Workshop

"Models versus physical laws/first principles, or why models work?"

Wolfgang Pauli Institute, Vienna, Austria, February 2-4, 2011

A special feature as of all previous is a small number of participants (about 20) with plenty of time for discussions. The main concern is about conceptual (and similar, e.g. basic) issues in modeling involving people from various subcommunities in turbulence research – not just “modelers”! This is why I listed a set questions like “Why modeling works?" “What is the meaning of the term `works’ ”? "Modeling versus physics and mathematics in turbulence", "What is the meaning of experimental validation of models?" "Can models clarify the physics and produce genuine predictions or they are just a kind of ‘post-diction’ and sophisticated methods of data description/fitting?" like "Models versus physical laws/first principles". On top of this I ventured to reiterate that one of the main lines in the meeting should be a dialogue between applied/modeling and basic research turbulence sub-communities: I believe that both need this kind of discussion/dialogue; and that, one of the main attributes of the speakers is the ability the give a talk in the spirit as mentioned above (an open minded dialogue, etc.) rather than just a factual presentation!

I have written deliberately the above in a pretty broad style. This is because I do not think that for such a meeting one should dictate too much especially to open-minded people. After all such people do not start from an empty set: they have thought about similar things long before. I used this approach before several times - I dare to say – very successfully. Another aspect is that too narrow "specification" can harm the whole idea of such a meeting. The bottom line is that the "specification" is to some extent an outcome of who will come. Indeed, the hope that this will be not a set close to the empty realized.

Thanks to ALL for coming.

Special thanks are to the WPI making meetings in such a valuable format possible.

Arkady Tsinober

LIST OF PARTICIPANTS

Workshop "Models versus physical laws/first principles, or why models work?"

Claude Bardos	Univ. Pierre et Marie Curie, Paris	claude.bardos@gmail.com
Katarina Bodova	Univ. Bratislava	Katarina.Bodova@fmph.uniba.sk
Gregory P. Chini	Univ. of New Hampshire	greg.chini@unh.edu
Charlie Doering	Univ. of Michigan, Ann Arbor	doering@umich.edu
Igor Esau	Bjerknes Centre for Climate Research. Norway	igor.ezau@nersc.no
Bettina Frohnapfel	Center of Smart Interfaces, TU Darmstadt	frohnapfel@csi.tu-darmstadt.de
Christer Fureby	FOI,Sweden	fureby@foi.se
William George	Univ. de Lille and IC	georgewilliamk@gmail.com
Fernando Grinstein	Los Alamos National Laboratory	fgrinstein@lanl.gov
Harmen Jonker	Delft Univ. of Technology	h.j.j.jonker@tudelft.nl
Alan Kerstein	Sandia National Laboratories	arkerst@sandia.gov
Alexander Liberzon	Tel Aviv Univ.	alexlib@eng.tau.ac.il
Beat Lüthi	ETH Zürich	luethi@ifu.baug.ethz.ch
Michael Leschziner	Imperial College	mike.leschziner@imperial.ac.uk
Andreas Muschinski	Univ. of Massachusetts at Amherst	muschins@ecs.umass.edu
Ivan Marusic	Univ. of Melbourne	imarusic@unimelb.edu.au
Charles Meneveau	Johns Hopkins Univ.	meneveau@jhu.edu
Robert Rubinstein	NASA Langley Research Center	r.rubinstein@nasa.gov
Robert L. Street	Stanford Univ.	street@stanford.edu
Peter Sullivan	Colorado State Univ.	pps@ucar.edu
Arkady Tsinober	Tel Aviv Univ.	tsinober@post.tau.ac.il
Christos Vassilicos	Imperial College	j.c.vassilicos@imperial.ac.uk
Vladimir Zeitlin	Ecole Normale Superieure	zeitlin@lmd.ens.fr

Workshop

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All lectures in Seminarraum C714, 7th floor Nordbergstrasse 15

Wednesday, February 2, 2010

9:00-9:30		***Registration and Welcome***
9:30-10:20	Igor Essau	**Turbulence numerical model as a research tool**
10:20-10:50		**Coffee Break**
10:50-11:40	Gregory P. Chini	**Exploiting Structure: Asymptotically-Reduced and Low-Order Models of Convective and Shear Turbulence**
11:40-12:20	Peter P. Sullivan	**High Reynolds Number Large Eddy Simulation: Where Real and Virtual Turbulence Meet**
12:20 – 13:00	Harmen Jonkers	**Modeling, validation and physics of turbulent flows: opportunities offered by petascale Direct Simulation**
13:00-14:30		**Lunch**
14:30-15:20	Fernando F. Grinstein	**Simulating vortex dynamics and transition to turbulence in complex high-Re flows**
15:20-16:10	Michael Leschziner	**Single-point second-moment turbulence models – why, where and where not?**
16:10-16-50	Alex Mahalov	**3D Dynamics and Turbulence Induced by Mountain and Inertia-Gravity Waves in the Upper Troposphere and Lower Stratosphere**
16:50 - 18:20		**Discussions and Coffeee**

Thursday, February 3, 2010

9:00-9:50	Robert L. Street	Real flows have walls
9:50 -10:40	Ivan Marusic	Modelling approaches in wall turbulence
10:40 -11:10		Coffee break
11:10-11:50	Bettina Frohnapfel	Flow Control and Turbulence Modelling
11:50-12:30	Christer Fureby	Can Modeling of Reactive Flows Describe Reality?
12:30- 13:10	Allan R. Kerstein	Turbulence Still Surprises: Explorations Using a 1D Model
13:10 -14:40		Lunch
14:40 -15:20	William K. George	Does turbulence need God?
15:20 -16:00	Christos Vassilicos	Decay of homogeneous turbulence: theory, modeling, experiments
16:00 -16:40	Robert Rubinstein	A perturbation theory approach to turbulence modeling
16:40 - 18:20		Discussions and coffee

Friday, February 4, 2010

9:00 - 9:50	Charlie Doering	Bounds on turbulence: what does it mean when they exist, and what does it mean when we don't know if they exist?
9:50 -10:30	Claude Bardos	Boundary effect in the Euler limit
10:30 - 11:00		Coffee Break
11:00 -11:50	Vladimir Zeitlin	Rotating shallow water turbulence
11:50 -12:30	Charles Meneveau	"Managing" turbulence theory instead of "curing" turbulence theory – and a case study: the wind turbine array boundary layer
12:30 - 13:10	Anrdeas Mushinski	Vertical Fluxes of Local Structure Parameters in the Convective Boundary Layer
13:10 -14:40		Lunch
14:40- 17-30		*General Discussion*
14:40 -15:10	Arkady Tsinober	Introductory notes for the general discussions
15:10 – 17:30		General Discussions and Coffeee

Workshop

"Models versus physical laws/first principles, or why models work?"

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February 2-4, 2011.

Abstracts

Claude Bardos
Laboratory J. L. Lions, Universit´e Pierre et Marie Curie, Paris, 75013; Wolfgang Pauli Institute, Vienna, Austria; claude.bardos@gmail.com

Boundary effect in the Euler limit

About a joint work in progress with Francois Golse.

In this talk I intend to underline the similarities that exist between the inviscid limit of solutions of the Navier Stokes equation and the limit of solutions of the Boltzmann equation in the low mach high Reynolds number.
1. In both cases things are well understood for Navier-Stokes with the slip boundary condition and for Boltzmann when the accomodation coefficient goes to zero.
2. For the no slip boundary condition for Navier Stokes and in the presence of “strong accommodation” for the Boltzmann equation the problem is (in both cases) completely open. The only mathematical result is due to Kato and without solving the problem it connects the non-convergence with non trivial dissipation of energy at the limit and with production of vorticity in a small boundary layer.
Similar situation seems to be present in the Boltzmann limit...
Finally, I consider that with this dissipation of energy the above case 2 corresponds the best to what could be a deterministic approach of turbulence.

Gregory P. Chini
Mechanical Engineering Department, University of New Hampshire, Durham, NH 03824, USA;
greg.chini@unh.edu

Exploiting Structure: Asymptotically-Reduced and Low-Order Models of Convective and Shear Turbulence

Transport and mixing in many forced-dissipative turbulent flows is mediated by streamwise vortices, thermal convection plumes, and other quasi-coherent flow structures. Although intermittent in space and time, these structures form recurrent patterns about which the turbulent dynamics self-organizes. In this seminar, three different classes of reduced PDE/ODE models of convective and shear turbulence will be discussed. It will be shown how the reduced models can be systematically derived from the primitive governing equations using formal analytic methods that exploit the underlying flow structure.

1. Asymptotically Reduced PDE Models of Constrained Turbulent Flows. In turbulent flows with strong constraints, mode coupling in certain directions is inhibited, and multiscale asymptotic techniques can be used to derive reduced PDE models of the resulting anisotropic dynamics. Examples including “Langmuir turbulence" in the upper ocean and low-Re plane Couette flow turbulence will be described.

2. Multiscale Equation Hierarchies for Geophysical Turbulence. Multiscale asymptotic techniques can also be used to derive equation hierarchies that consistently describe the leading order turbulence dynamics over particular scale ranges as well as the dominant inter-scale couplings. This formalism is proving particularly effective for geophysical flows, and an application to the ocean surface boundary layer will be outlined.

3. A Priori Low-Order Models from Upper Bound Theory. We have developed a novel model reduction scheme for obtaining low-order ODE models of spatiotemporally complex flows.

Unlike popular, but empirical POD-based methods, this approach does not require extensive data sets from experiments or DNS and, thus, yields truly predictive models. Instead, a priori basis functions are obtained by solving a constrained optimization problem from upper bound theory. An application of this new methodology to porous medium convection will be described.

It is argued that collectively these approaches have the virtue of being fully predictive and, thus, more robust than ad hoc turbulence models while being more computationally efficient than DNS and more flexible than truly rigorous analytic methods. The chief virtue of the reduced models may be their utility in facilitating the quest for improved physical insight into complex flow phenomena.

Charles R. Doering,
Departments of Mathematics & Physics, and Center for the Study of Complex Systems, University of Michigan, Ann Arbor, MI 48109-1107 USA ;, doering@umich.edu

Bounds on turbulence: what does it mean when they exist, and what does it mean when we don't know if they exist?

In a number of interesting cases rigorous analysis of the Navier-Stokes equations yields physically meaningful limits on bulk averaged quantities in accord with turbulent theory. But there are some seemingly simple situations where we do not know how to produce such bounds. In several cases we do not even know for sure if a statistically stationary (turbulent) state exists. We discuss the significance (or the lack of significance) of these observations.

Igor Essau
G.C. Rieber Climate Institute of the Nansen Environmental and Remote Sensing Center, Thormohlensgate 47, 5006, Bergen; igor.ezau@nersc.no

Turbulence numerical model as a research tool

In contemporary science, the growth of knowledge is impossible or at least inefficient without numerical modeling. The computational fluid dynamics is arguably on the forefront of model applications with a large fraction of important results obtained through numerical simulations. Many scholars, especially among those working with model development, consider the numerical modeling as fully legitimate and straightforward "calculations", i.e. quantitative interpretations of qualitative propositions provided by one or another existing turbulence theory. The theory is supposed to be based on the first principles and therefore approximating the nature. Thus, those modelers are working within the "normal" science frameworks proposed by Thomas Kuhn, i.e. they assume the role of calculators for research leaders who post problems for them and determine quality criteria for their results.

The "culture of calculation", as we may name it, have at least two drawbacks. Firstly, the results which do not pass the imposed quality criteria are omitted and the model which produces such results is to be corrected. It helps to conduct efficient calculations for engineering projects. For research problems however, elimination of the anomalous results may lead to dead-loop of increasing support basis of erroneous theoretical constructions. As a concrete example, we will consider the modeling of the turbulence within the surface sub-layer of the stratified boundary layer flow. The models systematically provide anomalous results, i.e. results in disagreement with the dominant variant of the Monin-Obukhov theory [Brasseur et al., 2009]. Since observations are interpreted in frameworks of the dominant theory, the model-to-theory discrepancy was seen as the model-to-nature one, and therefore, the model was given the status of non-approximating within the surface sub-layer ([Mason, 1994] publication gives clear example of this line of arguments). This view has been adopted despite the clear answer from the numerical scheme analysis that it is not the case. The large body of literature is devoted to correction of the model "faults". Secondly, the results which do pass the imposed quality criteria tend to be seen as independent support for the theory. For instance, direct numerical simulations (DNS) are used to be seen as a better research tool than large-eddy simulations (LES) within the surface sub-layer despite the fact that they both fail to resolve important parts of the turbulent spectra. Moreover, the scaling analysis suggests that the latter ones should be given priority as they resolve motions carrying the bulk share of energy whereas the former ones resolve only quickly decaying turbulence in the dissipation interval of scales (conceptual discussion of physics as applied to the surface layer were given by [Hunt et al., 2000]). Nevertheless the culture of calculation requires matching of LES to DNS as DNS are seen *prima facie* as calculations of the more basic theory.

Philosophy of science helps us to create a different view on the modeling as a research tool. We may name it as the "culture of simulations". The models are seen as research approaches independent both from observations and theories. Each modeling approach – a consequence of models with gradually corrected errors – is internally consistent but not necessarily should approximate the object of study in terms of pre-imposed criteria. Criteria are now external relative to the model and therefore cannot be used to judge the simulation results. One of the first steps in this direction of thoughts was done by [Mushinski, 1997] who considered the LES results as observations of LES-fluid and proposed to compare properties of the LES-fluid with the natural fluid to identify the object of study. There are no erroneous results in the culture of simulations if the simulations are internally consistent. However, the object of study, e.g. LES-fluid, may not be similar in some sense to any natural object of interest. The step done by Mushinski bears a deep similarity to the step done by [Leray, 1934; Ladyzhenskaya, 1962] in the mathematical theory of the Navier-Stokes equations (NSE). The major advantage of the culture of simulations is that the anomalous results, which the simulations provide, are not automatically seen as errors to be eliminated. Just opposite, the results are seen as illuminative. The results are in fact new propositions to be falsified by other methods (observations, models and theories). Now, the very ability of models to produce the anomalous and therefore non-trivial results becomes the quality criteria of the research model. The trivial results or calculations in our terminology are useless for the growth of knowledge. The non-trivial results or simulations increase knowledge either progressively by discovering unknown facts or regressively by identifying the non-observed relationships. Thus, we came to the methodological falsification program by Imre Lacatos and Karl Popper.

We highlight the advantage of the culture of simulations with a specific example. Turbulence-resolving simulations of the surface sub-layer were, and largely still are, seen as erroneous calculations of the natural object – the turbulent boundary layer flow. Rejecting the culture of calculations, we see the simulations as models of artificial objects which may or may not have useful similarities to the object of study. The more observed facts model can reproduce the more progressive model is. But model does not reproduce all facts and many facts could be misinterpreted as well. Therefore, the higher quality models must produce facts not observed yet or at least not recognized. In the surface layer, the LES produced anomalies of the Monin-Obukhov non-dimensional gradients in a very special way. The analysis of these anomalies by [Zilitinkevich et al, 2008, 2010] suggested a missing theoretical link between the turbulence kinetic and potential energies leading to the total turbulence energy theory.

Bettina Frohnapfel
Center of Smart Interfaces, Technische Universität Darmstadt; frohnapfel@csi.tu-darmstadt.de

Flow Control and Turbulence Modelling

The reduction of skin friction drag in turbulent flows is a technological objective with the potential for immense environmental and financial benefits. This is particularly the case in the worldwide transport sector. A large amount of scientific research is presently being carried out in this field, often motivated from the fact that the physics behind drag reduction in turbulent flows are not well understood yet. The „unsolved turbulence problem“ is the essential research challenge in the modelling community. Therefore, it is of interest to investigate to what extent research into flow control can benefit from turbulence modeling.

In particular in the field of active flow control for skin friction drag reduction, most of the research is currently performed numerically due to various challenges (and limitations) of experimental investigations. Numerical simulations that are used in this context are typically Direct Numerical Simulations (DNS), where the Navier-Stokes equations are solved numerically without modelling. This results in extremely high computing costs. The no-modeling approach is chosen to obtain the required reliability of the results, however, the high computational cost limits its applicability to flows with simple geometries and low Reynolds number. This casts doubt on the meaning of results to the high Reynolds number flows typically found in applications. There have been a few attempts to employ rather high resolution Large Eddy Simulations (LES) to provide simulations of flow control at increased Reynolds numbers, but LES is not established as an alternative to DNS in this field.

The potential benefits of turbulence modeling for flow control are two-fold. The first advantage is rather straightforward: Flow control can benefit from the physical insight that turbulence models can provide. In our research, flow control ideas are thus often derived from modelling lines of thought. The second potential benefit is obvious but might be far out of reach at the moment: The use of turbulence models for the prediction of controlled flows, allowing to assess the effects of higher Reynolds number flows. Naturally, this would require “genuine predictions“ and not just “…‘post-diction’ and sophisticated methods of data description/fitting”. I would therefore like to raise the question whether the successful prediction of skin friction flow control could be considered as one of the ultimate challenges for the validation of a turbulence model?

Christer Fureby
The Swedish Defense Research Agency – FOI, SE 147 25, Tumba, Stockholm, Sweden;
fureby@foi.se

Can Modeling of Reactive Flows Describe Reality?

The desire to reduce transport times at the same time as we need to reduce our dependence of fossil fuels and decrease emissions, requires improved propulsion systems for aircrafts, ships and cars. In addition, we need to improve the efficiency in power generation based on fossil and bio-derivative fuels. Such developments require substantial research efforts combining experimental and numerical techniques in disciplines such as fluid dynamics, thermodynamics, structural dynamics chemical kinetics and numerical methods. Currently, it is not feasible to perform detailed measurements and flow visualizations in real engines, such as in an annular multi-burner combustor of a jet engine or in a supersonic combustion ramjet engine, whereas simulations (of different fidelity) can be performed. The simulation models (typically based on Large Eddy Simulations) cannot resolve all relevant flow structures, include all relevant chemical reactions and properly model the turbulence chemistry interactions, but still provide remarkably realistic results that agree well with the (global) data available for comparison. Considering the simplifications made and the underlying assumptions it is not obvious that this should work, and to test this, comparisons are made with experimental data from laboratory experiments. Again, surprisingly good agreement is often reached, even for moderate resolutions, but the predictions show a very strong sensitivity to how accurately the boundary conditions are modeled and how well critical, but not obvious, geometrical features are represented. The described experience is partially in contrast to the theoretical expectations, and currently lacks a proper explanation. The aim of this contribution will be to discuss these features and to seek plausible explanations to these observations that are in line with observations from other fields.

William K. George
Universite de Lille and Marie Curie Professor, Dept of Aeronautics, Imperial College of London; georgewilliamk@gmail.com

Does turbulence need God?

The recent book The Grand Design by Stephen Hawkings and Leonard Mlodinow has generated enormous public interest because it revises their earlier view that God (or at least a Creator) needed to be present to set the evolution of the universe off onto its present path. Now they argue that in fact the equations of physics contain within them the possibility of a spontaneous beginning which sets the initial conditions. These in turn determined the universe we have. Other conditions, equally probable, would have determined a very different universe. This of course means that there is no longer the need for a God, at least to set the initial conditions.

This paper will review how our views of turbulence have evolved over the past century from one in which the details of initial conditions were believed to be asymptotically forgotten and irrelevant, to the increasingly popular view that they really do matter forever. (e.g., 1, 2) The latter view appears to be consistent with both the equations and recent experiments (3,4). This presents a particular problem to the turbulence modelers, since all present RANS models are based on the first idea., and unfortunately the asymptotic effect of the initial conditions resides in the model coefficients (5). It will be concluded that while a God (if he/she exists) is not necessary to set the initial conditions, the turbulence community could most certainly use his help in figuring out what to do next.

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Fernando F. Grinstein
X-Computational Physics Division, XCP-4, MS F644, Los Alamos National Laboratory,
Los Alamos, NM 87545, USA; fgrinstein@lanl.gov

Simulating vortex dynamics and transition to turbulence in complex high-Re flows

Turbulent flow complexity in applications in engineering, geophysics and astrophysics typically requires achieving accurate and dependable large scale predictions of highly nonlinear processes with *under-resolved computer simulation models.* Laboratory observations typically demonstrate the end outcome of complex non-linear three-dimensional physical processes with many unexplained details and mechanisms. Carefully controlled computational experiments based on the numerical solution of the conservation equations for mass, momentum, and energy, provide insights into the underlying flow dynamics.

Relevant computational fluid dynamics issues to be addressed relate to the modeling of the unresolved flow conditions at the subgrid scale (SGS) level – *within a computational cell*, and at the supergrid (SPG) scale – *at initialization and beyond computational boundaries*. SGS and SPG information must be prescribed for closure of the equations solved numerically. SGS models appear *explicitly or implicitly* as additional source terms in the modified flow equations solved by the numerical solutions being calculated, while SPG models provide the necessary set of initial and boundary conditions that must be prescribed to ensure unique well-posed solutions. From this perspective, it is clear that the simulation process is inherently determined by the SGS and SPG information prescription process. On the other hand, observables in laboratory experiments are always characterized by the *finite scales* of the instrumental resolution of measuring/visualizing devices, and subject as well to SPG issues. *It is thus important to recognize the inherently intrusive nature of observations based on numerical or laboratory experiments* [1]. Ultimately, verification and validation (V&V) frameworks and appropriate metrics for the specific problems at hand are needed to establish predictability of the simulation model.

Direct numerical simulation (DNS) – resolving all relevant space/time scales, is prohibitively expensive in the foreseeable future for most practical flows of interest at moderate-to-high Reynolds number (Re). On the other end of the simulation spectrum are the Reynolds-Averaged Navier-Stokes (RANS) approaches – which model the turbulent effects. In the large eddy simulation (LES) strategies [2], the large energy containing structures are resolved, the smaller structures are filtered out, and unresolved SGS effects are modeled. By necessity – rather than choice, LES effectively becomes the intermediate approach between DNS and RANS.

Extensive work has demonstrated that predictive simulations of turbulent velocity fields are possible using a particular LES denoted implicit LES (ILES) [3], using the class of non-oscillatory finite-volume (NFV) numerical algorithms. Use of the modified equation as framework for theoretical analysis, demonstrates that leading truncation terms associated with NFV methods provide implicit SGS models of mixed anisotropic type and regularized motion of discrete observables. Tests in fundamental applications ranging from canonical to very complex flows indicate that ILES is competitive with conventional LES in the LES realm proper – flows driven by large scale features.

High-Re flows are vortex dominated and governed by short convective timescales compared to those of diffusion, and kinematically characterized at the smallest scales by slender *worm* vortices with insignificant internal structure. This motivates nominally inviscid ILES methods capable of capturing the high-Re dissipation dynamics and of handling vortices as shocks in shock capturing schemes. Depending on flow regimes, initial conditions, and resolution, additional modeling may be needed to emulate SGS driven physics, such as backscatter, chemical reaction, material mixing, and near-wall flow-dynamics – where typically intertwined SGS/SPG issues need to be addressed. A major research focus is recognizing when additional explicit models and/or numerical treatments are needed and ensuring that mixed explicit and implicit SGS models can effectively act in collaborative rather than interfering fashion.

We survey our present understanding of the theoretical basis of ILES, including connections with the classical LES and finite-scale dynamics perspectives. Examples from recent I L E S studies are presented, including canonical turbulence test cases and shock driven turbulence; relevant V&V issues are demonstrated in this context.

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Harmen Jonkers,
Clouds, Climate and Air-Quality group, Department of Multi-Scale Physics, Delft University, the Netherlands; h.j.j.jonker@tudelft.nl

Modeling, validation and physics of turbulent flows: opportunities offered by petascale Direct Simulation

Modeling can only 'work' when sufficiently constrained by (experimental) validation. An important distinction to be made in this respect is whether the model predictions are validated or, more directly, the physical hypotheses underlying the model. Geophysical flows in general share the additional problem that, on the relevant lengthand time scales, it is hard to perform experiments that are sufficiently controllable and reproducible, both of which are key scientific aspects. Important advances in our understanding of geophysical flows have therefore originated from idealized down-scaled laboratory experiments. However, on a number of important aspects these experiments have also generated a substantial degree of controversy which to date still exist.

In this discussion I want to point to the prospects offered by petascale/exascale Direct Numerical Simulation, which can form a suite of 'ideal' experiments, resolve existing controversies, and allow validation not only of model predictions but also of the underlying physical assumptions. As a specific example we focus on the growth-rate law for the evolution of atmospheric convective boundary layers. For weather, climate, and air quality models, it is of vital importance to correctly forecast the evolution of the boundary layer, which grows in time due to daytime heating, wind-shear, etc, but the most widely employed growth rate law is still riddled with controversy: results from atmospheric observations, large eddy simulations, and laboratory experiments are mutually inconsistent and display substantial scatter rendering an accurate prediction of the boundary layer height based on these results questionable.

Our goal was to end this controversy by conducting ground truth Direct Numerical Simulation (DNS) of convective boundary layers. Of course one cannot simulate the high Reynolds number of atmospheric turbulence, but present computer resources do allow one to faithfully simulate the classical laboratory experiments that gave rise to the existing growth rate laws for the ABL, and to even reach Reynolds numbers more than ten times higher than the classical experiments. These simulations, conducted at the Bluegene supercomputer in Juelich, used 3072x3072x1536 gridpoints employing 32,768 cores in parallel.

The simulations shed light on why different laboratory experiments, conducted in the past by various groups using different methods, gave different growth-laws. By mimicking these experimental conditions in our simulations, that is by accounting for the actual fluid properties that were used in the experiments, we could exactly simulate those historical experiments and get insight into how the fluid-properties (in particular its viscosity, conductivity/diffusivity) must have influenced previous findings on the boundary layer growth-rate.

Allan R. Kerstein
Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94551-0969;
arkerst@sandia.gov

Turbulence Still Surprises: Explorations Using a 1D Model

One computational strategy for capturing micro-scale processes not affordably resolved in multi-dimensional turbulence simulations is to represent these processes by a lower dimensional formulation. An approach formulated in one spatial dimension, denoted One-Dimensional Turbulence (ODT), is outlined. ODT combines two 1D approaches that have individually proven successful: stochastic iterated maps and dimensional reduction of the governing equations using the boundary-layer approximation. Within ODT, sub-processes based on these two approaches are coupled so as to represent both turbulent cascade dynamics and micro-physics at dissipative scales, including their two way interaction. ODT has predictive capability for canonical flows and has been implemented as a sub-grid closure for 3D flow simulation. (Its simpler predecessor, the Linear Eddy Model, predicts mixing in specified turbulent flow states.) The use of these models for computationally affordable exploration of otherwise inaccessible flow and mixing regimes has led to surprising insights, indicating that it can be hazardous to extrapolate empirical understanding of turbulence phenomena beyond well studied regimes.

Michael Leschziner
Imperial College London, Aeronautics Department, Prince Consort Rd., London SW7 2AZ; mike.leschziner@imperial.ac.uk

Single-point second-moment turbulence models – why, where and where not?

The writer once overheard a well-known *turbulence purist* contemptuously mutter under his breath "*nothing but glorified curve fitting*" while listening to a presentation on the construction and application of statistical turbulence models. The writer begs to differ and to challenge the implied denigration of the intellectual substance - and, yes, a good measure of rigor - underpinning such models. In any event, might it be helpful to remind this purist – and probably others who hold similar views - that flying safely in an aircraft at 35000 ft, with engines 1000 times more powerful and 10 times more reliable than a BMW power plant, has much more to do with turbulence modeling than one's insight into the universality of the dissipative processes in isotropic homogeneous turbulence?

Over the past two decades, scale-resolving simulations (DNS and LES) have gradually sidelined statistical modeling in turbulence research, and the writer has himself contributed to this move. However, the oft-heard prediction that "*LES will become the default design tool in fluid-flow engineering within 5 years*", has turned out to be a serious exaggeration, except in so far as the 5-year span seems to remain invariant as the clock ticks. The most outlandish prediction currently in vogue is that a direct numerical simulation of an entire aircraft should be possible by 2080. Fact is that statistical models remain the basis for the large majority of engineering-related predictions for high-Reynolds-number flows. Indeed, statistical models are acquiring an enhanced lease of life in being used (some would say, wrongly) within hybrid RANS/LES for high-Reynolds-number near-wall flows – arguable, the only realistic approach to the exploitation of LES in practice.

Statistical models "work", albeit with variable accuracy, and only if applied within constraints dictated by choices made and decisions taken during their construction. If statistical models have acquired something of a poor reputation then it is mostly because of lack of insight into the differences between model classes and variants, lack of understanding of their inherent limitations, ill-informed use and commercially-motivated hyperbole by software vendors. A critical appreciation of the capabilities and limitations of models, based on much experience and insight, is the key to a productive exploitation of turbulence models. The cardinal rule is to restrict modelling to flows that do not feature influential coherent and periodic components with scales overlapping the stochastic range, and/or in which the length and time scales associated with the mean motion are significantly larger than the corresponding turbulence scales.

Of the many approaches to single-point closure, that based on the solution of transport equations for the second moments has the strongest fundamental foundation. Its principal advantage is that the production rates of the second moments are represented exactly (in a formal sense). This is the most important contributor to the correct prediction of turbulence anisotropy in complex strain. However, other important processes that require modeling, most notable pressure-velocity correlations and dissipation, are also very influential, and therein lies the main closure challenge. There are many options for approximating these processes. All involve a mix of rational principles, intuition and calibration, as is the case with most models. The talk will introduce the closure framework, highlighting the importance of production in particular strain fields, outline some closure approximations and associated limitations, and discuss, particularly in respect of separated near-wall flows, the contribution of data derived from highly-resolved LES, including second moment budgets, to the study and optimization of such models.

Alex Mahalov
Center for Environmental Fluid Dynamics, Department of Mechanical and Aerospace Engineering, School of Mathematical and Statistical Sciences, Arizona State University; mahalov@asu.edu

3D Dynamics and Turbulence Induced by Mountain and Inertia-Gravity Waves in the Upper Troposphere and Lower Stratosphere (UTLS)

The generation and physical characteristics of inertia-gravity waves radiated from an unstable forced jet at the tropopause are investigated through high-resolution numerical simulations of the three-dimensional Navier-Stokes anelastic equations. Such waves are induced by Kelvin-Helmholtz instabilities on the flanks of the inhomogeneously stratified jet. From the evolution of the averaged momentum flux above the jet, it is found that gravity waves are continuously radiated after the shear-stratified flow reaches a quasi-equilibrium state. The time-vertical coordinate cross-sections of potential temperature show phase patterns indicating upward energy propagation. The sign of the momentum flux above and below the jet further confirms this, indicating that the group velocity of the generated waves is pointing away from the jet core region. Space-time spectral analysis at the upper flank level of the jet shows a broad spectral band, with different phase speeds. The spectra obtained in the stratosphere above the jet show a shift toward lower frequencies and larger spatial scales compared to the spectra found in the jet region. The three-dimensional character of the generated waves is confirmed by analysis of the co-spectra of the spanwise and vertical velocities. Imposing the background rotation modifies the polarization relation between the horizontal wind components. This out-of-phase relation is evidenced by the hodograph of the horizontal wind vector, further confirming the upward energy propagation. The background rotation also causes the co-spectra of the waves high above the jet core to be asymmetric in the spanwise modes, with contributions from modes with negative wave-numbers dominating the co-spectra. In the second part of the talk, we present high resolution simulations in real atmospheric conditions of mountain waves in the UTLS during the Terrain-induced Rotor Experiment (T-REX). In these simulations, the finest nest of WRF is coupled with microscale nests, within which the three-dimensional fully nonhydrostatic compressible moist atmospheric equations are solved with Comparison of simulations with in situ balloon and aircraft measurements obtained during T-REX show favorable agreement.

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Ivan Marusic
Department of Mechanical Engineering, University of Melbourne, imarusic@unimelb.edu.au

Modelling approaches in wall turbulence

My talk will consider different approaches to the problem of numerically simulating wall-bounded turbulent flows under different conditions: from varying pressure gradient flows to high Reynolds numbers. Each method involves some modeling, whether using simple algebraic relations to ones based on coherent vortex structure concepts. The advantages and disadvantages, both theoretical and practical, will be discussed. The role of experimentation for validation or providing empirical input will also be considered.

Charles Meneveau
Johns Hopkins University, Department of Mechanical Engineering and
Center for Environmental and Applied Fluid Mechanic meneveau@jhu.edu

"Managing" turbulence theory instead of "curing" turbulence theory – and a case study: the wind turbine array boundary layer

Thinking about the state of turbulence modeling, we draw loose parallels to cancer research, where great strides have been made in "managing the disease" even though no "cure" has ever been found. To frame the discussion in more concrete terms, we describe the specific case of the turbulent boundary layer, about which much is known empirically in terms of statistics, coherent structures, universal properties, and scaling laws. A test of our ability to "manage" the problem is whether, when one is confronted with a different (new) boundary layer flow, the accumulated knowledge and models still can be applied to provide useful and quantitative insights. In this presentation, I will discuss the case of a new type of boundary layer that has begun to attract considerable attention because it is expected to become widespread: the wind turbine array boundary layer. While many "wind industry CFD codes" have been developed to predict performance of wind turbine arrays under various practical conditions, relatively little is known from a fundamental viewpoint about this flow. I will discuss the role played by classical boundary layer momentum theory in elucidating the fundamental structure of such boundary layers.

Andreas Mushinski
Department of Electrical and Computer Engineering, University of Massachusetts Amherst, Amherst, MA 01003-9284; muschinski@ecs.umass.edu

Vertical Fluxes of Local Structure Parameters in the Convective Boundary Layer

Vertically pointing clear-air radar wind profilers and sodars have been widely used to measure vertical profiles of the vertical wind velocity and of clear-air reflectivity.
The clear-air radar reflectivity is proportional to the refractive-index structure parameter, C^2_n, and the clear-air sodar reflectivity is (approximately) proportional to the temperature structure parameter, C^2_T . The convective boundary layer is characterized by intermittent turbulence. That is, turbulence statistics such as local structure parameters vary randomly in space and time, often with approximately lognormal probability density functions (e.g., Muschinski, Frehlich, and Balsley, 2004: *J. Fluid Mech.*, 515, 319-351). If there are nonzero vertical fluxes of the local refractive-index and/or temperature structure parameters (that is, if the local structure parameters are correlated with the local vertical wind velocity), then biases may occur, such that the mean radar and/or sodar Doppler velocity is different from the mean vertical wind velocity. I will discuss observational, theoretical, and computational aspects of vertical fluxes of local refractive-index and temperature parameters.

Robert Rubinstein

Computational Aerosciences Branch, Mail Stop 128, NASA Langley Research Center, Hampton, VA 23681; Robert.Rubinstein-1@nasa.gov

A perturbation theory approach to turbulence modeling

It is a truism that the main obstacle to formulating a statistical theory of turbulence is the lack of a natural small expansion parameter. Modeling should have an advantage because it requires the space and time scales of turbulence to be small compared to those of the mean flow. This hypothesis of "scale separation" underlies perturbation schemes like Yoshizawa's two-scale direct interaction approximation.

We extend these ideas by formulating a general approach to deriving finite dimensional models from statistical closure theories. We assume that the closure theory admits a family of exact solutions parameterized by a small number of key variables and ask for equations of motion for these variables that lead to new, approximate solutions of the closure theory. The required equations prove to be the compatibility conditions that permit computing perturbation theory to arbitrary order. This method produces a "two-equation model" if the family of exact solutions is parameterized by two parameters, for example, by an energy and a length scale, but it would lead to more complex models if the solution is parameterized, for example, by descriptors of anisotropy of turbulence.

In the case of time-dependent solutions of the classical Heisenberg model constructed from local Kolmogorov steady states, it can be shown that this theory makes possible a demonstration of the Tennekes-Lumley balance under some explicit hypotheses and suggests alternatives when these hypotheses are not valid.

Robert L. Street
School of Engineering, Stanford University; street@stanford.edu

Real flows have walls

As an engineer and/or meteorologist, my objectives almost always include the prediction of flow behavior in three-dimensional, unsteady, and inhomogeneous cases relative to particular physical situations, ranging from weather forecasting, to detection of mines buried in the ocean floor, or to defining the bathymetry of a river or stream solely by remote sensing and numerical simulation. My flows all have walls that play a deciding role in the flow conditions.

Drawing from experience in mechanical engineering, civil engineering and meteorology, we examine herein flows that occur in some realistic wall-bounded flow cases where numerical simulations have shown new phenomena or explicated results obtained in experiments. We distinguish between the physical laws which are assumed to be represented adequately by the Navier-Stokes equations and numerical simulation codes which we can consider to be models of the equations. We will touch on issues such as why certain models work and some do not and what "validation" of model results usually is accepted and how good a measure of success that might be.

We begin with the lid-driven cavity problem which is a surrogate for wall cutouts for heat transfer in mechanical engineering equipment and the channels on microchips for computers. There are two lessons here in a non-turbulent flow, viz., (1) successful simulation codes have to include algorithms that can actually reproduce the flow physics, i.e., adequately represent the Navier-Stokes equations, and (2) experiments can show that otherwise well-behaved and properly formulated simulations are incorrect.

Next we turn to sediment transport where over a decade we have come to the stage where a numerical large-eddy simulation can elucidate the precise physics of the generation of ripples and dunes from a flat bed. First, we look at the oscillating flow over vortex ripples to see the value of LES in understanding physics; second, we examine the evolution of ripples from a flat bed with a bed-following moving grid.

Finally, we explore the role of turbulence modeling in simulations of the atmospheric boundary layer with attention to the idea of incorporating as much physics "as is needed" into our large-eddy simulation models in order to correctly predict flow behavior. Our linear algebraic subgrid scale model with reconstruction of the resolved subfilter scales is featured.

Thus, we suggest that "Yes!" is answer to the question: "Can models clarify the physics and produce genuine predictions?"

Peter P. Sullivan
National Center for Atmospheric Research, Boulder; pps@ucar.edu

High Reynolds Number Large Eddy Simulation: Where Real and Virtual Turbulence Meet

Atmospheric and oceanic boundary layers provide the interfacial glue that connects land-atmosphere and atmosphere-ocean and thus geophysical boundary layers are one of the key building blocks for weather and climate. For example, the maximum surface layer winds in typhoons - the horizontal scale of a typhoon is O(100 km) - are dictated by the sea surface drag which results from the interaction between small scale turbulence, O(100 m) or less, and a dynamic surface gravity wavefield. Outdoor boundary layers are abundant with physical processes that span a wide range of time and space scales, e.g., thermal plumes, hairpin vortices, and surface and internal waves. Boundary-layer turbulence evolves at high Reynolds number, is always three-dimensional, and spans more than six decades in scale. The boundary-layer measuring environment is often harsh and acquiring three-dimensional datasets is challenging. Consequently, turbulence resolving high Reynolds number large eddy simulation (LES) plays an important role in elucidating boundary-layer dynamics. LES allows systematic hypothesis testing and on occasion can guide the direction of future measurements.

In this presentation, we show recent LES of marine boundary layers in the presence of moving surface waves. These idealized computations provide surprising insights as to the interaction between winds, waves, and currents, and in particular the development of wave-driven winds in the atmosphere and Langmuir turbulence in the ocean. We also ask a basic question of our LES: Do LES solutions converge with mesh refinement? We attempt to answer this question by performing a grid resolution study of the familiar canonical daytime convective boundary layer over flat terrain. LES generated velocity and scalar statistics and entrainment rates are compared on meshes varying from 323 to 10243. Finally we ask what observations are needed to improve subgrid-scale modeling in LES. Observations of subgrid-scale variables in the atmospheric surface layer highlight the importance of anisotropic flux production when the LES filter scale approaches the integral scale of the turbulence. The above results illustrate LES nicely compliments observations but there are improvements to be made in the technique.

Christos Vassilicos
Imperial College London, Aeronautics Department, Prince Consort Rd., London SW7 2AZ; j.c.vassilicos@imperial.ac.uk

Decay of homogeneous turbulence: theory, modeling, experiments

The talk will start with a review of the invariance properties of decaying homogeneous isotropic turbulence as derived from the von-Karman-Howarth equation. It will be shown that this equation actually implies an infinity of possible invariants corresponding to an infinity of different asympotic behaviors at infinity. If different initial conditions can dictate different such asympotic behaviours then the invariance properties of the von-Karman-Howarth equation are not very binding on the nature of turbulence decay. This has direct consequences on turbulence modelling, e.g. k-epsilon which critically relies on assumptions about universal turbulence decay. Wind tunnel experiments where homogeneous near-isotropic turbulence is generated with different initial conditions, some multiscale some single scale, show that, indeed, there is more than one class of decaying homogeneous turbulence. At least two classes seem to be currently identified. They differ qualitatively in terms of interscale energy transfers, one of two showing evidence of absence of the usual Richardson-Kolmogorov cascade.

Vladimir Zeitlin
Laboratoire de Meteorologie Dynamique, Ecole Normale Superieure, 24 Rue Lhomond 75231 PARIS CEDEX 05; e-mail:zeitlin @lmd.ens.fr
Authors: N. Lahaye and V. Zeitlin, LMD, ENS-UPMC

Rotating shallow water (RSW) model is the simplest retaining all essential features of more complicated geophysical fluid dynamics (GFD) models. A characteristic property of GFD is wave -vortex dichotomy, i.e. existence of two main types of dynamical entities: the slow (or so-called balanced) vortex motions, and the fast inertia-gravity waves. Theoretically, reduction to the vortex component results in dynamics close to that of incompressible 2D fluid, with similar characteristics of turbulent regimes, while elimination of the balanced component results in nonlinear wave dynamics with typical wave-turbulence predictions.
Recent progress in finite-volume methods for shallow water type systems allows for efficient direct numerical simulations of nonlinear phenomena in RSW, including the inherent front (shock) formation. We use such simulations for investigation of elementary dynamical processes and of fully turbulent regimes. We first study the interaction of elementary vortex structures: the modons, which were recently discovered in the RSW model, and show that their collisions are of 4 main types : elastic, with an exchange of cyclonic or anticyclonic partner, elastic with formation of modons of a new type, inelastic with a coherent tripole formation, and inelastic ones with stretching and reorganization of one component. Surprisingly, these highly nonlinear processes have a very small wave signature. It should be stressed that existence of stable tripoles and far-separated modons of "nonlinear" (according to their scatter plot) type were unknown in RSW. We show then how all this interactions shape the RSW turbulence in simulations initialized with a large number of modons.
We then study the purely wave RSW turbulence, by initializing our simulations with an ensemble of random-phase inertia gravity waves. We show that, at least at our (rather high) resolution, none of the spectra predicted for wave turbulence in this model ("weak" turbulence, "shock" turbulence) is realized.
The RSW turbulence is then studied in detail in different regimes of parameters by initializing the DNS with ensembles of modons. All standard characteristics of such turbulence are obtained (spectra, structure functions etc), but no convergence to the 2D turbulence results is observed, even in the regimes which should be close according to (asymptotic) theory. We tentatively explain this result by the wave admixture to the vortex component.