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We provide a summary of our accomplishments under a three-year "mini URI" program in collaboration with researchers at Yale and Princeton universities. Whereas the central theme of the program is high Reynolds number wall-bounded turbulence, studies at Penn State included (1) analysis of fundamental issues of scale interactions in high Reynolds number turbulence dynamics, (2) the use of the wavelet decomposition and generalized filtering techniques in describing the relationship between the Fourier-spectral description of scale and the physical-space description of structure, (3) direct numerical simulation of passive scalar sources in low Reynolds number turbulent boundary layers and analysis of scalar evolution in relationship to laboratory data, (4) the relationship between homogeneous turbulent shear flow and the inertial sublayer in high Reynolds number turbulent boundary layers, and (5) the development and application of sophisticated data analysis techniques which intimately combine graphical and quantitative analysis within a fully interactive "Analytical Environment." A brief summary of the accomplishments in each area of development is presented.

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THE STRUCTURE OF HIGH REYNOLDS NUMBER TURBULENT BOUNDARY LAYERS, PART A

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Abstract

We provide a summary of our accomplishments under a three-year "mini URI" program in collaboration with researchers at Yale and Princeton universities. Whereas the central theme of the program is high Reynolds number wall-bounded turbulence, studies at Penn State included (1) analysis of fundamental issues of scale interactions in high Reynolds number turbulence dynamics, (2) the use of the wavelet decomposition and generalized filtering techniques in describing the relationship between the Fourier-spectral description of scale and the physical-space description of structure, (3) direct numerical simulation of passive scalar sources in low Reynolds number turbulent boundary layers and analysis of scalar evolution in relationship to laboratory data, (4) the relationship between homogeneous turbulent shear flow and the inertial sublayer in high Reynolds number turbulent boundary layers, and (5) the development and application of sophisticated data analysis techniques which intimately combine graphical and quantitative analysis within a fully interactive "Analytical Environment." A brief summary of the accomplishments in each area of development is presented.

I. PARTICIPATING RESEARCHERS

The program is in collaboration with A.J. Smits of Princeton University and K.R. Sreenivasan of Yale University. The following researchers at Penn State are, or have been involved in aspects of this research program, but not necessarily funded on this grant:

Supported from the grant (partially or fully)

- Prof. James G. Brasseur Principal Investigator.
- Dr. P.K. Yeung Research Associate, 12/89-3/92 (took up a faculty position at Georgia Tech. in March 1992). Partial support from this grant.
- Qunzhen Wang Ph.D. Candidate (full support from this grant): Will complete his Ph.D. requirements in February, 1994.
- Brian Moquin Ph.D. student (full support from this grant): beginning 8/93 is being supported through an A.R.O. AASERT grant.
- Chao-hsuan Wei M.S. student; (partial support one semester from this grant): M.S. Degree 8/91 (currently working for a company in Taiwan)

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Unsupported from this grant, but carrying out related analyses

- **Wen-quei Lin** Ph.D. Candidate, supported on AFOSR-89-0026: received Ph.D. 8/93. He is now employed with Analysis and Design Application Co. (ADAPCO), Long Island, New York).
- **Samir Khanna** Worked on this program one semester with T.A. support from the Department of Mechanical Engineering at Penn State. Supported from ARO grant on Atmospheric Turbulence from 7/92 to present.
- **Dr. Lian-Ping Wang** Research Associate, 9/92-present. Supported for 1 year in part with leftover funds from AFOSR-89-0026. Continues with partial support from ARO grant on Atmospheric Turbulence.

II. RESEARCH OBJECTIVES

This U.R.I. program was in collaboration with Professors K.R. Sreenivasan of Yale University and A.J. Smits of Princeton University. The research objectives of the program as a whole, as described in the original proposal, extend beyond those described here. This report confines itself to those objectives under the Penn State portion of the program which include:

A. Development and analysis of a direct simulation of the flat plate turbulent boundary layer in which are embedded sources of passive scalar.

- Development of a direct numerical simulation of the flat-plate turbulent boundary layer with spanwise passive scalar sources embedded along the wall and within the boundary layer.
- Analysis of passive scalar evolution with two primary themes in mind: (a) general issues of transport of passive scalar in wall bounded flows, (b) interpretation of passive scalar structure and evolution in relationship to structure and evolution of the underlying hydrodynamic field.

B. Structure of the inertial sublayer of the high Reynolds number turbulent boundary layer in relationship to homogeneous turbulent shear flow.

- Objectives include the determination of the extent to which the inertial sublayer in a high Reynolds number turbulent boundary layer is dominated by effects of shear and may be approximated locally as homogeneous turbulent shear flow with appropriate nondimensional parameters.

C. Relationship between scale and structure through development of wavelet and generalized filtering techniques.

- Analysis of scale-dependent attributes of fully turbulent flows using wavelet transforms and other generalized filtering techniques.
- Application to the determination of reduced modal bases for simulating high Reynolds number turbulence.

D. Analysis of fundamental issues of scale interactions in high Reynolds number turbulence dynamics.

- Fundamental physics analyses of scale interactions in high Reynolds number turbulence.

- In combination with item 2, longer term objectives include the development of dynamical approaches to simulate fully three-dimensional high Reynolds number turbulence using reduced modal bases in a fully spectral approach.
- Supported in part by AFOSR-89-0026.

E. The development and application of an "Analytical Environment"

- development of a fully object-oriented, fully extensible and fully interactive programming environment (HOOP)
- development of a fully object-oriented, fully extensible and fully interactive "Analytical Environment" of sophisticated data analysis and visualization tools for real time analysis of multidimensional space-filling data with complex structure.
- Application of the Analytical Environment to the analysis of the turbulent boundary layer and other data as part of the U.R.I. program.

III. RESEARCH SUMMARY

A. Development and analysis of a direct simulation of the flat plate turbulent boundary layer in which are embedded sources of passive scalar. (Yeung, Moquin, Khanna and Brasseur)

1. The Numerical Simulation

P.K. Yeung spearheaded the effort to implement Spalart's "fringe" algorithm for a direct simulation of the flat plate, zero pressure gradient boundary layer within sources of passive scalar to study the underlying mechanisms which lead to the evolution, structure and dispersion of concentration fields within wall-bounded shear flows. P.K. learned and applied the version of the algorithm developed by Diane Bell, student of Joel Ferziger at Stanford University, with much help from Diane. The algorithm makes use of "fringe" regions at opposite extremes of the computational domain in which sinks are placed to remove momentum and passive scalar. Momentum, in particular, is continuously removed in order that periodic boundary conditions may be used in the streamwise direction while, at the same time, allowing for natural growth of the boundary layer. In this way, both the streamwise and spanwise directions are periodic and expanded in Fourier series, while Jacobi polynomials are used in the inhomogeneous direction normal to the plate.

Modifications to Diane's code were carried out by P.K. to include passive scalar sources in at three locations near the upstream end of the turbulent boundary layer:

- A "heated" spanwise strip at the wall, approximating the ejection of dye from a spanwise slot at the wall under a flat-plate turbulent boundary layer.
- Two spanwise sources of passive scalar within the boundary layer, one at the outer edge near δ_{99} , and one in the inertial sublayer (if it exists) at $y^+ \cong 70$.

In an effort to minimize human time and use computer resources most wisely, we provided Diane Bell with a significant portion of our available computer time at NAS to aid her in carrying out the fine-grid calculation of the hydrodynamic field. From Diane's statistically stationary solution, we began our simulation with passive scalar from a hydrodynamic field well resolved on a $720 \times 70 \times 256$ grid (12.9 million nodes). The momentum thickness Reynolds number varies from $R_\theta \sim 315$ to $R_\theta \sim 780$ from the upstream to the downstream side of the computational domain with about 10000 and 1300 wall units in the streamwise and spanwise directions, respectively. To minimize the effect of the imposition of a uniform free stream velocity on the

development of the interface, the computational domain in the normal direction is about five boundary layer thicknesses, where the boundary layer extends to about 300 wall units at the middle of the computational domain.

Calculations were carried out with the three scalar sources within Schmidt (or Prandtl) number or one switched on simultaneously when the simulated hydrodynamic field had reached a stationary state. The calculations were computationally very expensive. Over two years of simulation at the NAS facility at NASA-Ames Research Center, 1700 Cray-2 (850 Cray Y-MP) hours were consumed. Two types of data were collected: (1) full field data of all velocity, velocity-gradient components and three passive scalars, separated in time by about 4 near-wall time units, and (2) highly time-resolved data at 9,000 spatially chosen spatial locations within the boundary layer. The first data provides full 3D data sufficiently well resolved in time to follow evolutionary development of the scalar and hydrodynamic field. From this data set extensive graphical and quantitative analysis of structural development has been carried out, which continues. The second data set is equivalent, experimentally, to placing over 9000 hot-wire probes simultaneously in a boundary layer and recording with sufficient time resolution and over sufficient time period to carry out a wide array of statistical studies using pdf and conditional sampling techniques. Unlike the experimental counterpart, however, all velocity and velocity-gradient components are being stored in the simulation with no probe interference.

We have placed a great deal of emphasis on the design of the numerical protocols on the careful collection of high quality data which can be archived and used over a number of years for a variety of studies, some planned and some not yet conceived. Consequently, a valuable data set has been created which should be useful for years to come. One difficulty we have had, however, is the extreme volumes of data which, it turns out, can only be manipulated effectively at NASA-Ames where the simulation is run. It has become apparent the primary bottleneck in very high resolution simulations is more the data storage, manipulation and transfer difficulties than the carrying out of a simulation.

2. *Statistical Analysis of Passive Scalar Flux (Yeung, Moquin, Brasseur)*

A statistical study of passive scalar flux has been carried out and presented at the International Conference on near-wall Turbulence in Tempe, Arizona, March 1993 the details of which appear in Yeung, Brasseur & Bell (1993) (see references). The three spanwise passive scalar sources were introduced in the boundary layer with $Pr = 1$. As described above, the wall source was modeled as a spanwise strip of high constant temperature with a Gaussian temperature profile in x and an initially exponentially decreasing temperature in y . The interior sources are modeled through source terms added to the scalar equation; passive scalar (or temperature) was introduced within spanwise constant regions of elliptical cross section centered at $y^+ = 70$ and at $y \approx \delta_{99}$ at the upstream side of the boundary layer. Because the algorithm was designed for constant temperature wall boundary conditions, much of the high temperature passive scalar introduced by the heated strip was removed by a large temperature flux into the wall just downstream of the strip. For this reason, we have focused primarily on the outer passive scalar sources.

Figures 1 and 2 show instantaneous and spanwise averaged passive scalar profiles on the x - y plane well after the middle source is switched on. Note that the instantaneous scalar profiles show large corrugations in the edge of the boundary layer nearly to wall, very much like flow visualization studies using dye injection (e.g., Falco 1991, *Phil. Trans. R. Soc. Lond. A* 336, p.103), whereas the averaged profiles show a spread in scalar from the source both away from the wall and towards the wall, indicating scalar flux in both directions. Spanwise averaged vertical scalar flux is shown in figure 3. Whereas on average scalar flux is away from the wall (positive) in the outer boundary layer and towards the wall (negative) in the near-wall region, significant negative scalar flux occurs locally in the outer part of the boundary layer. Counter-gradient diffusion (which invalidates gradient transport models) occurs in the streamwise direction below and close to the source. Elsewhere, eddy diffusivity is at least consistent with the sign of scalar

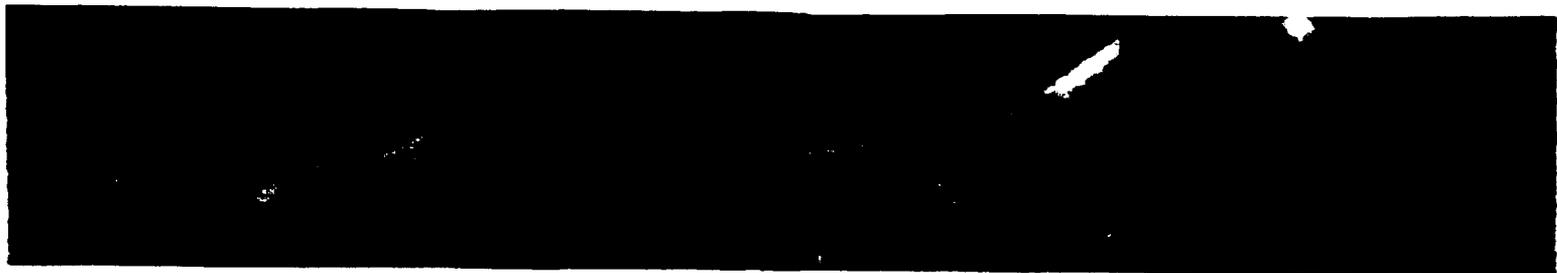


Figure 1. Instantaneous isocountours of total passive scalar on a plane normal to the wall (y) and in the streamwise direction (x). The flow is from right to left. The image is $1500 \Delta^*$ in x and $270 \Delta^*$ in y , and begins $3900 \Delta^*$ downstream of the source. Note the large-scale corrugations at the interface of the passive scalar marking the outer large-scale motions. These corrugations, we find, are similarly marked by the low-magnitude isocountours of the total vorticity field.

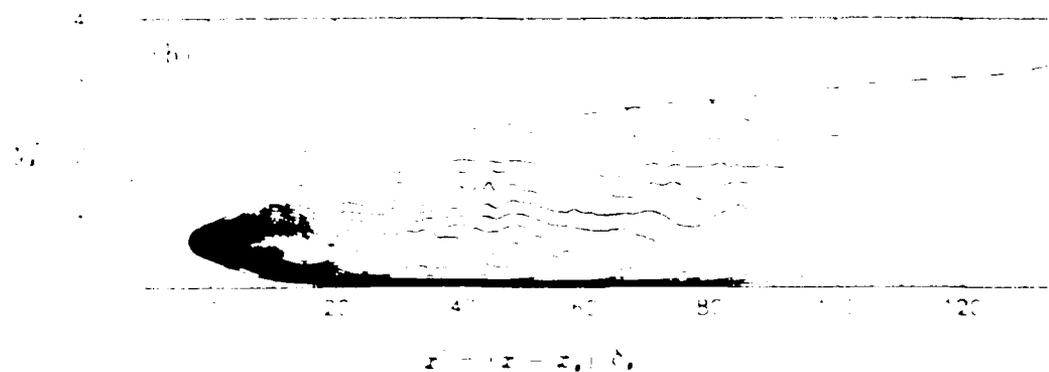


Figure 2. Spanwise averaged isocountours of total passive scalar (Φ) throughout the computational domain after time $24 \tau_{\nu} U_{\tau}$ from the initiation of the passive scalar source located at $y^+ = 70$. The average edge of the boundary layer (δ_{ν}^+) is shown with a dotted line.



Figure 3. Spatially averaged isocountours of vertical vorticity (ω_z) at the same time as Figure 2.

flux, although the eddy diffusivity is strongly anisotropic over most to the boundary layer. Except in regions where the total flux is relatively small, normal scalar flux is associated with Q2 and Q4 momentum transport events, with Q2 dominating away from the wall. Visualization-based studies indicate that the locally outward motions in the outer boundary layer may be found within convoluted regions of interconnected concentrations of vorticity with many, but not all, of these regions associated with hairpin-like structures in the outer part of the turbulent boundary layer. Much of the statistical structure of temperature field and the relationship between momentum and scalar flux may be found in Yeung *et al.* (1993). Additional statistical analysis is continuing with the goal of developing a new manuscript for submittal to a journal.

3. *Local Analyses of Passive Scalar and Scalar Flux in the Turbulent Boundary Layer* (Moquin, Yeung, Brasseur)

One of the primary aims of the numerical experiment is to characterize the transport of passive scalars in terms of the underlying hydrodynamic field with two interrelated themes in mind: (1) determining from flow visualization experiments the proper interpretation of structure in the massive scalar field in terms of structure in the hydrodynamic field, particular the vorticity field, and (2) characterizing the local processes which contribute to the *flux* of passive scalars both away from and towards the wall. Relative to this latter issue, one aim is to develop better understanding of the dynamics which transports heat, contaminants and, indirectly, momentum in the region outside the viscous sublayer in a turbulent boundary layer.

(a) *Structure.*

It is instructive to briefly review the history of our approach and the way it has evolved. We began the study, in the tradition of Steve Robinson and Steve Kline, by attempting to draw direct structural correspondences among individual structural elements within the vorticity, velocity and passive scalar fields. We carried out a great deal of analysis using isosurfaces and applying the event extraction technology developed by Lin and Brasseur and discovered a variety of evolutionary events taking place. The difficulty in the approach, however, is that the complexity is overwhelming and in carrying out analyses of local, individual events one easily loses sight of the global evolution which involves all interacting events. Whereas this localized approach makes sense in the near-wall viscous-dominated region where local instabilities dominate the dynamics, we learned that the approach is less rewarding in the outer layer where the turbulence is fully developed, a much wider range of turbulence scales exists and, most importantly, the local structure is not describable in terms of simple paradigms involving multiple interactions of a simple type. Indeed, it took us some time to recognize that turbulence in the outer regions is "messy" and must be viewed, as it were, from a distance; by focusing on the many branches we were losing sight of the tree. We have therefore modified our approach and are now focussing on larger three-dimensional regions of activity above the sublayer within the boundary layer of order 300 wall units in the streamwise direction and 150 wall units in the spanwise direction (what Falco calls "large scale motions"). We have observed that it is within regions of roughly this size in which scalar, scalar flux, momentum and vorticity are carried in both directions within the boundary layer.

We currently approach analysis of the outer layer motions and scalar flux from the perspective of an experimentalist using sophisticated flow visualization techniques to analyse structural evolution in the turbulent boundary layer (Smits, Falco, Smith, etc.), thus requiring the development of different visualization techniques so as to mimic the visualization of fluorescence dye or oil droplets, for example, inserted upstream through a slot in the wall. However, in addition to drawing correlations with flow-visualization-based experimental measurements, the focus is on those dynamical processes which create the visual image and which transport contaminants, heat and momentum both away from and towards the wall.

Figures 1 and 4 show passive scalar in mutually orthogonal planes visualized so as to simulate the passage of a laser sheet through the turbulent boundary layer seeded with fluorescence dye. Figure 1 shows a streamwise-normal plane (x - y), while figure 4 shows a plane horizontal to the wall, both over a streamwise extent of 1500 wall units (Δ^+), or about beginning about $4000 \Delta^+$ from the scalar source; flow is from right to left. The vertical extent of figure 1 is $238 \Delta^+$, approximately the edge of the boundary layer based on the mean velocity profile. The horizontal slice in figure 4 is at $y^+ = 151$, in the outer region of the boundary layer, and covers a spanwise distance of $529 \Delta^+$, about 2.2δ , where δ is the boundary layer thickness. In both cases the streamwise extent of the images is $1500 \Delta^+$, or 5.5δ , with $R_\theta \sim 565 - 660$.

Compare figure 4 with figure 5, taken from Delo & Smits in a boundary layer with $R_\theta = 525$, slightly lower than the Reynolds number of the simulation results of figures 1 and 4. In the Delo & Smits work, a laser sheet is passed horizontally through a boundary layer in water in which fluorescence dye is released from a spanwise slot in the wall well upstream of the image. Note that the *same* qualitative features may be observed in figures 4 and 5. Furthermore the scales of these outer layer large-scale motions are very similar. To see this, a box has been drawn on each figure with approximately the same scale relative to the boundary layer thickness. Relative to this box, both the streamwise and spanwise extent of the scalar concentration structure in the simulated boundary layer is very close to that visualized in the experiment.

The analysis of the outer large-scale motions within the passive scalar field is continuing, with the current focus being the origin and three-dimensional evolution of these motions. Comparison with more recent three-dimensional visualizations of Delo and Smits is continuing as well. In fact, Carl Delo will spend one to two weeks at Penn State in April for a period of collaborative data analysis using the Analytical Environment, developed at Penn State as part of the URI program. During this period Carl and Brian will analyze concurrently three-dimensional visualizations of experimental and numerical data using combinations of visual and quantitative tools. Brian has been improving and extending the "extraction" technique developed by Lin & Brasseur for application to analysis of the outer-layer motions in the turbulent boundary layer simulations and experiments.

4. *Continuing and Related Studies*

Because the funded U.R.I. program has come to an end and Dr. Yeung has taken up a faculty position at Georgia Tech, only Brian Moquin continues to concentrate on the analysis of the boundary layer data. As a result, continued analysis of the data will be slow. However, the analysis of the structure underlying the scalar and scalar flux, and the study of the evolution of local passive scalar concentrations in relationship to laboratory studies continues. In October of 1993, for example, James Brasseur and Brian Moquin visited Dave Walker and Chuck Smith at Lehigh University, and Lex Smits at Princeton University to discuss further our numerical experiments on passive scalar structure. As mentioned above, Carl Delo from Lex Smit's lab will visit Jim Brasseur's group in April 1994. Furthermore, in March 1994, Jim Brasseur is returning to Lehigh to present a seminar on the turbulent boundary layer simulation results.

B. Structure of the inertial sublayer of the high Reynolds number turbulent boundary layer in relationship to homogeneous turbulent shear flow.

Additional analysis of the numerical data has been carried out by Samir Khanna, primarily to document moments, pdf's and other basic statistics from the experimental work of Randy Smith and Lex Smits in the turbulent boundary layer with R_θ up to 13,000, from experimental work documented in the literature, and from the direct simulations, for use in a study comparing the inertial layer of the turbulent boundary layer with homogeneous turbulent shear flow. This comparison between the inertial layer (or 'log' layer) and homogeneous shear flow centers on the hypothesis that the effects of shear on the structure and statistics in this regions of the

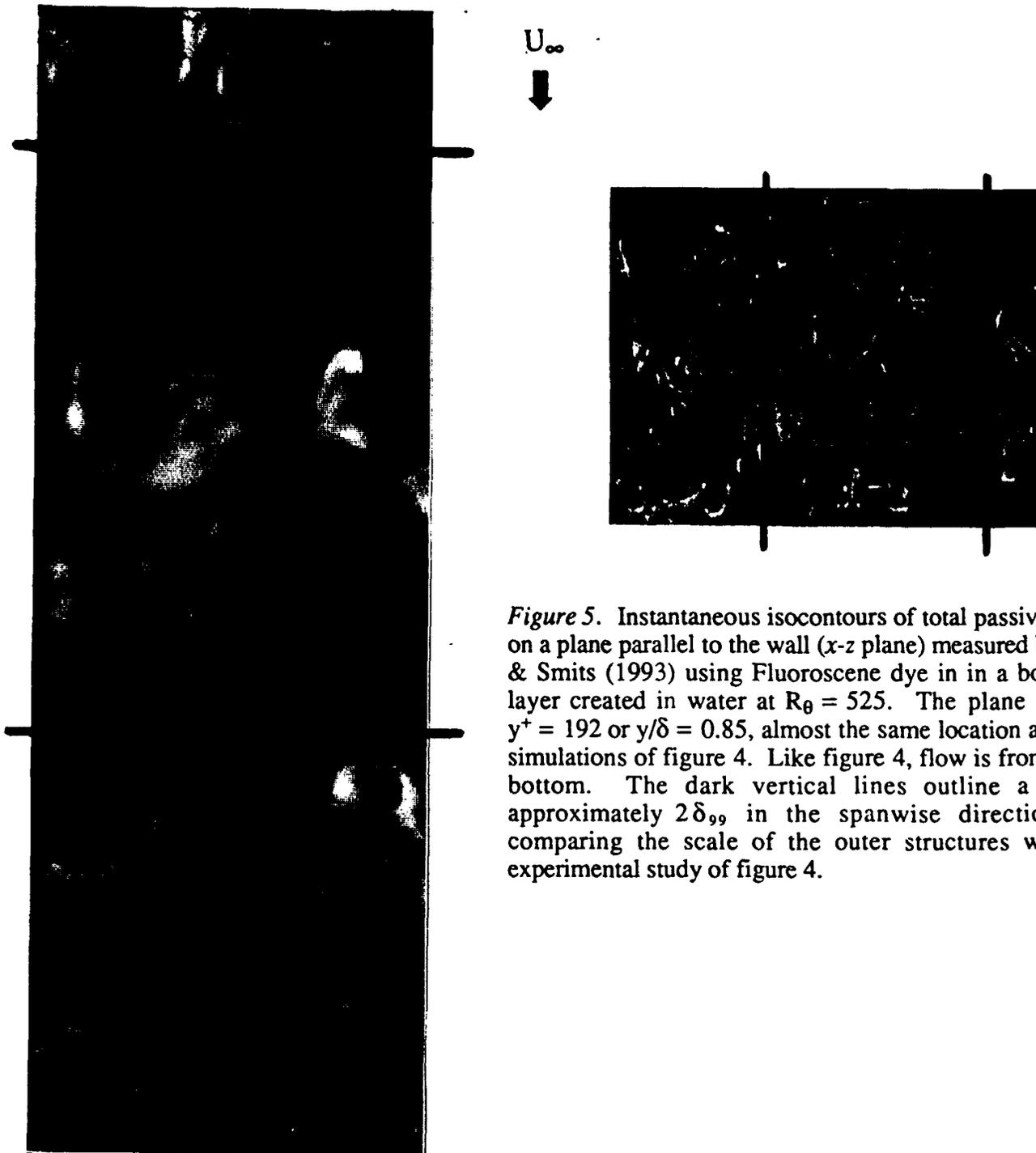


Figure 5. Instantaneous isocontours of total passive scalar on a plane parallel to the wall (x - z plane) measured by Delo & Smits (1993) using Fluorescence dye in a boundary layer created in water at $Re_\theta = 525$. The plane is at $y^+ = 192$ or $y/\delta = 0.85$, almost the same location as in the simulations of figure 4. Like figure 4, flow is from top to bottom. The dark vertical lines outline a region approximately $2\delta_{99}$ in the spanwise direction, for comparing the scale of the outer structures with the experimental study of figure 4.

Figure 4. Instantaneous isocontours of total passive scalar on a plane parallel to the wall (x - z plane) at $y^+ = 238$ or $y/\delta = 0.87$, well into the outer region of the boundary layer. The flow is from top to bottom. As in figure 1, the image is $1500 \Delta^+$ in x and $529 \Delta^+$ in z , and begins $3900 \Delta^+$ downstream of the source. The dark horizontal lines outline a region approximately $3\delta_{99}$ in the streamwise direction, for comparing the scale of the outer structures with the experimental study of figure 5.

boundarylayer dominate locally over effects of inhomogeneity. Although the comparisons are made difficult by the necessarily low Reynolds numbers and incomplete data, the studies suggest substantial similarity in statistics and structure between the strictly homogeneous flow and the apparently "quasi-homogeneous" inertial layer at high Reynolds numbers. These studies have been documented in a preliminary report distributed among the three groups in the URI program.

C. Relationship between scale and structure through development of wavelet and generalized filtering techniques.

(Wang & Brasseur, and partially Lin)

The work described briefly in this section is discussed in detail in the soon-to-be-completed Ph.D. thesis of Qunzhen Wang. A copy of Qunzhen's thesis will be sent to the program monitor when it is available in March 1994.

1. Background and Motivations

It is difficult to extract dynamical details of interactions among scales within the physical-space view. For this reason, detailed dynamical analysis of scale interactions is best carried out within a decomposition explicitly focusing on scale. We use the Fourier representation as a useful decomposition in scale, where our focus is on the *three-dimensional* structure of Fourier decomposition. Fourier is a natural decomposition in homogeneous turbulence in that the three dimensional distribution of Fourier modes provides an elemental description of scale that includes direction, energy and phase information while at the same time providing a readily interpretable set of dynamical equations (which we have exploited in our work). Because a Fourier mode collects information from many ensembles of structures within the turbulent flow, when the turbulence structure is independent of position, the Fourier mode represents the net contribution to given harmonic scale in a given direction. (In this sense, the nonlocality of a Fourier mode is advantageous in homogeneous turbulence.)

Nevertheless, the main issue is not so much the decomposition itself, but rather the relationship between the three-dimensional time evolving structure within the decomposition and the three-dimensional time evolving structure of the signal. We take the position that once this relationship is clearly understood, the dynamics in Fourier space may be interpreted in terms of structural dynamics. More importantly, the studies linking the Fourier and physical-space views carried out by Qunzhen Wang within the U.R.I. program, in combination with work on scale interactions carried out by P.K. Yeung and Chao-hsuan Wei forms the foundation for the development of strategies for full simulation of high Reynolds number turbulence. This approach is based on the recognition that the simulation of high Reynolds number turbulence requires the ability to resolve a turbulent motions separated by orders of magnitude in scale, and that this resolution is only feasible if the scales themselves can be directly represented within the simulation framework, thus allowing direct control over which range of scales are to be directly resolved and with what accuracy. These strategies are currently under development for high Reynolds number homogeneous turbulence simulation within and ONR-supported research program.

The ultimate goal in these developments is the simulation of *nonhomogeneous high Reynolds number turbulence*. Whereas the Fourier decomposition is natural for homogeneous turbulence, it is useful in inhomogeneous turbulence (1) as a decompositional basis within quasi-local regions in inhomogeneous turbulence and (2) as the starting point from which other scale-decomposition strategies can be developed. This approach must follow current developments in the development of simulation strategies for high Reynolds number homogeneous turbulence.

2. *Application of Continuous Wavelet Transforms to the Analysis of Homogeneous Turbulence Simulations*

As a beginning in our understanding of the relationship between Fourier and physical space, a study was carried out in which Direct Simulations of isotropic and shear-dominated turbulence was carried out to study (a) the process by which nonlinearities in the Navier-Stokes equation created coherent regions of concentrated vorticity in the form of tubes, sheets, etc. by analyzing the transition between isotropic Gaussian initial conditions and isotropic turbulence; and (b) the process by which shear reorganizes the vorticity field into stretched, roughly aligned, vortex tubes by analyzing the transition between isotropic turbulence and shear-dominated homogeneous turbulence. These studies are described in detail in the publication by Brasseur & Wang (1992). In general terms we found:

- Small scales are always more intermittent than large scales, and the level of intermittency grows more rapidly than with large scales,
- the structural development of the turbulence at different scales is correlated both with the evolution of global statistical measures which dominate at those scales (specifically, energy and dissipation-rate) and with the evolution of the energy (or dissipation-rate) spectra.
- Equilibrium states are associated with changing levels of intermittency, whereas strongly nonequilibrium or relaxation states appear during periods of minimal structural change.
- The effect of mean shear on the large scales is very different from the effect of shear on small scales.
- The approach towards anisotropy due to shear is very different within those scales larger or smaller than the peak in the dissipation-rate spectrum.

In continuing studies (next), we have found that the development of anisotropy by shear, or by interscale interactions within an initially isotropic fields, are associated in Fourier space with (1) a redistribution of energy within three-dimensional k -space, and (2) the development of phase couplings among Fourier modes due to the dynamic interactions embedded within the Navier-Stokes equation. We conclude that the nonlinear evolution of high Reynolds number turbulence is associated with global alterations of local structure which, in a scale decomposition, are described by global modification of in the region of scale-space in which the dynamics takes place, and local modification of the phase relationships within scale-space.

3. *The Representation of Subsets of Physical-Space Structure by Localized Regions within Fourier-space.*

In continuing studies, we have found that the development of anisotropy by shear, or by interscale interactions within an initially isotropic fields, are associated in Fourier space with (1) a redistribution of energy within three-dimensional k -space, and (2) the development of phase couplings among Fourier modes due to the dynamic interactions embedded within the Navier-Stokes equation. Energy redistribution is related to the development of preferred directions and preferred scales, whereas phase coupling is associated with the particular structural forms observed in physical space. We have further discovered that a small fraction of the modes used in pseudo-spectral simulations carry most of the structural and phase information of the turbulent flow, suggesting that a lower-degree-of-freedom simulation is possible with the same dynamical and resolution characteristics.

D. Studies into large-small scale interactions, interscale dynamics, and the triadic structure of the Navier-Stokes equation in high Reynolds number turbulence.
(Brasseur, Yeung, Wei)

Approach

Much work has been carried out towards the analysis of the triadic structure of the Navier-Stokes equation. This work has been reported in a number of publications and manuscripts, including a paper to appear in February 1994 in the *Physics of Fluids* by Brasseur & Wei, and a paper currently under review for *J. Fluid Mech.* by Yeung, Brasseur & Wang. The essence of these works is the unraveling of interscale dynamics in terms of scale separation, location within the spectrum, and triadic structure in Fourier space.

Some Results

Much interesting and far-reaching knowledge has come from this program of study. A great deal of study, for example, has centered on the effect of large, energy-containing eddies on the smallest, most dissipative scales in a high Reynolds number turbulent flow. We learn that, in principle, a coupling exists and that this coupling intensifies with scale separation. Consequently it is possible, in principle, for small scales to be directly stimulated by the stimulation of large eddies. On the other hand, more local and nonlocal interactions act to remove information from the larger scales on the smallest scales. Which effect wins out depends on the global state of the flow, and its history. Turbulence in an equilibrium state has established an energy cascade within it internally in a local equilibrium state. In such a state, the net effect of local cascading processes apparently overwhelm the direct couplings between large and small scales, although recent evidence still suggests a significant role for these couplings. We have clearly shown, however, that when the turbulence is in a transitional, or nonequilibrium state, direct large-small scale interactions can be stimulated and can, over finite periods of time, dominate small scale dynamics.

Importance and Applications

The implications of these studies is far reaching and rather profound. The results suggest, for example, that turbulence closures which are to be applied in high Reynolds number turbulence which experience nonequilibrium transitional states, should include direct couplings between large and small scales if small scale dynamics plays a role in the processes of interest. Furthermore, these studies suggest that the details of small scale processes, mixing for example, may be altered or controlled via changes made at the large scales, through changes in the boundary conditions, for example. Finally, these studies add considerable depth to the simplistic description of turbulent energy cascade and the underlying hypotheses proposed by Kolmogorov in 1941, and leave open a rich field of new possibilities in our understanding of turbulence which demands further exploration.

E. The development of an "analytical environment" in which 3D visual and quantitative analysis may be combined within an interactive, extensible and dynamic graphically-based system.
(Moquin and Brasseur)

Concept

For the past two years we have been developing an "analytical environment," within the "Postprocessing and 3D Graphical Imaging Facility" at Penn State, a concept which centers on creative combinations of quantitative analysis with state-of-the-art 3D graphical imaging technology in a highly interactive, extensible and dynamic computational and visual environment. Within such an environment 3D graphical information of turbulence structure is readily interpreted by the human brain which interactively make decisions for quantitative analysis. The underlying

goal is the interweaving of human intelligence, computational power, and graphical imaging—the combination of the inherent strengths of the human mind directly with the inherent strengths of the computer—in the analytical process. The environment in which this activity takes place is what we call the "Analytical Environment."

Progress

Great progress has been made. The analytical environment has, at its core, the development of a fully object-oriented programming methodology which we call "Hyper-Object-Oriented Programming," or HOOP. The basis for the concept is programming in block diagrams, where each block may itself be a block. The key is intercommunication among blocks, and the ability to dynamically connect and disconnect blocks *during the analytical process*. These block, or "objects" can be either graphical or quantitative in nature. In this way it is possible to interactively integrate quantitative analysis with visual analysis. Furthermore, by designing *functions* among blocks, it is possible to dynamically carry out quantitative analysis while receiving visual queues and again visualize the consequence of the quantitative manipulation. Finally, we have developed the concept of "extraction" of data subsets within these fully object-oriented environment, making it possible to carry out interactive conditional sampling and to quantify local attributes within the data without leaving the environment.

HOOP consists of two new programming languages: HOOPX, a translator which is used to create new objects, and the ABSTRACTION LANGUAGE, which is used to interactively connect instances of objects or create systems of objects. Currently over thirty classes of objects have been created within a "Visualization Subsystem". HOOP and the Visualization Subsystem have been recently introduced for use by Dr. Brasseur's research group as a whole. In particular, the system is being used and improved in the context of analyzing the turbulent boundary layer simulations described in §3 above. As part of a new AASERT program under ARO, the underlying structure of HOOP is being completely rewritten, and further applications are being made for application of LES studies of the atmospheric boundary layer.

Importance and Applications

In the view of the P.I., the direction we have taken with the development of the Analytical Environment is absolutely critical to future progress in our understanding of complex three-dimensional phenomena, particularly turbulence. Whereas great progress has been made in developing more sophisticated techniques for producing scientific data, particular three-dimensional time-dependent data, relatively little effort has been made in developing new concepts in data analysis. It is in the analysis of data that we place our greatest emphasis, because it is only by analyzing data in creative and scientifically valuable ways that major advances in knowledge and understanding can be made in the study of turbulence.

Our developments in analysis, we feel, represent a unique direction that is not only valuable, but necessary for future progress. By the end of the granting period, we intend to have demonstrated the importance of this direction of development through the analysis of the turbulent boundary layer which would be difficult or impossible using traditional methods of analysis.

IV. PAPERS AND ABSTRACTS

A. Papers and Manuscripts

Wang, Q. 1994 Relationship between scale and structure in turbulence analysed using three-dimensional wavelet transforms. Ph.D. Thesis, Department of Mechanical Engineering, Pennsylvania State University.

- Vassilicos, J.C., Moquin, B.P., Brasseur, J.G. 1994 Self-similar spiral flow structure in low Reynolds number isotropic and decaying turbulence. under review, *J. Fluid Mech.*
- Brasseur, J.G. & Wei, C-H. 1994 Interscale dynamics and local isotropy in high Reynolds number turbulence within triadic interactions. *Phys. Fluids* 6 (2): 842-870.
- Yeung, P.K., Brasseur, J.G., Bell, D.M. 1993 Evolution of passive scalar sources in a numerically generated turbulent boundary layer. In R.M.C. So, C.G. Speziale & B.E. Launder (editors), *Near-wall Turbulent Flows*, Elsevier Science Publishers B.V., pp.307-316.
- Yeung, P.K., Brasseur, J.G. and Wang, Q. 1993 Dynamics of large-to-small scale couplings in coherently forced turbulence: concurrent physical and Fourier-space views. under review, *J. Fluid Mech.*
- Wang, Q. & Brasseur, J.G. 1993 Application of nonsymmetrical 3D wavelet filters to the analysis of anisotropic turbulence data. In: *ASME 1993 Forum on turbulent Flows, FED-Vol. 155*: 137-142.
- Wang, Q., Brasseur, J.G., Smith, R.W., Smits, A.J. Multi-dimensional wavelet transforms and applications to turbulence data. Original version presented at the "Wavelets and Turbulence Workshop," Princeton University, June 1991; revised version under review by Proc. Royal. Soc. London.
- Brasseur, J.G., Wang, Q. 1992 Structural evolution of homogeneous turbulence at different scales analysed using 3D wavelet transforms. *Phys. Fluids A* 4: 2538-2554.
- Wei, C-H. 1991 Interscale Couplings and Spectral Dynamics in High Reynolds Number Turbulence in terms of Triadic Interactions. M.S. Thesis, Department of Mechanical Engineering, Pennsylvania State University.
- Brasseur, J.G., Yeung, P.K. 1991 Large and small-scale coupling in homogeneous turbulence: analysis of the Navier-Stokes equation in the asymptotic limit. *Proc. Eighth Symposium on Turbulent Shear Flows*, Munich: 16-4-1 - 16-4-4.
- Yeung, P.K., Brasseur, J.G. 1991 The response of isotropic turbulence to isotropic and anisotropic forcing at the large scales. *Phys. Fluids A* 3: 884-897.
- Brasseur, J.G. 1991 Comments on the Kolmogorov hypotheses of isotropy in the small scales. AIAA Paper No. 91-0230, AIAA Aerospace Sciences Meeting, Reno, Jan. 1991.
- Brasseur, J.G., Lin, W.-Q. 1991 Structure and statistics of intermittency in homogeneous turbulent shear flow. *Advances in Turbulence 3*, Springer-Verlag, Heidelberg: 3-12.

B . Abstracts

- Brasseur, J.G., Wang, Q. 1993 Locality in Fourier space, locality in physical space, and the relationship between the two. *Bull. Amer. Phys. Soc.* 38 (12): 2228.
- Wang, L-P., Brasseur, J.G. 1993 Contribution of long-range interactions to small-scale phase changes in isotropic turbulence. *Bull. Amer. Phys. Soc.* 38 (12): 2243.
- Brasseur, J.G. 1992 How should one view "large" and "small" scales in fully developed turbulence? *Bull. Amer. Phys. Soc.*, 37(10):1703.
- Moquin, B.P., Brasseur, J.G. 1992 Applications of a fully object-oriented programming methodology to the analysis of multidimensional turbulence data. *Bull. Amer. Phys. Soc.*, 37(10):1781.

- Wang, Q., Brasseur, J.G. 1992 Application of nonsymmetrical 3D wavelet transforms in the analysis of anisotropic homogeneous turbulence. *Bull. Amer. Phys. Soc.*, 37(10):1755.
- Lin, W.-Q., Brasseur, J.G. 1992 Dynamics of small-scale structural development within turbulent shear flows. *Bull. Amer. Phys. Soc.*, 37(10):1776.
- Khanna, S., Smith, W.R., Brasseur, J.G., Smits, A.J., Sreenivasan, K.R. 1992 Comparison of the inertial range of a high Reynolds number turbulent boundary layer with homogeneous shear flow. *Bull. Amer. Phys. Soc.*, 37(10):1739.
- Brasseur, J.G., Wei, C.H. 1991 Spectral dynamics in high Reynolds number turbulence via triadic interactions. *Bull. Amer. Phys. Soc.* 36(10): 2627.
- Yeung, P.K., Brasseur, J.G. 1991 1991 Interscale dynamics in homogeneous turbulence: Fourier and physical space views. *Bull. Amer. Phys. Soc.* 36(10): 2628.
- Brasseur, J.G. 1990 The necessity of nonisotropy in the small scales: comments on the Kolmogorov hypotheses. *Bull. Amer. Phys. Soc.* 35 (10):2305.
- Yeung, P.K., Brasseur, J.G. 1990 Response of isotropic turbulence to anisotropic forcing at the large scales. *Bull. Amer. Phys. Soc.* 35 (10):2255.
- Lin, W.-Q., Brasseur, J.G. 1990 Kinematics and dynamics of intermittent regions in homogeneous turbulent shear flow. *Bull. Amer. Phys. Soc.* 35 (10):2268.
- Wang, Q., Brasseur, J.G., Sreenivasan, K.R. 1990 Application of a 3D wavelet transform to vortical evolution in homogeneous turbulence. *Bull. Amer. Phys. Soc.* 35 (10):2254.
- Moquin, B., Brasseur, J.G., Lin, W.-Q. 1990 The use of interactive 3D graphical imaging in the study of turbulence structure. *Bull. Amer. Phys. Soc.* 35 (10):2321.

C. Papers In Preparation

- Brasseur, J.G. & Lin, W-Q. Quantitative and graphical analysis of the intermittent structure of homogeneous turbulent shear flow using a new methodology.
- Brasseur, J.G. & Lin, W-Q. Structure, statistics and dynamics of the small-scale vorticity field associated with the creation of anisotropic shear-flow turbulence from isotropic turbulence.
- Wang, Q. & Brasseur, J.G. The relationship between scale and structure at the small scales in fully developed isotropic and anisotropic turbulence.
- Wang, L-P., Brasseur, J.G., Chen, S. Phase interactions associated with large-small-scale couplings in isotropic turbulence.
- Wang, L-P., Brasseur, J.G., Chen, S. Scale interactions between scalar and velocity modes in isotropic turbulence .
- Wang, L-P., Brasseur, Chen, S., J.G., Wyngaard, J. Analysis of Kolmogorov's refined similarity hypothesis: I. small-scale velocity differences in isotropic turbulence.
- Wang, L-P., Brasseur, J.G., Chen, S., Wyngaard, J. Analysis of Kolmogorov's refined similarity hypothesis: II. small-scale scalar differences in isotropic turbulence.

V. MEETINGS, SEMINARS, WORKSHOPS

A. Invited Papers and Workshops

- June 1994 Invited one hour paper at the AIAA Fluid Dynamics Conference, Colorado Springs, Colorado, "The wavelet decomposition: locality in Fourier space, locality in physical space and the relationship between the two."
- May 1994 Johns Hopkins University, "Interscale interactions in stationary vs. nonstationary nonequilibrium turbulence."
- March 1994 National Center for Atmospheric Research, "Local similarity at the small scales in low Reynolds number isotropic turbulence."
- March 1994 Lehigh University, "Structure and statistics of scalar evolution in the flat plate turbulent boundary layer using direct simulations."
- July 1993 Invited paper at the Nonlinear Dynamics and Stochastic Processes Workshop, Center for Nonlinear studies, Los Alamos National Lab, "Interscale interactions in high Reynolds number turbulence."
- Oct. 1992 Invited paper at SIAM Conference on Applications of Dynamical Systems, Salt Lake City, Utah, "The wavelet transform as a link between physical space and Fourier space."
- July 1992 Ecole Centrale de Lyon, France, "Intermittency and anisotropy analysed using 3D wavelet transforms."
- July 1992 Ecole Nationale Supérieure, Grenoble, France, "Interscale interactions in high Reynolds number turbulence."
- April 1992 CUNY/Levich Institute, "Issues in High Reynolds Number Turbulence."
- March 1992 Los Alamos National Labs, "Turbulence Dynamics via Triadic Interactions."
- March 1992 Brown University, "Combined Quantitative and Graphical Analysis of Intermittent Regions in Homogeneous Turbulence."
- April 1992 Yale University, "Interscale Interactions in High Reynolds Number Turbulence."
- Sept. 1991 First European Fluid Mechanics Conference, Cambridge, England. (Yeung.)
- Sept. 1991 Ecole Centrale de Lyon, France, "Large and Small Scale Couplings in High Reynolds Number Turbulence."
- June 1991 USA-French Workshop on Wavelets in Turbulence, Princeton University.
- April 1991 Rutgers University, "Interactive Use of Graphical Imaging and Quantitative Measures in the Analysis of 3D Turbulence Data Sets."
- March 1991 Pennsylvania State University, "Modification of Small Scale Structure by Large Scale Forcing."
- Feb. 1991 University of Maryland, "Analysis of Intermittent Regions in Homogeneous Turbulent Shear Flow."
- Nov. 1990 43rd Annual Meeting of the APS Division of Fluid Dynamics, Cornell University, NY, (7 papers).
- Sept. 1990 Invited participant and session recorder for 1990 Workshop entitled "New Approaches to Experimental Turbulence Research," Princeton University, New Jersey.

Aug. 1990 Invited participant at 1990 "Boundary Layer Structure Workshop," NASA-Langley, Virginia.

May 1990 Cornell University: "Characteristics of Intermittent Regions in Homogeneous Turbulent Shear Flow."

B. Meetings

August 1993 AFOSR Contractors Meeting, Flagstaff, AZ (attendee.)

March 1993 Multiscale Stochastic Processes Analyzed using Multifractals and Wavelets, Cambridge University, England (2 papers, and conference organizer along with J.C. Vassilicos, P. Flandrin and J. Hunt).

March 1993 Arizona State, International Conference on near-wall turbulent flows. (1 paper)

Nov. 1992 45th Annual Meeting of the APS Division of Fluid Dynamics, Florida University, FL (5 papers relating to this program).

June. 1992 AFOSR/ONR Contractors Meeting, IIT, Chicago, IL (one presentation).

June 1992 The 4th European Turbulence Conference, Delft, The Netherlands. (1 paper)

Nov. 1991 44th Annual Meeting of the APS Division of Fluid Dynamics, Stanford, CA (1 paper).

Sept. 1991 Eighth Symposium on Turbulent Shear Flows, Munich, Germany. (1 paper)

Sept. 1991 First European Fluid Mechanics Conference, Cambridge, England. (1 paper)

June 1991 USA-French Workshop on "Wavelets and Turbulence," Princeton University (1 presentation)

April 1991 AFOSR Contractor's Meeting, Ohio State, (2 presentations)

Jan. 1991 AIAA 29th Aerospace Sciences Meeting, Reno, Nevada (2 papers).

Nov. 1990 43rd Annual Meeting of the APS Division of Fluid Dynamics, Cornell University, NY, (5 papers relating to this program).

July 1990 The 3rd European Turbulence Conference, Stockholm, Sweden (1 paper)