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Wind regime and sand transport in the Sistan and Registan regions (Iran/Afghanistan)

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with 9 figures and 4 tables

Abstract. Both, the formation of aeolian dunes and the rate of sand transport in arid environments are controlled by the wind regime. The Sistan region in eastern Iran and the Registan region in Southwestern Afghanistan are strongly influenced by the wind of 120 days (Sadobist Roozeh wind), which is blowing along the Iran-Afghanistan border from North to South, then shifts it's direction toward the Southeast into the Sistan region and, finally, continues eastward into southwestern Afghanistan, forming the Registan sand seas. It blows during the hot season due to the pressure gradient between the Turkmenistan High and the Pakistan Low. In order to determine the wind regime and the sand transport, wind roses based on long-term datasets from 16 meteorological stations, the Drift Potential (DP), the Resultant Drift Direction (RDD), the Resultant Drift Potential (RDP) and the RDP/DP ratio have been calculated using the Fryberger (1979) method. The distribution of the Registan sand dunes was surveyed by using Landsat ETM data, Google Earth scenes and field operations (the latter only in the Iranian part). The spatial differences of the drift potential were also mapped using GIS and geostatistical methods overlaying the sand dune map. The results show that the drift potential (DP) increases from north to south along the border between Iran and Afghanistan and reaches to highest values in the Sistan region, then decreases gradually in the Registan sand seas. The highest wind energy, based on DP matches, was determined exactly where the ephemeral lakes in the northern part of the Sistan plain are located, which function as a source area of intense dust and sand storms during the dry season. The temporal trend of the DP showed an increase between 1999 and 2007, followed by a decrease until 2015 in Sistan. The results show that the wind regime in the Sistan and Registan regions is unimodal during the wind of 120 days (the Sadobist Roozeh) period, which is also supported by the dominance of transverse, barchanoid and barchans dunes in both regions.

1 *Introduction*

Effective winds play as key factor to abrade soil particles from aeolian sources, create dust and sand storm, and form dunes in desert area. Wind regime and aeolian sand transport used widely to identification dunes morphology (McKee 1979, Cooke et al. 1993, Lancaster 1995, Livingstone & Warren 1996, Thomas 1997) and dune formation (Breed & Grow 1979, Fryberger 1979, Wasson & Hyde 1983, Lancaster 1994, Livingstone & Warren 1996). A thorough understanding of the characteristics of the wind regime in which a sand transport is expected to work is a pre-requisite for the successful planning of any sand dune fixation projects. It also shows the spatial and temporal variability of wind speed and direction over Ergs which help to spatial prioritization of sand dunes stabilization.

To study wind regime and sand transport usually calculated sand drift potential (DP) and related key variables i.e. resultant drift direction (RDD), resultant drift potential (RDP) and unidirectional index (UDI = RDP/DP) with using wind speed and direction data. DP and key

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parameters related to DP represents wind power and describes the potential maximum amount of sand transport for each wind direction that includes values above the threshold velocity (Fryberger 1979). There are different methods to analysis sand transport potential (e.g. Fryberger 1979, Nickling & Wolfe 1994, Bullard et al. 1996, Bullard 1997) but Fryberger method (1978, 1979) has been the most widely used in most papers and its theoretical curve agree very well with wind tunnel measurement in compared other methods which tested by Belly (1964). The Fryberger method, which is a modification of the Lettau and Lettau (1978) equation, is designed to give a relative rather than absolute description of the effect of wind energy on sand drift. Sand drift potential (DP) is defined as the wind potential power to transport sediments in a given direction (Fryberger 1979) which also described wind energy environment.

Different annual trends of drift potential highlighted by some authors from different desert. Livingstone et al. (2010) in Namib Sand Sea digital database of aeolian dunes shows a time series data for annual DP, RDP and RDP/DP for the Gobabeb ground station covering the period 1980–2002, so this region has a low energy wind regime. Al Alwadi (2005) presented changes in the amount of DP in Kuwait's meteorological stations, and showed that 77 % of the annual resultant DP occurs during the summer period. Wang et al. (2007) showed changes in the wind energy environment and dune activity in China's deserts from 1990 to 1999, and classified most of China's deserts into moderate to low-energy wind environments on base of DP that decreased in most dune fields from 1980 to 2003. Jewell & Nicoll (2011) found that DP varied considerably over a 50 years in the Great Basin desert in the united State of America and found no relationship between DP and climate change. Zhang et al. (2015) concluded climate change did not obviously effect on calculated potential sand transport parameters (DP, RDP, RDD) and on the annual mean wind velocity in China Badain Jaran desert. In addition, some Iranian authors reported DP parameters for some meteorological stations. For example, Ahmadi & Mesbahzadeh (2012) calculated the annual DP amount in Yazd – Ardakan in central of Iran (118 V.U), greatest DP occurs in spring then winter, and the lowest DP occurs in autumn. Ekhtesasi & Dadfar (2014) investigated relationship between coastal storms and sand dunes morphology at Bandar-e-Jask and show the maximum of DP (336 V.U) occurred that lead to the formation of longitudinal dunes in South of Iran.

Sistan depression located on the east of Iran near Afghanistan border surrounded by six ephemeral lakes called Hamoun-e Puzzak, Hamoun-e Chonge Sork, Hamoun-e Baringak, Hamoun-e Sabari, Hamoun-e Hirmand and Gowd-e-Zareh. They played as major dust and sand sources in dry season in southwest Asia. A very strong wind entitles Sadobist Roozeh wind (the wind of 120 days) which forms in warm season due to the pressure gradient between the Turkmenistan (Kaviani & Alijani 1992, Saligheh 2011, Alijani & Raeespoor 2011, Kaskaoutis et al. 2015, Hamidian Pour et al. 2017) or Hindukush high pressure (Alizadeh-Choobari et al. 2014) and low pressure system common over Registan desert. In other hand, Siberian air stream which comes from north to south and different gradient between high lands and Low lands in Sistan and Registan desert forms a low level jet stream (Alizadeh-Choobari et al. 2014) which called Sadobist Roozeh wind in Sistan region. During the hot and dry season, it can easily drift the sediments of the dry lake beds, produce intense sand and dust storms that effected on the Sistan, southwest Afghanistan and north of the Pakistan (Goudie & Middleton, 2006, Alam et al. 2011, Rashki et al. 2012a, 2013c). Annual mean of dusty days in Zabol city reached to 174 days in duration 1995–2015 and peaked to 213 in 2000. WHO (2016) introduced Zabol as most polluted city in the world form PM2.5 particles concentration and third as PM10 in 2010. Drifting sand and migrating sand dunes damage to crops and farmlands, blocking of irrigation canals and roads, filling of water reservoirs, and burial of villages in Sistan and Registan every year. A Sistani quotation said, "Whatever brought with water is carried by wind".

In this paper, we investigated wind regime and erosive winds characteristics of Sistan and Registan desert, and show temporal and spatial variation wind regime.

2 *Study area*

The study area is extended between Sistan plain in east of Iran to Registan desert in southwestern Afghanistan (Fig. 1). It lies between 31.4° N –29.3° N to 61.1° E –66.1° E and the elevation change between 480 m in Hamoun lakes to 1200 m on the Registan sand sea near Ghandehar surrounded with mountains in east part. It is located between Zabol County of the Sistan and Baluchistan province in Iran and Nimruz, Helmand and Ghandehar provinces in Afghanistan. The Sistan region surrounded by six ephemeral lakes called Hamoun-e Puzzak, Hamoun-e Chonge Sork, Hamoun-e Baringak, Hamoun-e Sabari, Hamoun-e Hirmand and Gowd-e-Zareh. Dasht-e Margo (death desert) is adjacent to the study area. The annual precipitation in this region is 56 mm in the Sistan plain, 105 mm just near the Afghan border, and reach to 185 mm in Ghandehar. The annual mean air temperature is relatively high range from 21.6° in Zabol station to 18.6° in Ghandehar. The summers are hot and dry with average temperatures of up to 35° C and the winters are mild (8° C) with an average monthly precipitation of 20 mm. This classifies the region to extremely arid as a hot desert climate (BWh) after Köppen-Geiger (Peel et al. 2007).

3 *Materials and methods*

The speed and direction of hourly wind data were collected from 16 meteorological stations located in Sadobist Roozeh wind domain (Fig. 1) in Iran and Afghanistan. The data were recorded in intervals for 1 or 3 hourly for 24 h per day at height of 10 m above the ground. The data of Afghanistan's stations derived from the Iowa State University Data Centre online site (www. http://mesonet.agron.iastate.edu/request/download.phtml?network=IR__ASOS) in duration 2011 to 2014 or 2016 and the data of Iranian stations provided from Iran meteorological organization (IMO) from 1995 to 2015.

The wind rose, Sand rose, drift potential (DP), Resultant Drift Direction (RDD), Resultant Drift Potential (RDP) and the ratio of RDP/DP have been calculated using Fryberger's method (1979) according as follows as,

$$DP = V^2 (V - V_t) t \tag{1}$$

DP is a proportion of sand drift, V is average of wind velocity at 10 meter of height, Vt is impact threshold wind velocity, and t is time wind blew. The threshold velocity was considered 12 knots (about 6.2 m s^{-1}) under dry conditions.

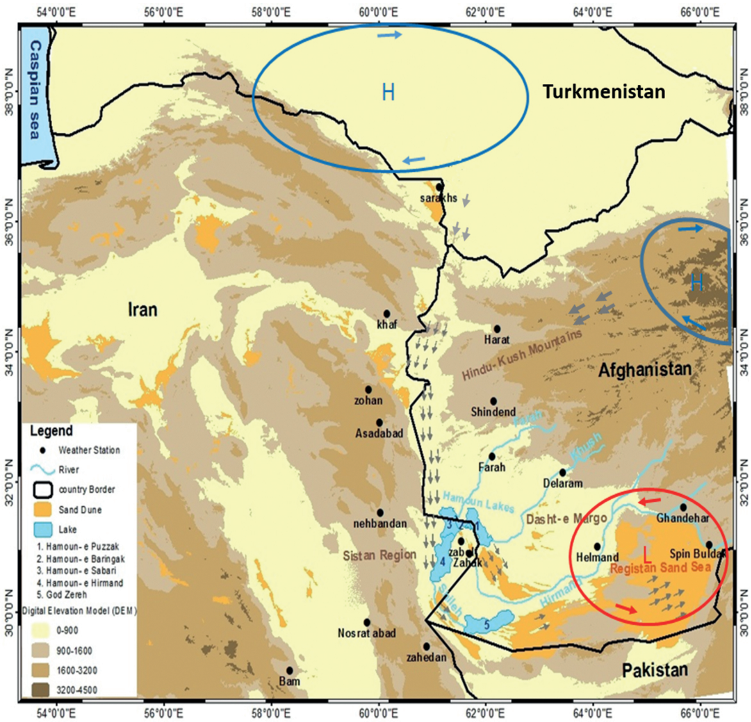

Fig. 1. The location of Sistan and Registan desert, the pressure gradient and direction of Sadobist Roozeh wind.

For comparing results of DP with Fryberger's class and other researches, the speed data were changed to knot although Bullard (1997) estimates also in m s^{-1} and provides calibration relations to correct different units.

$$\mathrm{RDP} = (\mathrm{C}^2 - \mathrm{D}^2)^{0.5} \tag{2}$$

$$\mathrm{C} = \Sigma(VU)\ Sin(\theta)$$

$$\mathrm{D} = \Sigma(VU)\ Cos(\theta)$$

(VU) vector units represents the DP in each wind direction (in this paper, we grouped winds into 16 sand transport directions, is the angle of midpoint of each wind direction class measured clockwise from 0° 0r 360° (north).

$$\mathrm{RDD} = \mathrm{Arctan}\ (\mathrm{C}/\mathrm{D}) \tag{3}$$

RDD is the angular direction at clockwise from the geographical north.

$$\mathrm{UDI} = \mathrm{RDP}/\mathrm{DP} \tag{4}$$

Unidirectional index (RDP/DP) is the ratio of the resultant drift potential (RDP) to the drift potential (DP) and shows directional variability. If the ratio of UDI values closes to 1 the wind regime will indicate a narrowly unidirectional with a single dominant drift direction, whereas if the values close to 0 there is a multidirectional wind regime with multiple significant drift

Table 1. The classification of wind energy environments using drift potential (DP) and directional variability (modified from Fryberger 1979).

DP (vector unit)	Wind energy environment	RDP/DP	Directional variability	Directional category (probability distribution)
< 200	Low	< 0.3	High	Complex or obtuse bimodal
200–400	Intermediate	0.3–0.8	Intermediate	Obtuse to acute bimodal
> 400	High	> 0.8	Low	Wide to narrow unimodal

directions environment. Table 1 shown the classification of the wind energy environment and directional variability by Fryberger (1979).

The spatial variation of DP was interpolated using ordinary kriging in geostatistical method by ArcGIS software version 10.4 (www.esri.com).

4 *Results and discussion*

4.1 *Wind velocity*

It is obviously that the regional topography effects the airflow acceleration, as highlighted by Wilson (1973) and Fryberger & Ahlbrandt (1979). As seen in Fig. 2, there is a narrow corridor between the Hindu-Kush Mountains in Afghanistan and the Bageran and Ahangran Mountains in southern Khorasan (Iran), which acts as an accelerator for the Sadobist Roozeh wind speed in that corridor during the warm season, which was also mentioned in context from Whitney (2006). The resulting annual mean wind velocity in the corridor and the Sistan area is with mean 4.5 m s^{-1} much higher than in the Registan desert.

The maximum mean wind velocity was 6.2 m s^{-1} at Zabol at the western of study area and the lowest mean velocity (2.9 m s^{-1}) was detected at Spin Buldak at the eastern edge of the Registan desert. The annual mean wind velocity at Zabol, Zahak are 6.2 and 4.8 m s-1, respectively (Table 2).

From this point of view, in comparison withother climatological station around of deserts for examples, Taklimakan (3.0 m s^{-1}), Tengger desert (3.8 m s^{-1}), Badain Jaran desert (4.7 m s^{-1}), Dasht Kavir desert (4.8 m s^{-1}) and Lut desert (5.9 m s^{-1}), Sistan desert has one of the highest of annual mean wind speed in the world. This zone of very high wind speeds in the Sistan region matches the location and extend of the ephemeral lakes and reduced surface roughness. It is clear that the maximum wind velocity occurred on north of Sistan region in which match exactly over ephemeral lakes and decreased gradually over Registan sand sea. In duration study, the strongest storm occurred at 2012 that wind speed recorded 20 m s^{-1} an averaged 12.5 m s^{-1} for 23 hour period. In addition, McMahon (1906) reported a storm over Sistan basin reached to 120 miles per hours (53.6 m s^{-1}) an averaged 88 miles per hours (39.3 m s^{-1}) for 16 hour period. The strongest storms in Helmand and Spin Buldak stations occurred 18 and 15 m s^{-1} in duration study, respectively.

In terms of time, the monthly average wind speed represented large seasonal variation in Sistan region (Zabol, Zahak stations), with minimum values from December to February and

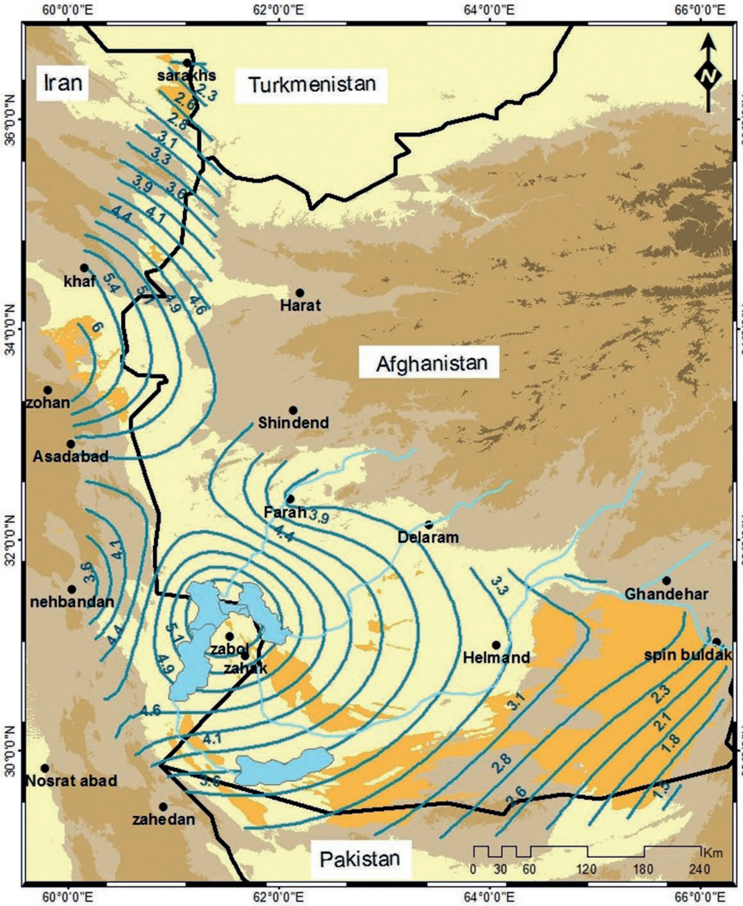

Fig. 2. Map of the annual mean wind velocities (in m/s) in the Sistan and Registan deserts.

Table 2. A summary of the wind velocity parameters from Sistan and Registan desert.

Station	Annual mean wind velocity (m s $^{-1}$)			Parameters wind velocity upper 6 (m s $^{-1}$)			
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	proportion
Zabol	6.2 ± 0.7	5.3	7.0	9.5 ± 0.8	7.9	10.7	46
Zahak	4.8 ± 0.6	3.2	5.6	8.2 ± 0.2	7.9	8.6	39
Delaram	3.4	–	–	7.2	–	–	18
Farah	3.1 ± 0.4	2.8	3.9	7.4 ± 0.3	6.9	7.7	16
Helmand	2.9 ± 0.2	2.6	3.5	7.3 ± 0.4	6.9	8.0	14
Ghandehar	3.1 ± 0.4	2.6	3.3	6.9 ± 0.4	6.5	7.5	16
Spin Buldak	2.4 ± 0.6	1.7	2.9	7.0 ± 0.3	6.6	7.9	13

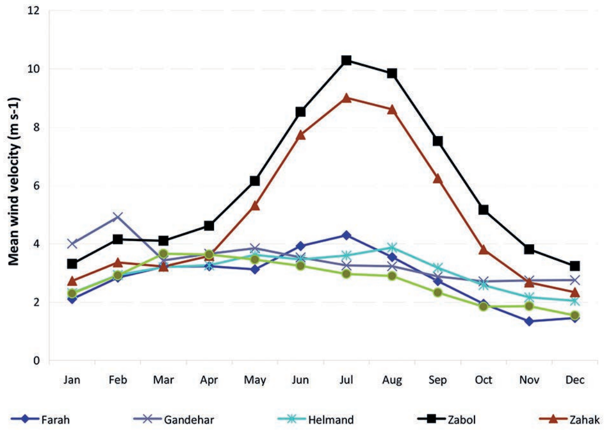

Fig. 3.Montly average of mean wind velocity for seven stations located in Sistan and Registan desert, duration of Iran Stations 1995–2016, Farah and Ghandehar 2010–2016, Delaram and Spin Buldak 2010–2014, Helmand 2012.

maximum values in June and August coincide with Sadobist Roozeh wind duration. In Sistan region, secondary wind named Levar blows in September also causes a fairly high average wind speed in autumn (Rashki 2012). Other local winds in Sistan region called Haftom (Gav Kush), goas and gebleh usually have low energy blowing at cold seasons.

In compression, it has mostly low variation in eastern study area e.g. Helmand and Spin Buldak that the maximum wind velocity occur from March to August and minimum wind velocity occur at Autumn (Fig. 3). The maximum wind velocity at Ghandehar occurs in February.

Table 2 represent the annual mean and annual mean wind velocities upper 6 m s^{-1} that is threshold velocity for sand movement in study area. The maximum mean wind velocity upper threshold velocity was for Zabol (10.7 m s^{-1}), versus a minimum of 7.0 m s^{-1} at Spin Buldak. In addition, the highest proportion of winds greater than the threshold velocity with 62 % was at Zabol and Zahak as well. It shows that erosive winds intensify at Sistan region.

Duration of Iran Stations 1995–2016, Farah & Ghandehar 2010–2016, Delaram & Spin Buldak 2010–2014, Helmand 2012.

4.2 *Wind direction*

Sistan region and Registan desert is domain of Sadobist Roozeh wind blowing from Northern to south on border of Iran and Afghanistan then it turns to northwestern to Southeast direction in Sistan region. Finally, it turns to west-east direction in southwestern Afghanistan, as seen in Fig. 4. The location of high-pressure system in northeast of Iran and north of Afghanistan and low-pressure system over Registan desert effect on Sadobist Roozeh direction. The dominant wind direction at Zohan, Asadabad, Nehbandan, Shindend and Farah is north. In Zabol and Zahak, the dominant wind direction is northwest. In Helmand, Ghandehar and Spin Buldak the prevailing wind direction is west. The wind directions in Delaram are complex with dominance east, west and northwest.

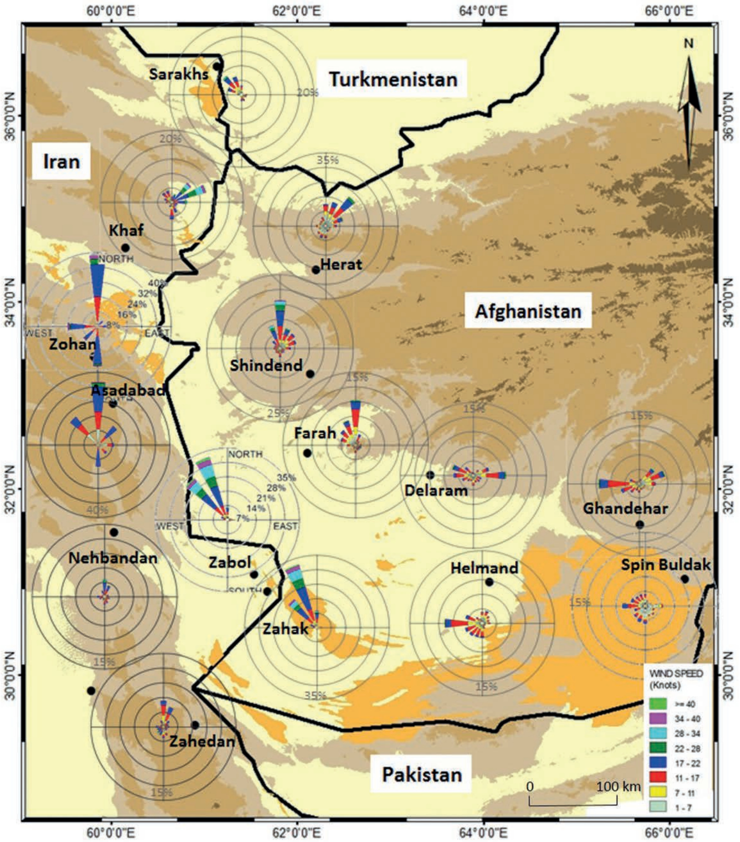

Fig. 4. Annual wind roses in Sadobist Roozeh wind domain, duration of Iran Stations 1995–2016, Farah & Ghandehar 2010–2016, Delaram & Spin Buldak 2010–2014, Helmand 2012, 36 sectors, with frequency in knot as a percentage of total winds.

Sometimes the location of low-pressure system lies on lower part as well and Sadobist Roozeh continues northerly direction in Sistan and effects some part of Baluchistan provinces on border of Iran and Pakistan.

Most of the effective wind directions clustered into the northeast at Khaf and Herat, north at Zohan, Asadabad, Nehbandan, Farah and Shindend, northwest at Zabol and Zahak, west (259–281°) at Helmand, Ghandehar and Spin Buldak and east (79–101°) at Delaram.

As seen in Table 3, the prevailing wind above threshold in Zohan was N (349–11°) with a frequency 37 % and secondary wind direction was S (169–191°) with a frequency 26 %. In Zabol and Zahak, the dominant wind direction was NNW (304–349°) with a frequency 31 % and secondary wind direction was NW (169–191°) with a frequency 22 and 16 %, respectively. At Farah, the prevailing wind direction above threshold was N (349–11°) with frequency 6 % and secondary wind direction was NNW (304–349°) with a frequency 4 %. At Helmand, Ghandehar and Spin Buldak, the dominant wind direction were W (259–281°) with a frequency that ranged

Table. 3. A summary of annual percentage of the two main wind direction with a velocity above threshold in Sistan and Registan desert.

Station	Prevailing wind		Second wind		sum
	Direction	%	Direction	%	
Zohan	N	37.0	S	25.8	62.8
Zabol	NNW	30.2	NW	21.7	51.9
Zahak	NNW	30.7	NW	15.6	46.3
Farah	N	6.3	NNW	3.8	10.1
Delaram	E	5.1	WNW	3.9	9.0
Helmand	W	4.0	WNW	1.8	5.8
Ghandehar	W	5.9	ENE	3.2	9.1
Spin Buldak	W	3.6	SSE	1.7	5.3

Duration of Iran Stations 1995–2016, Farah and Ghandehar 2010–2016, Delaram and Spin Buldak 2010–2014, Helmand 2012.

between 4 to 6 % and secondary wind direction were WNW (281–304°) ENE (56–79°) and SSE (146–169°) with a frequency 2, 3 and 2 %, respectively. The prevailing wind direction above threshold in Delaram was E (79–101°) with a frequency 4 % and secondary wind direction was WNW (281–304°) with a frequency 9 %.

4.3 *Spatial variability of Sand transport*

Drift potential (DP) is an index that shows the potential maximum of wind energy that could be moved sand in a region in a year (Pye & Tsoar 1990, Lancaster 1995). The distribution of erosive wind direction for the 16 compass directions is known as "sand rose diagram" (Fryberger 1979) shows at Sadobist Roozeh wind domain in Fig. 5. Spatial variability of annual drift potential (Fig. 6) indicate that it varies spatially among the region, is mostly similar wind speed pattern. The maximum value was in Zabol (2516 vector unit), versus a minimum of 101 vector units (VU) at Spin Buldak which represented in Table 4 for study area. From the point of view of wind energy, Sistan region classify into high energy and Registan desert into low energy environment. However, the current study result is much higher than the studies reported from different deserts such as 733 VU in Guaizi Lake Badain Jaran Desert (Zhengcai Zhang et al. 2015), 621 VU in Umm-Amara Kuwait (Al-Awadhi et al. 2005), 399 VU in Ruoqiang Taklimakan, 358 VU in Shapotou station, 540 VU in Bahrain, 658 VU in Ghudamia Libya, 391 VU Simpson Australia, 489 VU in An Nafud Saudi Arabia, 948 VU in Bilma Niger, 111 VU in Peski Karakumy Kazakhstan and 520 in Upington south Africa (Fryberger 1979). Although Tsoar (2001) reported 3999 VU for costal dunes of Ijmuiden in Netherlands because the wind speed is faster on ocean than land, therefore it is one of the highest sand drift potential in inland desert in the world. Actually, Sadobist Roozeh wind accelerated in the lower parts of corridor in north of Sistan region where it enters into desert area.

RDP were greatest at Zabol and Zahak with 2447 and 1638, respectively. These two stations also had the highest drift potential. RDP decreases gradually over Registan desert so that at

Table 4. Summary of annual mean of sand drift parameters in Sistan and Registan desert.

Station	Duration	DP (VU)	RDP	RDP/DP	RDD	Wind energy environment
Asadeyeh	1995–2010	286	174	0.6	184°	intermediate
Shindend	2010–2014	641	552	0.86	185°	high
Zohan	1995–2005	1023	289	0.3	112°	high6
Zabol	1995–2016	2516	2447	0.97	121°	high
Zahak	1993–2012	1716	6	0.95	119°	high
Farah	2010–2014	211	93	0.4	116°	intermediate
Delaram	2011–2012	188	25	0.1	107°	low
Helmand	2010–2016	140	6	0.5	73°	low
Ghandehar	2011–2016	168	31	0.2	95°	low
Spin Buldad	2010–2014	101	54	0.5	80°	low

DP: drift potential, RDP: resultant drift potential, RDD: resultant drift direction.

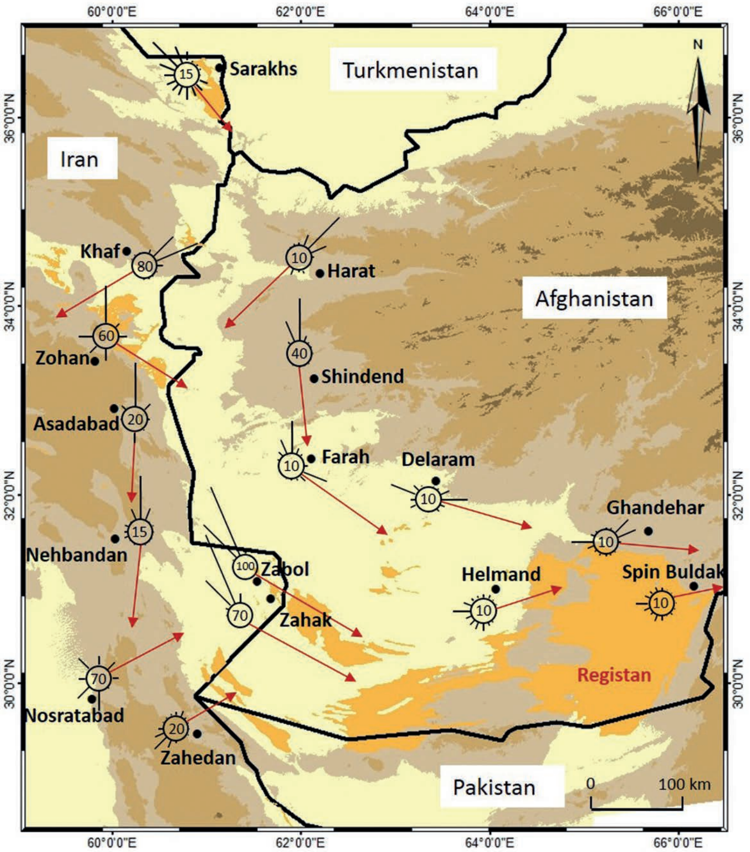

Fig. 5. Sand roses for the Sadobist Roozeh wind domain, during 1995–2016 for Iran stations and 2010–2016 for Afghanistan stations. Numbers into the roses are reduction factors for the adjacent sand rose of a given locality (criteria of Fryberger 1979).

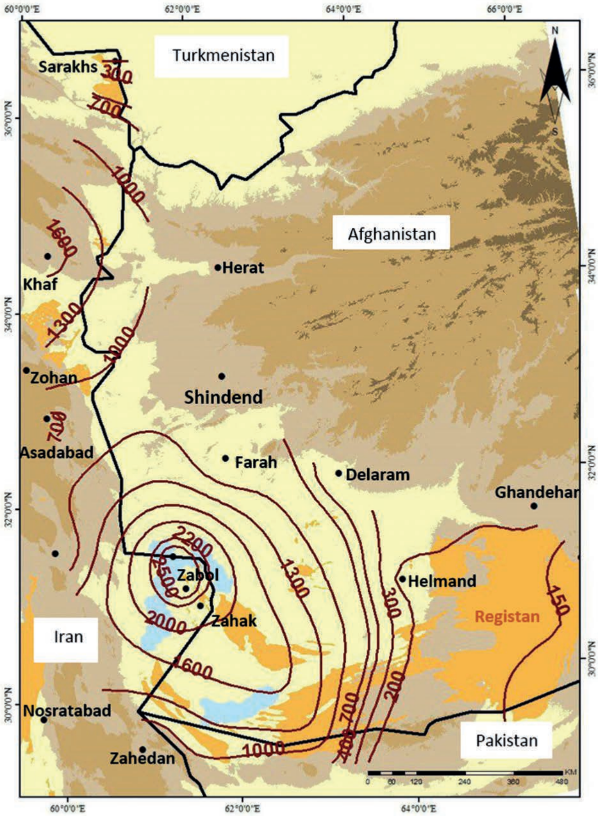

Fig. 6. The spatial distribution of DP in the Sadobist Roozeh wind domain.

Helmand, Ghandehar and spin Buldak reached to 69, 31 and 54, respectively. It is much higher than the studies reported from different inland deserts of world (Fryberger 1979, Zhengcai Zhang et al 2015, Al-Awadhi et al 2005, Livingstone et al 2010). The mean of Unidirectional index (RDP/DP) varies in study area from 0.97 to 0.1 at Zabol and Delaram. At Ghandehar and Spin Buldak, the value of UDI were 0.2 and 0.5, respectively. Totally, there is low variability (unimodal) wind at western part of study area (Sistan region) and intermediate to high variability direction (bimodal) at Eastern part of study area. This feature, unidirectional effective winds, were increased the dust process and shifting sediments on ephemeral lakes surface in Sistan region.

The angular direction of RDD, showing by red arrows in Fig. 5, varies with Sadobist Roozeh wind direction variability. It could be classified into three categories: 185° and 184° at Shindend and Asadeyeh, 121°, 119°, 116° and 107° at Zabol, Zahak, Farah and Delaram and 73°, 95° and 80° for Helmand, Ghandehar and Spin Buldak.

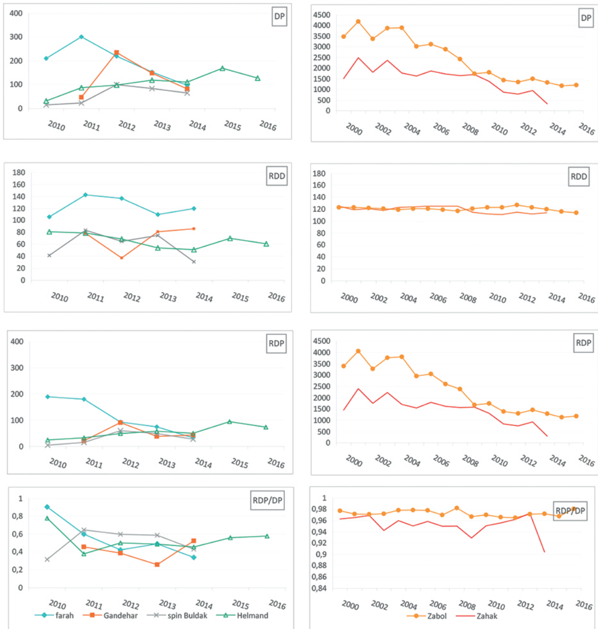

Fig. 7. Temporal variability of Sand transport characteristics in study area. DP: Drift potential, RDD: Resultant drift direction, RDP: Resultant drift potential, RDP/DP: Unidirectional index.

4.4 *Temporal variability of Sand transport*

The trends of annual DP, RDP, RDD and Unidirectional index (RDP/DP) provides at Fig. 7. The DP during 2000–2016 in Sistan region shows considerable temporal variation so that it raised up to 4183 vector units (VU), which is a record of drift potential in inland desert in the world, at Zabol station in 2001. Totally, DP were upper annual mean (2516 vector units) from 2000 to 2007 at Zabol but it experienced lower than from 2008 to 2016 as well as Zahak. The days with dust storm also were showed a similar trend upper annual mean (185 days) from 2000 to 2007 and lower annual mean (170 days) between 2008 and 2015 in Zabol station.

Unfortunately, there is no wind data available before 2010 for eastern part of study area. At Helmand, Ghandehar, and Spin Buldak, DP were less than 200 between 2010 and 2016. In other hand, Registan in east of study area has low energy wind. DP fluctuated at Farah between 2010 and 2014 but it had an intermediate wind energy environment in most years because it is located on the leeward side of Hindu-Kush Mountains as well as Delaram.

The trend of RDD is matched by Sadobist Roozeh wind direction in Study area in most of year. At Zabol and Zahak ranged from 114° to 125°, at Helmand ranged between 51° and 81°, at Farah and Zohan ranged from 99° to 143°, at Ghandehar and Spin Buldak generally ranged from 31° to 86°.

The annual directional variability (RDP/DP) at Zabol and Zahak were constantly ranged between 0.95 and 0.98 in duration 2000–2016. It means that effective wind blows a narrow unimodal direction with low variability at Sistan in this period. At Zohan, Farah, Helmand,

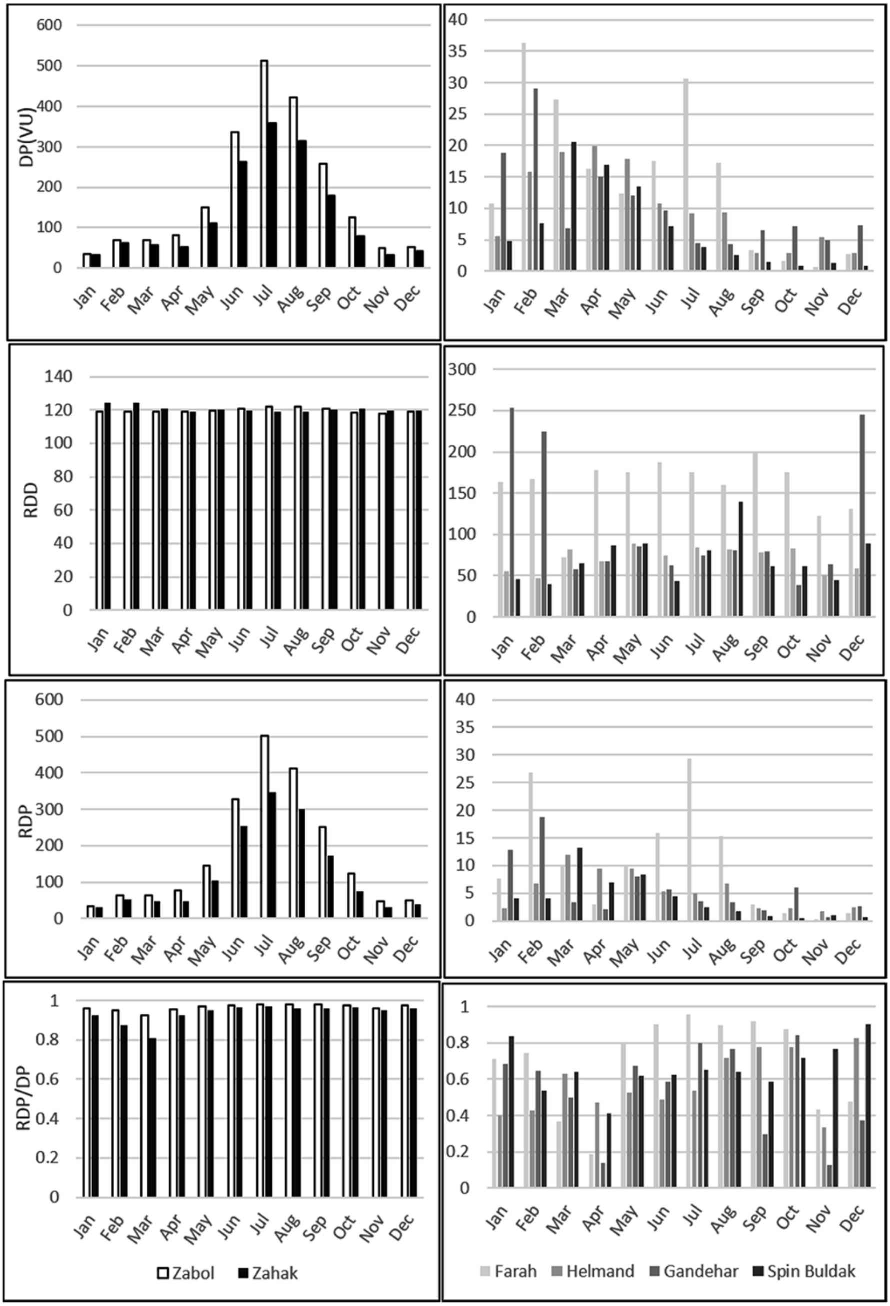

Fig. 8. Average monthly of DP, RDD, RDP and RDP/DP in the six stations around study area.

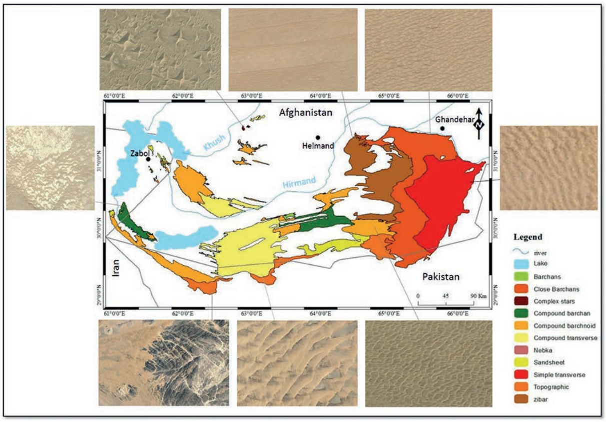

Fig. 9. Map of dune types in Sistan and Registan Sand Sea, with example Google earth images.

Spin Buldak and Ghandehar this ratio was mostly intermediate, with value between 0.3 and 0.8 exception: Farah at 2010 had low variability, Ghandehar had high variability in 2013 also Zohan in 2000, 2001 and 2002.

As seen in Fig. 8, the monthly of DP and RDP were high in July and August and low in September and January at Zabol and Zahak. Seventy percent of the average annual DP occurs between June and September (120 days) in these stations and it was greater than 400 vector units (VU) in July and August at Zabol. The RDD in all months was from NNW direction towards SSE, ranged from 118° to 124°, showed a very narrow unimodal direction in all seasons. The RDP/DP was near 1 in all months.

The monthly DP were high from February to August in Farah, Helmand, and Ghandehar and somewhat in Spin Buldak. RDD was consistently between 122° and 187° except March at Farah, between 47° and 89° at Helmand and between 40° and 139° at Spin Buldak. It is North-west direction with range of 38°–85° from SW direction for the period from March to November, while it varies slightly during December to February with a range of 225° to 253°.

4.5 *Morphology of dunes*

The variety of dune shapes depend on wind regimes and sand availability as well as grain size of sediment (Bagnold 1941, Lancaster 1995). McKee (1979) classified dunes on the basis of their shape and number of slip faces into crescentic, linear, reversing, star, and parabolic types which divided to varieties of simple, compound or complex. According this method, the morphology of sand dunes in Sistan and Registan was constructed based on visual interpretation of Landsat imagery supplemented with CNES/SPOT imagery via Google Earth in Fig. 9.

Totally, the most dune producing is associated with Sadobist Roozeh wind in Sistan and Registan sand sea therefore the most dunes type limited into the narrow unimodal wind regime and classified to crescentic shape. Garcia et al. (2015) shows that sand availability plays a major role on their formation and evolution transverse or barchan dunes in one wind direction regime. They shows barchans shape in low sand availability, barchanoid ridge in medium availability and transverse dune in high sand availability were formed in laboratory condition. We considered these forms of dunes in the classification of dunes morphology in study area.

In Sistan, Single barchans transport into four erosive corridors linking sand source zones in Hamouns lakes beds with depositional areas. The rate of barchans speed with 8–10 meter high into Sistan erosive corridor ranged 20–40 meter/year in field measurements in normal years. Sometimes, single barchans move alone from Sistan to Registan desert but in most cases, barchans joins and forms barchanoid ridges between Sistan region and Helmand province. Then, barchans and barchanoid ridges forms transverse dunes in Registan area, finally. In some area between Sistan and Registan, sand sheets formed as thin veneers of sand in transition area with rocky bed as reported by Kocurek & Nilson (1981). In addition, Zibar formed in some area that have sand thickness and roughly surface. Only in one case, star dunes created in a very small area near Delaram that the winds blew from many directions.

6 *Conclusion*

The outcome of our study may help to understanding the wind regime specifications and moving sand control in Sistan and Registan. As previous mentioned, Sadobist Roozeh wind (wind of 120 days) accelerated due to local topography over the border of Iran and Afghanistan and intensified over Hamoun-e Sabari and Hamoun-e Baringak lakes in Sistan region then it decreased gradually over Registan desert. In the context of wind energy environment according on Fryberger (1979) classification, Sistan region categorized into the high energy and Registan desert into intermediate to low energy. In addition, Drift potential is high in the western portion of study area and decreases gradually to east. The annual DP calculated in Sistan is one of the highest values (2516 vector units) in inland desert and categorized it into the windiest desert in the world. The trend of DP in Sistan indicated reduced considerable from 2000 to 2016 and the maximum annual sand DP is estimated to be 4183 vector units (VU) in 2001 (Fig. 7). Due to shortage data, the variation of wind energy is not clear in Registan desert but there is no considerable variation from 2010 to 2016.

The most dune producing is associated with Sadobist Roozeh wind in Sistan and Registan sand sea characterized by a narrow range of wind directions. The direction of this wind is northwest in Sistan, west to southwest in Helmand and west direction in Registan. According on unidirectional of effective winds, crescentic dunes are the dominant form which depend on sand availability can be divided to barchans, barchanoid ridge and transverse dune.

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