Morphology, flow and sediment transport over a natural 3D dune field: Rio Paraná, Argentina

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ABSTRACT: The morphology, flow and process mechanics of river dunes has attracted much interest over many years. However, many of these studies have concentrated on investigating two-dimensional (2D) bed features and their associated flow structures and bed stress distributions. This morphological simplification imposes inherent limitations on our interpretation and understanding of dune form and flow dynamics, as natural dunes are invariably three-dimensional (3D) with an associated fully 3D flow structure. For example, studies over 2D forms neglect the significant effect that lateral flow and secondary circulation may have on the flow structure and thus dune morphology. This paper details a field investigation of the interactions between the 3D morphology, 3D turbulent flow structure and suspended sediment movement over large alluvial sand dunes in the Rio Paraná, NE Argentina. Fixed point and moving vessel surveys enabled the links between three-dimensionality, large-scale turbulence and sediment suspension over the dunes to be investigated.

1 INTRODUCTION

Dunes are ubiquitous forms in river channels, occurring within a wide range of bed sediment sizes. The presence of dunes on the bed significantly influences both the nature of the mean and turbulent flow structure, and consequently exerts a strong control on the entrainment, transport and deposition of bed sediment. As a result of their importance, the morphology, flow and mechanics of river dunes have attracted much interest over many years (e.g. McLean and Smith 1986, Yalin 1992, Nelson 1993, McLean et al. 1994, Bennett and Best 1995, Best 1996, Amsler and García 1997, Shimizu et al. 1999, Kostaschuk 2000, Best and Kostaschuk 2002, Carling et al. 2000, Yue et al. 2003)

This interest in dune flow and form dynamics has enabled elucidation of the main characteristics of flow associated with dunes, which are: (a) accelerating flow over the dune stoss side, (b) flow separation or deceleration (Best and Kostaschuk 2002) from the dune crest in the lee side, (c) flow reattachment at 4 to 6 dune heights downstream, (d) a shear layer between the separated flow zone and streamwise flow above, which expands as it extends downstream, and (e) an internal boundary layer that grows from reattachment beneath the wake along the stoss slope of the next dune downstream. Most of the studies that have contributed to describing these key flow features over dunes have however concentrated on simplified two-dimensional (2D) bedforms, with constant heights and straight crestlines transverse to the flow. Given that natural bedforms are invariably three-dimensional (3D) (e.g. Allen 1982, Baas 1994) this morphological simplification has imposed inherent limitations on our interpretation and understanding of dune form and flow dynamics.

Natural dunes often have variation in crestline planform curvature, crestline height, and crestline continuity (Allen 1982, Dalrymple and Rhodes 1995, Roden 1998), with phase differences between successive crests often producing variability in dune wavelength and steepness (Gabel 1993). This three-dimensionality has significant implications for understanding the flow structure over dunes. For example simplified 2D forms do not possess lateral flows and secondary circulation present in more three dimensional forms, which will have major impacts on the lee side flow structure, bed shear stress and overall dune dynamics. This complexity of bedform morphology in alluvial environments has been known for many years (e.g. Sorby 1859, Neill 1965, Allen 1968) and the considerable complications that the three-dimensionality of form can introduce into the flow structure over bedforms highlighted (e.g. Allen 1968). However, only recently have the full 3D effects of dune form been investigated in detail in the laboratory (Maddux et al. 2003a,b, Venditti 2003). Maddux et al. (2003a,b) investigated dunes in which the planform crestline was straight (i.e. orthogonal to the mean flow at all positions), but where the dune height varied in the cross-stream direction in the form of a full cosine wave. Successive crestlines were 180 degrees out of phase, creating three-dimensional forms where the crest height maxima was followed immediately downstream by a crest height minima. Maddux et al. (2003a) found that these spanwise variations in form significantly altered the flow compared to that found over 2D dunes with a similar crest height. Maximum streamwise velocity was found to be highest over the crestline nodes, rather than the maxima in crestline height, and a significant amount of momentum flux over the dune was transformed into secondary currents induced by topographic forcing due to the three dimensionality in dune height (Maddux et al. 2003a).

Venditti (2003) also performed laboratory investigations into the effects of dune three-dimensionality on flow structure in which dune planform curvature was altered, but crest height and the three-dimensional volume of the dunes were maintained. Results indicate that a convex downstream planform crestline (a lobe) possesses lower average velocities for a given discharge than straight-crested 2D dunes. However, lobes were found to produce a well-defined lee side separation zone, with an intense downstream wake structure and an enhanced level of turbulence with more vigorous mixing in the separation cell than observed over 2D straight-crested dunes. In contrast, dunes with a crestline that is concave downstream (a saddle) were found to have higher average flow velocities, weakly defined separation cells, and wakes that were not a significant component of the flow field (Venditti, 2003). Venditti (2003) argues that lower mean velocities associated with the lobe were caused by higher turbulence intensities in the lee, as a result of flow divergence, whereas in the case of the saddle, convergence of flow in the lee of the dune results in lower turbulence intensities but higher average flow velocities.

The experiments of Maddux et al. (2003a,b) and Venditti (2003) demonstrate that even a simple three-dimensionality in dune form can significantly influence the average flow velocity and flow distribution, secondary currents and lateral flows, and the size and intensity of the separation zone, turbulence and downstream wake. There is thus a significant gap in the understanding of turbulent flow over fully 3D dunes and that there is a pressing need for studies and measurements over natural three-dimensional field dunes. This paper presents a first step towards this goal and details a study of a field of 3D dunes in the Rio Paraná, NE Argentina. A large (0.35 km wide, 1.2 km long) area of dunes was surveyed using a Multibeam Echo Sounder (MBES), providing high-resolution 3D detail of the river bed. Simultaneous with the MBES survey, 3D flow information was obtained with an acoustic Doppler current profiler (aDcp), including at-a-point velocity measurements over key areas of the channel bed. The present paper presents details of the methodology and results using this integrated approach that has enabled investigation of the interactions between the 3D morphology and 3D turbulent flow structure of large alluvial sand dunes. The turbulent flow structures over different sections of dunes with distinct 3D morphologies are also highlighted, and used to discuss the implications for understanding dune flow structure and dune dynamics.

2 FIELD SITE AND FIELD METHODS

The study area is a field of dunes in the Rio Paraná, 16 km north of the city of Corrientes, NE Argentina (Fig. 1). The Paraná River basin occupies 2,600,000 km^2, with a mean annual discharge of the Rio Paraná of 17,000 m^3 s^{-1} (Orfeo and Steveax 2002). At the field site, the Rio Paraná is approximately 2.5 km wide and 5-12 meters deep and, at the time of surveying in May 2004, the discharge of the full river section was about 11,000 m^3 s^{-1}. Measurements of the 3D bathymetry and 3D flow structure were made from a small vessel simultaneously using a Reson™ SeaBat® 8101 Multi-Beam Echo Sounder (MBES) and an RDInstruments™ RioGrande® 600 kHz acoustic Doppler current profiler (aDcp). Both instruments were located together spatially and temporally using a Leica™ differential global positioning system (DGPS) in real time kinematic (RTK) mode, which produced an accuracy in relative position of +/- 0.02 m and +/- 0.03 m in the horizontal and vertical positions respectively, with the boat velocity being approximately 1 m s^{-1} during measurements.

The Reson SeaBat 8101 MBES is a 240 kHz system, which measures the relative water depth across a wide swath perpendicular to the track of the survey vessel. A transmit projector array on the sonar head transmits pulses of acoustic energy into the water column, with reflections from the water column and bed being ‘heard’ on a semicircular receive array. The SeaBat 8101 has 101 beams with a total across-track subtended angle of 210 degrees, permitting the MBES to measure a swath width ~7.4 times the water depth. A combined motion and gyro sensor (a TSS® Meridian Attitude & Heading Reference System (MAHRS)) was used to provide full 3D motion and orientation data for the MBES processing, and the DGPS was set to output a pulse per second, which is used to remove all latency from the MBES processing. The MBES provides information on the river bed morphology at a centimetric resolution and millimetric precision over scales from ripples superimposed on dunes to the entire river reach, and provides an unparalleled methodology by which to examine the form of alluvial roughness.

Simultaneous with the MBES survey, the aDcp was used to quantify the 3D flow structure over the swath of dunes. The aDcp has a 4 beam (transducer) system, each with an orthogonal angle of 20 degrees in the vertical (RD Instruments, 2001), and emits acoustic pulses of energy that are backscattered by particles in the water column. The Doppler shift principle is used to convert the change in frequency into weighted averages of components of flow velocity within each depth range bin. The aDcp was set to pulse (or ‘ping’) at 5 Hz, although measurements were then averaged over 12 pulses to increase the signal:noise ratio, and yielded instantaneous 3D velocity profiles at ~0.54 Hz. Since all velocities measured by the aDcp are relative to the aDcp, and hence the boat velocity, these measured aDcp velocities must be corrected for this motion by removing the DGPS-derived boat velocity, thereby producing measurements of the flow velocity (cf. Yorke and Oberg, 2002). Flow velocities were finally converted from beam coordinates into an Earth referenced coordinate system, using the simultaneous measurements made by the aDcp’s ‘on-board’ attitude and gyro sensor. Since the boat velocity was ~ 1 m s^{-1}, each profile was averaged over an area of diameter ~1.5 m at the first sampling bin nearest the water surface. An inherent limitation of the aDcp is that since each beam is oriented at 20 degrees to the vertical, the measurements are being made, and averaged across, different volumes of fluid in the vertical profile. This limitation increases with depth of measurement, such that static measurements in 10 m of water produce readings at the bed that are averaged over an area of 9.7 m in diameter.

MBES and aDcp measurements were made along a total of 14 parallel streamwise transects, each approximately 25 m apart, and six spanwise cross-sections approximately 200 m apart. For analysis of the large scale turbulent structures associated with the dunes, aDcp measurements were then taken at two fixed (moored points) as guided by the MBES survey. This included a fixed point positioned close to a dune crest and a point over the dune lee.

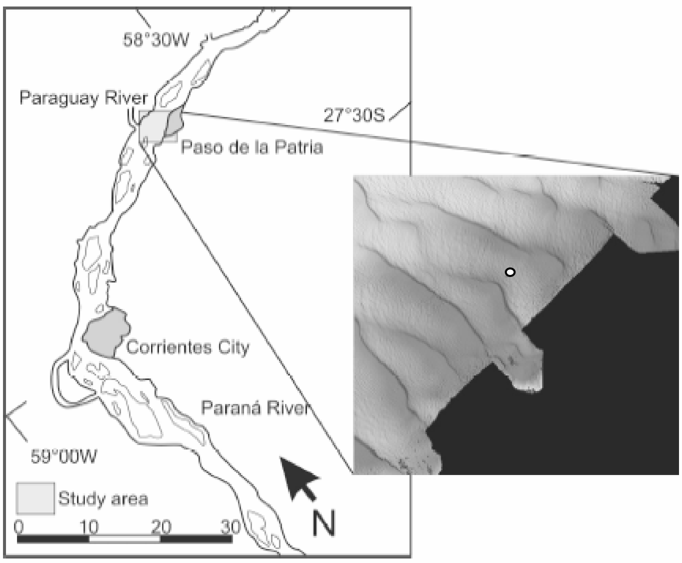

Figure 1. Field site location and inset (multibeam image of river bed). White dot indicates location of moored vessel measurements.

3 RESULTS

3.1 *Bed morphology*

Figure 2 shows the quantified bathymetry of the full field of dunes surveyed by the MBES. Flow depth increases to the SSW corner of the survey area, with a corresponding increase in dune size, and is related to the presence of a large mid-channel bar upstream of the survey area. Overall, the dunes have a relatively complex 3D pattern throughout the surveyed area (Fig. 2), with the dunes being ~1.2 to 2.5 m high and possessing a range of wavelengths from 45-85 m, yielding a range in the dune form index (or aspect ratio; height/wavelength) of ~ 0.021-0.029.

A streamwise profile through the field of dunes (Fig. 3, see location on Fig. 2) shows that the vast majority of the dunes are highly asymmetric, with lee side slope angles typically around ~8.5 to ~22

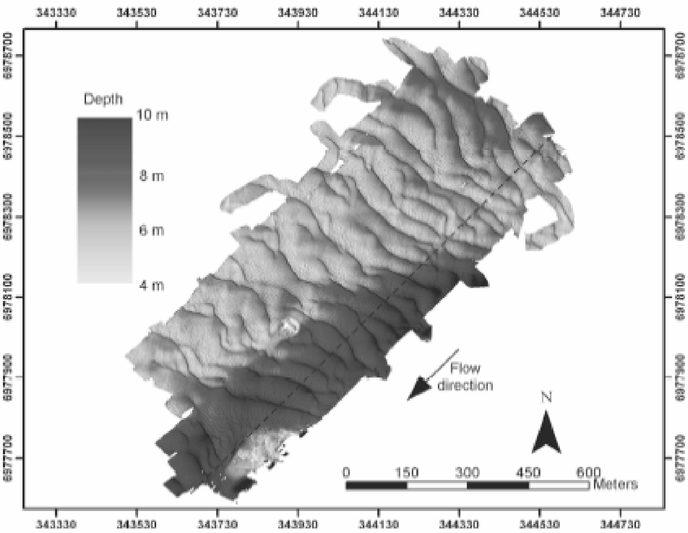

Figure 2. Bathymetric contour map of the dune field obtained using multibeam sonar.

The dunes have clearly identifiable crestlines in planform (Fig. 2), many of which are laterally continuous throughout the ~200 m width of the survey area. However, there are several discontinuous crestlines in-between the more continuous crestlines, frequently resulting in bifurcation of individual crestlines (Fig. 2). Most crestline planform profiles also have zones of pronounced curvature, which produces saddles (where the planform crestline is concave downstream) and lobes (where the planform crestline is convex downstream) along individual crestlines. Venditti (2003) suggests that such distortion is related to maintaining the 3D bed, which exerts a significant control on sediment transport over individual dunes and thus downstream changes in bedform morphology. Indeed one would expect the variations in dune height, and shear stress profiles, produced by planform curvature of the crestlines to produce preferential sediment pathways along a particular dune, with a subsequent influence on the dune dynamics immediately downstream. The control of sediment transport directions by crestline curvature is likely to be important within the study reach, and further influenced by the locations of crestline bifurcations and crestline junctions (Fig. 2).

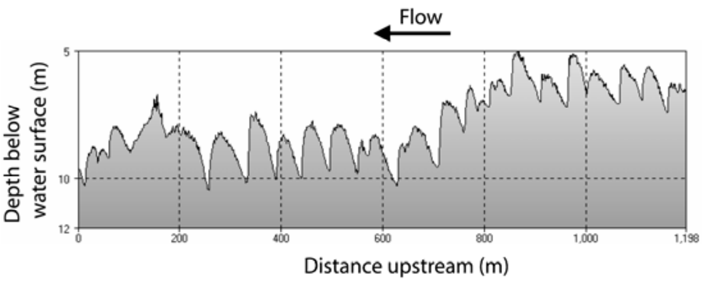

Figure 3. Profile of bed morphology, obtained with MBES, along the streamwise transect indicated in Fig. 2. Note the superimposed bedforms on the larger dunes and the crest-brink separation as shown by the gentle rounded nature of the surface close at the crest followed by a sharper break of slope into the lee.

Numerous variations in the crest heights are present within the dune field in the study reach, even along laterally continuous crestlines (Fig. 2). Moreover, the lee side troughs of many of the dunes also have a large variability in their scour depth, with such variability being up to ~1.5 m along an individual crest, which may be greater than the variation in the crest height between dunes. The variability in scour depth appears to be correlated to areas of planform crestline curvature, with saddle-shaped crests generally having greater, but more localized, areas of scour in their lee compared with straighter crested dunes (Fig. 2). Conversely, lobe-shaped crestlines appear to possess more laterally extensive but shallower lee side scour zones.

The stoss side slopes of the dunes in the reach are commonly convex up (Fig. 3). Most dunes also appear to have a distinct crest-brink parting (i.e. the highest point of the crest and the brinkline of any steeper slipface are not coincident), as indicated by the gentle rounded dips at the crest followed by a sharper break of slope into the lee (Fig. 3). This separation between the crest and the brink is known to have significant implications for shear and turbulence production in the lee side (Best and Kostaschuk 2002), with an influence on sediment movement over the dune crest into the lee side. Despite the variability in lee side angle across the field of dunes, most of the lee slope angles (~>10 degrees) may be expected to produce a separation zone in the dune lee (e.g. Ogink 1988, van Rijn 1993, Wilbers 2002), with low-angle dunes also possessing intermittent flow separation (Best and Kostaschuk 2002). The presence of lee side flow separation is a significant feature of the dune dynamics, exerting significant controls on turbulence production and sediment transport (e.g. McLean et al. 1994, Bennett and Best 1995).

The different aspects of dune three-dimensionality revealed by this MBES survey therefore appear interrelated and may be expected to influence the dune flow dynamics (e.g. Venditti 2003). Planform crestline curvature seems related to variations in crestline height and patterns of leeside scour depth. Moreover, the linkages between crestlines in terms of crestline discontinuities, bifurcations and junctions also appear related to the influence of the upstream dune three-dimensionality, and in particular dune height and variations in lee side scour.

3.2 *Flow structure*

The flow structure obtained with the aDcp over three dunes identified from the MBES survey are shown in Figure 4, 5 and 6. The dunes selected for more detailed analysis possess: a straight crest, a lobe-shaped crest, and a saddle-shaped crest, and were formed within similar flow depths with relatively uniform local crestal heights (2.1-2.3 m). Importantly, the high-resolution bed morphology obtained from the MBES is used to place the individual dunes and their associated flow fields into their full three-dimensional morphological context.

The straight crested dune (Fig. 4) shows many features present over 2D fixed dunes (e.g. McLean et al. 1994, Bennett and Best 1995), including acceleration of streamwise flow along the stoss side of the dune, particularly at the crest, associated with a zone of positive vertical velocity slightly removed from the bed. This is followed by a significant deceleration of flow and a zone of high negative vertical velocity in the dune lee, with a separation zone present in the lee side as indicated by the ~100 degree change in flow direction though the leeside scour (Fig. 4b). This flow separation is associated with a leeside angle of 18 degrees.

Over the saddle-shaped crestline (Fig. 5), a similar pattern of higher streamwise velocity over the stoss side and lower streamwise velocity in the dune lee is apparent, although the deceleration of velocity in the lee is not as marked as over the straight-crested dune. There is also a clear pattern of enhanced vertical velocity over the dune, with a zone of strong upwelling along the stoss side approaching the dune crest, and a stronger zone of downwelling throughout the region of lee side scour. The magnitude of the vertical velocity is also enhanced over the saddle-shaped crestline compared to the straight-crested dune, particularly in the region of downwelling in the dune lee. However, despite this clear pattern in vertical velocity, no flow separation zone is detected in the dune lee, probably due to the spatial sampling limitations of the aDcp. As the angle of the lee side slope over this saddle (14.5 degrees) would suggest that a permanent separation zone may be present, the non-detection of flow separation by the aDcp suggests that flow separation is probably spatially less extensive than associated with the straight-crested dune.

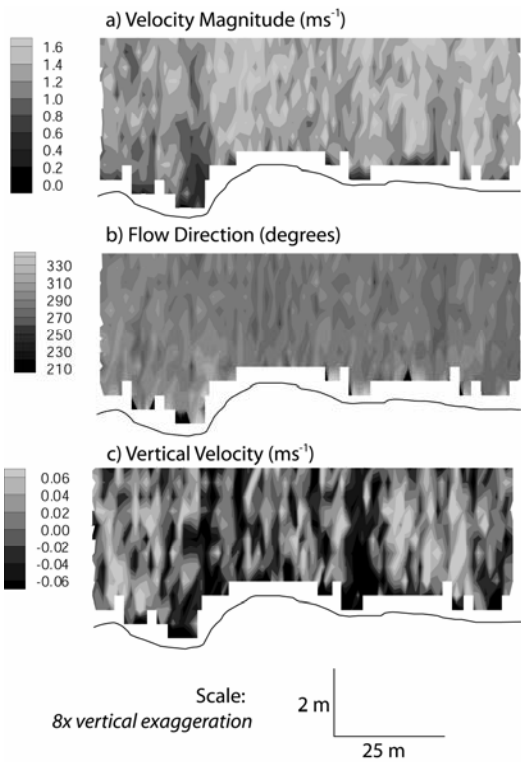

Figure 4. Flow velocity magnitude, direction and vertical velocity over a straight-crested dune. Flow is from right to left.

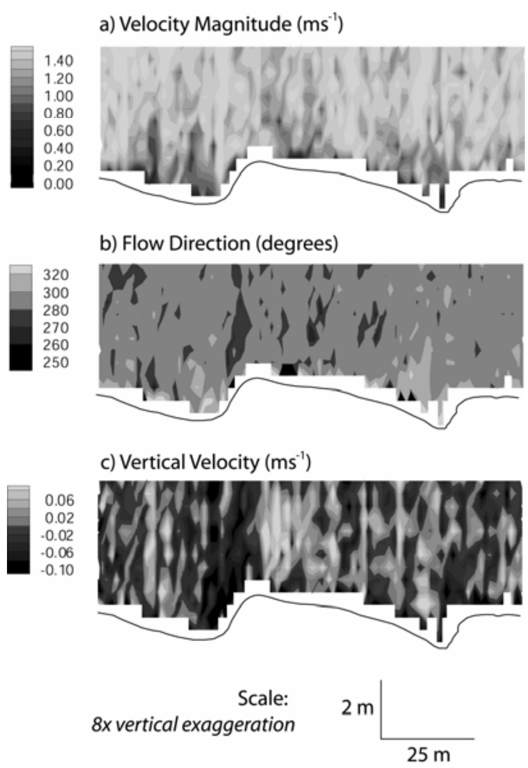

Figure 5. Flow velocity magnitude, direction and vertical velocity over a saddle-crested dune. Flow is from right to left.

In the case of the lobe-shaped crestline (Fig. 6), the general flow pattern is once again similar to the other two cases, although the velocity over the whole dune is slightly lower (1.2 ms^{-1}). A small zone of decelerated flow is again prevalent in the lee side, with the vertical velocity again being enhanced over the dune form, and being greater than the straight-crested dune but less pronounced than in the saddle-shaped crest. Despite the high negative vertical velocity in the lee side, there is no measured flow reversal, with only a ~20 degrees deviation in flow direction detected in lee side. Again, since the lee side angle of the dune (14 degrees) would suggest the likelihood of permanent flow separation, this suggests that the separation zone is again smaller than over the straight-crested dune.

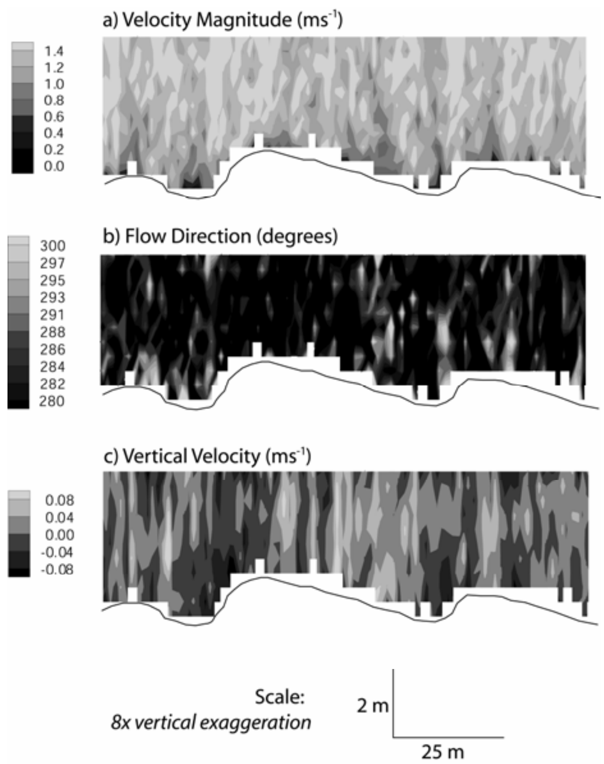

Figure 6. Flow velocity magnitude, direction and vertical velocity over a lobe-crested dune. Flow is from right to left.

These results from a field study of mean flow over 3D dunes, and the recent physical modeling studies of Maddux et al. (2003a, b) and Venditti (2003), have several important implications for sediment entrainment, deposition, sediment transport rates, dune migration and thus the overall stability of a sand bed. The smaller separation zones and lower velocity gradients associated with the leeside of 3D dunes may be associated with a smaller level of large-scale turbulence, and thus amount of sediment entrained into suspension (e.g. Jackson 1976, Kostaschuk and Church 1993) than their 2D counterparts. Moreover, as form drag can be reduced by ~52% over a 3D irregular dune pattern (Venditti, 2003) and turbulence intensities are generally less over 3D dunes compared with 2D dunes (Maddux et al. 2003a), the spatially-averaged bed shear stress is likely to be less over the whole dune: sediment transport rates may thus be expected to be lower over a 3D dune than over a 2D dune profile. The effects of differential dune height, wavelength and form index associated with dune three-dimensionality, which will affect the presence, location and permanence of flow separation, and their influence on flow structure and sediment entrainment may thus be expected to be important in affecting flow resistance over dune-covered beds. More research in this area is vital to better understand dune dynamics.

3.3 *Large-scale turbulence analysis*

The acoustic backscatter signal from the aDcp was used as a proxy for suspended sediment concentration (see Shugar 2005). The backscatter from each of the four instrument beams was averaged for of the bins in the vertical. Time series from a location close to the bed (about 2 m from the bed) at both the dune crest and dune trough were used for comparisons (see Fig. 1 for location).

Wavelet analysis was used to compare the time series. The wavelet transform was designed to analyze time series containing nonstationary power over many different frequency scales (see Daubechies 1990). The wavelet transform used herein is the continuous version, where the transform is calculated for all scales and positions in time. Wavelet analysis offers several advantages over more traditional spectral analyses based on the Fourier transform. The Fourier transform decomposes a signal into a series of sine and cosine waves, and expresses the signal in terms of the frequency (x) and power (y) of its constituent waves, without reference to when the frequencies occur. Furthermore, strong inhomogeneities in a turbulent series mean that the physical meaning of a Fourier decomposition is lost. Wavelet transforms however allow one to unfold a signal into both space and scale using analyzing functions called wavelets, which are localized in space (Farge 1992). A time series is decomposed into a set of scaled and translated versions of wavelet functions, with the scale of the wavelet varying with frequency. Thus, where a Fourier transform in the frequency domain yields a power value for each frequency and is inherently nonlocal, wavelet analysis produces power values for a set of locations in time and for a range of frequencies, the latter related to the scales of the wavelet function considered. Wavelet analysis is therefore useful in analyzing time series that contain nonstationary power at various frequencies and expresses a time series in three-dimensional space: time (x), scale/frequency (y) and power (z).

Figure 7 shows wavelet transforms for suspended sediment concentrations at 1 meter above (a) the crest surface and (b) trough locations over the dune. Wavelet analysis identifies coherent flow structures at a range of frequencies from 1 to $1x10^{-3}$ Hz, with structures having periods of ~100 seconds dominating the time series at both the crest and the trough, but with significantly lower wavelet power for the trough time series. Periodicities of flow structures with high suspended sediment content of 0.01 Hz are common, with both records exhibiting these larger, lower frequency structures. As these regions of enhanced suspended load correlate well with streamwise flow deceleration over both crest and trough, these events are interpreted as fluid ejections, which have a streamwise velocity lower than the average and are responsible for increased suspension of sediment. These results suggest that these larger scale structures (~100 s) move over the crest and are then transmitted through the lee side scour, with the lower wavelet power indicative of less coherence as the flow structure moves through the lee side.

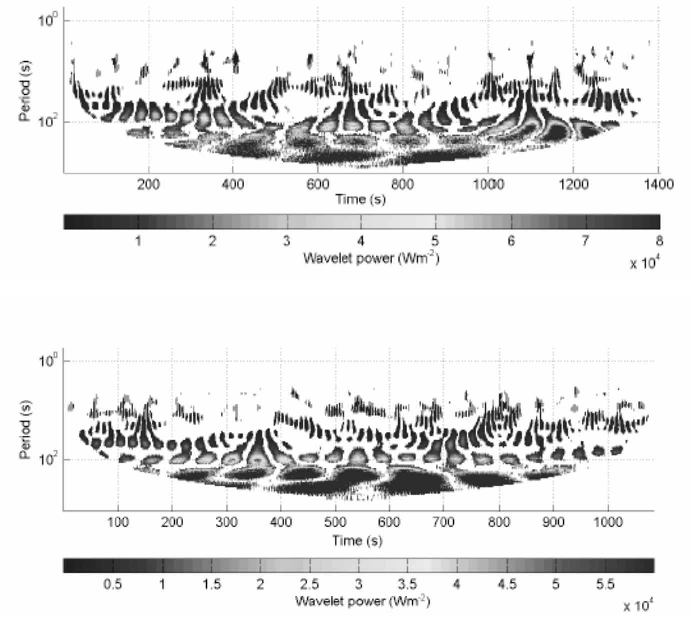

Figure 7. Wavelet power spectrums of calibrated suspended sediment concentration at (a) the dune crest and (b) at the dune trough. Both time series are taken 2 meters above the channel bed.

4 CONCLUSIONS

Detailed measurements of bed morphology and three-dimensional flow structure over a field of sand dunes in the Rio Paraná, Argentina, have enabled an initial field testing of recent laboratory findings concerning 3D dune morphology and flow dynamics.

Dune morphology is complex with considerable variations in dune height, wavelength, scour depth and crestline curvature. For instance, dune three-dimensionality may induce larger changes in dune height than the variation present between different dunes. Variability in crestline direction and curvature along with crestline continuity are also present. Crestline discontinuities, bifurcations and junctions appear related to the influence of upstream dune three-dimensionality.

Three-dimensionality in dune morphology is also shown to significantly influence the flow structure. Both lobe and saddle shaped dune crestlines produce smaller regions of lee side flow separation, with higher vertical velocities when compared with a straight crested dune. These findings suggest that if the flow structure over 3D dunes is associated with smaller levels of large-scale turbulence, this may also result in less suspension of bed sediment, and thus sediment transport over the dune field may be reduced.

This field study also highlights that further research is clearly required into the interacting effects of dune curvature and dune height on flow structure, from a combination of laboratory and theoretical work aligned with targeted field investigations. An advance in understanding is also required on the influence of natural 3D dune geometry on macroturbulent flow structures and their spatial variability. Furthermore, detailed information is needed as to how dune migration rates and sediment transport are linked to the morphology of natural 3D dunes, which can then be linked though to an increased understanding of the temporal changes in 3D dune flow structure.

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