Morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: Results from simultaneous multibeam echo sounding and acoustic Doppler current profiling

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[1] Most past studies of river dune dynamics have concentrated on two-dimensional (2-D) bed forms, with constant heights and straight crest lines transverse to the flow, and their associated turbulent flow structure. This morphological simplification imposes inherent limitations on the interpretation and understanding of dune form and flow dynamics in natural channels, where dune form is predominantly three-dimensional. For example, studies over 2-D forms neglect the significant influence that lateral flows and secondary circulation may have on the flow structure and thus dune morphology. This paper details a field study of a swath of 3-D dunes in the Rio Paraná, Argentina. A large (0.35 km wide, 1.2 km long) area of dunes was surveyed using a multibeam echo sounder (MBES) that provided high-resolution 3-D detail of the river bed. Simultaneous with the MBES survey, 3-D flow information was obtained with an acoustic Doppler current profiler (ADCP), revealing a complicated pattern of dune morphology and associated flow structure within the swath. Dune three-dimensionality appears intimately connected to the morphology of the upstream dune, with changes in crest line curvature and crest line bifurcations/junctions significantly influencing the downstream dune form. Dunes with lobe or saddle-shaped crest lines were found to have larger, more structured regions of vertical velocity with smaller separation zones than more 2-D straight-crested dunes. These results represent the first integrated study of 3-D dune form and mean flow structure from the field and show several similarities to recent laboratory models of flow over 3-D dunes.

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1. Introduction

[2] Dunes are ubiquitous bed forms in river channels and their presence 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 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 et al.*, 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.*, 2000a; 2000b; *Yue et al.*, 2003; *ASCE Task Force*, 2002, 2005; *Best*, 2005].

[3] This interest in dune dynamics has enabled elucidation of the main characteristics of flow associated with dunes, which are (1) accelerating flow over the dune stoss side, (2) flow separation or deceleration [*Nelson et al.*, 1993; *McLean et al.*, 1994; *Best and Kostaschuk*, 2002] from the dune crest in the leeside, (3) flow reattachment at 4 to 6 dune heights downstream [*Engel*, 1981], (4) a shear layer between the separated flow zone and streamwise flow above, which expands as it extends downstream, and (5) an internal boundary layer that grows from reattachment beneath the wake along the stoss slope of the next dune downstream.

[4] However, many studies that have contributed to describing the key flow features over alluvial dunes have concentrated on two-dimensional (2-D) bed forms, with constant heights and straight crest lines transverse to the flow [see review in Best, this issue]. As natural bed forms are invariably three-dimensional (3-D) in alluvial, estuarine and marine environments [*Allen*, 1982; *Baas*, 1994, 1999], this morphological simplification has imposed inherent limitations on the interpretation and understanding of dune form and flow dynamics. Dunes often have variation in crest line planform curvature, crest line height, and crest line

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continuity [*Allen*, 1982; *Dalrymple and Rhodes*, 1995; *Roden*, 1998; *Best*, 2005], with phase differences between successive crests frequently producing variability in dune wavelength and steepness [*Gabel*, 1993]. This three-dimensionality has significant implications for understanding the flow structure and sediment movement over dunes, since 2-D forms do not account for the significant affect that lateral flows and secondary circulation may have on the leeside flow structure, shear stress and overall dune dynamics. The three-dimensionality of dune form clearly has complicating implications for the formation of cross stratification within the sedimentary record, for instance in the range of dip angles and directions around a 3-D leeside slope [e.g., *Harms et al.*, 1982; *Allen*, 1982; *Rubin*, 1987], and thus our interpretations and reconstructions of former flow regimes based upon such strata [e.g., *Paola and Borgman*, 1991; *Leclair and Bridge*, 2001; *Leclair*, 2002]. Understanding the three-dimensionality of river dunes may also have implications for the formation of larger-scale fluvial bed forms such as midchannel, point or alternate bars [e.g., *Colombini et al.*, 1987; *Schielen et al.*, 1993], and thus larger-scale fluvial dynamics. Bed form three-dimensionality is also invariably present in other environments, including estuarine, coastal, marine and aeolian environments [*Allen*, 1982; *Aliotta and Perillo*, 1987; *Werner*, 1995; *Kostaschuk and Villard*, 1996; *Dyer and Huntley*, 1999; *Blondeaux*, 2001; *Cheng et al.*, 2004]. Although other complex factors, such as surface waves and nonuniform or oscillatory flows, are frequently present within these environments, it is often suggested that bed forms in all environments tend to be more three-dimensional where flows are more unidirectional with relatively high shear velocities [*Allen*, 1968]. However, bed form three-dimensionality and its implications remain poorly understood.

[5] Although the complexity of bed form 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 bed forms highlighted [e.g., *Allen*, 1968], only recently have the specific 3-D effects of dune form on flow structure been investigated in detail in the laboratory [e.g., *Maddux et al.*, 2003a, 2003b; *Venditti*, 2003; *Best*, 2005]. *Maddux et al.* [2003a, 2003b] investigated dunes in which the planform crest line 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 crest lines were 180° 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 2-D dunes with a similar crestal height. Maximum streamwise velocity was found to be highest over the crest line nodes, rather than the maxima in crest line 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]. *Maddux et al.* [2003a, 2003b] also found that friction coefficients were up to 50% higher over 3-D dunes, but that turbulence was much lower than over the 2-D forms, and suggested that this may be due to an increase in form-induced stress associated with the greater secondary currents over the 3-D dunes.

[6] *Venditti* [2003] also performed laboratory investigations into the affects 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 crest line (a lobe) possesses lower average velocities for a given discharge than straight-crested 2-D dunes. However, lobes were found to produce a well-defined leeside 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 2-D straight-crested dunes. In contrast, dunes with a crest line that was 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]. These differences associated with the lobe and saddle were attributed to variations in the lateral and vertical divergence and convergence of flow over the dune [*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 larger average flow velocities.

[7] *Venditti* [2003] also demonstrated that the flow dynamics were significantly altered by whether the dunes were arranged in regular or irregular patterns, since roughness arrangement has been found to alter flow and drag reduction over smaller form roughness [*Sirovich and Karlsson*, 1997]. *Venditti* [2003] found that irregularly placed lobes possessed a similar flow pattern to single saddles, and hypothesized that irregular-shaped dune forms have a lower drag than regular shaped forms.

[8] The elegant experiments of *Maddux et al.* [2003a, 2003b] and *Venditti* [2003] thus 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. *Best* [2005] highlights that there is a significant gap in the understanding of flow over fully 3-D dunes and that there is a pressing need for studies and measurements over three-dimensional field dunes linked to detailed laboratory studies. This paper presents a first step toward this goal and details a study of a field of 3-D 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 3-D detail of the river bed. Simultaneous with the MBES survey, 3-D flow information was obtained with an acoustic Doppler current profiler (ADCP). The present paper details the methodology and results using this integrated approach that has enabled investigation of the interactions between the 3-D morphology and 3-D flow structure of large alluvial sand dunes. The flow structures over different sections of dunes with distinct 3-D morphologies are highlighted, and used to discuss the

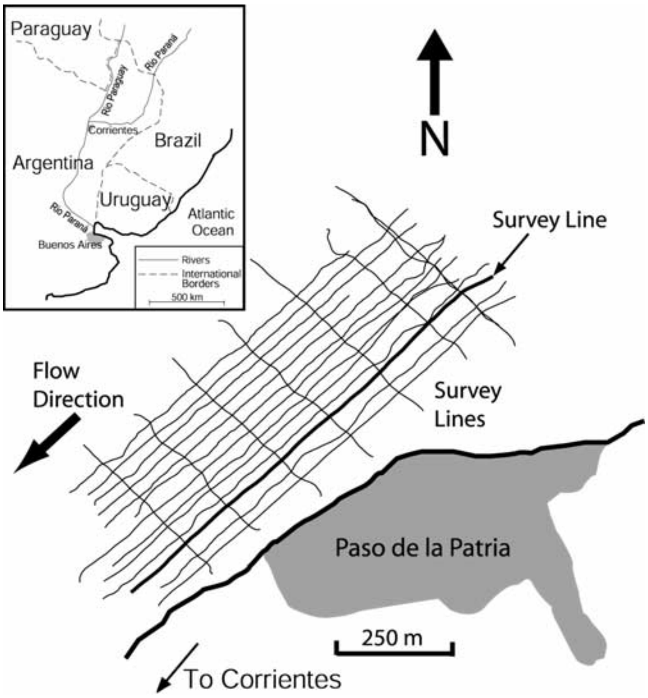

Figure 1. Location of the field site, Paraná River, Argentina. Paso de la Patria is 36 km north of the city of Corrientes (27°30′S, 58°50′W).

implications for understanding dune flow structure and dynamics.

2. Study Site and Field Methods

[9] The study area is a field of dunes in the Rio Paraná, just upstream of the confluence of the Rio Paraguay, 16 km north of the city of Corrientes, NE Argentina (Figure 1). The Paraná River basin occupies 2,600,000 km^2, mostly in Southern Brazil and Argentina, and the mean annual discharge of the Rio Paraná is ~17,000 m^3 s^{-1} [*Orfeo and Steveax*, 2002]. At the field site, the Rio Paraná is ~2.5 km wide and 5–12 m deep (Figure 1) and, at the time of surveying in May 2004, the discharge of the full river section was ~11,000 m^3 s^{-1}.

[10] Measurements of the 3-D bathymetry and 3-D flow structure were made from a small vessel simultaneously using a Reson™ SeaBat® 8101 Multi-Beam Echo Sounder (MBES) and an RD Instruments™ RioGrande® 600 kHz 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 (DGPS base station to mobile rover) of ±0.02 m and ±0.03 m in the horizontal and vertical positions respectively. The boat velocity and track position along the survey lines were monitored online and were held as constant as possible during surveying, with the boat velocity being ~1.1 m s^{-1}.

[11] 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 semi-circular receive array [*Reson Inc.*, 2002]. The bottom is detected using a combination of both amplitude and phase detection methods [*Reson Inc.*, 2002]. The SeaBat 8101 has 101 beams with a total across-track subtended angle of 210°, 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 3-D motion and orientation (attitude) data for the MBES processing, and the DGPS was set to output a pulse per second (PPS), which is used to remove all latency from the MBES setup. 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 [*Wilbers*, 2004]. MBES measurements were taken for the whole area of dunes at approximately 20 Hz, with a depth gate filter being set between 3 m and 20 m; tests for colinearity and brightness of each sounding are assigned by the system during data collection.

[12] Simultaneous with the MBES survey, an RD Instruments broadband 600 kHz ADCP was used to quantify the 3-D flow structure over the swath of dunes. The ADCP has a 4 beam (transducer) system, each with an orthogonal angle of 20° in the vertical (RD Instruments, San Diego, California, Acoustic Doppler current profilers, Principles of operation: A practical primer), and emits acoustic pulses of energy that are backscattered by particles in the water column. The backscattered signal is split into 128 equally spaced bins in the vertical, and 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 (RD Instruments). The ADCP was set to pulse (or 'ping') at 5 Hz, although measurements were then averaged over 12 pulses to reduce aliasing and increase the signal:noise ratio, and yielded instantaneous 3-D velocity profiles at ~0.5Hz. 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 "onboard" attitude and gyro sensor. Since the boat velocity was ~1.2 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° 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.

[13] MBES and ADCP measurements were made (Figure 1) along a total of 14 parallel streamwise transects, each approximately 25 m apart, and six spanwise cross sections approximately 200 m apart. Any interaction between the two acoustic instruments was assessed by running the instruments individually for short, repeated test runs and comparing the results obtained. No interaction in the mea-

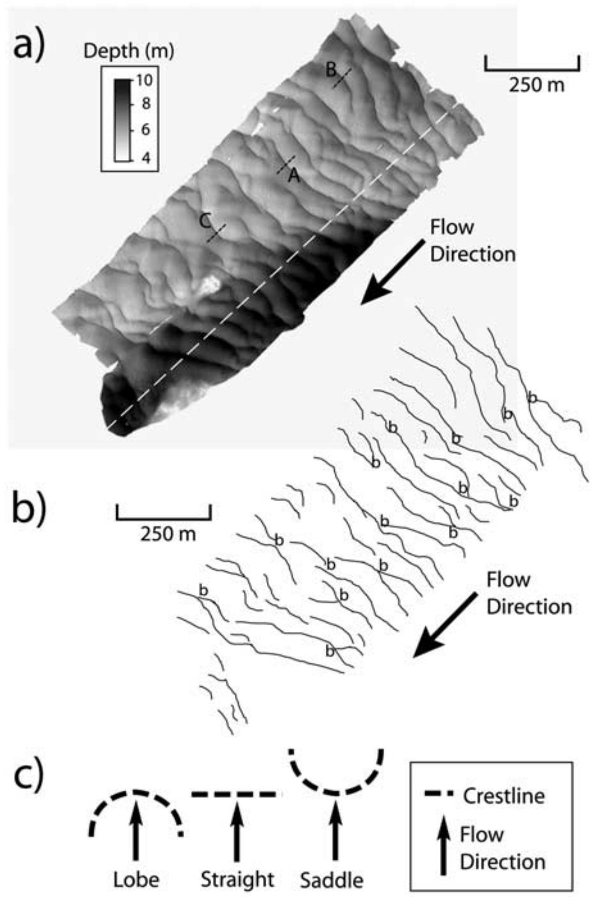

Figure 2. (a) Bathymetric contour map of the dune field. The location of the full length transect is shown as a dotted line, while the individual dune locations (A, straight; B, saddle; C, lobe) are highlighted. (b) Map showing the location of the dune crest lines, with the dune crest bifurcations indicated. (c) Schematic of classification of dune crest line shape.

sured values was detected. Postprocessing of the MBES data was achieved using CARIS HIPS®, in which all lines and soundings were merged and combined so that area-based filtering and editing could be employed to produce the final surface for analysis. Postprocessing of the ADCP data included conversion of longitude/latitude positions to match the UTM zone coordinates of the MBES data, and rotation of the flow velocities to the transects or sections surveyed, which then enabled the magnitude and direction of the flows, within their morphological context, to be calculated.

3. Results

3.1. Dune Morphology

[14] Figure 2a shows the quantified bathymetry of the full field of dunes surveyed by the MBES, gridded at a horizontal resolution of 0.25 m. 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 midchannel bar upstream of the survey area. Overall, the dunes have a relatively complex 3-D pattern throughout the surveyed area (Figures 2a and 2b), 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.

[15] A streamwise profile through the field of dunes (Figure 3; see location on Figures 1 and 2a) shows that the vast majority of the dunes are highly asymmetric, with leeside slope angles typically around ~8.5 to ~18°, but with lee slopes up to 22° in individual dunes. Dune stoss slope angles are much shallower, typically around ~1.5 to 2.5°.

[16] Despite the variability in leeside angle across the field of dunes, most lee slope angles ~>10° may produce a separation zone in the dune lee [e.g., *Ogink*, 1988; *van Rijn*, 1993; *Wilbers*, 2004], with lower-angle dunes also likely to possess intermittent separation [*Best and Kostaschuk*, 2002]. The presence of leeside 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 stoss side slopes of the dunes in the reach are commonly convex up (Figures 2a and 3) with most of the stoss slopes also possessing superimposed bed forms (Figure 3). Figure 4 shows the morphological detail of one area of the dune field, highlighting the superimposed forms which are ubiquitous on the stoss slopes of the dunes. These features are, however, notably absent in the lee side scour region and

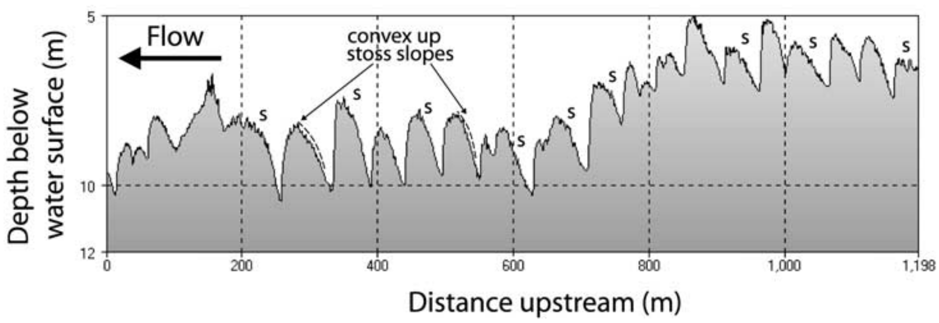

Figure 3. Profile of bed morphology along the streamwise transect indicated in Figure 2a. Note the superimposed bed forms (labeled "S") on the dunes and the crest-brink separation as shown by the gentle rounded nature of the surface close to the crest followed by a sharper break of slope into the lee.

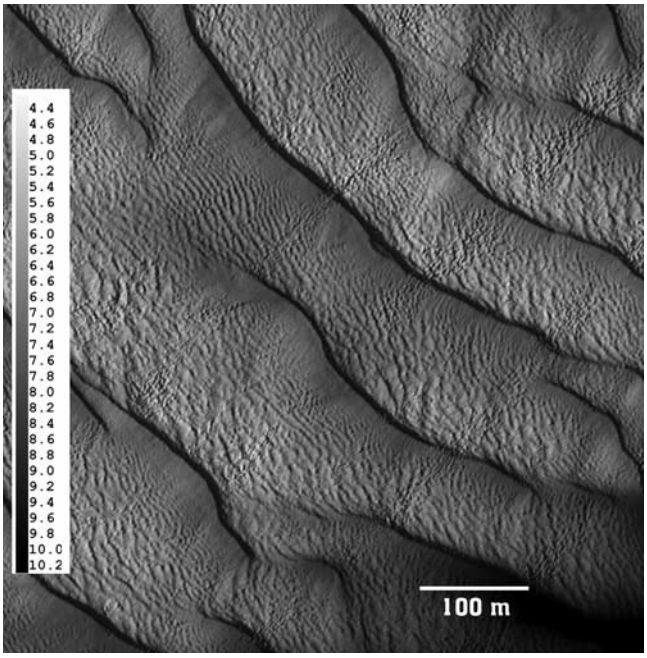

Figure 4. Bathymetric contour map of a section of the dune field, detailing the superimposed bed forms. Contour scale is depth in meters. Note the increase in size and three-dimensionality toward the crests and the absence of superimposed forms in the leeside scours. Flow is top right to bottom left.

tend to increase in amplitude and length toward the crest, reaching a maximum of ~300 mm in height and ~10 m in length (Figures 3 and 4). The three-dimensionality of the superimposed bed forms also appears to increase from the leeside to the dune crest, correlating with the increase in the scale of these superimposed forms (Figure 4). The increase in bed form size possibly relates to the increase in shear velocity as flow accelerates toward the dune crest and the greater time for bed form development downstream of the region of leeside erosion.

[17] Most of the dunes also appear to have a distinct crest-brink parting (i.e. the highest point of the crest and the brink line of any steeper slip face are not coincident), as indicated by the gentle, rounded dips at the crest followed by a sharper break of slope into the lee (Figure 3). This parting between the crest and brink is known to have significant implications for shear and turbulence production in the leeside [*Best and Kostaschuk*, 2002], with an influence on sediment movement over the dune crest into the leeside.

[18] The dunes have clearly identifiable crest lines in planform (Figures 2a and 2b), many of which are laterally continuous throughout the ~200 m width of the survey area. However, there are several discontinuous crest lines in between the more continuous crest lines, frequently resulting in the confluence and bifurcation of individual crest lines (Figure 2b). Most crest line planform profiles also have zones of pronounced curvature, which produces saddles (where the planform crest line is concave downstream) and lobes (where the planform crest line is convex downstream) along individual crest lines (Figure 2c), similar to the 3-D shapes of dunes investigated by *Venditti* [2003]. *Venditti* [2003] states that such distortion is related to maintenance of the 3-D bed, which exerts a significant control on sediment transport over individual dunes and thus downstream changes in bed form morphology. Variations in dune height, and shear stress profiles, produced by planform curvature of the crest lines will produce preferential sediment pathways along a particular dune [*Venditti*, 2003], with a subsequent influence on the dune dynamics immediately downstream. This control of sediment transport by crest line curvature is likely manifested within the study reach by the patterns of crest line bifurcations and junctions, and thus likely dune amalgamations (Figures 2a and 2b). For example, areas of high crest line curvature and crest height variability are often followed by a discontinuity or bifurcation in the crest line downstream (Figures 2a and 2b). *Venditti* [2003] describes how a crest line bifurcation can develop downstream of an area of locally high-elevation crest line, with this high region producing a zone of sediment starvation at the crest immediately downstream. Such sediment starvation causes a reduction in the local dune migration rate and thus results in the amalgamation of the crests, creating a bifurcation, which will further modify the flow field and sediment pathways across the zone.

[19] Numerous variations in the crest heights are present within the dune field in the study reach, even along laterally continuous crest lines (Figure 2a). Moreover, the leeside troughs of many of the dunes also have highly variable scour depths, with such variability being up to ~1.5 m along an individual crest line, 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 crest line curvature, with saddle-shaped crests generally having greater, but more localized, areas of scour in their lee than straight-crested dunes (Figure 2a). Conversely, lobe-shaped crest lines appear to possess more laterally extensive but shallower leesides (Figure 2a).

[20] The different aspects of dune three-dimensionality revealed by the MBES therefore appear interrelated and may be expected to influence the dune flow dynamics [e.g., *Venditti*, 2003; *Best*, 2005]. Planform crest line curvature is related to variations in crest line height and patterns of leeside scour depth. Moreover, the linkages between crest lines in terms of crest line discontinuities, bifurcations and junctions also appear related to the influence of the upstream dune three-dimensionality, and in particular dune height and variations in leeside scour. These findings begin to provide field corroboration for the laboratory results of *Venditti* [2003]. The following section examines the patterns of flow over these dune morphologies and assesses the implications for sediment pathways and variability in erosion and deposition along the dune crest line.

3.2. Flow Structure

[21] The flow structure revealed by the ADCP over a representative full-length transect across the dune field is examined first (Figures 1, 2a, and 5), before three individual dunes are subjected to further analysis (Figures 6, 7, and 8). 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 dunes selected for more detailed analysis possess (1) a straight crest, (2) a lobe-shaped crest, and (3) a saddle-shaped crest (see Figures 2a and 2c),

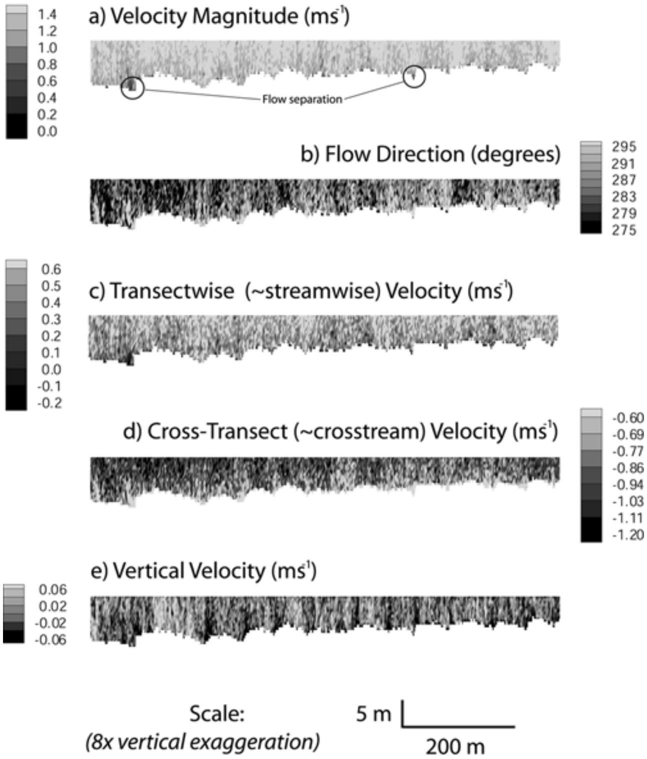

Figure 5. Three-dimensional flow structure over the streamwise transect of Figure 3, including (a) velocity magnitude, (b) velocity direction, (c) streamwise velocity, (d) cross-stream velocity, and (e) vertical velocity. See color version of this figure in the HTML.

and were formed within similar flow depths and had relatively uniform local crestal heights (2.1–2.3 m).

[22] Figure 5 illustrates the mean flow structure over the dunes for one of the full-length transects through the surveyed dune field (see Figure 1, 2a, and 3). The near-bed deceleration produced by the form drag and the strong topographic forcing of the dune morphology can be clearly identified and dominates the flow field. The deceleration of flow and a low velocity zone in the lee of the dunes, as found in many previous studies [cf. *Bennett and Best*, 1995, Table 1; *Kostaschuk et al.*, 2004], is also apparent. However, despite the clear deceleration, only two dunes show measured areas of flow reversal in the dune lee (Figure 5a). This lack of flow separation is most likely a function of two factors: (1) the low-angle of some of the leesides, which may result in permanent flow separation being absent [*Best and Kostaschuk*, 2002], and (2) limitations of the ADCP instrument [*Kostaschuk et al.*, 2004]. As detailed above, due to the beam spread of 20° and the larger spatial averaging of the measured velocity at the bed, many of the separation zones, particularly over the smaller dunes, will not be identified. Nevertheless, the ADCP records do reveal strong decelerations and accompanying deviations in lateral velocity in the lee of the dunes, as indicated by the plots of flow direction and cross-stream velocity (Figures 5b and 5d). Indeed, the topographic forcing of flow produced by the dunes can result in differences in flow direction of >15° between flow over the crest and flow in the leeside. These field results confirm the laboratory findings of *Maddux et al.* [2003a] who noted strong topographic forcing of dunes associated with variations in crest line height. Indeed, *Maddux et al.* [2003a] suggest that over natural dunes, which possess areas of discontinuous crest lines and greater variability in crest line height than in their experimental study, lateral topographic steering of the flow may be enhanced and could be relatively larger than measured in the laboratory. Such enhanced topographic steering of the flow, and the alterations in form drag and reduction in turbulence intensities that may result [*Maddux et al.*, 2003b], may have a significant influence on the distribution of shear stresses and sediment transport rates over the dune crests.

[23] The increase in positive vertical velocity (i.e. flow away from the bed) over the stoss sides of each dune is also clear (Figure 5e), as is a strong zone of downwelling (negative vertical velocity) in the leeside of each dune. As found in previous studies, [e.g., *McLean et al.*, 1994; *Bennett and Best*, 1995; *Kostaschuk et al.*, 2004], the positive vertical velocities are enhanced on the stoss sides of the dunes due to topographic forcing of the flow to the crest. Deceleration of flow in the region of expanding flow downstream of the crest, within the area of leeside scour,

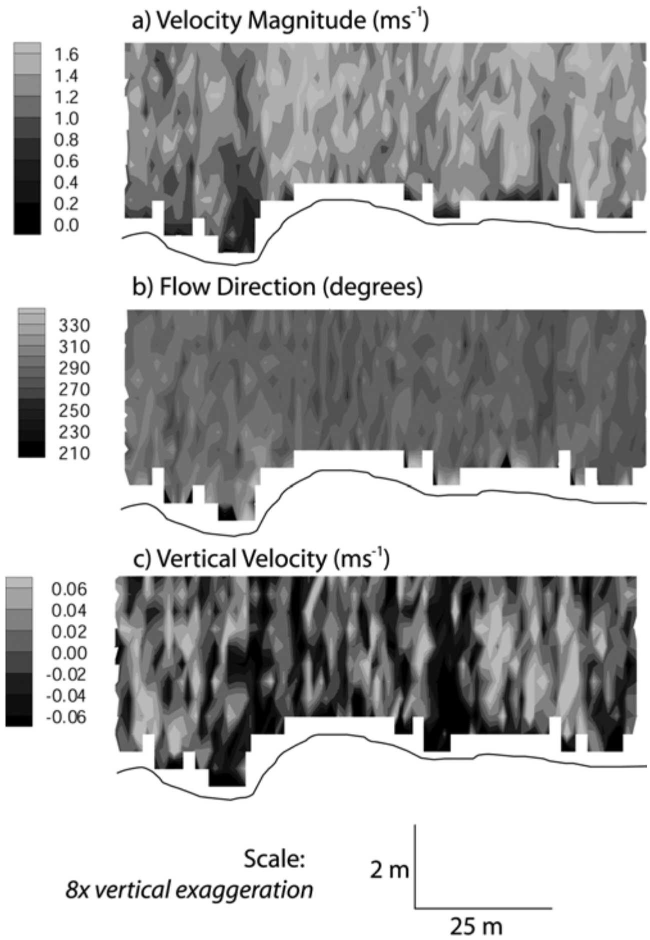

Figure 6. (a) Flow velocity magnitude, (b) direction, and (c) vertical velocity over a straight-crested dune. The location of the dune is illustrated and labeled as A in Figure 2a. See color version of this figure in the HTML.

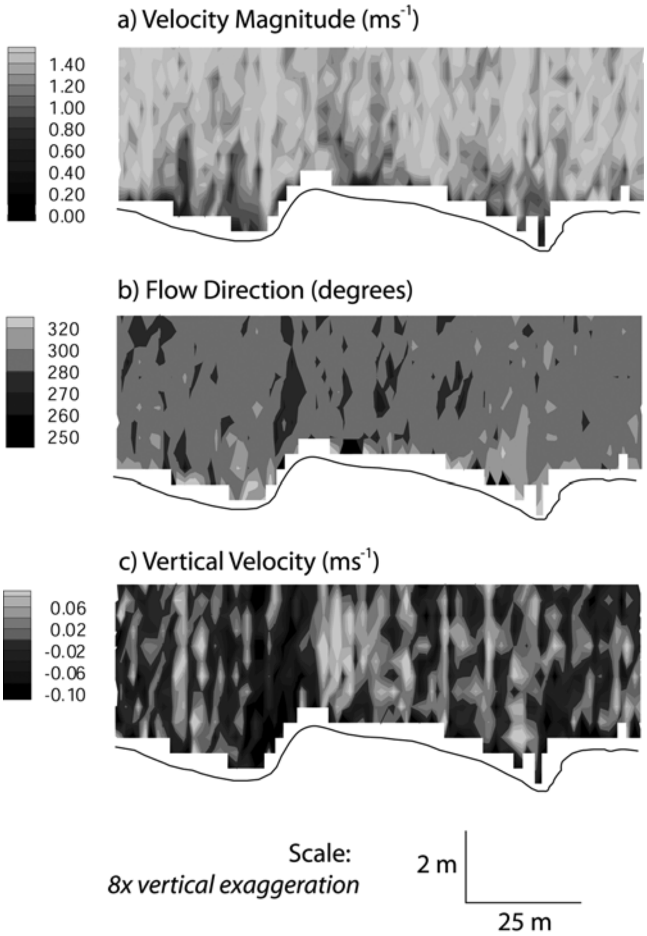

Figure 7. (a) Flow velocity magnitude, (b) direction, and (c) vertical velocity over a saddle-shaped dune. The location of the dune is illustrated and labeled as B in Figure 2a. See color version of this figure in the HTML.

results in the observed downwelling through, and slightly beyond, this zone in each of the dunes along the transect (Figures 5a and 5e).

[24] Figures 6, 7, and 8 illustrate the structure of flow over three individual dunes of similar height within the investigated area (see Figure 2a for locations), but with distinctly different crest line shapes: (1) straight, (2) saddle, and (3) lobe (Figure 2c). The straight-crested dune (Figure 6) shows many features present over 2-D 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 leeside as indicated by the ~120° change in flow direction though the leeside scour (mean flow direction over the dune field is toward 270°; Figure 1). This separation of flow is associated with a leeside angle of 17°.

[25] Over the saddle-shaped crest line (Figure 7), 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 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 leeside scour. The magnitude of the vertical velocity is also enhanced over the saddle-shaped crest line as 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 leeside slope over this saddle (14.5°) would suggest that a permanent separation zone may be present, the nondetection of flow separation by the ADCP suggests that flow separation is probably spatiality less extensive than associated with the straight-crested dune.

[26] In the case of the lobe-shaped crest line (Figure 8), 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 m s^{-1}). A small zone of decelerated flow is again prevalent in the leeside, with the vertical velocity again being enhanced over the dune form, and being greater than the straight-crested dune but less pronounced than associated with the saddle-shaped crest. Despite the high negative vertical velocity in the leeside, there is no measured flow reversal, with only a ~20° deviation in flow direction detected in leeside. Again, since the leeside angle

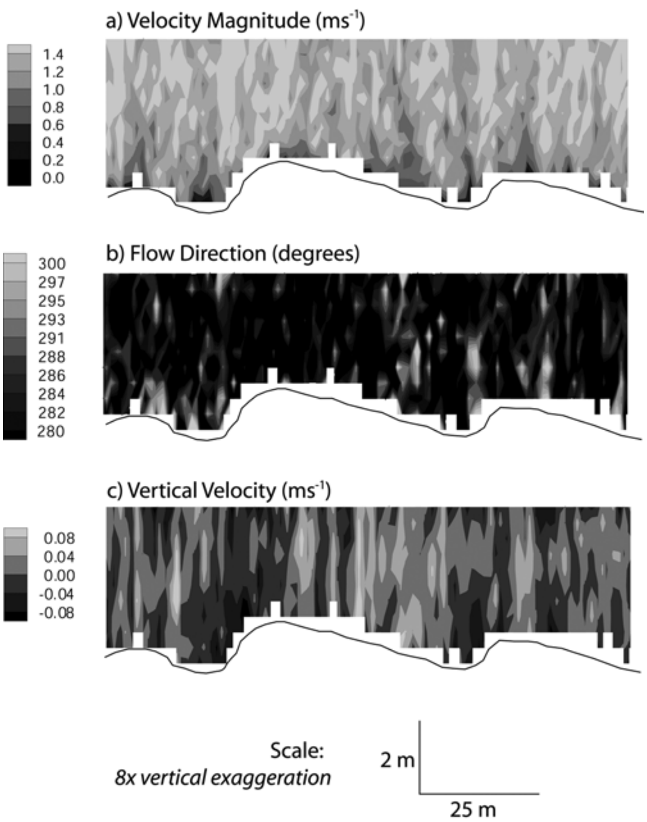

Figure 8. (a) Flow velocity magnitude, (b) direction, and (c) vertical velocity over a lobe-shaped dune. The location of the dune is illustrated and labeled as C in Figure 2a. See color version of this figure in the HTML.

of the dune (14°) would suggest the likelihood of permanent flow separation, this suggests that the separation zone is again smaller than over the straight-crested dune.

4. Discussion

[27] The results from this field study of form and mean flow structure over a dune field in the Rio Paraná, suggest the presence of greater vertical velocities over both the lobe and saddle shaped crest lines when compared with straight-crested dunes, although the separation zones tend to be smaller. If these results are compared with the recent work of *Maddux et al.* [2003a, 2003b] and *Venditti* [2003], there are some notable similarities and important differences. In laboratory experiments, *Venditti* [2003] found that dunes with saddle-shaped lobes have larger overall streamwise velocities, with greater vertical velocities and smaller separation zones, than straight-crested dunes. The field results presented herein confirm this pattern of flow over a natural saddle-shaped dune (Figure 7). However, *Venditti* [2003] found that lobe-shaped crest lines possess lower streamwise velocities with weaker vertical velocities, but larger separation zones, than straight-crested dunes. This is contrary to the results of the natural lobe-shaped dune crest lines presented above, in which flow over the lobe and saddle had similar overall patterns of flow when compared with the straight-crested dune. However, *Venditti* [2003] also found that the planform organization of the lobes and saddles was critical to the flow fields produced, and specifically whether the lobes exist in a regular or irregular planform configuration. *Venditti* [2003] reports that lobes within irregular dune crest lines affect the flow in a similar manner to saddle-shaped dune crest lines, where the vertical velocities are enhanced and the separation cell is only weakly defined. These findings appear applicable to the results presented herein (Figures 6, 7, and 8), in that the field of dunes investigated in the Rio Paraná are clearly not regular, and many dunes more closely resemble the irregular dune crest lines investigated by *Venditti* [2003] in the laboratory.

[28] These results from a field study of flow over 3-D dunes and the recent physical modeling studies of *Maddux et al.* [2003a, 2003b] 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. For instance, the smaller separation zones and lower-velocity gradients associated with the leeside of 3-D 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 2-D counterparts. Moreover, as form drag can be reduced by $\sim$52% over a 3-D irregular dune pattern [*Venditti*, 2003] and turbulence intensities are generally less over 3-D dunes compared with 2-D dunes [*Maddux et al.*, 2003a], the spatially averaged bed shear stress is likely to be less over the whole dune [*Maddux et al.*, 2003b]: sediment transport rates may thus be expected to be lower over a 3-D dune than over a 2-D 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.

[29] The presence of superimposed bed forms is particularly interesting, as is the increase in both superimposed bed form size and three-dimensionality from leeside to dune crest. This would seem to be related to flow acceleration at the crest of the larger dune forms, but the dynamics of superimposed bed forms and their influence on the fluid mechanics and sediment transport rates of the larger dunes is an area requiring further detailed investigations.

5. Conclusions

[30] 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 [*Maddux et al.*, 2003a, 2003b; *Venditti*, 2003] concerning 3-D dune morphology and flow dynamics.

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

[32] Three-dimensionality in dune morphology is also shown to significantly influence the flow structure. Both lobe and saddle shaped dune crest lines produce smaller regions of leeside flow separation, with higher vertical velocities when compared with a straight-crested dune. These findings suggest that if the flow structure over 3-D 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.

[33] 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 3-D dune geometry on macroturbulent flow structures and their spatial variability [e.g., *Williams et al.*, 2003]. Furthermore, detailed information is needed as to how dune migration rates, superimposed forms and sediment transport are linked to the morphology of natural 3-D dunes, which can then be linked through to an increased understanding of the temporal changes in flow structure associated with 3-D dunes.

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