

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

3

4

5

6

7

8

9

10

11

12

13 **Ian J. Walker***

14 Department of Geography

15 University of Victoria

16 P.O. Box 3050, Station CSC

17 Victoria, British Columbia

18 Canada V8W3P5

19 Tel: (250) 721-7347 Fax: (250) 721-6216

20 ijwalker@uvic.ca

21

22 **Dan H. Shugar**

23 Department of Geography

24 University of Victoria

25 P.O. Box 3050, Station CSC

26 Victoria, British Columbia

27 Canada V8W3P5

28 Tel: (250) 472-5930 Fax: (250) 721-6216

29 dshugar@uvic.ca

30

31

32 *corresponding author

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.

48
49 **KEYWORDS:** dunes, airflow, deflection, lee-side, interdune, dune migration

50 INTRODUCTION

51 The relations between the near-surface airflow field (i.e., height < 10 m), particularly
52 complex secondary lee-side flows, and sediment transport over dunes remain an elusive challenge
53 for modeling dune morphodynamics and migration (Walker and Nickling, 2002; Baddock et al.,
54 2007; Livingstone et al., 2007). It is known that dune form, alignment, and spacing are controlled by
55 the magnitude, frequency, and directionality of transporting surface wind (e.g. Bagnold, 1941;
56 Fryberger and Dean, 1979; Lancaster, 1983; Bullard et al., 1996; Ould Ahmedou et al., 2007) as
57 well as sediment characteristics (size and sorting) (Wilson, 1972) and availability (Wasson and
58 Hyde, 1983), moisture effects (Kocurek et al., 1992), topographic barriers (McCauley and Breed,
59 1980), and the presence of vegetation (Hesp, 1981; 1983; Wiggs et al., 1996). Other studies have
60 linked dune alignment to coherent atmospheric circulation patterns such as Ekman spirals (Hanna,
61 1969; Mabbut et al., 1969; Warren, 1976) and to the strongest transporting winds in the regime
62 (Glennie, 1970). Ultimately, however, dune alignment and migration is the net result of complex,
63 three dimensional sand transport patterns driven by all competent surface winds – including
64 secondary lee-side flows (Sweet and Kocurek, 1990; Frank and Kocurek, 1996; Walker and
65 Nickling, 2002; Baddock et al., 2007; Livingstone et al., 2007; Baddock et al., 2011; Weaver and
66 Wiggs, 2011). Nearly 30 years ago, Rubin and Hunter (1985), and later Hesp et al. (1989) and
67 Rubin (1990), observed that longitudinal dunes can migrate laterally, contrary to the prevailing
68 thought that such dunes advance downwind, or else extend at the terminal end (e.g. Bagnold,
69 1941; Tsoar, 1983). To date, however, there is limited research that links deflected airflow and
70 sediment flux in the lee of transverse dunes to their morphodynamics and migration (Walker, 1999;
71 Walker and Nickling, 2002; Baddock et al., 2007).

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

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 $>90^\circ$ 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

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;

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 ($i = 90^\circ$) might be
168 deflected 10° ($d = 100^\circ$) in the lee.

169

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 ($h = 1.2$

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 ($D = 150 \mu\text{m}$) and oriented transverse (75°
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 10 h) 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 $U_{5.2h}$ and $U_{4.6h}$

Comment [IW5]: OK... now, do we refer to these 5.2 and 4.6 h measurements or is everything always normalized by $u_{outer}/10h$? For e.g., I think the vectors are normalized by their respective crest outer measurements, not $10h$., whereas 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 $\approx 90^\circ$) to crest-parallel ($i \approx 180^\circ$) 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, $i \approx 90^\circ$) and slightly oblique (event 4, $i \approx 110^\circ$) 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, $i \approx 180^\circ$), 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

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 | 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

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 $\pm 2^\circ$ 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.

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

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 $\sim 20^\circ$ from transverse over the crest of the east dune transect ($i = 111^\circ$), the flow
301 was deflected $\sim 25^\circ$ ($d = 135^\circ$), while for event 5, with an angle of $\sim 40^\circ$ from transverse over the
302 crest ($i = 131^\circ$), the flow was deflected 40° ($d = 171^\circ$). Overall directional variability for both events
303 is very low ($SD^\circ < 11^\circ$) compared to the transverse condition ($SD^\circ ??$). 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 ($i \approx 145^\circ$) and 7 ($i \approx 0^\circ$) 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° , $d = 177^\circ$) but was deflected negligibly over the shorter (west) dune ($i = 146^\circ$, $d = 147^\circ$).
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 ($i = 2^\circ$ – 3°). All lee-side locations recorded faster flow than

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 repetitious? 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 ($i = 3^\circ$, $d = 346^\circ$). 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

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.

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?

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 $i < 40^\circ$ 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 overshoot 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 $i = 90 \pm 10^\circ$ to $\pm 20^\circ$). For instance, profiles and vectors for
461 event 4 ($i = 110^\circ$, 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. $70 \leq i \leq 110^\circ$) (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?

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. $i = 140^\circ$ - 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.

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. Generally, see what you can do to beef it up, give it some pizaaaz, 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).

523 **FIGURE CAPTIONS**

Comment [IW37]: Update as needed.

- 524 Figure 1: Map of study area showing location of the sampling array within transverse ridges on the
525 northern end of the Silver Peak dunefield in western Nevada, USA.
- 526 Figure 2: Instrument deployment over west and east sampling transects including location of the
527 flow visualization tower array. Instrument profiles characterize flow within discrete flow
528 regions shown in the upper figure. Vertical axis indicates height of instruments above the
529 lowest elevation in the interdune.
- 530 Figure 3: Study site setup. Unwind view (a) of instrument arrays (E=east, W=west), observation
531 tower (O), flow streamer towers (F); b) dense spacing of vanes and anemometers in the lee
532 on the east transect; c) view of transverse ridges looking NE into the study area (from
533 Walker and Nickling, 2002)
- 534 Figure 4: Flow visualization methods. a) 12-m observation tower with perch for aerial viewing of
535 streamer response; b) smoke tracer visualization of lee-side flow patterns and extent of
536 separation cell; c) flow streamer towers extending 9 m leeward from the crest. Five heights
537 relative to the dune are identified by different symbols. Observation of streamer deflection
538 and smoke patterns were used to complement limited wind vane data in the lee.
- 539 Figure 5: Time-averaged wind speed (u/u_{10h}) profiles for a series of events (2, 4, 7) spanning
540 transverse to crest-parallel flow conditions. Note that vertical axis shows sampling heights
541 relative to underlying surface not the interdune datum.
- 542 Figure 6: Time-averaged flow vectors for events 1 through 3. Upper values indicate direction (SD)
543 and lower italicised values are speed and [coefficient of variation]. Vectors show directions
544 at 3 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest
545 locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line
546 shows lee slope base and interdune
- 547 Figure 7: Time-averaged flow vectors for events 4 and 5. Upper values indicate direction (SD) and
548 lower italicised values are speed and [coefficient of variation]. Vectors show directions at 3
549 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest
550 locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line
551 shows lee slope base and interdune.
- 552 Figure 8: Time-averaged flow vectors for events 6 and 7. Upper values indicate direction (SD) and
553 lower italicised values are speed and [coefficient of variation]. Vectors show directions at 3
554 levels: surface, crest height (± 30 cm), and at half dune height. White arrows at crest
555 locations are at outer flow (5.2h on east and 4.6h on west profiles). Dashed vertical line
556 shows lee slope base and interdune.
- 557 Figure 9: Differential deflection of lee-side flow over closely spaced dunes for various incident
558 angles. Vectors are proportionally sized to normalized windspeed and show directional
559 variation from the surface (black) to above dune height (grey). Intermittent (white) and
560 transitional (lines) vectors are also shown.
- 561 Figure 10: Evidence for lee-side sediment transport processes over a transverse dune in the Silver
562 Peak dunefield, Nevada. A) active flow separation, suspended fallout, and deflected ripples
563 formed under approximately crest-transverse flow ($i \approx 90^\circ$); b) along-dune oriented ripples
564 on the lee slope looking east; c) small, bifurcated ripples on the upper lee slope and larger,
565 coarse granule ripples on the base (5 cm lens cap for scale). All photos taken in May 1997.
566 Photos b and c were taken after the transporting event shown in a.

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.

- 654 Lancaster N. 1991. The orientation of dunes with respect to sand-transporting winds: a test of
655 Rubin and Hunter's gross bedform-normal rule. *Acta Mechanica Supplementum* **2**: 89-102.
- 656 Lancaster N. 1995 *The Geomorphology of Desert Dunes*. Routledge: London
- 657 Lancaster N, Helm P. 2000. A test of a climatic index of dune mobility using measurements from
658 the southwestern United States. *Earth Surface Processes and Landforms* **25**: 197-207. DOI:
659 10.1002/(sici)1096-9837(200002)25:2<197::aid-esp82>3.0.co;2-h
- 660 Livingstone I, Wiggs GFS, Weaver CM. 2007. Geomorphology of desert sand dunes: A review of
661 recent progress. *Earth-Science Reviews* **80**: 239-257.
- 662 Lynch K, Jackson DWT, Cooper JAG. 2008. Aeolian fetch distance and secondary airflow effects:
663 the influence of micro-scale variables on meso-scale foredune development. *Earth Surface
664 Processes and Landforms* **33**: 991-1005. DOI: 10.1002/esp.1582
- 665 Lynch K, Jackson DWT, Cooper JAG. 2009. Fore-dune accretion under offshore winds.
666 *Geomorphology* **105**: 139-146. DOI: 10.1016/j.geomorph.2007.12.011
- 667 Lynch K, Jackson DWT, Cooper JAG. 2010. Coastal foredune topography as a control on
668 secondary airflow regimes under offshore winds. *Earth Surface Processes and Landforms* **35**: 344-
669 353. DOI: 10.1002/esp.1925
- 670 Mabbitt JA, Jennings JN, Wooding RA. 1969. The asymmetry of Australian desert sand ridges.
671 *Australian Journal of Science* **32**: 159-160.
- 672 McCauley CK, Breed WJ. 1980. Topographically controlled dune systems on Earth and Mars. In
673 *Aeolian Processes and Landforms: Reports of Planetary Geology Program*, Wirth P, Greeley R,
674 D'Alli RE (eds), TM-81776, pp. 255-56. National Aeronautics and Space Administration.
- 675 Mikkelsen HE. 1989 Wind flow and sediment transport over a low coastal dune. *GeoSkifter* 32,
676 Geologisk Institut, University of Aarhus: Aarhus
- 677 Muhs DR, Holliday VT. 1995. Evidence of active dune sand on the Great Plains in the 19th century
678 from accounts of early explorers. *Quaternary Research* **43**: 198-208.
- 679 Muhs DR, Maat PB. 1993. The potential response of eolian sands to greenhouse warming and
680 precipitation reduction on the Great Plains of the U.S.A. *Journal of Arid Environments* **25**: 351-361.
681 DOI: 10.1006/jare.1993.1068
- 682 Muhs DR, Wolfe SA. 1999. Sand dunes of the northern Great Plains of Canada and the United
683 States. In *Holocene climate and environmental change in the Palliser Triangle: a geoscientific
684 context for evaluation the impacts of climate change on the southern Canadian prairies*, Lemmen
685 DS, Vance RE (eds), pp. 183-197. Geological Survey of Canada, Bulletin 534.
- 686 Ould Ahmedou D, Ould Mahfoudh A, Dupont P, Ould El Moctar A, Valance A, Rasmussen KR.
687 2007. Barchan dune mobility in Mauritania related to dune and interdune sand fluxes. *Journal of
688 Geophysical Research* **112**. DOI: 10.1029/2006jf000500
- 689 Pearce KI, Walker IJ. 2005. Frequency and magnitude biases in the 'Fryberger' model, with
690 implications for characterizing geomorphically effective winds. *Geomorphology* **68**: 39-55. DOI:
691 10.1016/j.geomorph.2004.09.030
- 692 Rasmussen KR. 1989. Some aspects of flow over coastal dunes. *Proceedings of the Royal Society
693 of Edinburgh Section B: Biology* **96**: 129-147. DOI: doi:10.1017/S0269727000010897
- 694 Rubin CM, Ikeda H. 1990. Flume experiments on the alignment of transverse, oblique and
695 longitudinal dunes in directionally varying flows. *Sedimentology* **37**: 673-684. DOI: 10.1111/j.1365-
696 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

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

755

756

757

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 = $SD_{u_{5,2h}}/u_{5,2h}$). All events were recorded on the same day (1997 JD 155).

763

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

764