The influence of migrating bed forms on the velocity-intermittency structure of turbulent flow over a gravel bed

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[1] Modeling turbulent flows at high Reynolds number requires solving simplified variants of the Navier-Stokes equations. The methods used to close the resulting Reynolds-averaged, or eddy simulation equations usually follow classical theory and, at small enough scales, postulate universal scaling for turbulence that is independent of the velocity itself. This may not be the best way to conceptualize geophysical turbulence. Turbulent intermittency may be defined in terms of the local "roughness" of the velocity signal as measured by pointwise Hölder exponents. This study investigates the joint velocity-intermittency structure of flow over a gravel-bed surface with migrating bed forms. We report clear velocity-intermittency dependence and quantify its nature above the moving bed form profile. Our results imply differences in energy transfer close to bed forms at shorter wavelengths than those forced directly. Hence, progress in modeling flows of geophysical relevance may require a reconsideration of the principles on which turbulence closures are based. **Citation:** Keylock, C. J., A. Singh, and E. Foufoula-Georgiou (2013), The influence of migrating bed forms on the velocity-intermittency structure of turbulent flow over a gravel bed, *Geophys. Res. Lett.*, *40*, 1351–1355, doi:10.1002/grl.50337.

1. Introduction

[2] Environmental turbulent flows are highly complex because of the interaction between a flow with complicated physics, mobile and spatially variable boundary conditions, as well as possibly entrainable sedimentary particles. All of these phenomena exist in gravel-bed rivers and, as a consequence, one expects that flow patterns are more complex than classical flow patterns, such as a well-developed boundary layer [*Shvidchenko and Pender*, 2001; *Roy et al.*, 2004; *Hardy et al.*, 2007]. Hence, investigating the nature of turbulence in environmental flows is imperative if we are to improve our ability to model and predict pollutant dispersal and sediment transport in natural rivers.

[3] Classical turbulence theory stems from the work of Kolmogorov and his two-thirds and four-fifths laws [*Frisch*, 1995], both of which are based on a consideration of the moments of the spatial velocity differences or increments $\Delta u(r) = (u_x - u_{x+r})$ over a separation distance, r, for homogeneous isotropic turbulence. The former may be obtained from dimensional analysis and states that $\langle \Delta u^2(r) \rangle = C\epsilon^{2/3} r^{2/3}$, where ϵ is the average dissipation rate per unit mass and C is a constant. This leads directly to the well-known –5/3 law for the Fourier amplitude spectrum of a turbulent flow in the inertial regime. This was modified by *Kolmogorov* [1962] to incorporate the effect of intermittency [*Frisch et al.*, 1978]. In this extended theory, –5/3 holds on average with local fluctuations induced by the passage of energetic flow structures. These are described by a log-normal distribution or, in subsequent work, by log-Poisson statistics [*She and Leveque*, 1994]. However, all such studies have retained Kolmogorov's basic assumption that u and $\Delta u(r)$ may be treated independently. Experiments in the 1990s began to call this into question [*Praskovsky et al.*, 1993], and more recently, *Hosokawa* [2007] has proven that a dependence exists. The implication of this is that rather than assuming a universal distribution function for the intermittency (the form for which has never been proven), conditioning on the velocity should be undertaken explicitly.

[4] The dependence between u and Δu is likely to be greater in the natural environment where turbulence is not homogeneous or isotropic. However, this issue has not been explored until very recently [*Keylock et al.*, 2012b]. In this paper, we study this problem for water flow above a gravel bed with mobile bed forms and explain the observed velocity-intermittency pattern in terms of a coupling between turbulence and surface topography. We show that bed forms alter not only turbulence intensities but also the local scaling of turbulence. This scaling is not independent of the values for the velocity.

2. Velocity-Intermittency Structure and its Analysis

[5] *Keylock et al.* [2012b] introduced a method for studying velocity-intermittency coupling that is effective for much shorter time series than required by alternative methods, e.g., *Stresing and Peinke* [2010], where very long time series are needed to obtain converged results. This new method opens up the possibility of studying this phenomenon for flows with complex boundary conditions for which limited data typically exist. The technique requires a time series for the longitudinal velocity component, u, that is of sufficient duration and frequency to capture the various scales in the flow. Subtraction of the mean, U, gives the fluctuating longitudinal velocity: $u' = u - U$. If this was studied jointly with the fluctuating vertical velocity component v', we would obtain the classic quadrant technique for studying turbulence structure [*Bogard and Tiederman*, 1986], where

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ejections ($u^{\prime} < 0, v^{\prime} > 0$) and sweeps ($u^{\prime} > 0, v^{\prime} < 0$) contribute positively to the Reynolds stress and maintain the shape of the boundary-layer velocity profile.

[6] Instead, *Keylock et al.* [2012b] replaced $v^{\prime}$ with the fluctuating values for the pointwise Hölder exponents. The Hölder exponent $\alpha_u(t)$, of u, is defined as

$$|u(t) - u(t+\tau)| \sim C|\tau|^{\alpha_u(t)} \quad (1)$$

where C is a constant (see *Venugopal et al.* [2006] for a review). It measures the strength of the local singularity at time t as well as the local roughness scaling of u. The average of the time-varying $\alpha_u(t)$, $\overline{\alpha}_u$, can be viewed as the Hurst exponent [*Hurst*, 1951] for the time series, which is simply related to the fractal dimension, $D_f = 2 - \overline{\alpha}_u$. The fractal dimension has been widely explored in geophysics, commencing with Mandelbrot's pioneering work on the length of the British coastline [*Mandelbrot*, 1967] and includes work on the size distribution for fault displacements [*Marrett and Allmendinger*, 1992], river networks [*Lashermes and Foufoula-Georgiou*, 2007] and stratigraphic sequences [*Schlager*, 2004], as well as its central place in Kolmogorov's theory for turbulence. Note that a period in time when the signal is rougher (its local variance is greater), will result in a smaller $\alpha_u(t)$ and a higher fractal dimension, i.e., we move from a fractal theory for inertial regime turbulence with a single fractal dimension, $D_f = 5/3$, to a multifractal theory where $\overline{\alpha}_u = 1/3$ still holds on average, but with significant variation in the individual exponents. The method used to calculate $\alpha_u(t)$ is a variance-scaling approach [*Keylock*, 2008, 2009] that in comparative tests [*Keylock*, 2010] has been found to perform well.

[7] To give greater universality to our analysis, we form $\alpha_u^{\prime}(t) = \alpha_u(t) - \overline{\alpha}_u(t)$ and then $u^{\prime}$ and $\alpha_u^{\prime}$ are standardized by their respective standard deviations, σ:

$$\begin{aligned} u^{*\prime}(t) &= u^{\prime}(t)/\sigma(u) \equiv (u(t) - U)/\sigma(u) \\ \alpha^{*\prime}(t) &= \alpha_u^{\prime}(t)/\sigma(\alpha_u) \equiv (\alpha_u(t) - \overline{\alpha}_u)/\sigma(\alpha_u) \end{aligned} \quad (2)$$

As with normal quadrant analysis [*Bogard and Tiederman*, 1986], we then introduce a threshold hole size, H, defined in terms of the standard deviations of the two variables. Thus, a threshold exceedance is deemed to exist when

$$|u^{\prime}(t)\alpha_u^{\prime}(t)| \geq H[\sigma(u)\sigma(\alpha_u)] \quad (3)$$

and we record the proportion of the time that the flow occupies each quadrant as a function of H. In this way, we analyze the relative importance of the four turbulence states: fast-smooth; fast-rough; slow-smooth; slow-rough. *Keylock et al.* [2012b] showed that distinct velocity-intermittency signatures exist for various classical flow types and these are robust to changes in Reynolds number. Jets [*Renner et al.*, 2001] and wakes [*Stresing et al.* 2010], as well as surface and boundary layer flows [*Keylock et al.*, 2012a] were studied and are used herein as references for interpreting turbulence structure over a migrating bed form.

3. Results

[8] The data used in this study combined high frequency (200 Hz), long duration (3.6 million values for u in 5 h) velocity time series measured over a mobile gravel bed surface, with simultaneous bed elevation data, h, recorded at 0.2 Hz. The experiments were conducted in the 84 m long, 2.7 m wide Main channel facility at St. Anthony Falls Laboratory, University of Minnesota. The experimental design and measurement details are described more fully in *Singh et al.* [2009, 2010].

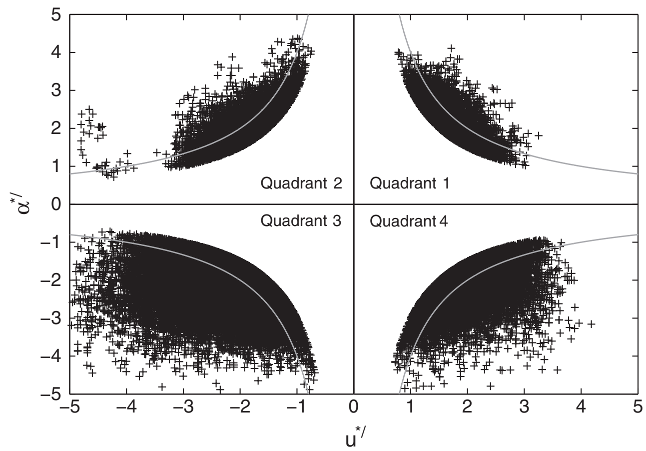

Figure 1. Longitudinal velocities over a gravel bed at 200 Hz together with their accompanying Hölder exponents plotted using the quadrant approach of *Keylock et al.* [2012b]. The data shown exceed a hole size, H = 3 and the H = 4 threshold is shown as a gray line. This graph is used to derive Figure 2. The quadrants 1 (fast-smooth), 2 (slow-smooth), 3 (slow-rough) and 4 (fast-rough) are marked for convenience.

[9] Figure 1 shows the joint distribution of $u^{*\prime}(t)$ and $\alpha_u^{*\prime}(t)$ with the threshold applied at $H = 3$ and with $H = 4$ shown as a gray line. It is clear that there is a lack of events in quadrant 1 (fast-smooth flow components) for $H > 3$ and a predominance of events in quadrant 3 (slow-rough flow components) depicting the complexity and anisotropic nature of the turbulent structures developing above the moving gravel bed. Calculating the percentage of time spent in each quadrant as a function of H gives the data shown as a thick black line in Figure 2, where the percentages are normalized so that the sum over all quadrants at any H is 100%. This line is superimposed on the results found in *Keylock et al.* [2012b] for four distinct flow types (see caption of Figure 2). It is seen that our analysis classifies flow over a moving gravel bed (black line) as having a mixture of characteristics. Behavior in quadrant 2 mimics that for the wake data, while quadrant 3 response is similar to, but even more extreme than the boundary-layer data. Quadrant 1 response is closer to that for surface layer/jet flow, while Quadrant 4 behavior is homogeneous and seems to reflect an averaging of wake and boundary layer responses. All cases are distinct to what might be expected from classical theory (horizontal lines at 25% in each quadrant).

[10] To understand this complex turbulence structure further, Figure 3 shows low-pass filtered time series of $u^{*\prime}(t)$ and $\alpha_u^{*\prime}(t)$ superimposed on the corresponding scaled bed elevation series. The filtering is over a 5 s bandwidth to reflect the different acquisition frequencies of the topographic and flow data. It is seen that immediately before a bed form (red line) passes beneath the probe (i.e., in the wake region behind the crest), we have an increase in the velocity caused by topographically induced acceleration and separation. In the majority of instances (as shown by the A labels in

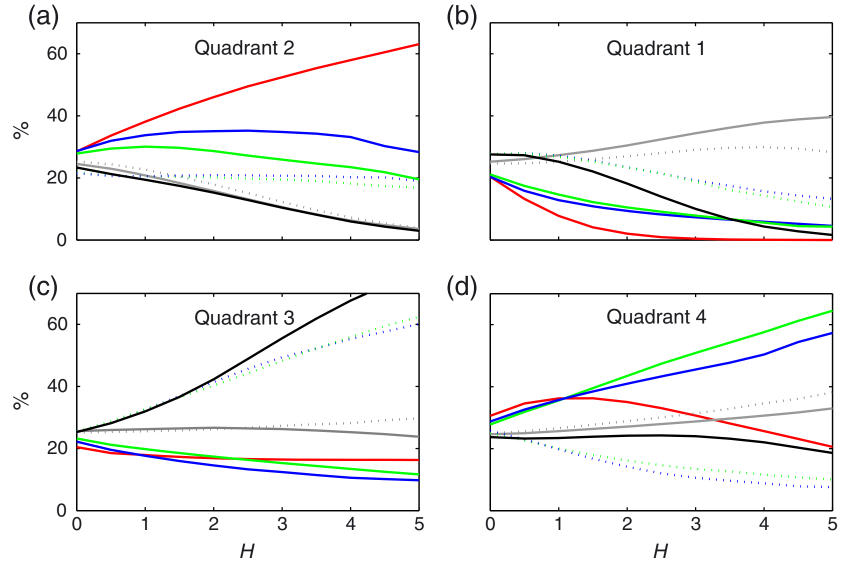

Figure 2. An analysis of velocity-intermittency for various experiments. The data from this study are shown as a solid black line, while other lines correspond to data from a turbulent jet experiment [*Renner et al.*, 2001] (red), wake data at 8.5 m s⁻1 (gray dotted) and 24.3 m s^{-1} (gray) [*Stresing et al.*, 2010], and data near the boundary (solid lines) and higher into the flow (dotted lines) at 6 m s^{-1} (blue) and 8 m s^{-1} (green) for the upstream boundary layer from the study by *Keylock et al.* [2012a]. Most of the data in this figure is taken from Keylock, C. J., K. Nishimura, and J. Peinke (2012), A classification scheme for turbulence based on the velocity-intermittency structure with an application to near-wall flow and with implications for bed load transport, J. Geophys. Res., 117, F01037, doi:10.1029/2011JF002127 (copyright American Geophysical Union) and is reproduced with the permission of the AGU.

Figures 3a–3c), these high velocities correspond to high turbulence fluctuations as revealed by the low value for $\alpha^{*/}_{filt}$ (black line), although the minimum for $\alpha^{*/}_{\text{filt}}$ may be delayed (label B in Figure 3a). Far less frequently, a rise may be observed (C in Figure 3d). If these topographically induced contributions are removed from the results in Figure 2, there is a reduction in quadrant 4 for higher *H*, resulting in a signal that is more similar to that for a boundary layer (dotted blue and green lines in Figure 2). Hence, from the perspective of the velocity-intermittency analysis, the bed form flow appears to be an approximate boundary layer with superimposed wake turbulence influences.

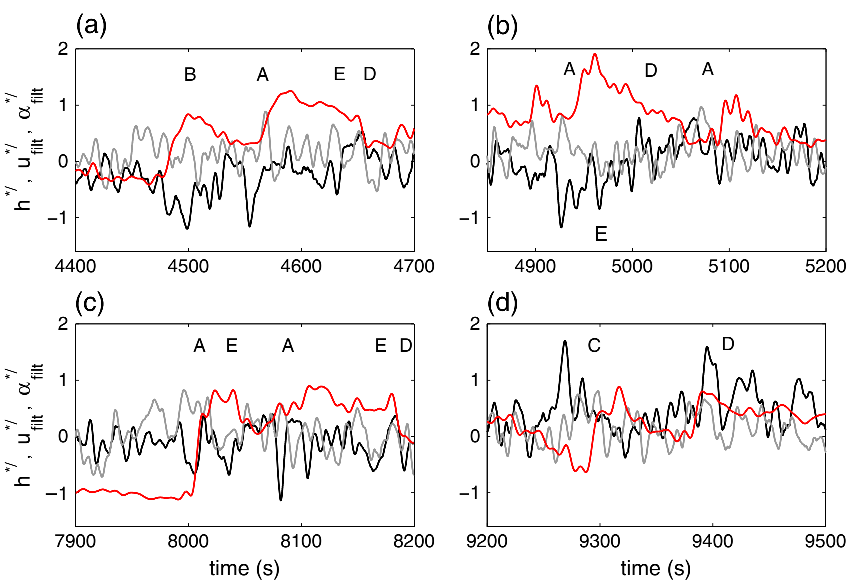

Figure 3. Comparison of the time series for peaks of the scaled bed elevation data sampled at 0.2 Hz, $h^{*/}$, in red, the filtered and scaled Hölder exponents, $\alpha^{*/}_{\text{filt}}$, in black, and the filtered and scaled velocity, $u^{*/}_{\text{filt}}$, in gray. The panels show the passage of different bed forms. Labels A–E are linked to description in the text.

[11] In Figures 3a–3d, positive spikes of $\alpha^{*/}_{\mathrm{filt}}$ are found preferentially on the front faces of the bed form (D) just before the crests. These are typically correlated with positive fluctuating velocities and would appear to represent flow that is relatively unperturbed by the shear layer and hairpin vortex systems that dominate the flow behind the crest. This is consistent with modeling work by *Omidyeganeh and Piomelli* [2011], who showed that acceleration and mean flow advection are high and turbulent transport is low in this region. Between (A) and (D), we tend to find a second minimum for $\alpha^{*/}_{\mathrm{filt}}$ (E) that is typically associated with negative values for $u^{*/}_{\mathrm{filt}}$ (note that in Figure 3b, this label is located towards the bottom of the panel). Turbulence generation at the top of the bed form would explain this low velocity and high intermittency. The very high values for quadrant 3 in Figure 2, compared to other flows, highlight the importance of such mechanisms for flows over mobile bed forms.

[12] It is important to note that these results are not an artifact of the technique used to calculate the Hölder exponents. The scaling regime used to compute the values for $\alpha_u(t)$ was ± 256 velocity samples, or ± 1.28 s, while the topographic data were sampled every 5 s. Hence, the relation seen between $\alpha^{*/}(t)$ and $h^{*/}(t)$ is a consequence of the effects of topography on the velocity field at frequencies greater than those used to derive the bed elevation data and not because the velocity at the bed form scale is directly incorporated into the velocity scaling. Hence, there is a connection between the directly forced and the smaller turbulence scales [*Ohkitani and Kida*, 1992].

[13] *Singh et al.* [2010] analyzed the same turbulence data and provided evidence for a feedback between flow and bed form dynamics as inferred by a spectral gap and a gradient of –1.1 in the velocity power spectrum at low frequencies, corresponding to the scales associated with the movement of developed bed forms. However, the question as to whether there is a topography-velocity feedback at scales smaller than the bed form movement scale was not investigated and is an important new result in the present study. *Singh et al.* [2011] also established the presence of multifractality in bed elevation series, and *Singh et al.* [2012] argued for the dependence between bed elevation and bed elevation increments (scale-coupling). Our results support those of *Singh et al.* [2012] and provide an explanation via the established turbulence-bed elevation dependence. The velocity-intermittency relation above the gravel bed in Figure 2 differs from that of classical boundary-layer turbulence, with a particularly strong signature in quadrant 3 (slow-rough flow) and also with excess contributions in quadrant 4 (fast-rough flow). The particular changes to the Hölder exponent above a bed form mean that the turbulence scaling (cascade of energy) is not spatially homogeneous and Figure 3 shows how topography induces this heterogeneity. Hence, departures from classical theory are not just due to the multifractal nature of turbulence: there are regions where lower or higher Hölder exponents (hence, turbulent scaling relations) are expected and these are not independent of u. The observed dependence between velocity and velocity increments raises fundamental questions concerning the way in which energy transfer in such flows is theorized. Our results have clear implications for development of a new generation of turbulence closures for modeling flows of geophysical importance that incorporate this dependence. This forms the basis of ongoing research.

4. Conclusion

[14] Using a recently developed method for analyzing the velocity-intermittency structure of turbulence [*Keylock et al.*, 2012b], we have, for the first time, provided a quantitative account of the complex structure of turbulence above a moving gravel bed form. We have shown that it exhibits attributes of wake, surface layer, and boundary layer flow. While it is well known that different regions within a bed form flow field have distinct velocity and turbulence characteristics [*Best*, 2005], our study shows that this extends to the local scaling of the turbulence and the velocity-intermittency coupling too. Our Figure 2 provides a means for comparing different flows based on this local scaling and its coupling to velocity. The bed form signature has an impact not only on the local turbulence but the statistics for the whole flow, supporting the conclusions of *Singh et al.* [2010, 2012]. Our results have implications for numerical techniques that resolve flow structure such as large and detached eddy simulation [*Koken and Constantinescu*, 2008; *Escauriaza and Sotiropoulos*, 2011; *Keylock et al.*, 2012c]. Conditioning Δu on u, and moving away from a universal scaling regime, would appear to be a more appropriate approach, particularly given the difference between quadrants 2 and 3 in Figure 2 for the flow over mobile bed forms. Work that uses the known velocity-intermittency structure to formulate appropriate closures would appear to be an important first step in this respect.

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