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Review Article

Quaternary Aeolian Landscape Development in Thar Desert and Its Drivers

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Research on the aeolian processes and landforms in the Thar Desert is not a very fertile academic field in India, especially because of the region's locational and climatic disadvantages. Studies by some dedicated groups over the past few decades helped to improve our understanding of the present-day process-form interactions in the desert. Linking those understanding with the results from optically stimulated luminescence dating of the sediments a broad framework of landscape development history during the late Quaternary period has been developed. The studies so far confirm that climate, especially its oscillations between warm wet and dry cool phases in an overall monsoon domain, was the most dominant driver of landscape development in our desert, and that the aeolian processes became more efficient during the transition from a drier to a wetter phase, rather than during the peak of dry period. There were, however, some notable exceptions to that rule. We highlight some of the unresolved issues, and discuss how analysis of the results from climate simulation modelling, understanding of the complementarities between aeolian and fluvial processes under different spatio-temporal contexts, and interpretation of the satellite sensor-based and ground-based observations of the modern processes can help to strengthen our knowledge on aeolian landscape development in the region.

Keywords: Phases; Sampling Strategy; Enigma; Palaeo-Wind; Complementarity of Processes; Dust Emission and Trajectories.

Introduction

The Thar, or the Great Indian Sand Desert (~290000 km^2 area), situated between the Aravalli Hill ranges and the Indus River, lies at the transition of the 'Monsoon wind' system in the east and the Mediterranean 'Westerly wind' system in the west. Therefore, the exogenic landscape processes here are much influenced by the periods of dominance and transition of the two systems over space and time. Based on the landform assemblages and their dominant characteristics, Kar (2014a) delineated the following seventeen major geomorphic provinces (GP) in Thar Desert: (1) Aravalli hills, (2) Alluvial plains of the north, (3) Star dune field, (4) Transitional parabolic dune field, (5) Luni alluvial plain, (6) Siwana hills, (7) Transverse dune field of NW, (8) Parabolic dune field of NW, (9) Hamada landscape, (10) Gravel pavements with sand streaks, (11) Parabolic dune field of south, (12) Nagarparkar upland, (13) Saline alluvial plain of NW, (14) Transitional parabolic dune field of NW, (15) Rohri upland, (16) Network dune field of west, and (17) Linear dune field with megabarchan fields in the west (Fig. 1). Since sand dunes and sandy plains constitute the most dominant landforms, most of the provinces essentially map the fields of dominant sand dune types. In fact, aeolian sand is almost ubiquitous in our desert, so much so that even the rocky and gravely areas have a veneer of aeolian sand.

Aeolian geomorphology of Thar Desert received some attention from researchers during the last few decades, especially on the processes and bedform characteristics, as well as on the evolution, including the chronometrically determined palaeo-environmental reconstruction for the last ~150 ka. Kar (1993, 2013 a, b) provided some useful summaries of the results on aeolian processes and bedform morphology, while

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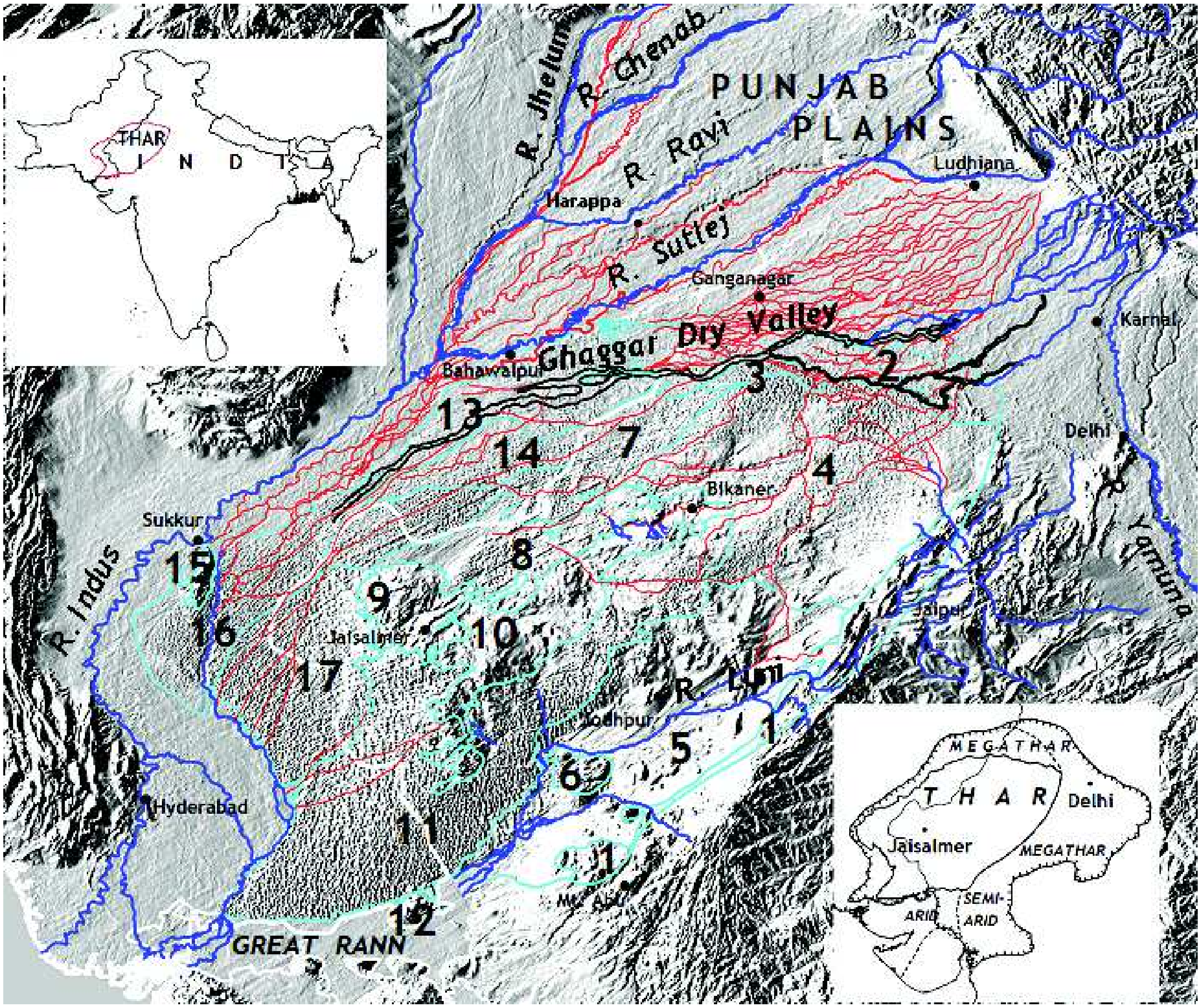

Fig. 1: Thar Desert and its surroundings, showing the boundaries of the desert's 17 geomorphic provinces (in cyan; numbers refer to provinces mentioned in the text), the palaeochannels (in red; mapped from visual analysis of Landsat and Sentinel-2 images, and digital analysis of ASTER, SRTM and ALOS-World3D data), and the present channels (in blue). Background image is a SRTM DEM. Lower inset map shows the approximate Megathar boundary

Kar *et al.* (2004), Singhvi and Kar (2004) and Singhvi *et al.* (2010) summarised the results on dating of aeolian deposits through Optically Stimulated Luminescence (OSL) methods. Although very little addition to the knowledge-base has taken place on the above aspects during the last few years, evolving ideas since the previous reviews and new results from some related fields have opened the scope for a fresh look at some of the results for new research. We provide here first a short overview of the major findings, and then discuss some of the results in the light of recent research in related fields to better understand the spatio-temporal context of aeolian processes and landscape development.

Antiquity of Aeolian Processes

The antiquity of aeolian activities in Thar Desert is enigmatic. Pre-Quaternary lithological sequences here reveal numerous sand beds of different geological periods, some having distinctly aeolian signatures. One such in the lithic sequences of the late-Jurassic Bhadasar Sandstone near Jaisalmer consists of thick beds of fine-grained aeolian sand, impregnated with innumerable ferricreted nodules, which suggest a near-shore deposition under a prolonged arid phase (Pareek, 1984). Interpretation of the Arabian Sea core data for the last 3 million years (Ma) revealed ~400 ka cyclicity in Earth's eccentricity that influenced the monsoon variability and aeolian dust deposition. Very weak monsoon and high dust deposition were recoded at the transition from the Pliocene to the Pleistocene (~2.6 Ma), and then at several time periods during the Pleistocene, the last notable increase being ~1.5 thousand years (ka) before present (Clemens and Prell, 1991, 2003; Pandey *et al*., 2016; Albani *et al.*, 2018; Wang *et al.*, 2019). The deciphered periods of weaker monsoon in the cores generally implied a reduced strength of the SW monsoon wind over the Thar Desert, but the higher dust concentrations were most likely due to strong westerly wind-driven supplies from the Middle East sources, rather than from the Thar Desert. This is analogous to the measured dust transport pathways from the Arabian Peninsula and the Iranian deserts to the Arabian Sea during strong dust activities in 1995 (Tindale and Pease, 1999) and 2016 (Rashki *et al.*, 2019). Ocean and continental records also revealed pulsating monsoon strength at timescales of 100, 40 and 21 ka, and at other shorter periods (Prell and Kutzbach, 1987; Clift and Plumb, 2008; Dixit *et al.*, 2018), which guided the relative dominance and complementarities of the fluvial and aeolian processes in Thar Desert. The Quaternary sedimentation in Thar Desert took place in several sub-basins that were bounded by rocky uplands (Wadhawan, 2018).

The Late Quaternary Record

The oldest preserved aeolian sequence dated so far in the Thar Desert was at the base of a hill-bordering linear dune near Didwana in the eastern Thar, where the oldest dune accretion age was recorded at ~150 ka and the youngest at ~6 ka, but in phases (Wasson *et al.*, 1983). Here strong horse-shoe vortices downwind of a quartzite hill formed a set of linear dunes along the hill's margins, while long-continued deflation in the wake of the hill gradually formed an ephemeral saline lake (playa or Rann; Kar, 1990). Such process-form interaction is continuing for ages in the desert.

Subsequent studies across the desert were carried out under a mega-project to understand through chronometry the Quaternary stratigraphy and palaeo-environmental history of the Thar Desert. These used the OSL method pioneered by Singhvi *et al.* (1982) in Physical Research Laboratory (PRL), Ahmedabad, and updated since then (Singhvi and Krbetschek, 1996). Briefly, the studies revealed that during the last ~200 ka major pluvial periods in our desert were ~200 ka (MIS 7.3), ~160 ka, ~126 ka (Climatic Optimum), ~90-80 ka, ~55 ka, ~30 ka, and 7-6 ka, which coincided with the phases of sustained high summer monsoon rainfall. The major periods of enhanced aeolian sand mobilization and accumulation, as well as high dune-building activities, largely coincided with the periods of transition to/from the peaks of vigorous SW monsoon, especially at ~190 ka (after the MIS 7.3), ~140 ka, 115-100 ka, 75-65 ka, ~55-50 ka, 30-25 ka, 14-7 ka, 5-3 ka and 2-1 ka (Kar *et al.*, 2001, 2004; Singhvi and Kar, 2004; Jain *et al.*, 2005; Dhir *et al.*, 2010). In the central and the eastern Thar the periods of relative calm and paucity in sand deposition mostly coincided with the peaks and the nadirs in the Prell and Kutzbach (1987) curve for mean SW monsoon rainfall deviation from the present normal. In many dunes in the southern half of the desert and its fringe areas a reddish hue is noticed in the upper part of the ~55-50 ka aeolian deposits, which acts as a marker horizon for widespread landscape stability due to high and sustained monsoon rainfall with marked seasonality (Tandon *et al.*, 1999, Juyal *et al.*, 2003). The feature gradually fades away northward. The Last Glacial Maximum (LGM), which experienced the maximum dryness during the last 100 ka, hardly recorded any sand deposition in the central Thar. Sand dunes in the southern and the northern fringe areas, however, recorded some LGM sedimentation (e.g., at Malpura, Dharoi and Tajpura in the south and Sahjasar in the north) despite the weak SW monsoon.

The LGM sand beds in the dunes of the Mahi and the Sabarmati river catchments beyond the desert's southern boundary were most likely related to a much lower sea level during the period. It allowed the newly exposed estuarine sand over a wide area to be processed and sorted upwind by a longer fetch of the strong westerly wind (Juyal *et al.*, 2003). In the northern fringe area, which lies in the transition from the SW to the westerly wind system, the retreat of the SW wind during LGM might not have large impact on dune growth and elongation, as a stronger westerly wind most likely continued the task from the pre-LGM period.

After the LGM, the monsoon started to regain its strength from ~16 ka, and the higher rainfall lagged the inception of high wind speed by years to centuries (Overpeck *et al.*, 1996; Sirocko, 1996). Large-scale re-mobilization of the old dunes and formation of new ones began within the desert and beyond it in the fertile alluvial plains of Punjab, Haryana, western UP and north Gujarat, as well as in the shallow soil areas of east Rajasthan. By 10 ka a sustained and vigorous monsoon rainfall began to stabilise the aeolian landscape beyond the present desert boundary, except along some wind gaps in the Aravallis where periodic sand accumulations continued due to the funnelling effect. The vestiges of this post-LGM aeolian phase beyond the Aravallis are now found as gullied and degraded 'fossil dunes' (Goudie *et al*., 1973; Juyal *et al.*, 2003; Kar *et al.*, 2004). The limits of those dunes marked the boundary of a Mega-Thar (Fig. 1, lower inset). By 7-6 ka the vigorous monsoon rains gradually established itself within the desert and its fringe areas, while the Westerlies also contributed some rains in the northern fringe areas, which further restricted the aeolian activities. This is attested by the freshwater deposits in most saline lakes (Ranns), but those to the west of 200 mm isohyet experienced very short periods of such interludes due to meagre contributions from both the air streams, and so experienced much shorter stabilization periods (Singh *et al.*, 1974, Kar *et al.*, 1998, Enzel *et al.*, 1999, Deotare and Kajale, 2004, Achyuthan *et al.*, 2007, Roy *et al.*, 2009, Dixit *et al.*, 2018).

Aeolian activities within much of the desert picked up again from ~5.0 ka to 3.5 ka when monsoon rains had declined. In between, the period ~4.5-3.9 ka witnessed the rise and fall of the pre-Harappan and the Harappan cultures along the misfit and the abandoned stream valleys in the desert's northern and the western fringe areas. Many source-bordering dunes along the palaeochannels of the Ghaggar and the Chautang, recorded a renewed phase of accretion around 5 ka (Shitaoka *et al.*, 2012). Subsequently, as the aridity peaked around 3.7 ka, the aeolian activities dwindled. The next burst of high aeolian activities from ~2.0 ka ended in the eastern fringe areas by ~0.8 ka, but continued till ~0.6 ka in the western part, as marked by a weakly developed palaeosol in the near-surface sand horizon in western Rajasthan, Punjab and Haryana (Naruse, 1985, Kar *et al.*, 2004). The latest phase of aeolian activities since ~0.3 ka is getting influenced additionally by increased human activities on the sandy landscape, leading to higher rates of sand mobility and dune movement than during the previous geological periods (Kar *et al.*, 1998).

Table 1: Major Holocene aeolian sand accumulation periods identified in Shergarh-Dechu area (Srivastava *et al.*, 2019a), and in parts of Thar Desert (as compiled in Kar *et al.*, 2004)

Srivastava *et al*. (2019a)	Kar *et al*. (2004)
0.6-0.2 ka	0.3 ka onwards
2.0-1.0 ka	2.0-~0.6 ka
~5.0-3.5 ka	5.0-3.5 ka
14.0-7.0 ka	14.0-7.0 ka

Discussion

The above broad framework of the late Quaternary aeolian activities and sedimentation in our desert still holds. As hinted earlier, the main focus of the studies were to reconstruct the major periods of aeolian sedimentation in the desert, match them with the results from global and regional proxies (oceanic, lacustrine, fluvial, etc.), and to derive broad conclusions on the efficacy of the aeolian processes over time. The generated data continues to be analysed to seek improved understanding of the landscape changes, but given the basic objectives of the studies and the sampling strategies employed, there is a limit to expectations from the chronometric data. Here we discuss some of those limitations and emerging issues, and how synergies with the complementary studies on atmospheric variables may help in understanding the spatio-temporal patterns of aeolian dynamics.

Sampling Strategy and Its Implications

The sampling strategies for OSL dating were highly skewed towards establishing the antiquity of aeolian deposits, rather than to understand the rates of aeolian processes, dune mobility, etc. Thus, sampling at multiple locations within a dune body, and along the breaks within a major unit, was sacrificed in favour of a single deep section to determine the mean periods of aeolian sedimentation. Although a process of homogenization of sediments in many pre-LGM deposits was a stumbling block in determining the breaks, this was not so in the younger units. Encouraging large sampling in representative shallow profiles on different dune types would have helped to better understand the chronometric context of dune growth sequences under different wind regimes, as was apparent from Kar *et al.* (1998). One of the fall-outs of ignoring a process-based sampling strategy was that >50% of the data from our desert was considered unsuitable for a global analysis of aeolian accumulation 'rates' and 'intensities' over time (Thomas and Bailey, 2019). This, however, does not nullify the importance of the results obtained, nor do they negate the concepts proposed for broad re-construction of the late-Quaternary aeolian depositional environment in the region.

In this context, a recent paper (Srivastava *et al.*, 2019a), based on few OSL dates on five parabolic sand dunes in the Jodhpur-Shergarh-Dechu tract, claimed to have identified several Holocene dune-building phases which they alleged our OSL-based data could not. To clarify the issue we provide here a summary of the major Holocene aeolian sand accumulation phases identified by them vis-a-vis our data (Table 1).

There is not much difference between the two sets of ages of sand accumulation. Our data showed that during the early part of the Holocene the SW wind continued to play its role within the desert but with falling vigour till 7 ka when higher monsoon rainfall stabilised the aeolian landscape. The next burst of aeolian activities from ~5 ka to 3.5 ka was recorded in all the sites within the desert. As we discussed earlier, the 2.0 ka event was ended by ~0.6 ka in the very dry western part. Srivastava *et al.*'s dune sites being located in the east-central part of the desert saw the end earlier, ~1.0 ka. We recorded the next burst of activities at ~0.3 ka onward, the intervening period being marked over large parts of the desert by a weakly developed palaeosol in the near-surface horizon, including at Chamu, which is within Srivastava *et al.*'s study area, but they missed it, and so concluded that the next phase of aeolian activities was from 0.6 ka to 0.2 ka. Srivastava *et al.* also conveniently overlooked our chronometric data on the rates of dune mobility in geological past and in modern times (e.g., Kar *et al.*, 1998), misread our view that the aeolian activities declined substantially *to* (rather than *in*) the east of Thar Desert after 5 ka, and made unjustified comments like "previous published luminescence ages from the Thar, even though with large errors, *do not* include evidence of dune building during the early Holocene" (p.14), and "Kar *et al.* (2004) noted very little trace of dune accumulation from ~5 ka onward *in* the eastern and southern part of the desert" (p. 14).

Another recent paper by Srivastava *et al.* (2019b) dated four linear dunes to the north of Bikaner, which is a welcome addition to the chronometric database on the Thar sand dunes. The Holocene sand accumulation phases recorded by them were: ~11.6-8.6 ka, ~4-3 ka, ~2-1 ka and ~0.5-0.3 ka, which fall within the age brackets reported in our studies from three linear dunes at Jamsar, Thirana and Sahjasar in the same area (e.g., Thomas *et al.*, 1999, Singhvi and Kar, 2004). They missed a ~5 ka event, possibly due to sampling gap or due to erosional breaks. Additionally, they found "minimum ages" of ~50 ka from two dunes, which qualify those dunes to be old, but periodically active. Unfortunately, while discussing their results Srivastava *et al.* (2019b, p.24) wrongly argued that the linear dune at Jamsar was mentioned by Singhvi and Kar (2004) as a 'parabolic dune'. We did not say so.

Curious Aeolian Lumps of ~82 ka

Moving beyond the controversy, the studies so far in the Thar Desert have brought out some findings that appeared enigmatic to the present author. An interesting but poorly understood feature in many deep aeolian sequences in the eastern, central and south-western Thar is the occurrence, below the ~100 ka carbonate-rich aeolian sand bed, of a moderately thick deposit of brownish aeolian sand that is devoid of any carbonate. Irregularly shaped aeolian lumps abound here amid a ground mass of loose sand, and give an age of ~82 ka, which is abnormal below a bed of ~100 ka. The carbonate-free lumps could be a result of long exposure to acid rain, but whether this was triggered by a sulphur-rich volcanic ash cloud, needs investigation. Since the sand pre-dates the Toba Ash bed (~74 ka) in the Narmada River basin (Raj, 2008; Williams *et al*., 2009), further studies on it may yield some interesting results.

Linking Results from Palaeo-wind Simulations

Climate simulation models are now providing systematic information on the likely past distribution pattern of many atmospheric variables. The datasets are generated for major climatic phases like Pliocene (Plio, ~3 Ma), Last Interglacial period (LIG, ~127 ka), LGM (~21 ka), Mid-Holocene (MH, 6.5 ka) and Pre-

Industrial period (PI, ~1800 AD), using different General Climate Models (GCMs) and Regional Climate Models (RCMs) under the Paleoclimate Modelling Intercomparison Project (PMIP) of the Coupled Model Intercomparison Project (CMIP) phases. Care is taken to match the results with the historical and proxy records from several biophysical archives. Although basic parameters like precipitation, temperature, air pressure, etc., have been simulated by all the climate models, simulation of the past wind systems have been attempted by only a few. Using the ECHO-G model, Kaspar and Cubasch (2007) simulated the global wind speed and direction during LIG at 125 ka and 115 ka, and during PI, which suggest that the wind speed, surface temperature and precipitation during summer in the northwestern part of India were higher during 125 ka than during PI. During the summer of 115 ka, when the earth's climate was transiting to a glacial phase, the wind over the region became feeble and both temperature and precipitation dropped.

One of the GCMs that adequately replicated the present wind pattern over the Thar Desert was Max Planck Institute's ECHAM5 model (Kar, 2012). Mutz *et al.* (2018) and Mutz and Ehlers (2019) used the ECHAM5 model to simulate the climate during PLIO, LGM, MH and PI. We used their mean monthly zonal and meridional wind data at 0.75º grids (https://esdynamics.geo.uni-tuebingen.de/wiki/), to map the mean winter, spring and pre-monsoon summer wind speed in the Thar-Megathar region during PLIO, LGM and MH as percentage of the PI distribution. During PLIO and LGM the northern fringe of Thar Desert and the adjoining northern part of Megathar showed much stronger wind from the N and NW in winter and spring than during the PI. The eastern fringe of the Thar and the adjoining part of Megathar also experienced higher than PI wind in spring and summer. During both the above periods, summer wind remained subdued in large areas of the Thar, but the northern part, including the Megathar, experienced much higher wind speed than during PI, with implications for dune mobility. This calls for some confirmatory chronometry. During MH, when the climate over the region was transiting from a wetter peak to a drier one, the northern part registered higher than PI wind from NW during spring, and almost identical to PI wind from SW during summer (Fig. 2a-f). Juxtaposition of such sand-shifting wind vectors played a major role in the formation of tall star dunes with a fern-leaf pattern along the desert's northern fringe (Kar, 1993). Another less-recognised process of wind speed-up with dune height accelerates the sand transport along a dune's windward slope to the crestal part, so long as the sand supply remains adequate (Ash and Wasson, 1983, Ramakrishna *et al*., 1990, Bo and Zheng, 2013). It must have played a crucial role across the desert in increasing the dune height and thickening of crestal sand.

To find out if the wind direction in the past was much different from the present, we first mapped the mean monthly 10 m wind velocity vectors over the Thar–Megathar region (averaged over the period 1981-2010), using the reanalysis data from NASA's Modern Era Retrospective analysis for Research and Applications (MERRA), ver. 5.12.4 (Fig. 3). Superimposition of the simulated past wind vectors from Mutz *et al.* (2018) over it did not show appreciable change over the time.

Fluvial System's Complementary Role in Dunefield Development

Apart from the wind, geomorphic settings also contributed much to the development of aeolian bedforms. In this context the complementary role of the fluvial system needs proper evaluation. Numerous abandoned stream courses, called the Naiwals in the northern fringe of the desert and the adjoining Punjab Plains, guided the wind flow pattern to form many sinuous source-bordering dunes along them through funnelling effect. In the north-central part of the desert, between Rawatsar, Pallu and Dungargarh, the remnants of a large palaeo-valley of the now-defunct Saraswati River from the Himalayas, although buried under a thick aeolian sand deposit, still tends to control through micro-topographic variation the wind flow pattern, which in turn makes subtle variations in dune shape and orientation along the valley's obscure margins.

In the northwest of the desert, the close proximity of a transverse dunefield (GP-7 in Fig. 1) with a linear dunefield to its south (GP-17) and a network dunefield to the southwest (GP-16) was most likely guided, apart from the wind, by the changing sediment regime along a major palaeo-valley system of the Saraswati River through Anupgarh, Khajuwala, Tanot, Shahgarh and further south to Umarkot (Ghose

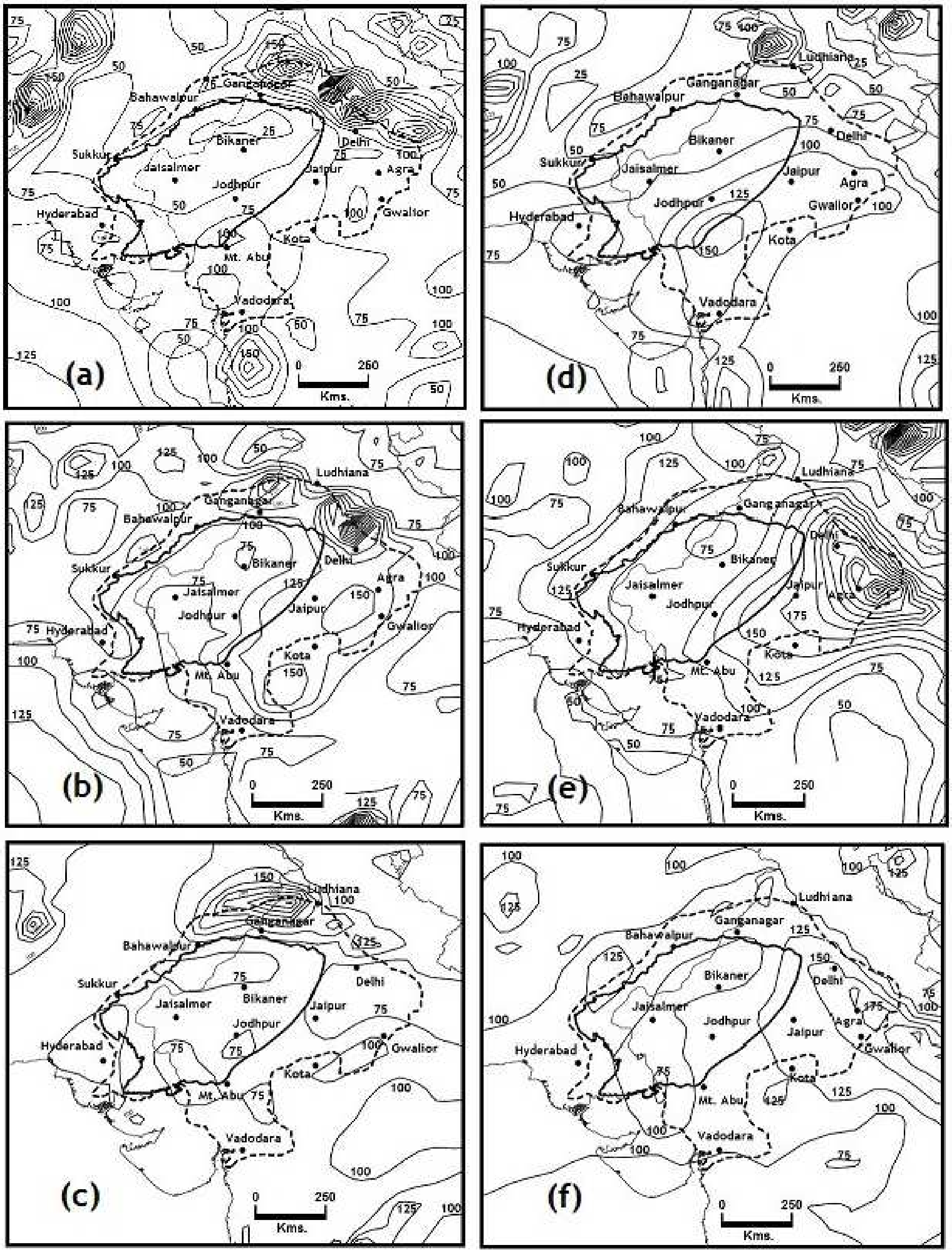

Fig. 2: Contours of mean bi-monthly wind speed at ~10 m height in the Thar-Megathar region during past climates, shown as percentage of the wind speed at ~10 m height during Pre-Industrial period. Values were derived from Mutz et al.'s (2018) ECHAM5-based zonal and meridional winds for the above periods. Figures (a) to (c) show the contours for March-April (Spring) for Pliocene, LGM and mid-Holocene, respectively. Figures (d) to (f) show the contours for May-June (Summer) for the above three periods, respectively

et al., 1979; Kar, 1987). The stream was more sand-dominated in its upstream reaches (i.e., Anupgarh area), and progressively more silt-dominated in the lower reaches, which possibly meant less availability of sand for aeolian processes in the downstream areas than in the upstream. Presumably, the shorter availability of dune-forming sand in the Umarkot-Shahgarh tract compelled the strong, unimodal SW

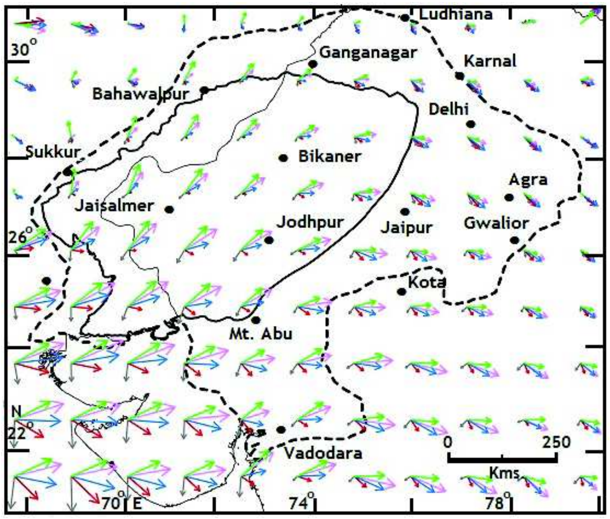

Fig. 3. Mean resultant wind vector (1981-2010) at 10 m height over Thar-Megathar region during winter (mean of Dec., Jan., Feb; black), March (red), April (sky blue), May (pink) and June (green), as derived from NASA's MERRA reanalysis data. Basic data was accessed from the NASA Giovanni site

wind to construct linear dunes (a dominantly sand-passing bedform), but as the same wind flowed downwind to Tanot-Anupgarh sector it started to pick up a very high load of sediments and soon became over-saturated. The consequence was large release of the load in rake-like fashion to form closely-spaced transverse dune chains (i.e., a sand-arresting form). Continuous supply from the sand-passing linear dunes and from the interdune plains led to the formation of tiers of bedforms in many tall transverse dunes (Kar, 2013a).

Dust Emission and Trajectories from the Desert

Every year the aeolian sand mobilization in the Thar leads to dust emission that gets carried away beyond the desert along some defined trajectories. Analysing the UV Aerosol Index (uv_AI) values from NASA's Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) for mid-March to mid-June, 1979-2018 (excepting the missing period 1993-1996), we found that, summarised over the Thar, the mean uv_AI values varied inversely with the previous year's rainfall that was derived from the global data repositories of VASClimo (1978-1999) and GPM-3IMERGM (2000-2018). Matching the uv_AI with the mean wind speed for March-June (derived from the MERRA-2 re-analysis dataset of NASA), we found broad agreement between the two datasets till the year 2000, but afterwards the mismatches became more apparent (Fig. 4). We presume this to be a consequence of immense churning of the erstwhile semi-stable sandy terrain in the desert through tractor ploughing, especially since the 1990s (Kar, 2014b), although other factors are also involved. Maximum AI values were recorded during May.

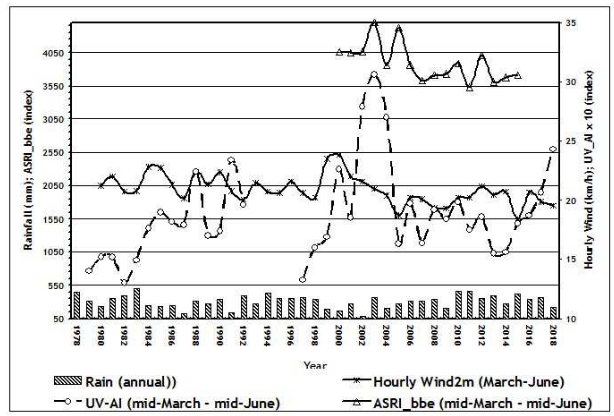

Fig. 4: Mean values of rainfall (annual total, mm), hourly surface wind speed (March-June, km/h), UV Aerosol Index (mid-March to mid-July) and ASRI_bbe index (mid-March to mid-July) for Thar Desert (1978-2018). Basic data was accessed from the NASA Giovanni site

To explore the relationship between wind speed and uv_AI with sand reactivation within the Thar we developed an Aeolian Sand Reactivation Index (ASRI_bbe) from the MODIS surface reflectance and broadband emissivity data (Kar, 2019). Calculation of the ASRI_bbe values at 1 km pixel resolution during each of the 8-day periods for mid-March to mid-June in the years 2000 to 2015, and averaging the results at regional level, we noticed a gradual decline in aeolian sand reactivation with a similar decline in mean wind speed, but no such relationship was apparent with the uv_AI (Fig. 4). When we mapped the TOMS Aerosol Optical Depth (AOD) for the Thar-Megathar region for 1980-2000 period we noticed the higher values always along the northern and western fringes of the Thar, e.g. in the long-term average for May (Fig. 5). This is despite the fact that during May almost the whole of the desert gets affected by sand/dust storms, and fine sediments constitute quite a significant area of the desert. Such mismatches needed some explanation.

To find reasons for such anomalies, we explored

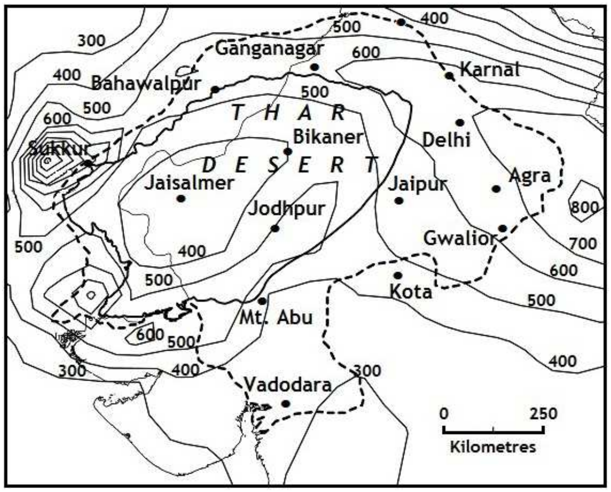

Fig. 5: Mean TOMS AOD contours over Thar-Megathar region for May, 1980-2000 (except for the missing period 1993 to 1996). Basic data was accessed from the NASA Giovanni site

the wind and dust trajectories during a severe dust storm across the desert on 27th May 2010, which was captured by the daytime image of the MODIS Terra satellite. The vertical structure of the dust column, captured at 23.00 h (UT) by the Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO) along a narrow strip through the vicinity of Bhavnagar, Mt. Abu, Jodhpur, Bikaner and Ganganagar, showed dust columns all along the desert overpass. Using the hourly wind speed data at surface and at several heights aboveground for the day (accessed from the Climate Forecast System Reanalysis, CFSR, of the US National Center for Environmental Prediction, NCEP), in a HYSPLIT model of NOAA, we simulated the likely forward trajectory of dust particles, if released from a height of 100 m and if allowed to travel for 12 hours. We also mapped the likely backward trajectory of the particles for the previous 12 h period, which confirmed NEward transportation of dust at that height (Fig. 6). Such simulation was done at other heights also, results from which were quite revealing. While at lower level the net transportation was NEward, with height gain the particles gradually moved eastward, especially in the northern part of the desert. At 7 km height the trajectory was in a SE direction (Fig. 7). The TOMS satellite sensed the aerosol clouds at this height, and not below it. Thus, it is now apparent that as the sand and dust particles are emitted from the desert surfaces during summer, the wind at lower height carries them NEward, but as the finer particles move up during their forward journey they get trapped in the NW-SE air stream along the northern fringe area and so travel SEward. Significantly, the air stream at this height lies above the silt-rich alluvium of the Panjnad-Sutlej-Yamuna plains, which contribute higher amounts of fine particles than the desert surface.

It would have been interesting to explore the dust AOD pattern during the past climates. Albani *et al.* (2014, 2016) simulated the global pattern of aerosol optical thickness (AOT; similar to AOD) values at 550 nm for LGM, MH and PI. Unfortunately, we found the MODIS-derived AOT values at 550 nm to be very unrealistic over the Thar Desert, and so are not yet sure about the applicability of the Albani *et al.* results.

Conclusions

Following major conclusions can be drawn from the present overview.

The chronometry-based studies so far have focused more on fixing the broad patterns of aeolian sedimentation in the desert. High potentials exist, however, in using chronometry to enumerate the spatio-temporal rates of aeolian process at dune type and dune field levels, for which the sediment sampling strategy needs to be based on a proper understanding of the morphology, growth and mobility pattern of different sand dune types.

LGM, although a dormant phase for both fluvial and aeolian processes over much of the desert, still remains enigmatic, and needs critical appraisal based on studies in the fringe areas of the desert and beyond. The complementary role of the past fluvial processes in aeolian accumulation pattern is another enigmatic field.

Since wind is a major determinant of aeolian sand accumulation and dune growth, it is important to match the stratigraphy- and chronometry-based assumptions on wind strength and distribution pattern with the results from climate observations and simulation modelling. Complementary results from atmospheric dust observations and modelling, and matching them with the trajectories of wind-sand streams will help to better understand the past settling of fine sand and dust beyond the desert.

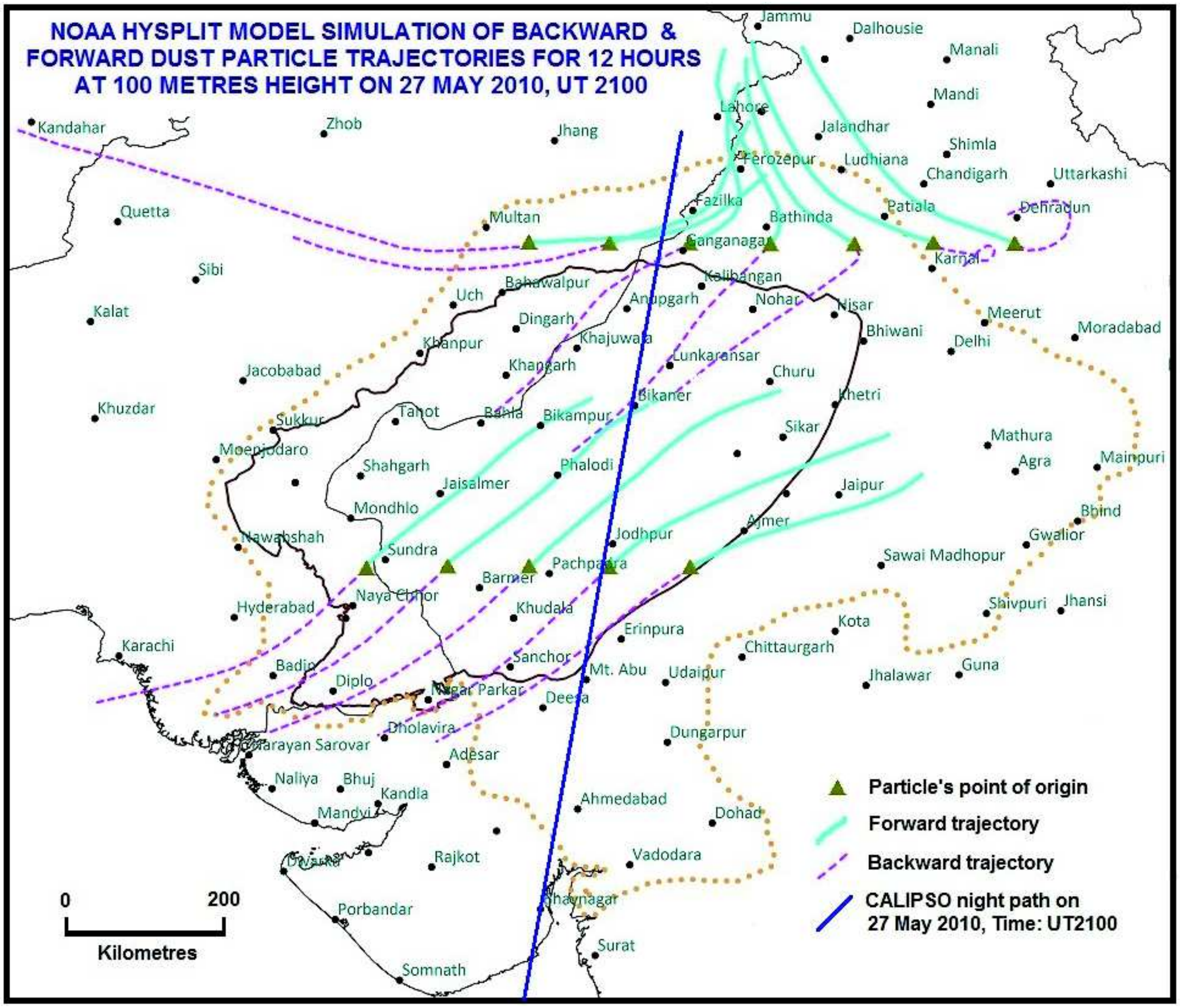

Fig. 6: NOAA HYSPLIT model simulation of backward and forward dust particle trajectories from selected locations in Thar Desert for 12 hours at 100 m height for 27 May 2010 (time UT 2100). Also shown is the CALIPSO satellite's night-time footprint through Mt. Abu, Jodhpur and Bikaner

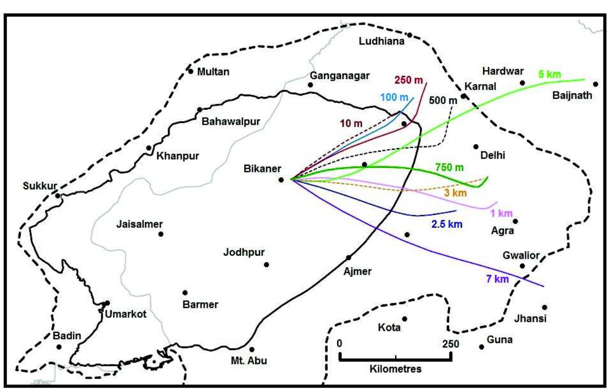

Fig. 7. NOAA HYSPLIT model simulation of forward dust particle trajectories at different heights near Bikaner for 27 May 2010 (time UT 2100)

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