Low-angle dunes in big rivers: morphology, occurrence and speculations on their origin

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ABSTRACT: Low-angle dunes (LADs), which have often been defined as those dunes possessing a leeside angle less than 30 degrees, have been reported from several large rivers and shown to possess a different fluid dynamics, and likely internal stratification, to those produced by high-angle dunes (HADs). Herein, we assemble and analyze available data to present a dataset concerning the leeside angle, morphology and classification of dunes in a range of large rivers. We find that low-angle dunes also co-exist with higher angle dunes in large alluvial channels, and suggest their presence is linked to several factors, including suspended sediment concentration, grain size and bedform superimposition. We propose that the classification of LADs should be based on the leeside angle at which permanent flow separation ceases to exist, or less than *c.* of 15°.

1. INTRODUCTION

Dunes are the most common bedform generated in sand-grade alluvial channels, and form the major building block within ancient sandy river channel sediments. Sand dune size ranges from decimetres to hundreds of metres in wavelength, and from *c.* 0.05m to maybe more than 10m in height in some of the worlds largest alluvial channels. Most interpretations of dunes have relied on analogies with dunes that have been well-documented in experimental studies and examination of smaller natural channels, in which the dunes possess a leeside angle at the angle-of-repose of the sediment. However, research over the past 20 years has shown the presence of dunes that possess a lower leeside angle, and which may have a more complex leeside morphology. Recent research has also documented the flow associated with such low-angle dunes, both in the laboratory (Best and Kostaschuk, 2002; Motamedi et al., 2012, 2014) as well as in the field (Roden, 1998; Best et al., 2007; Bradley et al., 2013). Laboratory models have demonstrated the presence of an intermittent zone of flow separation in the leeside of low-angle dunes, and suggested an angle of *c.* 15° is required to promote the onset of permanent flow separation (Best and Kostaschuk, 2002; Motamedi et al., 2012, 2014). Such modification of the leeside flow and flow separation zone has many implications for flow resistance and the parameterization of flow separation associated with dunes (Paarlberg et al., 2007, 2009).

Recent work has also suggested that low-angle dunes may be the predominant type of dune form in large rivers (Roden, 1998; Kostaschuk and Ilersich, 1995; Kostaschuk and Villard, 1996, 1999). Several explanations have been proposed for the origin of low-angle dunes, including: i) The presence of fine material in suspension, which is reasoned to dampen turbulence and lessen the leeside influence of flow separation (Baas et al., 2015; Naqshband et al., 2014; Saunderson and Lockett, 1983); ii) increased sediment bypass of the leeside face, leading to increased deposition in the trough region and thus lessening dune height; and iii) the influence and type of leeside grain avalanche processes that have been proposed to differ on low-angle dunes in large rivers (Hendershot et al., 2015)

Here, we present results concerning the morphological characterization of dunes from a range of the world's big rivers, including the

Amazon, Mississippi, Parana, Mekong, Columbia and Jamuna Rivers. We use this data to examine the magnitude and distribution of leeside angles, and utilize this dataset to discuss the full range of factors that may lead to such low-angle leeside slopes. We also propose a classification threshold for such dunes that relies on the leeside angle at which permanent flow separation is absent, which is *c.* 15°.

2. METHODS

We have assembled, compiled and analyzed data from a wide range of sources that have reported on the form of dunes within large alluvial channels. This data ranges from longitudinal traces of dunes obtained using single beam echo sounder surveys, through to full 3D characterization of the bed using multibeam echosounding. The datasets are analyzed to quantify the leeside angle of dunes, as well as leeside shape, dune height, dune wavelength, the presence and type of bedform superimposition and the relationship of dune height to water depth.

3. RESULTS

Our results show that many large rivers contain dunes that possess a wide range of leeside angles, and that low-angle dunes are not the only type of dune present in these channels (Figure 1). However, lower leeside angles are dominant in the rivers analyzed (Figure 1). Leeside angle is found to vary considerably across the width of an individual sinuous-crested dune, and also between successive downstream dunes. This suggests that the processes that control production of these dunes are not related solely to suspended sediment concentration or water depth, and that a range of factors are influential in determining the leeside angle. Analysis of these datasets allows plotting of probability distributions (pdfs) of leeside angle for a range of large rivers. Figures 1b,d show the pdfs of two dune datasets from the Missouri River and Parana River, showing average leeside angles are 9.5 and 6.2° respectively, with between 80 and 90% of the leesides being less than 15°. These pdfs are seen to fit well with a gamma distribution. We also present examples of the longitudinal profiles of a range of morphometric types of dunes in large rivers, including those with high-angle leesides, humpback-shaped dunes with a brink point upstream of the crest, dunes with and without secondary superimposed bedforms, and low-angle dunes with a more simple morphology (Figure 1c).

These data are used to highlight several factors that may influence the leeside angle of dunes within large rivers, including:

1) The grain size and grain size distribution of the sediment.
2) The presence of fine material in suspension that is reasoned to dampen leeside turbulence.
3) The influence of superimposed bedforms that serve to erode the leeside during bedform amalgamation and may lead to lower-angle leeside slopes.
4) The influence of superimposed bedforms that may act to provide a region of sheltered flow in the leeside region that can affect both the nature/extent of flow separation and the ability for smaller bedforms to rework with leeside slope.

Lastly, our review of the literature suggests that the classification of dunes as low-angle or high-angle should be based on a physical rationale rather than an arbitrary value, such as 30°, which may vary with grain size and grain size sorting. Rather, we propose a definition of low-angle dunes as those that do not possess a zone of permanently separated flow in the leeside. Experimental (Best and Kostaschuk, 2002; Motamedi et al., 2012, 2014) and numerical (Kotapati et al., 2014) modelling suggests that 15° may be an appropriate angle on which to base this classification.

4. CONCLUSIONS

Dunes formed in sand-grade material in large rivers show a range of leeside angles that span from several degrees and up to, and beyond, the angle of repose (*c.* 30°), but appear dominated by leeside slopes less than 10°. Low and high-angle dunes may co-exist within the same reach of an alluvial channel, and suggest that suspended sediment and water depth are thus not the sole factors responsible for their generation. Bedform superimposition, and the influence of smaller, more rapidly migrating bedforms, upon the leeside flow field and dune leeside slope, are important in producing low-angle dunes.

5. ACKNOWLEDGMENTS

We are grateful to our many colleagues who provided access to datasets concerning dune morphology from their research, and which allowed compilation of this dataset.

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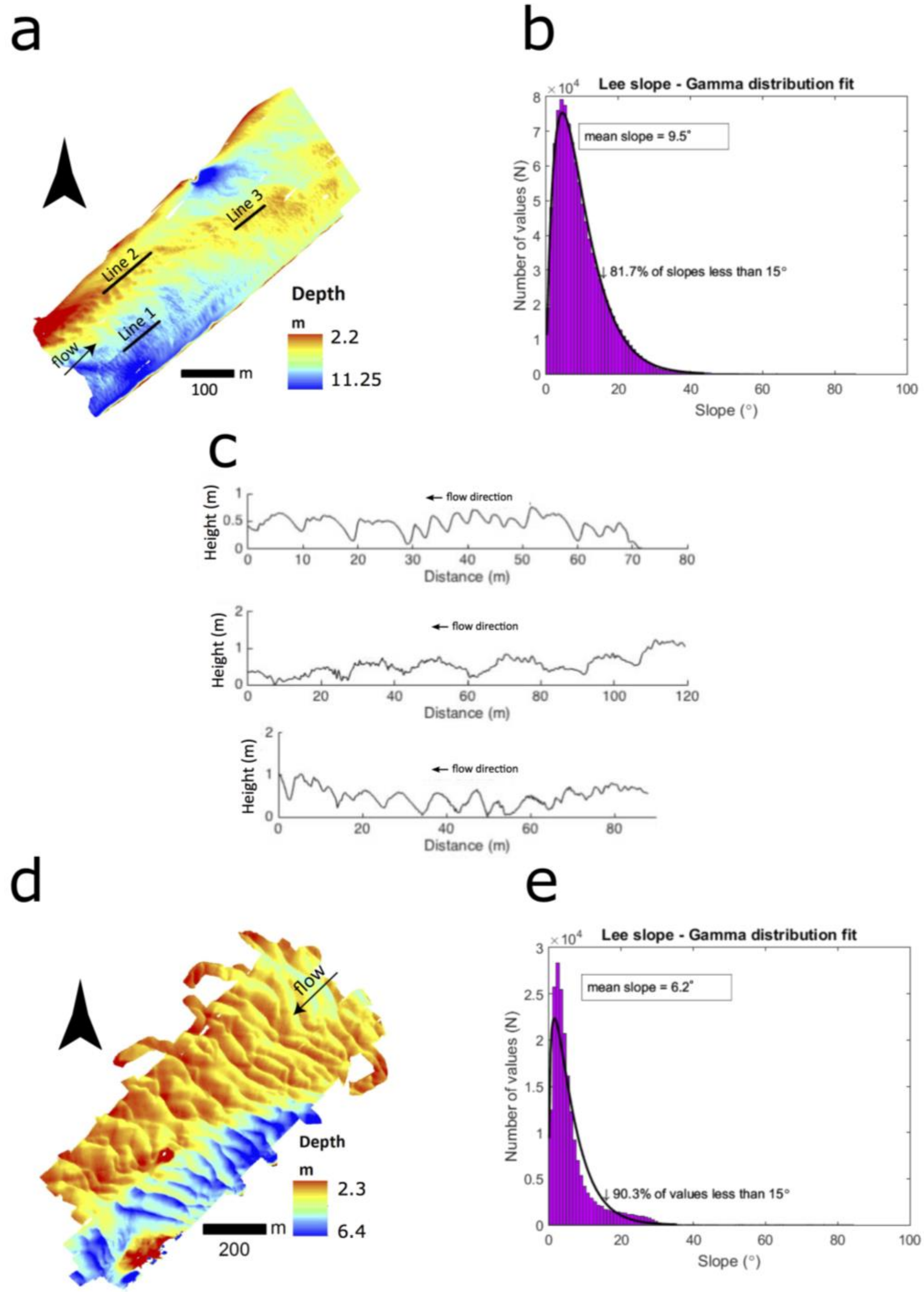

Figure 1. Example of the leeside angles of sand dunes in the a-c) Missouri River, USA, and d,e) Parana River, Argentina, using MBES survey data. a,e) Plots showings bed elevation, illustrating a range of different size sand dunes. b,e) Frequency distribution of lee slopes (+/- 80º) from flow direction and the resulting stoss slopes; c) Bed elevation profile of bedforms from the Missouri River (x10 vertical exaggeration). From top to bottom: Line 1 dunes with a characteristic wavelength of *c.* 5 m; Line 2 dunes with a characteristic wavelength of *c.* 10 m and smaller superimposed dunes on the stoss side; Line 3 dunes with a characteristic wavelength of *c.* 10 m.