanford from 2000 - 2001. She joined the faculty of the Mechanical and Aerospace Engineering Department at Princeton University from 2001 until 2009. She is now an Associate Professor in the Aerospace Engineering Department at the University of Maryland. Her research interests include work in the broad areas of Computational Physics, Applied Mathematics and Fluid Dynamics, with a particular affinity to turbulence including high Mach number and high temperature Physics.

**Charles Meneveau** is a Professor in the Department of Mechanical Engineering at Johns Hopkins University which he joined in 1990. He also has a joint appointment in the Geography and Environmental Engineering Department and serves as the director of the Center of Environmental and Applied Fluid Mechanics. He received his B.S. degree in Mechanical Engineering from the Universidad Técnica Federico Santa María in Valparaíso, Chile, in 1985 and M.S, M.Phil. and Ph.D. degrees from Yale University in 1987, 1988 and 1989. During 1989/90 he was a postdoctoral fellow at the Stanford University/NASA Ames' Center for Turbulence Research. His area of research is focused on understanding and modeling hydrodynamic turbulence, and complexity in fluid mechanics in general. He combines experimental, computational and theoretical tools for his research. Special emphasis is placed on the multiscale aspects of turbulence, using appropriate tools such as subgrid-scale modeling, downscaling techniques, fractal geometry, wavelet analysis, and applications to Large Eddy Simulation.

**Kyle Squires** is a Professor and Director of the School of Mechanical, Aerospace, Chemical and Materials Engineering in the Ira A. Fulton Schools of Engineering at Arizona State University where he has been since 1997. He received his Ph.D. in Mechanical Engineering from Stanford University in 1990 and was a post-doctoral research associate at the Center for Turbulence Research from 1990-1991 where he worked on subgrid-scale modeling of compressible turbulence. His first faculty appointment was at the University of Vermont in 1991. Squires' research expertise encompasses computational fluid dynamics, turbulence modeling of both single-phase and multi-phase flows, and high-performance computing. Specific interests include the use of direct numerical simulation and large eddy simulation applied to particle-laden turbulent flows and the development of hybrid Reynolds-averaged and large eddy simulation techniques for high Reynolds number wall-bounded flows. Squires applies his expertise to exploration of ways to improve the aerodynamics of aircraft, ground vehicles, and sports equipment.

**Katepalli Sreenivasan** is a University Professor at New York University, with joint appointments in the Department of Physics and the Courant Institute of Mathematical Sciences. He received a B.E. degree from Bangalore University in 1968 and M.E. and Ph.D. degrees in 1970 and 1975 from the Indian Institute of Science. He has taught earlier at Yale, the University of Maryland and the Graduate Program in Fluid Mechanics at the University of Trieste, Italy. His research expertise is fluid dynamics in a broad sense, turbulence in particular. His recent interests have been passive scalars, high-Rayleigh-number thermal convection and superfluid helium. He is interested in experimental, observational, computational as well as theoretical aspects of fluid dynamics.

**James Wallace** is a Professor of Mechanical Engineering at the University of Maryland at College Park. He received his B.S. and M.S. degrees in 1962 and 1964 at the Georgia Institute of Technology and his D. Phil. in Engineering Science at Oxford University in 1969. He was a research scientist at the Max-Planck-Institut für Strömungsforschung in Goettingen, Germany from 1969 until he joined the faculty of the University of Maryland in 1975. Wallace does experimental research on turbulent shear flows, in particular with the development of techniques for measuring and analyzing velocity gradient fields. He has recently investigated scalar dispersion in shear flows with environmental and mixing applications, as well as turbulence in high temperature flows.

## Graduate Student and Post-Doc Participants Contact Information

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