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Bed load and suspended load contributions to migrating sand dunes in equilibrium

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Abstract Dunes dominate the bed of sand rivers and are of central importance in predicting flow roughness and water levels. The present study has focused on the details of flow and sediment dynamics along migrating sand dunes in equilibrium. Using a recently developed acoustic system (Acoustic Concentration and Velocity Profiler), new insights are obtained in the behavior of the bed and the suspended load transport along mobile dunes. Our data have illustrated that, due to the presence of a dense sediment layer close to the bed and migrating secondary bedforms over the stoss side of the dune toward the dune crest, the near-bed flow and sediment processes are significantly different from the near-bed flow and sediment dynamics measured over fixed dunes. It was observed that the shape of the total sediment transport distribution along dunes is mainly dominated by the bed load transport, although the bed load and the suspended load transport are of the same order of magnitude. This means that it was especially the bed load transport that is responsible for the continuous erosion and deposition of sediment along the migrating dunes. Whereas the bed load is entirely captured in the dune with zero transport at the flow reattachment point, a significant part of the suspended load is advected to the downstream dune depending on the flow conditions. For the two flow conditions measured, the bypass fraction was about 10% for flow with a Froude number (Fr) of 0.41 and 27% for flow with Froude number of 0.51. This means that respectively 90% (for the $Fr = 0.41$ flow) and 73% (for the $Fr = 0.51$ flow) of the total sediment load that arrived at the dune crests contributed to the migration of the dunes.

1. Introduction

Sand dunes are rhythmic features resulting from the interaction between flow and sediment transport and form the main source of hydraulic roughness of the river bed. Dunes can reach heights up to one third of the water depth and therefore dominate the entire flow field. Both the mean and the turbulent flow structures and consequently the sediment pick up and deposition are strongly influenced by dunes. Particularly during floods, dunes are observed to grow rapidly resulting in significant changes of the hydraulic roughness and water levels.

Sediment in rivers is transported as bed material load and wash load. Wash load is fine sediment that is transported in permanent suspension and does not usually contribute to the morphological development of dunes. Bed material load consists of sediment that originates on the bed and is subdivided into bed load and suspended bed material load. Bed load moves close to the bed in traction and saltation and suspended bed-material load (hereafter referred to as “suspended load” for brevity) is transported above the bed in intermittent suspension. Sediment transport that contributes to the migration of dunes is often assumed to be bed load [e.g., Carling *et al.*, 2000; Jerolmack and Mohrig, 2005; Kostaschuk *et al.*, 2009, and references therein], although several researchers have demonstrated that a significant fraction of the total sediment transport in sand bed rivers may consist of suspended load [e.g., Smith and McLean, 1977; Kostaschuk and Villard, 1996; Kostaschuk, 2005; Nittrouer *et al.*, 2008]. In addition, a large number of numerical and experimental studies have illustrated that suspended load is crucial in changing the dune form. Smith and McLean [1977] found that, in the Columbia River, asymmetric dunes with flow separation occurred when bed load was the dominant transport mechanism while symmetric dunes without flow separation zone (low-angle dunes) developed when most sand is transported in suspension. They suggested that the steep lee sides of asymmetric dunes are maintained by avalanching of bed load down the lee slope, whereas the much lower angle lee sides of symmetric dunes result from deposition of sand from suspension in the lee side and trough between dunes [Best and Kostaschuk, 2002]. This was also concluded from the field measurements performed by Kostaschuk and Villard [1996], Kostaschuk [2000], and Amsler *et al.* [2003]. Field data from the Rio

Paraná in Argentina, collected by *Kostaschuk et al.* [2009], showed that about 17% of the suspended load transported over the dune crest was deposited on the lee side slope of the dune before it reached the trough.

Stability analysis carried out by *Fredsøe* [1981] on the role of sediment transport on dune morphology illustrated that an increase in bed load transport will lead to an increase in the dune height while an increase in suspended load transport will result in a decrease of the dune height. *Amsler and Schreider* [1999] found that with an increasing ratio of suspended load to bed load, dune heights were reduced during floods in the Rio Paraná. *Kostaschuk* [2005] and *Kostaschuk and Best* [2005] concluded from field and numerical studies that deposition of suspended sediment in the trough and on the lee side slope of dunes results in a reduction of dune height and lowering of lee slope angle.

Suspended sediment transport is also found to contribute to the transition of dunes to upper stage plane beds [e.g., *Best*, 2005a, and references therein]. In a recent study *Naqshband et al.* [2014] illustrated that the transition from dunes to upper stage plane beds can only occur if sufficient sediment is transported into suspension depending on the magnitude of the bed shear stress and the Froude number.

Although it is likely that suspended sediment transport contributes to the migration of dunes [*Kostaschuk et al.*, 2009], it is not yet exactly known how suspended load contributes to dune morphology and migration and how this compares to bed load. In particular, we have no insight into the contribution of suspended load to sediment erosion on the stoss side of the dune and deposition on the lee side of the dune while the dune is migrating. The fraction of the total sediment transport that is not captured in the dune trough and therefore does not contribute to the migration of dunes (bypass fraction) is also not yet properly quantified. As highlighted by *Parsons and Best* [2013], sediment transport and the exact nature of lee side deposition processes are key to predicting dune migration. *Coleman and Nikora* [2011] attributed this gap of knowledge partly to the fact that most of the experimental studies associated with dunes have focused on flow and sediment dynamics above fixed beds [e.g., *Cellino and Graf*, 2000; *Best and Kostaschuk*, 2002; *Kleinhans*, 2004; *Best*, 2005a, 2005b; *Venditti*, 2007]. The advantage of utilizing fixed bedforms is that they allow detailed flow measurements without the complications of both a migrating and changing bedform and the difficulties of flow measurement in the presence of sediment transport over a fully mobile bed [*Best and Kostaschuk*, 2002].

Another reason why the contributions of bed load and suspended load to dune migration have not yet been fully determined is that there are inherent limitations of the instruments available for the simultaneous measurement of both flow velocity and sediment concentration, mainly in the near-bed region. Experimental studies conducted with mobile dunes focusing on the direct measurement of sediment fluxes, both in the flume as in the field, have therefore been limited to the simultaneous measurement of flow velocity and sediment concentration above a considerable distance from the migrating dune bed [e.g., *Parsons et al.*, 2005; *Wren et al.*, 2007; *Coleman et al.*, 2008; *Wren and Kuhnle*, 2008; *Kostaschuk et al.*, 2009; *Shugar et al.*, 2010]. Consequently, only a fraction of the suspended load is measured while the bed load cannot be determined at all. Furthermore, for determining sediment fluxes, usually two different instruments are deployed to measure the flow velocity and sediment concentration and they do not measure at the same point in the flow. As a result, the measured sediment flux cannot be referenced to an exact location along the dune bed. *Wren and Kuhnle* [2008] used a Laser Doppler Velocimeter and an acoustic backscatter system to measure coupled flow and sediment motion over mobile sand dunes. To determine the suspended sediment transport and deposition over a mobile dune, *Kostaschuk et al.* [2009] deployed an acoustic Doppler current profiler (ADCP) for flow velocity measurements while suspended sediment concentration was measured with an in situ laser diffraction transmissometer (LISST-100C). By calibrating the acoustic backscatter signal of the ADCP using different instruments, *Kostaschuk et al.* [2009] also obtained concentration measurements which abled them—to an extent—to measure sediment fluxes with the ADCP [see also *Shugar et al.*, 2010]. In addition, using two different systems for the measurement of flow velocity and sediment concentration limits the sediment flux studies to flow scales larger than the separation distance between the two instruments. In particular, turbulence processes, which are the most important mechanisms of sediment entrainment and transport, cannot be addressed directly [*Hurther et al.*, 2011].

A newly developed acoustic system, the Acoustic Concentration and Velocity Profiler (ACVP) developed by *Hurther et al.* [2011], now allows us to measure colocated, simultaneous, and high temporal and spatial resolution profiles of both two-component flow velocity and sediment concentration referenced to the exact position at the bed. The ACVP also measures both in the bed load layer and in the suspended load layer over the entire water column (see section 2.1 for more details on the ACVP). Recently, the ACVP has been successfully

Figure 1. Side view of the flume used, adapted from Tuijnder *et al.* [2009]. Water flow is from left to right and is supplied to the flume from a constant head tank. Equilibrium flow conditions are reached by adjusting the flume slope and the weir at end of the flume.

applied under waves [Hurther and Thorne, 2011; Ruessink *et al.*, 2011]. By deploying the ACVP in the present study, we obtain quantitative knowledge of the flow and sediment transport distribution along mobile, equilibrium sand dunes. In particular, we measure the contributions of both bed load and suspended load to dune morphology and migration.

2. Flume Experiments

2.1. Experimental Setup and Instrumentation

The experiments were conducted in the Hydraulics Laboratory of the Leichtweiss Institute of the Technical University of Braunschweig, Germany. The flume has a width of 0.5 m and a length of 30 m, where the effective measuring length for dune morphology was approximately 8 m (Figure 1). Flow discharge to the flume was delivered from a constant head tank approximately 5 m above the flume level. Stacked tubes were used to direct the flow into the flume. Using an Inductive Discharge Measurement device, the desired discharge was set with an accuracy of 1%. The flume slope and the weir at the end of the flume were adjustable, which made it possible to achieve equilibrium flow conditions at a predefined discharge and water depth. The sediment at the end of the flume was caught by a funnel and transported back to the upstream end of the flume after the completion of each experiment. At the effective measurement section of the flume, the bed and water levels were measured continuously using echo sounders that were mounted on a semi-automatic measurement carriage. The water level was measured at the center of the flow, where the bed level measurements were taken at three parallel transects across the flume width. The accuracy of the bed level measurements was determined by repeatedly measuring a fixed bed profile. The vertical standard deviation was less than 1 mm, where the horizontal standard deviation was approximately 3 mm. In the horizontal direction the accuracy of the echo sounders is determined by the area of the acoustic footprint at the bed, which was a few centimeters in diameter [Tuijnder *et al.*, 2009]. This makes the echo sounders suitable for studying large-scale features of the dunes, but the grain scale processes cannot be resolved.

Figure 2. Front view of the Acoustic Concentration and Velocity Profiler (ACVP) configuration with one piezoelectric transmitter (middle) and two side receivers.

To study the contributions of bed load and suspended load to dune migration, sediment fluxes are measured over the entire flow depth using the ACVP developed by Hurther *et al.* [2011]. The ACVP (Figure 2) combines an Acoustic Doppler Velocity Profiler [Hurther and Lemmin, 2001] with an Acoustic Backscatter System [Thorne and Hanes, 2002] in a single measuring tool enabling the direct measurement of sediment fluxes in the suspension layer and in the bed load layer. The major advantage of this single system is that it provides bed referenced, simultaneous, colocated profile measurements of two-component flow velocity and sediment concentration at high temporal (25 Hz)

Figure 3. (a) Flattened sand bed, before the start of the experiment and (b) developed dune field at the end of the experiment.

and spatial resolution (3 mm). Sediment concentration profiles are determined by applying the dual-frequency inversion method to the ACVP backscattered signal. Compared to the well-known implicit iterative [Thorne *et al.*, 1993] and the explicit inversions [Lee and Hanes, 1995], this technique offers the unique advantage of being unaffected by the nonlinear sediment attenuation effect across highly concentrated flow regions [Hurther *et al.*, 2011]. The sand bed interface and the interface between the suspended load and the bed load are determined by identifying, in the backscattered signal profile, the nonmoving bed echo characterized by its immobility and the echo from the suspended sediment concentration, respectively. These two near-bed echoes can be separated when the acoustic intensity profile is derived from the demodulated Doppler signals since the acoustic scatters constituting the nonmoving sand bed produce a constant voltage with negligible signal variance (for more details on the acoustic interface detection methods, see Hurther and Thorne [2011] and Hurther *et al.* [2011]). This results in the time evolution of the nonmoving sand bed, the overlaying high sediment concentration layer (the bed load layer), and the suspended load layer including both the two-component flow velocity and the sediment concentration data in these three zones.

Whether the region in between the two interfaces corresponds to the physical bed load layer is difficult to validate. This is mainly due to different definitions used for the thickness of the bed load layer in literature. In addition, due to instrumental limitations, no data could be collected to trace sediment movement or sediment paths in this layer and to determine whether the sediment in this layer was transported while remaining primarily in contact with the immobile bed. However, using the interface detection method, the bed load layer that was identified within several millimeters from the nonmoving sand bed is the same order of magnitude of the bed load layer thickness reported by several researchers [see, e.g., Van Rijn, 1984, and references therein]. A more physical definition for the thickness of the high near-bed sediment concentration layer, termed the sheet flow layer, is given by Dohmen-Janssen *et al.* [2001] as the distance between the nonmoving bed and the level where the time-averaged concentration reaches a value of 8% volume concentration (212 kg m^{-3}). However, sheet flow conditions are typically reached for Shields parameter θ between 0.8 and 3 depending on the sediment grain size [Camenen *et al.*, 2006] where values of θ in the current study varied between 0.31 and 0.69 (see Table 1). Therefore, the sheet flow layer definition of Dohmen-Janssen *et al.* [2001] is not applicable in the current study.

2.2. Experimental Procedure

A sand layer approximately 25 cm thick was installed over the entire length of the flume and flattened at the beginning of each experiment (Figure 3). For each experiment, the water discharge and water depth were predefined (see section 2.3). The flume was slowly filled with water from both the downstream and upstream end of the flume to make sure the bed was not disturbed. Subsequently, the predefined discharge was

Figure 4. Acoustic Concentration and Velocity Profiler (ACVP) fixed in a PVC box filled with water (not to scale) and positioned just below the water surface. T, R₁, and R₂ are the piezoelectrical transmitter, the downstream side receiver, and the upstream side receiver, respectively.

bedform tracking tool of Van der Mark *et al.* [2008]. Average and standard deviations of dune height and length were determined over the effective measurement section of the flume (section 2.3).

The measurements of flow velocity and sediment concentration with the ACVP started as soon as equilibrium flow condition was obtained and the dunes were observed to be in the dynamic equilibrium. The carriage with the ACVP was placed at a fixed position along the flume and the dunes migrated underneath the carriage with a constant speed. One dune length was typically covered within 1 h of ACVP measurement. As the sediment transport through the flume was not recirculated back to the upstream end of the flume, an erosion wave was generated at the upstream end of the flume. Generally, three dune lengths were covered by the ACVP measurements before the dynamic equilibrium in the effective measurement section of the flume was disturbed by this migrating erosion wave. An averaging period of 10 s was chosen for the ACVP measurements so that bed displacement within this period was small compared to the dune length. This results in a maximum bed displacement of 0.7 to 1.3 cm for a dune length of 2.25 m (EXP1) and 4.35 m (EXP2), respectively (Table 1). In addition, this averaging period of 10 s was chosen to encompass both the short-term turbulent events (small burst and sweeps) and relatively long-term turbulent events (larger energy-carrying structures: vortices and eddies).

The ACVP should be submerged totally in the flow. As the water depth in the experiments was limited (25 cm), this would reduce the measurement height above the bed significantly. In addition, due to its dimensions, the ACVP would act as an obstacle and effect the flow and the bed. To avoid this, a partly enclosed PVC box was constructed and filled with water to produce negative pressure in the box. The ACVP was fixed in this box and located just below the water surface enabling the measurement of flow velocity and sediment concentration over almost the entire water depth (Figure 4).

After the completion of each experiment, the discharge through the flume was stopped and the sediment accumulated at the end of the flume was returned to the upstream end of the flume. The bed was flattened and the same procedure outlined above was repeated, capturing at least 10 different dunes with the ACVP for two different flow conditions (Table 1).

2.3. Flow, Sediment, and Bed Conditions

To study bed and suspended load contributions to migrating dunes, two different experiments were conducted under equilibrium flow conditions. Table 1 gives an overview of the flow, sediment, and bed conditions for both experiments. The experiments were carried out with two different flow strengths where the water depth was kept constant. A discharge of $0.08 \text{ m}^3 \text{ s}^{-1}$ was used for the low flow strength experiment (EXP1) where a discharge of $0.10 \text{ m}^3 \text{ s}^{-1}$ was used for the high flow strength experiment (EXP2). The bed shear stress τ_b was calculated using the hydraulic radius R_b where the method of Vanoni and Brooks [1957] is used to correct for the influence of sidewall roughness. Applying the bedform stability diagram of Van den Berg and Van Gelder [1993], uniform sand with D_{50} of 0.29 mm was used to obtain 2-D dunes in the flume.

set and the required water depth was obtained by adjusting the flume slope and the weir level at the downstream end of the flume. The sand bed and water levels were measured continuously over the entire effective measurement section of the flume using echo sensors fixed on the carriage (Figure 1). Every 2 to 3 min, the carriage made a scan of the entire flume in the streamwise direction at three parallel transects across the flume width. The stored data were processed and analyzed directly after each bed scan to monitor the water and bed level development in the flume. The weir level was adjusted when the water depths in the flume significantly (more than 10%) differed from the predefined water depth as a result of developing bedforms. Starting from plane beds, ripples appeared instantaneously as the flow was introduced in the flume. Dunes subsequently developed and finally a steady state condition was obtained where the dunes migrated through the flume with a constant speed and without significantly changing form. This dynamic equilibrium was found by analyzing dune height and length statistics from the measured bed profiles using the

Table 1. Flow, Sediment, and Bed Conditions for the Two Experiments

Parameter ^{a,b}	EXP1	EXP2
Discharge Q ($\text{m}^3 \text{s}^{-1}$)	0.08	0.10
Flume slope $S \times 10^{-3}$	1.0	2.20
Water depth h (m)	0.25	0.25
Mean bulk velocity U (m s^{-1})	0.64	0.80
Froude number Fr	0.41	0.51
Hydraulic radius R_b (m)	0.15	0.15
Bed shear stress τ_b (Pa)	1.47	3.24
Bed shear velocity u_* (m s^{-1})	0.038	0.057
Shields parameter θ	0.31	0.69
$D_{10} \times 10^{-3}$ (m)	0.21	0.21
$D_{50} \times 10^{-3}$ (m)	0.29	0.29
$D_{90} \times 10^{-3}$ (m)	0.40	0.40
Equilibrium dune length λ_e (m)	2.25	4.35
Equilibrium dune height Δ_e (m)	0.082	0.072
Equilibrium dune steepness Δ_e / λ_e	0.036	0.018
Time to equilibrium T_e (min)	150	90
Equilibrium migration speed $C_e \times 10^{-4}$ (m s^{-1})	7.0	13.0

^aThe bed shear stress is corrected for the influence of sidewall roughness using the method of Vanoni and Brooks [1957] for the calculation of the hydraulic radius R_b .

^bFlume with B equals 0.50 m. The following expressions are used for different parameters: $U = Q/(hB)$, $Fr = U/\sqrt{(gh)}$, $\tau_b = \rho_w g R_b S$, $u_* = \sqrt{(\tau_b / \rho_w)}$, $\theta = \tau_b / (\rho_s - \rho_w) g D_{50}$ with ρ_s the sand and ρ_w the water density, respectively.

Figure 5 displays the bed evolution in time along the effective measuring section of the flume. The time T_e needed to reach dune dynamic equilibrium was determined by considering the average and standard deviations of dune height and length over the effective measuring section of the flume ($x = 10$ to 18 m, Figure 6). For EXP1, approximately after 2.5 h, the standard deviations for both average dune height and length decreased significantly and remained constant. For EXP2 dune equilibrium was reached after approximately 1.5 h because the greater flow strength results into larger sediment transport capability of the flow (higher bed shear stress τ_b , see Table 1) and the steady state condition is reached faster. This is also reflected in the equilibrium migration speed of dunes C_e for EXP2 which is almost two times larger than for

Figure 5. Bed evolution in time along the flume with blue dotted lines indicating the effective measuring section of the flume, (a) EXP1 and (b) EXP2.

Figure 6. Average μ and standard deviation σ for the dune height Δ for (a) EXP1 and (c) EXP2. Average μ and standard deviation σ for the dune length λ for (b) EXP1 and (d) EXP2.

EXP1. Furthermore, for both experiments equilibrium dune heights Δ_e are quite similar (Table 1), while—despite the similar water depths h for both experiments—equilibrium dune lengths λ_e for EXP2 are twice the dune lengths reached under EXP1. Although it is generally accepted that the dune length is a function of the water depth (e.g., $\lambda/h = 7.3$) [see *Van Rijn, 1984*], *Naqshband et al. [2014]* showed that relative dune length (λ/h) increases with increasing amount of sediment into suspension.

The ACVP data examined in this study correspond to the period of time needed for the migration of at least one entire dune length beneath the ACVP. As the dune migration speed in equilibrium C_e is nearly constant, multiplying the measured time by the migration speed converts time to streamwise distance x along the dune. Furthermore, the horizontal x and vertical z axes are made dimensionless using the measured dune length and height, respectively.

3. Flow Structure

The mean flow structure over migrating dunes was examined by velocity and turbulence relations generally used to describe flow fields over bedforms. This includes the mean streamwise and vertical velocities, mean streamwise and vertical turbulent intensities, and Reynolds shear stresses.

The mean streamwise $\bar{u}$ and vertical $\bar{w}$ flow velocities are defined in equation (1). The instantaneous flow velocities are denoted by u_i and w_i and n is the total number of measurements within the averaging period of time. With a measuring frequency of 25 Hz and an averaging period of 10 s, $n = 250$.

$$\bar{u} = \frac{1}{n} \sum_{i=1}^n u_i \quad \text{and} \quad \bar{w} = \frac{1}{n} \sum_{i=1}^n w_i \quad (1)$$

The mean streamwise I_u and vertical I_w turbulent intensities are defined in equation (2) with $u' = u_i - \bar{u}$ as the streamwise velocity fluctuation and $w' = w_i - \bar{w}$ as the vertical velocity fluctuation.

$$I_u = \left[\frac{1}{n} \sum_{i=1}^n (u')^2 \right]^{\frac{1}{2}} \quad \text{and} \quad I_w = \left[\frac{1}{n} \sum_{i=1}^n (w')^2 \right]^{\frac{1}{2}} \quad (2)$$

The Reynolds shear stress τ_{uw} is calculated from equation (3) with ρ_w the fluid density.

$$\overline{u'w'} = \frac{1}{n} \sum_{i=1}^n (u_i - \bar{u})(w_i - \bar{w}) \quad \text{and} \quad \tau_{uw} = -\rho_w \overline{u'w'} \quad (3)$$

Figure 7. Contour maps and selected profiles of the mean streamwise flow velocity $\bar{u}$ (m s^{-1}) for (a, b) EXP1 with a dune length of 2.25 m and (c, d) EXP2 with a dune length of 4.35 m. The arrows represent the mean velocity vector field $V(\bar{u}, \bar{w})$ and the solid line shows the dune profile with open circles indicating the flow reattachment point. Flow direction is from left to right. Vertical, solid lines along the dune bed indicate the location of the velocity profiles origin with negative velocities to the left and positive velocity to the right of this line. The distance between two vertical lines scales with $\bar{u} = 1.25 \text{ m s}^{-1}$.

3.1. Mean Flow Field

Figure 7 shows the contour maps and selected profiles of the mean streamwise flow velocity $\bar{u}$ along dunes for the low flow strength experiment with a dune length of 2.25 m (EXP1) and for the high flow strength experiment with a dune length of 4.35 m (EXP2). The arrows represent the time-averaged velocity vector field $V(\bar{u}, \bar{w})$ overlaid onto the contour maps. The mean position of the dune bed is shown by the solid black line and the flow is from left to right. Irregularities in the dune topography, in both experiments,

Figure 8. Contour maps and selected profiles of the mean vertical flow velocity $\bar{w}$ (m s^{-1}) along dunes for (a, b) EXP1 and (c, d) EXP2. The arrows represent the mean velocity vector field $V(\bar{u}, \bar{w})$. Vertical, solid lines along the dune bed indicate the location of the velocity profiles origin with negative velocities to the left and positive velocity to the right of this line. The distance between two vertical lines scales with $\bar{w} = 0.5 \text{ m s}^{-1}$.

indicate the presence of small, mobile secondary bedforms that migrate on the stoss side of the main dune toward its crest. In our experiments, these secondary bedforms reached heights of several centimeters and they clearly display a flow recirculation area at their lee sides that can have local effects on the near-bed flow and sediment dynamics.

Several time-averaged flow features over dunes are observed in Figure 7 that have been described in other studies [e.g., Raudkivi, 1966; Parsons et al., 2005; Venditti, 2007; Coleman et al., 2008; Grigoriadis et al., 2009; Shugar et al., 2010; Bradley et al., 2013]. This includes (1) a zone of lee side flow reversal or deceleration, (2) flow acceleration due to convergence on the stoss side of the dune toward the dune crest with largest mean streamwise velocities at the crest area, (3) flow deceleration due to expansion in the wake region with

negative velocities in the flow separation zone, (4) an outer, near-surface region with higher velocities overlying the flow separation zone, and (5) development of an internal boundary layer starting on the stoss side of the dune toward the dune crest. Furthermore, the mean distance from the separation point to the flow reattachment point (indicated with open circles in Figures 7a and 7c), the flow separation length, is found to be 5 to 6 times the equilibrium dune height Δ_e , which is in good agreement with values reported in previous studies [e.g., *Paarlberg et al.*, 2007, and references therein]. The exact location of the flow reattachment point at the bed is the boundary between the negative and the positive mean streamwise flow velocities. The flow reattachment point is located at 0.1 to 0.2 times Δ_e which is higher than the minimum dune trough level.

In addition to topographic forcing effects, the near-bed mean streamwise flow velocity above mobile dunes also seems to be affected by the presence of a dense mobile sediment layer close to the bed. As a result, the near-bed mean streamwise velocity above mobile beds deviates from the logarithmic profile often observed above plane or fixed dune beds. *Sumer et al.* [1996] measured a small, nearly constant mean streamwise velocity in the high sediment concentration layer near the bed and found that the velocity outside this layer follows the logarithmic law. This behavior of the mean streamwise flow velocity close to the bed, as shown in Figure 7, is also observed in the current experiments. The sediment concentration plots in section 4.1 (Figure 12) confirm the presence of high sediment concentration in this near-bed layer where the mean streamwise velocity profile deviates from the logarithmic law. Furthermore, the mean streamwise velocities close to the bed are also affected by the presence of secondary bedforms. The experimental study of *Carling et al.* [2000] showed that secondary bedforms had a significant effect on the near-bed flow, inducing low velocities near the bed and accelerated flow above the height of the secondary bedforms. As a result, the mean streamwise velocity profiles also deviated from the logarithmic velocity profiles displaying small, nearly constant velocities in the vicinity of the bed and much larger velocities toward the water surface [see *Carling et al.*, 2000, Figure 12].

The contour maps and selected profiles of the mean vertical flow velocities $\bar{w}$ along dunes for both experiments are shown in Figure 8. The clockwise flow rotation formed in the flow separation zone is clearly observed. Negative (directed toward the bed) mean vertical velocities are localized in the trough region downstream of the dune crest. Due to topographic forcing effects, positive (directed toward the water surface) mean vertical velocities are present almost along the entire dune surface with largest values occurring at the midstoss side of the dunes between $x/\lambda = 0.2$ and $x/\lambda = 0.6$. Although the flow strength is larger for EXP2 than EXP1, due to a much smaller dune steepness (Δ_e/λ_e) for EXP2 (Table 1), the mean vertical velocities for this experiment are generally smaller compared to EXP1.

3.2. Mean Turbulent Field

The mean streamwise I_u and vertical I_w turbulent intensities for both experiments are shown in Figures 9 and 10, respectively. Similar behavior of mean turbulent intensity is observed for both experiments. The contour maps show zones of high turbulence intensity behind the dune lee side and in the trough region of the dunes with maximum values occurring within and just downstream of the flow separation zone. Where high values of the mean streamwise turbulent intensities I_u are localized in the trough area of the dune, high values of vertical turbulent intensities I_w are advected toward the water surface over the midstoss side of the dune. Selected profiles of I_u (Figures 9b and 9d) and I_w (Figures 10b and 10d) show, behind the dune crest, peaks that illustrate the development of a wake structure and a separating shear layer. Over the entire stoss side of both dunes, I_u shows little variation and is more or less constant toward the water surface. The I_w over the stoss side of the dunes, on the other hand, is observed to increase with increasing distance from the bed. Similar to the behavior of the near-bed mean streamwise velocity profiles along the dune stoss side (see Figure 7), I_u and I_w profiles seem to be affected by near-bed flow and sediment processes (large sediment concentration and secondary bedforms). The magnitudes of I_u and I_w are constant and nearly zero near the bed while an increase is observed at higher distances from the bed.

Figure 11 shows the contour maps and selected profiles of the Reynolds shear stresses τ_{uw} along dunes for both experiments. Close to the dune bed, τ_{uw} values are small and negative while positive values are observed elsewhere along the dune. Maximum values of τ_{uw} occur at and just downstream of the

Figure 9. Contour maps and selected profiles of the mean streamwise turbulent intensity I_u (m s^{-1}) along dunes for (a, b) EXP1 and (c, d) EXP2. Vertical, solid lines along the dune bed indicate the location of the profiles origin and the distance between two vertical lines scales with $I_u = 0.8 \text{ m s}^{-1}$.

reattachment zone along the separating shear layer. Toward the water surface, τ_{uw} values decrease strongly over the flow separation zone of the dunes while less variation is observed in τ_{uw} values over the stoss side of the dunes.

The near-bed behavior of mean and turbulent flow evolution over mobile dunes observed in this study is significantly different from the near-bed flow evolution over fixed dunes reported in the literature. This is probably due to the presence of a dense sediment layer close to the bed and due to the effects of migrating secondary bedforms. In particular, the small and nearly constant mean streamwise flow velocity close to the bed is not observed over fixed dune measurements. In addition, the small and negative values of the Reynolds shear stresses observed close to the bed are not identified along fixed dunes. Farther above the dune bed, the patterns of mean and turbulent flow evolution are consistent with observations from previous

Figure 10. Contour maps and selected profiles of the mean vertical turbulent intensity I_w (m s^{-1}) along dunes for (a, b) EXP1 and (c, d) EXP2. Vertical, solid lines along the dune bed indicate the location of the profiles origin and the distance between two vertical lines scales with $I_w = 0.1 \text{ m s}^{-1}$.

experimental and numerical studies over fixed and mobile dunes [e.g., Bennett and Best, 1995; Cellino and Graf, 2000; Grigoriadis et al., 2009; Omidyeganeh and Piomelli, 2011, and references therein].

4. Sediment Transport Processes

4.1. Mean Sediment Concentration

Contour maps and selected profiles of the mean sediment concentration $\log_{10}(c)$ [kg m^{-3}] along dunes for both experiments are shown in Figure 12. The black, dotted line represents the interface between the suspended load and the bed load layer determined by the acoustic interface detection method [Hurther and Thorne, 2011; Hurther et al., 2011]. This interface clearly represents a concentration threshold. Typically, the concentration threshold varies between 40 and 60 (kg m^{-3}) which is much smaller than 212 (kg m^{-3}) used as

Figure 11. Contour maps and selected profiles of the Reynolds shear stress τ_{uw} (Pa) along dunes for (a, b) EXP1 and (c, d) EXP2. Vertical, solid lines along the dune bed indicate the location of the profiles origin and the distance between two vertical lines scales with $\tau_{uw} = 15$ Pa.

sheet flow layer threshold by *Dohmen-Janssen et al.* [2001]. The sediment concentration at the bed equals the bulk density $\rho_s(1 - \epsilon) = 1590$ (kg m^{-3}), where $\rho_s = 2650$ (kg m^{-3}) is the sand density and $\epsilon = 0.4$ (—) is the sand porosity. The highest sediment concentration is found within the bed load layer, whereas much smaller concentrations (up to 1 order of magnitude) are observed in the suspension layer. Similar large sediment concentration gradients above river dunes were found by *Shugar et al.* [2010] and *Kostaschuk and Villard* [1999] where a tenfold decrease was found in the mean sediment concentration—relative to near-bed concentration—throughout the water column. *Johns et al.* [1990] also reported a similar concentration gradient over tidal dunes.

Figure 12. Contour maps and selected profiles of the mean sediment concentration $\log_{10}(c)$ (kg m^{-3}) along dunes for (a, b) EXP1 and (c, d) EXP2. The black, dotted line is the interface between the suspended load and the near-bed load layer determined by acoustic interface detection method. Vertical, solid lines along the dune bed indicate the location of the mean concentration profiles origin.

Typically, sediment concentration decreases with increasing distance from the bed over the entire dune and becomes very small near the water surface. The concentration profiles (Figures 12b and 12d) along the dunes demonstrate that this decrease of sediment concentration toward the water surface occurs more gradually over the trough and the lee side of the dune compared to the crest and the stoss side of the dune. Due to flow deceleration and associated turbulence generation in the trough region of the dune, sediment is picked up and transported to higher distances from the bed compared to the dune crest where flow is accelerated. In addition, the magnitude and intensity of suspension peaks are largest in the trough region

Figure 13. Contour maps and selected profiles of the mean streamwise $\overline{cu}$ sediment fluxes ($\text{kg m}^{-2} \text{s}^{-1}$) along dunes for (a, b) EXP1 and (c, d) EXP2. Vertical, solid lines along the dune bed indicate the location of the profiles origin and the distance between two vertical lines scales with $\overline{cu} = 8 \text{ (kg m}^{-2} \text{s}^{-1})$. The open circles in the dune bed indicate the flow reattachment points.

downstream from the dune crest and the vertical decrease of sediment concentration toward the water surface occurs more gradually. The intensity and the number of suspension peaks were also greater for this experiment.

4.2. Mean Sediment Fluxes

The contour maps and selected profiles of the mean streamwise sediment flux $\overline{cu}$ for both experiments are shown in Figure 13. The fluxes are largest close to the bed and decrease with distance toward the water surface. On the stoss side of the dune in the bed load layer, $\overline{cu}$ is positive and increases toward the dune crest due to flow acceleration and the associated increase in the bed shear stresses. At a farther distance from the bed and above the dune trough, $\overline{cu}$ displays local peaks that decay toward the dune stoss side. These peaks are related to the turbulence generation due to the developing shear layer. On the lee side of the dune and mainly in the flow separation region close to the bed, sediment is transported in the opposite direction toward the dune crest while at higher distance from the bed a positive sediment flux is observed. Although most of the sediment that is transported over the stoss side of the dune remains in the same dune by deposition on the lee side and in the trough of the dune thus contributing to dune migration, a significant amount of sediment in suspension is advected toward the following dune (positive transport rates downstream of the flow reattachment points indicated in Figure 13). This fraction of the sediment that is not captured into the dune forms, also termed the bypass fraction, is important for the prediction of dune migration and dune behavior [Mohrig and Smith, 1996].

and decay toward the crest where turbulent energy is much lower (see Figures 9–11). Using phase coherence wavelet analysis, Shugar *et al.* [2010] showed that streamwise flow deceleration in the dune trough is linked to the vertical flux of fluid toward the water surface in the form of large turbulent fluid ejections. They showed that regions of high suspended sediment concentration are strongly correlated with such events.

In the trough region of the dunes, the profiles of mean sediment concentration (Figures 12b and 12d) display a “bulging” shape which is in agreement with the theory of flow separation effects on the suspended sediment distribution [e.g., Zyserman and Fredsøe, 1994; Carling *et al.*, 2000]. Close to the bed and mainly within the bed load layer, the concentration profiles display a linear decreasing trend with increasing distance from the bed.

The patterns of mean sediment concentration discussed above are consistent for both experiments. Due to larger flow strength and thus larger bed shear stresses (see Table 1), sediment concentration is generally higher for EXP2. For EXP2, the high sediment concentration persists over a larger distance

Figure 14. Contour maps and selected profiles of the mean vertical $\bar{c}_w$ sediment fluxes ($\text{kg m}^{-2} \text{s}^{-1}$) along dunes for (a, b) EXP1 and (c, d) EXP2. Vertical, solid lines along the dune bed indicate the location of the profiles origin and the distance between two vertical lines scales with $\bar{c}_w = 0.35$ ($\text{kg m}^{-2} \text{s}^{-1}$).

Contour maps and profiles of the mean vertical sediment flux $\bar{c}_w$ (Figure 14) show that the largest values are close to the bed and that they drastically decrease with increasing distance from the bed. Positive (upward) sediment fluxes are observed over the entire dune with large peaks on the stoss side of the dune downstream of the flow reattachment point, reflecting the pickup of sediment. These peaks result from the shear layer vortices that impact the dune bed, generating turbulent sediment bursts that are absent elsewhere. Negative (downward) sediment fluxes are observed on the stoss side of the dune and over the dune crest in the dune lee side, with the largest values over the dune crest and dune lee side reflecting sediment deposition in these locations. In addition, in the dune trough close to the bed, upward vertical fluxes are coupled with small downward fluxes farther from the bed, illustrating the turbulent behavior of the flow in the flow separation zone. Although sediment is deposited over the entire dune profile, the dune is migrating, and thus, the effect of the mean streamwise sediment fluxes $\bar{c}_u$ is much larger than the effect of the mean vertical sediment fluxes $\bar{c}_w$. This is reflected in the values of $\bar{c}_u$ being an order of magnitude larger than $\bar{c}_w$ (Figures 13 and 14).

4.3. Mean Bed and Suspended Load Transport

Sediment transport rate T ($\text{kg m}^{-1} \text{s}^{-1}$) is calculated from the integration of the streamwise flux profiles over depth z .

$$T = \int_{z=a}^{z=b} \bar{c}_u dz \quad (4)$$

For the total load transport T_{tot} , the integration boundaries a and b are the nonmoving bed and the water surface, respectively. For the bed load transport T_{bed} the boundaries a and b are the nonmoving bed and the interface between bed and suspended load transport determined from the acoustic interface detection method, respectively. For the suspended load transport T_{susp} , the integration boundaries are the interface position and the water surface. The total, the suspended, and the bed load transport distribution along migrating dunes for both experiments are shown in Figure 15. As expected for migrating dunes in equilibrium, the measured total sediment transport (Figures 15a and 15d) follows more or less the dune shape with increasing transport toward the dune crest, deposition at the lee and trough side of the dune, and negative sediment transport within the flow reattachment zone. Although the bed and the suspended load transport are of the same order of magnitude, the shape of the total sediment transport distribution along dunes is dominated by the bed load transport (Figures 15b and 15e). Where the bed load transport displays a small, positive gradient over the entire stoss side of the dune toward the dune crest, the suspended load transport (Figures 15c and 15f) mainly increases over a small distance on the stoss side of the dune and remains nearly constant toward the dune crest. This means that the bed load transport is more effective in dune migration, that is, erosion on the stoss side and deposition on the lee side of the dune. The high

Figure 15. Total T_{Tot} , bed T_{Bed} , and suspended T_{Susp} load transport distribution along dunes for (a–c) EXP1 and (d–f) EXP2. The vertical arrows indicate the position of the flow reattachment points.

variability observed in the bed load transport is caused by the irregularities in the bed due to secondary bedforms on the stoss side of the dune that are migrating toward the dune crest [see also *Carling et al.*, 2000, and references therein].

Figure 16 shows the bed and the suspended load transport distribution in the trough of the dunes. The dashed, vertical lines indicate the brinkpoint position and the position of the flow reattachment point. Whereas the dune crest is the highest point at the dune, the dune brinkpoint is where bed load avalanching begins and produces a straight lee face depositional slope. The sediment avalanching process is clearly observed from the immediate decay of the bed load transport while approaching the dune lee side. The suspended load is advected a little farther downstream and is more gradually deposited on the lee side and in the trough of the dune. At the flow reattachment points the total sediment transport is positive (see arrows in Figure 15) and equal to the transport of suspended sediment as the bed load transport is practically zero at these locations. This part of the suspended load is neither deposited on the dune lee side nor in the dune trough and therefore does not contribute to dune migration. The bypass fraction is thus the suspended load transport at the flow reattachment point relative to the total sediment transport (bed load + suspended

Figure 16. Enlarged lee side of the dunes for (a) EXP1 and (b) EXP2 showing the bed and the suspended load transport distribution. The black solid line is the dune bed where the dashed lines indicate (left) the brinkpoint position and (right) the flow reattachment point.

load) arriving at the dune crest. For EXP1 the bypass fraction is about 10% and for EXP2 the bypass fraction is about 27%. This increase in the bypass fraction can be explained by the relative increase in the mean streamwise flow velocity from EXP1 to EXP2. If compared to the suspended sediment transport arriving at the dune crest, for EXP1 the bypass fraction is 16% and for EXP2 39%. This clearly shows that a substantial part of the suspended load transport is not captured in the dune form and thus does not contribute to dune migration, whereas the entire bed load transport arriving at the dune crest avalanches on the dune lee side and takes part in dune migration. Contrary to *Mohrig and Smith* [1996] who use the horizontal lee side distance (slip face distance) for the calculation of the bypass fraction, assuming that all the sediment that is deposited at farther distance downstream than the horizontal slip face distance does not contribute to dune migration, we argue that sediment particles with greater excursion lengths than the slip face distance but smaller excursion lengths than the flow separation length still contribute to dune migration as these particles are transported toward the dune lee side (negative transport rates in the dune trough, see Figure 16). Therefore, under same flow conditions, the bypass fraction calculated using the model of *Mohrig and Smith* [1996] will result in an overestimation of the actual sediment fraction that is not contributing to dune migration, compared to our results. However, it should be noticed that the dunes observed in the field have much smaller lee side slopes (low-angle dunes) that results in a zone of highly intermittent or nonexistent flow reversal [e.g., *Best*, 2005a; *Shugar et al.*, 2010; *Bradley et al.*, 2013]. Therefore, sediment particles with greater excursion lengths than the slip face distance might not be transported back toward the dune lee side and thus not contribute to dune migration.

5. Discussion and Recommendations

The present study has focused on the details of flow and sediment dynamics along mobile, migrating sand dunes in equilibrium. In particular, the distribution of sediment transport along dunes and the contributions of both bed and suspended load to dune morphology and migration were investigated. Measurements were carried out using the ACVP during a series of mobile bed experiments. The experiments illustrated that, due to the presence of a dense sediment layer close to the bed and migrating secondary bedforms over the stoss side of the dune toward the dune crest, the near-bed flow and sediment processes are significantly different from the near-bed flow and sediment dynamics measured over fixed dunes.

Application of an interface detection method revealed the distribution of the bed load and the suspended load transport along migrating dunes. It was observed that the bed load was entirely captured in the dune with zero transport at the flow reattachment point, while a significant part of the suspended load was advected to the downstream dune depending on the flow conditions. The bypassed suspended sediment probably plays an important role during the transition of dunes to upper stage plane beds where dunes are flattened and eventually washed out [e.g., *Naqshband et al.*, 2014]. Therefore, further research is needed on the quantification of this fraction during the dune transitional stages under nonequilibrium flow conditions.

The bypass fraction can be compared to the following sediment transport balance. The mass of sand (per unit channel width) transported by the flow over an entire dune length M_{flow} , calculated from Figures 15a and 15d using equation (5), is 215.9 (kg m^{-1}) for EXP1 and 504.8 (kg m^{-1}) for EXP2. The integration boundaries a and b in this equation are the nonmoving bed and the water surface, respectively. The dune period is represented by the ratio of dune length λ_e to dune migration speed C_e .

$$M_{\text{flow}} = \frac{\lambda_e}{C_e} \int_{z=a}^{z=b} \bar{cu} \, dz \quad (5)$$

The sand mass M_{flow} is compared to the sand mass derived from the dune shape measurement M_{shape} using equation (6). Here $z(x)$ is the nonmoving bed height along the streamwise dune position with $z=0$ at the dune trough, $\rho_s = 2650$ (kg m^{-3}) is the sand density and $\varepsilon = 0.4$ (–) is the sand porosity (see Figures 15a and 15d).

$$M_{\text{shape}} = \rho_s (1 - \varepsilon) \int_{x=0}^{x=\lambda_e} z(x) \, dx \quad (6)$$

For EXP1, M_{shape} equals to 185.5 (kg m^{-1}) and for EXP2, M_{shape} is 377.3 (kg m^{-1}). The difference between the two calculated sand masses (M_{flow} and M_{shape}) is 16% for EXP1 and 34% for EXP2 which is in good

agreement with the bypass fractions calculated from the relative difference in sediment transport at the flow reattachment point and at the dune crest (see section 4.3).

Another aspect of measuring sediment fluxes that is not treated in this paper is the relative importance of turbulent fluxes to the total sediment fluxes along migrating dunes. Using two separate instruments for the measurement of flow velocity and sediment concentration limits sediment flux studies to flow scales larger than the separation distance between the two instruments. In addition, the measured sediment fluxes cannot be referenced to an exact location along the dune bed. The ACVP, on the other hand, provides direct flux measurements referenced to the exact location at the bed. As a result, both the mean and the turbulent part of sediment fluxes are addressed. The turbulent part of sediment fluxes might be dominant in the flow separation zones where turbulence is generated. This aspect will be addressed in future work.

Other important direction for future research is linking the results of this study to complex numerical models that describe the development and migration of dunes [e.g., *Nabi et al.*, 2013]. In particular, the near-bed flow behavior above migrating dunes observed in this study should be well reproduced by numerical models. In addition, the new insights obtained in this research on the distribution of bed load and suspended load can be used as reference for modeling sediment transport. However, it should be noticed that the results of this study are strongly related to 2-D dune topography in a laboratory flume. Future research is needed to investigate whether these findings are consistent for field conditions with a strong 3-D dune topography.

6. Conclusions

The present study has provided new insights in the flow and sediment dynamics over migrating dunes in equilibrium. The main findings of this study can be summarized as follows:

1. A dense sediment layer close to the bed and migrating secondary bedforms over the stoss side of the dune toward the dune crest result in near-bed flow and sediment processes that are significantly different from the near-bed flow and sediment dynamics measured over fixed dunes. In particular, the near-bed mean streamwise velocity above mobile beds deviates from the logarithmic profile often observed above plane or fixed dune beds. The near-bed concentration profiles above mobile beds also deviate from the near-bed concentration profiles observed above fixed dunes, displaying a linear decreasing trend with increasing distance from the bed.
2. The pattern of the total sediment transport distribution along dunes is dominated by the bed load transport although the bed load and the suspended load transport are of the same order of magnitude. This implies that bed load transport is responsible for the continuous erosion and deposition of sediment along the migrating dunes.
3. The bed load distribution at the lee side of the dunes decays rapidly because of sediment avalanching on the dune slip face. The suspended load transport, on the other hand, is advected farther downstream and is more gradually deposited on the lee side and in the trough of the dune.
4. Whereas the bed load is entirely captured in the dune with zero transport at the flow reattachment point, a significant part of the suspended load is advected to the downstream dune depending on the flow conditions. For the two flow conditions measured, the bypass fraction was about 10% for flow with $Fr = 0.41$ and 27% for flow with $Fr = 0.51$. This means that, respectively, 90% (for the $Fr = 0.41$ flow) and 73% (for the $Fr = 0.51$ flow) of the total sediment load that arrived at the dune crests contributed to the migration of the dunes.

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