Turbulence in Grand Passage, Nova Scotia: Measures of Intermittency

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A. Motivation

The need for improved knowledge of turbulence in high-flow tidal channels has arisen because of developments associated with extracting renewable electrical energy from these natural flows using in-stream hydrokinetic energy conversion devices (i.e. turbines). The scales of turbulent motions are such that, instantaneously, the flow past the turbine varies significantly across the area swept out by the blades, in principal even reversing direction. These variations affect not only turbine performance in terms of energy production, they produce time-varying loads on the blades which lead to material fatigue and thus shorten turbine operating life (Marsh, 2009).

The spatial scales in a turbulent tidal flow span many orders of magnitude, from the largest eddies with scales comparable to the water depth, i.e. 30 to 50 m typically, to the mm-scales at which the kinetic energy in the turbulence is dissipated as heat by molecular viscosity. The average distribution of eddy kinetic energy across this range of scales -- the turbulent kinetic energy (TKE) spectrum -- is characterized by three ranges. From the largest to the smallest scales, and highest to lowest (one-dimensional) spectral densities, these are: the production range, the inertial subrange, and the dissipation range. From the perspective of impact on tidal turbines, the dissipation range is least important, being the least energetic and having spatial scales too small to affect the forces on turbine blades. Thus, the primary interest vis-à-vis tidal power is the production range (PR) and the inertial subrange (ISR).

A primary goal of the present project is to quantify the variability of turbulence statistics at both small (ISR) and large (PR) scales.

Turbulence intensity is not a simple function of the local flow conditions. One cannot -- based on the local flow speed and water depth alone -- predict the levels of turbulence with any degree of accuracy. The reason for this is that turbulence in tidal channels is generated by the interaction between the flow and the bottom topography, which is highly variable from location to location. The local seabed conditions at the turbine site are not sufficient: previous results (e.g. Hay et al., 2013; McMillan et al., 2016) have documented the pronounced ebb/flood asymmetry in turbulence and boundary layer properties arising from differences in the bathymetry upstream.

A second primary goal is to quantify the dependence of turbulence statistics on both height above bottom and along-channel position, relative to measures of local and upstream bottom roughness.

To become economic, turbines will ultimately have to be deployed in arrays. Consequently, a central question concerns optimal array design, given the interaction among turbines via their wakes (Myers and Bahaj, 2010). In a recent study, Churchfield et al. (2013) used a sophisticated numerical modelling technique -- Large Eddy Simulation (LES) -- to investigate the interactions between the turbulence generated in turbine wakes and turbulence in the ambient flow. They predict that turbines in a closely-spaced array can – depending upon the array geometry – perform more efficiently than an isolated turbine. However, as they state, the accuracy of these predictions will be assessed “as experimental *field data* become available” (my italics).

To summarize:

- Knowledge of turbulence is necessary to optimize turbine design both for turbine performance and turbine durability.

- Numerical modelling of turbulent flows relevant to tidal power has reached an advanced stage of development
- Turbulent conditions are highly site specific
- Field data to validate these models are lacking

These four points together indicate the need for an approach in which turbulence measurements are combined with turbulence models to characterize the flow variability at sites targeted for tidal power development, and motivated the present project. At the same time – as might be inferred from the lack of suitable field data identified by Churchfield et al. – making turbulence measurements in high-speed flows presents a significant technical challenge. While significant progress has certainly been made on this front (e.g. Lu et al., 2000; Milne et al., 2013; Thomson et al., 2012), approaches to this challenge have by no means been exhausted.

Thus, a primary motivation for my undertaking a program of research directed towards quantifying turbulence statistics in high flow tidal channels – a program of which the present project is one component – is to test and validate different turbulence measurement techniques. In particular, because of the technical challenges associated with deploying a turbulence sensor at mid-depth in 3 to 6 m/s flows, emphasis is placed upon testing and validating acoustic remote sensing techniques using bottom-mounted instrument packages.

B. Project Overview

The project is an investigation of turbulence intermittency in high flow tidal channels based on Acoustic Doppler Current Profiler (ADCP) data acquired in Grand Passage, NS. Turbulence characteristics are investigated at both the small scales at which turbulent energy is ultimately dissipated as heat, and the scales at which the largest turbulent eddies are produced. The applicability of existing theories and spectral representations, including those used in the wind energy industry, are examined.

C. Results

The Data Set

The primary results of this project are based on data acquired with bottom-mounted, fast-sampling ADCPs deployed in Grand Passage in 2012 and 2013 at the locations are shown in Figure 1. These data were collected as part several related projects (see Section E below).

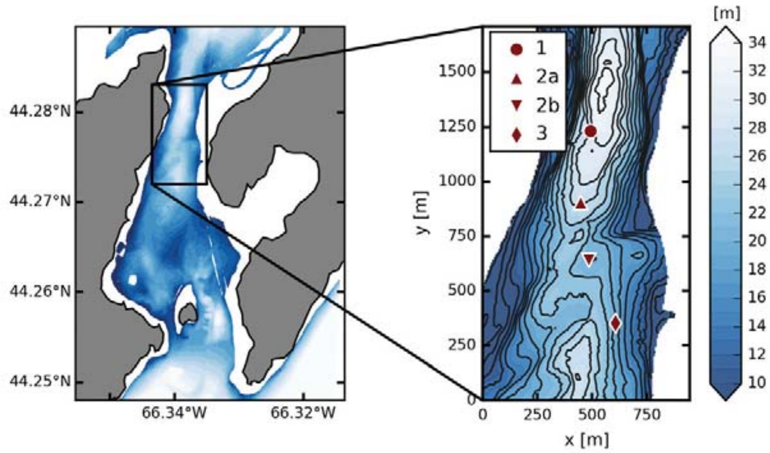

Figure 1: *Grand Passage bathymetry and bottom-mounted ADCP locations. The contour interval at right is 2 m. The Stablemoor buoy was deployed 40 m to the east of location 1. (from McMillan and Hay, 2017).*

Small-scale Intermittency

As indicated in Section A above, "small scale" is meant here to denote the Inertial Subrange (ISR) in which the turbulence is expected to be locally isotropic, and TKE spectral densities to be proportional to the dissipation rate to the 2/3 power. Because of the "patchiness" in the instantaneous spatial distribution of turbulence intensity, the dissipation rate is also patchy, and measurements of dissipation at a fixed point exhibit pronounced intermittency as function of time due to this patchiness being advected by the mean flow past the sensor. Consequently, the statistics of dissipation rate in high Reynolds number flows are non-Gaussian, being lognormally distributed instead. *Thus, a critical test of the effectiveness of remote acoustic techniques for turbulence measurement is whether or not estimates of dissipation rate are lognormally-distributed.* To my knowledge, this question had not been previously addressed in high-speed tidal channels.

We had shown previously (McMillan et al., 2016) that *time-averaged* dissipation rates at mid-depth estimated from ADCP data were comparable to direct estimates obtained with the shear probes on the Stablemoor. The next step was to obtain dissipation rate estimates on time scales short enough to investigate their statistical distribution. This need for estimates at shorter times scales led us to implement structure function methods – which are based on 2nd and 3rd order moments of along-beam (i.e. spatial) differences in the ADCP velocity estimates – in addition to and for comparison to the (time-domain) spectral method. Again, to my knowledge such a comparison had not been attempted previously. The results are presented in Figure 2, from which it is clear that both methods give the same result on average.

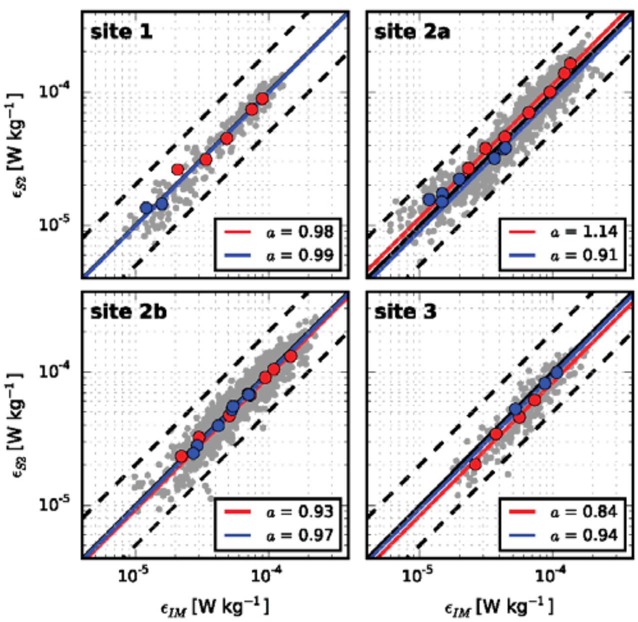

Figure 2*. Comparison of the dissipation rates at each site as computed from the second-order structure function (S2) and the integral method (IM), i.e. our implementation of the spectral method. Averages within 0.2 m/s speed bins are plotted in red and blue for the flood and ebb tides, respectively. The values of the best-fit slope, a, to the speed bin averages are shown in the legend. The 1:1 line is solid black, whereas the 1:2 and 2:1 lines are dashed. (from McMillan and Hay, 2017).*

What is not clear from Figure 2, but which is documented in our published paper, is that the structure function method is more robust, yielding more reliable estimates on shorter time scales than the spectral method for this data set. Thus, the structure function estimates were used for the investigation of small-scale intermittency: i.e. whether or not the dissipation rates are lognormally-distributed. The results, shown in Figure 3, clearly indicate that they are.

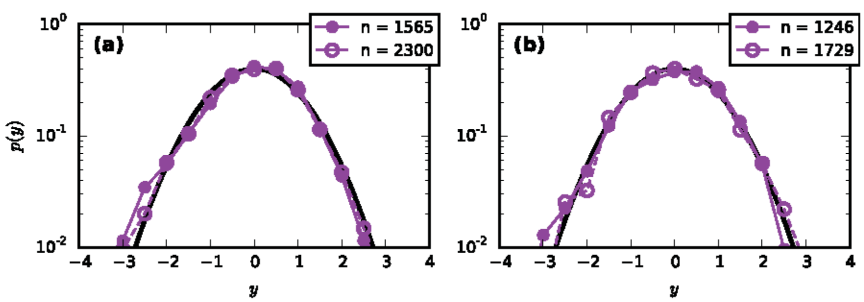

Figure 3*. Probability Density Functions (PDFs) of the base-10 logarithm of the normalized dissipation rates for mid-depth flow speeds of 1.4 to 1.8 m/s (a), and 1.8 to 2.2 m/s (b). Solid lines and filled circles indicate the IM, and dashed lines and open circles indicate the SF2 method. The number of ensembles n for each PDF is indicated in the legend, and the black curves are the normal distributions. (from McMillan and Hay, 2017).*

An unexpected outcome of the structure function work was a *decrease* in the *apparent* Doppler noise level with increasing flow speed (black points in Figure 4). This result was unexpected because of the factors affecting the Doppler noise level (turbulence, advection, beam divergence) all *increase* with increasing flow speed, and so required explanation. That there be an explanation is important because of the connection between Doppler noise and turbulence. Estimating the noise level correctly is required for estimating the dissipation rate. We were able to show (the details are in the published paper) using simulated turbulence that the effect arises because of the spatial filtering associated with the ADCP's finite measurement volume, and to derive a correction factor based on the simulation results. This correction factor removes the apparent flow-speed dependence, as indicated by the green points in Figure 4.

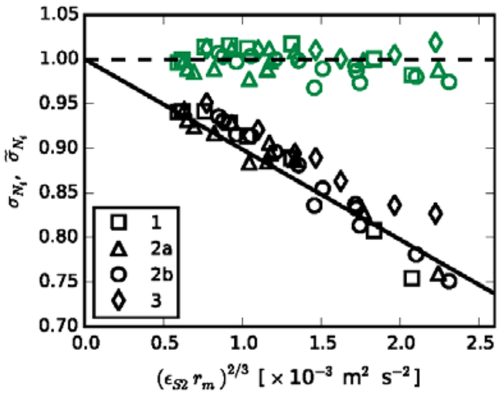

Figure 4. *Normalized Doppler noise standard deviations for all four sites. The plotted values are averages among the four ADCP beams, where the black and green markers correspond to the uncorrected and corrected values, respectively. (from McMillan and Hay, 2017).*

Large-scale Intermittency

The goal of this part of the project was to determine whether or not the turbulence spectrum in the production range (PR) was better represented by the Kaimal (K) or the von Karman (vK) spectrum. Both forms were developed to represent the energies at larger scales, and in the case of the von Karman spectrum specifically to target the gustiness in wind as part of aeronautical engineering development in the 1950s. Both forms are in use by the wind power industry (e.g. Jonkman, 2009) to represent the large-scale eddy kinetic energy in turbine design, operation and lifetime estimation. The underlying principal behind both spectral forms is compatibility with the expected power-law dependencies of spectral density on spatial wavenumber in the PR and ISR at large and small scales respectively. The differences between the two forms reside in the assumptions made vis-à-vis isotropy at large scales.

To my knowledge, neither spectrum has been investigated in the context of the vertical structure of turbulence statistics in high-flow tidal channels. Yet the presence of the water surface represents not only an upper bound on the vertical scale of the largest eddies, i.e. the water depth, but also a constraint on the vertical turbulent velocity as this boundary is approached. Neither effect is present in the atmospheric boundary layer under the neutral conditions comparable to the well-mixed (and therefore unstratified) water column in a high Reynolds number tidal channel. Justine McMillan has carried out comparisons between the K and vK forms using the ADCP data from the four locations in Figure 1. The results are presented in the final chapters of her doctoral thesis, which was submitted to her committee for review in mid-March. Given that the thesis is in the review stage, and that the results have yet to be submitted for publication, I am requesting OERA's permission to withhold the details until after the thesis defense. In the interim, two figures exemplifying the direction of this aspect of Justine's doctoral research are presented below.

A comparison between the Kaimal spectral form and the spectra obtained from ADCP data at mid-depth is shown in Figure 5, for three different values of an anisotropy index: the ratio of the standard deviation of the horizontal velocity fluctuations to the friction velocity. The goodness of fit clearly depends on the value of this ratio, particularly at larger scales (lower frequencies).

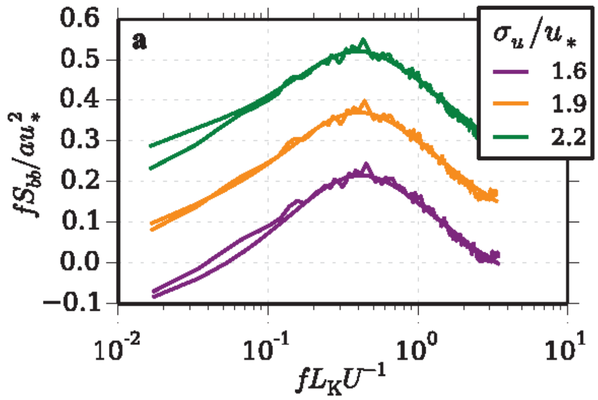

Figure 5. *Example fits to the Kaimal spectrum of ADCP data at mid-depth in Grand Passage for different values of the anisotropy index. The abscissa is frequency non-dimensionalized by the advective time scale. (Figure taken from Justine McMillan's doctoral thesis, submitted).*

In the context of her investigation of the statistics of large-scale turbulence, Justine has examined the dependence of boundary layer and turbulence properties on bottom roughness, finding that the thickness of the boundary layer is related to the average upstream bottom roughness (Figure 6), largely explaining the observed ebb/flood asymmetry as the collective effect of wakes from bathymetric features upstream. This is the first time to my knowledge that such a relationship has been established in tidal channel flow. We are not suggesting that relationship will hold in general (and have therefore deliberately not provided a least-squares fit to these data). Rather, the emphasis is on the implications the result has for the turbulent kinetic energy budget: i.e. the terms contributing to the local, time-averaged, flow-speed-dependent turbulent kinetic energy integrated over the full spectrum. It is clear from the result in Figure 6 that this balance is influenced by non-local effects.

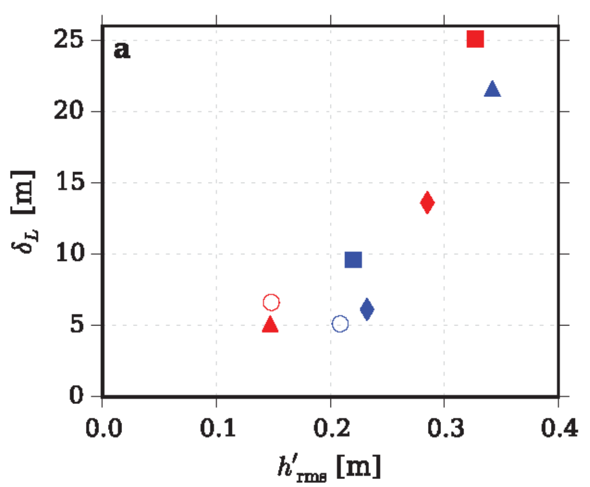

Figure 5. *Bottom boundary layer thickness vs. root-mean square upstream bottom roughness. The different symbols represent different ADCP locations (Figure 1). Red denotes flood, blue ebb. (Figure taken from Justine McMillan's doctoral thesis, submitted).*

D. Training

The objectives of this project have been the focus of graduate student Justine McMillan's doctoral research during the past year. The project has also provided a partial basis for two related studies initiated in 2016: that by Postdoctoral Fellow Rachel Horwitz of turbulence in Petit Passage (the results are in press in *Renewable Energy*: see Horwitz and Hay, 2017), and that by MSc. candidate Colleen Wilson of wave-current interaction – which can have important implications for turbulence levels – in Grand Passage. Research Associate Richard Cheel has been actively involved in this project.

E. Synergy

This project is part of my program of research on turbulence in high-flow tidal channels, a program which started 4 years ago and is increasingly receiving recognition internationally. Funding for this research from the OERA has been critically important. In particular, the Stablemoor buoy, purchased with OERA funds, enabled the successful application for an NSERC Engage Grant with Rockland Scientific International (RSI) and thereby the MicroRider data set. The importance of the 2013 MicroRider and (nearly) collocated bottom-mounted ADCP data cannot be overstated. These data provided, for the first time, validation of remote acoustic measurements of turbulence at mid-depth in a high-speed tidal flow (McMillan et al., 2016). By validating the remote measurement, this comparison laid the basis for our further investigations of turbulence properties in the ADCP data (McMillan and Hay, 2017; McMillan's doctoral thesis, submitted). Without the OERA seed funding, none of this would have happened.

The research program continues to develop. The collaboration with RSI is ongoing, funded via the joint Canada-UK project InSTREAM (*In Situ* Turbulence Replication Evaluation And Measurement) with partial support from OERA, the goal being to downscale correctly real-world turbulence measurements in the Minas Passage to the conditions in the FloWave facility at the University of Edinburgh. The approach in the InSTREAM project is based on further comparisons between acoustic and shear probe measurements of turbulence dissipation rates.

The Vectron Project, a collaboration with FORCE, the Minas Passage berth holders, and colleagues at the University of New Brunswick, Acadia University and Memorial University of Newfoundland, was very recently awarded an NSERC Collaborative Research and Development Grant. The goal of the Vectron Project is to obtain remote acoustic measurements of turbulence using a wide-baseline system with convergent acoustic beams, thereby overcoming the major limitation of standard divergent-beam ADCPs: the need to average over sufficiently long times to permit the assumption of horizontal homogeneity in the turbulence statistics so as to be able to combine 2^{nd}-order turbulence quantities from the different beams.

An ultimate goal of my research program in tidal channel turbulence is to validate numerical models of turbulence in these high-speed flows. This effort requires collaboration among those making the measurements and the modelling community. This collaboration is a key component of the Vectron Project, with colleagues Dr. Andrew Gerber and Dr. Tiger Jeans at UNB and their students carrying out high-level Detached Eddy Simulation (DES) and Large Eddy Simulation (LES) of the turbulence itself, and Dr. Richard Karsten and his students at Acadia providing the

Bay of Fundy tidal circulation model needed to drive the limited area turbulence model at UNB. We are also collaborating with Dr. Dominic Groulx at Dalhousie, who is developing a tidal channel model based on 2nd-order turbulence closure (Leroux et al., 2016).

F. Dissemination

Published or In Press

Horwitz, R. and A. E. Hay, 2017. Turbulence dissipation rates from horizontal velocity profiles at mid-depth in fast tidal flows, *Renewable Energy*, in press, 18 Mar 2017, 10.1016/j.renene.2017.03.062.

McMillan, J.M. and A.E. Hay, 2017. Spectral and structure function estimates of turbulence dissipation rates in a high flow tidal channel using broadband ADCPs, *J. Atmos. Ocean. Tech.*, 34(1), 5-20.

McMillan, J.M., A.E. Hay, R. Lueck, and F. Wolk, 2016. Rates of dissipation of turbulent kinetic energy in a high Reynolds number tidal channel, *J. Atmos. Ocean. Tech.*, 33(4), 817-837.

Conference Proceedings

Leroux, T., N. Osbourne, J.M. McMillan**,** D. Groulx, and A. E. Hay, 2016. Numerical modelling of a tidal turbine behavior under realistic unsteady tidal flow, *Proc. 3rd Asian Wave and Tidal Energy Conf.*, Singapore, 24-28 Oct..

Hay, A.E., L. Zedel, S. Nylund, R. Craig and J. Culina, 2015. The Vectron: A pulse coherent acoustic Doppler system for remote turbulence resolving velocity measurements, *Proc. IEEE/OES/CMTC Eleventh Current, Waves and Turbulence Measurement Conf.*, St. Petersburg, FL, Mar.2-6. **(Best Paper Award)**.

McMillan, J.M., A. E. Hay, R. G. Lueck, and F. Wolk, 2015. An assessment of the dissipation rates at a tidal energy site using a VMP and an ADCP, *Proc. 11th European Wave and Tidal Energy Conf.*, Nantes, Fr., 6-11 Sept.

McMillan, J.M**.**, A.E. Hay, R.H. Karsten, G. Trowse, D. Schillinger, and M. O'Flaherty-Sproul, 2013. Comprehensive tidal energy resource assessment in the lower Bay of Fundy, Canada. *Proc. 10th European Wave and Tidal Energy Conf.*, Aalborg, Den., 2-5 Sept.

Hay, A. E., J. McMillan, R. Cheel and D. Schillinger, 2013. Turbulence and drag in a high Reynolds number tidal passage targetted for in-stream tidal power, *Proc. Oceans'13*, San Diego, USA.

Selected Presentations

McMillan, J. M., A. E. Hay, R. G. Lueck, and F. Wolk, 2016. Measurements of the rate of dissipation of turbulent kinetic energy in a high Reynolds number tidal channel, Ocean Sciences, 21-26 Feb., New Orleans.

Horwitz, R. and A. E. Hay, 2016. Horizontal structure of turbulence on decimeter to 10m scales in fast tidal flows, *ibid.*

McMillan, J., A. E. Hay, and R. G. Lueck, Vertical profiles of turbulence metrics in Grand Passage, Nova Scotia, presented at the ICOE, Halifax, November 2014.

Hay, A., R. Lueck, F. Wolk and J. McMillan, Turbulence measurements from a streamlined instrument platform moored at mid-depth in a swift tidal channel. Presented at the Ocean Sciences Meeting, Honolulu, Hawaii, 23-28 Feb 2014.

Wolk, F., R. Cheel, P. Stern, A. Hay, and R. G. Lueck, A moored instrument for turbulence measurements in swift tidal channels, Presented at the Ocean Sciences Meeting, Honolulu, Hawaii, 23-28 Feb 2014.

Hay, A., R. Lueck, F. Wolk and J. McMillan, Turbulence measurements from a moored platform at mid-depth in a swift tidal channel. Presented at the European Geophysical Union General Assembly, Vienna, Austria, 27 Apr-2 May 2014.

Hay, A. E., J. McMillan, R. Cheel and D. Schillinger, Turbulence and drag in a high Reynolds number tidal passage targetted for in-stream tidal power, presented at Oceans'13, San Diego, USA, 23-26 Sept. 2013.

G. Achievements Relative to the Original Objectives

We have achieved what had been proposed, and more. In particular, these achievements are:

- Demonstrating that remotely-measured turbulence dissipation rates using standard ADCPs are lognormally-distributed, consistent with expectations for small-scale intermittency in the inertial subrange
- Demonstrating that turbulent spectral densities at large scales in tidal channels are consistent with the forms expected based on atmospheric boundary layer measurements (e.g. Kaimal), provided that anisotropy is taken into account.

H. Conclusions, and Future Directions

The primary conclusion from the research that has been carried out in this overall research program to date is that 2^{nd}-order turbulence quantities (spectra, dissipation rate, Reynolds stress, TKE, production) can be estimated from fast-sampling divergent-beam ADCPs in high-speed tidal channels, at least for speeds of 3 m/s or less. Further work is needed to determine the reliability of this approach at higher flow speeds, taking advantage of recent advances in commercially-available ADCP technology: i.e. faster sampling rates, and the introduction of a fifth (vertical) beam.

Second-order turbulence quantities, however, do not adequately address a fundamental question for the tidal power industry, and that is the probability distribution of extreme events. The Vectron Project, enabled by the Vectron's ability to measure the three Cartesian velocity components within a single measurement volume at high sampling rates, will enable this fundamental question to be addressed.

Finally, it is important to recognize that, while the emphasis here vis-à-vis intermittency is on the use of ADCP data, this does not mean that shear probes were unsuitable for this purpose. Shear probes provide information on turbulence which is not accessible to ADCPs. The circumstances leading to our decision to focus on the ADCP data for estimates of intermittency were not the result of any perceived limitations of the shear probe as a turbulence measurement device. Instead, these circumstances had everything to do with the difficulties associated with our first-time implementation of shear probes on the Stablemoor buoy, as explained in the Addendum below.

J. References (see F. Dissemination, for those not listed below)

Churchfield, M. J., Y. Li, and P. J. Moriarty, 2013. A large-eddy simulation study of wake propagation and power production in an array of tidal-current turbines. *Phil. Trans. Roy. Soc. A* 371: 20120421.http://dx.doi.org/10.1098/rsta.2012.0421.

Jonkman, B. J., 2009.*TurbSim User's Guide: Version 1.50*, NREL Tech. Rep. TP-500-46198, [Available online at http://www.nrel.gov/docs/fy09osti/46198.pdf].

Lu, Y., R. G. Lueck and D. Huang, 2000. Turbulence Characteristics in a Tidal Channel, *J.Phys. Oceanogr.* 30, 855-867.

Marsh, G., 2009. Wave and tidal power: an emerging new market for composites. *Reinf. Plast.* 53, 20–24. (doi:10.1016/S0034-3617(09)70220-6)

Milne, I. A., R. N. Sharma, R. G.J. Flay, and S. Bickerton, 2013. Characteristics of the turbulence in the flow at a tidal stream power site. *Phil. Trans. R. Soc. A* 371: 20120196. http://dx.doi.org/10.1098/rsta.2012.0196

Myers, L. E. and A. S. Bahaj, 2010. Experimental analysis of the flow field around horizontal axis tidal turbines by use of scale mesh disk rotor simulators, *Ocean Eng.* 37, 218–227.

Thomson, J., B. Polagye, V. Durgesh, and M. C. Richmond, 2012. Measurements of turbulence at two tidal energy sites in Puget Sound, WA., *J. Oceanic Eng*., 37(3), 363–374.

K. Addendum

The basic measurement made by the shear probes is flow acceleration. As outlined in the Interim Report for this project, the probability distribution of acceleration differences were computed and their departures from Gaussian behaviour investigated. The resulting higher-order statistics were found to exhibit the expected behaviour: e.g. kurtosis values greater than the value (3) expected for Gaussian statistics. However, the dependence on the Taylor microscale was inconsistent with results from the atmospheric boundary layer. One possible explanation is contamination of the shear probe data by the buoy motion. It should be noted that, from the outset of this project, the possibility that contamination of the shear probe signals by buoy motion might preclude determination of the higher order turbulence moments was always in view. It is worth recalling that the 2013 experiment was the first time that the Stablemoor/MicroRider combination had been attempted, anywhere in the world. It should also be remembered that the 2013 deployment occurred 2 weeks after the -- very late -- delivery of the Stablemoor, and consequently that the buoy had to be trimmed in the field the week before the deployment, and furthermore that the manufacturer had misplaced the position of the yoke axle which required adding 20 kg of additional ballast in the nose, and 10 kg of additional buoyancy in the tail. It should not be concluded therefore, that Stablemoor/MicroRider approach to turbulence measurement is intrinsically unsuitable for measurements of the higher-order statistical moments in high-flow tidal passages. Subsequent improvements to the buoy geometry, and to the motion sensor package in the MicroRider, have led to reduced contamination levels in subsequent deployments. Because (1) of the (potentially large) investment of time that would have been required to deal with the noise in the shear probe data at what was then late stage in Justine's program; (2) the fact that the shear probe data had served its primary purpose (i.e. the independent estimates of dissipation rate published in McMillan et al., 2016); and (3) the interest among the tidal power research and development community in establishing the shape of the large-scale turbulence spectrum (i.e. the production range), it was decided to focus on turbulence at production scales using the ADCP data.