Temporal Characteristics of Coherent Flow Structures generated over Alluvial Sand Dunes, Mississippi River, revealed by Acoustic Doppler Current Profiling and Multibeam Echo Sounding

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ABSTRACT: This paper investigates the flow in the lee of a large sand dune located at the confluence of the Mississippi and Missouri Rivers, USA. Stationary profiles collected from an anchored boat using an acoustic Doppler current profiler (ADCP) were georeferenced with data from a real-time kinematic differential global positioning system. A multibeam echo sounder was used to map the bathymetry of the confluence and provided a morphological context for the ADCP measurements. The flow in the lee of a low-angle dune shows good correspondence with current conceptual models of flow over dunes. As expected, quadrant 2 events (upwellings of low-momentum fluid) are associated with high backscatter intensity. Turbulent events generated in the lower lee of a dune near the bed are associated with periods of vortex shedding and wake flapping. Remnant coherent structures that advect over the lower lee of the dune in the upper portion of the water column, have mostly dissipated and contribute little to turbulence intensities. The turbulent events that occupy most of the water column in the upper lee of the dune are associated with periods of wake flapping.

1 INTRODUCTION

Dunes are ubiquitous features in large sand bed rivers and many researchers have sought to understand the flow over, and the morphodynamics of, fluvial dunes (see review in Best 2005). Flow over fluvial dunes consists of five major flow regions: (1) a region of flow separation just downstream from the dune crest, with reattachment of the flow generally occurring 4-6 dune heights downstream from the crest; (2) a shear layer that divides the flow separation region from the free stream velocity above, with turbulence generated in this region by Kelvin-Helmholtz instabilities manifested as vortex shedding and by wake flapping, which is the expansion and contraction of the flow separation region; (3) a region of flow expansion in the lee of the dune; (4) an internal boundary layer downstream from the point of flow reattachment, which grows as flow reestablishes itself and develops a normal logarithmic profile; and (5) a region of maximum horizontal velocity over the crest of the dune (Best 2005).

Kelvin-Helmholtz instabilities generate large-scale vortices that arise along the shear layer, giving rise to turbulent events that have been termed quadrant 2 events (e.g. Bennett & Best 1995). Quadrant 2 denotes that the streamwise velocity fluctuation is negative while the vertical velocity fluctuation is positive (i.e. away from the bed). Quadrant 4 events have the opposite sign, with a positive streamwise velocity fluctuation and negative vertical velocity fluctuation. The coherent structures generated by quadrant 2 turbulent events are advected with the mean flow and can erupt on the water surface as “boils” (Nezu & Nakagawa 1993). The coherent flow structures may also contain higher sediment concentrations than the ambient flow (Lapointe 1996, Best 2005).

The purpose of the present study is to investigate the flow fields in the lee of a large sand dune at the confluence of the Mississippi and Missouri Rivers, and investigate the origins and spatio-temporal evolution of large-scale turbulence associated with these bedforms.

2 FIELD SITE

The study was conducted at the confluence of the Mississippi and Missouri Rivers (38°48'N, 90°7'W) just northeast of St. Louis, Missouri, USA. The locations of the stationary profiles over a dune are shown in Figure 1. The low-angle dune studied in this paper had smaller dunes superimposed on both its stoss and lee sides.

The Mississippi and Missouri Rivers are major USA shipping channels, and sand transport and deposition, largely in the form of dunes, can obstruct navigation. Dunes also create resistance to the flow in the river while the flow causes the dunes to mi-

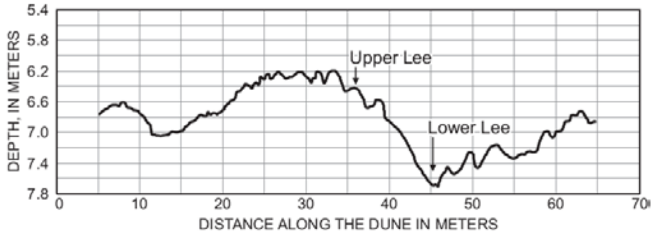

Figure 1. Location of stationary profiles over the dune.

grate downstream. Dunes are important for vertical mixing in rivers while providing low-velocity regions for fish in their lee side.

3 DATA COLLECTION AND PROCESSING

The flow measurements were made during a moderate rise of the Mississippi River. The mean daily flow at St. Louis on October 19, 2007 was 6,590 m^3s^{-1} (a low-medium flow), with 3,740 m^3s^{-1} from the Mississippi River and the remainder from the Missouri River.

The acoustic Doppler current profiler (ADCP) data analyzed in this paper were collected on October 19, 2007 onboard the US Geological Survey's *M/V Iroquois*. A Teledyne RD Instruments 1200 kHz Rio Grande ADCP was employed, using water mode 1 with a bin size of 0.2 m (Note: Any use of trade, product, or firm names is for descriptive purposes only and does not constitute endorsement by the US Government). One ensemble (measurement of velocity and backscatter) was collected every 0.32 s with no averaging. The distance from the water surface to the center of the first bin was 0.71 m. The data from the lower 6% of the profile were not used because of contamination by side-lobe interference (Simpson 2001).

A RESON 7125 multibeam echo sounder (MBES) was used to map the bathymetry of the confluence and provided a morphological context for the ADCP measurements. Data from both the ADCP and MBES were georeferenced by means of a Leica real-time kinematic differential global positioning system (RTK DGPS). The RTK DGPS was used as the reference for the velocity measurements.

Velocity profile time series were collected at 2 locations from an anchored boat using an ADCP. Although the anchor kept the boat from moving downstream, the boat moved side-to-side over a distance generally less than 3 m. Data were collected in the lee of a low-angle dune having an average lee-side slope of 6°. The first time series was obtained near the bottom of the lee side of the dune (hereafter referred to as lower lee) and the second time series was obtained closer to the crest near the top of the lee-side slope (hereafter referred to as upper lee; see Figure 1). Both ADCP time series were collected for just over 12 min, although half way through the lower lee time series, a barge passed downstream along the eastern shore and the resulting disturbance significantly influenced the vertical velocities even though there was no noticeable change in pitch and roll. The time series collected at this location was thus truncated in order to remove the data influenced by the disturbance created by the passage of the barge. The entire time series collected at the upper lee was used in the analysis.

The time-series data included vertical profiles of velocity magnitudes and directions in the horizontal plane, vertical velocities, and backscatter intensities corrected for signal attenuation. The velocities measured by the ADCP were calculated using all four beams, whereas the backscatter intensities were computed based on the forward and aft beams only, as these beams were aligned with the flow. It is assumed with ADCP measurements that the flow being sampled by the 4 diverging beams is relatively uniform. Although the flow is never exactly uniform (especially near the bed), given the scale of the dune and the ADCP beam footprint, this assumption and the accompanying spatial averaging seems reasonable. The average velocity direction of the flow was computed by time-averaging and then depth-averaging the velocity direction profile. The velocity magnitudes and directions were decomposed into a component parallel to the average velocity direction (the streamwise component) and a component perpendicular to this direction (the transverse component). The streamwise direction is defined as positive downstream, the transverse component is defined as positive 90° counterclockwise from the streamwise direction, and the vertical component is defined as positive in the upward direction. Invalid or missing velocity values were interpolated from valid velocity measurements before and after the period of invalid data.

Backscatter intensity, the intensity of sound returned to the ADCP from particles in the water column, can be influenced by suspended sediment and entrained air. For these analyses, changes in backscatter intensity were attributed to changes in suspended sediment concentration (SSC) based on field observations, field notes, and previous work. During these measurements, no concurrent samples of SSC were obtained that could be used to correlate SSC with backscatter intensity, and therefore the interpretation of high SSC is qualitative. However, past work (e.g. Gartner 2004) has shown how such relations can be used to estimate SSC within the flow.

4 RESULTS

Average profiles for streamwise velocity, transverse velocity, vertical velocity, and backscatter intensity (u, v, w, and b, respectively) were obtained by temporally-averaging the profiles. Depth-averaged values of u, v, w, and b were computed for each time series and are designated U, V, W, and B respectively. The instantaneous deviations, or fluctuations, about the time-averaged profiles, u, v, w, and b, were computed as u', v', w', and b', respectively.

4.1 *Time-averaged velocity profiles*

The average streamwise velocity profiles at both positions in the lee of the dune are shown in Figure 2. The same profiles are shown in dimensionless form in Figure 3, using dimensionless depth, z/H, and dimensionless streamwise velocity, u/U, where z is 0 at the water surface, H is the total depth given by the average of the four beams, u is the time-averaged velocity profile, and U is the depth-average of the streamwise velocity profile in the vertical. The flow velocity increases from the lower lee to the upper lee, and reflects the accelerated flow near the dune crest. It is noticeable that the flow velocities are consistently downstream during these measurements, and no region of permanent flow reversal can be detected. Not detecting this region may be caused in part by the limited spatial resolution of the ADCP near the bed, but also by the intermittency of flow separation. It is also likely that smaller separation/deceleration zones exist in the lee side of lower angle dunes (Best & Kostaschuk 2002).

The specific discharge (q), depth multiplied by the average streamwise velocity, was computed for each profile. In the lower lee, $q_{lowerlee} = 10.8\ m^3s^{-1}$, and in the upper lee, $q_{upperlee} = 11.1\ m^3s^{-1}$.

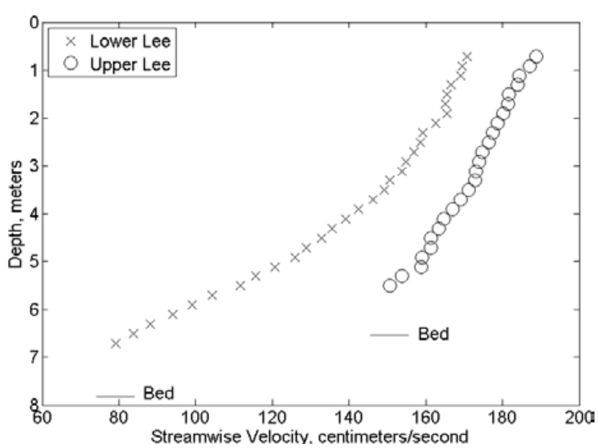

Figure 2. Streamwise velocity profiles.

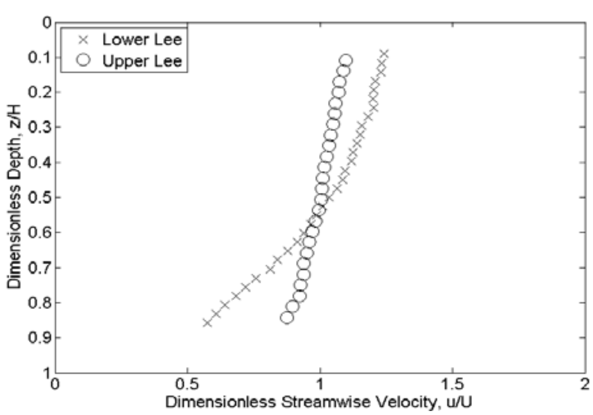

Figure 3. Dimensionless streamwise velocity profiles.

4.2 *Temporal variations in velocity profiles*

For a subset of the data analyzed, streamwise and vertical velocity vectors over approximately 32 s are superimposed on the contour of backscatter intensity for both the lower lee and upper lee in Figures 4, 5, respectively. For visualization purposes, the velocity data were smoothed using 3 depth cells in the vertical and 3 ensembles in the horizontal. Smoothing was not used for the cross-correlation and frequency analyses (described below).

Periods of lower streamwise velocity, which are associated with upward vertical velocities (quadrant 2 events), are apparent in Figure 4 between 249 and 252 s near the water surface and in Figure 5 between 40 and 45 s throughout the majority of the water column. These events are also associated with periods of higher relative backscatter intensity. Periods of higher streamwise velocity, which are associated with downward vertical velocity (quadrant 4 events), are present in Figure 4 between 252 and 254 s near the water surface and in Figure 5 between 58 and 60 s throughout the majority of the water column. These periods, when fluid rushes towards the bed, are asso-

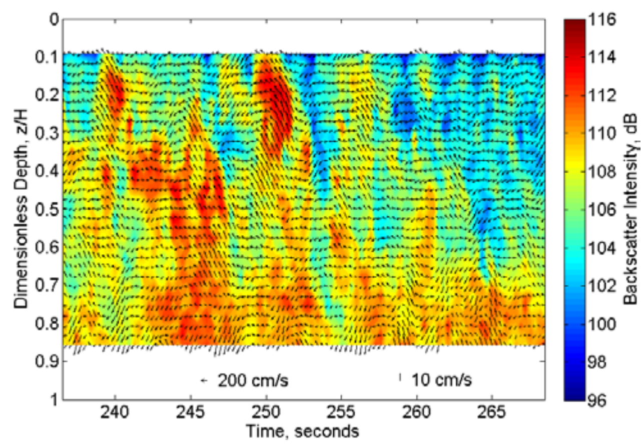

Figure 4. Backscatter intensity contours with streamwise and vertical velocity vectors in the lower lee of the dune.

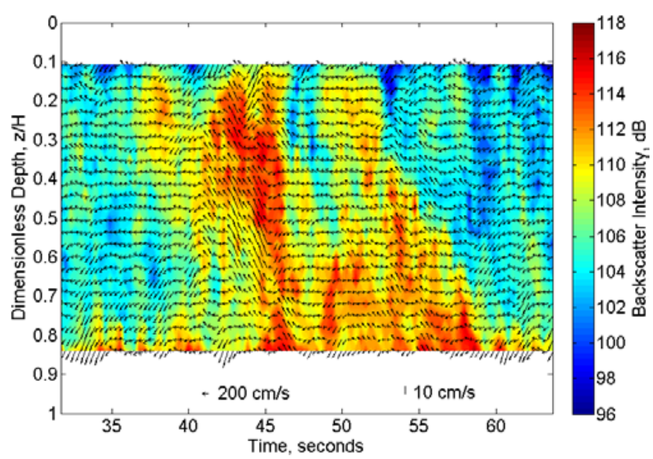

Figure 5. Backscatter intensity contours with streamwise and vertical velocity vectors in the upper lee of the dune.

ciated with areas of lower relative backscatter intensity.

In the lower lee, the backscatter intensity contour shows two distinct zones (Fig. 4). One zone extends between about 0.6 z/H and the bed where backscatter intensity is almost always relatively high. In this zone, the vertical velocities fluctuate every few seconds. We hypothesize that this zone is in, or near, the region of expanded flow that may experience intermittent flow separation in the lee and also may possess a bounding shear layer with free stream fluid above. A second distinct zone of backscatter characteristics exists between the water surface and 0.6 z/H, and is characterized by intermittent high backscatter intensities (Fig. 4). In this zone, the vertical velocities are large and upward when the backscatter intensity is highest. This zone is interpreted as showing the advection of intermittent upward-moving fluid and high backscatter intensity, which may have been generated from the lee of this dune or possibly from a dune upstream.

In the upper lee, the backscatter intensity is periodically high throughout the water column (Fig. 5). When the backscatter intensity is high, the vertical velocities are large and upward. At this location, the flow structures and high backscatter intensity appear to be more intermittent, especially in the upper flow field.

4.3 *Cross-correlation analysis*

Cross-correlations were computed between combinations of streamwise velocity fluctuations, vertical velocity fluctuations, and backscatter intensity fluctuations for each measurement location (Figs 6, 7). For both measurement locations, the cross-correlations generally agreed with the interpretations of Figures 4, 5, namely that the vertical velocity fluctuations are positively correlated with the backscatter intensity fluctuations throughout the water column. This confirms that upward vertical velocity fluctuations are associated with higher values of backscatter intensity. The streamwise velocity fluctuations were negatively correlated with both the vertical velocity fluctuations and the backscatter intensity fluctuations. This is indicative of quadrant 2 and 4 events.

The maximum value, or peak, of the cross-correlation does not always occur for the two time series simultaneously, and the peak of the cross-correlation often has a time offset. This offset indicates the time shift between the two series when they are most highly correlated. For both measurement locations, the cross-correlation time offsets show similar results (Figs 8, 9), with the vertical velocity fluctuations occurring at approximately the same time as the fluctuations in backscatter intensity. This indicates that backscatter intensity fluctuations and vertical velocity fluctuations are simultaneous. For

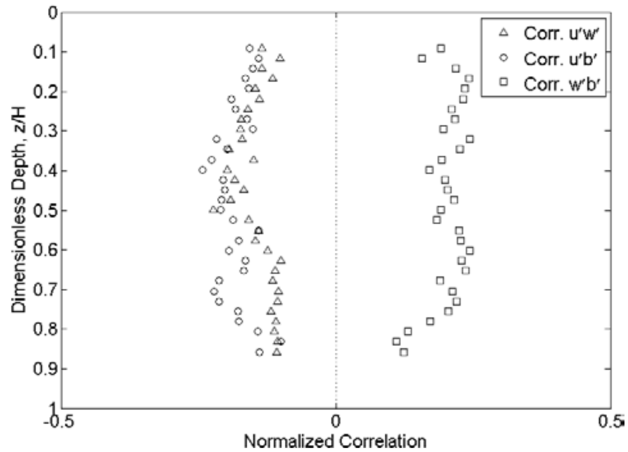

Figure 6. Cross-correlation in the lower lee of the dune.

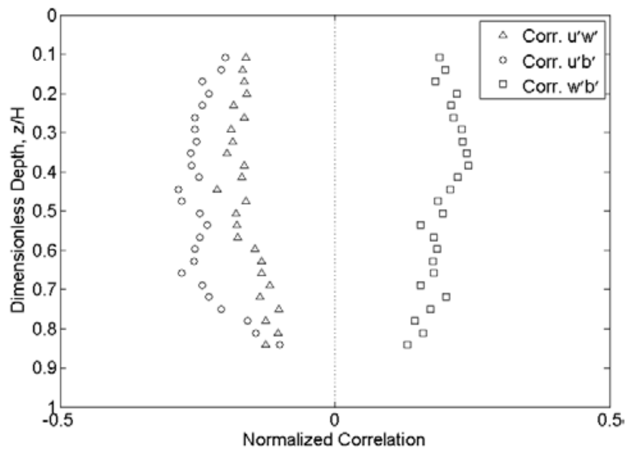

Figure 7. Cross-correlation in the upper lee of the dune.

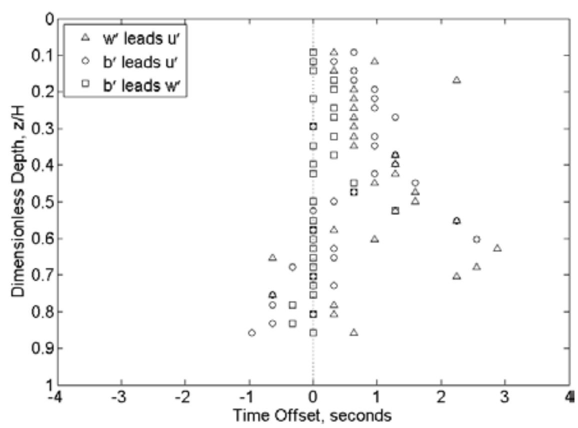

Figure 8. Cross-correlation peak time offset in the lower lee of the dune.

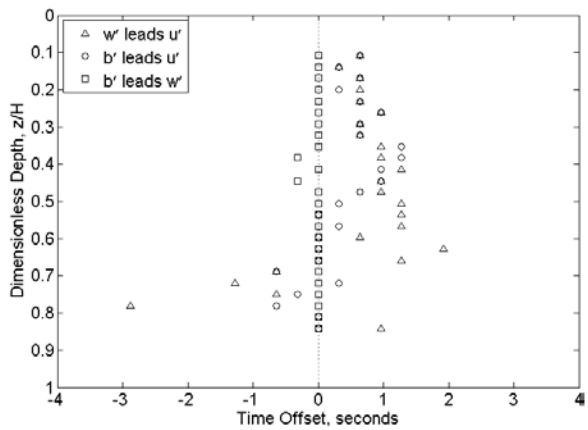

Figure 9. Cross-correlation peak time offset in the upper lee of the dune.

most of the water column, both the vertical velocity fluctuations and the backscatter intensity fluctuations occur earlier than the streamwise velocity fluctuations in time. The streamwise velocity follows an average vertical profile such that streamwise velocity is low near the bed and increases upwards in the flow (Figs 2, 3). If an upward velocity fluctuation occurs, lower streamwise velocity fluid is brought up into a region that has higher streamwise velocity, causing a negative streamwise velocity fluctuation which lags the vertical velocity fluctuation.

4.4 *Frequency analysis*

Intense turbulence is generated in the shear layer in the lee of a dune (Best 2005), and arises from Kelvin-Helmholtz instabilities leading to vortex shedding and from wake flapping, which is the expansion and contraction of the flow separation region. The frequencies at which turbulence is generated by these two mechanisms are described by Simpson (1989):

$$f_v \approx \frac{0.8U_o}{x_r} \tag{1}$$

$$f_w < \frac{0.1U_o}{x_r} \tag{2}$$

where f_v is the frequency of vortex shedding, f_w is the frequency of wake flapping, U_o is the mean velocity upstream from the dune (~1.38 ms^{-1}), and x_r is distance from the crest of the dune to the flow reattachment point. Bennett & Best (1995) suggest the distance x_r = 4.25h where h is the dune height, approximated as the difference in depth between the lower lee and upper lee, $H_{lowerlee} – H_{upperlee}$ = 7.8m – 6.5m (~1.3 m). However, Carling et al. (2000) suggest the distance x_r = 8.3h. These two methods of determining the reattachment point are used to determine the approximate bounds on the vortex shedding and wake flapping frequencies. It should be noted that the length of the separation zone in the lee of a low-angle dune may be much less than a typical angle-of-repose dune (Best & Kostaschuk 2002). Using these methods as a guide, the predicted frequency of vortex shedding is approximately 0.10 – 0.20 s^{-1}, which corresponds to a period of approximately 5 – 10 s. The predicted frequency of wake flapping is approximately 0.013 – 0.025 s^{-1}, corresponding to a period of approximately 40 – 78 s.

In Figure 4, near the bed, quadrant 2 and 4 events can be seen that correspond approximately to the period given by Simpson's equation for vortex shedding. These events may have been generated by vortex shedding from the shear layer associated with this dune. Figures 4, 5 show large-scale quadrant 2 and 4 events (described above) that have a period which approximately corresponds to that given by Simpson's equation for wake flapping.

The power spectral density of the streamwise velocity time series was computed for each location in the vertical profile. The power spectral density at each location in the vertical are contoured in Figures 10, 11, and provide an indication of the dominant periods corresponding to a particular time series.

In the lower lee (Fig. 10), the dominant periods appear in two distinct zones. Between 0.6 z/H and the bed, dominant periods are between 5 and 15 s, corresponding to the periodicities of vortex shedding. Between 0.5 z/H and the bed, the dominant periods are mostly between 20 and 80 s, corresponding to the periodicities of wake flapping.

In the upper lee, dominant periods appear in one distinct zone. Throughout nearly the entire water column, the dominant periods are between 25 and 80 s, which correspond to wake flapping of the shear layer, perhaps wake flapping of the shear layer of the upstream dune which then advects downstream. It is also possible that these periods represent the movement of the shear layer of this dune into the upper lee. In the upper lee, vortex shedding was not yet fully developed. We hypothesize that vortex shedding requires a greater downstream length for generation

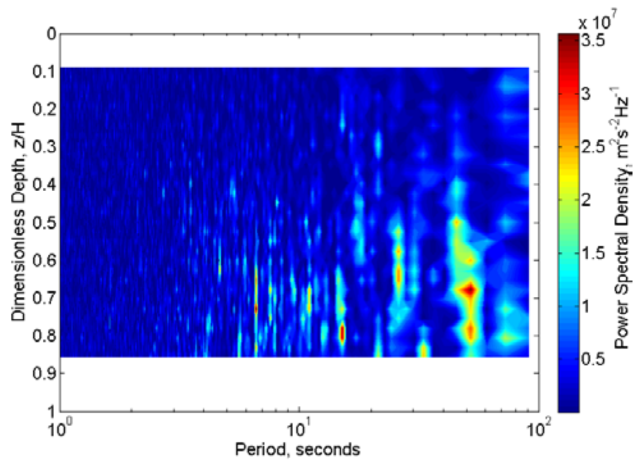

Figure 10. Power spectral density of streamwise velocity in the lower lee of the dune.

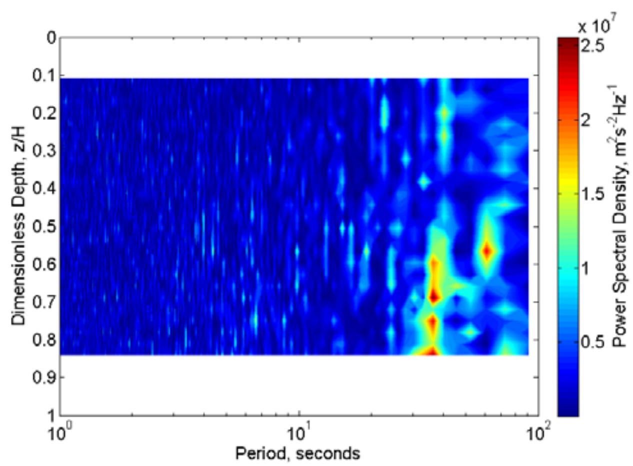

Figure 11. Power spectral density of streamwise velocity in the upper lee of the dune.

and evolution to a scale detectable by the ADCP, and thus these are detected further downstream in the lower lee and assume a greater component of the total turbulent energy.

5 DISCUSSION

These ADCP measurements in the lee of an alluvial sand dune show that vertical velocity fluctuations are positively correlated with backscatter intensity fluctuations and both of these are negatively correlated with streamwise velocity fluctuations. These are likely the manifestation of large-scale turbulence, quadrant 2 or 4 events that are generated in the lee of a dune and are responsible for lifting sediment into suspension. This corresponds with past observations including those by Lapointe (1996) Backscatter intensity and vertical velocity fluctuate simultaneously. Fluctuations in vertical velocity and backscatter intensity occur earlier than fluctuations in the streamwise velocity. Vertical velocity fluctuations move streamwise velocity fluid down or up into the flow causing streamwise velocity fluctuations.

Turbulence is likely generated from vortex shedding from the shear layer and shear layer wake flapping. Turbulence associated with vortex shedding occurs at a period of approximately 5 – 15 s, while wake flapping occurs at significantly longer periods of approximately 20 – 80 s.

In the lower lee, turbulence is generated by vortex shedding and wake flapping in the lower half of the flow. These turbulent events propagate through the water column and are advected downstream by the mean flow. Mature coherent structures advect by the lower lee in the upper portion of the water column, and are likely remnants of older structures that have dissipated and that contribute little to turbulence intensities.

In the upper lee, turbulent events generated upstream may have grown and evolved to extend through a greater portion of the water column. Turbulence associated with large-scale wake flapping is evident as larger structures generated from upstream advect past the upper lee. It is also possible that turbulence associated with wake flapping represents the movement of the shear layer of this dune in the upper lee. The results also indicate the lesser importance of turbulence associated with vortex shedding in the upper lee. In the upper lee smaller instabilities will be generated in the initial region of any shear layer, and it is likely that their scale and influence within this region is less significant than in the lower lee, where these structures have evolved and grown in scale.

6 CONCLUSIONS

The flow fields in the lee of a large sand dune at the confluence of the Mississippi and Missouri Rivers show many similarities with current conceptual models of flow over dunes. In these measurements, the maximum horizontal velocity occurs near the upper lee of a dune. As expected, quadrant 2 events are associated with high backscatter intensity. Turbulent events generated in the lower lee of a dune near the bed are associated with periods of vortex shedding and wake flapping. These turbulent events grow and advect downstream. Remnant coherent structures advect past the lower lee, in the upper portion of the water column, which have mostly dissipated and contribute little to turbulence intensities. In the upper lee, turbulent events occupy most of the water column and are associated with periods of wake flapping. Turbulence associated with vortex shedding is less evident in the upper lee.

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REFERENCES

Bennett, S.J. & Best, J.L. 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: implications for sediment transport and bedform stability. *Sedimentology* 42: 491-513.

Best, J.L. 2005. The fluid dynamics of river dunes: A review and some future research directions, *J. Geophys. Res.* 110: F04S02.

Best, J.L. & Kostaschuk, R.A. 2002 An experimental study of turbulent flow over a low-angle dune. *J. Geophys. Res.* 107: 3135-3153.

Carling, P.A., Williams, J.J., Gölz, E., & Kelsey, A.D. 2000. The morphodynamics of fluvial sand dunes in the River Rhine, near Mainz, Germany. II. Hydrodynamics and sediment transport. *Sedimentology* 47: 253-278.

Gartner, J.W. 2004. Estimating total suspended solids based on backscatter intensity from acoustic Doppler current profiler in San Francisco Bay, California. *Marine Geology* 211:169-187.

Lapointe, M.F. 1996. Frequency spectra and intermittency of the turbulent suspension process in a sand-bed river. *Sedimentology* 43: 439-449.

Nezu, I. & Nakagawa, H. 1993. *Turbulence in Open-Channel Flows*. A. A. Balkema, Brookfield, Vt.

Simpson, M.R. 2001. *Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler*. United States Geological Survey OFR 01-1. Sacramento, CA.

Simpson, R.L. 1989. Turbulent boundary-layer separation. *Annu. Rev. Fluid Mech.* 21: 205-234.