

The Nature of High Reynolds Number Turbulence

26 August to 19 December 2008

Report from the Organisers:

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Scientific Background

Turbulence holds a unique place in the field of classical mechanics. Despite the fact that the governing equations have been known since 1845, there is still surprisingly little we can predict with relative certainty. Yet turbulence is of immense importance in engineering, geophysics and astrophysics. It controls the drag on cars, aeroplanes and bridges, and dictates the weather through its influence on large-scale atmospheric and oceanic flows. The liquid core of the earth is turbulent and it is this which maintains the terrestrial magnetic field against the natural forces of decay. Solar flares are a manifestation of turbulence, being triggered by the vigorous motion on the surface of the sun. Turbulence is even important in accretion discs, providing a mechanism by which material can accrete radially inwards.

From a physical point of view turbulence may be regarded as an evolving velocity field which is spatially complex, contains a very wide range of scales, and is chaotic in both space and time. Despite this complexity, it is observed that turbulence exhibits many near-universal features, particularly at high Reynolds numbers. Near boundaries, for example, the distribution of the mean component of velocity, as well as the fluctuating components of motion, are found to have a near-universal statistical form, being the same on an aircraft wing, in a pipe, or in the atmospheric boundary layer. Away from boundaries, the way in which energy is distributed among the eddies of different scales is also found to be nearly universal, following (at least approximately) laws proposed by Kolmogorov. Universality is also observed in turbulence subject to a strong background rotation or stratification, and such turbulence is of crucial importance in geophysics and meteorology. In rapidly rotating turbulence, for example, the large-scale eddies are observed to take the form of long-lived, columnar cyclones, aligned with the rotation axis, while in stratified turbulence the large eddies are flat and pancake-like. Even in magnetohydrodynamic (MHD) turbulence, where magnetic fields play a key role and which is so ubiquitous in astrophysics, there are many universal characteristics, the most striking of which is its streaky pattern aligned with the mean magnetic field.

Some of this universality was anticipated by the pioneers of the subject, such as Richardson, Prandtl and Kolmogorov, and the various theories they developed are still highly influential in our thinking. However, for a long time most of these theories had the status of plausible conjecture, or else regarded as mere cartoons which were consistent with observation. So turbulence came to be thought of as a largely unsolved problem, or rather a set of many unresolved problems. In recent years, however, there has been some room for cautious optimism. In near-wall turbulence, for example, large-scale experiments and computer simulations have allowed us to understand much better the kinds of dynamical cycles and vortical structures which dominate the turbulent motion, and it turns out that these cycles and structures have much in common with those recently discovered in the context of transition to turbulence. Away from boundaries, other vast computer simulations have provided new insights into the mechanisms by which energy is passed down from the

largest to the smallest eddies in turbulence and this, in turn, has helped to provided a more mechanistic understating of Kolmogorov's statistical laws. Recent experiments and computer simulations have also yielded new insights into rotating, stratified and MHD turbulence. For example, we now understand the origin of the columnar cyclones which dominate rotating turbulence, and can predict the rate of decay of energy in MHD turbulence.

This programme addressed all of these fundamental issues and many more, attracting theoreticians and experimentalists from a wide range of backgrounds, including engineering, mathematics, geophysics, meteorology, solar physics and astrophysics. The goal, which was achieved, was to bring together the world's leading experts to debate the fundamental nature of turbulence, ranging from how it is initially triggered through to its asymptotic state at high Reynolds number, and how its structure is affected by adding rotation and stratification, as in our oceans and atmosphere, or adding magnetic fields, as in astrophysics.

Structure of the Programme

Around 240 mathematicians and scientists from 16 countries participated in the programme, including 48 long-stay visiting fellows and 41 programme participants who stayed for a several weeks.

8-12 September 2008	Workshop # 1	Wall Bounded Shear Flows: Transition and Turbulence
26 September 2008	1-day meeting	Prospects of High Performance Computing in Turbulence Research
29 September – 3 October 2008	Workshop # 2	Inertial-Range Dynamics and Mixing
31 October 2008	1-day meeting	Euler at Newton: The Inviscid Equation
3-7 November 2008	Workshop # 3 (Satellite held at Warwick)	Structure and Waves in Anisotropic Turbulence
17 November 2008	1-day meeting	Open for Business: Turbulence in Fluids
8-12 December 2008	Workshop # 4 (Co-sponsored by IUTAM)	Rotating Stratified Turbulence and Turbulence in the Atmosphere and Oceans

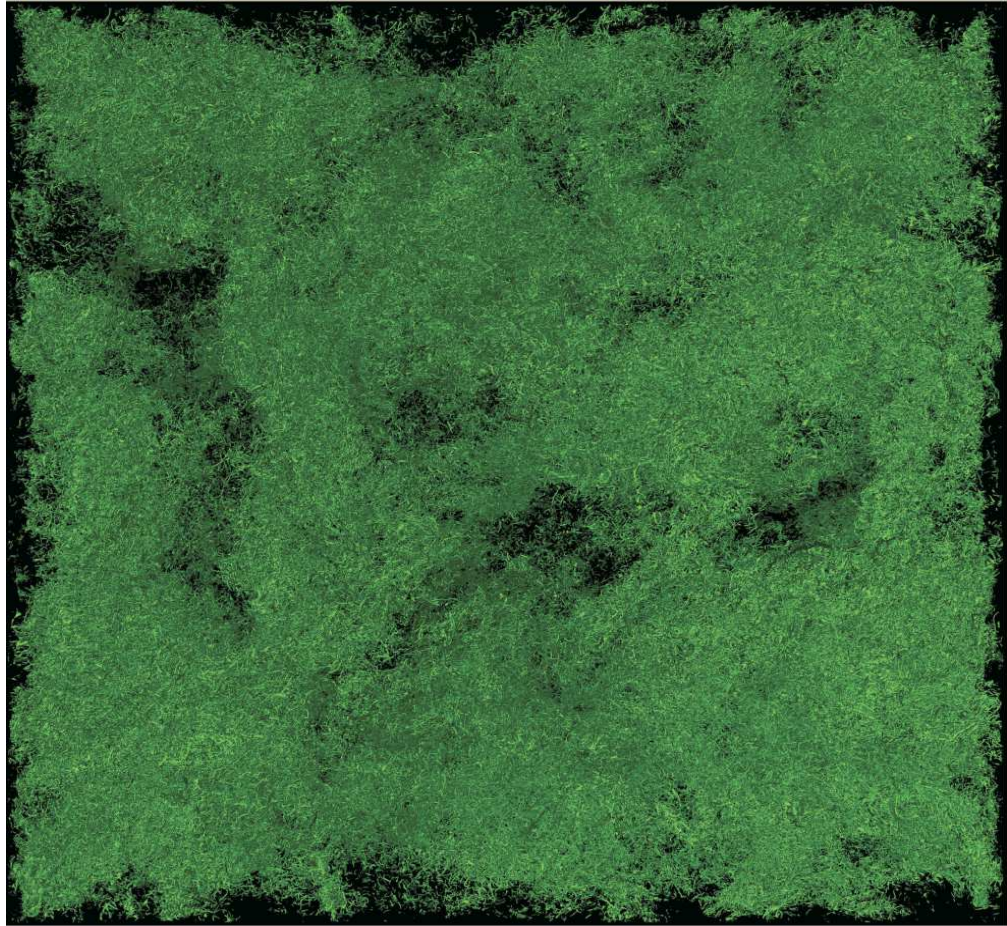


Figure 2: The small scale structure of turbulence, as computed on the Earth Simulator in Japan. The figure shows the vorticity field in the turbulence. This consists of a multitude of very fine-scale tubular vortices, as anticipated by Burgers over half a century ago. (Courtesy of T. Ishihara and Y. Kaneda.)

The various meetings organised during the programme are shown above. The programme started with a workshop on wall-bounded shear flows, including transition to turbulence, and ended with a workshop on rotating stratified turbulence and turbulence in the atmosphere and the oceans. Partway through the programme there was another workshop on the small-scale structure of turbulence (the so-called inertial range) and turbulent mixing. All three workshops attracted around 100 participants and lasted one week. In addition, a satellite workshop was organised at Warwick on the interaction of waves and turbulence. All of the workshops were successful, receiving very high approval ratings from the participants. Two of the workshops, 1 and 3, deliberately mixed people from quite different backgrounds and in both cases this sparked a vigorous and exciting debate.

Between workshops we had a regular diet of around three seminars a week, as well as special themed days, including a meeting on the future role of high performance computing and another on the inviscid Euler equation and associated finite-time singularities. In total 211 talks were given at the institute and a further 44 talks elsewhere in the UK. We organised an open day on turbulence, which attracted key people from industry, government agencies and the world of finance, and arranged exchange talks with the our companion programme on Anderson localisation. Our Rothschild Visiting Professor was K. R. Sreenivasan, whose lecture on super-fluid turbulence stretched the capacity of the institute's largest lecture theatre.

All of these activities provoked much animated discussion. However, judging from the questionnaires completed by the programme participants, the most important

interactions were the informal discussions at blackboards and around the coffee machine which became a regular feature of the programme.

Workshops and Themed Days

Workshop 1. Wall Bounded Shear Flows: Transition and Turbulence

8-12 September 2008

Organisers: P. A. Davidson, R.R. Kerswell, H. Nagib, T. Nickels & K.R. Sreenivasan

Participants: 95

The aim of this workshop was to bring together experimentalists and theorists interested in high Reynolds (Re) number boundary layers with those working at transitional and low (weakly turbulent) Reynolds numbers in sheared systems. Traditionally these communities have been separated by approach (as well as Re) since the direct methods used at low Re are impractical at the high Re of industrial and atmospheric applications. However, advances in computing and recent successes applying dynamical systems ideas to the Navier-Stokes equations have opened up the real possibility of closing this gap. Special efforts were made to introduce and orientate one community to the issues and recent successes of the other through two introductory lectures given on the first day. The 95 participants (33 UK, 20 US, 25 European, 6 Japanese, 3 Indian, 3 Australian, 2 Israeli, 1 Chinese, 1 Russian & 1 Iranian) were roughly split evenly between the two communities and the 60 research talks arranged loosely in themes and interwoven to emphasize the synergies between the communities. Subjects discussed at the workshop included dynamical system approaches to shear flows, numerical and experimental investigations of the spatiotemporal dynamics of transitional and fully-developed flows (especially the role of coherent structures), near-wall and outer scale interactions, scaling and universality. A particular feature of the workshop was the success of impromptu discussion sections arranged for the end of each day to discuss issues raised during the workshop. Also, unusually, the workshop closed with a two-hour discussion period on the Friday afternoon which was extremely well attended and productive.

Prospects of High Performance Computing in Turbulence Research

26 September, 2008.

Organiser: Y. Kaneda

Participants: 47

The aim of this one-day meeting was to help the turbulence research community make the best use of the unprecedented development in computer power, and use it to improve our understanding of the nature of high Reynolds number turbulence. The meeting consisted of four 45-minute invited lectures by leading experts: M. Yokokawa and T. Zachariah in computer science, and J. Jimenez and P. K. Yeung in turbulence research. Following the lectures there was an animated discussion session on the future prospect and role of high performance computing in turbulence research.

Workshop 2. Inertial-Range Dynamics and Mixing

29 September -3 October 2008

Organisers: P. A. Davidson, Y. Kaneda & K.R. Sreenivasan

Participants: 105

The aim of this workshop was to bring together researchers in the communities of theory, modelling, numerical simulations, laboratory experiments and field-observations, to discuss and exchange new ideas on fundamental but unanswered questions of turbulence related to

inertial-range dynamics and mixing. The focus was on the near-universal physics of such phenomena as observed in canonical turbulent flows at high Reynolds number. The workshop attracted 105 researchers from 15 countries, of whom 39 were from the UK. The workshop consisted of 56 talks and 12 poster presentations. These presentations covered a wide range of problems of turbulent flows from the quantum to the cosmological scale. The topics discussed included vortex dynamics and structure, intermittency, anomalous scaling, turbulent diffusion, Lagrangian dynamics, turbulence modelling, super-fluid turbulence, MHD and 2-dimensional turbulence.

Thanks to recent spectacular advances in the numerical simulation of turbulence, together with those in computer visualization, the simulations have now reached a stage which allows us to directly probe and visualize the fundamental structure of high Reynolds number turbulence, and to interrogate its statistical properties, rather than having to rely on uncertain conjectures or indirect measurements for this information. In parallel with the simulations, high quality experimental and observational data are also becoming available. These advances have helped us examine and develop theories of turbulence, and deepen our understanding. Presentations and discussions based on these advances invoked new ideas and insights among the participants. Attention focused particularly on the problems of the geometrical structure of turbulence, the energy cascade and dissipation in classical and super-fluid turbulence, the origin and growth of singularities, Lagrangian dynamics and scaling, and scaling in atmospheric turbulence.

Euler at Newton: The Inviscid Equation

31 October 2008

Organisers: J Gibbon, R Kerr & R.R. Kerswell

Participants: 43

The aim of this one-day meeting was to assess scientific progress one year on from the IUTAM Symposium 'Euler250' which marked the 250th anniversary of the publication of Euler's equations. The meeting consisted of five invited one-hour talks given by M. Brachet, P. Constantin, K. Ohkitani, P. Orlandi and A. Pouquet which concentrated on detailing recent analytical and numerical advances in understanding how solutions of the (inviscid) Euler equations are related to those of the (viscous) Navier-Stokes equations and ultimately turbulence.

Workshop 3. Structures and Waves in Anisotropic Turbulence

3-7 November 2008

Organisers: S. Nazarenko, C. Connaughton, P. Bartello, P. A. Davidson & A. Schekochihin
(A satellite meeting at the Warwick Mathematics Institute)

Participants: 47

This workshop was a satellite event of the Isaac Newton Institute programme and also a follow-up to the activities of the Warwick Turbulence Symposium. The workshop focused on fundamental effects in turbulence arising from the presence of waves or structures in anisotropic media. Turbulence anisotropy may be caused by an externally applied magnetic field (plasma and MHD systems), or by rotation and stratification. The talks covered a range of application areas, from astrophysical to geophysical to laboratory systems, with the main emphasis on finding common features in these different flows, as well as identifying their fundamental differences.

Speakers included: O. Alexandrova (Koeln), P. Bartello (McGill), P. Berloff (Woods Hole), W. Bos (Lyon), J-M. Chomaz (CNRS-Ecole Polytechnique), S. Cowley (UCLA), P. A. Davidson (Cambridge), D. Dritschel (St. Andrews), R. Ecke (CNLS-LANL), S. Fauve (ENS Paris), J.-B. Flor (Grenoble), B. Galperin (Florida), S. Galtier (U.Paris-Sud), J.C.R. Hunt (UCL), R. Kerr (Warwick), M. McIntyre (Cambridge), H.K. Moffatt (Cambridge), A. Pouquet (NCAR), F. Sahaoui (CNRS), A. Schekochihin (Imperial), J. Shipton (Oxford), C. Staquet (Grenoble), S. Sukoriansky (Ben Gurion), B.J. Taylor (JET), C. V. Tran (St. Andrews), J.C. Vassilicos (Imperial), T. Yousef (Cambridge), V. Zeitlin (ENS Paris).

Our main goal was to encourage people from different research areas (geophysical turbulence and plasma turbulence) to interact, exchange ideas and learn from each other. We felt that this interaction would allow us to benefit from each other's experience and knowledge of tackling similar physical problems arising in these different areas. Thus we encouraged an informal character of presentations aimed at reaching out to interactivity, with plenty of questions asked and comments made during the talks. The approach was successful and, as a result, we had many fruitful discussions during the workshop. Numerous participants commented that they appreciated these discussions, they learned new things from the talks, and they generally enjoyed the workshop (e.g. as expressed by Moffatt, Chomaz, Ecke, Dritschel, Pouquet, Rincon, Alexandrova, Schekochihin, Galperin, Sukoryanski, Staquet, Taylor, Yousef, Zeitlin and Tran).

Open for Business: Turbulence in Fluids

17 November 2008

Organisers: Sir David Wallace (Director, INI), R. A. Leese (Smith Institute) & P. A. Davidson (Cambridge)

Participants: 17

This meeting attracted leading people from industry, government agencies and finance. After a key-note talk by Prof. K.R. Sreenivasan (Director, ICTP, Trieste), there was a wide-ranging discussion coordinated by a panel of experts, which included Lord Hunt (UCL), Tony Hutton (Airbus), Tim Palmer (ECMWF), and Tony Purnell (FIA). The discussion centred on the importance of turbulence for the wider community, including commerce and government agencies. It continued over dinner at Churchill College.

Workshop 4. Rotating Stratified Turbulence and Turbulence in the Atmosphere and Oceans

8-12 December 2008

Organisers: David Dritschel (St Andrews), Peter Bartello (McGill), Peter Davidson (Cambridge), Ross Griffiths (ANU, Canberra), Keith Moffatt (Cambridge), Joel Sommeria (LEGI, Grenoble), Kraig Winters (UCSD), Shigeo Yoden (Kyoto)

Participants: 86

This workshop/symposium, jointly supported by the International Union of Theoretical and Applied Mechanics, focused on the fundamental structure of atmospheric, oceanic and planetary circulations, and in particular on the way in which small-scale turbulence collectively organises such flows on large scales. Themes included the emergence of 'jets' or currents and 'eddies' or spinning coherent masses of fluid (vortices), the 'equilibration' of turbulence through the saturation of fluid dynamical instabilities, possible routes to turbulence via natural instability processes (barotropic, baroclinic, inertial, zig-zag, etc.), the effect of rotation and stratification on scale cascades (e.g. upscale or downscale energy transfers), the importance - or not - of gravity-wave emission in turbulent flows, 'balance' or the proximity of geophysical flows to a gravity-wave-free state, state-of-the-art

numerical methods for the simulation of turbulent geophysical flows, statistical properties of turbulent mixing and the role of mixing in the formation of coherent vortices, the energetics of ocean dynamics (the role of tides, gravity waves, vortices, surface buoyancy forcing, etc), as well as turbulence in magnetised fluids.

The workshop demonstrated that there is a very rich diversity of ways in which turbulence plays a major part in naturally-occurring fluid flows, and in which researchers seek to understand it. Rotation and stratification clearly complicate matters, by introducing a number of new parametric dependencies, but they also simplify some aspects, by exhibiting an astonishing degree of organisation, consisting of long-lived vortices, fronts, and global-scale circulation patterns like the zonal bands on Jupiter. This is scientifically fascinating, and deeply challenging - it is clear that we are only at the beginning of piecing together the puzzle. The huge interest generated by this workshop is encouraging.

Speakers included many world-leading experts such as Peter Rhines (University of Washington), Jim McWilliams (UCLA), Gregory Falkovich (Weizmann Institute), Fritz Busse (University of Bayreuth), Michael McIntyre (Cambridge), Geoff Vallis (Princeton University), Jack Herring (National Center for Atmospheric Research), James Riley (University of Washington), Jean-Marc Chomaz (Ecole Polytechnique, Paris), and Lord Julian Hunt (Imperial College and former Director of the UK Meteorological Office), who introduced the workshop.

Altogether, there were 60 presentations (40 talks and 20 posters), and the meeting was attended by more than 100 people, of which 86 were official participants in the INI programme. Ample time in breaks and after sessions permitted in-depth discussions, and social occasions like the guided tour and the conference dinner at St John's allowed participants to relax and get to know each other personally.

Outcome and Achievements

The four workshops were an important part of our programme, and the participants judged them to be a great success. As with all good workshops, they allowed leading researchers to exchange ideas and younger people to meet older, established figures. Two of the workshops proved particularly interesting as they brought together quite different communities. In workshop 1, researchers in the area of transition and dynamical systems were thrown together with the high-Reynolds number turbulence community, while workshop 3 had equal numbers of participants from astrophysics and geophysics. In both cases the result was a spectacular success, with the different communities interacting in a lively fashion.

The first workshop brought together for the first time two large but distinct communities working in adjacent areas: transition to turbulence and high-Reynolds boundary layers. The result was an great deal of animated discussion between researcher who would otherwise rarely meet. This was a great success and a follow-up meeting is being discussed.

The INI/IUTAM workshop was the first major international conference devoted specifically to the nature and role of turbulence in geophysical (atmospheric and oceanic) flows. The workshop highlighted the importance of ageostrophic fronts at the surface of the ocean for coastal circulations, the dominant role played by coherent structures (vortices

or eddies) and their interactions, and highly-anisotropic behaviour resulting from stratification and rotation, effects not present in classical homogeneous turbulence.

The tranquil setting of the INI is ideal for research and a great deal of fruitful collaboration developed amongst the long-stay participants. This was evident at the time from the frequent appearance of small clusters of participants huddled around blackboards, and was confirmed when participants completed questionnaires at the end of their stay.

Many of our programme participants were invited to give seminars outside the Institute and, in addition to the many presentations given within Cambridge University, 44 seminars were given at other UK universities. This gave the UK mathematics community the opportunity to meet many of the leading figures in turbulence and hear at first hand about their current research interests.

In parallel with our programme there was a second one on Anderson Localisation. It was a pleasure to meet regularly with the organisers of that programme and to learn more about their subject. We organised exchange seminars in which we and they presented the key ideas and challenges in our subjects. We even shared a wine reception.

The INI is committed to opening its doors to the broader community, and to that end the meeting ‘Open for Business: Turbulence in Fluids’ was a considerable success, attracting leading people from industry, government agencies and finance. The wide-ranging panel discussion centred on the questions of: what do commerce and government agencies expect from academics working on turbulence, are these expectations realistic and how should we proceed from here?

Finally, four books were inspired by the programme. Cambridge University Press has agreed to publish three of them and the fourth will be published by Springer as part of their IUTAM symposium series. The books are:

- The Nature of Turbulence, Edited by P. A. Davidson, Y. Kaneda & K.R. Sreenivasan, Cambridge University Press.
(The eleven chapters, which take the form of reviews, will be written by leading experts in the field.)
- Geophysical and Astrophysical Turbulence, by P.A. Davidson & J.J. Riley, Cambridge University Press.
(This will be a comprehensive monograph covering turbulence in geophysics and astrophysics.)
- Twelve Chapters in the History of Turbulence, Edited by P.A. Davidson, Y. Kaneda, H.K. Moffatt & K.R. Sreenivasan, Cambridge University Press.
(This book will tell the story of turbulence through a series of interrelated biographies of the most famous names in turbulence. The biographies will be written by leading experts in the field.)
- Turbulence in the Atmosphere and Oceans, Edited by D.G. Dritschel, Springer.
(This book represents the proceedings of the IUTAM/INI workshop.)