PREFACE

JSPS Supported Symposium on Interscale Transfers and Flow Topology in Equilibrium and Non-Equilibrium Turbulence, September 2014, Sheffield, U.K.

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1. Preface

This collection of papers is a selection of the work presented at the symposium on *Interscale Transfers and Flow Topology in Equilibrium and Non-Equilibrium Turbulence*, held at the Department of Civil and Structural Engineering, University of Sheffield, on the 15th and 16th of September, 2014. The meeting was kindly supported by the generosity of the Japan Society for the Promotion of Science (JSPS) in London and Professor Kunio Takeyasu, the Director of JSPS London, came to Sheffield to deliver an enthusiastic welcome address to the attendees, who had travelled from universities in Japan, the U.K., France, and Germany.

Whilst the papers in this collection span the breadth of work presented, and in some cases are a result of collaborations initiated at that meeting, any reflection on the success of the symposium is tainted by the sadness that we all felt following the death of Norbert Peters in July 2015. Norbert's contributions to both turbulence and combustion were immense and his novel approaches to conceptualising turbulence phenomena will long be of use to the community. Norbert enthusiastically participated in all aspects of the Sheffield meeting, from the proposal writing stage through to acting as a Guest Editor for this special issue.

Consequently, it is only befitting that the first paper in this volume is an appreciation of Norbert as scientist and human being, written by his long-term collaborator, Heinz Pitsch.

The title for the symposium was suggested by Christos Vassilicos who, along with Norbert, also undertook a great deal of work behind the scenes to help this meeting take place. It refers to some of the theoretical and practical complexities that result from studying turbulence dissipation and the manner by which energy, helicity and other quantities move from large to small scales when production and dissipation are not necessarily in balance locally. Even in the classical case of the study of energy transfers in equilibrium, there are ongoing uncertainties regarding a description of the pertinent mechanisms, whether this is regarding intermittency corrections to structure function scaling laws, or the topology of vortex interaction in the transfer process. Add to this a solid boundary, as arises in most industrial or environmental applications, and the departure from isotropy causes further complications. Force a flow at multiple scales (as arises in canopy flows in nature, for example) rather than a single large scale and there will be further difficulties in applying classical theory. Because an understanding of such matters is of importance in a variety of industrial and environmental situations, a future generation of numerical models will be predicated on this more nuanced physics if they are to model turbulence dissipation and production correctly.

The presentation at the meeting by Christos Vassilicos on the nature of dissipation set the scene in this regard, and his major review of recent progress in this area was published soon after the meeting (Vassilicos, 2015). From a more applied perspective, Chris Keylock's invited contribution for the fiftieth anniversary special issue of *Water Resources Research* drew heavily on issues and concepts discussed in Sheffield to propose a future research agenda for fluvial fluid mechanics research (Keylock, 2015). Consequently, this is a timely collection of papers with respect to both fundamental and applied concerns in contemporary fluid dynamics research. It is therefore a privilege to present the set of papers in this special issue that address this fascinating research area from a variety of perspectives.

In the first paper in the collection, Ohkitani (2016) considers the nature of regularity in the Navier-Stokes equations and the appropriate norms bounding blow-up of the solutions. This mathematical framework links a consideration of energy, vorticity and helicity, with connections to the topology of turbulence (vortex rings lead to optimal growth of the enstrophy bound). Numerical studies with different initial conditions show that a term based on the square root of the product of the energy and enstrophy is an effective replacement for the Cauchy-Schwartz inequality for the $H^{1/2}$ norm. This leads to a clearer physical insight into our understanding of the mathematics of bounds on the regularity of the Navier-Stokes equations.

In the second paper, Goto and Vassilicos (2016) focus on a fundamental issue at the heart of this symposium: the validity of the equilibrium hypothesis introduced by Kolmogorov, and its connection to Taylor's work on the energy dissipation rate. Their numerical study forces the Navier-Stokes equations in a steady, spatially periodic fashion, but this leads to a temporally quasi-periodic response as a consequence of the evolution of large scale flow structures. Other quantities, such as dissipation and the Taylor length, exhibit various phase differences to the evolution of the integral scale. With the energy cascade found to occur in the classical fashion for the vortex tubes, the critical issue is establishing the large-scale tubes in the vortex sheets by the external forcing. Hence, the cascade occurs in a cyclic fashion. A consequence of this is the invalidity of the local equilibrium hypothesis because of the time taken for the cascade to occur.

In the third and fourth papers, various aspects of grid turbulence are considered. Boschung et al. (2016) compare numerical simulations of statistically stationary turbulence and of fractal grid-generated turbulence (Laizet et al., 2015) using the streamline segment analysis technique that focuses attention on the turbulence structure between the Taylor and Kolmogorov scales. The joint density function for the streamline segment lengths and their velocities is clearly different for the real flows compared to phase-randomised synthetic data as a consequence of the asymmetry induced by the derivative skewness of turbulence in the cascading scales. The streamline segment method is shown to be sensitive to the nature of the large scale forcing as turbulence in the production region of the fractal grid exhibits different behaviour to that in the decay region, with the latter tending towards the equilibrium, stationary case. Hence, a technique that samples turbulence at dissipative scales is able to detect differences that reflect the level of non-Gaussianity at large scales or the degree of disequilibrium in the production-dissipation process. Zhou et al. (2016) are also able to determine a clear difference in turbulence behaviour in the production region where the disequilibrium is of significant importance to the dynamics. However, in their case, flow through a single square grid, is simulated and the alignment between the velocity and vorticity fields is studied. Helicity is found to develop through wake interactions at a distance downstream of the grid that corresponds to a peak in both the turbulence intensity and the development of three-dimensionality to the flow, as evidenced by the loss of orthogonality between the velocity and vorticity vectors.

The fifth and sixth papers focus on some of the issues that arise in transfers between scales in boundary-layer flows. Keylock et al. (2016) use a previously published experimental dataset on boundary-layer structure (Ganapathisubramani et al., 2012) to examine the modulation effect of the large scale velocity on the small scale intermittency at a point. By analysing the latter in terms of pointwise Hölder exponents, it is possible to employ continuous descriptors of the modulation effect. The correlation between the large scale velocity and small scale intermittency is significantly negative near the wall and changes in sign to being significantly positive as one moves towards the boundary-layer height. By formulating velocity-intermittency quadrants, it is shown that irrespective of the sign of the correlation, the dominant coupling involves the negative fluctuating large-scale velocity states. This is either with the relatively smooth parts of the small scale velocity signal (negative correlation near the wall), or the highly intermittent regions (positive correlation far from the wall).

Keylock and Nishimura (2016) make use of wavelet transforms and measures of phase coupling to study the relations between the longitudinal and vertical velocity components as a function of wavenumber. The strength of the phase coupling between velocity components is greatest when the same wavenumber bands are compared. The histograms of the phase differences show a unimodal distribution at high wavenumbers, flatten at intermediate wavenumbers and becomes bimodal at low wavenumbers. The change in the shape of these histograms corresponds to a change in the nature of the interactions between wavenumbers, with large scales for the longitudinal velocity more closely coupled to small scales for the vertical velocity at high wavenumbers and the inverse the case for low wavenumbers. When the phase coherence plots are normalised by the local mean velocity, they collapse apart from the positions nearest the wall, which exhibit greater relative coherence. This departure indicates the importance of near wall coherent structures for inducing coupled behaviour between velocity components.

The final set of three papers either apply large-eddy simulation (LES) methods to examine the nature of turbulence behaviour in flow domains with significant complexity, or consider the import of more refined theories for turbulence energy transfers for the development of large-eddy simulation methods. Watanabe et al. (2016) examine the transport of a passive scalar in a planar jet at various Reynolds and Schmidt numbers using LES. They focus, in particular, on the dissipation of the scalar compared to the turbulent kinetic energy dissipation, and find that the scaling region for the latter (which arises some 25 jet diameters downstream) is steeper, with a -2.5 slope compared to -1.6 for the former. Away from the jet centreline, where turbulent/non-turbulent mixing results in a flow that is far from isotropy, the ratio of the turbulent and scalar mixing timescales increases dramatically. Scalar concentrations near the turbulent/non-turbulent interface vary with orientation, with a marked difference arising for the cross-streamwise edges where turbulent fluid moves outward and the non-turbulent fluid moves inward in a relative mean sense. Hence, the propensity for mixing is dependent on the detailed behaviour of the interfacial region.

The study by Wang et al. (2016) has some similarities to that of Zhou et al., except that the orifices considered are no longer square, but range from circular to a hexagram with re-entrant angles. Isosurfaces are presented that identify regions of enstrophy dominance, as well as the nature of the turbulence structures generated. The hexagram exhibits a different behaviour as a consequence of the contrast between the concave and convex corners. The preferential movement of momentum outwards from the concave corners maintains vortex sheets for longer compared to the hexagonal case, and breakdown is delayed. There is a concomitant reduction in the pressure drop in this case. Hence, in the near-orifice production region, the nature of the forcing has a marked effect on the details of vortex behaviour, which is in agreement with other studies in this special issue and has an impact on the distance at which decay towards equilibrium arises.

Wang et al.'s use of LES and adoption of vortex sheet identification methods developed by Horiuti and Takagi (2005), leads to a clear connection to the final paper in the special issue. This is by Horiuti et al. (2016) and integrates a consideration of many of the aspects of turbulence dynamics considered by the other authors, including dissipation, non-equilibrium dynamics, vortex topology and helicity. A perturbation expansion of Kolmogorov's -5/3 law reveals additional components as a consequence of fluctuations in the dissipation rate that imply an absence of a simple equilibrium between production and dissipation. These are then identified in a direct numerical simulation using conditional sampling, and related to modes of organisation of vortex tubes and surrounding sheets, thereby reflecting some of the concerns explored by Goto and Vassilicos (2016). Transition between these modes arises when the magnitude of the helicity production becomes small. This physical behaviour then leads to a suggested form for a LES sub-filter scale model that incorporates temporal phase lags in the response of the energy, production and dissipation terms, in contrast to the equilibrium between energy and dissipation in the one equation sub-filter scale treatment. Cross-correlations between simulated turbulence energy quantities at the filter and sub-filter scales using this model are shown to replicate those observed in a filtered direct numerical simulation.

In conclusion, it is perhaps possible to summarise the central concerns of this symposium with reference to some well-known verses penned about turbulence. Richardson (1922) proposed a picture for inter-scale transfers in turbulence in his parody of Swift:

“Big whirls have little whirls,

That feed on their velocity;

And little whirls have lesser whirls,

And so on to viscosity.”

An alternative picture of this phenomenon was given by Betchov (1976), who suggested that

“Big whirls lack smaller whirls,

To feed on their velocity.

They crash and form the finest curls

Permitted by viscosity.”

With apologies to both of these authors, this meeting hinted at a suite of complexities that mean:

“Until big whirls have lesser whirls,

To balance dissipation with mean-squared velocity,

Intriguing non-equilibrium effects arise,

That are mediated by helicity.”

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