

1 UAV-SfM Based Field Quantification of Barchan Dune Celerity and 2 Morphodynamics in Gonghe Basin

3 Abstract

4 Barchan dunes do not often co-exist with grasslands. However, in Gonghe Basin, north-
5 eastern part in Qinghai-Tibetan Plateau (QTP), China, many barchan dunes distributed
6 on the grassland at high-altitude. Identifying celerity and morphodynamics of barchan
7 dunes, exploring the interaction between barchans and grassland landscape can help us
8 to better understand aeolian system sand mitigate damages. In this work, we tracked
9 dune celerity and observed three-dimensional changes of symmetrical and
10 asymmetrical barchan dunes in Ertala based on high resolution UAV-SfM
11 reconstruction in short-term monitoring and discussed the factors influencing dune
12 celerity and deformation at high-altitude. The results revealed that the barchan dunes
13 are highly mobile with average celerity of 0.85 m/M for the whole study area. Based
14 on observations of dune morphology and dynamics, we found: (1) The dune
15 deformation degree in a short time is not large, but is widespread, especially in the
16 elongated arm of asymmetric dune. The deformation of symmetric dune is symmetrical,
17 while that of dune with extended horn is asymmetrical; (2) The sand supply, vegetation,
18 and airflow at low air density all influence the celerity and deformation degree in the
19 development of barchan dunes; (3) The asymmetric air flow and sediment supply are
20 important cause of dune asymmetry. The above results help us to understand the
21 deformation of barchan dune from the three-dimensional, especially the difference
22 reflected by the symmetry of barchan dune at high-altitude.

23 **Keywords:** dune celerity, deformation, asymmetrical and asymmetrical barchan dunes

24 1 Introduction

25 Barchan dunes are crescentic dunes classically formed in a supply-limited
26 environment, uni-directional wind and no vegetation (Bagnold, 1941; Cooke et al.,
27 1993; Elbelrhiti, 2012). They are usually discrete although sometimes merged with
28 another dune (Assis et al., 2022), and they occur in both coastal and continental regions
29 (Finkel, 1959; Hesp and Hastings, 1998). They also form in water bodies (Hersen, 2005;
30 Alvarez and Franklin, 2020). Barchans are migrating bedforms (Wu, 2003; Vermeesch
31 and Drake, 2008) and their movement within a largely unimodal wind regime is
32 relatively simple: the stoss slope of the barchan dune is eroded; and the sand is
33 transported in creep, saltation and occasionally suspension, is deposited downwind of
34 the brink, and is redistributed on the slip-face by avalanches (Andreotti et al., 2002;
35 Zhang et al., 2022). One of the important actions in aeolian geomorphology has been
36 to study and understand barchan dune celerity and deformation to better understand the
37 risks of sand encroachment to infrastructure and down-wind at-risk communities (Long
38 and Sharp, 1964; Zhu et al., 1964; Slattery, 1990; Bruno et al., 2018).

40 1.1 Spatial analysis of barchan dunes

41 For decades, scientists have reported results of observation and experiments on barchan
42 dunes, and measuring their formation, erosion and deposition, activity or stability,
43 turbulent flow structures and the size distribution of associated sand grains (Beadnell,
44 1910; Cornish, 1914; Finkel, 1959; Fedolovich, 1962; Jimenez et al., 1999; Andreotti
45 et al., 2002; Baddock et al., 2011; Hamdan et al., 2016; Havivi et al., 2018; Ding et al.,
46 2020; Zhang et al., 2022). Their celerity and morphodynamics have commonly been
47 studied at the dune scale over several years using a combination of field and remote
48 sensing data (Zheng et al., 2022).

49 Dune celerity refers to the speed of dune migration which is measured in meters per
50 unit time (Sam et al., 2015). Measuring dune celerity can provide an unambiguous
51 indicator of active sand transport and that is a crucial step towards understanding
52 aeolian system operation (Muhs and Holliday, 1995; Vermeesch and Drake, 2008;
53 Hugenholtz et al., 2012; Bryant and Baddock, 2022; Zhang et al., 2022). Traditional
54 field surveying methods (e.g., Dong et al., 2000) offer high levels of accuracy but are
55 time consuming and offer a limited space/time sample. There are two broad categories
56 from a remote sensing perspective, manual tracking, and automated extraction of dune
57 celerity (Bryant and Baddock, 2022; Zheng et al., 2022). Manual extraction of dune
58 celerity information includes approaches such as: (i) measuring the distance between
59 two lines in the continuous position of the dune (Gay, 1999), (ii) recording the average
60 length of several lines drawn are common manual methods to track the dune celerity
61 (e.g. Hunter et al., 1983), and (iii) using an area integrated method (e.g. Levin and Ben-
62 Dor, 2004). With the development of remote sensing technology, it is possible to
63 automated interpret dune activity by using changes in dune DEMs and spectral
64 reflectance (e.g. Hamdan et al., 2016; Zhang et al., 2018). In recent years, COSI-Corr
65 has been particularly notable in automated mapping dune movement and sand flux
66 (Leprince et al., 2007; Vermeesch and Drake, 2008; Scheidt and Lancaster, 2013; Baird
67 et al., 2019).

68 As an important step in dynamic monitoring of dunes, the morphodynamics of dunes
69 has attracted significant attention (Frank and Kocurek, 1966; Sweet and Kocurek, 1990)
70 since Zhu et al (1964) described the formation change during the evolution of dunes. In
71 recent years, research on establishing the relationship between morphological
72 characteristics, wind flow and the evolution of barchans have been making great
73 progress (Finkel, 1959; Long and Sharp, 1964; Hastenrath, 1967, 1987; Tsoar, 1985;
74 Hesp and Hastings, 1998; Bourke and Goudie, 2009). Initially, three-dimensional
75 assessments of dune morphodynamical change (including assessment of locations of
76 erosion and deposition) was determined via use of digital terrain data generate by use
77 of hard and soft copy analysis of aerial photographs (e.g. Brown and Arbogast, 1999;
78 Ojeda et al., 2005). Subsequently, LiDAR data have used to determine volume change
79 of sand dune area (Pedersen et al., 2015). Vermeesch and Drake (2008) used COSI -
80 Corr to calculate the dune mass flux. In some cases, it may be more effective to use
81 field-based measurements (GPS and total station) to measure dune surface changes
82 (Coursin, 1964; El-Sherbiny and Bofah, 1982; Dong and Huang, 2014; Guo et al., 2016).

83 Recent studies in numerical simulation and flume (wind tunnel) experiments have
84 shown that the importance of dune morphological evolution has become an import
85 research priority (Walmsley and Howard, 1985; Wippermann and Gross, 1986; Duran
86 et al., 2010; Lv et al., 2018; Hugenholtz, 2010; Andreotti et al., 2002). At present, we
87 still have a limited understanding of the process of changes in dune morphology, as
88 morphodynamics analysis has traditionally been based on the assumptions associated
89 with two-dimensional dune morphology, essentially ignoring components of the three-
90 dimensional morphology that may be pertinent (Scheltinga, 2022). Consequently, high-
91 frequency three-dimension DEM data are needed to resolve the observed rapid
92 morphodynamical response of dunes to prevailing wind flow. Emerging technologies,
93 such as the use of UAV (Unpiloted Aerial Vehicle), provide possibilities for dune
94 morphodynamical surveying (Luo et al., 2020; Bryant and Baddock, 2022).

95 Dune shape and asymmetry can vary in space/time because dune morphodynamics is
96 dynamic rarely observed in equilibrium. Also, in vegetated areas, the supply of
97 sediment (which can be controlled by vegetation changes) can directly impact the rate
98 of movement (Xu et al., 2015). The simplest expression of asymmetry, the horn
99 extension, can be used to distinguish between bimodal wind conditions and dune
100 collisions, which are factors that alter dune morphology on larger scale (Bourke, 2010;
101 Tsoar and Parteli, 2016). It can also be used to infer upwind currents, modification of
102 the sedimentary dynamics of barchan dunes, and, for where no data are available, local
103 topography of an area (Bourke, 2010; Merwe et al., 2022). However, we note that these
104 inferences cannot be drawn from a single observation of a barchan dune, and in order
105 to be truly valid, multiple observations over different time periods are needed to fully
106 understand the dynamics within the dune region (Merwe et al., 2022). Small-scale
107 aeolian landforms, such as sand ripples, evolve very quickly with time. Wind tunnel
108 experiment results show that the original particles can drift about 1 cm downward every
109 5 minutes (Fryberger et al., 1992). The timescale of normal ripples is minutes
110 (Anderson, 1990), while the Mega-ripples is days (Sakamoto-Arnold, 1988) and years
111 (Bagnold, 1941). Bogle et al (2015) repeatedly tracked the locations of several active
112 barchan dunes at irregular intervals ranging from 24 to 169 days. Ewing et al (2015)
113 believed that dune field was composed of different types of bedforms, which reflected
114 the changes of environmental boundary conditions on a wide range of time scales, and
115 dune field models of different scales and types should be analyzed at different stages.
116 Kocurek et al (1992) made seasonal observations on some dune fields on Padre Island,
117 Texas, and found that the dune fields would become flat in winter, and then would
118 reconstruct in spring and summer.

119 In fact, most barchan dunes in nature are asymmetrical. The potential causes of the
120 asymmetry of barchan dunes include asymmetric bidirectional wind conditions,
121 topography, asymmetry of inflow and dune collision (Parteli et al., 2014; Tsoar and
122 Parteli, 2016). It has been found that where the divergence angle between the main
123 winds and secondary winds is low, the two horns remain similar and both are thick and
124 short (Lv et al., 2016). However, when the divergence angle is obtuse, these asymmetric
125 bimodal wind conditions will lead to the extension of the dune horn (Tsoar and Parteli,
126 2016; Bourke, 2010), and where the transport ratio of the two exceeds 25%, an

127 asymmetric barchan dune may evolve into seif dune (Parteli et al., 2014). There are two
128 classical models for the evolution of barchan dunes into seif dunes, (Bagnold, 1941;
129 Tsoar,1984). Using numerical simulation, many scholars have conducted validation
130 experiments, and the evolutionary mechanisms attributed to the two are a matter of
131 debate. Some scholars suggest that there may be a threshold between the two
132 evolutionary mechanisms (e.g. Lv et al., 2016; Robson and Bass, 2023), but others have
133 divergent views (e.g. Tsoar and Parteli, 2016). In addition, although topography, inflow
134 asymmetry and dune collision can cause dune asymmetry, models suggest that these
135 factors may not cause barchan dunes to evolve into seif dune (Tsoar and Parteli, 2016).
136 Although many studies have been carried out to investigate and model the asymmetric
137 evolution of barchan dunes, there are some inevitable limitations. These include a lack
138 of field observation data and the need to simplify aspects of the wind conditions.
139 Ultimately observations of the morphological evolution of sand dunes in the field be
140 critical in minimising model uncertainty and validate the simulation results in the
141 laboratory.

142 1.2 Land degradation, dune stabilisation and mitigation in China

143 In recent decades, some parts of China have experienced serious land degradation,
144 especially in the northern drylands. Desertification is the most prominent and
145 concentrated ecological problem among them (Jiang et al., 2020). China is one of the
146 countries seriously affected by desertification, accounting for 17.93% of its land area
147 (Xu and Zhang, 2021). The research results show that the risk of desertification in China
148 will increase over time by the end of this century (Huang et al., 2020), local land
149 degradation was expanding in northern China, mainly in semi-arid areas (Guo et al.,
150 2022). The activation and stabilization process of sand dunes is closely related to
151 climate change, environmental changes and human activities, and has been widely
152 concerned by the academic community. Baas and Delobel's (2022) research shows that
153 the projected increased potential for many dune fields in China by 2100 is associated
154 with climate changes in The Hadley circulation, tropical cyclone activity, and monsoon
155 systems. However, human activities can also seriously interfere with them, and the
156 changes of dune field in the symbiotic system of dune and vegetation are rarely
157 discussed in these studies. Many works on dunes morphodynamics, stabilisation and
158 migration have been carried out on various deserts, sandy lands and basins in China (He
159 et al., 2011; Chen et al., 2018; Luo et al., 2019; Yang et al., 2019; Ding et al., 2020).
160 These works contribute to our understanding of the development and evolution of
161 aeolian dunes in different area.,

162 Vegetation plays an important role in dune stabilization. Sand dunes in some areas are
163 very sensitive to the change of desert-grassland boundary. Rapid accumulation of
164 aeolian particles will significantly change the surface, especially affecting the change
165 of vegetation on the dunes, which in turn can also affect the spatial-temporal pattern of
166 aeolian sand position. Studies have shown that stable sand dunes may be more and more
167 susceptible to blowing with the gradual decline of shrub vegetation coverage
168 (Fearnough et al., 1998). However, in the same region, bare sand dunes and vegetated
169 sand dunes may exist simultaneously, which is called the bistable state of dunes (Chen

170 et al., 2021). Dune activity is regarded as an important source of information for
171 reconstructing paleoclimate on a regional scale and predicting future climate change in
172 arid areas (Guo et al., 2019). There are many deserts and sandy lands in China, and
173 various types of sand dunes have developed, the movement and change of dunes have
174 received extensive attention (Ding et al., 2020; Yang et al., 2019; Yang et al., 2021).

175 1.3 Aims and objectives.

176 As we note, there are still some challenges associated with observation of the rapid
177 morphodynamics of dunes (Bryant and Baddock 2022; Zheng et al., 2022). In addition,
178 our understanding of the morphodynamics of barchan dunes that coexist with vegetation
179 in high-altitude settings (with low air density and low temperature, is poorly constrained
180 (e.g. Dörwald et al., 2023). At the same time, field observations of the dynamic
181 development of asymmetric barchan dunes that can augment modelling approaches (e.g.
182 Robson and Baas., 2023) are also limited (e.g. Lü et al., 2022). The Gonghe Basin is
183 located on the north-eastern margin of the Qinghai-Tibet Plateau (QTP, Figure 1), the
184 north-western edge of the Asian monsoon region, at an altitude of 3400 m (Liu et al.,
185 2014). Grassland is the main land cover type in Gonghe Basin, accounting for 79.52%
186 of the total area, and land use for grazing (Sha et al., 2005). There are many isolated
187 and fully active barchan dunes in the grassland in Gonghe Basin, there is a lot of
188 vegetation growing in the interdunes, and no vegetation growing on the surface of the
189 dunes. The results of wind tunnel experiments also show that at a certain wind speed,
190 the sand transport capacity decreases at low air density, but the salting height increases
191 (Han et al., 2014). Because of the difficulties in controlling air pressure and temperature,
192 laboratory experiments cannot easily provide this understanding. Most previous studies
193 on the effects of low density and low temperature have focused on extraterrestrial
194 environments, such as Mars (Ryan and Henry, 1979; Iversen et al., 1976). Gonghe
195 Basin is located at a high altitude, and the air density limits the wind erosion and
196 transport process of sand, thus strongly affecting the airflow characteristics (Dong et
197 al., 2017). Therefore, the barchan dunes in Gonghe Basin provide a natural
198 experimental site for us to further understand the morphologic dynamics of dunes
199 coexisting with the grassland landscape and reveal the migration characteristics of
200 dunes at low density and low temperature.

201 We track the barchan dune celerity and assess rapid morphodynamics ($t = 17$ months)
202 using DOM (Digital Orthophoto Maps) and DSM (Digital Surface Model) generated
203 using UAV-SfM. Our observations based on dunes in the Ertala in Gonghe Basin and
204 monitor these for the period March 2019 to August 2020. Our objectives of this study
205 are to: (1) quantify the celerity and deformation of isolated symmetrical and
206 asymmetrical barchan dunes coexist with vegetation at high-altitude; (2) discuss the
207 influence of sand supply, vegetation, sand flow and high-altitude on dune celerity and
208 deformation. (3) explore the controlling factors of asymmetric barchan dune evolution.
209 In this paper, section 2 describes the methodology, section 3 presents the results, section
210 4 presents the discussion and section 5 illustrates the conclusions.

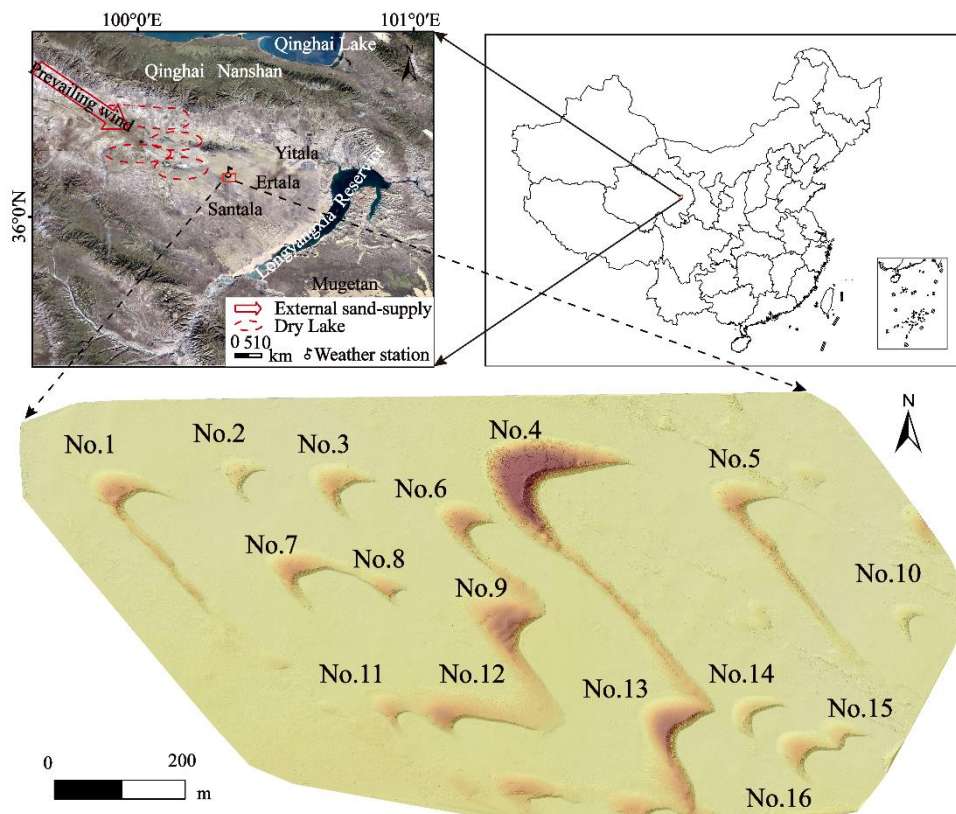
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212 **2 Study area and methodology**

213 2.1 Study area

214 The Gonghe Basin is about 210 km long, 90 km wide and 30 km narrow, with a total
215 area of $1.38 \times 10^4 \text{ km}^2$, between $35^\circ 27' \sim 36^\circ 56' \text{N}$, $98^\circ 46' \sim 101^\circ 22' \text{E}$, surrounded by the
216 Qilian Mountains and the Erla Mountains of the Kunlun-Qilian Mountains. It extends
217 from northwest to southeast in the west, and is narrow in the west and wide in the east
218 in the shape of a gourd. It is a region where the distribution of aeolian landforms is
219 concentrated (862 km^2) (Xu et al., 1982; Dong et al., 1993), which are distributed in
220 upland plains and on terraces of the Yellow River. The surface of the basin is dominated
221 by stabilized and semi-stabilized sand dunes, which are concentrated in Talatan,
222 Mugetan and the tail reaches of Shazhuyu River (Liu et al., 2014). From west to east,
223 three large sand belts comprising hundreds of kilometres of dune fields are proximal to
224 the Longyangxia reservoir, which acts as a sediment sink (Shao et al., 2021). In order
225 to investigate dune dynamics in this important and dynamic location, we selected 16
226 representative barchan dunes in the region of Ertala to monitor their celerity and
227 deformation changes. The study area is located at $36.144166667^\circ \sim 36.150555556^\circ \text{N}$,
228 $100.341111111^\circ \text{E} \sim 100.357222222^\circ \text{E}$ and covers an area of 0.9 km^2 (Figure 1).

229



230

231 Figure 1. The location of the study area and geographical sketch map with dune number of each

232 barchan studied.

233 2.2 Methodology

234 We went to the Ertala in March 2019, July 2019, January 2020 and August 2020 to
235 monitored the barchan dunes by using UAVs and RTK-GPS, obtained four DOMs and
236 DSMs of the barchan dunes in the study area through post-processing, extracted the
237 morphological parameters and analyzed their celerity. We measured the surface airflow
238 and sand transport characteristics of No.2 dune in the study area in April 2019 in order
239 to further explore the morphodynamic process. This section describes our field
240 measurement and analysis methods in detail.

241 2.2.1 Monitoring and measurement of 3D dune morphology

242 (1) Equipment

243 The field measurement of dune movement and morphology undertaken here was
244 divided into two complimentary approaches: (a) UAV-SfM and (b) RTK-GPS (Real-
245 time kinematic Global Positioning System). UAV-SfM technology is a method
246 developed in recent years, which has the advantages of high efficiency, high precision,
247 time, and labour saving (Balek, 2017; Qian et al., 2019; James et al., 2019; Bryant and
248 Baddock., 2022). UAV-SfM can track topography at the centimetre level, which can
249 overlap with requirements of topographic survey, but at a large scale (Aguera-Vega et
250 al., 2018; Luo et al., 2020; Shao, 2021).

251 Here we monitored dune form variation using a DJI phantom 4 Pro V2.0 in Ertala
252 sandy land of Gonghe Basin, Qinghai Province in March, July of 2019 and January and
253 August of 2020, respectively. The camera image sensor of this drone is 1 inch CMOS
254 with 20 million effective pixels, and the photo size is 5472×3078. The RTK-GPS
255 (TOPCON, GR-3) not only has higher accuracy than the traditional total station and
256 dumpy level measurement instruments, but also does not require visual communication,
257 which greatly simplifies field work and has a more stable performance (Luo et al., 2019;
258 Yang, 2019). The Figure S1 shows the UAV and RTK-GPS we used.

259 (2) Survey Design

260 The flight parameters are as follows: the flight altitude was 74 m (110 m in March
261 2019), the photo overlap ratio was 85%/70% (heading/sideways), the camera tilt angle
262 was -90° (Luo et al., 2020, Shao, 2021). Sample dates, specific flight parameters, and
263 parameters setting used in each case are shown in a supplementary file (Table 1 and
264 Table S1).

265 Table 1. The flight parameters of the four monitoring using UAV

Date	Flight altitude(m)	Heading overlap (%)	Sideways overlap (%)	Camera tilt (°)	GSD(m)	Number of GCP	Number of CP
2019.03	110	85	70	-90	2.03	24	9
2019.07	74	85	70	-90	2.14	20	6
2020.01	74	85	70	-90	2.05	15	5
2020.08	74	85	70	-90	2.18	25	4

266 Note: GSD represents ground sampling distance, GCP represents Ground Control point,
267 CP represent Check Point.

268 (3) Survey Execution

269 In order to improve the measurement accuracy of UAV-SfM, we established many
270 ground control points and check points in the field. On the one hand, the matching
271 points in the post-processing process can be increased, and on the other hand, the error
272 can be controlled within the centimetre level. 43 ground control/check points were set,
273 which were coordinated using RTK-GPS (TOPCON, GR-3) with 10-20 mm planform
274 and 20-30 mm vertical accuracy (Figure S1 and Figure S2).

275 (4) Photogrammetric Processing

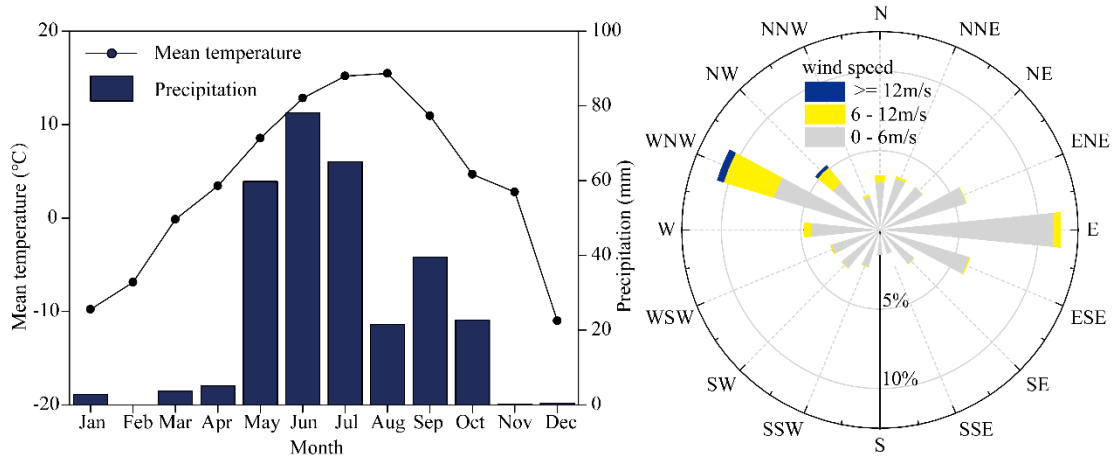
276 PIX 4D 4.4.10 software was utilised to produce DOM and DSM products. Each
277 project must go through three steps of initial processing, point cloud and mesh, DSM
278 and DOM. The camera model used for data splicing is FC6310_8.8_5472*3648 (RGB),
279 the geographic coordinate system coordinate of images is WGS84 (EGM96 Geoid), and
280 the output geographic coordinate system is UTMzone 47N (EGM96 Geoid). The details
281 of the parameters used in data processing were described in the supplementary file.

282 (5) Error Reporting

283 We used the measurement results of RTK-GPS to calibrate the coordinates of
284 UAV-SfM, and used horizontal error, vertical error and RMSE of ground control points
285 and check points to evaluate the accuracy of UAV-SfM. In this article (Luo et al., 2020),
286 the feasibility of using UAV-SfM in the study area from the point, line, and surface
287 perspectives all have been evaluated and discussed. We give the error of all ground
288 control points and check points in this study (Table S2).

289 2.2.2 Climate data

290 Climate data were obtained from a meteorological station (HOBO RX3000, with
291 five probes measuring temperature, precipitation, relative humidity, wind speed and
292 direction (100°20'29.81"E, 36°9'8.05"N). The weather station was located in the
293 upwind direction of Ertala sandy land in the Gonghe Basin (Figure1). The wind speed
294 and direction data were automatically recorded by an anemometer and a 16-azimuth
295 weathervane. The wind direction range was 0~360 ° (the north direction was set as 0
296 °). In this study, the meteorological station recorded parameters with a five-minute
297 interval. During the monitoring period (2019.08 - 2020.08), the average annual
298 temperature in the study area was 3.39°C, the hottest month was August (15.48 °C), and
299 the coldest month was December (-11.01 °C). The annual precipitation is 298.88 mm,
300 mainly occurring in the period May to July (Figure 2). The wind below 6 m/s accounts
301 for 92.75%, while wind greater than 12 m/s have a very low frequency, accounting for
302 only 0.66%. The study area has a bimodal wind regime, and the WNW and E are the
303 main wind direction, with a frequency of 11.93% and 12.9%, respectively. However,
304 the wind above 6 m/s was mainly WNW, with a frequency of 51.93% (Figure 2).



305

306

Figure 2. The mean temperature, precipitation and wind rose of the study area from August 2019 to August 2020.

307

308

2.2.3 Measurement of barchan dune celerity and morphological parameters

309

We obtained contour and brink information for barchan dunes based on data extraction from DOMs produced via UAV-SfM. In this work, the celerity of dunes was defined as the ratio of the distance a dune moved to its time in two adjacent monitoring periods (Sam et al., 2015). In addition, we also quantified changes in dune morphological parameters between specific monitoring periods. Figure 3a shows a schematic diagram of the dune celerity measurement approach adopted here (Zheng et al., 2022; Bristow, 2019), and figure 3b outlines the dune morphology parameters that we used (Yang et al., 2021; Merwe et al., 2022). In this paper, the derived dune morphological parameters included: dune height (H), dune length (L), the length of left horn (L_L), the length of right horn (L_R), the length of windward slope (L_W), dune width (W), and the basal area of the dune (S). Changes in these morphological parameters (ΔL , ΔH , ΔW , ΔS) between two sample periods were calculated using equations (2) to (5). Due to differences in the movement rates of the left and right horns of the dune and the dune slipface, we measure the movement of the two horns and slipface, where D_L represents the movement distance of the left horn, D_R represents the movement distance of the right horn, and D_C represents the movement distance of the slipface. The dune celerity is calculated using the following formula:

325

326

$$V_C = \frac{D_C}{\Delta t} \quad (1)$$

327

Where V_C represents the celerity of the dune, m/M; Δt represents the time interval, month(M).

328

329

$$\Delta L = L_1 - L_2 \quad (2)$$

330

$$\Delta H = H_1 - H_2 \quad (3)$$

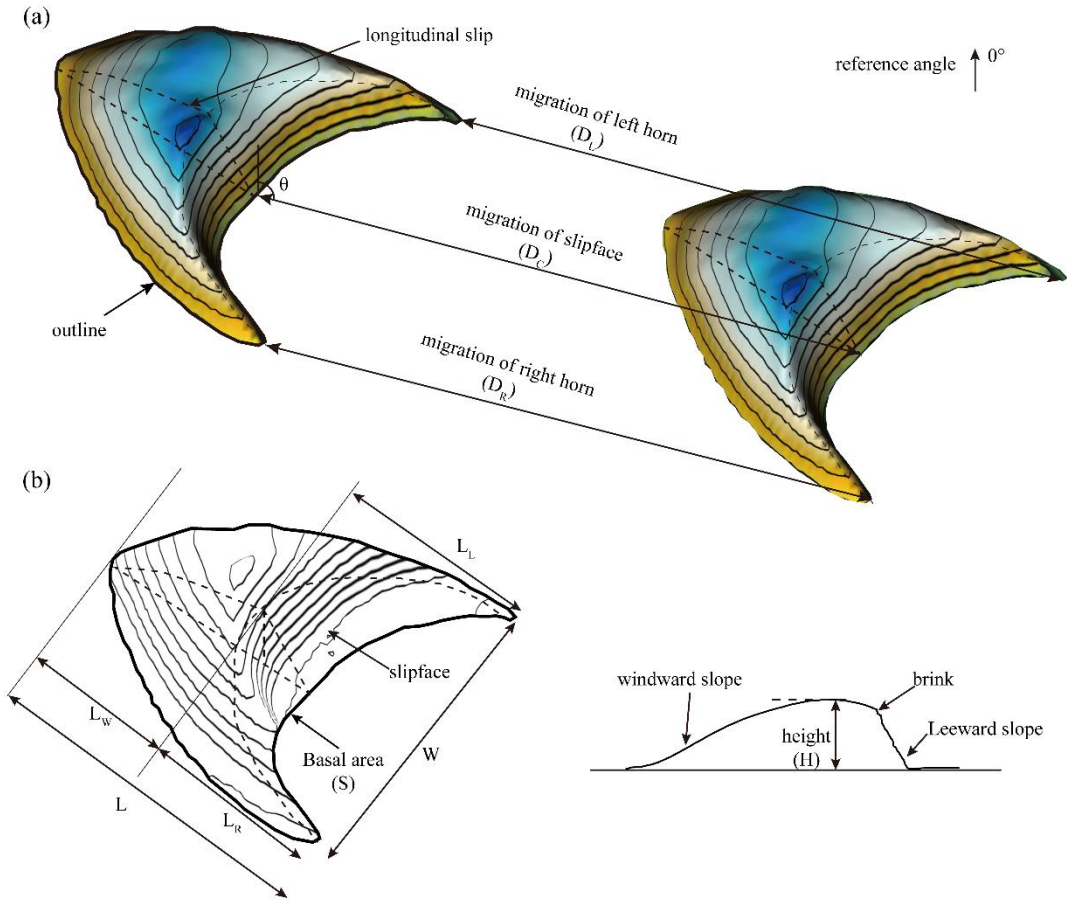
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$$\Delta W = W_1 - W_2 \quad (4)$$

332

$$\Delta S = S_1 - S_2 \quad (5)$$

333 Where L_1 , H_1 , W_1 and S_1 represent the dune morphology parameters of the former
 334 period, L_2 , H_2 , W_2 and S_2 represent the dune morphology parameters of the latter period.



335
 336 Figure 3. Schematic representation of the measurements of barchan dune celerity(a) and
 337 morphological parameters (b) used in this study.

338 Here, changes of erosion and accumulation were also evaluated. The net change
 339 of the dune surface, termed the erosion/accumulation depth (ΔDSM) was obtained by
 340 subtracting two elevation data sets (see eq.6). A negative value for ΔDSM indicates net
 341 erosion, and a positive value indicates a net accumulation.

342
$$\Delta DSM = DSM_2 - DSM_1 \quad (6)$$

343 Where DSM_1 represents the DSM of the previous period, the DSM_2 represents the
 344 DSM of the latter sample period.

345 2.2.4 Dune deformation analysis

346 The difference in length between the two barchan horns is also an important
 347 component of barchan dune morphology. Here we used the L_w/W ratio (a/c, Long and
 348 Sharp, 1964), and differences in horn length to assess the asymmetry of the dunes in
 349 the study area and to monitor their dynamic changes over time.

350 We also used D (total planform deformation), D_a (even deformation) and D_{na}
 351 (uneven deformation) to describe the dune deformation. Total planform deformation

352 measures the overall change in shape of the dune, considering both even and uneven
 353 deformation. The even deformation parameter is the homogeneous strain of dunes. The
 354 uneven change parameter represents the residual displacement after even
 355 transformation, meaning the amount of deformation that cannot be explained by the
 356 even deformation parameter. The calculation steps for these planform deformation
 357 parameters, based on two dune images, are as follows (Figure 4 a, c):

358 (1) Extract the dune outline from the DOMs for two monitoring periods, then
 359 translate the outline of the later period (t_2) to the former (1). The distance
 360 between the two was D_C , and the direction of translation for the outline is the
 361 opposite direction of dune movement in the two sample periods.

362 (2) Extract the location of sample points from the outline and calculate the total
 363 planform deformation. The extraction and calculation of samples points are
 364 explained in detail in Figure 4.

$$365 \quad D = \| r'_i - r_i \| \quad (7)$$

366 Where D is the total planform deformation, m/M , r_i represents the position
 367 coordinates of the dune outline points at the earlier stage, and r'_i is the position
 368 coordinates of the dune outline points at the later stage.

369 (3) Calculate the uneven (D_{na}) and even (D_a) planform deformation parameters of
 370 the dune.

$$371 \quad D_{na} = \sum_{i=1,2,\dots} \| r'_i{}^A - r_i \|$$

$$372 \quad = \sum_{i=1,2,\dots} \sqrt{(x'_i{}^A - x_i)^2 + (y'_i{}^A - y_i)^2} \quad (8)$$

$$373 \quad D_a = \sum_{i=1,2,\dots} \| r'_i - r'_i{}^A \|$$

$$374 \quad = \sum_{i=1,2,\dots} \sqrt{(x'_i - x'_i{}^A)^2 + (y'_i - y'_i{}^A)^2} \quad (9)$$

$$375 \quad r'_i{}^A = E(t, \delta_t, r_c) r'_i \quad (10)$$

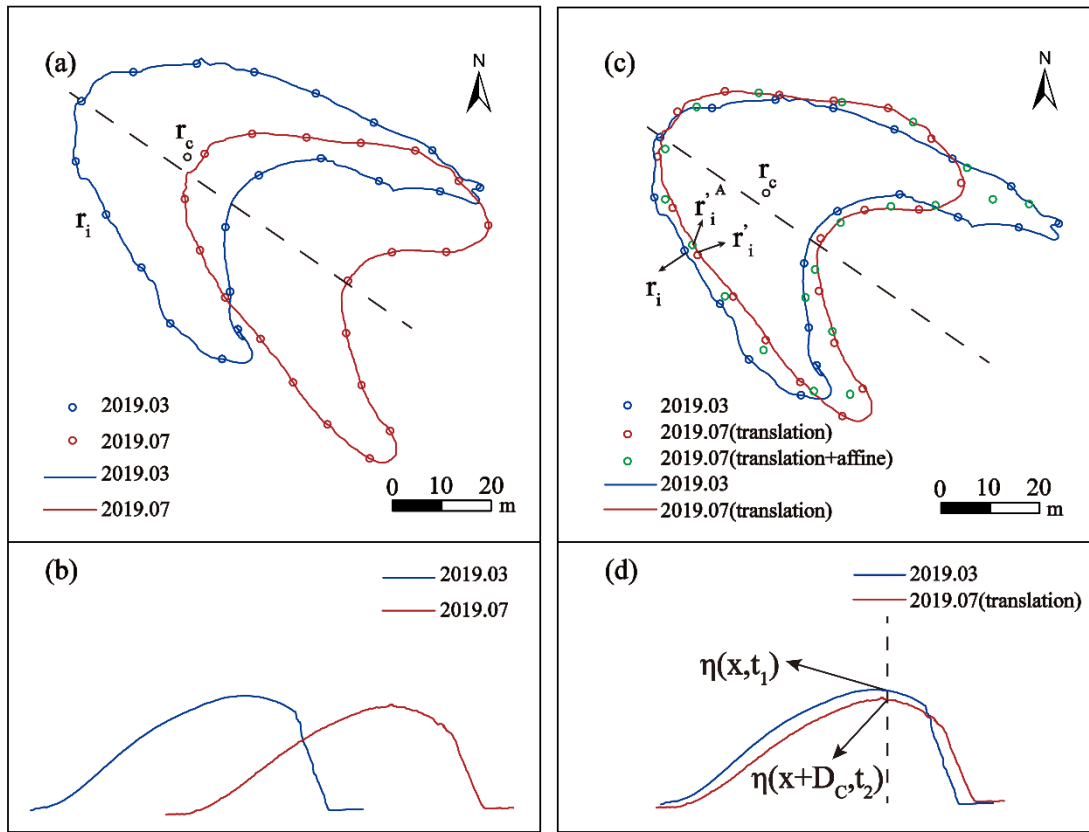
376 where (x_i, y_i) represents the location of sample point i at the earlier stage, and $(x'_i,$
 377 $y'_i)$ represents the location of sample point i at the later stage, $(x'_i{}^A, y'_i{}^A)$ represents the
 378 location that (x'_i, y'_i) would be in if all deformation occurred along the even
 379 deformation matrix A . $E(t, \delta_t, r_c)$ represents the even transformation matrix. D_a and
 380 D_{na} are dimensionless parameters.

381 In this work, we use the residual elevation differences, Π (m/M , the interval of
 382 each measurement was several months so the deformation of the dune was represented
 383 by m/M here). Π represents the vertical deformation at each point on the dune (Lee
 384 et al., 2019), which directly measures the accumulation/erosion of the barchan dune.

385 The calculation steps of Π based on two dune images are as follows (Figure 4 b, d):
 386 (1) Extract the elevation and coordinate location of the dune profile along the
 387 central axis of the dune in two images.
 388 (2) Shift the later dune profile to the former, the distance of which was the D_C , the
 389 direction of which was the opposite direction of dune movement in the two
 390 periods.
 391 (3) Calculate the vertical deformation parameter of the dune using the following
 392 formula:

$$393 \quad \Pi = \frac{\eta(x+D_C, t_2) - \eta(x, t_1)}{\Delta t} \quad (11)$$

394 where $\eta(x+D_C, t_2)$ represents the elevation at time t_2 , m; $\eta(x, t_1)$ represents the
 395 elevation at time t_1 , m; Δt represents the time interval. In this study, the image of the
 396 dune taken in March 2019 (Figure 4) was taken as a reference, and the dunes in the
 397 image of the other three periods were shifted.



398
 399 Figure 4. Definition sketch for deformation variables used here (a) and (c) show the calculation
 400 principle of planform deformation; (b) and (d) represent the calculation principle of vertical
 401 deformation. The two different coloured lines represent the dune planform outline and profile
 402 sampled at two different months, March (blue) and July (red) 2019. The lines in figure b and d
 403 represent the same profiles but with the red line (July) shifted back by the profile travel distance,
 404 D_C . The selection method for even and uneven deformation points was as follows: firstly, the
 405 position of the bottom edge of the windward slope of the dune was selected, and then the remaining

406 points were selected by using an equal proportion method according to the relative circumference
407 of the dune (Modified from Lee et al., 2019).

408 2.2.5 Air flow and sand transport

409 (1) Equipment

410 Ultrasonic anemometer (UA) is providing a new insight into turbulent
411 characteristics and subsequent sediment transport studies while challenges remain in
412 field setup and post-processing (Smith et al., 2017). In this study, a calibrated two-
413 dimensional ultrasonic anemometer (DS-2) was used in April 2019 to observe wind
414 speed and direction on dune surface. The instrument provided an integrated
415 measurement of wind speed and direction. The resolution of wind speed was 0.01 m/s,
416 the range of wind speed was 0~60 m/s, the resolution of wind direction was 1°, and the
417 observation range of wind direction was 0~360°.

418 (2) Survey Design and Execution

419 The measured height was about 5 cm from the dune surface, and the synchronous
420 observation was adopted to obtain the surface synchronous airflow. Therefore, the
421 observation of the near-formation airflow was only carried out on a small dune (No.2
422 dune) in the study area (Figure 1). The windward slope of the dune is 47.1m long, the
423 width of the dune is 57.6 m, and the height of the dune is 3.44 m. A total of 31 UA (DS-
424 2) were arranged to measure the airflow (Figure S3a and S3c). The measurement
425 frequency was 0.1 HZ, and the measurement time was 20 minutes.

426 At the same time, a vertical step-like sand collector (see Figure S3b) was used in
427 April 2019 to observe the sand transport flux within a height of 1 m on the surface of
428 No. 2 dune (see Figure 1). The size of sand inlet was 0.02 m high × 0.02m wide, with
429 a total of 50 layers. A total of 6 sand collecting instruments were set on the surface of
430 the dune, and the sand collecting time was 10 minutes. During sand collection, the step-
431 like sand collectors were placed in a position which faces the direction of the incoming
432 wind flow. When sand entered the sand collector at each height, the sand was
433 transferred from the collecting port and stored in the rear sand collecting container.
434 Finally, the collected sand samples of each height layer were weighed and recorded
435 with a 1/1000 electronic balance. Since the weight of the sand collected above 0.4 m
436 was negligible, only the sand accumulation data below 0.4 m was used for calculation
437 and analysis here. To facilitate the analysis, we convert the sediment weight into the
438 sediment transport rate in grams per minute (g/m).

439 (3) Data processing

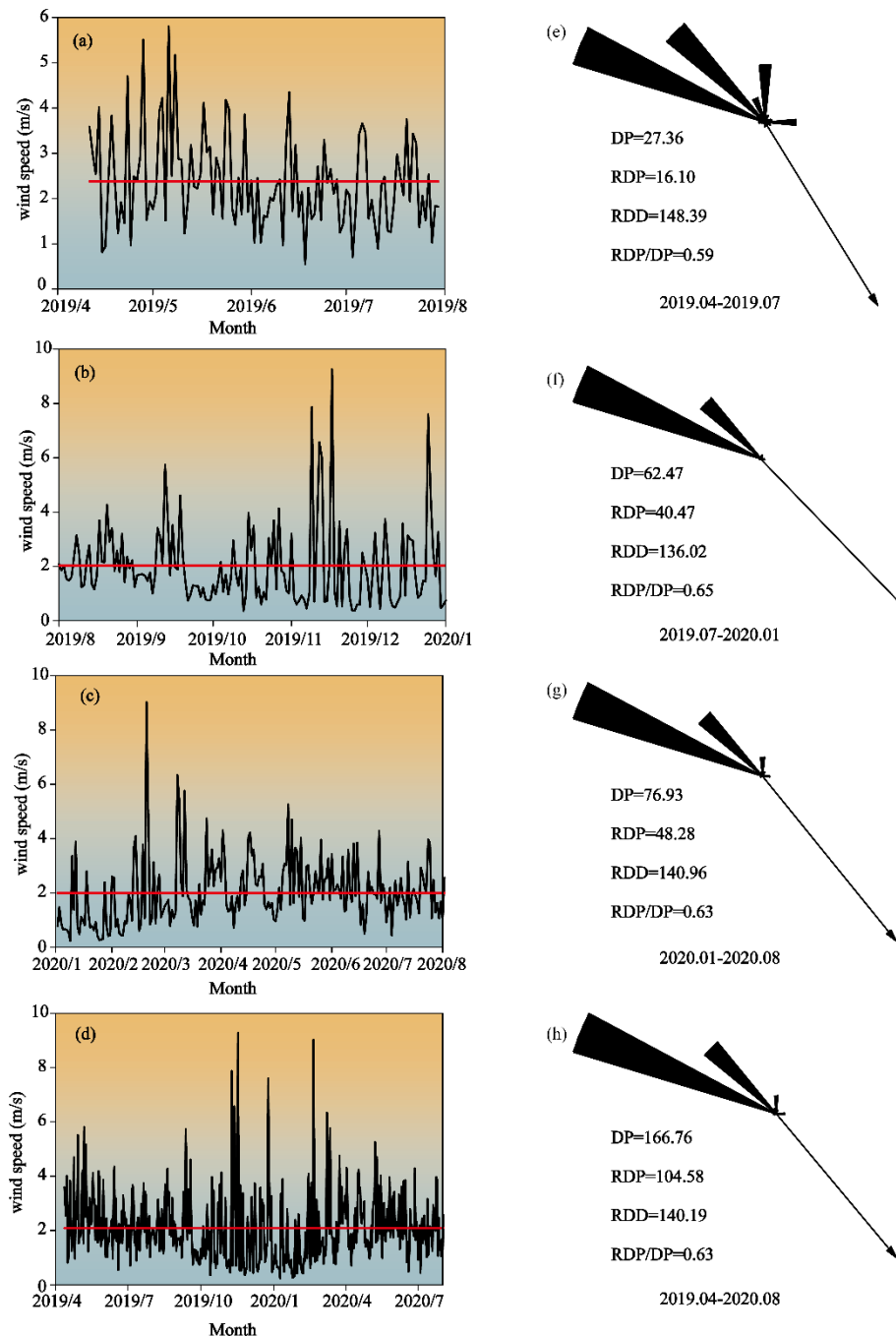
440 In this study, surfer13 software was used for air flow data processing. The specific
441 processing steps were as follows. (a): The point data was interpolated into grid data.
442 The wind speed and direction data of each point measured in the field are in text format.
443 Firstly, the Kriging interpolation method is used in surfer software to generate grid data
444 of wind speed and direction data. When interpolating, the variance model defaults to
445 linear with slope of 1 and aniso of 1 and 0 respectively. The difference interval between
446 the x and y axes is the default. The conversion function of Z values is linear. (b): Add

447 DSM data to the created project file as the base map of the flow field. This step also
448 requires converting the DSM data into a grid file now. (c): Load vector files (pre-
449 processed grid files of wind speed and direction) on the existing base map. (d): Adjust
450 the Angle and coordinate system of the vector file. The coordinate system is polar, and
451 the Angle 0 is set to north.

452 **3. Results**

453 3.1 Wind regime

454 The average daily wind speed in the study area was within the range of 0-10 m/s
455 (Figure 5a-d), the average wind speed during the entirety of each monitoring period was
456 between 2-3 m/s, and the average annual wind speed was 2.02 m/s. The average annual
457 wind speed in Gonghe Basin is therefore slightly lower than for other deserts in China
458 (Liu, 2018; Gu et al, 2022). In the study area, the average daily wind speed in winter
459 and spring is significantly higher than that in other seasons. Resultant drift potential
460 reflects the potential transport capacity of wind for sand in a region, according to the
461 meteorological data and surface sample data collected in the study area is 5.48 m/s, and
462 the resultant drift potential in each monitoring period is calculated based on this. During
463 the entire monitoring period (16 months), the total resultant drift potential of the study
464 was 166.76 VU, and the annual resultant drift potential was 125.07 VU, which is a low
465 wind energy environment (Figure 5 h). The direction of sediment transport is 140.19°,
466 the wind variability index is 0.63, which belongs to the medium ration. Among the three
467 monitoring periods, the resultant drift potential of the third monitoring period is the
468 largest, while that of the first period is smallest. It should be noted here that the resultant
469 drift potential of the first period is one month later than the measurement time of the
470 UAVs. The direction of synthetic sediment transport in each monitoring period is
471 consistent, indicating that the regional synthetic wind direction is mainly WNW, and
472 the wind direction variability is around 0.6 (Figure 5 e-h).



473

474 Figure 5. Daily mean wind speed and sand driving wind rose in every monitoring period. Figure (a)-
 475 (d) represent the daily mean wind speed variations in the study area, and the red line is the average
 476 wind speed in each monitoring period. Figure (e)-(h) show the resultant drift potential in each
 477 monitoring period.

478 3.2 Barchan dune shape

479 In this study area, detailed morphological parameters were generated for 16 dunes.
 480 According to the morphological classification standard (Long and Sharp, 1964), within
 481 our sample there are 2 slim types ($L_w/W < 0.5$) types, 7 normal types ($0.5 \leq L_w/W < 0.75$)
 482 types, 3 pudgy types ($0.75 \leq L_w/W < 1$) and 4 fat types ($L_w/W > 1$). Most barchan dunes
 483 in the study area were asymmetrical. Only dune No. 10 and No.14 displayed roughly

484 equivalent (symmetrical) arms. Among the asymmetric dunes right dunes horns (except
 485 dune No. 12 and No. 15) were typically extended further than the left, occasionally even
 486 reaching 15.58 times of the length of the left horn (Table 2).

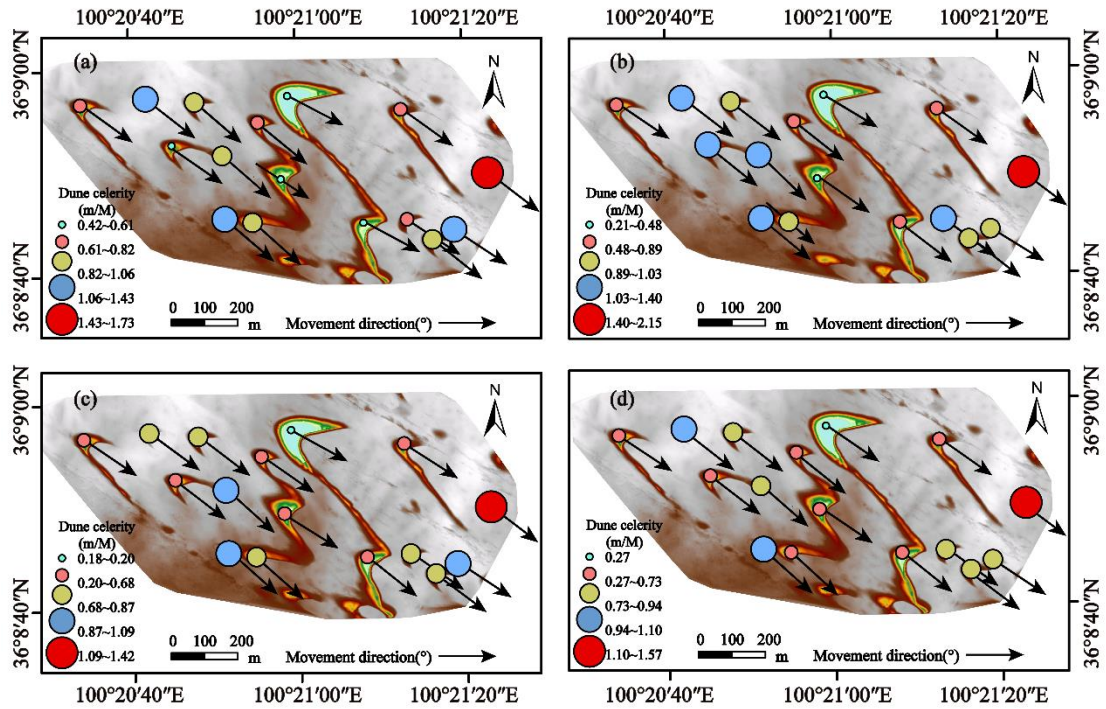
487 Table2. The barchan dunes morphological parameters

Dune number	H(m)	L/W	L _w /W	L _R /L _L
No.1	6.6	3.31	0.67	3.72
No.2	3.44	1.51	0.82	2.03
No.3	5.65	1.58	0.77	1.47
No.4	14.42	2.96	0.45	4.85
No.5	5.71	3.93	0.67	3.49
No.6	6.22	4.7	1.2	4.17
No.7	6.09	1.49	0.64	1.71
No.8	4.16	2.87	1.78	9.59
No.9	8.1	2.55	1.06	15.58
No.10	2.49	1.33	0.72	0.81
No.11	3.36	2.88	1.71	1.9
No.12	5.17	0.95	0.69	0.18
No.13	8.04	1.87	0.56	6.13
No.14	3.67	0.92	0.46	0.98
No.15	4.1	0.97	0.76	0.25
No.16	4.97	1.46	0.74	1.52

488

489 3.3 Barchan dune celerity

490 Figure 6 shows that the average celerity of all dunes in the study area was about
 491 0.85 m/M ('m/M' = meters of movement per month) between March 2019 to August
 492 2020. The celerity per dune was classified using the Zhu et al (1981) scheme, and fast
 493 (>10 m/yr) types accounted for the largest proportion (50%), followed by medium
 494 (5~10 m/yr, 44%), and slow (<5 m/yr, 6%). As expected, dune celerity data here
 495 exhibited the significant variability in relation to dune size, where the maximum rate
 496 was up to 10 times the minimum. For example, in July 2019, the dune celerity of No.10
 497 (the location see Figure 1) was 2.15 m/M, and that of dune No.4 (the location see Figure
 498 1) was 0.21 m/M. The average dune celerity between July 2019 and January 2020 was
 499 also faster than other periods, and the third measurement period (from January 2020 to
 500 August 2020) was the slowest. We also measured the celerity of left and right horns of
 501 the barchan dunes (Table S3). In the three measurement periods (2019.03~2019.07,
 502 2020.01~2020.08 and 2019.03~2020.08), the movement of the left horns was faster than
 503 the right. In the second period (2019.07~2020.01), the movement of the right horns was
 504 faster. Figure 6 and table S3 all show that the symmetry of barchan dune have no
 505 obvious influence on the dune celerity.



506

507 Figure 6. Maps of barchan dunes' celerity and direction. (a) The celerity and direction of dunes in
 508 2019.03-2019.07. (b) The celerity and direction of dunes in 2019.07-2020.01. (c) The celerity and
 509 direction of dunes in 2020.01-2020.08. (d) The celerity and direction of dunes in 2019.03-2020.08.
 510 'm/M' represents meters per month.

511

3.4 Vertical dune deformation

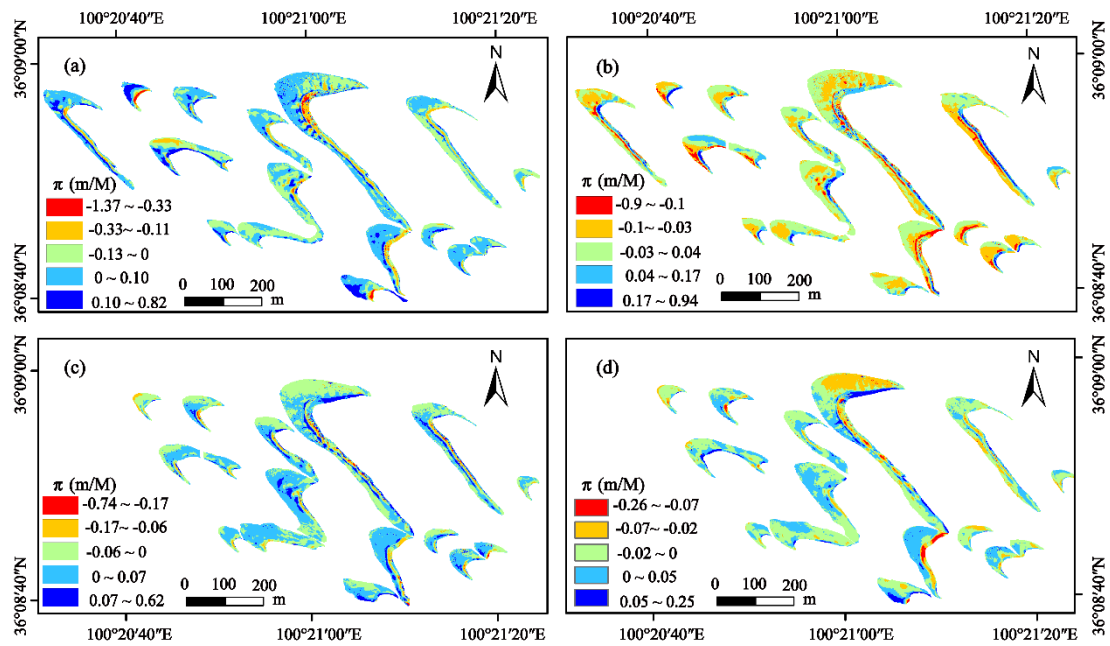
512

We calculated the parameter Π , which represents the vertical deformation of the
 513 dunes across our different monitoring periods (Figure 7). We observe that smaller
 514 absolute values of Π equate to lower erosion/deposition magnitude. Also, higher
 515 absolute values of Π reflect greater is the vertical deformation. The value of Π from
 516 March 2019 to August 2020 ranged from ± 0.3 m/M, which was a little higher than
 517 the calculations of Lee et al (2019) (± 2 m/yr). We see a broad trend, whereby vertical
 518 deformation degree for smaller dunes was slightly higher than that of larger dunes but
 519 note that the correlation between these data is not strong.

520

Across the study region, higher accumulation and erosion was observed on the
 521 leeward slopes and the extended right horn of our dunes. The characteristics of dune
 522 erosion and accumulation in the first (2019.03~2019.07) and third periods
 523 (2020.01~2020.08) were similar; whereby windward slopes experienced relatively low
 524 levels of accumulation, and accumulation depths were typically within 0.13 m. While
 525 in the second period, the windward slope was dominated by low rates of erosion, and
 526 the erosion depth was typically within 0.10 m.

527



528

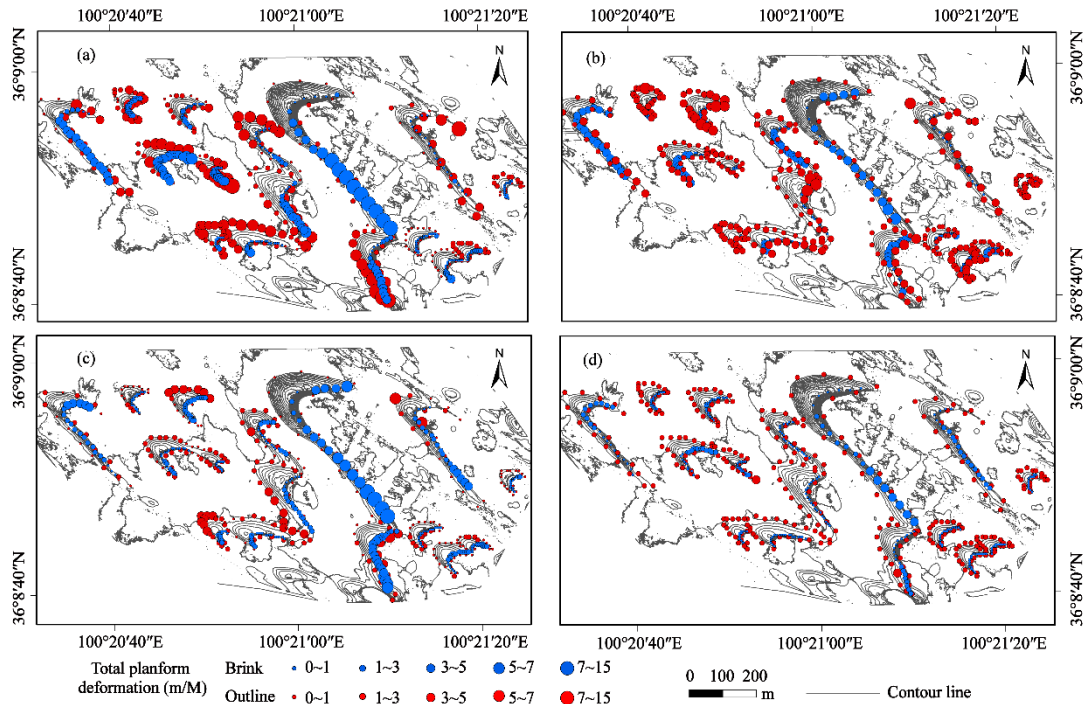
529 Figure 7. Distribution maps of vertical deformation of individual dune in the barchan dune field.
 530 (a) The monthly vertical deformation in 2019.03-2019.07. (b) The monthly vertical deformation in
 531 2019.07-2020.01. (c) The monthly vertical deformation in 2020.01-2020.08. (d) The monthly
 532 vertical deformation in 2019.03-2020.08.

533 3.5 Planform deformation

534 3.5.1 Total planform deformation

535 During the whole monitoring period, small dunes (height < 5 m) showed a trend
 536 of shortening, widening, an increase in height, and an increase in the basal area. Large
 537 dunes (height > 5 m) showed a trend of lengthening, widening, an increase in height
 538 and an increase in the basal area (see Figure S4). Figure 8 provides a temporal and
 539 spatial summary of the distribution of the total deformation characteristics of dune
 540 outlines and brinks in our study area. These data were classified into five categories
 541 according to the natural discontinuity classification method. The total planform
 542 deformation D of the dune outlines in the study area ranges from 0 to 15 m/M. The
 543 summary value of D in the first monitoring period (Figure 8a) was significantly higher
 544 than that of the other monitoring periods (Figure 8b, c, d). Spatially, with an increase
 545 of dune scale, the value of D for dune outlines increased, and the degree of the total
 546 deformation on the windward slope was generally greater than that of the leeward slope.
 547 The degree of total planform deformation at the brink was smaller than that at the
 548 outline, but we found a consistent trend at the barchan dune scale whereby large dunes
 549 (dune height > 5 m) showed generally greater brink deformation than that at the small
 550 dunes (dune height < 5 m). The average of the former was 1.64 m/M, while the latter
 551 was 0.76 m/M. The value of total planform deformation at the brink of the large dunes
 552 even reached 11.06 m/M, commonly associated with the extended horns of asymmetric
 553 dunes.

554



555

556 Figure 8. Temporal and spatial distribution of total planform deformation of barchan dunes. (a) The
 557 monthly total planform deformation in 2019.03-2019.07. (b) The monthly total planform
 558 deformation in 2019.07-2020.01. (c) The monthly total planform deformation in 2020.01-2020.08.
 559 (d) The monthly total planform deformation in 2019.03-2020.08.

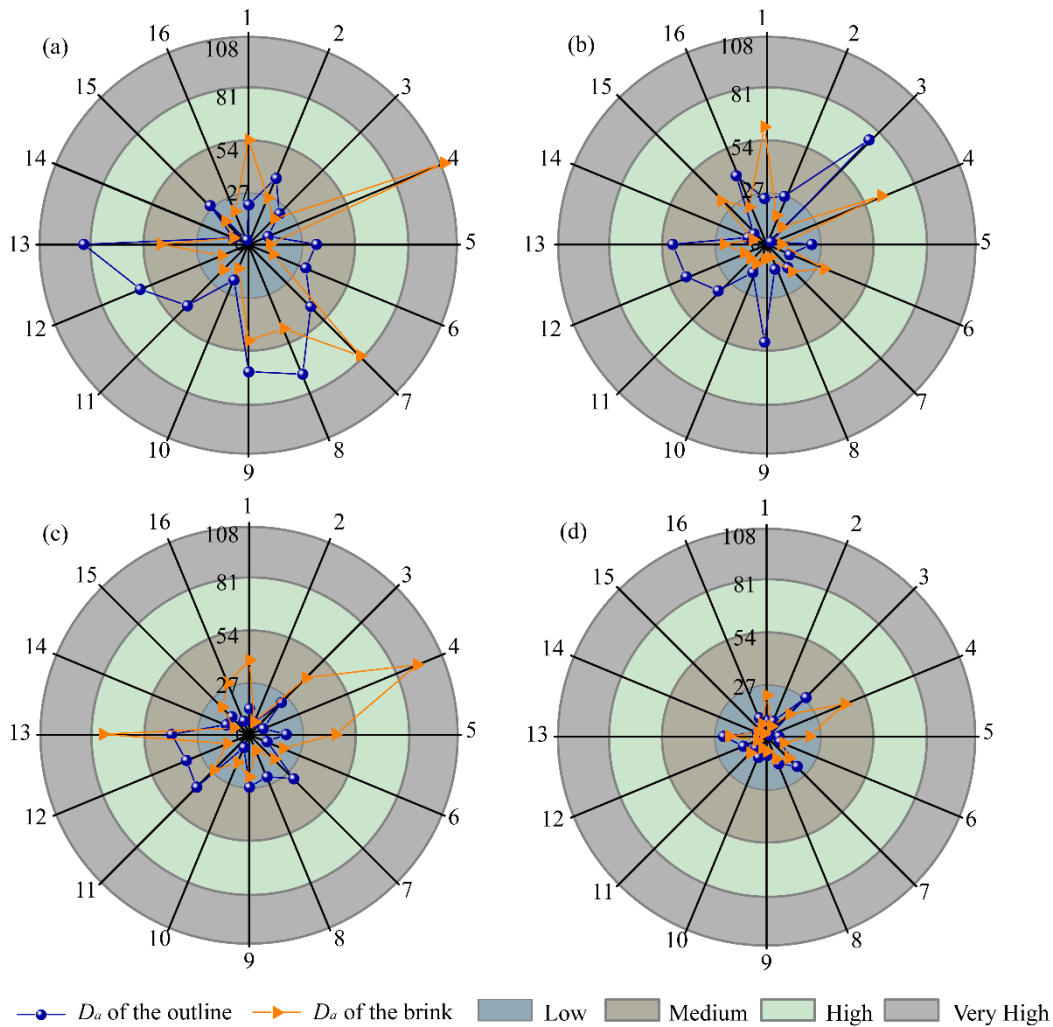
560

3.5.2 Even deformation

561

Even deformation refers to the homogeneous strain of dunes, and, as noted above
 562 refers to the uniform (homogeneous) change in shape of the dune, where all parts of the
 563 dune are assumed to change by the same amount. However, it is difficult to directly
 564 reflect the characteristics of even planform deformation for dunes due to the large
 565 differences in D_a . Here, D_a was divided into 4 types by quartile of the maximum D_a ,
 566 and the classification type and range for these are shown in figure9. The results show
 567 that D_a varied from 1.53 to 84.16 for dune outlines and was distributed from 2.07 to
 568 107.89 for dune brinks. The even deformation of different dunes varied greatly within
 569 and between each monitoring period (Figure 9). For example, the D_a of dune No.13 for
 570 its outline was 84.16 from March 2019 to July 2019, while that of dune No.16 was only
 571 2.48. As shown figure 9, the degree of even deformation of the 16 dunes in the study
 572 area mainly skewed towards low deformation (70.3%), followed by medium
 573 deformation (21.1%), high deformation (6.3%), and very high deformation (only 2.3%).
 574 The degree of even planform deformation in the total monitoring periods was lowest
 575 between March 2019 to August 2020 where the low deformation class accounted for
 576 more than 94%.

577



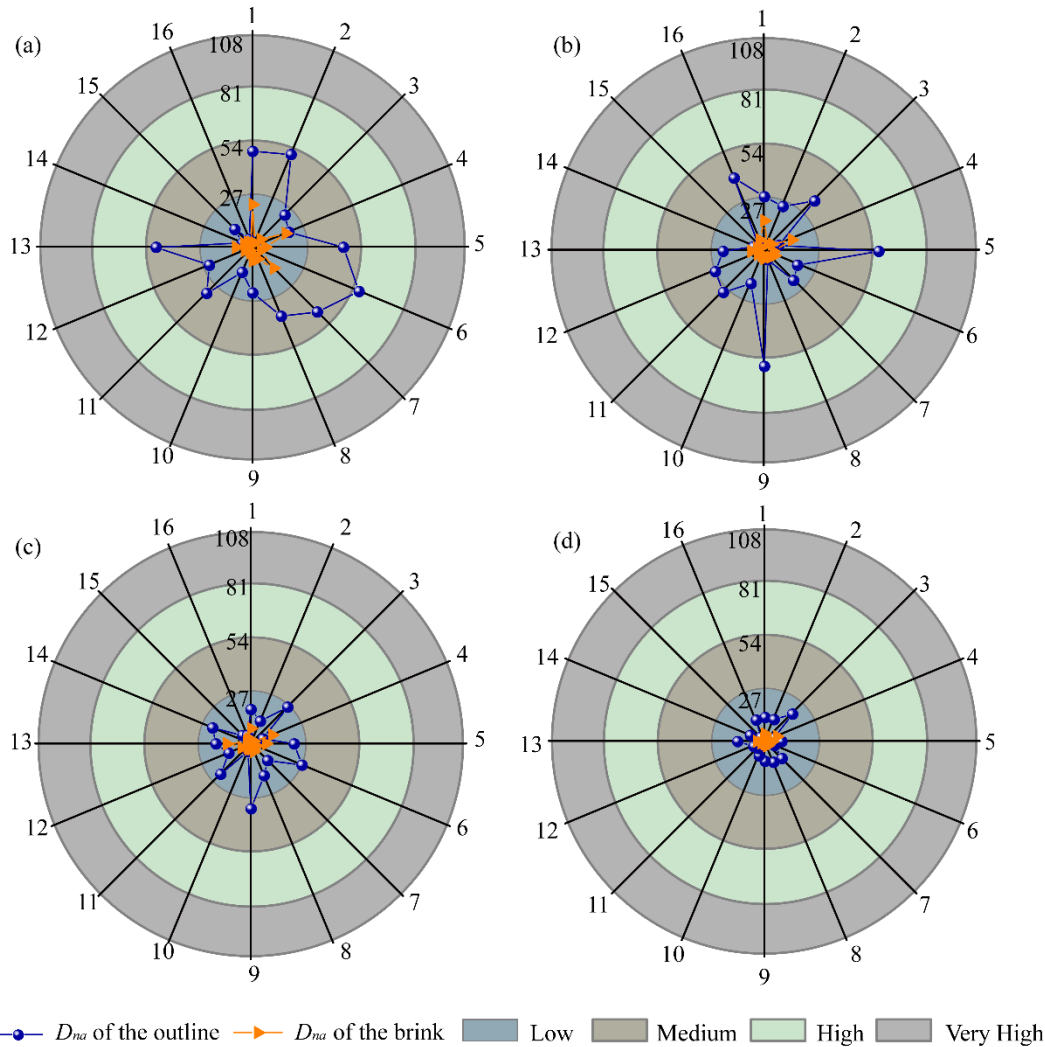
578

579 Figure 9. The value of even planform deformation of individual dune on the counter and brink (1-
 580 16 in the figure represents the number of dunes. (a) The even planform deformation in 2019.03-
 581 2019.07. (b) The even planform deformation in 2019.07-2020.01. (c) The even planform
 582 deformation in 2020.01-2020.08. (d) The even planform deformation in 2019.03-2020.08. Low (0-
 583 27), Medium (27-54), High (54-81), Very High (81-108).

584 3.5.3 Uneven deformation

585 Uneven deformation accounts for the residual deformation after even deformation
 586 calculation for dunes. The results here show that the D_{na} ranged from 3.15 to 58.67 for
 587 dune outlines and from 0.75 to 21.78 for dune brinks (Figure 10). D_{na} was less than D_a
 588 in both range and mean. The variation of D_{na} was consistent with that of total planform
 589 deformation D and even deformation D_a . The degree of uneven deformation was the
 590 lowest during the monitoring period from March 2019 to August 2020 (table 3). The
 591 mean value of D_{na} from March 2019 to August 2020 for dune outlines was 9.57, while
 592 that of dune brinks was only 2.17. D_{na} decreased over time, and the mean value of D_{na}
 593 at the dune brink was less than that at the outline in each period, which was different
 594 from D_a . D_{na} was also classified in order to facilitate the analysis of the degree of uneven
 595 deformation (Figure 10). The results show that the degree of uneven deformation was

596 mainly low deformation (86.7%), followed by medium deformation (10.9%), and
 597 finally high deformation (2.3%). There was no very high deformation type in the
 598 uneven deformation, and the degree of uneven deformation of the dunes was lower than
 599 its even deformation. Low (0-27), Medium (27-54), High (54-81), Very High (81-108).



601 Figure 10. The value of uneven planform deformation of individual dune on the counter and brink
 602 (1-16 in the figure represents the dune number, which is link to the figure 1. (a) The uneven planform
 603 deformation in 2019.03-2019.07. (b) The uneven planform deformation in 2019.07-2020.01. (c) The
 604 uneven planform deformation in 2020.01-2020.08. (d) The uneven planform deformation in
 605 2019.03-2020.08.

606 The proportions of even and uneven in the total deformation of dunes were
 607 calculated to reflect which kind of deformation the dunes tend to have. Table 3 shows
 608 that the deformation at the brink of a dune tends towards even deformation, while the
 609 deformation at the outline of the dune is roughly equal to even deformation and uneven
 610 deformation. In the deformation of a dune outline, there was little difference between
 611 even deformation and uneven deformation, where the proportion of even deformation
 612 was slightly larger (about 52%), and this proportion remained stable in each monitoring
 613 period ($\pm 2\%$). At the brink of the dunes, the proportion of even deformation was much
 614 larger than that of uneven deformation, with the former accounting for 81.5% and the

615 latter 18.5%, and the proportion of the two changes greatly in each monitoring period,
 616 with a decrease of about 8% from the second monitoring period to the third monitoring
 617 period.

618 Table 3. The proportion of even deformation and uneven deformation of dunes

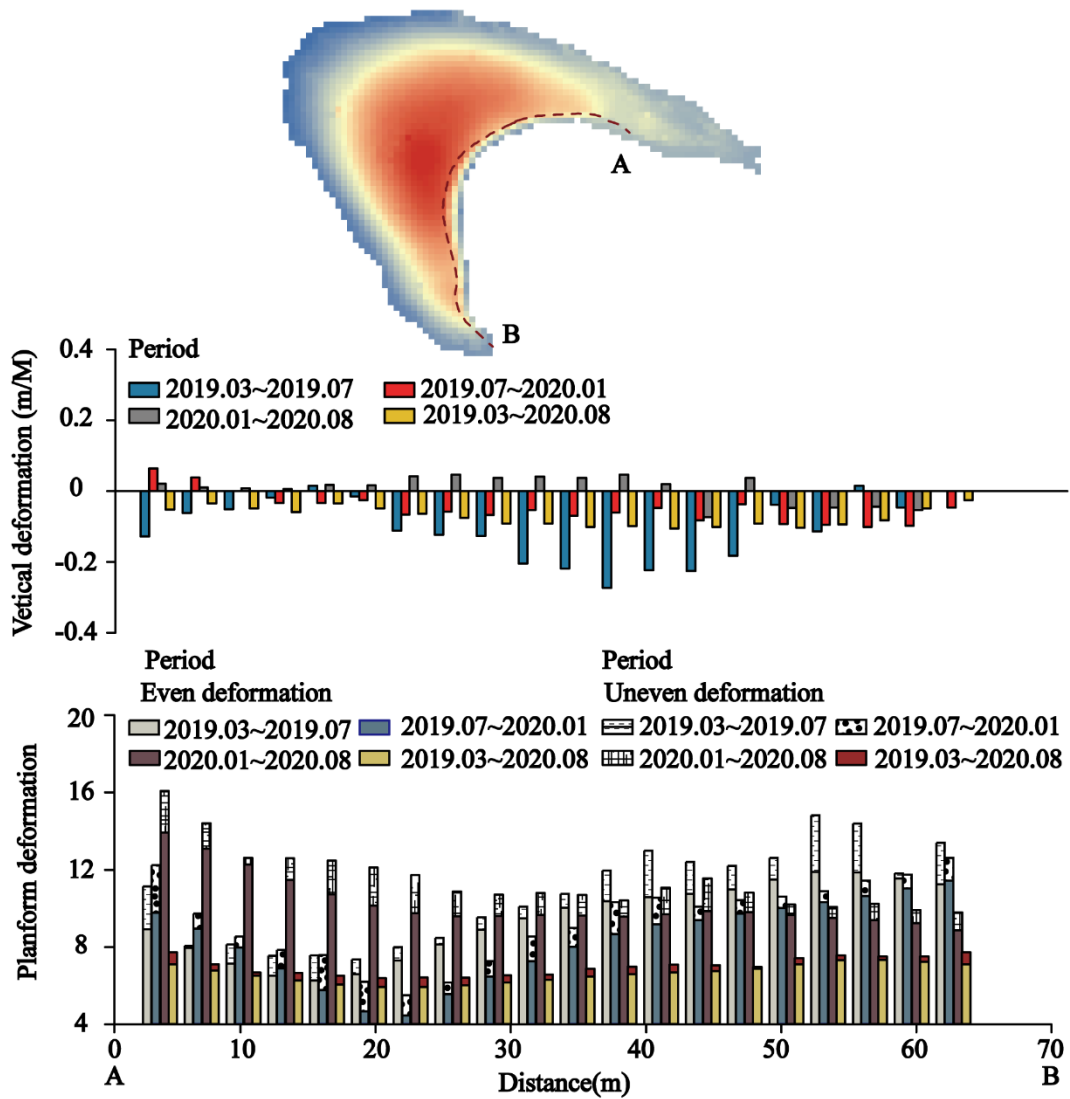
Position	Parameter	2019.03~	2019.07~	2020.01~	2019.03~
		2019.07	2020.01	2020.08	2020.08
Outline	D_{na}	0.479	0.478	0.463	0.480
	D_a	0.521	0.522	0.537	0.520
Brink	D_{na}	0.195	0.238	0.154	0.153
	D_a	0.805	0.762	0.846	0.847

619 3.6 Three-dimensional deformation of symmetrical and asymmetrical barchan

620 Eastwood et al (2012) show that the dunes gradually deform in response to each
 621 sand transport wind event as deposition and erosion on the leeward surface is unlikely
 622 to be uniform. Livingstone (2003) demonstrated that the shape of the top of a dune can
 623 reflect annual climate changes, principally reflecting seasonal changes in wind
 624 orientation. In addition, results of the flume experiments also indicate that dune
 625 deformation is commonly observed (e.g. Scheltinga et al., 2020).

626 Figure 11 and Figure 12 show the elevation profile and deformation at the brink
 627 (from A to B) of dunes No.10 and No.4. The two horns of dune No.10 were symmetrical,
 628 and its planform and vertical deformation were also symmetrically distributed with the
 629 central axis of the dunes at the midpoint. In contrast, the two horns of dune No.4 were
 630 asymmetrical. In the vertical direction, the brink of dune No.10 was mainly eroded (the
 631 vertical deformation was negative), and, of note, the erosion was the largest observed
 632 in the first monitoring period. From the left horn of the dune No.10, the vertical
 633 deformation increased first, reaching a maximum value near the central axis of the dune
 634 No.10, and then gradually decreased. In the planform direction, the deformation of the
 635 brink of dune No.10 was mainly even deformation. Starting from the left horn of the
 636 dune, the deformation gradually decreased towards the central axis of the dune, and
 637 then gradually increased, demonstrating high deformation on the two horns and low
 638 deformation in the middle. The variation trend of vertical deformation was opposite to
 639 that of planform deformation. The brink profile on dune No.4 can also be divided into
 640 two parts, with the main part of the dune on the left and the extended part of the right
 641 horn on the right. In the vertical direction, the brink of the dune was mainly eroded.
 642 From the left horn of the dune to the right horn of the dune No.4, the vertical
 643 deformation degree gradually increased from the central axis of the dune, and gradually
 644 decreased until the middle of the elongated horn. The deformation of an asymmetric
 645 dune does not have obvious symmetry, which is different from that of a symmetric dune.
 646 In the planform direction, the brink of the dune was dominated by even deformation,
 647 and the deformation degree of the main part of the dune was significantly lower than

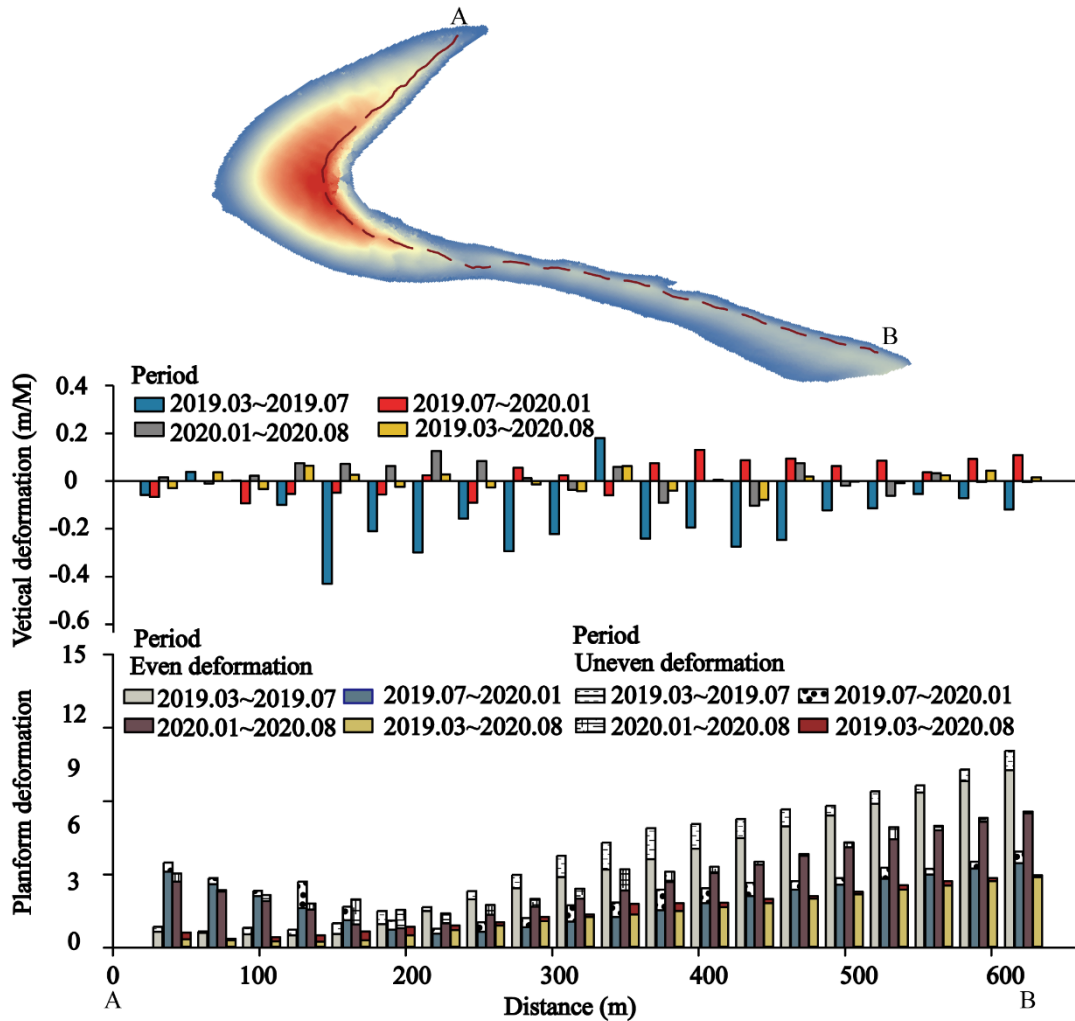
648 that of the dune extension. Therefore, the deformation characteristics of the dune brink
649 maybe closely related to its extended horn.



650

651

Figure 11. Three-dimensional deformation at the brink of a symmetrical barchan dune



652

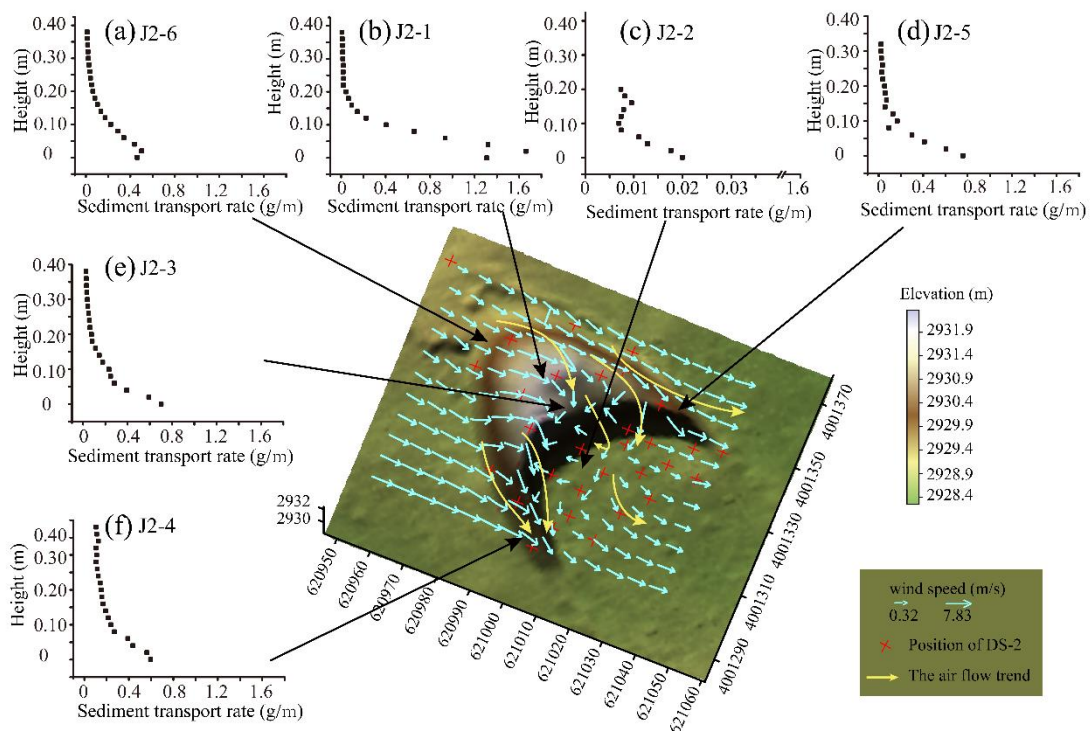
653 Figure 12. Three-dimensional deformation at the brink of an asymmetrical barchan dune.

654 3.7 Near-surface airflow and sand transport

655 The data of the reference point set by the upwind direction of the dune show that
 656 the airflow entered from the upwind direction of the dune at a speed of 6.26 m/s and an
 657 angle of 275°, and the flow direction was about 40° diagonally intersected with the
 658 direction of the dune (Figure 13). Then the air flow climbs along the windward slope,
 659 during which the surface air flow was divided into three branches. The first air flow
 660 passed along the axis of the barchan dune and its direction was basically unchanged
 661 before reaching the brink. The flow speed first accelerated and then decelerated, finally
 662 separated at the brink. One part of the air flow deflected to the northwest direction along
 663 the slip face, speed up the flow, the other part of the air flow generated eddy current on
 664 the slip face and the velocity slowed down, at the bottom of the slip face velocity to the
 665 lowest value, finally the flow resumed its original direction. The second air flow was
 666 deflected to the left side of the dune, its direction was relatively stable as it moved
 667 forward, but the velocity increased. This flow separated at the horn, and one stream
 668 continued in the original direction, while the other, deflected southwest and crossed the
 669 bare land of the leeward downwind to the right horn after crossing the brink. The third

670 airflow to the right horn of the dune, moved southward along the right horn, and
 671 complex changes occurred in the process. The direction of the airflow to the north of
 672 the brink basically remained unchanged, and the airflow adjusted to the southwest on
 673 the brink to advance along the brink. The air flow on the south side of the brink was
 674 greatly deflected, and the air flow also moved along the right horn.

675 Within 0.4 m height from the surface of the dune, there are some differences in the
 676 sediment transport rate and direction of the 6 characteristic parts of the dune. The
 677 direction of sediment transport at the bottom of the windward slope is 275° , the
 678 direction of sediment transport at the middle and top of the windward slope has little
 679 change (281° and 279° respectively), while the direction of sediment transport at the
 680 bottom of the leeward slope is deflected (84°). The direction of sediment transport on
 681 the two horns of the dune is basically consistent with the windward slope, with the left
 682 horn being 292° and the right horn being 285° . The sediment transport rate increases
 683 first and then decreases along the windward slope. The sediment transport rate on the
 684 leeward slope (0.116 g/m , Figure 13c) is much lower than that on other parts of the
 685 dune, and the sediment transport rate on the right side (4.43 g/m , Figure 13f) of the
 686 dune is higher than that on the left side (2.87 g/m , Figure 13d), which was mainly caused
 687 by the convergence and separation of air flow. The separated air flow carried the sand
 688 grains to both sides of the left horn, and the sand transport was naturally low. The
 689 extended horn of the dune was represented by the convergence of air flow, which
 690 collected sand grains from the windward slope and falling slope to the right horn,
 691 resulting in higher sand transport. The asymmetric air flow and sediment supply may
 692 result in the asymmetrical barchan dune in the study area.



693

694 Figure 13. Characteristics of sediment transport rate and air flow on the dune surface of a barchan
 695 dune present within the studied barchan field

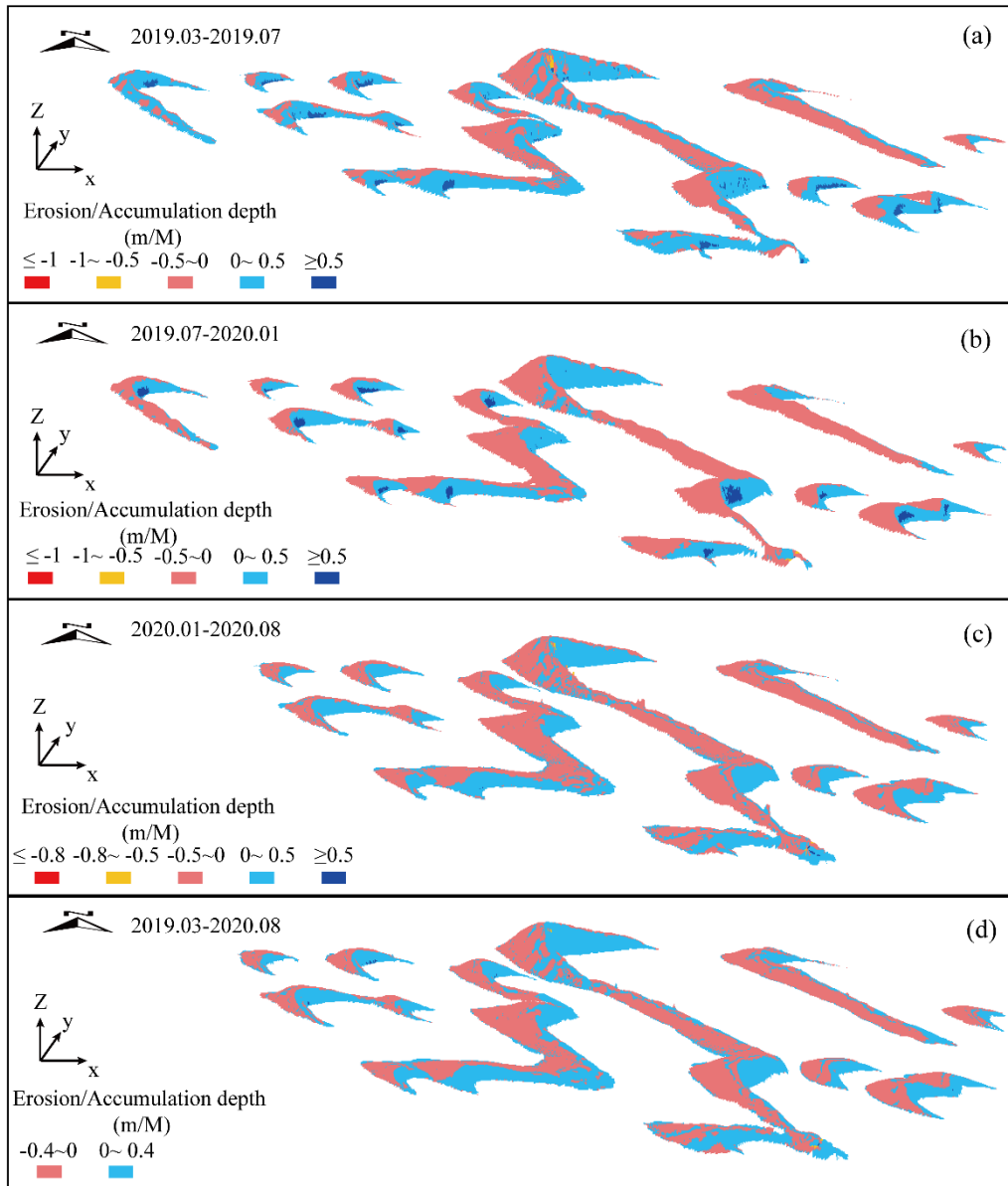
696 4. Discussion

697 4.1 Barchan dune morphological changes

698 In most cases, quantification of either vertical or volume changes for dunes via
699 remote sensing images is challenging, but these components are necessary for the
700 characterization of sand transport rates and associated dune morphological responses
701 (Hugenholtz, 2010; Bryant and Baddock 2022). Vertical dune deformation has been
702 carried out with the support of existing DEM and remote sensing data. For example,
703 shadow effects assessed by satellite images have been used to measure dune
704 morphological changes (Levin et al., 2004), and SRTM/ASTER GDEM data have been
705 used to measure giant dunes (e.g. Blumberg, 2006), solve dune replacement and
706 quantify spatial changes in sand supply (e.g. Hugenholtz and Barchyn, 2010), initial
707 conditions for hydrodynamic simulation of dune field and validation of numerical
708 model of dune (Jackson et al., 2011; Reitz et al., 2010). However, the limited x,y,z
709 resolution of most global DEMs restricts the extent to which variation in vertical
710 changes within dune fields can be derived (not least as a function of time), especially
711 for small isolated dunes at the year/sub-year timescale.

712 In this work, in addition to derivation of deformation metrics, vertical variation for
713 isolated dunes was analysed using DSM data produced by UAV-SfM on a monthly
714 scale. Calculation was derived by direct subtract of paired DSM images without
715 translation, which adds to our understanding of vertical deformation of the dunes
716 discussed above by allowing metrics that more closely align with existing studies.
717 Figure 14 summarises the respective rate of erosion and accumulation. The rate of
718 erosion and accumulation was between ± 0.5 m/M on the windward slope and the
719 leeward slope. In the second monitoring period, both dune erosion rate and erosion area
720 were significantly higher than those in the other three monitoring periods. The dune
721 erosion and accumulation rate in the fourth period were the lowest at 0.4 m/M. Only
722 the central leeward slopes in the first two monitoring periods had a high accumulation
723 rate, with a monthly accumulation depth of more than 0.5 m.

724 These data provide several insights that augment the deformation data analysis
725 above. Firstly, the amount of vertical deformation is obviously much smaller than the
726 amount of direct erosion/accumulation. This is because the vertical deformation
727 removes the redundant deformation caused by the displacement of the dune. Secondly,
728 the direct erosion and accumulation amount reflects the simple erosion and
729 accumulation law for different parts of the dunes. The windward slopes mainly erode,
730 and the leeward slopes mainly accumulate. However, we note that the erosion and
731 accumulation rates for the windward and leeward slopes of the dunes were different in
732 each of the monitoring periods, and sometimes, even opposite. Therefore, we feel that
733 the vertical deformation metrics calculated in this paper are better able to reflect the
734 real rates of dune deformation at appropriate space/time scales.



735

736 Figure 14. Characteristics of barchan dune surface erosion and accumulation in different monitoring
 737 periods. a: the erosion and accumulation of barchan dunes in 2019.03-2019.07; b: the erosion and
 738 accumulation of barchan dunes in 2019.07-2020.01; c: the erosion and accumulation of barchan
 739 dunes in 2020.01-2020.08; d: the erosion and accumulation of barchan dunes in 2019.03-2020.08.
 740 Negative values indicate erosion, positive values indicate accumulation. The units are meters per
 741 month.

742

4.2 Factors affecting dune celerity and deformation

743

744 The factors influencing the formation and morphology of dunes are complex
 745 (Gifford et al., 1979), and include the wind intensity, wind direction and duration; the
 746 nature, extent, and rate of erosion at the sediment source; distance from the source;
 747 grain size; underlying and surrounding topography; the amount and type of vegetation
 748 (Gillette and Chen, 2001; Duran et al., 2010; Baddock et al., 2011; Hamdan et al., 2016).
 It must be emphasized that because of the flat underlying terrain, sparse to zero

749 vegetation, smooth bed surface and low rainfall we focus specifically on the impacts of
750 sand supply, vegetation, and airflow transport.

751 4.2.1 Sand supply

752 Dunes of different heights have different shapes, thus, there should exist (at least)
753 a typical length scale in the mechanisms leading to the dune propagation because the
754 dunes cannot develop infinitely. Where able, barchan dunes can or will reach an
755 equilibrium state (Narteau et al, 2009; Gao et al., 2015). The equilibrium state refers to
756 a constant interaction occurs between shape, flow, and sand delivery/transport and
757 produces an equilibrium three-dimensional shape which constantly adjusts to maintain
758 a ‘perfect’ aerodynamic (Hesp and Hastings, 1998). And one of the most important
759 factors in determining that state and, by inference the dune height, is the sand supply
760 (Gunn et al, 2022). As the dune develops, more sand will be transported to the top of
761 the dune, increasing its height until it reaches an equilibrium state under the constant
762 interaction of morphology, wind flow and sediment transport (Hesp and Hastings, 1998).

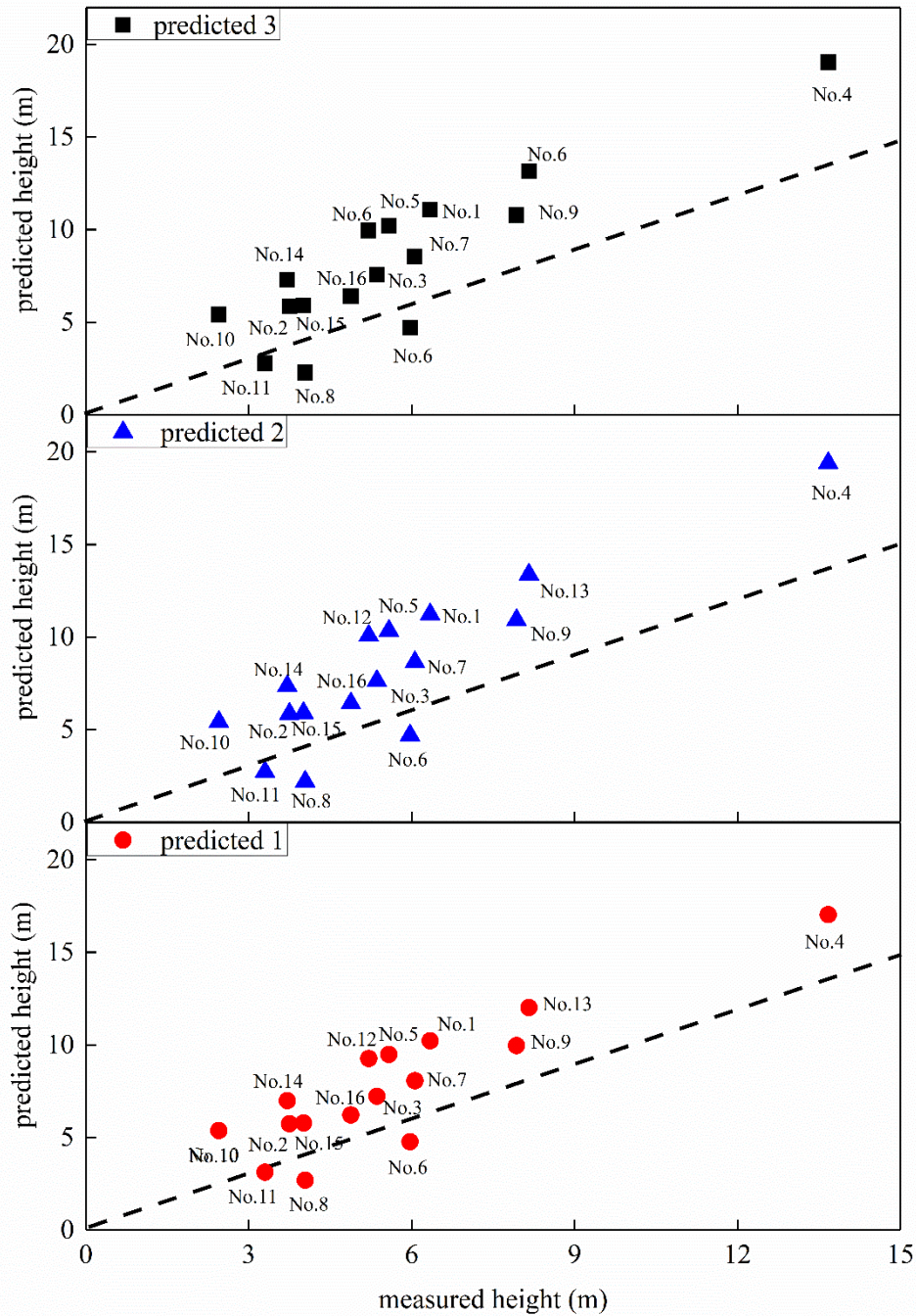
763 In this paper, the height of 16 dunes in the study area was predicted according to
764 the height/width ratio formula of dune equilibrium state proposed by Hesp and Hastings
765 (1998) and Andreotti et al (2002), and the results are shown in figure 15. The height of
766 13 of 16 dunes was lower than the predicted height, and only dune NO.6, NO.8 and
767 NO.11 met or exceeded the predicted height. It was initially believed that the dunes in
768 the study area have not reached an equilibrium state, and that the dune heights might
769 continue to develop further. However, in charting dune movement and change in this
770 paper (2019.03~2019.07, 2019.07~2020.01, 2020.01~2020.08), both shape and size of
771 16 dunes changed irregularly with time, including periods of expansion and shrinking,
772 without showing a significant trend towards further enlargement (Table 4). In this study
773 area, the sand supply limited by vegetation, and sufficient sand is not always available
774 to ensure the continuous increase in size of the sand dune, which accounts for vertical
775 and horizontal morphological deformation over time. We will discuss the influence of
776 vegetation on the supply of sand sources in the next section to further reveal the
777 influence of vegetation on the morphologic dynamics of sand dunes in the study area.
778 Studies have shown that dunes may grow indefinitely in principle, but growth depends
779 on morphology, slows with increasing size, and may ultimately be limited by sand
780 supply (Gunn et al, 2022). Even when sand supply is low, sand dunes may become
781 smaller over time (Yang et al, 2019). Here we see that the size of smaller dunes in the
782 study area decreased while that of large dunes increases. Given that the sand transport
783 flux of a barchan dune is proportional to its width (Kroy et al, 2005), it is likely that
784 under conditions of sand source limitation, small dunes in the study area may provide
785 a sand source for the larger dunes.

786 An evaluation of sand-supply is considered here in both qualitative and
787 quantitative ways. Qualitative analyses mainly consider three aspects (i) sediment
788 supply, (ii) wind transportation and (iii) sediment availability. The sediment supply in
789 Gonghe Basin can also be divided into two components, internally derived sand and
790 externally derived sand (Figure 1). The external sand supply for the Gonghe Basin is
791 mainly derived from the Qaidam Basin, but this supply type is very limited due to

792 topographic obstruction via mountain ranges (see figure1). Therefore, the sand source
793 in this basin is expected to be dominated by internal sediment stores associated with
794 fluvial and lacustrine strata deposited in the early Quaternary (Xu et al., 1982), such as
795 Shazhuyu River, Dalianhai et al (Liu, 2018). Any internal sediment supply from upwind
796 dry rivers and lake basins is deemed to be insufficient. A large number of coarse
797 particles are distributed on the surface of the inter dune area, also reflected the restricted
798 availability of sediment in this area. Based on field monitoring via a local weather
799 station, the annual sand drift potential (DP) in the study area was calculated as 125.07
800 VU, which belongs to low energy environment, much lower than that of Aaidam Basin
801 (199~328 VU) (Bao et al., 2015) and Tengger Desert (358.7 VU) (Zhang et al., 2008),
802 which suggests that the sand carrying capacity is limited due to the relatively low wind
803 energy in Gonghe Basin. Therefore, we qualitatively suggest that the Gonghe Basin is
804 sand-supply limited. To further quantify the sand supply magnitude, we use the
805 coefficient C proposed by Gillette and Chen (2001) to measure the degree of sand-
806 supply to characterize the basin's sand source limitation. According to the classification
807 given by Gillette and Chen (2001), the regional sand source is limited when the value
808 is less than 3.2. The closer the value gets to 0, the more constrained it is. The value of
809 C of the study area is 0.146, which confirms that the sand-supply here is indeed
810 restricted.

811 Studies have shown that the appearance of a dune also depends on the amount of
812 sand available for transport (Mckee, 1979; Narteau et al, 2009; Gao et al, 2015; Lv et
813 al, 2018; Yang et al, 2019). According to the calculations presented here, the vertical
814 deformation extent for the extending right horns of dunes was obviously higher than
815 that of other parts, and especially we saw that the erosion and accumulation changes for
816 the dune brinks were very large. At the same time, the planform deformation along the
817 brink of the elongated horn was also high, and this was especially the case when an
818 increase of dune scale led to increased deformation.

819



820

821 Figure 15. A comparison between the measured height and the predicted height of the barchans in
 822 the study area. (The dashed gray line indicates that the actual measured height is the same as the
 823 predicted height) The predicted height 1 using the equation of Hesp and Hastings (1998):
 824 $H=L/2*0.194$, where s slope angle of 11° is taken as a typical average value for the side slopes of
 825 a barchan. The predicted height 2 using the equation of Andreotti et al (2002), $W=8.8+8.6H$. The
 826 predicted height 3 using the equation of Hesp and Hastings (1998): $W=8.82H+7.65$, the data for
 827 this fitting formula is derived from Finkel (1959), Hastenrath (1967;1987), Khalaf and Al-Ajmi
 828 (1993).

829

Table 4. Dune morphology changes in the whole monitoring period

Dune code	$\Delta L/m$	$\Delta W/m$	$\Delta H/m$	$\Delta S/m^2$
-----------	--------------	--------------	--------------	----------------

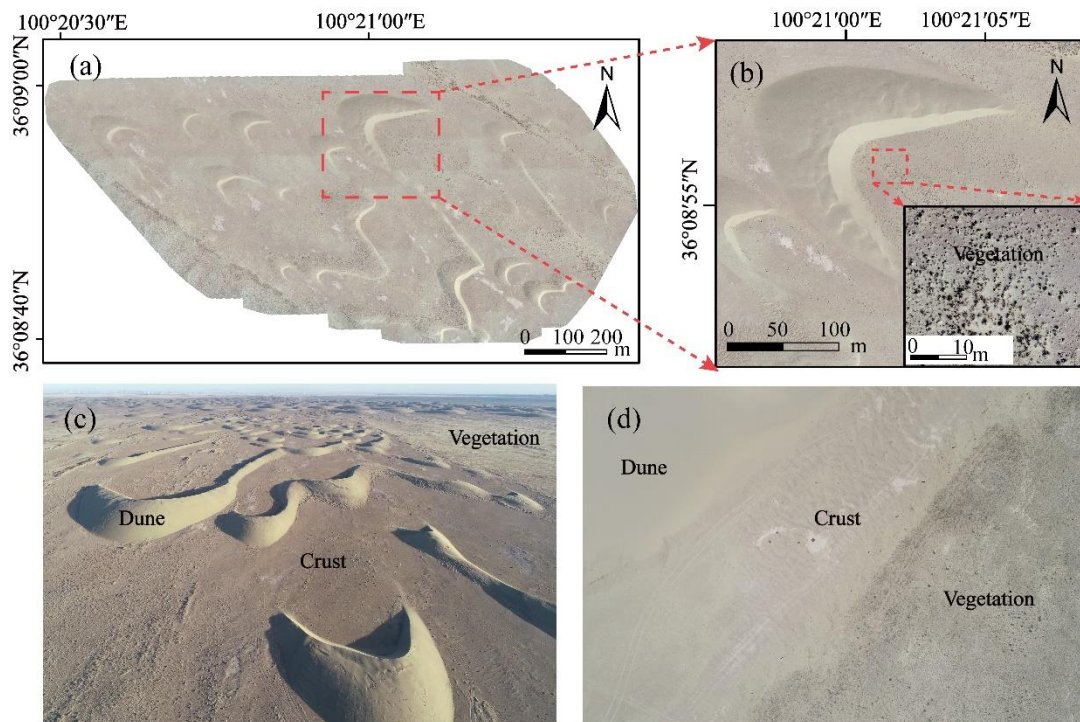
1	9.82	-7.18	-0.11	-86.41
2	-23.23	1.5	0.06	-409.24
3	-11.32	-1.34	-0.27	-116.09
4	-20.05	-1.77	-0.46	-33.15
5	-8.41	-1.26	0.06	185.75
6	-39.91	5.8	-0.12	1020.09
7	1.93	1.78	0.09	-66.35
8	1.9	5.93	-0.13	-436.52
9	-14.18	2.28	0.38	709.44
10	-1.58	-6.82	-0.1	-240.04
11	4.54	6.14	0.46	808.08
12	7.21	-2.49	-0.19	2053.18
13	-24.73	4.88	-6.34	3634.7
14	22.58	-3.44	0.15	51.18
15	30.54	7.22	-0.34	-86.41
16	4.76	3.6	1.06	-409.24

830 4.2.2 Vegetation and barchan dunes celerity

831 Vegetation affects sand supply, sand availability decreases as vegetation cover
832 increases, further reducing the transport rate. Vegetation is expected to trap wind-blown
833 sediment and inhibit movement of wind-blown sediment (Kuriyama et al., 2005). The
834 results of laboratory experiments and field measurements show that vegetation reduces
835 the movement of surface sediments, and an area with 15% vegetation coverage can
836 reduce the sediment transport rate by 99%. (Lancaster and Baas, 1998). The vegetation
837 coverage in the study area is between 0.15-0.45 (Shao et al., 2021), which belongs to
838 the low-medium coverage type, can effectively reduce the sediment transport rate and
839 limit the supply of downwind sand sources.

840 On isolated dunes with limited sand supply, mobility is more sensitive to changes
841 in vegetation cover. Compared with vegetated dunes, the near-surface wind speed and
842 shear stress on bare dunes increased significantly, and the surface activity varied by
843 three times (Wiggs et al., 1994). On the interdune and lower slopes, sediment movement
844 was mainly limited by wind energy, while on the dune top and higher slopes it was
845 mainly controlled by vegetation cover (Wiggs et al., 1995). The stable morphology of
846 the dune is determined by the ratio of the deposition rate of the sliding surface to the
847 deposition tolerance of vegetation. Due to the fixed sediment tolerance, the sliding
848 surface of large slow-moving dunes has a low sedimentation rate and will freeze once
849 vegetation is introduced. Relatively small, fast dunes have a high slip deposition rate,
850 are easy to evolve into other forms, and often collide during stabilization (Barchyn et
851 al., 2012). Vegetation in the interdune also plays an important role in dune mobility. An
852 increase in downwind plant density leads to an increase in vegetation-induced
853 morphological resistance, which leads to a decrease in dune mobility (Lee et al., 2019).
854 The Orthomosaic of the study area showed the vegetation cover in spring in the dune
855 field (Figure 16). The vegetation of the dune field in the study area mainly grows in the
856 interdune, and then scattered in the foot of the windward slope of the large dune, so the

857 dune surface activity is relatively active.



858

859 Figure 16. The vegetation cover and bed conditions in the barchan dune field. (a) The orthomosaic
860 of the barchan dune field. (b) Local enlarged view of sand dunes and vegetation cover. (c) and
861 are the oblique photographic image of the dune field which show the bed condition and vegetation
862 cover in the study area.

863 4.2.3 Sand transport and dune morphodynamics at high altitude

864 Wind shapes the morphology of dunes and influences their migration, playing a
865 critical important role in their development and evolution (Bagnold, 1941; Wu, 2003;
866 Hesp et al, 2007). The shape of the dune crest positively reflects the natural climate
867 changes from year to year (Livingstone, 2003). Dune morphology is also strongly
868 influenced by complex seasonal variations in wind direction. Air flow field and
869 sediment transport rate play important roles in understanding the formation and
870 evolution of aeolian bedforms on the microcosmic level. Historically, the relationship
871 between dune morphology and wind regime has been used to represent morphological
872 changes of dunes at relatively large scales (Yang et al., 2011). At the dune scale, the
873 interaction between topography and air flow as well as air flow and sediment transport
874 process largely determine its morphological evolution (Vandijk et al., 1999), especially
875 regarding dune asymmetry (Bagnold, 1941; Rim, 1958; Lancaster, 1982). Some field
876 experiments have identified complex, topographically-induced flow structures
877 including flow stagnation downwind of the dune toe, compressed and accelerated flow
878 on the stoss slope, detachment and flow expansion at the crest, recirculation or
879 deflection in the lee, and downwind flow recovery (Smith et al., 2017).

880 The surface airflow has an important effect on dune migration. The average annual
881 dune movement rate measured in Gonghe Basin is 10.2 m/yr, which is relatively low.

882 Aerodynamic resistance is proportional to air density, and extreme temperatures will
883 lead to significant differences in wind transport capacity, so temperature and air density
884 may be related to unique aeolian deposition patterns (Smith, 1966; Selby et al., 1974).
885 Extensive measurements and wind tunnel experiments by many scholars show that the
886 air flow pattern on the windward slope is mostly similar, and the air flow will converge
887 and accelerate during its ascent along the windward slope of the dune, and the speed
888 lines from the foot of the windward slope to the top of the windward slope will meet
889 more and more densely (Wiggs et al., 1996; Dong et al., 2017). However, the
890 morphological change of the part will affect the near-surface air flow along the
891 windward slope, and the air flow will converge at the bulge and diverge at the top of
892 the dune with relatively flat slope (Wu et al., 2011;). On the leeward side of dune, the
893 airflow structure evolves from airflow diffusion with instantaneous airflow dispersion,
894 and then completes airflow separation and re-attachment (Walker and Nickling, 2002;
895 Baddock et al., 2011; Qian et al., 2021). At high altitudes, for a given volume flow, a
896 lower air density produces a higher threshold frictional wind speed (Han et al., 2015).
897 According to the existing research results, the altitude varies from 1140 meters to 5076
898 meters, and the air density changes from 1.074 to 0.676 kg · m⁻³ (Han et al., 2015).
899 Taking the parameter of the study area (Che et al., 2021) as an example, the frictional
900 wind speed at 3 meters of the two is 4.79 and 6.04 m/s, respectively. The air density in
901 the study area is 0.862 kg·m⁻³, and the frictional wind speed at 3 meters is 5.48 m/s.
902 Therefore, the increase of altitude in the study area reduces the sediment transport by
903 increasing the starting wind speed.

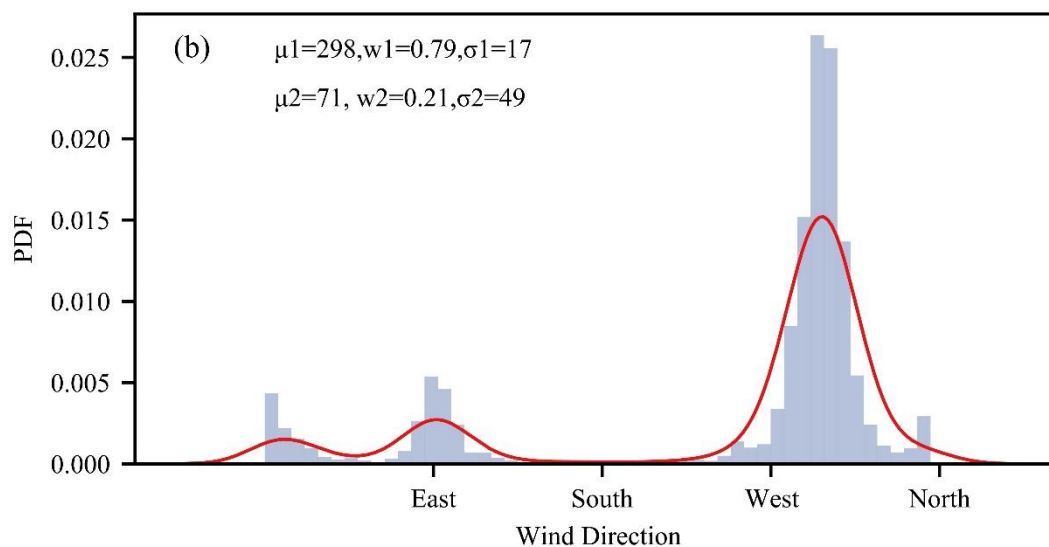
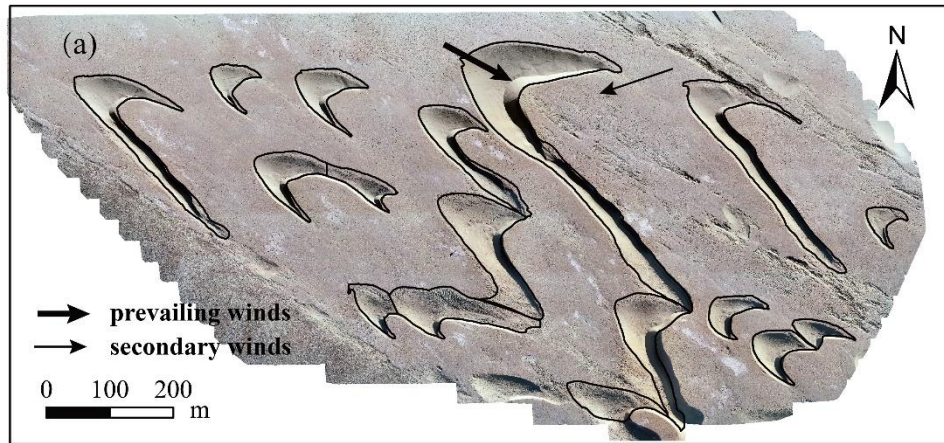
904 An increase in altitude also results in a corresponding increase in the rate and
905 height of saltation. The results of wind tunnel experiments show that when the wind
906 speed exceeds 10 m, most of the sand particles move at 10-14 cm in the altitude layer
907 at low air density, and 6-8 cm at high expired density (Han et al., 2015). The results of
908 sediment accumulation in this study show that 4-6 cm of sand accounts for about 30%
909 of the total sediment transport within 2-40 cm height, and 76% to 91% of the sand
910 saltation within 2-14 cm. Of course, the saltation height is also highly related to the type
911 of bed surface. Even at high altitudes, there are significant differences in bed/sand
912 availability by area. For example, Kumukuri Desert, the most distributed modern desert
913 in the world, has continuous distribution of sand dunes on the surface and abundant
914 sand supply, which is a typical erodible bed with high sand availability (Li, 1992). On
915 the southeastern edge of Qaidam Basin, that is, around Qarhan Salt Lake, because the
916 surface is mostly salt crust, there are many non-erodible beds with low sand availability
917 (Xu et al., 2017). There are many lakes and river channels in Qinghai-Tibet Plateau,
918 and some climbing dunes are distributed on floodplains, river terraces and hillsides,
919 among which floodplains are erodible beds, and hillsides are mostly non-erodible beds,
920 while river stages are between completely erodible and completely non-erodible. The
921 bed in this study area is crust as well as grassland (Figure 16 c and d), which is of low
922 sand availability type, and many isolated dunes are deposited on the surface which is
923 difficult to erode. Therefore, low air density at high altitude may be a major factor
924 hindering dune migration in the study area.

925 The aeolian sand flow has great influence on the shape of dune. The agent-based

926 model indicates that both the degree of overlap between the upwind dune and
927 downwind dune and the size of the adjacent dunes will influence the interaction (Genois
928 et al., 2013). Different combinations of overlapping degree and dune size will create
929 different results, such as merging, exchanging and generating a new dune. However,
930 the latter two results have not been observed in this study due to the observation
931 duration of the study, only the merging phenomenon of two arms of adjacent dunes
932 caused by interaction between dunes is analysed here. Studies show that when there are
933 other dunes near the independent dune, an acceleration zone will be generated between
934 the two dunes, and the air flow on both sides of the horns is asymmetric (Bristow et al.,
935 2018), thus changing the morphology of the horn of the dune. The extended horn
936 received more sand based on the fact that the flux ejected by the horns is saturated or
937 close to saturation (Sauermann et al., 2000; Elbelrhiti, 2012).

938 4.2.4 Asymmetry barchans and barchan-seif dunes

939 As shown in Table 2, there are both symmetric and asymmetric barchan dunes in
940 the study area, with both left horns extension and right horns extension, and their main
941 control factors are different. Lv et al (2016) put forward that expectation-maximization
942 algorithm to fit the flux orientation distribution with a Gaussian mixture model can help
943 us to identify the prevailing and secondary winds. Figure 17 shows the distribution of
944 the wind direction. Thick arrow represents the stronger wind, thin arrow represents the
945 gentler wind. The red line in the figure 17 b show the bimodal distribution of the wind
946 regime in the study area with symmetric and asymmetric barchan dunes. The main wind
947 comes from WNW (298°), with a weight of 0.79, and the secondary wind comes
948 from ENE (71°), with a weight of 0.21. the ratio of the weights of the two winds is close
949 to 4, and the angle between the two winds is 227° . The direction of all barchan dunes
950 is consistent with the prevailing wind, indicating that they are formed under the action
951 of stronger wind. The data in the figure 17 suggest that the horns of large barchans
952 extend farther on the side farthest from the gentler wind, whereas the limb closest to
953 the gentler wind is eroded, which is consistent with the evolution model of seif dune
954 proposed by Tsao (1984).



955

956 Figure 17. Figure 17. wind regime characteristics in areas with symmetric and asymmetric barchan
 957 dunes. (a) The prevailing winds and secondary wind in the study area. (b) The wind direction
 958 distribution during the period from August 2019 to August 2020 based on the 5 minute-interval data.
 959 For the dominant wind direction 1 and 2, the μ orientation (north=0°), w weight (ratio of the
 960 frequency of the strongest of the two dominant winds to the frequency of the gentler dominant wind),
 961 (the standard deviation of the wind orientation), PDF proportion of the total number of winds
 962 recorded.

963 Asymmetric barchan dunes caused by wind conditions will show the same
 964 extension of horns (Tsoar and Parteli, 2016), which is obviously inconsistent with the
 965 study area. In the study area, the right horn of large dunes extends, while that of small
 966 dunes is different, which shows that wind condition is important to the extension of
 967 large sand dunes, while the effect on the extension of small sand dunes is secondary.
 968 [The impact of collision and inflow asymmetry on the wing elongation of small dunes
 969 is more significant.](#) It can be found that only two dunes (No.12 and No.15) have left
 970 horn extensions, whose right horn/left horn values are 0.18 for the former and 0.25 for
 971 the latter (Table 2). These two dunes are not isolated dunes, but merge with other dunes.
 972 There are five modes of interaction between dunes, namely chasing, merging, exchange,
 973 fragmentation-chasing and fragmentation-exchange (Assis and Franklin, 2021). In the

974 study area, dune No.11 and No.12 have collided and presented a merging mode, with
975 the left horn of the former intersecting with the right side of the windward slope of the
976 latter, which means that the wake of the former will disturb the latter and even absorb
977 part of the sand, and the latter may not supply enough sand, thus preventing the
978 extension of its right horn. Although dune No.15 and No.16 also showed a merging
979 pattern, they remained parallel downwind, sharing a horn, so that the right horn had
980 significantly more sediment supply than the left horn. More sediment supply would
981 prevent erosion and downwind movement of the dune horn, so the horn with less sand
982 supply would extend more than the horn with more sand supply (Tsoar and Parteli,
983 2016). The elongation of a horn may depend on the shape of the dune itself (Tsoar and
984 Parteli, 2016). The symmetry barchan dunes (No10, No.14) and that with left horn
985 extension tend to be short and fat, while the barchan dunes with right horn extension
986 tend to be tall and thin.

987 Seif dunes are a type of linear dunes that grow in unvegetated areas, form under
988 bidirectional wind conditions, are parallel to the dominant wind direction, and have a
989 meandering shape and sharp crest (Tsoar, 1983; Parteli et al., 2009; Tsoar and Parteli,
990 2016; Pang et al., 2020). The elongated right horns of large barchan dunes (No.1, No 4,
991 No 5, No 6) in the study area has slightly meandering shape, sharp crest, and with
992 continuous extension, so these asymmetrical barchan dunes should belong to the
993 barchan-seif dune. By contrast, some asymmetrical barchan dunes with elongated right
994 horn in the study area, like other symmetrical and asymmetrical barchan dunes with
995 elongated left horn, still belong to asymmetric barchan dunes, not seif dunes. However,
996 the mechanism of which dunes will extend into seif dunes in the study area is still
997 unknown, and we need to follow up the morphodynamics characteristics and processes
998 of dunes with longer time series to further explore.

999 **5 Conclusion**

1000 In this paper, 16 isolated symmetric/asymmetric barchan dunes distributed in
1001 Ertala, Gonghe Basin were monitored using UAV-SfM to obtain the 4 high-resolution
1002 DOM and DSM. Celerity, vertical deformation, and planform deformation (total
1003 deformation, even deformation and uneven deformation) were detected based the DOM
1004 and DSM data. We qualified the morphodynamic characteristics of symmetry and
1005 asymmetry of barchan dunes, and analyzed the influences of sand supply, vegetation
1006 and high-altitude on barchan dunes celerity and deformation. Combining the field
1007 monitoring of dune surface airflow and the collected wind data, the controlling factors
1008 of asymmetric dune evolution are discussed. During the monitoring, we found that the
1009 scale and development process of large barchan dunes will be hindered because of the
1010 low sand supply conditions and dense vegetation distribution in the study area, which
1011 is located at a high altitude. Before the size of the dune reaches the equilibrium state,
1012 the degree of vertical deformation is large, and the dune increases continuously through
1013 accretion, the size increases, and the shape changes dramatically. When the dune
1014 reaches the equilibrium state, the shape of the dune, the air flow and the sand transport
1015 interact with each other, and the shape is adjusted to maintain the aerodynamic
1016 equilibrium state. Even under the influence of external conditions, one horn of the dune

1017 gradually extends, and finally reaches the “equilibrium state”.

1018 In summary, we obtained the following insights on the morphological dynamics
1019 and characteristics of symmetric/asymmetric barchan dunes from our study: (i) barchan
1020 dune celerity is related to the dune size, but the symmetry of barchan dune has no
1021 obvious influence celerity; (ii) the deformation of the elongated arm of a barchan dune
1022 is more obvious, and symmetry may therefore play an important role in rates and extent
1023 of deformation; (iii) observed deformation at the brink of a barchan dune tends towards
1024 “even” compared with that of the outline; (iv) the sand supply, vegetation and airflow
1025 at high-altitude all influence the celerity and deformation degree in the development of
1026 barchan dunes; (v) asymmetric bidirectional winds, asymmetric inflow and interaction
1027 between dunes account for the formation of asymmetric dunes in this area.

1028

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