How fast or how many? Sources of sediment transport intermittency

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ABSTRACT

Near the threshold of grain motion, sediment flux is on-off intermittent, characterized by large but rare bursts of transport, separated by long periods of low transport. Without predictive models that can tell us when and how much intermittency will be present, one risks incorrectly measuring averages, which might be off by an order of magnitude – something problematic for calibrating transport laws used in many engineering applications. Despite its known presence and impact, the physical origin of the on-off intermittency in sediment transport, as well as its relation to other observations of intermittency, is still unknown. In particular, it is not clear whether the on-off intermittency is present in the number of moving grains (‘grain activity’), or the grain velocities, which together determine the sediment flux. In this study, using particle

tracking data from a series of flume experiments, we show that the on-off intermittency has its origins in the velocity distributions of the grains that are ‘rolling’ on top of the bed. On the other hand, the grain activity is not on-off intermittent, even at the lowest transport stages. This knowledge can inform the development of mechanistic models of intermittent sediment transport and improve predictions of important quantities such as time-averaging windows.

INTRODUCTION

Sediment flux fluctuations

In gravel-bedded rivers, sediment transport occurs through bed load, where grains roll, skip, and collide in an irregular fashion, leading to noisy sediment flux statistics (Parker et al., 2007; Figure 1). Near the threshold of motion, these fluctuations are accompanied by large bursts, making the flux intermittent and resulting in non-Gaussian probability distribution functions (PDFs) with large tails (Gomez, 1991; Ancey et al., 2006, 2008; Singh et al., 2009). When taking averages of intermittent time-series, the number of large bursts observed can significantly alter the calculated mean, resulting in very long time-windows being required for a properly converged average (Bunte and Abt, 2005; Singh et al., 2009; Ancey and Pascal, 2020). This, in turn, poses a challenge for quantitative predictions of sediment flux, which rely on empirical laws based on a series of time-averaged flux measurements in different flow conditions (Ancey, 2020a, 2020b). These laws are applied in many engineering contexts, such as flood mitigation, dam construction, and coastline erosion, as well as in understanding future and past landscape evolution (Bridge and Demicco, 2008). A predictive theory of what time-windows are required for properly converged averages, given the flow and channel conditions, can be a helpful tool in field work and experimental studies. Such a predictive theory must come from a mechanistic understanding of the underlying cause of the intermittency.

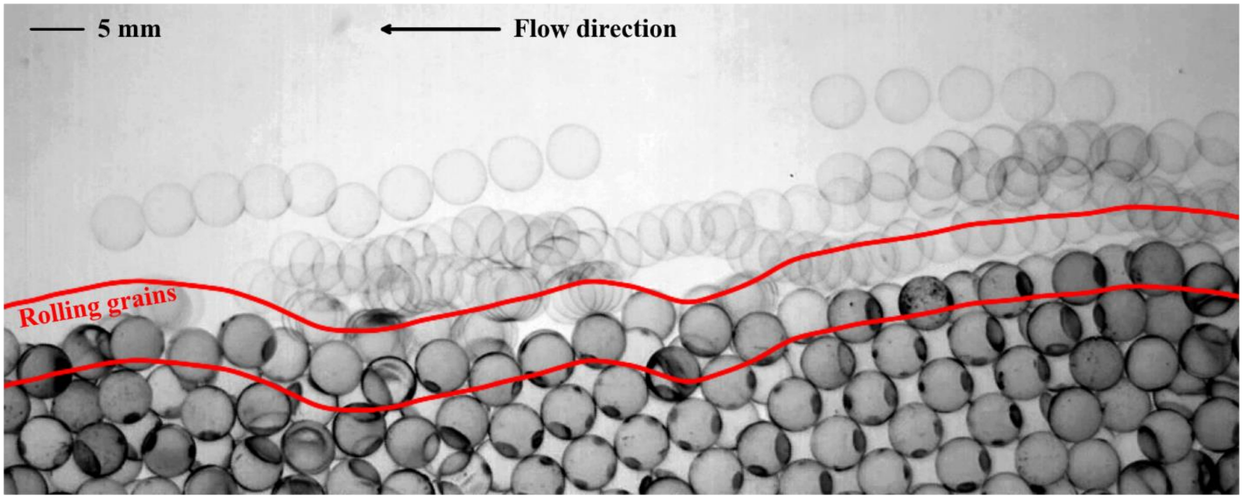

Figure 1. A strobed time-lapse of grain motion in a sample experiment, demonstrating the various modes of transport which can coexist, manifested by differences in velocities and height above the bed. The two red lines denote the 'rolling grains' population, whose centers lie within three grain diameters above the bed (defined in the text). The snapshot is composed of 5 frames taken 0.01 seconds apart by the high-speed camera. Frames like these were used in the grain tracking analyzed in this work.

Current theories and observations on intermittency in sediment transport

A common approach is to consider each dynamical component that contributes to the flux separately, namely the velocity of the grains and some measure of the number of grains moving, or 'grain activity' (Ancey et al., 2008; Lajeunesse et al., 2010; Furbish et al., 2012a; Roseberry et al., 2012; Ancey, 2020a). Since grain velocities are believed to have either exponential or Gaussian statistics (Lajeunesse et al., 2010; Roseberry et al., 2012; Martin et al., 2012; Furbish and Schmeeckle, 2013; Fan et al., 2014; Heyman et al., 2016), studies on intermittency tend to focus on the role of grain activity. One such study by Ancey *et al.* (2008) successfully predicted the number of grains in their experimental window to have a Negative Binomial distribution, resulting in larger-than-Gaussian fluctuations, in other words, intermittency. They attributed the intermittency to the dependence of entrainment rate on the number of grains currently entrained, commonly referred to as ‘collective entrainment’.

While insights gained from their model have influenced future studies on the origin of intermittency (Lee and Jerolmack, 2018), it does not reproduce a different type of intermittency found closer to the threshold of motion, called *on-off intermittency* (Fujisaka and Yamada, 1985; Platt et al., 1993; Heagy et al., 1994; Ott and Sommerer, 1994; Aumaître et al., 2005, 2006; Benavides et al., 2021), which is apparent in the lowest transport stages of some previous studies, e.g. Ancey et al., 2015, and quantified in terms of the total sediment flux more recently by Benavides *et al.* (2021). Importantly, the theory of on-off intermittency can account for the observed distribution of waiting times between flux events of a certain size, which have been found to follow a power law with an exponent close to -1.5 (Ancey et al., 2008; Carneiro et al., 2015; Liu et al., 2019), and contribute significantly to the long averaging convergence times. Moreover, it predicts the appearance of intermittency and the divergence of this convergence time as the threshold of grain motion is approached. These powerful theoretical tools require the addition of one new piece of information about the system, beyond the usual average shear stress and critical shear stress: the ‘bed sensitivity’ S, which measures the strength of shear stress fluctuations.

Although a theoretical description of it exists, the physical origin of on-off intermittency in bed load sediment transport remains unclear. Without an understanding of what is causing it, we have little hope of developing a mechanistic model for on-off intermittency, which can help us connect bed and channel properties to important parameters in the theory, such as the bed sensitivity. In this work, using particle tracking data from a series of flume experiments, we take an important step in that direction by showing that the on-off intermittency has its origins in the velocity distributions of the grains that are ‘rolling’ on top of the bed, a population which contributes significantly to the transport (Böhm et al., 2006; Schmeeckle, 2014). This goes against the current consensus that intermittency is only found in the grain activity (Ancey, 2020a). On the other hand, the grain activity is not on-off intermittent and instead its statistics agree with the theory of Ancey *et al.* (2008), even at the lowest transport stages.

ON-OFF INTERMITTENCY IN EXPERIMENTS

We performed a series of flume experiments under bed load transport conditions (Figure S1, Supplemental Material). In each run we set the sediment feed rate and water discharge, allowed the sediment bed to aggrade until the bed reached a constant slope angle and the sediment flux out of the downstream end of the flume equaled the sediment feed rate, and then captured the motions of grains from the side using a high-speed camera. Image frames from each experiment were then analyzed with a grain detection and tracking algorithm yielding grain positions, tracks, and velocities for each frame (Supplemental Material). In this work we analyze data from experiments in a narrow flume (10 mm wide), using glass spheres (5 mm in diameter) as the grains (Figure 1).

For each experiment we measured the time-averaged non-dimensional shear stress, $\langle\tau^*\rangle$, also sometimes referred to as the Shields Number, where $\langle\cdot\rangle$ denotes a time average. The shear stress acts as a control parameter, quantifying the ability of the fluid to move sediment, with larger shear stress values corresponding to more transport. A critical shear stress $\langle\tau^*\rangle_c$ exists, below which no grain motion is present. For each experiment we also used the results of the grain tracking to measure the time series of an observable of interest (to be described below) and quantify its statistical properties.

Experimental observations of on-off intermittency in sediment flux

In Benavides *et al.* (2021), we analyzed time series of the instantaneous non-dimensional downstream sediment flux, q^* (Supplemental Material), and found that the sediment flux time series became more and more intermittent as the critical shear stress was approached. Although observations of intermittency increasing as the threshold of motion is approached exist, the statistics of the intermittent time series did not match those predicted in the theory of Ancey *et al.* (2008). We instead connected our observations to the theory of on-off intermittency, which arises in systems that undergo a bifurcation in the presence of multiplicative noise. In sediment transport, this corresponds to the threshold of grain motion in the presence of noisy shear stress. More broadly, the generic conditions required for its presence mean that this type of intermittency is observed in many other fields, and indeed it was originally found in noisy phase transitions in condensed matter systems (Horsthemke and Malek-Mansour, 1976; Kabashima et al., 1979) as well as reaction-diffusion equations (Pikovsky, 1984).

The theory of on-off intermittency makes predictions for the PDF of sediment flux, as well as the waiting time distribution of sediment flux events, as a function of the shear stress, critical shear stress, and the bed sensitivity S, defined to be the autocorrelation of the zero-mean shear stress fluctuations. In particular, it states that, for small values of flux, the PDF of sediment flux will be a power law with an exponent equal to $(\langle\tau^*\rangle - \langle\tau^*\rangle_c)/S - 1$, so that at the critical shear stress the exponent is equal to -1. When $\langle\tau^*\rangle < \langle\tau^*\rangle_c + S$, the time series is intermittent: the PDF has a maximum at zero flux, making it the most likely value, reflecting the fact the sediment flux time series spends most of its time close to zero, but experiences rare, large bursts of flux. By comparing the PDFs of the sediment flux for various values of the shear stress, Benavides *et al.* (2021) used the theoretical predictions to measure the critical shear stress (finding $\langle\tau^*\rangle_c = 0.026 \pm 0.002$ for the glass spheres) and bed sensitivity for their setup, allowing them to then make estimates of convergence times for experiments at other shear stress values.

Despite the success of this theory in explaining the statistics of sediment flux, the model used in the theory remains entirely empirical, based on an approximation to an unknown dynamical equation for q^*. We would like to understand what physical process leads to on-off intermittency, much like the work of Ancey *et al.* (2008) was able to associate the intermittency observed in their experiments to collective entrainment. This could lead to a better understanding of how the various parameters, such as bed sensitivity, depend on the properties of the channel, grains, and more.

Analysis of grain activity and velocities

By tracking individual locations and velocities of the grains, we were able to disentangle the statistics of the sediment flux into that of grain velocity and grain activity. In Benavides *et al.* (2021), we looked at the downstream sediment flux through a cross section in our channel ('gate'), calculated by summing the stream-wise component of velocity for each grain weighted by their cross-sectional area intersecting the gate. Now we turn to further analysis where we look at time series of (i) the average stream-wise component of velocity of the grains intersecting the gate at one time, which we will denote as v (m/s), and (ii) the total grain area intersecting the gate at one time, which we will denote as n (units of grain cross-sections). In our measurements of n and v, we only count grains which have moved significantly in an interval of 1.5 seconds; otherwise they are considered as part of the bed (any grain centers below the lower red line in Figure 1 are in the bed). In this study, n acts as a measure of the grain activity. We should note that this definition is different from other measures of grain activity in previous work, which include the so-called 'particle activity' (Furbish et al., 2012a) and the number of entrained grains in an experimental window (Ancey et al., 2008). Our definition better suits the nature of our experimental data, and we believe that its statistical properties will carry over to the other measures of grain activity.

Since q^* depends on both n and v, it is not a given that one can consider the statistics of n and v separately. This is only justified if the two variables are uncorrelated, which would imply that the time-averaged sediment flux is proportional to the product of their time averages, $\langle q^* \rangle \propto \langle n \rangle \langle v \rangle$. We find that the sediment flux calculated using $\langle n \rangle \langle v \rangle$ results, on average, in a 25% error compared to the true $\langle q^* \rangle$, although the percent error is slightly larger closer to the threshold of motion (Figure S2). Despite nonzero correlation, which itself has been the subject of various past studies (Furbish et al., 2012b; Ancey and Heyman, 2014; Ancey, 2020a), we consider it to be small enough to justify our decomposition.

We begin by looking at the PDFs of n and v for three sample experiments that represent low, medium, and high transport stages in our setup (Figure 2, A and B). We find that the PDFs of grain velocities fall under the statistics predicted by on-off intermittency. Namely, the PDF of v, for small values of v, follows an approximate power law, whose exponent decreases linearly towards -1 as the critical shear stress is approached (Figure 2, B). We see that this remains true when fitting the tail exponents for all 7 experiments in this study (Figure 2, D). On the other hand, the grain activity does not follow this pattern, and instead we find that a Gamma distribution (the continuous version of Negative Binomial distribution) produces an adequate fit to the data in the smallest transport stages (Figure 2, A). Note that large values of n are more likely than for a Gaussian, implying that the grain activity is intermittent, just not of the on-off type. The PDF seems to transition to something that resembles more of a Gaussian PDF at higher transport stages. Indeed, the skewness of the PDF of n for all 7 experiments monotonically approaches zero (the skewness of a Gaussian PDF) as the shear stress increases (Figure 2, C), signaling the reduction of intermittency intensity, as has been observed in previous experiments (Ancey et al., 2008; Singh et al., 2009), although some recent numerical work finds the opposite effect (González et al., 2017).

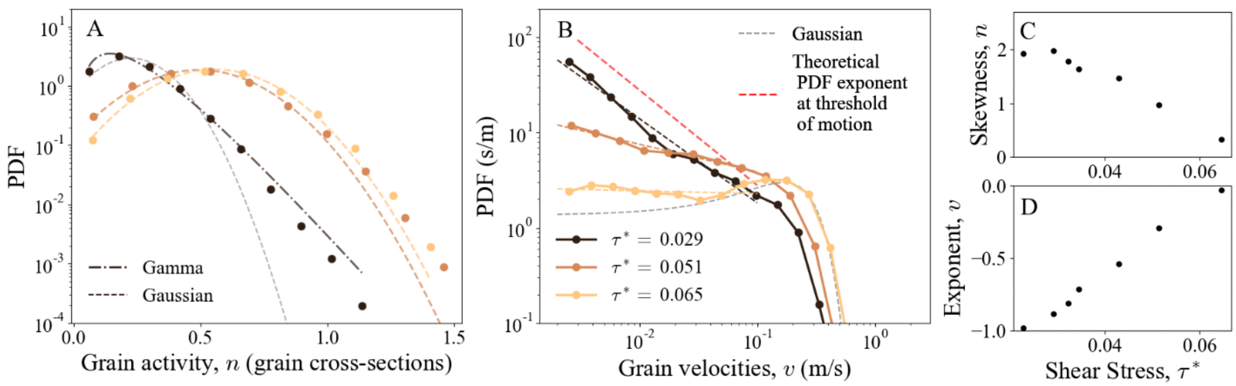

Figure 2. Intermittent statistics of grain activity n (A) and grain velocity v (B) for a series of sample experiments ranging from low to high sediment flux. The skewness of the grain activity PDF for all experiments is calculated in C, showing a gradual transition to Gaussian statistics. The power law exponents of the PDF tails for v are shown in D, based on power-law fits (e.g., the dashed lines, overlain on data in B). These show a linear approach to the theoretical exponent of -1, predicted by the theory of on-off intermittency.

To investigate the mechanisms responsible for on-off intermittency in the grain velocities, we analyzed how the statistics of the grain velocities depend on their height above the bed. For the three example experiments in Figure 2 A and B we measured the joint probability distribution of v and the average y-location (in units of grain radii) of the grain centers intersecting the gate at one time (Figure 3). The bed line (bottom red line in Figure 1) corresponds to $y = 0$, and we denote the 'rolling' population as those grains whose centers lie within three grain radii of the bed line ($y = 3$, top red line in Figure 1). From this analysis we observe a clear difference between the velocity distribution of rolling grains and those which are traveling in the bulk flow. The rolling grains experience velocities that range from 10^{-3} m/s to 10^{-1}m/s, with a PDF that peaks at the smallest values, suggesting on-off intermittency. The grains travelling in the bulk flow, on the other hand, show a much smaller spread in velocities and follow a velocity profile similar to that of the fluid, which increases with height. This suggests that the on-off intermittency found in lower transport experiments are due to the significant contribution of rolling grains to the sediment flux. Indeed, at higher transport stages (Figure 3 C), there are almost no rolling grains, resulting in a PDF of v and q^* with weak intermittency.

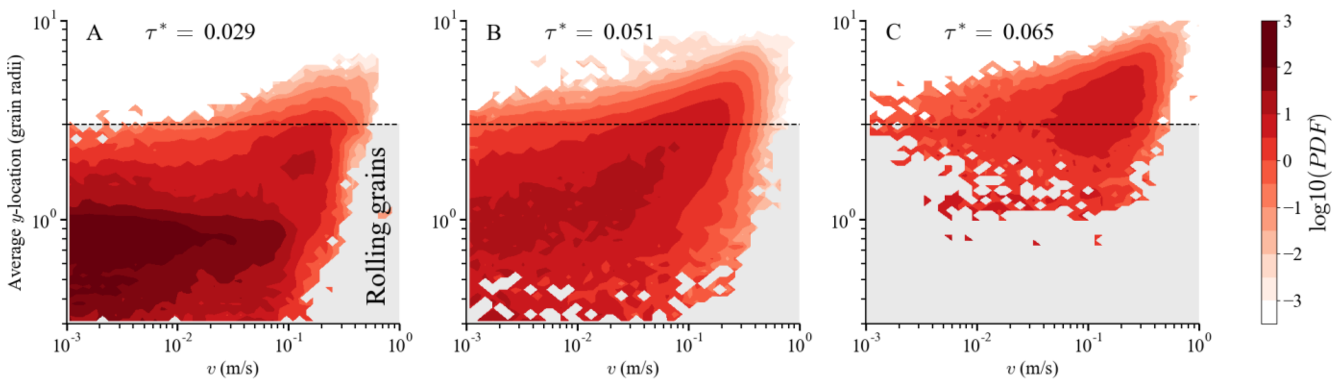

Figure 3. Joint probability distribution of the grain velocities v and their average height above the bed, for the three sample experiments. The rolling grain population is defined as the grains whose centers lie less than three grain radii above the bed (grey area below the black dashed line, see Figure 1).

A tentative explanation for why the rolling grains experience on-off intermittency is found by considering the necessary ingredients for its presence – noise near a threshold. The shear stress at the bed surface is, by definition, at the threshold of being capable of moving grains downstream. Since the fluid is turbulent, and the surrounding grain landscape is irregular, the stresses on the rolling grains fluctuate, meaning that, despite moving downstream on average, some grains are temporarily below the threshold of motion, resulting in on-off intermittent motion.

CONCLUSIONS

Our observations point to an updated picture of intermittency in bed load sediment transport close to the critical shear stress. We found that two types of intermittency coexist in the different components that make up sediment flux. Whereas it was previously accepted that the intermittency lies entirely in the grain activity, we have shown that the grain velocities also contribute significantly to the intermittency, and, in particular, experience on-off intermittency. The intermittent statistics of the grain activity, ranging from an intermittent Gamma distribution near the threshold of motion towards more Gaussian statistics as the shear stress increases, are consistent with previous experimental and numerical studies (Ancey et al., 2008; González et al., 2017). We have also shown that the intermittent grain velocities come from the population of grains that are near the bed (‘rolling’), and that the amount of on-off intermittency observed in an experiment therefore depends on the fraction of rolling grains present. This seems consistent with Heyman *et al.* (2016), who found that grains close to the bed followed exponential PDFs whereas those above two grain diameters followed Gaussian PDFs. Without the ability to resolve small velocities, however, it’s possible that previous studies have captured only the exponential tails of the PDF predicted by on-off intermittency, concluding that the velocities were not intermittent.

With these new insights on intermittency in bed load sediment transport, we hope we can inform the creation of future simplified statistical models which incorporate both the grain activity and grain velocities, with the goal of correctly capturing all types of intermittency observed in experiments and in the field. This could provide crucial information on the dependence of on-off intermittency parameters with channel and flow properties, allowing for better predictions of sediment flux fluctuations and averaging convergence time-scales.

ACKNOWLEDGMENTS

…Matthew Rushlow…

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