

1 Long Wavelength Sinuosity of Linear Dunes on Earth and Titan and the Effect of 2 Underlying Topography

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22 Key Points:

- 23 • Local variations in dune trend are identified in some linear dunefields on Earth and Titan.
- 24 • The cause is identified as underlying topographic relief resulting in down-slope
25 deflection of dunes.
- 26 • Dunefield patterning offers the potential to infer topographic relief, with implications for
27 identifying planetary lander sites.
28

29 **Abstract**

30 On both Earth and Titan, some linear dunefields are characterized by curvilinear patterning
31 atypical of the regularity and straightness of typical longitudinal dunefields. We use remotely
32 sensed imagery and an automated dune crestline detection algorithm to analyze the controls on
33 spatial patterning. Here it is shown that topography can influence the patterning, as dune
34 alignments bend to deflect downslope under the influence of gravity. The effect is pronounced in
35 a terrestrial dunefield (the Great Sandy Desert, Australia) where substantial topography
36 underlies, but absent where the dunefield is underlain by subdued relief (southwestern Kalahari).
37 This knowledge allows the inference of subtle topographic changes underlying dunefields from
38 dunefield patterning, where other sources of elevation data may be absent. This methodology is
39 explored using the Belet Sand Sea of Titan, and likely areas of topographic change at resolutions
40 finer than those currently available from radar altimetry are inferred.

41

42 **Plain Language Summary**

43 Linear dunes form large dunefields both on Earth and Saturn's moon Titan, and look remarkably
44 similar on both worlds. They are characterized by repeated ridges of sand which extend
45 approximately parallel to the wind, and may continue unbroken for tens or even hundreds of
46 kilometers. Perhaps their most remarkable feature is their regularity, and consistent orientation of
47 the dunes. In a few locations, however, the dunes form distinctive curved patterns. This study
48 investigates the causes of this phenomenon, by comparing two dunefields on Earth; Australia's
49 Great Sandy Desert, where the curved dunes are abundant, and the Kalahari of southern Africa,
50 where they are absent.

51 The cause of the curved dunes is shown to be underlying topography. The Kalahari is very flat,
52 and thus the dunes form straight lines. But the Great Sandy Desert lies over a long-dry river
53 valley system, and where the dunes encounter slopes, they deflect downslope. On Titan,
54 knowledge of surface elevations and topography is patchy, and with lander missions planned
55 better understanding is important. The method of analysis proposed here is demonstrated on
56 radar data from the Belet dunefield of Titan, and we show that topography can be inferred from
57 dune patterning alone.

58

59 **1 Introduction**

60 Accurate determination of surface topography is crucial for the success of planetary landers (e.g.
61 Braun & Manning, 2007; Golombek et al., 1997; Striepe et al., 2006; Witte et al., 2016).
62 Although final guidance is typically done autonomously (e.g. using LiDAR; Johnson et al.,
63 2002), initial site selection remains crucial if hazard avoidance is to be maximized. This is often
64 hampered by a lack of high-resolution imaging and/or topographic data of a world's surface,
65 perhaps best illustrated by the design of the Huygens lander for Saturn's moon Titan as part of
66 the Cassini-Huygens mission, given that at the time of launch it was unclear whether the landing
67 would be on a solid or liquid surface (Zarnecki et al., 2005). The fact that the surface was
68 revealed during the descent of the lander not only to be solid, but topographically complex
69 (Soderblom et al., 2007), makes the successful landing even more remarkable. The continued
70 Cassini Prime, Equinox, Solstice and Grand Finale missions (2005-2017) included a total of 127
71 Titan close flybys, and yet the most robust published elevation model for Titan (Corlies et al.,
72 2017), based on radar altimetry, radar SAR and photogrammetry, is still based on just 9.2%
73 coverage, with the rest interpolated. Both for reasons of understanding geological processes
74 (Corlies et al., 2017), but also in the light of future exploration of Titan (Lorenz et al., 2017;
75 Turtle et al., 2018), better understanding of Titan's topography is needed.

76 Linear dunes (that is, dunes forming approximately longitudinal to the net sand-moving winds;
77 Fryberger & Dean, 1979; Lancaster, 1982; Tsoar, 1983) are the most abundant desert dune type
78 on Earth (Lancaster 1989; Lancaster, 1995). They also form the most extensive dune system in
79 the solar system as an equator-encircling belt on Titan covering as much as 15% of the body
80 (Lorenz & Radebaugh, 2009; Lorenz et al., 2006; Radebaugh et al., 2008; Radebaugh et al.,
81 2010). Whether linear dunes align with the net annual sand transporting wind (McKee, 1979), to
82 maximize the net annual sand transport across the crest of the dune (Rubin & Hunter, 1987), or if
83 there is a supply-limited control on their orientation (du Pont et al., 2014; Ping et al., 2014) is
84 debated. Their remarkable regularity and consistency in terms of orientation, relief and spacing
85 across distances of 1-10³ km distinguish them; "Earth has no landform more regular and
86 extensive" (Cooke et al., 1993; p.374). Typically, this regularity is expressed in landforms which,
87 on Earth, are 5 – 120 m high, extend for 10 – 100 km, are regularly spaced on the order of 500 –
88 5000 m, and which typically occur in groupings of up to 1000 with orientations deviating by
89 only a few degrees over the course of 100s of km (Fig. 1a, 1b; Lancaster, 1995). On Titan, an
90 estimated 2 × 10⁵ km³ of organic material is distributed in the equatorial belt of linear dunes,
91 typically approaching ~100 m high where measurements are possible, and similarly arranged in
92 regular, repeated patterns of hundreds of adjacent dunes (Lorenz et al., 2008; Lorenz &
93 Radebaugh, 2009; Lorenz et al., 2006; Radebaugh et al., 2008; Rodriguez et al., 2014).

94 Although linear dunes are characterized by their regularity and organization relative to the
95 regional wind regime, their orientation and planform patterning can also be influenced by
96 obstacles within the dunefield. On both Earth (Fig 1c) and Titan (Fig 1d) dunes are seen to
97 reorient themselves upwind of topographic obstacles. This topographic steering is well-reported
98 for terrestrial coastal dunes (e.g. Bauer et al., 2012; Walker et al., 2009), and the mechanism
99 relates to feedbacks with the deformable bed and boundary layer which propagate upwind
100 (Wilson, 1972), by which bedforms may be deflected even kilometres upwind of the obstruction
101 to sediment transport.

102 In some dunefields, however, a singular, preferential orientation of the dunes is less pronounced;
103 the dunes' orientation over a given region, whilst spacing remains regular, is more complex. This
104 effect is seen in areas of the Great Sandy Desert of northwestern Australia (Fig. 1e), as well as
105 the Australian Great Victoria Desert (Hesse, 2010; 2011) and is also observed on some of Titan's
106 dunefields (Fig. 1f). In both of these cases, the dunes have a pronounced, large-scale curvilinear
107 patterning in planform, resulting in long-wavelength (~10-100 km) sinuosity of the dunes
108 without obvious topographical obstructions causing the deflections in patterning (Lucas et al.,
109 2015), as well as the continental-scale (100-1000 km) curvature shown by some dunefields
110 relating to synoptic-scale changes in typical wind regime (e.g. Hesse, 2010; Lancaster, 1981).
111 There is, however, pronounced variability in the topography underlying the Great Sandy Desert,
112 and it is this topographical influence that we seek to investigate. This paper thus aims to 1)
113 investigate the causes of broad-scale linear dune curvilinearity in the terrestrial setting, and 2)
114 explore the analogue inferences that can thus be derived for Titan's dunefields. We do this by
115 investigating 1) the Great Sandy Desert of western Australia, where locally curvilinear
116 dunefields are found, 2) the southwestern Kalahari, where a regional shift in linear dune
117 orientation exists but localized variability is absent and 3) the Belet Sand Sea on Titan, where
118 localized shifts in dune orientation are apparent. This enables us to deduce the topographic
119 influences on different terrestrial dunefields and to explore the likely inferences for planetary
120 topography that can be interpreted from dunefield patterning.

121 **2 Materials and Methods**

122 We use the Aster GDEM (NASA/METI, 2001), and Landsat8 RGB (Red:Green:Blue – Bands 4-
123 2) and panchromatic data (Band 8), to analyse a) a region of the Great Sandy Desert in
124 northwestern Australia, between 19 - 21°S and 122 - 125°E, b) the southwestern Kalahari of
125 southern Africa, between 24 - 27°S and 19-21 °E. All analysis was performed within ArcGIS
126 10.3. The Linear Dune Oriented (LIDO) algorithm presented by Telfer et al. (2015) was used on
127 the 15 m resolution panchromatic Band 8 data to define dune crestlines based on changes in
128 image brightness apparent at the crests of the dunes. A pan-sharpened RGB composite was used
129 for validation of the automated classification of crestlines. Full methodological details of the
130 algorithm, its accuracy and precision, and details of the images used are provided in Telfer et al.
131 (2015) and in the Supplementary Material, but in summary, the routine uses a pair of 5x5 Sobel
132 operators on the panchromatic image to derive gradient magnitude and direction. These are used
133 to identify reflectance gradients within $\pm 45^\circ$ of the modal direction (which correspond to dune
134 crest orientation), and the reflectance gradient magnitude is then used to define candidate
135 crestline pixels. In this instance, the recursivity of defining strong and weak candidate dune
136 crest-line zones proposed in Telfer et al. (2015) was not found necessary, and pixels were
137 included where the gradient magnitude exceeded $\mu + (1.25 \times \sigma)$ (where μ is the mean reflectance,
138 and σ the standard deviation). Resultant zones of less than 4500 m² were excluded to reduce
139 noise, and candidate pixels were then vectorized using ArcGIS's ArcScan tool (see
140 Supplementary Material for details of the settings employed). Only vectorized crestline sections
141 in excess of 1 km length were considered for further analysis to further reduce noise. ArcGIS's
142 Linear Directional Mean tool was used to derive a regional average orientation for the dunes, and
143 the variation of individual dunes from this mean was subsequently classified using the Natural
144 Breaks method with Jenks optimization within ArcGIS.

145 For the Belet dunefield of Titan, we use a mosaic of the equatorial, trailing hemisphere T8 and
146 T61 Cassini Synthetic Aperture RADAR (SAR) swaths. These offered a pixel size of
147 approximately 180 × 180 m. The study area extends from latitudes -5.6° to -10.2°– -12.3° and
148 longitudes 108.7° to 124.3°; a total area of approximately 180,000 km². The dunes on Titan are
149 characterized by a change in their 2.17 cm SAR reflectance relative to the surrounding terrain,
150 with dunes being SAR-dark and underlying materials, and sometimes crestline reflections, being
151 SAR-bright, similar to 3-cm SAR observations of fine dune sand on Earth. This, together with
152 presence in some areas of apparently sandy interdunes and relatively poor image resolutions,
153 means that rather than observing the change in visible light at the crestline (i.e. the contrast
154 between illuminated and shadowed flanks of the dunes), we note that we are likely to be
155 mapping the dune/interdune margin (e.g. Savage et al. 2014). Nonetheless, examples of the
156 resultant digitization (see Supplementary Material) suggest that the routine accurately captures
157 overall trends at the scales investigated here. The LIDO algorithm was again used to define dune
158 trendlines, although the different characteristics of the SAR observations necessitated some
159 modification of the protocol. Due to the noisier nature of the Cassini SAR data compared to the
160 Landsat images, a 3 × 3 low-pass filter was applied initially to reduce the influence of unduly
161 SAR-bright pixels. This was then passed with the same pair of Sobel operators, from which
162 gradient magnitude and direction were calculated. Despite clear visual differentiation of many of
163 the dunes, the strength of the gradient was highly variable on a pixel-by-pixel basis, and a
164 relaxed criterion of $\mu - (0.25 \times \sigma)$ sigma was required. Combined with a slightly widened
165 criterion for inclusion in terms of gradient direction ($\pm 60^\circ$ of the mode), suitable delineation of
166 dune sections was achieved. Once again, relatively small candidate zones were removed (< 1.6

167 km²) and trendlines vectorized with ArcScan. Reflecting the lower resolution of the SAR data,
168 only sections longer than 3 km were included for further analysis.

169 **3 Results**

170 *3.1 Great Sandy Desert*

171 The LIDO algorithm identified a total of 44 823 crestline sections in excess of 1 km in length
172 (mean = 2.14 km, standard deviation = 1.36 km, maximum = 39.70 km) for the studied sector of
173 the Great Sandy Desert. This region epitomizes the long-wavelength, sinuous linear dunes, and is
174 topographically characterized by a broad E-W drainage in its northern half (the Mandora
175 palaeodrainage (Tapley, 1988; Wyrwoll et al., 1986); the catchment is currently dry), with ~230
176 m relief, and highlands (~250 m elevation) in the south (Fig. 2a). The dunes propagate
177 essentially westwards under the influence of easterly net sand-transporting winds associated with
178 the continental anticyclone (Hesse, 2010; Kalma et al., 1988). Linear dunes (Fig. 2b) are widely
179 distributed across the region, and do not show clear regional trends in abundance, though there
180 are, as is common in linear dunefields, some localized groupings of dunes, especially in the
181 southern part of the study area. However, when the deviation of individual dune orientation is
182 calculated against the regional mean (roughly E – W: 281.4°; Fig. 2c), a relationship with the
183 topography (Fig. 2a) becomes apparent. When the deflection from Fig. 2c is averaged to a 5km
184 grid (Fig. 3a), the zonal nature of the local reorientation of the dunes can be clearly seen, and is,
185 in, part, related to landscape roughness, in this case the standard deviation of elevations from
186 Fig. 2a over a 5 km grid (Fig. 3b). However, it is when the slope orientation, derived from the
187 regional elevation data from Fig. 2a and gridded to 5 km squares, shown as arrows in Fig. 3c, is
188 shown against the 5 km gridded dune deflection (3a) that the true nature of the relationship
189 becomes apparent (Fig. 3c). Dunes deflect northwards (red colors) when the slope descends
190 towards the north, and southwards (blue) in the case of south-dipping slopes. Given the westward
191 propagation of the dunefield, dunes deflect downslope when obliquely encountering both rising
192 and falling topography.

193 *3.2 Southwestern Kalahari*

194 The studied sector of the southwestern Kalahari dunefield occupies a broad swathe of dunes
195 trending approximately NNW-SSE, and the LIDO algorithm identified 30 782 crestline sections
196 in excess of 1 km in length. The topography of the region is very subdued (Fig. 4a) and has
197 indeed led to the coining of the term ‘geomonotony’ (Eckhardt, 2010); dunes are on the order of
198 8 – 10 m in elevation, and the few dry valleys that dissect the dunes are typically broad (~10 km)
199 and shallow (~30 m). Deviations to the mean regional trend of the dune crestlines are limited to a
200 shift from north-south trending at the northern end of the study area to northwest-southeast
201 trending at the southern edge of the dunefield (Fig. 4b and 4c). This overall pattern is well-
202 reported, and typically associated with the southern African continental anticyclone (Lancaster,
203 1980; Lancaster, 1981; Lancaster, 1988). Although some very localized reorganisation of pattern
204 and orientation in the vicinity of dry valleys is apparent along the Auob and Nossop river valleys
205 (Fig. 4a; Bullard & Nash, 1998, 2000), in general, the zonal variability evident in the Great
206 Sandy is absent here. Similarly, no clear relationship exists between the deflection of the dunes
207 (Fig. 5a) and the minimal landscape roughness (Fig 5.b), or the low-relief slopes evident
208 throughout the dunefield (Fig. 5c). Only in a small region adjoining the Nossob catchment in the

209 far north of the study region does enhanced topography coincide with local deflection of the
210 dunes at the scale investigated here.

211 **4 Discussion**

212 The findings presented in the preceding section can be summarized; where substantial
213 topographic variation exists beneath a linear dunefield, it can result in downslope deflection of
214 the dunes and disruption of the regional pattern. This effect is quantified in Figure 6. For the
215 Great Sandy Desert, with its substantial (~200 m) local variation in topography, there is a strong
216 correlation between the incidence angle between the dunes and the underlying slope, and the
217 resultant deviation from the regional mean trend of the dunes (Fig. 6a). This correlation is further
218 increased (Fig. 6b) when the incident angle of the dune trend/slope angle is weighted by the
219 magnitude of the slope; that is, steeper local slopes seem to deflect dunes more than shallow
220 gradients. The magnitude of the deflection of the dune is maximized when the dune/slope
221 intercept reaches 90° (that is, when the dune trend is orthogonal to the local slope). By contrast,
222 for the Kalahari, with its low relief underlying the dunefield, no such correlation is apparent,
223 either unweighted (Fig. 6c) or weighted (Fig. 6d). Although the effect is seen here manifested
224 around a large valley system, the presence of deflection even on dunes extending up slopes
225 implies that similar effects are likely on positive relief.

226 A number of possibilities exist for the mechanism controlling this effect. Because, by definition
227 of their topographic expression, aeolian entrainment and deposition on dune surfaces is rarely on
228 horizontal, flat surfaces, the influence of slope on aeolian processes has been studied using
229 numerical modelling (e.g. Tsoar et al., 1996; White & Tsoar, 1998), computational fluid
230 dynamics (Faria et al., 2011; Huang et al., 2008) and wind tunnel experimentation (Bullard &
231 Nash, 1998; Bullard et al., 2000; Iversen & Rasmussen, 1994, 1999; White & Tsoar, 1998). Few
232 studies have focussed at the landform scale, and fewer still consider the role of oblique slopes.
233 However, wind tunnel experimentation has suggested that the net result of oblique winds
234 incident to a valley is the deflection of the wind along the valley (i.e. in the opposite direction to
235 that observed here for downward slopes) (Bullard and Nash, 2000; Garvey et al., 2005). This
236 suggests that a mechanism other than simple topographic steering of winds along valleys is
237 necessary to explain the observations.

238 Two possibilities are suggested here for a mechanism by which the dunes are deflected
239 downslope. Firstly, it may simply be a gravitational effect, as whether dunes are descending or
240 ascending incident oblique slopes, the deflection is downhill. Whilst gravity-driven (that is,
241 katabatic) winds are known to be influenced by topography (e.g. Nylen et al., 2004), it is also
242 possible that gravitational effects would also presumably affect individual transported grains by
243 preferential settling on deposition from aeolian transport downslope; on deposition, grains might
244 roll downhill, but will not roll uphill. Extrapolated to the landform scale, the result would be the
245 deflection of the dune crestline down the slope. Alternatively, it may be that the effect of the
246 valley on the localized wind regime acts in a manner analogous to that known to occur over
247 positive topographic features, such as coastal foredunes. Here, the effect of topography in
248 steering incident winds towards the normal direction of the crestline is well described (reviewed
249 in Hesp et al., 2015), and results from the pressure gradient force resulting from differential flow
250 acceleration associated with oblique incident winds. Whilst the impacts of such topographic
251 steering have predominantly been studied on dunes transverse to the net air flow, it is possible

252 that pressure-driven force associated with flow separation could deflect the linear dunes. Such
253 effects have been modelled using wind tunnels and differing geometries of valley (Bullard et al.,
254 2000), and whilst it was generally observed that the effect of negative topography was the
255 steering of streamlines along the valley line (i.e. the opposite direction to that observed here), it
256 is also noted that the effects are a function of a complex set of variables including valley
257 geometry, thermal stability of the airmass and wind regime. Further study is needed to
258 disentangle the relative roles of gravity-driven mechanisms and possible localized effects of
259 topography on the wind regime in realigning the dunes.

260 These results suggest a method for identifying topography from dunefield patterning where no
261 such elevation data might otherwise be sparse, or missing, at the relevant scale. Here we apply
262 the dune trendline detection method to the Belet dunefield on Titan, where similar curvilinear
263 dune patterning to that observed in the Great Sandy Desert is present. The studied region consists
264 of a broad belt of west-east trending dunes (sand transport direction inferred to be eastward from
265 dune interactions with obstacles; Radebaugh et al. 2010) with several radar-bright obstacles
266 interrupting the patterning, and a dark, largely dune-free corridor to the southeast of the images.
267 The LIDO algorithm identifies 5322 dune sections of at least 3 km length within the studied
268 region, with a radial mean orientation of 79°.

269 When the deviation in the dune orientations from the regional mean is considered (Figure 7a),
270 the superficial similarity with the Great Sandy Desert is further supported. Unlike in the
271 Kalahari, variation in dune orientation occurs at a relatively local scale. In some instances
272 (Figure 7b), such as in the far northwest of the studied area, these deviations are clearly adjacent
273 to radar-bright gaps in the dune sands, and this effect is both well-reported (Ewing et al., 2015;
274 Lorenz et al., 2006; Radebaugh et al., 2008; Radebaugh et al., 2010; Savage et al., 2014), and
275 likely to be due to deflection of dunes around obstacles (i.e. mountains or hills) standing proud of
276 the dunefield. But in other areas, localized variance in dune trendline is not obviously associated
277 with obstacles, and thus we propose that this is likely the result of underlying topography at a
278 scale not observed by Cassini SAR and radar altimetry data. The resultant likely topographic
279 trends are illustrated in Figure 7b, and are likely to be at a scale more subtle than that observable
280 from the Titan Digital Elevation Model (DEM) (Corlies et al., 2017). While some lineations in
281 the southern and eastern part of the image can still be observed but not selected by the LIDO
282 algorithm, it is tempting to suggest that at least a portion of that corridor is, in the light of its
283 morphology and the inferred slopes down into this region, a fluvial or relic fluvial valley (Birch
284 et al., 2016; Burr et al., 2013; Jaumann et al., 2008; Langhans et al., 2012; Lorenz et al., 2008).
285 It is also possible that small-scale (i.e. individual dune) deflections evident in some parts of the
286 studied area are indicative of localized dune trends, but further work is needed to confirm this.
287 Such information may prove valuable in planning lander sites for future missions to Titan, as it
288 offers additional information regarding the surface of potential landing sites and their surface
289 topography. In addition to the likely increase in surface roughness associated with fluvial erosion
290 creating local topographic relief, it is also likely that Titan's fluvial channels, especially those
291 that are radar-bright, may have increased frequency of fluvially-derived clasts (Burr et al., 2013),
292 an additional hazard for planetary landers.

293 It has been noted that despite the differences of Titan's different atmospheric density (146 KPa,
294 or 145% that of Earth), gravity (1.35 m s^{-2} , or 14% that of Earth) and likely particle density (0.4-
295 1.5 g cm^{-3} , or 15-55% that of Earth's silicate sands), the similarity of the resultant aeolian

296 landforms to terrestrial dunes is striking (Lorenz et al., 2006). The presence of curvilinear
297 longitudinal dune forms is further evidence of this similarity. It is possible that their presence on
298 Titan, given the low gravity and very low particle/fluid density ratio (Burr et al., 2015), might
299 favour pressure-gradient mechanisms.

300 **5 Conclusions**

301 We investigate the properties of linear (longitudinal) dunefields where the typically highly-
302 consistent orientation of dunes is less pronounced, and curvilinear, long-wavelength sinuosity is
303 apparent. Such patterning is scarce on Earth, but relatively common on Titan. We show that on
304 Earth, such patterning results from underlying topography causing the dunes to deflect
305 downslope as they form and propagate. The effect is maximized as the incidence angle between
306 the dunes and the slope approaches 90° , and is further shown to be dependent on the gradient of
307 the slope, with steeper slopes resulting in more pronounced deflection. Dune morphometry thus
308 offers an additional source of information regarding local and regional topography where such
309 information is scarce, as is the case for some planetary dunefields. The mechanism by which the
310 dunes are deflected likely relates to either gravity-driven processes affecting either the airflow or
311 settling grains, or by local pressure gradients related to airflow separation; the presence of the
312 curving dunes even in Titan's low gravity may favour the latter. We demonstrate the potential of
313 this method to infer topography in a region of the Belet Sand Sea in Titan's equatorial belt, and
314 suggest it offers the potential to increase topographic understanding of the surface of Titan both
315 for geological purposes and in terms of identifying optimal lander sites for future missions. To
316 find the lowest relief areas amongst the dunes, future landers would be best guided away from
317 areas where dunes demonstrate long-wavelength sinuosity.

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 320 affiliations for any author that may be perceived as having a conflict of interest with respect to
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 324 Planetary Data System (PDS). Detail of the LIDO workflow used within ArcGIS is provided in
 325 the Supplementary material.

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328

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494 **Figure 1.** Linear dunes are typified by remarkably regular planform patterning, with dunes
 495 aligned approximately parallel to the net sand-transporting regional winds. Examples from a) the
 496 Simpson Desert, Australia and b) the southwestern Kalahari of central southern Africa highlight
 497 this regularity. In the case of the Kalahari, the orientation patterns demonstrate the occasional
 498 tendency of these dunefields to reflect changes in the orientation of regional-scale atmospheric
 499 circulation patterns. Such dunes may reorient around topographic obstacles to sand-transporting
 500 wind flow, illustrated here from c) the Libyan Sahara (23.75°N, 21.38°E) and d) the Belet
 501 dunefield of Titan (from the T61 swath, Aug. 2009). Figure 1a, 1b, 1c and 1e are courtesy of
 502 Google Earth/SPOT/CNRS. In some regions, however, the dunes take a curvilinear form without
 503 obvious topographic obstructions causing the change to patterning, seen here in e) the Great
 504 Sandy Desert of northwestern Australia and f) the Belet dunefield (from T8, October 2005).

505 **Figure 2.** Topographic data and dune alignment for the Great Sandy Desert. a) The relief of the
 506 Great Sandy Desert, b) Dune crestlines as determined by the LIDO automated detection routine,
 507 and c) the deflection of the dune orientations relative to the regional mean (red = northwards;
 508 blue = southwards), which highlights the localized nature of the pattern deviation. Net sand
 509 transport is east-west.

510 **Figure 3.** The influence of relief on the orientation of sand dunes in the Great Sandy Desert. a)
 511 shows the deviation in the regional directional trend from 2c shown here as 5 km-gridded means;
 512 b) landscape roughness (here calculated as the standard deviation of elevations within a 5 km
 513 grid) can be seen to closely resemble the pattern of dune deflection; c) the relative orientation of
 514 the slope (arrows point downslope and are scaled by gradient) correlates most closely with the
 515 deflection of the dunes (see Fig. 6).

516 **Figure 4.** Topographic data and dune alignment for the Kalahari. a) The relief of the
 517 southwestern Kalahari, whilst showing greater regional changes than the Great Sandy, has much
 518 more subdued local expression of relief. b) The dunes occur in a broad swathe with net sand-
 519 transporting wind from the north-northwest and c) deviations in the dune crestline orientations,
 520 unlike the Great Sandy, do not show pronounced local variation (cf Figure 2c), but instead reflect
 521 large-scale regional changes.

522 **Figure 5.** The influence of relief on the orientation of sand dunes in the Kalahari. a) The
 523 southwestern Kalahari's regional trend in dune orientation is largely independent of the relief,
 524 and b) the topographic roughness (again, shown as standard deviations of elevation around a 5
 525 km downsampled grid of the Aster GDEM v2.0 data) is much lower throughout the dunefield.
 526 The higher relief mountains in the southwestern corner of the image are beyond the dunefield
 527 limits. c) The magnitude and orientation of local slopes again highlights the lower relief apparent
 528 here.

529 **Figure 6.** The relationship between the deflection of the dunes and the incident slope angle is
 530 dependent upon the degree of underlying topography. a) The deflection of the Great Sandy's
 531 dunes from the regional mean (approximately east-west; 280.4°) plotted as a function of the
 532 relative orientation of the 5 km gridded local slope, and b) the same data, but weighted according
 533 to the magnitude of the gradient. Here a cubic fit is used to reflect the likely maximum deflection
 534 as slope incidence approaches +/- 90°. By contrast, no trend is apparent for the low-relief
 535 southwestern Kalahari, with the data either c) unweighted or d) weighted.

536 **Figure 7.** The orientations of dune section at the eastern end of the Belet dunefield, as
537 determined reveals some dune deviations attributable to deflection around obstacles, but also
538 some which are not apparently associated with this mechanism. a) The dune trends mapped as
539 deviations from the regional mean with major radar-bright obstacles highlighted in white, and b)
540 annotated inferences reveal deviations likely due to not just topographic obstacles to airflow
541 (white arrows), but also those likely due to underlying topography. Here, the inferred
542 topographic trend is illustrated with a black arrow pointed downslope. These reveal details of
543 topography not apparent from either c) the Imaging Science Subsystem (ISS) imagery or d) the
544 derived elevation model data product (here from Lorenz et al., 2013).

Figure 1.

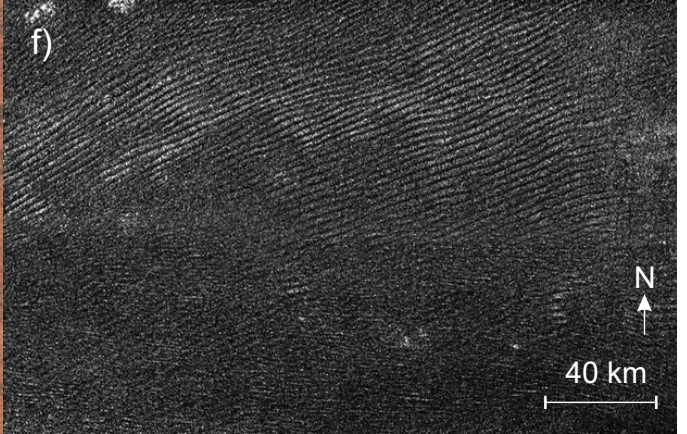
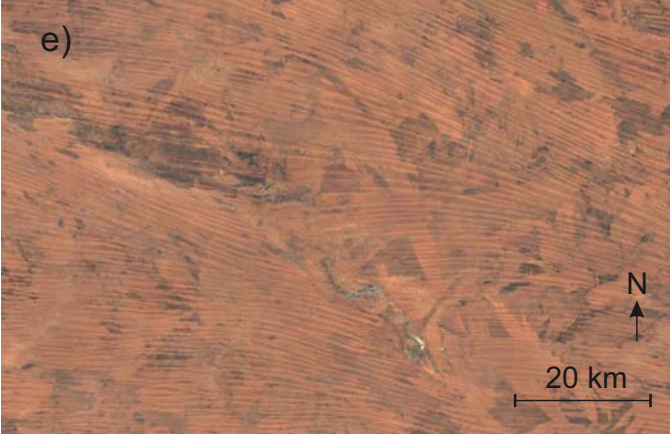
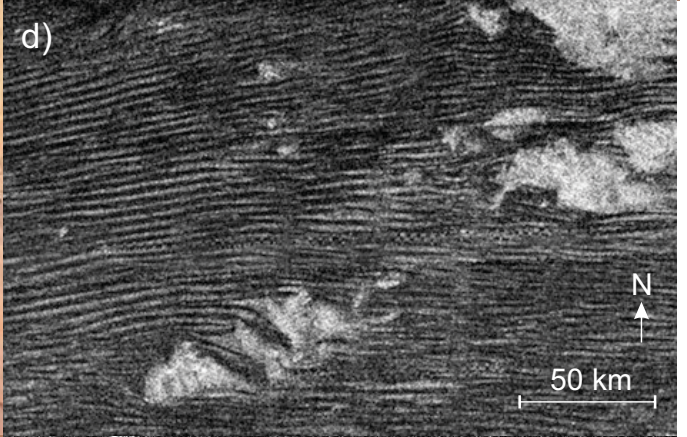
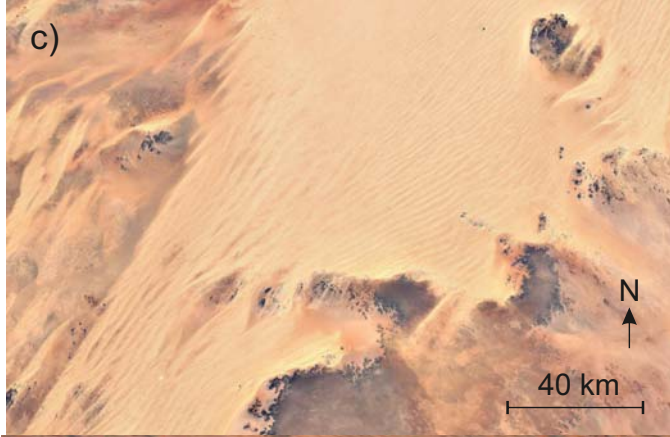
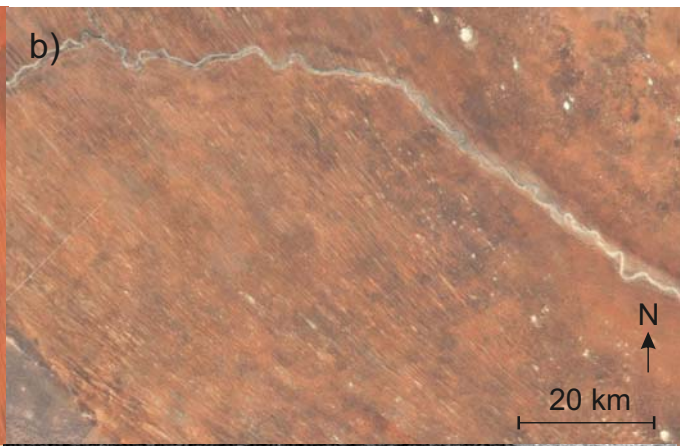
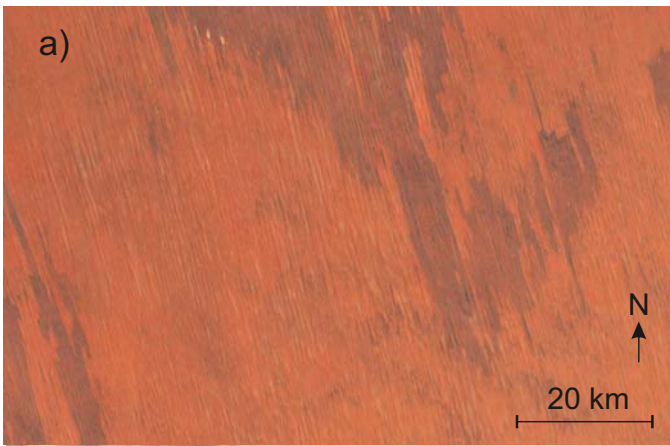
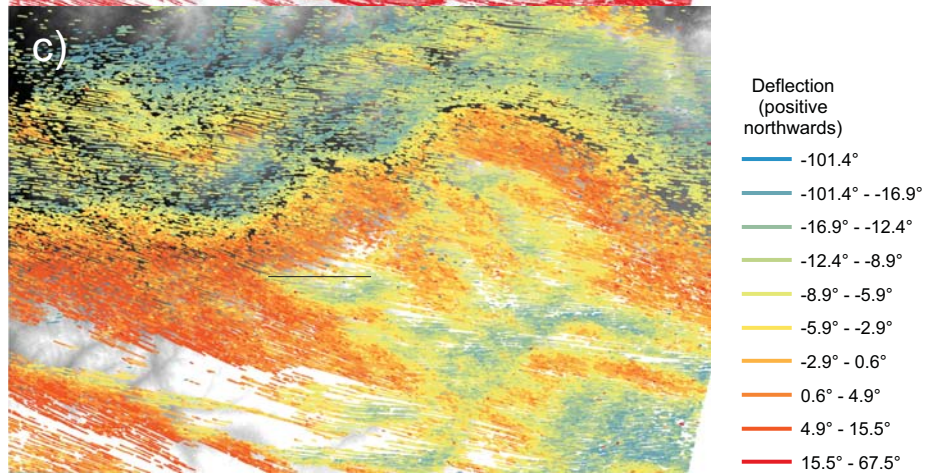
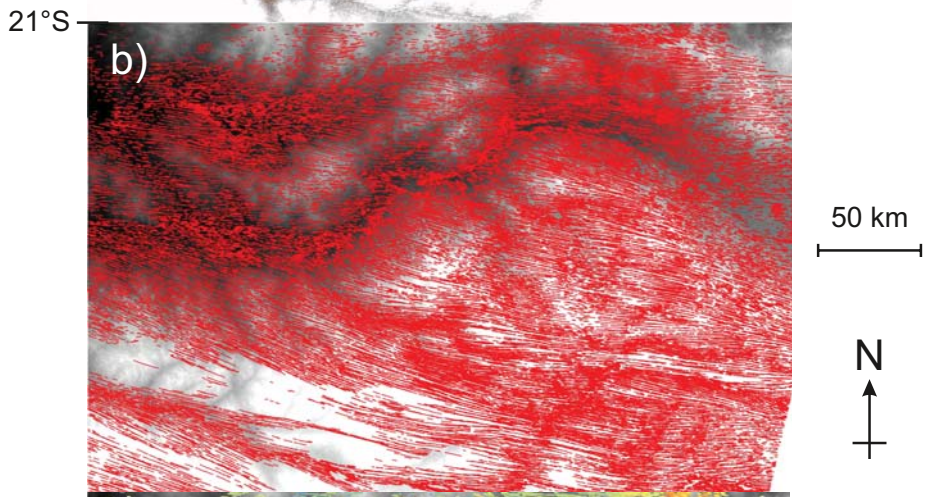
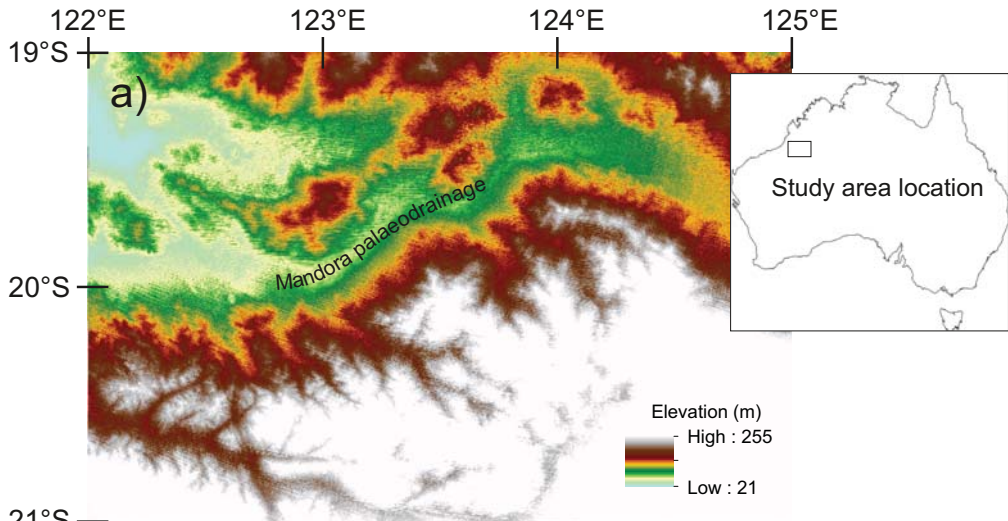


Figure 2.



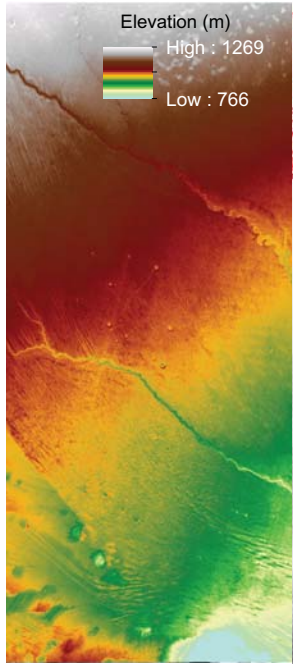
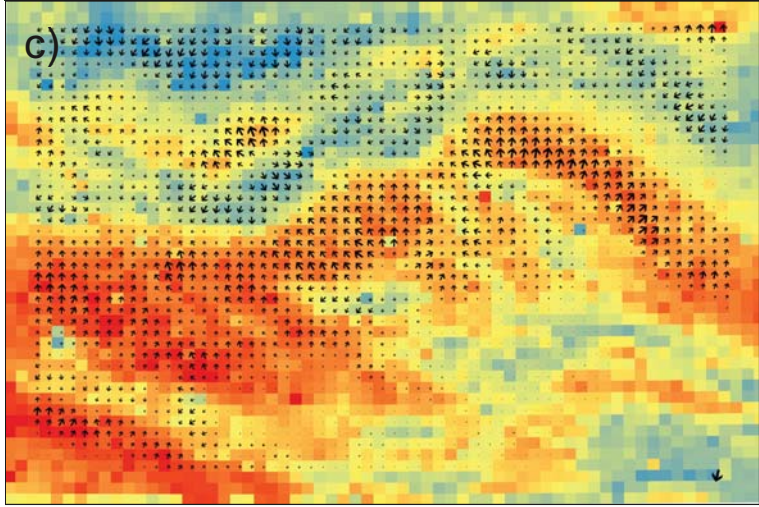
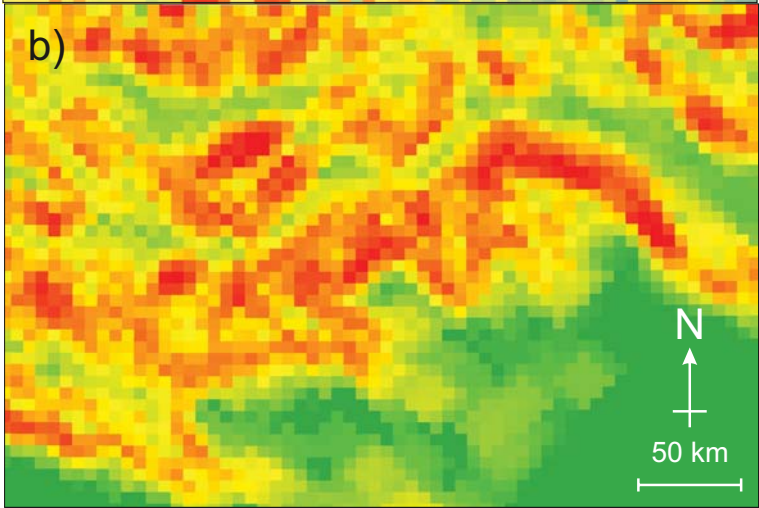
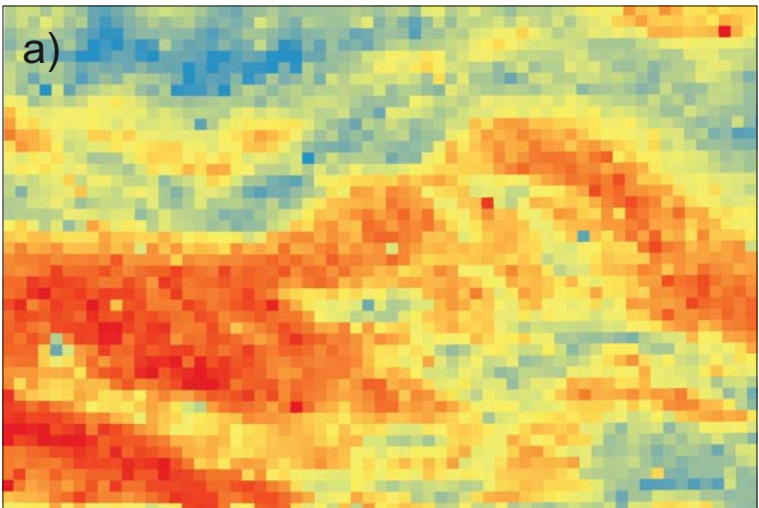


Figure 3.



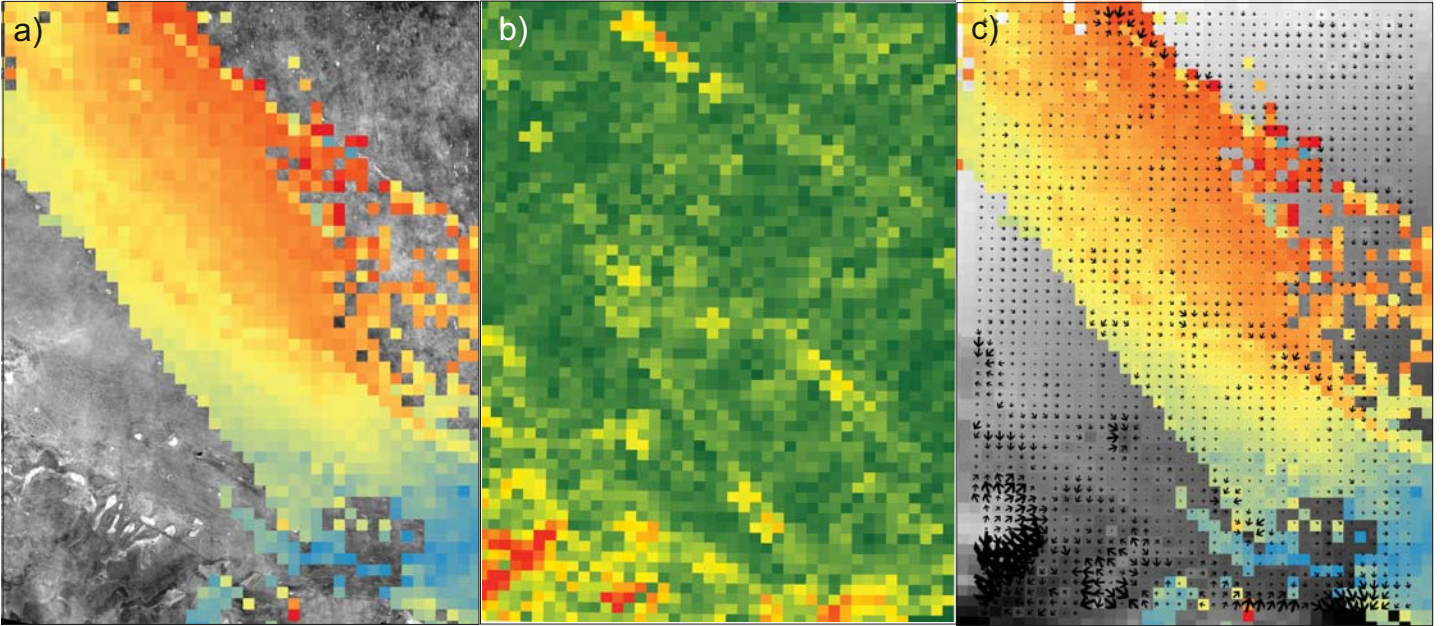


Figure 4.

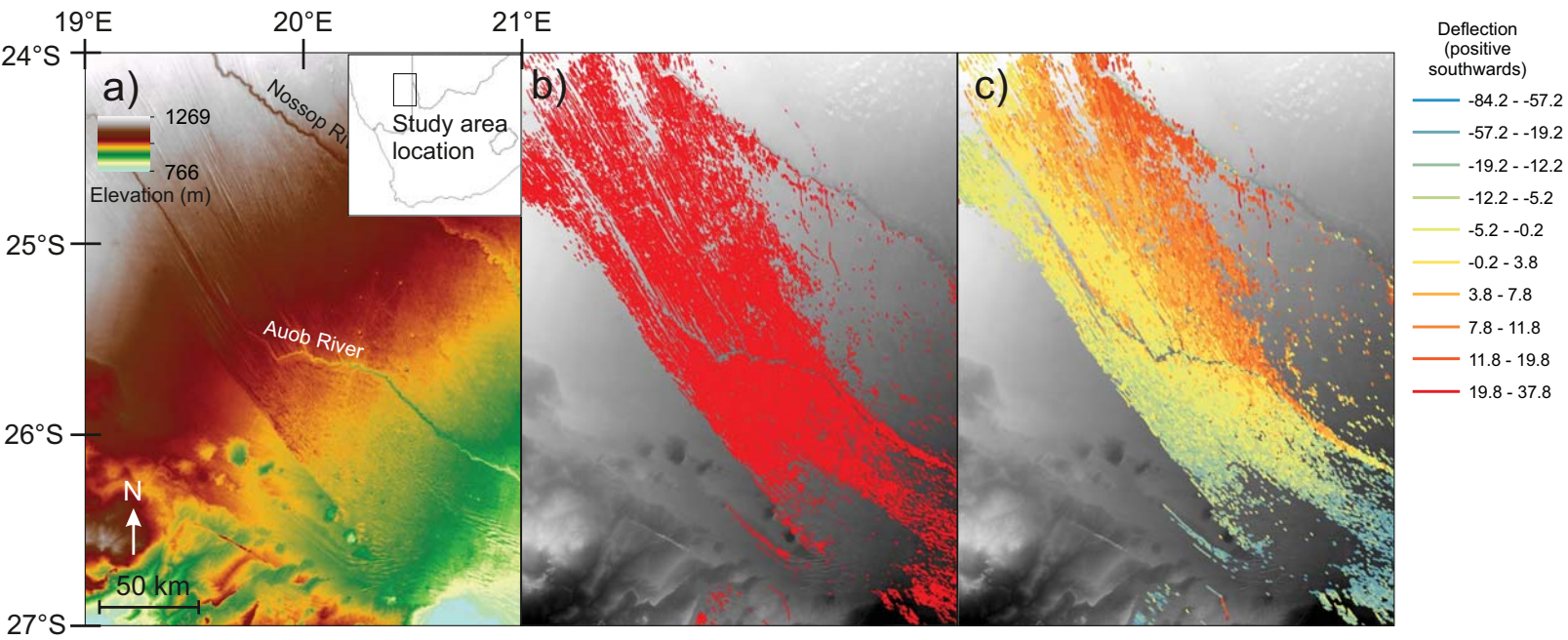


Figure 5.

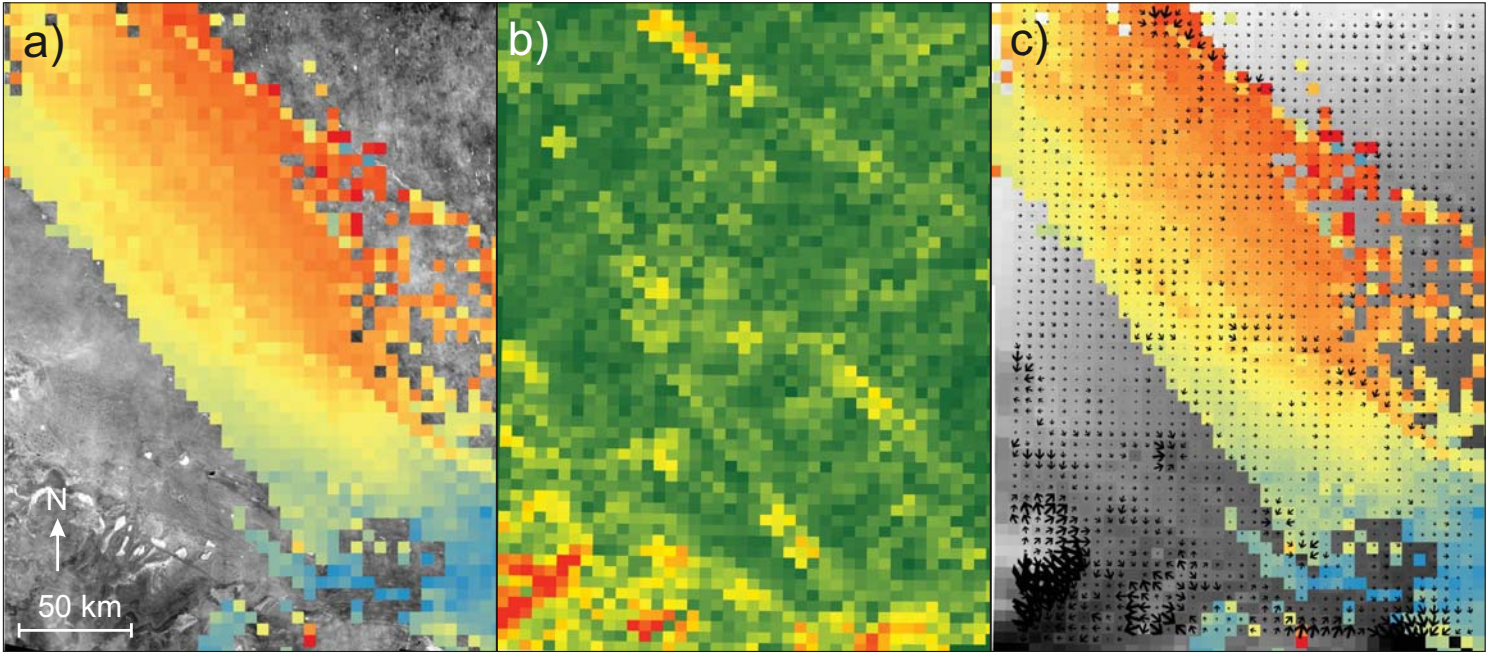


Figure 6.

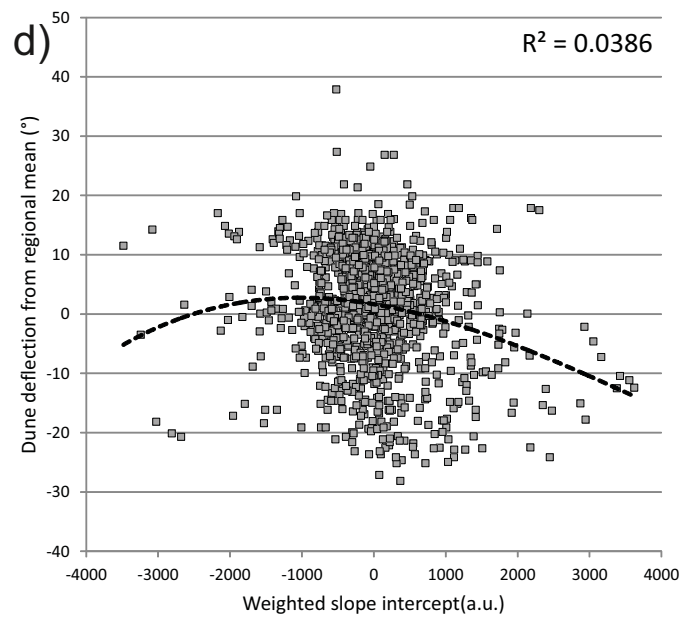
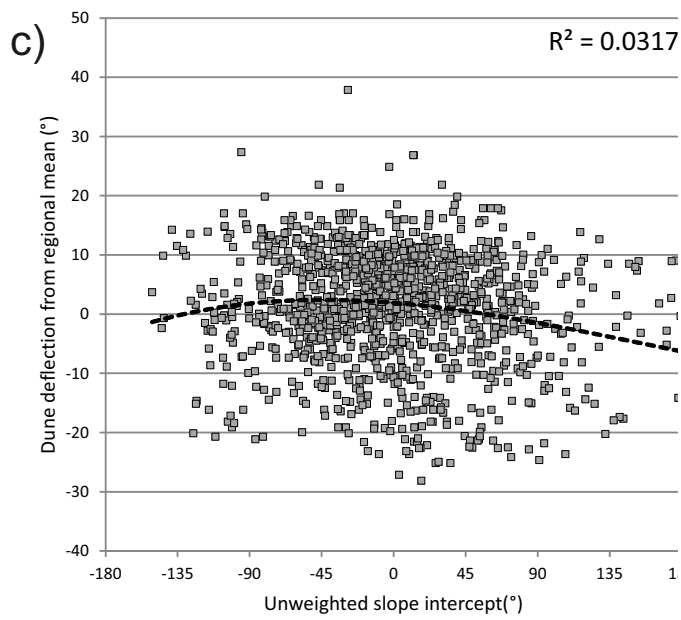
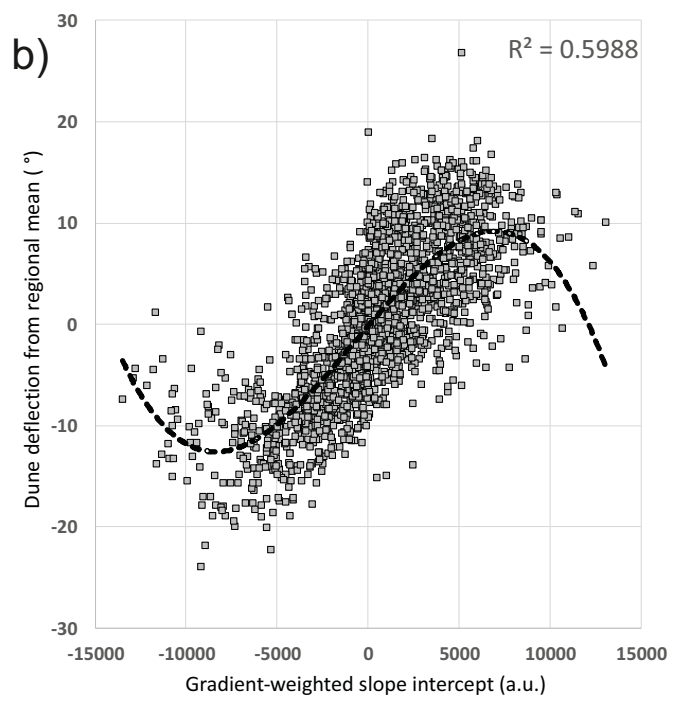
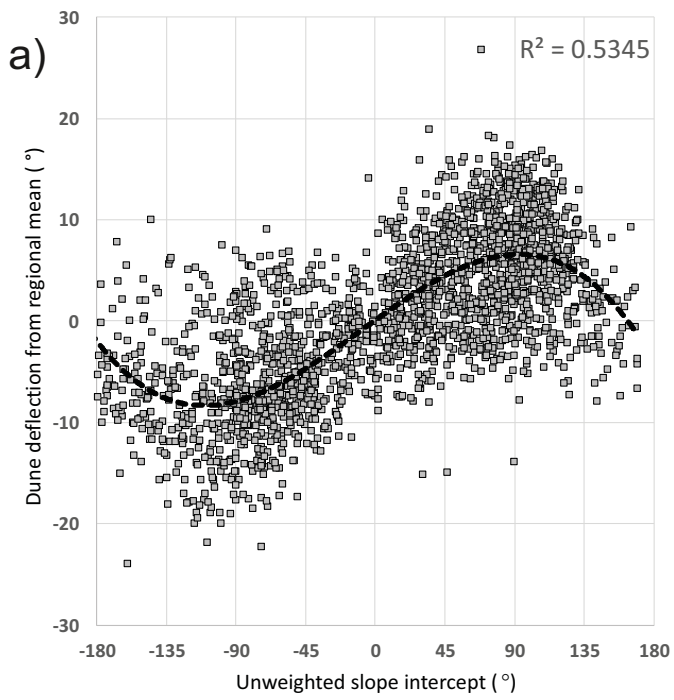


Figure 7.

