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Secondary flow deflection in the lee of transverse dunes with implications for dune morphodynamics and migration

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1 **Can transverse dunes move sideways? Secondary flow deflection in the lee of transverse**
2 **dunes with implications for dune alignment and migration**
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33 **ABSTRACT**

34 Measurements of lee-side airflow response from an extensive array of meteorological instruments

35 combined with smoke and flow streamer visualization is used to examine the development and

36 morphodynamic significance of the lee-side separation vortex over closely spaced transverse dune

37 ridges. A differential deflection mechanism is presented that explains the three-dimensional pattern

38 of lee-side airflow structure for a variety of incident flow angles. These flow patterns produce

39 reversed, along-dune and deflected surface sand transport in the lee that result in a net 'lateral

40 diversion' of sand mass transport over one dune wavelength for incident angles as small as 10°

41 from crest-transverse (i.e., 80° from the crest line). This lateral displacement in fluid mass transport

42 increases markedly with incident flow angle, when expressed as the absolute value of the total

43 deflection in degrees. Reversed flow and multidirectional sand transport occur for incident angles

44 between 90 and 50°. These results document the three-dimensional nature of flow and sand

45 transport over transverse dunes and provide empirical evidence for an oblique migration model that

46 challenges the applicability of the 'gross bedform-normal' rule for explaining transverse dune

47 morphodynamics and migration.

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49 **KEYWORDS**: dunes, airflow, deflection, lee-side, interdune, dune migration

INTRODUCTION

The relations between the near-surface airflow field (i.e., height < 10 m), particularly complex secondary lee-side flows, and sediment transport over dunes remain an elusive challenge for modeling dune morphodynamics and migration (Walker and Nickling, 2002; Baddock et al., 2007; Livingstone et al., 2007). It is known that dune form, alignment, and spacing are controlled by the magnitude, frequency, and directionality of transporting surface wind (e.g. Bagnold, 1941; Fryberger and Dean, 1979; Lancaster, 1983; Bullard et al., 1996; Ould Ahmedou et al., 2007) as well as sediment characteristics (size and sorting) (Wilson, 1972) and availability (Wasson and Hyde, 1983), moisture effects (Kocurek et al., 1992), topographic barriers (McCauley and Breed, 1980), and the presence of vegetation (Hesp, 1981; 1983; Wiggs et al., 1996). Other studies have linked dune alignment to coherent atmospheric circulation patterns such as Ekman spirals (Hanna, 1969; Mabbut et al., 1969; Warren, 1976) and to the strongest transporting winds in the regime (Glennie, 1970). Ultimately, however, dune alignment and migration is the net result of complex, three dimensional sand transport patterns driven by all competent surface winds – including secondary lee-side flows (Sweet and Kocurek, 1990; Frank and Kocurek, 1996; Walker and Nickling, 2002; Baddock et al., 2007; Livingstone et al., 2007; Baddock et al., 2011; Weaver and Wiggs, 2011). Nearly 30 years ago, Rubin and Hunter (1985), and later Hesp et al. (1989) and Rubin (1990), observed that longitudinal dunes can migrate laterally, contrary to the prevailing thought that such dunes advance downwind, or else extend at the terminal end (e.g. Bagnold, 1941; Tsoar, 1983). To date, however, there is limited research that links deflected airflow and sediment flux in the lee of transverse dunes to their morphodynamics and migration (Walker, 1999; Walker and Nickling, 2002; Baddock et al., 2007).

Morphodynamically, dunes are often classified based on their orientation to some resultant transport direction as transverse (perpendicular to the transport direction), longitudinal (transport-parallel), and oblique (15 – 75° to the resultant transport direction) forms (Fryberger

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75 and Dean, 1979; Hunter et al., 1983; Lancaster, 1983; Rubin and Ikeda, 1990). Fryberger and

76 Dean's (1979) widely cited global assessment attributed the development and maintenance of

77 specific dune types to the ratio of the resultant vector of sand transport, or drift potential (RDP), to

78 total drift potential from all wind directions (DP). Fryberger and Dean found that simpler dune forms

79 (e.g., barchans, transverse ridges) develop in less variable wind regimes with high sand transport

80 potential (RDP/DP) while more complex dunes (e.g., star dunes) occur in highly variable wind

81 regimes where the transport potential is lower.

82   Regional winds used to describe dune form using Fryberger and Dean's (1979) technique

83 are usually measured at a standard height of 10 m, often from locations tens to hundreds of

84 kilometers away from actual dune features (Hunter et al., 1983; Carson and MacLean, 1986).

85 However, localized secondary airflow patterns such as flow deflection, topographic steering, and

86 flow separation and reversal, often diverge greatly from the regional trend (e.g. Pearce and Walker,

87 2005; Lynch et al., 2008; 2009; Walker et al., 2009; Jackson et al., 2011) and can be competent

88 enough to drive deflected interdune sand transport (Walker, 1999) and, thus, contribute to three-

89 dimensional variations in dune sediment budgets. Thus, simple regional assessments of wind

90 regime – dune form relations may be insufficient as they do not accommodate more complex

91 natural flow – form – transport interactions (Walker and Nickling, 2002).

92   This has generated some debate in the literature on wind regime – dune form relations

93 (Hunter et al., 1983; Carson and MacLean, 1985; Hunter et al., 1985; Carson and MacLean, 1986).

94 For instance, Carson and McLean (1986) noted an increase in oblique dune size in a reversing

95 wind regime toward the direction of an along-dune oriented resultant transport vector (shown in

96 their Figure 5). This complicated their interpretation of these dunes as true flow-transverse forms

97 and they suggested the term 'hybrid' dunes as both longitudinal and transverse transport

98 processes appeared to be contributing to their morphodynamics. This is essentially synonymous

99 with the 'oblique' dunes documented earlier by Hunter et al. (1983) in coastal Oregon. In either

100 case, it is possible that the resultant sand transport vector (RDP), driven by winds transverse or

101 slightly oblique to the dune crest, may actually align more so with deflected, along-dune oriented

102 lee-side secondary flow patterns. Sand transport by such secondary winds may be responsible for

103 the downwind 'bulking' of Carson and MacLean's dunes (1986, see p.1983-1984).

104   Other studies have shown that directional variability (i.e., dominant modes in the regional

105 wind regime) control dune morphodynamics and alignment. For instance, Rubin and Hunter

106 (1987) and Rubin and Ikeda (1990) showed that dune alignment follows a gross bedform-

107 normal rule such that, under variable flow directions, bedforms align so as to maximize the

108 amount of crestline-normal transport. In other words, bedforms orient as transverse as possible

109 to the resultant of all bedform-normal transport components and not necessarily to the resultant

110 transport vector. Rubin and Ikeda (1990) stressed that opposing vector components in the

111 transport regime should not be cancelled out (as in the RDP approach) as they may both be

112 formative in maintaining a single dune orientation. For instance, transverse forms are

113 maintained for divergence angles (i.e., angle between dominant direction modes) up to 90° or

114 equal to 180° (i.e., a reversing regime), or when transport is dominated by one direction mode.

115 Longitudinal dunes often orient with the dune axis within 15° of the mean wind direction (Hunter et

116 al., 1983) and are maintained in bi-modal wind regimes with divergence angles >90° providing

117 equivalent transport in both directions. As such, dune-parallel wind flow is not a requirement for

118 longitudinal bedform maintenance (Lancaster, 1982; Tsoar, 1983; Rubin and Ikeda, 1990).

119 Transitional, or oblique dunes occur for intermediate divergence angles from 90 to 112.5° (or

120 'obtuse-bimodal' per Fryberger and Dean, 1979) and are controlled by both transverse and

121 along-dune oriented transport processes (Carson and MacLean, 1986). Rubin and Ikeda (1990)

122 conclude that, despite alignment, all free dune forms are governed by the same essential

123 dynamics in that they will orient as perpendicular as possible to the maximum bedform-normal

124 components of transport. As such, divergence between directional modes and the ratio of sand

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125 transport by these modes is more important in dune maintenance and migration than the net
126 resultant vector.

127   As recognized by Fryberger and Dean (1979, p.145), however, it is important to note that
128 the regional scale sand transport regime assessments provide only a first order estimate of the
129 transport regime and are unable to incorporate other key transport- and supply-limiting factors
130 (including grain size, soil moisture, vegetation, surface roughness) as has been explored by
131 subsequent research on aeolian sand transport potential and dune mobility (e.g. Muhs and Maat,
132 1993; Gaylord and Stetler, 1994; Muhs and Holliday, 1995; Wiggs et al., 1995; Bullard et al., 1996;
133 Wolfe, 1997; Tsoar and Illenberger, 1998; Kocurek and Lancaster, 1999; Muhs and Wolfe, 1999;
134 Lancaster and Helm, 2000; Tsoar, 2002). These factors are particularly important when examining
135 regional to landform-scale characterizations of sand transport behaviour in vegetated, temperate
136 and/or coastal environments (Pearce and Walker, 2005; Lynch et al., 2008; 2009; Walker et al.,
137 2009; Jackson et al., 2011).

138   Emphasis has shifted from research on regional scale flow regime – dune form relations to
139 examining landform scale interactions between near-surface secondary flow and resulting sand
140 transport patterns that drive dune morphodynamics in both coastal and desert settings (e.g. Tsoar,
141 1983; Howard, 1985; Hesp et al., 1989; Rasmussen, 1989; Cooke et al., 1993; Arens et al., 1995;
142 Lancaster, 1995; Hesp and Hyde, 1996; Wiggs, 2001; Walker and Nickling, 2002; Baddock et al.,
143 2007; Ould Ahmedou et al., 2007; Lynch et al., 2008; 2009; Walker et al., 2009; Weaver and
144 Wiggs, 2011). Despite this recognition, very few models of secondary flow and dune
145 morphodynamics exist, particularly on how these flow and sand transport patterns change with the
146 incident flow angle and what this means for dune sediment budgets and migration (Walker and
147 Nickling, 2002; Hesp and Walker, In press). Instead, most existing models of flow over bedforms
148 view the system as two-dimensional and consider only limited flow conditions (i.e., transverse,
149 unseparated) over relatively isolated dunes (Sweet and Kocurek, 1990; Frank and Kocurek, 1996;

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150   Baddock et al., 2011). However, in nature secondary flows and closely spaced dune configurations

151   generate mass and energy transfers that are three-dimensional. For instance, Walker (1999)

152   showed that appreciable sand transport can occur in deflected, reversed, and along-dune

153   directions within the interdune and cautioned that secondary lee flows create additional mass

154   transport components that must be considered for sediment continuity and, hence, for

155   interpretation of dune dynamics, maintenance, and migration.

156   This study measures and examines the responses of three-dimensional lee-side flow

157   structure and interdune sand transport to changes in incident flow angle. Flow visualization and

158   concurrent measurements of lee-side sediment transport over the same dune (Walker, 1999) are

159   used to show a lateral diversion of sand mass transfer over flow-transverse dunes. From this, a

160   differential deflection mechanism is presented that explains secondary lee-side flow structure

161   implications for dune maintenance and migration. An empirical model for oblique migration of

162   transverse dunes is presented that challenges the applicability of the 'gross bedform-normal' rule

163   for explaining dune morphodynamics. The convention to describe flow direction for this study is

164   such that incident wind direction, i, measured at the crest of the dune is transverse to the crestline

165   at 90° and parallel to the crestline at 0° (west) or 180° (east). When discussing deflected flow, d, in

166   the lee of the study dune on the stoss slope of the downwind dune, we use the same coordinate

167   system as for incident flow. For example, incident flow transverse to the crest (i = 90°) might be

168   deflected 10° (d = 100°) in the lee.

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170   **METHODS**

171   Wind speed and direction were measured along two crest-transverse transects spaced

172   approximately 18 m apart in the lee of a small reversing dune in the Silver Peak dunefield, Clayton

173   Valley, west-central Nevada (Walker, 1999) (Figure 1). Dune geometry differed slightly between

174   sampling transects, as the east dune profile was slightly larger (h = 1.36 m) than the west (h = 1.2

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Comment [D1]: Ian, how's this expanded description of i and d?

Comment [IW2]: Presumably, you wanted to add the symbol i here? I also thinned e/w text a bit.

Comment [IW3]: This font looks weird in my vers.

175   m). The study dune was located within a successive grouping of similarly sized (h = 1 to 2 m),

176   unvegetated, transverse ridges composed of fine sands (D = 150 μm) and oriented transverse (75º

177   or approximately E-W) to a relatively consistent north-south reversing wind regime. During the

178   period of study the dune profile had a sharp crestline with a distinct, southward facing lee slope.

179   Each instrument transect extended 12 m leeward and perpendicular to the crest and

180   consisted of 25 RM Young cup anemometers and six wind vanes strategically located to capture

181   windspeed and direction variations in the immediate lee (Figures 2, 3). Instruments were extended

182   on 1.2-m booms from one of four aluminum masts and were connected to dataloggers via cable.

183   Near-surface anemometers were placed at 0.3 m to characterize transporting windspeeds ($u_{0.3}$).

184   Further details of the study site and sampling design are discussed in Walker (1999; 2000).

185   Extended periods of consistent winds ranging in duration from 1 to 10 hours were sampled

186   at 1 Hz and recorded as one-minute averages by datalogger. All speeds were normalized by an

187   outer windspeed (u_{10h}) measured at 12.4 m (approximately 10h) above the interdune datum atop

188   an observation tower located between the sampling transects, where wind speeds ranged from 2

189   to 15 m s^{-1} during the period of study. Incident flow speed and direction data were also measured

190   at 3.8 m above the dune on the crest profile (i.e., $u_{5.2h}$ on east and $u_{4.6h}$ on west profiles,

191   respectively). In total, 45 events were recorded over a 15-day period in May 1997 to yield an

192   extensive dataset of over 22,000 minutes of flow measurements for a variety of incident flow

193   speeds and directions. Contiguous transporting flow events (i.e., above an assumed transport

194   threshold of 6 m s^{-1}) ranging 7 to 24 minutes in duration and spanning incident flow angles were

195   identified (Table 1). These events all occurred on the same day and, as such, dune form remained

196   essentially constant between events.

197   Flow patterns during the events presented here were also visualized using smoke tracers

198   and a vertical array of streamer flags (Figure 4), which was essential for reconstructing lee side

199   flow structure within the measurement array. A transect of 9 flow streamer towers was erected 2 m

Comment [D4]: I think I've now fixed everything to U5.2h and U4.6h

Comment [IW5]: OK… now, do we refer to these 5.2 and 4.6h measurements or is everything always normalized by uouter/10h? For e.g., I think the vectors are normalized by their respective crest outer measurements, not 10h., whwereas the profiles may have been. Doublecheck and clarify.

200 east of a 12-m observation tower in the centre of the study site (Figure 2b). The streamer towers

201 were spaced 1 m apart and extended leeward from the crestline. Each tower was 3 m tall and had

202 5 streamer flags each. Flow streamer behaviour in plan view at different heights above the

203 interdune surface was recorded by video camera from atop the observation tower in the centre of

204 the instrument array. Smoke tracer patterns were photographed in profile from the interdune

205 corridor. Both sources of flow visualization were used to qualitatively confirm measured flow

206 responses and help construct the extent and behaviour of interpreted flow patterns from the

207 instrument array.

208

209 **RESULTS**

210 *Time-averaged velocity profiles*

211 Time-averaged, normalized wind speed profiles for six locations on each dune transect are

212 shown in Figure 5. For clarity, data from only three events (2, 4, and 7) ranging from transverse (i

213 ≈ 90°) to crest-parallel (i ≈ 180°) are shown. Summary statistics are provided in Table 1. Profile

214 gradient responses provide a good relative indicator of momentum extraction and fluid shear

215 generated by the form as well as subsequent internal boundary layer redevelopment after

216 reattachment.

217 For relatively transverse (event 2, i ≈ 90°) and slightly oblique (event 4, i ≈ 110°) winds, flow

218 over the crest was nearly uniform with increasing height above the surface for both east and west

219 transects, whereas for crest-parallel flow (event 7, i ≈ 180°), a slightly kinked velocity profile was

220 observed over the crest on both transects. On the east profile, the inflection point occurred only 0.7

221 m above the crest surface (1.5h above interdune datum) for event 7, while on the west profile, it

222 occurred at 1.6 m above the surface (2.4h). On the east profile, the crest-parallel incident flow

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223   (event 7) was fastest at the highest sensor, 3.8 m above the crest surface (5.2h), while on the west

224   profile, crest-parallel incident flow was slightly less than the transverse incident flow (4.6h, event 2).

225   All three events shown in Figure 5 exhibited similar general trends in lee-side flow profile

226   response, although magnitudes differed. Flow visualization confirmed that flow separation and

227   intermittent reversal was present for all transverse wind events. In general, crest-parallel incident

228   flows were faster over lee slope (near-surface) and stoss locations than other flows. Lee slope

229   profiles for crest-transverse and oblique flows were inflected with a very steep gradient below dune

230   height. This is due to flow separation and wake sheltering effects and indicates a region of high

231   shear along the line of separation. The speed-height gradient was steeper for transverse incident

232   flow (event 2) than for crest-parallel incident flow (event 7). On the east profile, near-surface flow

233   was slowest in event 2, and fastest for event 7. Higher into the flow over the lee slope of the east

234   profile, flow during event 7 (crest-parallel incident flow) was only marginally slower than other

235   incident conditions. Over the lee slope of the west profile, near-surface speeds were generally

236   faster than over the east transect, but during event 4 (initially slightly oblique to the crest), flow was

237   slightly faster than during crest-parallel incident flow (event 7). As on the east profile, flow during

238   event 7 had the shallowest gradient.

239   The well-developed separation cell extended to about the stoss base, at which point the

240   flow returned to a linear velocity profile. Flow visualization and onsite ripple patterns revealed that

241   flow reattachment occurred between the interdune and stoss base locations on the east transect

242   and further downwind between the stoss base and lower stoss I profiles on the west transect.

243

244   *Lee-side flow vectors*

245   Time-averaged flow vectors were derived from direction and speed data obtained at

246   locations in the flow field where a wind vane and anemometer were co-located (see Figures 2, 3b).

247   These vectors and associated summary statistics are displayed in plan view (Figures 6-8) and

8

248   provide useful indications of flow variability and directional response at different heights in the

249   secondary flow region compared to outer flow above the dune crest.

250   Figure 6 shows lee-side flow vector response for three crest-transverse events that increase

251   in speed (events 1-3). Incident flow speeds at the top of the crest profiles ($u_{5.2h}$ on east, $u_{4.6h}$ on

252   west) ranged from 0.84 – 0.92 of the outer flow (10h) and variability was less than 10% (i.e., CV_{ui} <

253   0.10). Incident direction ranged ±2° from transverse (e.g. i = 88 to 92°) and directional variability

254   was less than 6° for all events. Overall variability in direction increased with incident speed

255   although steadiness in flow speed was highest at faster speeds (see CV_u values in Figure 6c).

256   Near-surface (z = 0.3 m) vectors on the lee slope for these events show net downwind flow

257   with bi- or multi-modal directional variation indicating flow deflection and unsteadiness. Intermittent

258   upslope (reversed) flow was observed at these locations but is not reflected in the vectors because

259   of the relatively long (1 min.) averaging intervals. Speeds on the lee slope ranged approximately 30

260   to 70% that of the outer flow at 10h and were slower on the east transect due to the increased

261   sheltering offered by the taller dune. This sheltering effect increased with incident speed at all lee

262   slope locations. The amount of flow deflection on the lee slope also increased with speed and dune

263   height.

264   There are two flow vector measurement points on the interdune and stoss base profiles

265   that are staggered slightly for strategic placement within the separation region (see Figures 2, 3b).

266   The interdune vectors, located just downwind of the lee slope base, characterized flow in the core

267   of the separation cell (2nd sensor, 0.8 m above surface) and just above crest height (4th sensor, 1.8

268   m). Vectors on the stoss base profile were located on the toe of the downwind dune the surface

269   (0.3 m) and just above dune height (1.3 m). Over the interdune, flow at half-dune height was

270   deflected more than that on the lee slope surface. Variability in direction at this location increased

271   with incident speed and reversed flow occurred within the separation cell at the highest incident

272   speed on the west transect (Figure 6c). Highly variable, multi-modal reversed flow was also

Comment [IW6]: Double check the figure numbers throughout have been updated.

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273 observed just above dune height ("upper" arrow) at this location for all events. The high SD° values
274 at this location (particularly on the west transect) indicate high turbulence along the shear zone, as
275 described above from Figure 5. Speeds above the separation cell in the interdune were
276 comparable to incident speeds 3.8 m above the crest ($u_{5.2h}$ and $u_{4.6h}$ for east and west profiles,
277 respectively) and, in general, were faster than at the stoss base location downwind due to flow
278 expansion (and deceleration) downwind of separation at the crest.

279 Surface vectors at the toe of the downwind dune (stoss base) were multi-modal on the east
280 transect and strongly oblique to incident flow. Flow visualization and surface ripple patterns showed
281 that this location was just downwind of flow re-attachment. Upper and half-height flow vectors were
282 also multi-modal but more aligned sub-parallel to incident flow. Half-height vectors on the west
283 transect were deflected more than those on the east transect. These vectors show that near-
284 surface deflection is greater (at the toe of the downwind dune, or near the point of re-attachment)
285 over the taller dune (east) and that this pattern increased with faster incident speeds. This suggests
286 that the flow separation cell was slightly larger over the taller dune and for faster wind speeds, as
287 expected. Flow direction above this location (upper height) was less variable and less deflected
288 than at half-height. The lower stoss vector (furthest downwind), which was higher above the
289 surface, showed low variability in direction, was aligned more crest-transverse, and had slower
290 relative speeds than the stoss base location. This indicates flow direction returning to crest-
291 transverse up the stoss of the downwind dune.

292 Figure 7 shows lee-side flow vector response for two oblique flow events with incident
293 angles of approximately 110° (event 4, Figure 7a) and 130° (event 5, Figure 7b). These events
294 show that the amount of flow deflection on the lee slope increased with the angle of obliquity
295 (approximately doubling with a twofold increase in obliquity angle from transverse) and for the taller
296 dune (e.g., from 24° to 40° on the taller east transect compared to only 3° to 7° on the shorter west
297 transect, for the 110° and 130° events, respectively). Thus, under the same incident flow

Comment [IW7]: This sentence needs simplification

10

298 conditions, deflection of oblique flows was greater over the larger dune and the angle of deflection

299 on the lee slope was approximately the same as the angle from transverse. For example, for event

300 4 with an angle of ~20° from transverse over the crest of the east dune transect (i = 111°), the flow

301 was deflected ~25° (d = 135°), while for event 5, with an angle of ~40° from transverse over the

302 crest (i = 131°), the flow was deflected 40° (d = 171°). Overall directional variability for both events

303 is very low (SD° < 11°) compared to the transverse condition (SD° ??). Flow vector orientations in

304 the lee slope through stoss slope regions show that flow deflection was greatest near the surface

305 (reaching a maximum at the stoss base surface location) and decreased with height and beyond

306 the interdune toward the downwind dune. The half height sensor on the west transect

307 malfunctioned partway through data collection, so those vectors are not shown for events 4–7

308 inclusive (Figures 7, 8).

309 Flow vector response for highly oblique to crest-parallel events 6 (i ≈ 145°) and 7 (i ≈ 0°) are

310 shown in Figure 8. Event 6 exhibited a similar deflection trend as events 4 and 5. Although the

311 absolute magnitudes of deflection angles were greater, they generally decreased with height and

312 distance beyond the interdune. Lee slope flow deflected by about 30° on the taller (east) dune (i =

313 146°, d = 177°) but was deflected negligibly over the shorter (west) dune (i = 146°, d = 147°).

314 Normalized windspeeds elsewhere in the lee (from anemometer-only locations that could not be

315 converted to vectors, see Figure 5a for velocity profiles) were faster than crest values at all

316 locations beyond the lee slope on the east transect and in the immediate lee and interdune regions

317 on the west transect. Near-surface lee slope speeds during this event were 0.59 and 0.84 that of

318 the outer flow on east and west transects respectively. Speeds and flow deflection were greatest

319 within the interdune to stoss base regions on both transects, which indicates strong along-dune

320 flow within the interdune corridor.

321 Flow direction for event 7 (Figure 8b) was aligned approximately parallel to the crest and

322 unlike all other events was from the west (i = 2°-3°). All lee-side locations recorded faster flow than

11

Comment [D8]: OK Ian – does this make sense? I changed the wording a fair bit from the thesis (p94). Or maybe we should just delete these half dozen lines b/c as you said in a comment it's repetitive? What's not clear to me is what the smaller dune (and not that much smaller) produced such negligible deflection.

Comment [IW9]: Let's just leave for reviewer to decide.

Comment [D10]: This bit was lifted direct from your thesis, but I don't understand it at all. You don't specify what the directional variability is for the transverse conditions, but from Table 1, it appears to be ranging from 2.6-5.8. What's odd about it, is that there is nothing like 11deg for SD in that table. There is a value of 0.11 for CV. Did you mean CV instead of SD? Check out Table 1 and see what you think.

Comment [IW11]: Beats me. Perhaps an error in my earlier interp of the text? I do recall that directional variability was still low, regardless, so update with SD values in the table, ok?

323 those near the crest surface and the west transect showed lee-side deflection back toward the

324 dune and up the lee slope on the west transect (i = 3º, d = 346º). This pattern is similar to those

325 documented by Tsoar (1983: 570, Figure 4) over a linear (seif) dune.

326

327 **DISCUSSION**

328 *Lee-side flow deflection and secondary flow structures*

329   Flow-form interactions over complex dune terrain generate significant alterations in the

330 magnitude and direction of near-surface sand-transporting winds. This results from topographically

331 forced variations in the pressure field over dunes and creates various secondary flow patterns

332 including flow accelerations on the stoss slope; flow separation, expansion, and reversal in the

333 lee; and directional variations of attached, near-surface flow that is deflected or steered in

334 directions that differ significantly from the regional wind (Walker and Nickling, 2002; Walker et

335 al., 2006; Walker et al., 2009). Research on flow over coastal foredunes has shown that,

336 generally, winds approaching at an oblique angle tend to be deflected toward crest-normal

337 (Svasek and Terwindt, 1974; Jackson, 1977; Rasmussen, 1989; Arens et al., 1995) and that this

338 steering effect is greatest when incident angles are between 30 to 60° to the crestline. Winds

339 with approach angles less than 30° (i.e., highly oblique) are often deflected parallel to the crest

340 (e.g. Mikkelsen, 1989; Arens et al., 1995). Crestward steering on the stoss slope occurs

341 essentially because perturbation pressures and resulting topographic flow accelerations

342 increase the crest-normal (transverse) component of local flow vectors up the stoss slope

343 (Jackson, 1977; Tsoar, 1983). Beyond the crest, abrupt changes in surface slope and potential

344 flow separation, expansion, and deceleration cause a reduction in the transverse component of

345 local flow vectors that, in turn, causes flow to deflect in a more crest-parallel direction (Tsoar,

346 1983; Walker, 1999). The morphodynamic implications of flow deflection are twofold. First,

347 under increasingly oblique (i.e., less crest-transverse) conditions, the dune appears less steep

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Comment [IW12]: I think there is a walker et al ref 2006 maybe that also shows this and should be added.

Comment [IW13]: Again, I think one of our PEI papers also showed this… don't have access to them at the mo, however. Add if you can.

Comment [IW14]: Svasek and Terwindt 1974 may also have said this… I should have a copy or could find online. Can't log in to library website for pDF access for some damn reason and my Mendeley won't work tonight either… ugh.

348   to oncoming flow, which results in less flow acceleration up the stoss slope and, in turn, reduced

349   sand transport potential up the stoss slope. Second, incident flow angle determines the effective

350   fetch for sand transport development (see discussion in Walker et al., 2006). In coastal settings,

351   offshore to oblique onshore winds can be steered alongshore on the beach and even deflected

352   back toward the foredune, resulting in sand being cycled along the beach and back to the dune,

353   thus promoting dune maintenance (Walker et al., 2006).

354   This study shows that the degree of flow deflection is a function of the incident wind angle

355   and dune form, which corresponds with observations by Sweet and Kocurek (1990) and Lancaster

356   (1995). More transverse incident winds appear to be deflected more than airflow aligned oblique or

357   parallel to the crest. This results from steeper pressure gradients over the dune under more

358   transverse flow conditions. In other words, the apparent 'steepness' (or aspect ratio) of the dune as

359   experienced by incoming airflow varies significantly depending on the incidence angle and dune

360   height; airflow perpendicular to the crest will encounter a much steeper dune and will generate a

361   larger separation cell than will airflow that approaches at more oblique incident angles (Baddock et

362   al., 2011; Walker and Hesp, In press). This can result in less flow deceleration in the lower stoss

363   and reduced transport potential up the stoss slope (see discussion in Walker et al., 2006). In

364   this study, lee-side flows were fastest when incident flow over the crest was crest-parallel,

365   reflecting a lower aspect ratio and reduced, or non-existent separation (and recirculation) cell.

366   Over transverse dunes, Sweet and Kocurek (1990) documented that lee slope windspeeds

367   approached zero as incident angle became more transverse (i.e., as i approaches 90°) due to

368   flow separation. Lee slope speeds increased rapidly between i = 70 to 90°. Sweet and Kocurek

369   (1990) concluded that dune shape was an important control on lee flow response such that dunes

370   with low aspect ratios and/or oblique incident winds favoured attached and relatively high lee-side

371   surface windspeeds while dunes with high aspect ratios and/or transverse incident flows

372   demonstrated lower speeds (e.g. Best and Kostaschuk, 2002). In terms of sediment transport,

Comment [IW15]: I find this a bit weak for a couple reasons. First, morphodynamic implications (i.e., how the process [flow] pattern relates to form response via transport and deposition patterns) are not fully expanded/explained. Second, the fetch effect from coastal is not fully applicable here as it imposes supply limiting conditions (i.e., water line or increased moisture content limits sand supply to otherwise competent winds) that do not always exist in desert settings. See what you can do to boost this. On the first point, sort of… for the same incident wind speed, more oblique flow will experience less flow acceleration and may result in lower sand transport toward the crest… however, and relating to the second point, there is a longer fetch development distance under oblique conditions which could result in increased supply IFF the interdune is not bare (i.e., hardpan or water table controlled).

Comment [IW16]: Seems vague to me and I might prefer the previous iteration where we expand a bit on what this function looks like… is it inverse? For example… elaborate.

Comment [IW17]: I think Parsons et al. 2004 also explored this.

13

373   Sweet and Kocurek (1990) observed that deflected lee flow speeds were 60-80% of crest speeds

374   and were associated with along-slope sediment transport. Transverse flows favoured sediment

375   avalanching and fallout

376   Near-surface flow patterns for a full range of events spanning transverse to highly oblique

377   incident wind conditions documented in this study show that lee-side flow deflection often aligned

378   sub-parallel to the crest. At three sites in the Netherlands, Arens et al. (1995) found similar

379   deflection to crest-parallel in the lee of coastal foredunes during offshore winds, but towards crest-

380   normal during onshore winds. Over a 12-m high, steep foredune in Prince Edward Island, Canada,

381   Walker et al. (2009) observed significant onshore steering of near-surface flow towards crest-

382   normal. In an earlier study on a nearby 9-m high foredune, Walker et al. (2006) observed

383   offshore to oblique onshore winds being steered alongshore on the beach and even deflected

384   back toward the foredune, resulting in sand being cycled along the beach and back to the dune,

385   thus promoting dune maintenance. A series of studies at Magilligan Strand, Northern Ireland,

386   have shown that lee-side flow response is also governed by variations in morphology as well as

387   incident flow angle (Lynch et al., 2008; 2010; Jackson et al., 2011), where attached and

388   deflected lee-side flow is thought to arise when the abrupt break in slope required for separation

389   is absent. Lynch et al. (2010) observed varying flow response over dunes of different heights

390   and shapes. A tall (11.4-m) sharp-crested foredune produced flow separation and a recirculation

391   cell. A smaller (6.6-m tall), rounded foredune exhibited attached lee-side flow that was deflected

392   towards crest-parallel, while flow over a lower (4.6-m tall), incipient foredune exhibited no flow

393   deflection in the lee. In an earlier study, Lynch et al. (2008) demonstrated that offshore winds

394   that result in flow reversal do not significantly contribute to sand drift potential. Instead, it was

395   winds deflected alongshore that were associated with the most saltation activity. They conclude

396   therefore, that these deflected flows should be considered a key variable when linking micro-

397   and meso-scale sediment transport studies.

Comment [IW18]: These are the refs I was referring to cite earlier, as you see fit.

Comment [IW19]: This is pretty good. Thanks for working it in. Just watch, though, someone will criticize us for incorporating the coastal lit as these dunes have veg (additional roughness) and are typically more steep than any desert dunes (which results in steeper pressure gradients). Perhaps a sentence or 2 to highlight the differences at the end would be a good idea, thereby stressing the point that more work on deflection and morphology need be done in desert settings, perhaps?

14

398   In this study, a twofold increase in the amount of lee-side flow deflection for obliquity angles

399   in the range of 20 to 40° was observed (Figure 8). Others have found that the magnitude of

400   deflected flow on the lee slope is a cosine function of the angle of incidence and crest speed

401   (Tsoar, 1983; Tsoar et al., 1985; Sweet and Kocurek, 1990; Lancaster, 1995). A wind tunnel study

402   by Tsoar *et al.* (1985) explored the influence of 3 incident flow angles (15°, 25°, and 35° relative to

403   the crest) on lee-side flow separation and deflection over linear dunes. They found that lee-side

404   flow deflects from the incident direction toward that aligned with the crest and that sediment

405   transport patterns follow this deflection pattern. Earlier field research by Tsoar (1983) showed that

406   the rate of sand transport increased for more oblique angles when i < 40° and that deposition on

407   the lee flank of a longitudinal (seif) dune occurred as incident flow angles became more transverse.

408   Over transverse dunes, Sweet and Kocurek (1990) documented that lee slope windspeeds

409   approached zero as incident angle became more transverse due to flow separation. Lee slope

410   speeds increased rapidly as i approached 70° and Sweet and Kocurek (1990) concluded that dune

411   shape was an important control on lee flow response such that dunes with low aspect ratios and/or

412   oblique incident winds favoured attached and relatively high lee-side surface windspeeds, while

413   dunes with high aspect ratios and/or transverse incident flows demonstrated lower speeds. These

414   observations are similar to those made in fluvial environments (e.g. Best and Kostaschuk, 2002;

415   Kostaschuk et al., 2009), where flow over low angle dunes tends to remain attached and flow

416   reversal is relatively rare. Compiling data from several rivers, Kostaschuk (2005) concluded that

417   deposition of suspended sediment in the trough and on the dune lee side acts to reduce dune

418   height and lower the lee slope angle, thus underscoring earlier studies (e.g. Smith and McLean,

419   1977; Kostaschuk and Villard, 1996; Kostaschuk, 2000) that showed that increased suspended

420   sand transport relative to bedload, was associated with flatter dunes and lower lee slope angles. In

421   terms of aeolian sediment transport, Sweet and Kocurek (1990) observed that deflected lee flow

422   speeds were 60 to 80% of crest speeds and were associated with appreciable along-slope

Comment [IW20]: Don't think we need to ital. for the draft and some journals don't anyway.

Comment [IW21]: fix/replace: e.g., and i.e., always have commas.

Comment [IW22]: Hmm… maybe I'm missing something but not sure how this relates to aeolian where there is essentially no susp transport… revise. The analogy to aeolian dunes is best made with studies that focus on (only) bedload transport and (as reviewed in my Treatise chapter or our CFS II chapter) there are relatively few of these.

423 sediment transport, whereas, transverse flows favoured sediment avalanching and fallout

424 deposition in weak back-eddy flows.

425   In terms of three-dimensional flow behaviour, results presented here indicate that lee-side

426 flow deflection is greatest at the surface near the base of the lee slope and on the interdune

427 corridor upwind of flow re-attachment where maximum flow expansion and deceleration occur. In

428 this region, the crest-parallel component of the net flow vector has a greater effect on flow

429 deflection, thereby promoting more along-dune oriented flow within the separation cell. As surface

430 flow accelerates beyond re-attachment, vectors gradually deflect back toward bedform-normal up

431 the stoss slope of the downwind dune in response to increases in the crest-transverse component

432 of the net flow vector. This rather simple deflection mechanism explains why, in part, longitudinal

433 flows are observed in the lee (Sharp, 1966; Tsoar, 1983; Tsoar et al., 1985) and, in this case,

434 under relatively transverse incident flow conditions.

> **Comment [IW23]:** Add e.g., in front of these refs

435   The lee-side flow responses and flow visualizations described above were used to compile

436 a differential flow deflection model in the lee of transverse and relatively straight-crested dunes,

437 which is demonstrated conceptually in Figure 9. Based on several non-continuous measurements,

438 which is still common in aeolian research as continuous profiling technologies do not yet exist, this

439 model assumes a linear change in deflection and flow speed with increases in height above the

440 surface. In this conceptual model, flow deflection on the lee slope occurs toward an angle that is

441 more oblique than that of the incident wind, thereby increasing the bedform-parallel component of

442 secondary flow and, if competent, sand transport (discussed further in the following section). Flow

443 vectors and visualization observations both show that the amount of lee-side flow deflection

444 decreases with height above the surface such that flow at/above dune height is less deflected than

445 near-surface flows in response to relatively faster overshot flow above the separation cell (c.f.

446 Walker and Nickling, 2002). Hence, dune-parallel components of the local flow vectors are

447 proportionately less. The relative amount of deflection also increases with incident speed and dune

448   height due to the greater overall speed differentials (i.e., greater flow sheltering) that occur in the

449   separation region. Under transverse flow conditions, a high-speed shear zone extends further

450   leeward with increased incident speed, causing the point of maximum deflection above dune height

451   to progress downwind (see Figure 4). Thus, maximum deflection occurs closer to the dune near

452   the surface and further downwind in the upper wake region (approximately over the toe of the

453   downwind dune). This differential deflection mechanism likely contributes to the development of

454   roller and/or helical vortices in the separation region. Thus, even under relatively transverse flow

455   conditions, longitudinal components of secondary flow patterns may contribute significantly to lee-

456   side momentum transfers and must be considered for characterization and modeling of flow and

457   sediment transport continuity.

458   Results from other studies show that lee-side flow shifts from a closed-loop recycling roller

459   vortex to a longitudinal (along-dune) helix (c.f. Walker and Nickling, 2002) under slight increases in

460   flow obliquity from transverse (i.e. from i = 90 ±10° to ±20°). For instance, profiles and vectors for

461   event 4 (i = 110°, Figures 5, 7) suggest that flow is separated and has a strong deflected

462   component in the lee. However, the separation region appears to be less extensive, particularly

463   over the larger (east) dune transect. Qualitative flow streamer visualization observations under

464   similar conditions (not shown here) indicated that the helical vortex was not only less extensive, but

465   also less coherent (i.e. intermittent and poorly developed). Although a recycling helical pattern was

466   observed, it is suggested that this pattern is an intermittent transitional phase between the roller

467   vortex and the attached, deflected flow of more oblique incident conditions. This does not detract,

468   however, from the observation that both deflected along-dune and recycling upslope flow and

469   sediment transport may occur under relatively transverse incident flows (i.e. $70 \leq i \leq 110°$) (c.f.

470   Walker, 1999). It follows that, under transporting windspeeds, these patterns could contribute

471   appreciably to dune sediment dynamics, morphology, and migration.

472

Comment [D24]: Ian, did you mean Fig 4, which is now photos of the vis setup or fig 6 (old 4), which is the vectors for events 1-3?

Comment [IW25]: Not sure, but it would seem to make sense that we were talking about the profiles here… should also cite W&N 2002 flow model, specifically the figure, from that paper for reference as it was derived from the same dunes.

Comment [IW26]: Cite the specific figure from that paper that shows this conceptually

Comment [IW27]: See my earlier question on the same… I thought you fixed this for consistency? If so, it was not clear to me earlier in the text… you seem to use it to define incident angle relative to transverse i=90, whereas I think in the lit (e.g., Tsoar, sweet and kocurek, etc.) and in the prev. draft I meant some measure of obliquity FROM crest transverse… can you fix for consistency throughout??

Comment [D28]: I'm not sure I completely understand your comment, but how's this now?

17

Implications for dune migration

474   The lee-side flow patterns discussed above have important implications for sediment mass

475   transport patterns and the resulting migration of closely spaced transverse dune forms. This study

476   and concurrent research on sand transport patterns by Walker (1999) at the same site shows that

477   competent, deflected secondary interdune flow patterns can transport appreciable amounts of

478   sediment parallel to the crest along the interdune corridor, even under relatively transverse flow

479   conditions. Morphodynamically, then, these patterns may have a significant influence on the

480   direction of dune migration. For instance, along-dune oriented sediment transport and ripple

481   migration were observed during a high-speed storm event that caused migration of the dune crest

482   by approximately 1.25 m downwind (Figure 10). Direct measurements of lee-side sediment flux

483   during subsequent transporting events at the same study site (Walker, 1999) suggest a three-

484   dimensional sediment budget that, under relatively consistent conditions, would promote

485   migration in an oblique direction, rather than in a bedform-normal direction (e.g. Rubin and

486   Hunter, 1987; Rubin and Ikeda, 1990; Lancaster, 1991) (Figure 10). This study shows that in

487   addition to conventional fallout deposition and lee slope avalanching (Anderson, 1988;

488   Anderson and Walker, 2006), other longitudinally oriented transport mechanisms (e.g. along-

489   dune ripple migration, deflected interdune saltation and fallout transport) contribute to

490   transverse dune migration and morphodynamics.

491   Figure 11 is a stylized empirical model of near surface flow (solid arrows) and deflected

492   sediment transport vectors (dashed short arrows) that occur in the lee of relatively straight

493   transverse dunes. Sediment transport vectors were are interpreted and/or directly measured

494   (from ripples and/or trap measurements, see Walker, 1999) and their patterns represent where

495   sediment mass is directed during the respective driving incident flow conditions. As incident flow

496   becomes less transverse to the crest, lee-side separation cells become less extensive, and flow

497   remains attached for nearly crest-parallel incident flows (e.g. i = 140°-160°). Similarly, as incident

Comment [IW29]: At least 2 key studies by the Nickling, Lancaster and Mckenna neuman group need to be cited here… again, I think they were cited in the Anderson and walker paper or in the Treatise chapter.

Comment [IW30]: Again, check fig numbers because in the files, fig 10 shows the deflection and transport patterns (with implications we're discussing here). Fix please.

Comment [IW31]: Remove the text part, leave only Walker 1999 in brackets.

498 flow becomes less transverse, flow speeds in the lee increase due to the apparent reduction in
499 dune aspect ratio. The effectiveness or overall contribution of these mechanisms, and their
500 relation to migration rates, depends though on secondary flow magnitude, duration, and incident
501 direction and requires more extensive research. Future work should also incorporate issues of
502 dune spacing, as Baddock et al. (2007) have shown that interdune dynamics are strongly
503 influenced by interactions between reattachment and downwind dune stoss positions.

504

505 **CONCLUSIONS**

506   In order to conserve fluid momentum and sediment mass, deflected components of
507 secondary flow and interdune sand transport must be considered in approaches to model airflow
508 and sediment transport over dunes. Flow separation, reversal, and lateral deflection cause three-
509 dimensional variations that, in terms of a budget approach, represent a deficit of fluid mass and
510 transported sediment from simple two-dimensional models. Even under relatively transverse flow
511 conditions, where lee-side flow above the separation cell and downstream of re-attachment may
512 travel in an essentially streamwise direction, lateral deflection occurs in near-surface surface flow
513 and resulting sediment transport. Thus, budget approaches to conceptualizing flow and net
514 sediment transport over dunes should not be viewed simply as a two-dimensional system of
515 bedform-normal components. This study has demonstrated that flow over transverse dunes is
516 deflected in the lee to a degree that increases as incident flow becomes less transverse. As flow
517 becomes increasingly oblique to the crest, the effective aspect ratio (and, hence, form roughness)
518 encountered by the wind decreases and patterns of flow acceleration, separation, and potential
519 recirculation on sediment transport are diminished. Further, oblique incident conditions offer a
520 greater fetch. The implications for sediment transport and dune migration are that transport
521 potential increases with increasing flow obliquity (towards crest-parallel) compared with transverse
522 flows, and that transverse dunes can migrate sideways.

19

Comment [IW32]: Could make some brief linkage here to Baddock's work and his summary model on interdune regions?

Comment [D33]: You've tried to get me to include discussion of Baddock's stuff a few times now, to the point that I think I'm missing something in his papers! As far as I could remember, he never discusses deflection and his interdune model (2007 paper) is all about dune spacing, which we don't delve into here at all. Am I missing something? Or maybe you get a kickback if you cite him ;)

Comment [IW34]: Also, supply as they had hard interdune surfaces… some review/mention of this in the treatise chapter.

Comment [IW35]: Should elaborate and clarify a bit more with direct reference and explanation of patterns a-d in the figure.

Comment [IW36]: Can't put my finger on it, but I don't like how this ends. The last sentence is off. See earlier wording re: sediment mass transfers, etc. Generaly, see what you can do to beef it up, give it some pizaaz, up the octane, whatever. Also, generally, we should pepper the conclusion with some facts or bullet points to be more concise (for those lazy readers who will only skim the abstract and conclusions).

FIGURE CAPTIONS

Figure 1: Map of study area showing location of the sampling array within transverse ridges on the northern end of the Silver Peak dunefield in western Nevada, USA.

Figure 2: Instrument deployment over west and east sampling transects including location of the flow visualization tower array. Instrument profiles characterize flow within discrete flow regions shown in the upper figure. Vertical axis indicates height of instruments above the lowest elevation in the interdune.

Figure 3: Study site setup. Unwind view (a) of instrument arrays (E=east, W=west), observation tower (O), flow streamer towers (F); b) dense spacing of vanes and anemometers in the lee on the east transect; c) view of transverse ridges looking NE into the study area (from Walker and Nickling, 2002)

Figure 4: Flow visualization methods. a) 12-m observation tower with perch for aerial viewing of streamer response; b) smoke tracer visualization of lee-side flow patterns and extent of separation cell; c) flow streamer towers extending 9 m leeward from the crest. Five heights relative to the dune are identified by different symbols. Observation of streamer deflection and smoke patterns were used to complement limited wind vane data in the lee.

Figure 5: Time-averaged wind speed (u/u_{10h}) profiles for a series of events (2, 4, 7) spanning transverse to crest-parallel flow conditions. Note that vertical axis shows sampling heights relative to underlying surface not the interdune datum.

Figure 6: Time-averaged flow vectors for events 1 through 3. Upper values indicate direction (SD) and lower italicised values are speed and [coefficient of variation]. Vectors show directions at 3 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line shows lee slope base and interdune

Figure 7: Time-averaged flow vectors for events 4 and 5. Upper values indicate direction (SD) and lower italicised values are speed and [coefficient of variation]. Vectors show directions at 3 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line shows lee slope base and interdune.

Figure 8: Time-averaged flow vectors for events 6 and 7. Upper values indicate direction (SD) and lower italicised values are speed and [coefficient of variation]. Vectors show directions at 3 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line shows lee slope base and interdune.

Figure 9: Differential deflection of lee-side flow over closely spaced dunes for various incident angles. Vectors are proportionally sized to normalized windspeed and show directional variation from the surface (black) to above dune height (grey). Intermittent (white) and transitional (lines) vectors are also shown.

Figure 10: Evidence for lee-side sediment transport processes over a transverse dune in the Silver Peak dunefield, Nevada. A) active flow separation, suspended fallout, and deflected ripples formed under approximately crest-transverse flow (i ≈ 90°); b) along-dune oriented ripples on the lee slope looking east; c) small, bifurcated ripples on the upper lee slope and larger, coarse granule ripples on the base (5 cm lens cap for scale). All photos taken in May 1997. Photos b and c were taken after the transporting event shown in a.

20

567   Figure 11: Lateral diversion of secondary lee-side flows and surface winds in response to various
568   incidence angles over closely spaced dunes. Short arrows indicate sediment transport
569   direction and dashed arrows indicate intermittent transport.
570

571 **REFERENCES**

572 Anderson JL, Walker IJ. 2006. Airflow and sand transport variations within a backshore–parabolic
573 dune plain complex: NE Graham Island, British Columbia, Canada. *Geomorphology* **77**: 17-34.
574 DOI: 10.1016/j.geomorph.2005.12.008

575 Anderson RS. 1988. The pattern of grainfall deposition in the lee of aeolian dunes. *Sedimentology*
576 **35**: 175-188. DOI: 10.1111/j.1365-3091.1988.tb00943.x

577 Arens SM, Van Kaam-Peters HME, Van Boxel JH. 1995. Air flow over foredunes and implications
578 for sand transport. *Earth Surface Processes and Landforms* **20**: 315-332. DOI:
579 10.1002/esp.3290200403

580 Baddock M, Livingstone I, Wiggs G. 2007. The geomorphological significance of airflow patterns in
581 transverse dune interdunes. *Geomorphology* **87**: 322-336. DOI: 10.1016/j.geomorph.2006.10.006

582 Baddock MC, Wiggs GFS, Livingstone I. 2011. A field study of mean and turbulent flow
583 characteristics upwind, over and downwind of barchan dunes. *Earth Surface Processes and*
584 *Landforms* **36**: 1435-1448. DOI: 10.1002/esp.2161

585 Bagnold RA. 1941 The Physics of Blown Sand and Desert Dunes. Muthuen: London

586 Best J, Kostaschuk R. 2002. An experimental study of turbulent flow over a low-angle dune.
587 *Journal of Geophysical Research* **107**: 3135. DOI: 10.1029/2000jc000294

588 Bullard JE, Thomas DSG, Livingstone I, Wiggs GFS. 1996. Wind energy variations in the
589 southwestern Kalahari Desert and implications for linear dunefield activity. *Earth Surface*
590 *Processes and Landforms* **21**: 263-278. DOI: 10.1002/(sici)1096-9837(199603)21:3<263::aid-
591 esp627>3.0.co;2-i

592 Carson MA, MacLean PA. 1985. Storm-controlled oblique dunes of the Oregon coast: Discussion
593 and reply. *Geological Society of America Bulletin* **96**: 409-410. DOI: 10.1130/0016-
594 7606(1985)96<409:sodoto>2.0.co;2

595 Carson MA, MacLean PA. 1986. Development of hybrid aeolian dunes: The William River dune
596 field, Northwest Saskatchewan, Canada. *Canadian Journal of Earth Sciences* **23**: 1974-1990. DOI:
597 10.1139/e86-183

598 Cooke RU, Goudie AS, Warren A. 1993 Desert Geomorphology. UCL Press: London

599 Frank A, Kocurek G. 1996. Toward a model for airflow on the lee side of aeolian dunes.
600 *Sedimentology* **43**: 451-458. DOI: 10.1046/j.1365-3091.1996.d01-20.x

601 Fryberger SG, Dean G. 1979. Dune forms and wind regimes. In *A Study of Global Sand Seas,*
602 McKee E (eds), pp. 137-169. U.S. Geological Survey Professional Paper 1052.

603 Gaylord DR, Stetler LD. 1994. Aeolian-climatic thresholds and sand dunes at the Hanford site,
604 south-central Washington, U.S.A. *Journal of Arid Environments* **28**: 95-116. DOI: 10.1016/s0140-
605 1963(05)80041-2

606 Glennie KW. 1970 Desert Sedimentary Environments. Elsevier: Amsterdam

607 Hanna SR. 1969. The formation of longitudinal sand dunes by large helical eddies in the
608 atmosphere. *Journal of Applied Meteorology* **8**: 874-883. DOI: 10.1175/1520-
609 0450(1969)008<0874:tfolsd>2.0.co;2

610 Hesp P, Hyde R, Hesp V, Zhengyu Q. 1989. Longitudinal dunes can move sideways. *Earth*
611 *Surface Processes and Landforms* **14**: 447-451. DOI: 10.1002/esp.3290140510

612 Hesp P, Walker IJ. In press. Fundamentals of Aeolian Sediment Transport: Coastal dunes. In
613 *Aeolian Geomorphology, Treatise on Geomorphology,*(eds), 11. Elsevier, Oxford.

614 Hesp PA. 1981. The formation of shadow dunes. *Journal of Sedimentary Research* **51**: 101-112.
615 DOI: 10.1306/212f7c1b-2b24-11d7-8648000102c1865d

616 Hesp PA. 1983. Morphodynamics of incipient foredunes in New South Wales, Australia. In *Eolian
617 Sediments and Processes,* Brookfield ME, Ahlbrandt TS (eds), pp. 325-342. Elsevier, Amsterdam.

618 Hesp PA, Hyde R. 1996. Flow dynamics and geomorphology of a trough blowout. *Sedimentology*
619 **43**: 505-525. DOI: 10.1046/j.1365-3091.1996.d01-22.x

620 Howard AD. 1985. Interaction of sand transport with topography and local winds in the northern
621 Peruvian coastal desert. In *Proceedings of International Workshop on the Physics of Blown Sand,*
622 Barndorff-Nielsen OE, Møller JT, Rasmussen KR, Willetts BB (eds). Aarhus, Denmark, 511-544.

623 Hunter RE, Richmond BM, Alpha TR. 1983. Storm-controlled oblique dunes of the Oregon coast.
624 *Geological Society of America Bulletin* **94**: 1450-1465. DOI: 10.1130/0016-
625 7606(1983)94<1450:sodoto>2.0.co;2

626 Hunter RE, Richmond BM, Alpha TR. 1985. Storm-controlled oblique dunes of the Oregon coast:
627 Discussion and reply. *Geological Society of America Bulletin* **96**: 410. DOI: 10.1130/0016-
628 7606(1985)96<410:sodoto>2.0.co;2

629 Jackson DWT, Beyers JHM, Lynch K, Cooper JAG, Baas ACW, Delgado-Fernandez I. 2011.
630 Investigation of three-dimensional wind flow behaviour over coastal dune morphology under
631 offshore winds using computational fluid dynamics (CFD) and ultrasonic anemometry. *Earth
632 Surface Processes and Landforms* **36**: 1113-1124. DOI: 10.1002/esp.2139

633 Jackson PS. 1977. Aspects of surface wind behaviour. *Wind Engineering* **1**: 1-14.

634 Kocurek G, Lancaster N. 1999. Aeolian system sediment state: theory and Mojave Desert Kelso
635 dune field example. *Sedimentology* **46**: 505-515. DOI: 10.1046/j.1365-3091.1999.00227.x

636 Kocurek G, Townsley M, Yeh E, Havholm K, Sweet ML. 1992. Dune and dune-field development
637 on Padre Island, Texas, with implications for interdune deposition and water-table-controlled
638 accumulation. *Journal of Sedimentary Petrology* **62**: 622-635. DOI: 10.1306/D4267974-2B26-
639 11D7-8648000102C1865D

640 Kostaschuk R (2005) Sediment transport mechanics and dune morphology. In: *River, Coastal and
641 Estuarine Morphodynamics: RCEM 2005* (Eds Parker G, Garcia M), pp. 795-803. Taylor & Francis,
642 London, Urbana, Illinois.

643 Kostaschuk R, Shugar D, Best J, Parsons D, Lane S, Hardy R, Orfeo O. 2009. Suspended
644 sediment transport and deposition over a dune: Rio Parana, Argentina. *Earth Surface Processes
645 and Landforms* **34**: 1605-1611.

646 Kostaschuk RA. 2000. A field study of turbulence and sediment dynamics over subaqueous dunes
647 with flow separation. *Sedimentology* **47**: 519-531. DOI: 10.1046/j.1365-3091.2000.00303.x

648 Kostaschuk RA, Villard P. 1996. Flow and sediment transport over large subaqueous dunes:
649 Fraser River, Canada. *Sedimentology* **43**: 849-863. DOI: 10.1111/j.1365-3091.1996.tb01506.x

650 Lancaster N. 1982. Linear dunes. *Progress in Physical Geography* **6**: 476-504. DOI:
651 10.1177/030913338200600401

652 Lancaster N. 1983. Controls of dune morphology in the Namib sand sea. In *Developments in
653 Sedimentology, 38,* Ahlbrandt TS, Brookfield ME (eds), 38, pp. 261-289. Elsevier, Amsterdam.

23

Lancaster N. 1991. The orientation of dunes with respect to sand-transporting winds: a test of Rubin and Hunter's gross bedform-normal rule. *Acta Mechanica Supplementum* **2**: 89-102.

Lancaster N. 1995 The Geomorphology of Desert Dunes. Routledge: London

Lancaster N, Helm P. 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. *Earth Surface Processes and Landforms* **25**: 197-207. DOI: 10.1002/(sici)1096-9837(200002)25:2<197::aid-esp82>3.0.co;2-h

Livingstone I, Wiggs GFS, Weaver CM. 2007. Geomorphology of desert sand dunes: A review of recent progress. *Earth-Science Reviews* **80**: 239-257.

Lynch K, Jackson DWT, Cooper JAG. 2008. Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development. *Earth Surface Processes and Landforms* **33**: 991-1005. DOI: 10.1002/esp.1582

Lynch K, Jackson DWT, Cooper JAG. 2009. Foredune accretion under offshore winds. *Geomorphology* **105**: 139-146. DOI: 10.1016/j.geomorph.2007.12.011

Lynch K, Jackson DWT, Cooper JAG. 2010. Coastal foredune topography as a control on secondary airflow regimes under offshore winds. *Earth Surface Processes and Landforms* **35**: 344-353. DOI: 10.1002/esp.1925

Mabbut JA, Jennings JN, Wooding RA. 1969. The asymmetry of Australian desert sand ridges. *Australian Journal of Science* **32**: 159-160.

McCauley CK, Breed WJ. 1980. Topographically controlled dune systems on Earth and Mars. In *Aeolian Processes and Landforms: Reports of Planetary Geology Program,* Wirth P, Greeley R, D'Alli RE (eds), TM-81776, pp. 255-56. National Aeronautics and Space Administration.

Mikkelsen HE. 1989 Wind flow and sediment transport over a low coastal dune. GeoSkrifter 32, Geologisk Institut, University of Aarhus: Aarhus

Muhs DR, Holliday VT. 1995. Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers. *Quaternary Research* **43**: 198-208.

Muhs DR, Maat PB. 1993. The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A. *Journal of Arid Environments* **25**: 351-361. DOI: 10.1006/jare.1993.1068

Muhs DR, Wolfe SA. 1999. Sand dunes of the northern Great Plains of Canada and the United States. In *Holocene climate and environmental change in the Palliser Triangle: a geoscientific context for evaluation the impacts of climate change on the southern Canadian prairies,* Lemmen DS, Vance RE (eds), pp. 183-197. Geological Survey of Canada, Bulletin 534.

Ould Ahmedou D, Ould Mahfoudh A, Dupont P, Ould El Moctar A, Valance A, Rasmussen KR. 2007. Barchan dune mobility in Mauritania related to dune and interdune sand fluxes. *Journal of Geophysical Research* **112**. DOI: 10.1029/2006jf000500

Pearce KI, Walker IJ. 2005. Frequency and magnitude biases in the 'Fryberger' model, with implications for characterizing geomorphically effective winds. *Geomorphology* **68**: 39-55. DOI: 10.1016/j.geomorph.2004.09.030

Rasmussen KR. 1989. Some aspects of flow over coastal dunes. *Proceedings of the Royal Society of Edinburgh Section B: Biology* **96**: 129-147. DOI: doi:10.1017/S0269727000010897

Rubin CM, Ikeda H. 1990. Flume experiments on the alignment of transverse, oblique and longitudinal dunes in directionally varying flows. *Sedimentology* **37**: 673-684. DOI: 10.1111/j.1365-3091.1990.tb00628.x

697 Rubin DM. 1990. Lateral migration of linear dunes in the Strzelecki Desert, Australia. *Earth Surface*
698 *Processes and Landforms* **15**: 1-4. DOI: 10.1002/esp.3290150102

699 Rubin DM, Hunter RE. 1985. Why deposits of longitudinal dunes are rarely recognized in the
700 geologic record. *Sedimentology* **32**: 147-157. DOI: 10.1111/j.1365-3091.1985.tb00498.x

701 Rubin DM, Hunter RE. 1987. Bedform alignment in directionally varying flows. *Science* **237**: 276-
702 278. DOI: 10.1126/science.237.4812.276

703 Sharp RP. 1966. Kelso dunes, Mojave Desert, California. *Geological Society of America Bulletin*
704 **77**: 1045-1073. DOI: 10.1130/0016-7606(1966)77[1045:KDMDC]2.0.CO;2

705 Smith JD, McLean SR. 1977. Spatially Averaged Flow Over a Wavy Surface. *Journal of*
706 *Geophysical Research* **82**: 1735-1746. DOI: 10.1029/JC082i012p01735

707 Svasek JN, Terwindt JHJ. 1974. Measurements of sand transport by wind on a natural beach.
708 *Sedimentology* **21**.

709 Sweet ML, Kocurek G. 1990. An empirical model of aeolian dune lee-face airflow. *Sedimentology*
710 **37**: 1023-1038. DOI: 10.1111/j.1365-3091.1990.tb01843.x

711 Tsoar H. 1983. Dynamic processes acting on a longitudinal (seif) sand dune. *Sedimentology* **30**:
712 567-578. DOI: 10.1111/j.1365-3091.1983.tb00694.x

713 Tsoar H. 2002. Climatic factors affecting mobility and stability of sand dunes. In *Proceedings of*
714 *ICAR5/GCTE-SEN Joint Conference,* Lee JA, Zobeck TM (eds).Center for Arid and Semiarid
715 Lands Studies: Texas Tech University, Lubbock, 423.

716 Tsoar H, Illenberger W. 1998. Re evaluation of sand dunes' mobility indices. *Journal of Arid Lands*
717 *Studies* **7S**: 265-268.

718 Tsoar H, Rasmussen KR, Sorensen M, Willetts BB. 1985. Laboratory studies of flow over dunes. In
719 *Proceedings of International Workshop on the Physics of Blown Sand,* Barndorff-Nielsen OE,
720 Møller JT, Rasmussen KR, Willetts BB (eds). Aarhus, Denmark, 271-300.

721 Walker IJ. 1999. Secondary airflow and sediment transport in the lee of a reversing dune. *Earth*
722 *Surface Processes and Landforms* **24**: 437-448. DOI: 10.1002/(sici)1096-
723 9837(199905)24:5<437::aid-esp999>3.0.co;2-z

724 Walker IJ. 2000. *Secondary airflow and sediment transport in the lee of transverse dunes*,
725 University of Guelph, Guelph, 256 pp.

726 Walker IJ, Hesp P. In press. Fundamentals of Aeolian Sediment Transport: Airflow over dunes. In
727 *Aeolian Geomorphology, Treatise on Geomorphology,*(eds), 11. Elsevier, Oxford.

728 Walker IJ, Hesp PA, Davidson-Arnott RGD, Bauer BO, Namikas SL, Ollerhead J. 2009.
729 Responses of three-dimensional flow to variations in the angle of incident wind and profile form of
730 dunes: Greenwich Dunes, Prince Edward Island, Canada. *Geomorphology* **105**: 127-138. DOI:
731 10.1016/j.geomorph.2007.12.019

732 Walker IJ, Hesp PA, Davidson-Arnott RGD, Ollerhead J. 2006. Topographic steering of alongshore
733 airflow over a vegetated foredune: Greenwich Dunes, Prince Edward Island, Canada. *Journal of*
734 *Coastal Research* **22**: 1278-1291. DOI: 10.2112/06a-0010.1

735 Walker IJ, Nickling WG. 2002. Dynamics of secondary airflow and sediment transport over and in
736 the lee of transverse dunes. *Progress in Physical Geography* **26**: 47-75. DOI:
737 10.1191/0309133302pp325ra

738 Warren A. 1976. Dune trend and the Ekman spiral. *Nature* **259**: 653-654. DOI: 10.1038/259653a0

25

739   Wasson RJ, Hyde R. 1983. Factors determining desert dune type. *Nature* **304**: 337-339. DOI:
740   10.1038/304337a0

741   Weaver CM, Wiggs GFS. 2011. Field measurements of mean and turbulent airflow over a barchan
742   sand dune. *Geomorphology* **128**: 32-41.

743   Wiggs GFS. 2001. Desert dune processes and dynamics. *Progress in Physical Geography* **25**: 53-
744   79. DOI: 10.1177/030913330102500103

745   Wiggs GFS, Livingstone I, Thomas DSG, Bullard JE. 1996. Airflow and roughness characteristics
746   over partially vegetated linear dunes in the southwest Kalahari Desert. *Earth Surface Processes*
747   *and Landforms* **21**: 19-34. DOI: 10.1002/(sici)1096-9837(199601)21:1<19::aid-esp508>3.0.co;2-p

748   Wiggs GFS, Thomas DSG, Bullard JE, Livingstone I. 1995. Dune mobility and vegetation cover in
749   the Southwest Kalahari desert. *Earth Surface Processes and Landforms* **20**: 515-529. DOI:
750   10.1002/esp.3290200604

751   Wilson IG. 1972. Aeolian bedforms - their development and origins. *Sedimentology* **19**: 173-210.
752   DOI: 10.1111/j.1365-3091.1972.tb00020.x

753   Wolfe SA. 1997. Impact of increased aridity on sand dune activity in the Canadian Prairies. *Journal*
754   *of Arid Environments* **36**: 421-432. DOI: 10.1006/jare.1996.0236

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758 Table 1: Summary of wind events recorded on east (E) and west (W) sampling transects ordered
759   from relatively transverse conditions to crest-parallel flow. Note that flow from the west is 0°,
760   east is 180°. Data are based on 1 minute averages sampled at 1 Hz (e.g. $u_{5.2h}$ = incident
761   speed at 3.8 m above east dune crest, SD = standard deviation, CV = coefficient of
762   variation = $SD_{u5.2h}$ /$u_{5.2h}$,). All events were recorded on the same day (1997 JD 155).

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Event	Time [duration]	Direction (°)	SD (°)	Incident speed ($u_{5.2h}$, m s^{-1}) [average]	CV (u_i)	crest speed $u_{0.3}/u_{12}$	lee-side speeds $u_{0.3}/u_{12}$
1E	19:18 - 19:35	91	4.9	3.8 – 5.5 [4.59]	0.10	0.82	0.41 – 0.59
1W	[0:19]	89	5.8	4.2 – 5.6 [4.84]	0.09	0.90	0.47 – 0.73
2E	19:43 – 20:01	89	3.5	5.4 – 7.7 [6.54]	0.10	0.79	0.30 – 0.52
2W	[0:20]	88	2.6	5.6 – 8.0 [6.91]	0.10	0.87	0.37 – 0.53
3E	21:03 - 21:23	89	5.5	7.6 – 10.0 [8.83]	0.09	0.73	0.27 – 0.51
3W	[0:21]	89	5.6	8.2 – 10.5 [9.17]	0.07	0.80	0.35 – 0.50
4E	3:10 - 3:33	111	3.6	3.9 – 5.6 [6.27]	0.09	0.79	0.44 – 0.61
4W	[0:24]	110	3.5	5.5 – 7.3 [6.52]	0.08	0.88	0.54 – 0.81
5E	4:51 - 5:11	131	3.9	4.7 – 6.7 [5.74]	0.11	0.70	0.52 – 0.78
5W	[0:21]	130	3.9	4.9 –7.1 [5.98]	0.09	0.77	0.53 – 0.79
6E	2:34 - 2:52	146	5.3	5.4 – 7.6 [6.52]	0.10	0.69	0.59 – 0.80
6W	[0:19]	146	5.3	5.1 – 7.3 [6.32]	0.10	0.73	0.61 – 0.84
7E	1:29 - 1:35	3	2.6	4.5 – 5.5 [4.96]	0.08	0.60	0.63 – 0.67
7W	[0:07]	2	3.6	3.9 – 5.1 [4.47]	0.10	0.58	0.59 – 0.75

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