Turbulent Structures and Suspended Sediment Over Two-Dimensional Dunes

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Abstract

Observations have shown that the sediment transport field over dunes in open-channel flows is time-dependent, and fluctuations in concentration may correspond to large coherent turbulent structures. Visualization experiments over two-dimensional dunes in a laboratory flume were conducted using high-speed video and a laser sheet. A PIV method is presented by which a two-dimensional velocity field is measured at a rate which is high enough to follow the motion of turbulent structures. The visualization and PIV studies reveal that the separation region is highly dynamic, with a continuous incorporation and periodic expulsion of fluid. Large-scale vortical structures are also shed at the time of fluid expulsion, and the downstream vorticity of these structures rapidly becomes nearly as large as the cross-stream vorticity. In the downstream half of the stoss of the bedform, the large turbulent structures lose strength and coherency as the result of topographically-induced acceleration. A simulation of the suspension of sediment over dunes is presented, where the motion of a large number of particles is driven by the velocity from numerical simulations of turbulence. These sediment simulations reveal that the concentration field is periodic due to the expulsion of fluid from the separation layer and the diversion of sediment into the interior at the time of the shedding of large-scale vortical structures.

1. Introduction

Even a casual observation reveals the presence of boils on the surface of a river which flows over a dune-covered bed. Many have observed that a large amount of suspended sediment is contained within these boils compared to the surrounding fluid (e.g. Jackson [1976], Coleman [1969]). These macroturbulent structures are apparent because they have a surface expression. Less is known about macroturbulent structures which may not have a surface expression. Ikeda and Asaeda [1983] were perhaps the first to systematically study the importance of macroturbulent events on the suspended sediment profile. Using an optical back scatter instrument to make instantaneous measurements of suspended concentration over three-dimensional ripples, they showed that sediment concentrations fluctuated significantly and periodically, and tied the periodic sediment concentrations to shedding of structures from the ripple crest.

Despite the findings that turbulent structures may be very important to the sediment transport field, there remains no quantitative method by which to approach sediment suspension over dunes from a turbulent structure viewpoint. Therefore, the use of the Rouse profile in combination with an empirical boundary condition and eddy viscosity remains the best choice for suspended sediment discharge calculations over dunes, even though it is known that such methods fail when there are significant eddy motions which are nearly as large as the flow depth, and where production and dissipation of turbulent energy is not balanced throughout the flow.

A quantitative approach to sediment suspension which incorporates information about coherent turbulent structures has yet to be formulated because such an approach requires simultaneous data of the entire velocity field at a frequency which resolves the primary mass and momentum carrying eddies. In a companion paper (Shimizu et.al. this volume) a method is presented by which the turbulence over two-dimensional dunes can be numerically simulated. In this paper we present experiments on the visualization of flow structures over two-dimensional dunes in a laboratory flume using high speed video. Then a high frame-rate particle image velocimetry, PIV, technique is developed from the visualizations to measure two-dimensional velocity fields at rates high enough to follow the full development and motion of flow structures The accuracy of the PIV measurements and numerical simulations are verified by comparison with a dense grid of two-dimensional laser Doppler velocimetry measurements. Finally, the 3-D numerical simulations of Shimizu et.al. are used to drive the motion of a large number of suspended particles to provide a quantitative elucidation of the interaction of suspended particles with turbulent structures over two-dimensional dunes.

2. Visualization Experiments

Several researchers have attempted to visualize turbulent structures over dunes. Müller and Gyr [1986] used flourescine dye, a light sheet, and video. Nezu et al. [1996] used both dye and hydrogen bubbles in conjunction with video to study turbulent structures over dunes, and Bennett and Best [1995] took long exposure photographs of small neutrally buoyant particles to view the paths of fluid particles. These studies elucidated some central features. Downstream of the point of separation, a shear layer develops, and transverse vortices are generated which are shed and generally move along the separation layer and interact with the bed near the point of reattachment. Intermittently, the shear layer vortices will move into the interior of the flow and may interact with the water surface, thus producing surface boils.

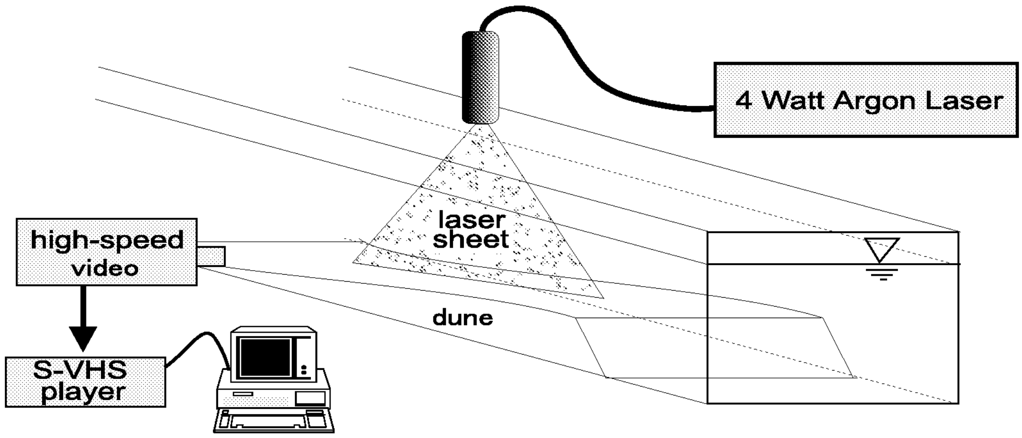

Figure 1: Setup for visualization experiments.

In order to obtain a more complete dynamical understanding of the production, motion, and dissipation of turbulent structures over dunes, a series of visualization studies were conducted over two-dimensional dunes in a recirculating open-channel flume. The general setup and flow conditions of these dune experiments are identical to those described in Shimizu et.al.(this volume). (See Figure 1 of Shimizu et.al. for a plot of the dune geometry and basic turbulence statistics obtained from 2-dimensional LDV measurements.) Here, a laser light sheet, nearly neutrally buoyant particles, and high speed video were used to obtain a visualization of the motion of particles in an entire 2-dimensional plane. For the light sheet, a 4 Watt Argon-ion laser beam was fed into a fiber optic cable and then spread into a 3mm thick sheet by a half-cylinder lens. The laser sheet entered the flow from the water surface and illuminated a cross-stream plane, thus making it possible to see motion in the downstream and vertical directions. A 4cm by 30cm piece of clear acrylic was placed on the water surface to provide a stationary surface for the light sheet to enter the water. The depth of the sheet below the water surface was just enough so that bubbles did not pass underneath it, which was about 2 to 3mm. The entire volume of water in the recirculating flume was seeded copiously with 125 micron, high-density polyethylene particles with a density of 0.96 g/cm^3. Images of the motion of the particles were recorded onto S-VHS tape with a high-speed video camera, which captures 250 fields per second. Flow over a single dune was taped in 35cm, 25cm, and 15cm sections; the taping of larger flow areas captures the development of structures over large areas of the bed at the expense of detail. After filming of flow structures, a grid was photographed in the flow at the exact position of the laser sheet, so that the relationship between video and real-world coordinates could be measured. Figure 2 is a portion of a video frame used for the visualization experiments. Two fields separated by 1/250th of a second have been interlaced. Therefore, the streakiness of the particles gives an indication of the speed of the particles. A white line has been drawn at the approximate position of the shear layer interface, and the length of the particle streaks can be seen to be much greater above this interface. Arrows indicate the general direction of motion. The shear interface and arrows were drawn after repeated slow motion viewing of video sequences before and after this particular frame.

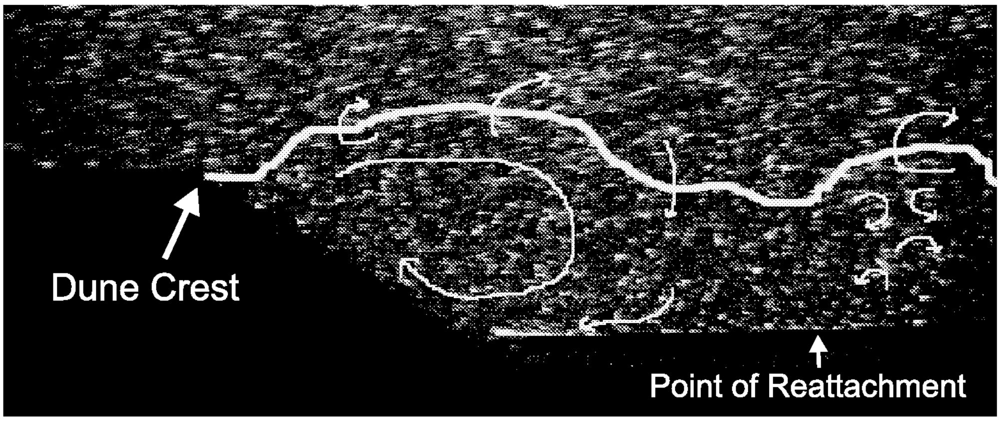

Figure 2: Video frame of flow over dune crest. The real-world width of the picture here is 25cm.

3. PIV Experiments

The same setup was used for the PIV measurements of the flow field, except that the camera was turned on its side so that the greater resolution of the captured video was in the vertical direction, and the horizontal width of the picture was only 10cm. Each field was then captured from video tape to a personal computer at a 720 by 240 pixel resolution. Because the camera was turned on its side, the 720 pixel rows were in the vertical direction. The reason for doing this is that, because the main direction of flow is downstream, the average downstream pixel shift between consecutive frames would be very large if it coincides with the greater resolution direction. Therefore, a shift of several tens of pixels between successive frames in the downstream direction would coincide with an average of only a couple of pixel shifts in the vertical direction, and very poor resolution of the vertical velocity would be the result.

A set of PIV algorithms was written specifically for the described experimental setup. The review by Adrian [1991] and book by Raffel et al. [1998] provide a comprehensive introduction and review of PIV techniques. The basic PIV algorithm is to perform a cross-correlation of the pixels of the same small 'interrogation' area of two consecutive frames. The cross-correlation of these two interrogation areas is very efficiently calculated by fast Fourier transforming both areas, multiplying the transform of one of the areas by the complex conjugate of the other and then performing an inverse FFT. The peak value in the cross-correlation field gives, in some sense, an average pixel shift of the particles in the interrogation area.

Choosing an optimal PIV setup for a given experiment and set of equipment requires consideration of a large number of trade-offs between precision, accuracy, and size of coverage. If a larger total coverage area is chosen, the pixel shift of particles between frames is very small, and, thus, the precision is poor. Interpolation of the cross-correlation field is almost always used to calculate the cross-correlation peak at values between the center of pixel coordinates. This helps to increase accuracy, but it is not clear how much, because there is a general background cross-correlation noise, which for this experiment was about 20 percent of the peak correlation. This noise can seriously affect the position of the sub-pixel interpolated peak. The problem of precision can only be reliably resolved by calculating cross-correlations between frames which are farther apart in time or by decreasing the field of view of the camera. However, increases in the time of frame separation result in a loss of accuracy because a large number of particles can move into and out of the laser sheet as the time separation between fields increases. Also, with larger pixel shifts, a greater percentage of the particles move into and out of the chosen interrogation area, regardless as to whether or not they remain in the light sheet. This can be remedied by shifting the position of the interrogation region between frames by a good guess of the pixel shift in the interrogation area. It can also be remedied by increasing the size of the interrogation area, but this reduces the accuracy and increases the chance of error because there is greater shear within the interrogation region between frames.

Given the dimensions of the frame and resolution of the images used here, the average pixel shift between two consecutive fields separated by 1/250th of a second is around three pixels in the downstream direction and about zero or one in the vertical. The accuracy of these shifts are very good, but very imprecise. So, larger field separations were chosen. For each calculated velocity field at a specific time, six fields were used– three fields previous and three fields after. The algorithm begins by calculation of the pixel shift between the third and fourth frames. From this information it is possible to extrapolate a reasonable pixel shift to larger frame separations, and use it to shift the interrogation regions. Thus, the interrogation regions of the first and fifth and second and sixth frame are calculated. If these two pixel shifts do not correspond to one another, or if there is an insufficient number of particles in any of the fields, the velocity for that interrogation area is not calculated. Finally, a linear subpixel interpolation is used to find the correlation peak by assuming that the correlation slope is symmetric on all sides of the peak. This allows only the use of the largest correlation pixel shift and its immediate neighbors, whereas smoother schemes generally must incorporate points further away so that first derivatives can be calculated.

4. Results

A typical video field in which the PIV measured velocity vectors have been overlaid is shown in Figure 3. This picture shows that there are holes in the resulting velocity coverage. These occur in places where there are insufficient particles for accurate measurements and where the shear is large. A comparison of the turbulence statistics between the PIV and LDV was made to check the accuracy of the PIV velocity measurements. These comparisons are shown in Figure 4 for two vertical sections: 25cm downstream of the crest and 75cm downstream of the crest. The PIV measurements for these plots is from the analysis of 6 seconds (1500 fields) of video. The PIV method proposed here, apparently, accurately measures the two dimensional velocity components. However, there is sometimes a substantial loss of coverage due to the criteria for an acceptable calculation of the velocity components in an interrogation region.

The visualization experiments and PIV measurements revealed some important details about turbulent structures. Separation begins at the dune crest, as one would expect. Small vortices, between about 1/5th and 1/10th the height of the dune crest, are continually produced at the shear interface. Occasionally these vortices will grow larger and will become incorporated into the separation bubble in the triangular region between the crest, slip face, and shear layer. Sometimes these vortices will grow and move downstream, thus producing a roll-up of nearly the entire separation region. Such

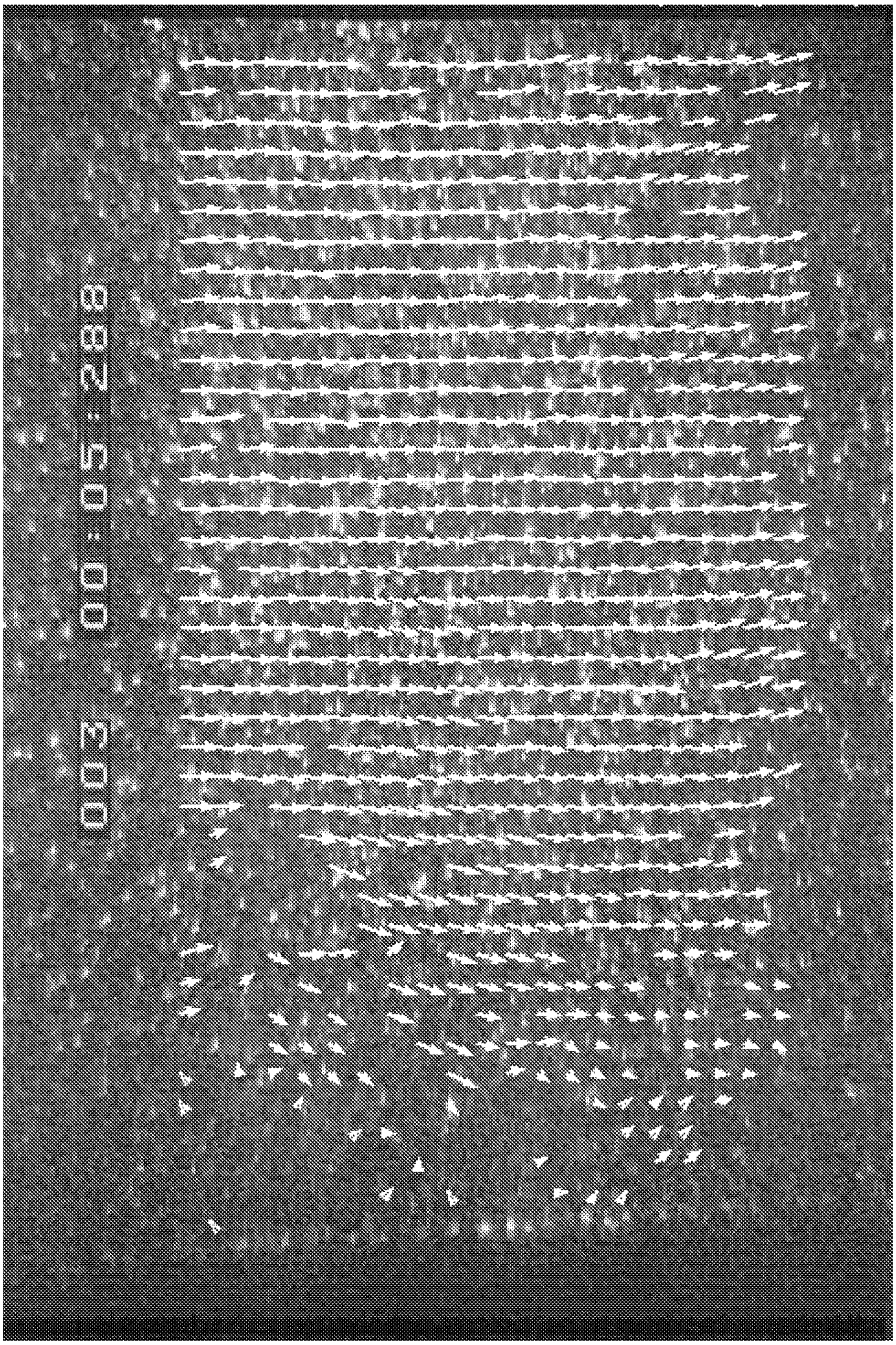

Figure 3: Overlay of PIV measured velocity vectors on video field. The width of this picture is 10cm, and the center is 25cm downstream of the crest.

an instance is depicted in Figure 2, and the bulging upward of the shear layer above the height of the crest is typical during such a large scale roll-up. This process of separation layer roll-up is similar to that depicted in the direct numerical simulations of flow over a backward step by Le et al. [1997]. After roll-up of the separation layer, the strong cross-stream vortex moves downstream and begins to break up into smaller vortices, and in the process transports material from the separation area into the interior at the upstream side of the vortex, with the opposite effect on the downstream side. During the breakup and downstream advection of the separation roll-up, fluid particles traveling downstream near the crest experience large upward velocities and are transported into the flow interior rather than the usual path which returns them to the near-bed region upstream or just downstream of the point of reattachment. It is probably this process which gives rise to the large instantaneous upward velocities just downstream of the separation point and suspends a large amount of sediment grains as was measured and visualized in the Ikeda and Asaeda [1983] experiments.

There is a continual incorporation of fluid into the separation bubble region at the shear layer interface due to small and large scale vortical structures, and periodic expulsion of fluid at the downstream end of the recirculation area, which is accompanied with vertical motion of the shear layer interface. This process of fluid exchange between the separation region and interior flow means that it is very difficult to define a point of reattachment, except in a time-mean sense. At any given time, the separated region may appear to be composed of two or three large vortices extending from the shear layer interface to the bed. Occasionally the entire region will roll up into a single vortex cell as shown in Figure 2, and at other times there are only small scale vortical motions. Also, there are strong cross-stream velocities in the separation area, as evidenced by divergence and convergence of the two-dimensional velocity field.

At the shear layer interface there is vigorous extraction of energy from the mean flow to transverse vortical structures. Downstream of the point of reattachment, these near-bed vortical structures grow and become highly three-dimensional as evidenced by strong divergence in the two-dimensional velocity field near the bed. The view of these structures on the video is of a large (several dune heights in the downstream direction) uplift of fluid beginning from the bed and extending into the flow. The vertical extent of these structures grows from approximately one dune height near the point of reattachment to about half the depth of flow at the midpoint of the stoss slope of the dune. Downstream of the midpoint, these structures break up into smaller vortical motions, and only a few of the strongest structures continue to grow past the stoss midpoint and eventually encompass the entire flow depth. This process of large structure destruction near the peak of the topographically induced acceleration is precisely what was found in the numerical simulations of Shimizu et. al.(this volume) and is not found in backward step simulations with no topographic acceleration [Neto et al., 1993]. As argued by Nelson et al. [1993], the acceleration forced by the upsloping dune surface damps the larger eddies by acceleration-induced vortex stretching.

As would be expected from structures which consist of rapid uplift of fluid from the near-bed region, the downstream velocity of the fluid is less than the mean fluid velocity at the same vertical position. Thus, these structures are similar to the burst-sweep sequence of wall boundary layers, but on a much larger scale.

5. Suspended Sediment

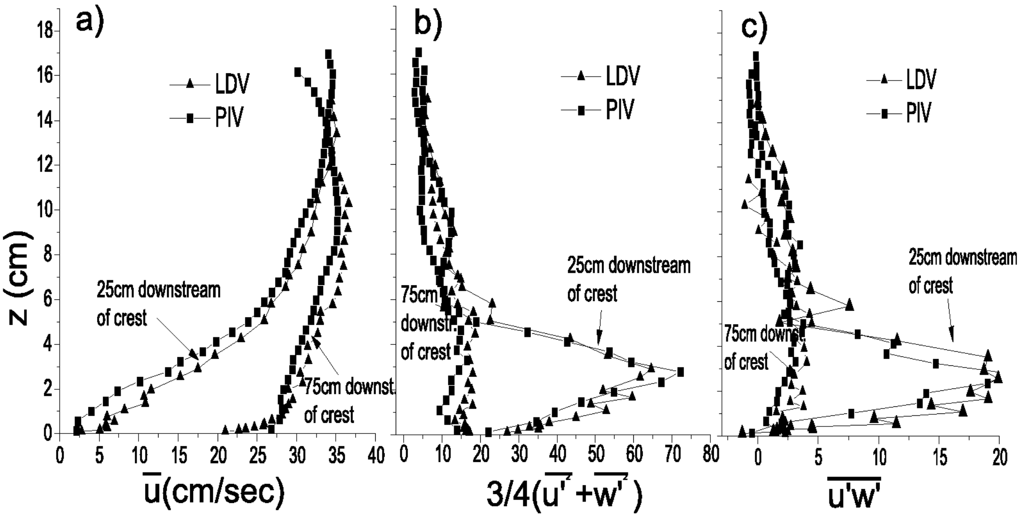

Figure 4: Comparison of turbulence statistics by PIV and LDV. a) Average downstream velocity versus distance above the bed. b) Turbulent kinetic energy. c) Reynolds shear stress.

A calculation of sediment suspension using the numerical simulation of Shimizu et. al.(this volume) illustrates the importance of the discussed flow structures to the sediment transport field. The output of the Shimizu et al. numerical simulation of turbulence was used to drive the motion of a large number of suspended particles. In this simulation, suspended particles were assumed to have the same velocity as the fluid in the downstream and cross-stream directions. The vertical velocity of the particles was assumed to be the vertical fluid velocity minus a constant settling velocity. A simulation which includes erosion and deposition of particles is not possible, because very little is known about the coupling between the near-bed turbulence and entrainment and disentrainment of suspended sediment. Therefore, a lower boundary of 4mm was imposed, below which particles could not pass. Periodic boundary conditions were imposed at the sides, and particles which traveled downstream of the computational domain were introduced upstream. The simulation was for run 10 seconds and the new position of each particle was calculated every 1/50th of a second, which is the rate at which data was provided by the flow simulation. Initially, $4x10^5$ particles with a settling velocity of 1cm/s were introduced randomly in a horizontal plane between 0.5cm and 1.5cm above the crest. After about 4 seconds of the simulation, the concentration pattern appeared to be constant with little effect of the initial condition. However, throughout the simulation more and more particles became trapped in the separation area. Figure 5 is a gray-scaled contour plot of N, the number of particles per unit volume, after 8 seconds of the simulation. The cross-stream and downstream fluid vorticity fields are also included to show the relationship between the turbulence structure and suspended sediment field.

The simulations reveal that pulses of sediment are transported downstream with the shedding and downstream movement of vorticity generated in the separation region. Figure 5 shows a pulse of sediment centered between 30 and 35cm downstream, which

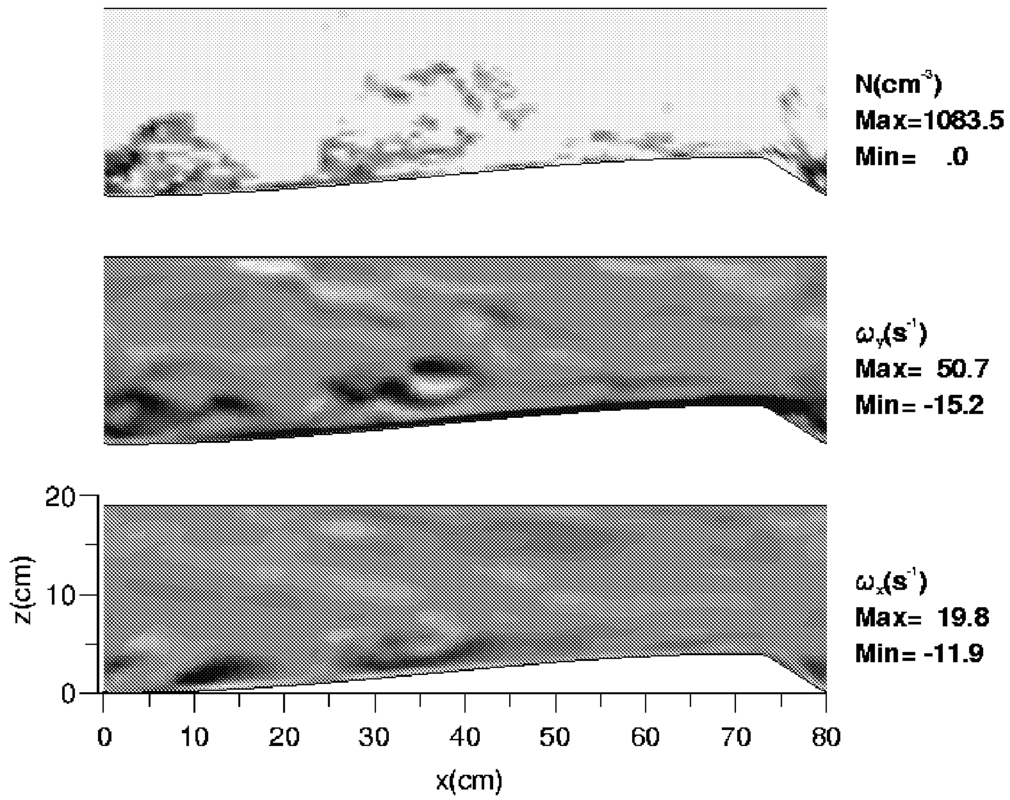

Figure 5: Gray scale contour diagrams of the number of sediment particles per unit volume, N, and the vorticity in the cross-stream, ω_y, and downstream, ω_x directions at the cross-stream center of the computational domain.

corresponds to a region of high fluid vorticity. The transport of sediment with these vortical structures appears to occur for two reasons. First, the shedding of large scale vorticity is generally preceeded by a vertical rise of the position of the shear layer which diverts particles travelling over the crest into the interior of the flow, and then, rather then experiencing a sharp downward vertical velocity, the particles are transported downstream with the shed structure. Second, the shedding of large-scale vortical structures from the separation region corresponds to an expulsion of fluid from the separation zone. The fluid in the separation region has a large sediment concentration due to trapping of sediment, so that expulsion from the separation region gives rise to the downstream movement of a large number of particles.

Suspension is maintained by the portion of the vortical structures having upward velocities, and is diminished in other areas. As the structures experience topographic acceleration over the stoss of the bedform, their strength and coherency is greatly reduced, and the ability of the structures to maintain the suspension is also reduced, with the result that sediment pulses rapidly fall out of suspension as they move downstream toward the dune crest.

6. Summary and Conclusions

A picture of the suspended sediment field emerges which is largely incompatible with the mechanics behind the Rouse profile. The sediment concentration is highly time-varying, and is dependent on the detailed dynamics of the flow separation region and topographic acceleration over the stoss of the dune. The separation region is shown to be highly dynamic, with continuous incorporation and periodic expulsion of fluid. A simulation of sediment suspension elucidates the implications of this model of the separation region in contrast to a time-averaged, closed-recirculation approach. Suspended sediment traveling over the dune crest is frequently trapped within the separation region during fluid incorporation, and is diverted into the interior of flow and expulsed from the separation region with the downstream convection of a large scale roll-up of the separation region. Between the point of reattachment and about the midpoint of the stoss of the dune, large-scale downstream vortical structures are capable of maintaining a large amount of sediment suspension. This capability is diminished downstream, because topographically-induced acceleration causes the loss of strength and coherency of the vortical structures. It is possible to use numerical simulations of turbulence and imaging techniques to calculate this complex field, provided an understanding of entrainment and disentrainment from the bed is obtained in future research.

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