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Introduction: scaling and structure in high Reynolds number wall-bounded flows

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According to Lighthill (1995), Prandtl's (1904) boundary layer has had the same transforming effect on fluid dynamics as Einstein's 1905 discoveries had on other parts of physics, which, by the way, were celebrated in 2005 as the World Year of Physics. That the boundary layer becomes turbulent was formally known to Blasius (1908), though, of course, the origin of turbulence in a pipe was studied earlier by Reynolds (1883). The problem of the turbulent boundary layer has since been a paradigm in the field of turbulence. Its practical importance in flows over air and water vehicles as well as in geophysical fluid dynamics has been recognized for nearly a century now. Advances in our understanding of the boundary-layer scaling and structure can be expected to shed further light on the complex and multiscale flow dynamics, and also offer basic input to flow control strategies for practically relevant problems such as reducing large vehicle drag (and hence, by implication, emission levels).

The first systematic account of turbulent boundary layer was given probably by Prandtl (1942), followed by Schlichting (1956) and a more modern version by Monin & Yaglom (1971). Advances in the subject, particularly its scaling properties, have been the subject of various classical reviews such as Clauser (1956) and Coles & Hirst (1969). The importance of the flow structure was highlighted, with different emphasis, by Townsend (1956, 1976) and Kline *et al.* (1967), and it is fair to say that, in one form or the other, the interaction between the flow structure and scaling properties of the turbulent boundary layer has been the subject of major study since then. This interplay has been the subject of reviews such as Cantwell (1981) and Sreenivasan (1989). The last major review of structure and scaling in boundary layers, and in wall-bounded flows in general, appeared approximately 10 years ago (Panton 1997). In the intervening period, experimental attention has focused on the form of the boundary-layer scaling at Reynolds numbers much higher than before. The debate on logarithmic versus power-law scaling of the mean velocity (Barenblatt *et al.* 1997; Zagarola & Smits 1998) and on whether, in general, the flow close to a wall can be regarded as universal—in the sense that the influence of the outer flow is negligible—have

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One contribution of 14 to a Theme Issue 'Scaling and structure in high Reynolds number wall-bounded flows'.

spurred serious high Reynolds number experiments and a re-examination of the basis of asymptotic scaling relationships. Similarly, computational efforts have nudged upwards in Reynolds numbers. This issue is a collection of selected papers which encompass these new developments.

Generating well-controlled wall flows at very high Reynolds numbers has become expensive and specialized, as is the task of making well-resolved measurements. It has been recognized of late that a significant international collaboration will be required in the field, in order to make new measurements at very high Reynolds numbers and to consolidate the data for analysis by independent groups for the purpose of addressing outstanding questions. This cooperation has been fostered, at least in part of the community, through annual workshops on high Reynolds number wall-bounded flows, initiated and organized in 2003 by Ivan Marusic (University of Minnesota), Hassan Nagib (Illinois Institute of Technology), Lex Smits (Princeton University) and Katepalli Sreenivasan (International Centre for Theoretical Physics, Trieste). A group of researchers has met several times since then to discuss the status of our understanding of wall flows. There have been frank and constructively engaging discussions.

The idea for a new journal issue on high Reynolds number wall flows arose from these discussions at which most (though not all) of the authors have been attendees. As such, the papers in this issue describe views of one set of researchers on the current status of the scaling and structure of incompressible wall-bounded flows at high Reynolds numbers. Perhaps, there is room for other views, which should be considered at another time. In this collection, the focus is on the data arising from both experimental and numerical works, and on the conclusions to which they lead. If, even within this collection, strikingly different views of the correct form of scaling in wall flows (boundary layers in particular) are advocated, and different notions of the boundary-layer structure are proposed, this state of affairs should be put down to the great difficulties accompanying the generation of wall flows at very high Reynolds numbers, and the limitations on the accuracy of data for even the most carefully designed experiments. And, of course, the analytical difficulties of the problem have not diminished one bit since the days of Reynolds decomposition.

The papers in this issue fall into one of the following categories. Each paper considers several aspects, so this classification is no more than a rough guide.

- Fundamental scaling relations for canonical flows and asymptotic approach to infinite Reynolds number: Allen *et al.* (2007), George (2007), McKeon & Morrison (2007), Nagib *et al.* (2007), Panton (2007), as well as others.
- Large and very large scales in near-wall turbulence: Balakumar & Adrian (2007), Hutchins & Marusic (2007), as well as others.
- The influence of roughness and finite Reynolds number effects: Allen *et al.* (2007), McKeon & Morrison (2007), Nagib *et al.* (2007), as well as others.
- Comparisons between internal and external flows and the universality of the near-wall region: George (2007), Morrison (2007), as well as others.
- Qualitative and quantitative models of the turbulent boundary layer: Jiménez & Moser (2007), Klewicki *et al.* (2007), Nickels *et al.* (2007), as well as others.
- The neutrally stable atmospheric surface layer as a model for a canonical zero-pressure-gradient boundary layer: Metzger *et al.* (2007), Narasimha *et al.* (2007), as well as others.

An experimental investigation into the behaviour of the flow at very high Reynolds numbers is presented in the paper by Allen *et al.* (2007). The data obtained at Princeton in the Superpipe have not only set a record for the Reynolds number, but have also underlined the difficulties in resolving the small-scale motion. One of the controversies surrounding the earlier data has concerned the smoothness of the pipe at the high end of the Reynolds number range (see Barenblatt *et al.* 1997; Perry *et al.* 2001). To address this issue, the present authors study the effects of roughness in a honed pipe; honing is chosen because it is the most common machining process used commercially.

One of the inferences of the authors is that their earlier pipe was hydrodynamically smooth except for the highest Reynolds numbers, as originally claimed by Zagarola & Smits (1998). The primary interest of Allen *et al.* (2007) here is, however, the study of transitional and fully rough cases in pipes. The roughness geometry considered by the authors is similar to that characteristic of the nominally smooth wall, though, of course, the amplitudes are larger. The authors summarize earlier results and present new ones on the mean velocity, streamwise spectra and friction factor. These results broadly support Townsend's outer-layer similarity hypothesis for rough wall flows (i.e. they collapse on the same scaling as for smooth pipes), confirming that the effects of roughness are confined to the inner region—at least for the small roughness height to pipe diameter ratios of these experiments.

Perhaps, the more far-reaching conclusion of the authors is that their friction factor data are significantly different from those indicated on the classical, and widely used, Moody diagram. The data display inflectional behaviour observed for the sand-grain surface roughness by Nikuradse (1933), in contrast to the monotonic interpolations used by Colebrook for natural and commercial rough surfaces. Is the time ripe now for a revision of the Moody diagram on which generations of engineering students have grown up (Shockling *et al.* 2006)?

A new observation in recent years concerns the existence of the so-called very-large-scale motions (VLSMs), which are long streamwise scales of the order of tens of pipe radius (or boundary-layer thickness) and larger. This is the subject of Balakumar & Adrian (2007). Kim & Adrian (1999) had already observed that these scales contain a significant fraction of the streamwise energy, and that this fraction increased with increasing Reynolds numbers. Subsequently, at much higher Reynolds numbers than those of Kim & Adrian (1999), Morrison *et al.* (2004) observed that the VLSM contains more than half the energy of streamwise fluctuations.

This journal issue also contains several further treatments of the VLSM in different wall-bounded flows. Following the earlier work of Hutchins & Marusic (2007), in which they identified the footprint of the VLSM on streamwise energy spectrum all the way through the wall layer, these same authors now demonstrate the importance of the VLSM as a modulating factor on the near-wall turbulence cycle, previously considered to be autonomous. The large-scale motions parallel to the wall are identified as being responsible for some degree of organization of the smaller scales and the amplification of energy fluctuations at the corresponding scale. VLSM has an important bearing on the interpretation of the frequency results obtained from a velocity record by standard Fourier techniques, because the latter mask the effect of a low-frequency amplitude modulation. Balakumar & Adrian (2007) provide evidence of the seemingly universal influence of VLSM in both channel and boundary-layer flows, but the VLSM is found to be shorter in these cases than in the pipe, which was the object of the earlier study by Guala *et al.* (2006); however, the common feature shared by all these flows is that VLSM contains a large share of the kinetic energy.

It appears now that the VLSMs do exist in velocity signals, but were not recognized previously, perhaps, owing to the way the velocity signals were measured and processed. It is thus useful to speculate about the origin of the VLSM. A mechanism that is conjectured by Balakumar & Adrian (2007) relates to the autogeneration and alignment of hairpin-vortex packets. This view must be reconciled with the fact that VLSM is sometimes deduced to be of the order of the length of the apparatus itself (Ganapathisubramani *et al.* 2006).

Further speculations are varied. One suggestion has been that the VLSM may be related to large-scale pressure fluctuations in experimental facilities. If so, it would not be as interesting as one might now imagine. Another suggestion is that it arises from the statistical merger of many wall-layer streaks beyond a certain Reynolds number, much like the percolation structures that span the entire size of a percolating medium as soon as the probability of occurrence of site percolation exceeds a threshold value. It must also be said that the detection of VLSM has relied heavily on the use of Taylor's hypothesis. For instance, even in PIV measurements, two-dimensional data frames of finite streamwise extent are tagged together using Taylor's hypothesis, a practice whose reliability for the purpose needs critical examination.

If VLSM is indeed real, what is its significance? If a considerable fraction of the energy in the overlap region is associated with VLSM, and if this fraction is different for different flows as claimed by Balakumar & Adrian (2007), it is clear that VLSM has an important bearing on the so-called universal scaling in the overlap region. The seminal ideas of Townsend (1956), concerning 'active' and 'inactive' motions, or the distinction between motions that contribute to the production of turbulent energy via the shear stress and those that can be regarded as quasi-inviscid and responsible for local 'sloshing' (i.e. the slow modulation of the local streamwise velocity), are relevant here.

Indeed, several papers in this collection discuss the nature of active and inactive motions. Morrison's (2007) paper is one. Expanding the ideas of Townsend (1956), Morrison (2007) demonstrates that a naive theory of inactive motion relates a linear approximation to the slow modulation by the wall of the shear-stress-bearing motion. In this description, the active and inactive motions are essentially decoupled. In reality, as shown by the failure of the inner scaling to collapse experimental data (for example, the scaling of the root-mean-square velocity in the streamwise direction, see also later), this decoupling is most probably questionable, and the interaction between the inner and outer vorticity fields should be considered to be nonlinearly coupled.

The contribution of numerical simulations to the understanding of the near-wall region of wall flows is reviewed by Jiménez & Moser (2007). That the experiments and simulations are complementary is underscored by the wealth of simulation data available, especially in the region very close to the wall where it is hard to obtain experimental data with full resolution. If the universality of the near-wall region, when normalized by wall variables, were to be rigorously true, the simulations at low or moderate Reynolds numbers would be an adequate, though pragmatic, way of addressing all issues of interest. Unfortunately, as several papers in this issue make clear, the near-wall flow is much more complex—this being an aspect with which analytical theories have yet to come terms—and the moderate Reynolds numbers of simulations will therefore have their intrinsic limitations. However, the Reynolds numbers of simulations have been inching up and, as stated by Jiménez & Moser (2007), 'The cascade of momentum across the range of scales in the logarithmic layer is probably the first three-dimensional self-similar cascade that will be accessible to computational experiments.' In the present paper, the authors show that about half of the energy in the viscous and buffer layers is traceable to a family of well-defined structures and surmise that the rest comes from bursting (see also the later discussion in the paper by Narasimha *et al.* (2007)).

Perhaps, one general comment should be made about computational efforts, which have deservedly assumed an important role. The target of simulations is to resolve at most the viscous length-scale, but not smaller. The expectation is that there are no smaller scales that are dynamically significant. It is however probable, as the Reynolds number grows, that the smallest dynamically important scales of wall turbulence become an increasingly smaller fraction of the viscous length. It is now certainly understood that the smallest scale in homogeneous turbulence becomes an increasingly smaller fraction of the Kolmogorov scale (Yakhot & Sreenivasan 2005). If an analogy with wall turbulence can be made, then the need to resolve scales becomes increasingly more stringent with increasing Reynolds number, and the promise of how high a Reynolds number one can achieve for a given computer power becomes somewhat more pessimistic than now. Nevertheless, there is no doubt that numerical simulations have an important role to play. As Jiménez has emphasized elsewhere, an important and unique role of computations is their ability to switch off one mechanism at a time to decide upon the relative importance for a given physical phenomenon.

The paper by Panton (2007) provides a review of the method of composite asymptotic expansions for wall turbulence. The first half of the article is a review and summary of the conventional wisdom (Millikan 1938). Complete descriptions of the profiles of Reynolds shear stress and mean velocity in channel flow are laid out in the framework of matched asymptotic expansions, claiming good agreement with both DNS and experimental data. This part is followed by a critique of various modifications suggested, though the article does not discuss the incomplete similarity due to Barenblatt, which, as mentioned earlier, leads to power laws for the mean velocity. In the remainder of the article, Panton (2007) examines a three-layer expansion of the streamwise Reynolds stress to account for the inactive motion of Townsend, employing different scales from those characterizing the active motion. It is the author's opinion that concepts like the mesolayer or the critical layer (Long & Chen 1981; Sreenivasan 1987) are not required. In particular, the comment applies to the multilayer models proposed in the paper by Klewicki *et al.* (2007). However, the critical layer may be important, as we shall describe below, if only because it determines the lower bound of the log law. At the least, it suggests that some new physics is required to cover the region between the wall layer and the seat of the critical layer (i.e. the peak position of the Reynolds shear stress). This feature comes through in the paper by McKeon & Morrison (2007), who claim that the structure of the mean velocity in just this region of the boundary layer is substantially richer than has been thought to be the case. This may well be one of the major lessons from the recent work.

The next few papers consider scaling at very high Reynolds numbers, specifically in boundary layers and pipes. Nagib *et al.* (2007) focus on the skin friction and mean velocity in turbulent boundary layers, with a view to ascertaining the asymptotic behaviour. These authors make two points of general importance. First, the skin friction has to be measured directly and accurately in order to draw useful conclusions on the scaling of the boundary-layer properties. The required accuracy according to them is something of the order of 0.1%, hardly ever attained in existing measurements. The authors claim that this accuracy is attained in their oil film measurements. It is clear that attempts to infer scaling properties of turbulent wall flows without an independent means of skin-friction measurement are not useful, and the limitation of something like the Clauser chart ought to be particularly kept in mind.

The general second point of Nagib *et al.* (2007) concerns the support of recent hot-wire data at high Reynolds numbers, such as those acquired at Kungliga Tekniska Högskolan (KTH) and in the National Diagnostic Facility (NDF) at the Illinois Institute of Technology (Österlund *et al.* 2000), for classical conclusions concerning mean-velocity scaling and integral parameters. One of their important inferences is that the log law with a Kármán constant of 0.384 is the correct velocity distribution in the overlap region. Their Kármán constant is smaller than the accepted value of *ca* 0.4, which itself is smaller than the value of 0.42 advocated by researchers working with the Superpipe. It is heartening that one can, these days, have enough confidence in measurements to claim that 0.38 and 0.42 are, in fact, different without rounding them both off to a 'universal' value of 0.4. If further assessments support these claims, it is apparent, at the least, that the log law, if it exists, is not universal.

Another point of emphasis placed in this paper is the excessive slowness with which the normalized properties of the boundary layer, such as the shape factor and the skin-friction coefficient, decay with the Reynolds number. This aspect is, of course, evident from the many empirical correlations in vogue, but to see several of them plotted on a single graph paper is quite revealing. It is particularly interesting to note that, while several existing empirical correlations agree with each other, as well as with the existing data, over the available span ($Re_\theta < 10^4$, say), they diverge significantly from one another beyond this realm. One does not therefore have a good guidance as to which, if any, of the several existing correlations provides a trustworthy extrapolation in the limit; so much for the help rendered to a ship designer by laboratory data! It is worth drawing attention to a similar conclusion drawn from the considerable effort spent on this same issue a few years ago at NASA Langley.

The smooth-wall results from the Princeton Superpipe (Zagarola & Smits 1998; McKeon *et al.* 2004; Morrison *et al.* 2004) are drawn together in the paper by McKeon & Morrison (2007), in which high Reynolds number scaling is described in terms of the spectral separation of the energy-bearing and dissipative scales, and a gradual approach to inertial scaling, in both physical and spectral spaces. While this concept in itself is not new, by a simultaneous consideration of spatial and spectral fluxes and the development of the overlap layer as a spatial analogue of Kolmogorov's (1941) inertial subrange, these authors show that distinct changes in the flow scaling, indicated by early analyses of the Superpipe data, become consistent with traditional estimates for scale separation as the Reynolds number increases. Thus, it is proposed that the emergence of the logarithmic law for the mean-velocity scaling with the Kármán constant $\kappa=0.42$ for $y^+>600$, when $R^+>5000$, corresponds to the emergence of the inertial range, or at least self-similar, $-5/3$ scaling, in the turbulent spectrum. This feature indicates that the emergence of a self-similar spectrum and the approach to local isotropy of fluctuations in the overlap region may go together.

An important comment should probably be made on the lower limit of the logarithmic region. The traditional belief has been that this limit is fixed in terms of y^+ (see Coles & Hirst 1969); a number that has been cited in various textbooks is that it corresponds to a y^+ of *ca* 30. McKeon & Morrison's (2007) analysis (and those of several earlier Superpipe data analyses) shows that the logarithmic region does not begin until a y^+ of 600 is reached, while most experimenters of the past had inferred a logarithmic region well below y^+ of 600!

One conspicuous point is that the Reynolds number in the Superpipe is much larger than in any flow before. The importance of scale separation lies at the heart of asymptotic arguments concerning the existence of any similarity law, and it is perhaps the case that past inferences from lower Reynolds number pipe flows were far from being definitive. This has been discussed, among others, by Wosnik *et al.* (2000). Perhaps, one observes something of the scaling region only in the more recent high Reynolds number experiments (summarized here by Allen *et al.* (2007), McKeon & Morrison (2007) and Nagib *et al.* (2007)). The possibility, then, is that the lower limit of the log region is itself Reynolds number dependent, which, in turn, suggests that some additional physics is called for in the region below the log layer. This is precisely where the critical layer, discussed above, enters. Add to this claim of new physics the present experimental finding that the log-law constant in the pipe is 0.421 (McKeon & Morrison 2007) while that in the boundary layer is 0.384 (Nagib *et al.* 2007), and the situation does not augur well for a universal log law.

In the present collection, George (2007) tackles the issue of universality from the streamwise momentum equations for different turbulent wall-bounded flows. By this means, he calls into question the log law (for the boundary layer). His proposal is to replace the log law by a power law, with corresponding important implications for the underlying asymptotic physics. This has been claimed also by Barenblatt, Chorin and collaborators, though their arguments have little to do with George's (see also George & Castillo 1997). In Barenblatt *et al.* (1997), the basic notion is that the viscous effects never disappear even outside the wall region, perhaps because the finite cores of the ubiquitous hairpin vortices persist at all Reynolds numbers. Whatever is the final word, the small-viscosity asymptotics have remained a great challenge in turbulence theory and need some careful thought. George (2007), in particular, has argued here that while logarithmic scaling is justifiable from the equations of motion for pipes and channels, the boundary-layer power law precludes universality (see Wosnik *et al.* 2000).

To a keen experimentalist, the frustration has been the difficulty in deciding unequivocally as to whether the data support the log law or the power law. Serious people have differed on the outcome for the same data. It is astonishing that seemingly elementary issues—such as whether a log law exists, and, if one exists, whether the log-law constant is the same for boundary layers and pipes—have remained elusive even after many years of research. We suppose that it underlines the difficulty of deciding the issue using the mean velocity alone, and one needs to consider other quantities for which the different ways of doing asymptotics yield zeroth-order differences: a log law and a power law with small exponent can often be mistaken one for the other. It is possible to consider fluctuations and high-order moments, as has been done in the examination of the classical inertial scaling in spectral dynamics (or its equivalent) in homogeneous turbulence, but the great regret presently is that the decreasing resolution of measurements near the wall do not allow any definitive inferences to be drawn from the measurements of mean squares and high-order moments. These difficulties have led many practitioners to the conclusion that, within the current experimental accuracy, a log law is an adequate description of the data. One should no doubt accept the power of tradition in coming to this conclusion.

Physical models for wall-bounded flows are presented by Nickels *et al.* (2007), and by Klewicki *et al.* (2007). In the former paper, the so-called 'attached eddy model' of Townsend, extended by Perry & Chong (1982) for vortex loops, is reviewed in the light of high Reynolds number experiments. Predictions based on the implied underlying structure are found to yield a consistent picture of the flow properties and Reynolds number variations, and illuminate possible reasons for recent observations, both for and against, on the k^{-1} (wavenumber) spectral scaling. Klewicki *et al.* (2007) have proposed an alternative physical model based on recent publications on a multiscale analysis of the Reynolds-averaged momentum balance. The new multilayer structure contrasts with the classical picture in spirit, but still yields logarithmic scaling of the mean velocity and offers some insight into vorticity dynamics throughout the boundary layer.

The final two papers include data from the atmospheric surface layer (ASL) under neutrally stable conditions. The near-neutral ASL has often been used to extend the Reynolds number range of laboratory studies by many investigators. The attraction is clearly that the Reynolds numbers are very high and even the smallest scales in the flow can be resolved quite adequately. Yet, the extent of the correspondence between the ASL and the canonical boundary layer remains to be fully characterized due to the influences of fetch, roughness, constancy of direction of the wind, stability of the flow and challenging operating conditions.

Some of the inherent challenges of using the ASL are addressed by Metzger *et al.* (2007). For some time, a consistent effort has been made on the salt flats in Utah, where, for certain times of the year and certain times of the day, the fetch, the wind direction and the ground conditions are quite close to what one might expect of a canonical boundary layer. The facility has gained the acronym SLTEST, standing for Surface Layer Turbulence and Environmental Science Test. The paper by Metzger *et al.* (2007) is an addition to the literature concerning measurements at SLTEST. It carefully examines the short window of near-neutrality and the non-stationary nature of the flow and time-scales associated with synoptic weather that overlie the turbulence. It also considers the balance between convergence considerations that dictate long record lengths. Using a set of synchronous measurements obtained during a 2005 field campaign at the SLTEST Facility on the Utah salt flats, mean and turbulent velocity characteristics over a range of wall-normal heights encompassing the viscous sublayer up through the overlap region, and at the highest terrestrially available Reynolds number, are summarized. Even though the wall is fully rough and there are intrinsic limitations on low-frequency resolution due to flow non-stationarity, qualitative agreement is obtained with the conclusions of Hutchins & Marusic (in press) concerning the broadband 'footprint' of the superstructures discussed earlier.

One of the conclusions from recent measurements and simulations is that the peak root-mean-square value of the streamwise velocity fluctuation, when scaled on the friction velocity, is an increasing function of the Reynolds number. This increase is roughly logarithmic (or, perhaps, a weak power law). This is one of the simplest manifestations of how the Reynolds number dependence appears in the near-wall properties, and hence quite important. Our confidence in this dependence comes in large measure from the SLTEST measurements, which provides the one point at very high Reynolds number connecting a cluster of points at laboratory Reynolds numbers. The strategic importance of this single result suggests that additional measurements with the intention of establishing Reynolds number dependence would be extremely valuable.

Finally, we discuss the paper by Narasimha *et al.* (2007). One of the questions in turbulence in general, and wall-bounded flows in particular, is whether the statistical outlook ought to contain a strongly 'episodic' character, i.e. events of a well-characterized structure repeatedly contribute significant amounts to statistical properties such as mean fluxes. It was clear from the work of Kline *et al.* (1967) and that of Rao *et al.* (1971) that the fluxes indeed have an episodic character to them at low Reynolds numbers. But is this property preserved at very high Reynolds numbers? This question is the principal drive for the paper, wherein the authors describe the results of measurements made in a near-neutral ASL within the overlap region. First, after a brief review of event-based decomposition of the instantaneous turbulent momentum flux, the authors introduce a new threshold method for the detection of shear stress events. Second, by considering the signatures associated with productive and counter-productive contributions to the flux, they show that their method permits a compact, episodic flux description which looks similar to a Mexican hat (with different signs for the productive and counter-productive parts). The lengthy time-scales associated with event duration and separation recall, in spirit, the outer scaling of events well within the wall-dominated layer, proposed now many years ago by Rao *et al.* (1971).

From the authors' data, the answer to the question posed just above should be regarded as positive: indeed, even at very high Reynolds numbers, even well outside the viscous-dominated wall region, there is an episodic character to the turbulent fluxes. It is not yet clear how to build this feature into the statistical description of fluxes, and the authors suggest that the productive part could be related to coherent structures (perhaps, formally through wavelets of the Mexican hat variety and, perhaps, physically through structures of the type discussed by Jiménez & Moser 2007), while the passive parts might be amenable to the usual Fourier description.

The final point of the paper is the correspondence of the productive and counter-productive parts with the active and inactive motions of Townsend. It would indeed be valuable if one could reduce the jargon in this subject where the same physical process is often described through several different terms, mostly because one is never sure as to what part of the process is central and what is peripheral. (Recall the parable of the elephant and the six blind men.) In the authors' terminology, both productive and counter-productive events would be regarded as active in the Townsend sense, and they occur on time-scales much larger than the characteristic wall unit; they regard the idle periods, or the low flux parts, as the 'passive' motion.

In the distinguished and, as yet, untamed field that is turbulent flow, the nature of turbulence close to a surface continues to yield its secrets piecewise and slowly. The notion that, somehow, one single clever idea will produce a flood of understanding is receding to the background. Or, is it that we are so burdened by what we immediately observe that penetrating the fog to see the light is becoming more difficult? To summarize the progress in a few sentences, however inadequately, we believe that the influence of the large scales is becoming ever clearer, in apparent contradiction to Townsend's inactive motion ideas. The concept of a universal inner layer that is independent of the outer flow seems to be limited in value. The very nature of the large structure in wall-bounded flows seems to be changing in our perception.

The study of non-canonical flows has offered additional insight into canonical flows. For example, every bit of understanding of the polymer drag reduction problem adds to the understanding of the canonical boundary layer itself; insight into the effects of acceleration, rotation, free-stream turbulence and other such auxiliary effects will also add to our understanding of canonical flows, but there is no doubt that the canonical flows will continue to be of interest in their own right. This has rightly been the subject of our attention here. This journal issue has drawn together a picture of current research. While it offers neither an exhaustive review nor detailed descriptions, we hope that recent progress and the potential for future work have been highlighted to the reader.

The issue of scale separation, if such in fact exists in wall-bounded flows, is at the heart of all scaling theories, and this likelihood increases with increasing Reynolds numbers. New experimental facilities have permitted the study of ever higher Reynolds numbers, and yet the measurement accuracy prevents us from distinguishing between opposing hypotheses concerning even the mean-velocity scaling. The greater urgency seems to be the ability to resolve all the scales, and not simply move towards ever increasing Reynolds numbers. Recent massive computations have augmented insight into the dynamics of the near-wall region, and now approach Reynolds numbers where the overlap layer may be simulated—but there is a long way to go before they approach experiments. The academic challenges have thus remained, even as practical needs for better understanding have mounted. This is the dichotomy of the field.

It remains to offer sincere thanks to all the authors for contributing the exciting pieces of 'Scaling and structure in high Reynolds number wall-bounded flows' and to the journal editor for agreeing to publish this thematic issue.

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