Boundary condition controls on the high sand flux regions of Mars

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Introduction
Data Repository materials include methodology details (Section 1-2), three tables with detailed information for High Resolution Imaging Science Experiment (HiRISE) bedform monitoring images (Table DR1), summary of regional surface properties (Table DR2), and regional boundary condition summary (Table DR3) results. Eight supplementary figures provide additional geographic context and details for bedform change detection results and various interpretations.

Included animations provide additional evidence for bedform activity or inactivity. Animations DR1, and DR4-DR8 were built using in-house software which takes orthophoto subsets, stacks them in chronological order, and provides relevant temporal and geographic context. Alternatively, Animations DR2-DR3 were built using Photoshop. As per convention, the solar longitude (Ls) range of 0°–360° defines a Mars Year (MY) and 11 April 1955 (Ls =0°) is the start of the Mars calendar at MY01 (see Piqueux et al. (2015) for details). See images listed in Table DR1. Similar animated GIFs of migrating dunes are located at http://www.uahirise.org/sim/ and Chojnacki et al. (2017, 2018).

Section 1. Derivation of dune topography and change detection
To quantify dune heights and movement, high-resolution HiRISE Digital Terrain Models (DTMs) were derived using stereo photogrammetry via SOCET SET® BAE system software (see Kirk et al., 2008), specifically with HiRISE data (0.25–1 m/pix) (McEwen et al., 2007) from the Mars Reconnaissance Orbiter. The resulting DTMs (horizontal post spacing of 1 meter) generally possess a vertical precision of ~25-35 cm and were registered to Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 2001) shot points for absolute elevation. The quality of pixel matching between monitoring images is provided by SOCET SET as a root mean square error that is typically 0.3–0.7 of the HiRISE pixel scale (i.e., 25 cm, reported in those Planetary Data Systems
products) (Kirk et al., 2008; Sutton et al., 2015), but often registration offsets were imperceptible during the analysis. The estimated displacement error is +/- 0.22 m, given the maximum RMS errors reported from SOCET SET or ENVI for image registration (~0.7 pixel) combined with human error in manual measurements (0.5 pixels). Any terrain artifacts created during the photogrammetric process (due to bland or deeply shadowed areas) were identified and avoided in co-registered Figure of Merit (FOM) maps (Mattson et al., 2012).

Stereo and monitoring images were then orthorectified to the DTM to allow change detection and bedform displacement quantification to be made. To restrict lighting and seasonal effects, images were restricted to increments of Mars years and ranged between 1.9-11 Earth years (EY) or 1-6 Mars years (MY). Dune lee-front advancements were recorded in two to three locations per dune and then averaged, but obvious areas of avalanches were avoided. Most dunes measured were crecentric in morphology (e.g., barchan, barchanoid) so lee-front measurements were performed at the perceived center of the slip face. Using the product of the dune migration rate (m/EY) and height (m), bedform sediment fluxes (m³ m⁻¹ yr⁻¹) were calculated (Ould Ahmedou et al., 2007; Bridges et al., 2012; Chojnacki et al., 2015). If dunes changed heights between time steps, it was assumed to be minimal and within the margin of error.

Dune and ripple measurements were collected from a variety of locations across Mars (see Fig. 1). 54 sites include locations where dune crest flux and migration rates were measured (495 individual dunes). Some of these were documented in previous reports. Eight sites (shown in Fig. 2 as “Other Mars Dunes”) were reported earlier in Meridiani (Chojnacki et al., 2017), four in Arabia Terra (Urso et al., 2018), 31 sites in Arabia Terra/Syrtis Major/Valles Marineris/ regions, and the remaining sites in Hellespontus and North Polar Erg are listed in Table DR2. Ripple rates described in the main text and bedform mobility (triangles in Fig. 1) were results in previously described work that examined 135 locations with bedforms, excluding TARs (Banks et al., 2015, 2018). Reported dune and ripple measurements were not necessarily all collected from the same sites, with some exceptions.

Section 2. Collection of regional surface properties and assessment of regional boundary conditions

To quantify regional surface properties (MOLA elevation, TES albedo, TES surface temperature, and maximum surface winds), profiles were made across regional dichotomies (e.g. impact basins, north polar cap) using the Java Mission-planning and Analysis for Remote Sensing (JMARS) (Christensen et al., 2009). TES bolometric albedo measurements (Christensen et al., 1992) were used along with estimated TES daytime surface temperature data using the KRC thermal model (Kieffer, 2013). These profiles were centered on bedform monitoring sites and extended several hundred kilometers in length across local topographic local dichotomies. For the example of Syrtis Major, the profiles began in western Isidis Basin (elevation=-4 km, albedo=0.225, temperature=195 K) and extended radially away to the northwest across the Syrtis plains (elevation=+1 km, albedo=0.14, temperature=205 K). Maximum surface wind speeds along these profiles were collected as modeled from the AMES Global Circulation Model (Haberle et al., 1993). Annual maximum wind speed maps are also provided for the three study regimes (Fig. DR2) (Haberle et al., 2011; Hollingsworth et al., 2011). Results are listed in Table DR2.
Qualitative and quantitative assessments of boundary conditions for high flux regions were also performed as inferred from results and prior publications (Table DR3). These include wind regime, sediment supply, sediment availability, climate factors, and topography. Simplified regional wind regime trends were inferred from bedform migration patterns (Table DR1) and modeling results (Toigo et al., 2002; Toigo and Richardson, 2003; Armstrong and Leovy, 2005; Michaels, 2011; Howard et al., 2012; Bridges et al., 2013; Smith and Spiga, 2017; Chojnacki et al., 2018). As a proxy for sediment supply, the fractional ratio of dune field to regional area was estimated using the dune field areas from previous mapping (Hayward et al., 2007, 2014; Chojnacki et al., 2018) and the regional areas displayed in Fig. 3. Sediment availability of bedform sand to be transported by the wind, and climate factors were inferred from various evidence from prior publications highlighting polar and middle-latitude seasonal processes (e.g., dune gullies, CO₂ frost, ground ice) (Fenton et al., 2003; Fenton, 2005; Tanaka et al., 2008; Ewing et al., 2010; Fenton and Hayward, 2010; Hansen et al., 2011; Diniega et al., 2017; Brothers and Kocurek, 2018; Banks et al., 2018). Regional topographic environments were summarized from prior mapping efforts (Tanaka et al., 2008, 2012, 2014; Fawdon et al., 2015).
Table DR1. HiRISE observations and sand transport results\textsuperscript{a} for Hellespontus and north polar dune fields\textsuperscript{b}.

<table>
<thead>
<tr>
<th>ID and site name\textsuperscript{c}</th>
<th>Images</th>
<th>Time duration</th>
<th>Rate</th>
<th>Height</th>
<th>Crest Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EY</td>
<td>MY</td>
<td>m/EY</td>
<td>m</td>
</tr>
<tr>
<td>0188-470 Kaiser Dunes</td>
<td>PSP_007110_1325</td>
<td>5.5</td>
<td>2.9</td>
<td>0.6</td>
<td>29.7</td>
</tr>
<tr>
<td>0446-414 Hellespontus Barchans*</td>
<td>ESP_045745_1380</td>
<td>8.1</td>
<td>4.3</td>
<td>0.9</td>
<td>14.2</td>
</tr>
<tr>
<td>0420-450 Hellespontus Erg</td>
<td>ESP_023130_1345</td>
<td>3.8</td>
<td>2.0</td>
<td>0.3</td>
<td>22.4</td>
</tr>
<tr>
<td>0420-423 Hellespontus Stardunes*</td>
<td>ESP_016326_1375</td>
<td>7.2</td>
<td>3.8</td>
<td>0.4</td>
<td>34.2</td>
</tr>
<tr>
<td>0455-415 Hellespontus Montes</td>
<td>ESP_016339_1380</td>
<td>7.4</td>
<td>4.0</td>
<td>0.4</td>
<td>15.2</td>
</tr>
<tr>
<td>0953+761 West Olympia Barchans</td>
<td>PSP_009743_2565</td>
<td>1.9</td>
<td>1.0</td>
<td>0.6</td>
<td>26.5</td>
</tr>
<tr>
<td>2329+840 Olympia Dunes</td>
<td>ESP_018427_2640</td>
<td>5.7</td>
<td>3.0</td>
<td>0.9</td>
<td>25.5</td>
</tr>
<tr>
<td>2705+761 Abalos Undae Erg</td>
<td>ESP_045262_2640</td>
<td>5.7</td>
<td>3.0</td>
<td>0.9</td>
<td>25.5</td>
</tr>
<tr>
<td>1186+835 West Olympia Scarp*</td>
<td>ESP_009394_2565</td>
<td>9.4</td>
<td>5.0</td>
<td>0.5</td>
<td>16.5</td>
</tr>
<tr>
<td>2121E+790 Gypsum Erg Margin</td>
<td>ESP_001712_2635</td>
<td>11.0</td>
<td>5.8</td>
<td>0.5</td>
<td>20.6</td>
</tr>
<tr>
<td>1788+816 Olympia Undae Erg</td>
<td>ESP_019023_2620</td>
<td>3.6</td>
<td>1.9</td>
<td>0.3</td>
<td>33.4</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Migration rate, height, and crest flux are averages across a given dune field (typically a dozen or more individual dunes).

\textsuperscript{b}Image and migration rate results for the five Syrtis Major sites and “Other Martian Dunes” are provided in Chojnacki et al. (2017, 2018).

\textsuperscript{c}Dune field site IDs, where the first four digits are the monitoring site’s centroid east longitude, the last three digits are the site’s latitude (each coordinate given to the first decimal place without the decimal), and the separating + or – sign indicating which hemisphere.

*Image pair temporal offsets from even increments of Mars years are noted with deviations of >0.10 Mars years.
Table DR2. Summary table of various parameters for high sand flux regions that illustrate variations across regional topographic transition zones.

<table>
<thead>
<tr>
<th>Region</th>
<th>Sediment supply</th>
<th>Approx. profile lengths</th>
<th>ΔElevation (km)</th>
<th>ΔBolometric albedo</th>
<th>ΔTemperature (K)</th>
<th>Max. annual wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isidis Basin - Syrtis Major</td>
<td>0.15%</td>
<td>625</td>
<td>4-5</td>
<td>0.10</td>
<td>10</td>
<td>13-20</td>
</tr>
<tr>
<td>Helles Basin - Hellespontus</td>
<td>0.64%</td>
<td>625</td>
<td>5-7</td>
<td>0.20</td>
<td>3</td>
<td>19-25</td>
</tr>
<tr>
<td>North Polar Cap - circum-polar erg</td>
<td>21.10%</td>
<td>750</td>
<td>0.7-0.9</td>
<td>0.15-0.25</td>
<td>23</td>
<td>24-34</td>
</tr>
</tbody>
</table>

* MOLA elevation, TES albedo, TES daytime ascending surface temperature, and maximum surface wind speeds from AMES Global Circulation Models (Haberle et al., 1993).
* Fractional dune field to regional area was estimated using the dune field areas from previous mapping (Hayward et al., 2014; Chojnacki et al., 2018) and regional areas displayed in Fig. 3.
* Elevation, albedo, and surface temperatures variations were collected across major topographic transition zones using JMARS numerical profiles.
Table DR3. Summary table of regional boundary conditions.

<table>
<thead>
<tr>
<th>Region – Regional topographic influence</th>
<th>Wind regime</th>
<th>Sediment supply</th>
<th>Sediment availability</th>
<th>Climate factors</th>
<th>Topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syrtis Major – Isidis Basin</td>
<td>Unidirectional (Anabatic) westward winds out of Isidis (Chojnacki et al., 2018; Cantor et al., 2019)</td>
<td>Limited - Putative scarp outcrop sand source (Fawdon et al., 2015; Bramble et al., 2017)</td>
<td>Unconsolidated sand ~100% (?) of the year</td>
<td>Tropical latitudes – dry condition, minimal volatiles</td>
<td>Intracrater, fosse, patera, and plains (Fawdon et al., 2015; Bramble et al., 2017)</td>
</tr>
<tr>
<td>Hellespontus – Helles Basin</td>
<td>Anabatic (broadly) westward winds nearest Montes, reversing flow to SW (Fenton, 2005; Armstrong and Leovy, 2005; Bridges et al., 2011; Guzewich et al., 2017)</td>
<td>Limited - Putative scarp outcrop sand sources (Fenton et al., 2003; Fenton, 2005)</td>
<td>Largely unconsolidated sand near Hellespontus, but increasing influence of seasonal volatiles to the SW (Fenton and Hayward, 2010; Dundas et al., 2015; Banks et al., 2018)</td>
<td>Mid-Latitude Southern Highlands – some seasonal CO₂ or ground ice to the SW</td>
<td>Mountains, rim elements, and intracrater with low-moderate relief</td>
</tr>
<tr>
<td>North circum-polar erg - North Polar Cap</td>
<td>Katabatic unidirectional winds nearest the cap with polar vortex influence. Additional wind regimes near southern erg boundary (Guzewich et al., 2016, 2017; Smith and Spiga, 2018)</td>
<td>High - Basal Unit sand source (Tanaka and Hayward, 2008; Ewing et al., 2010; Brothers and Kocurek, 2018)</td>
<td>Unconsolidated sand ~40-50% of year (Bourke et al., 2010; Hansen et al., 2011; Diniega et al., 2017)</td>
<td>Polar – seasonal autumn/winter CO₂/H₂O ice coverage restricts aeolian processes for half of the year. Frost related alcove formation may promote lee-side sand movement (Diniega et al., 2017)</td>
<td>Polar deposits adjacent to basin</td>
</tr>
</tbody>
</table>
Figure DR1. HiRISE images of three high- and one low-flux dune field in (clockwise from upper left): Nili Fossae (Syrtis Major), Hellespontus, Olympia Undae, and the south polar (low-flux) regions.
Figure DR2. Annual maximum wind speed maps for the three study regimes. Wind vectors were the output from the Ames GCM where winds are taken from the mid-point of the bottom atmosphere layer, which is approximately 5 meters above the surface (Hollingsworth, J., R. Haberle et al. NASA Ames GCM run09.41). Although these regions show reasonable results, GCMs fail to resolve localized boundary layer turbulence (small-scale topographic, katabatic/anabatic slope winds) that may cause gusts above threshold (Ewing et al., 2010; Bridges et al., 2011; Michaels, 2011). Red polygons show dune field distributions. Compare with Fig. 3.
Figure DR3. A ~6-km-wide perspective view of a dune field in Hellespontus; migration is controlled by converging wind regimes. Field of view boxes are provided for Animations DR4 (to the SW) and DR5 (to the ESE) and site location (star) near Hellas is shown in the MOLA map (inset, upper right corner, same symbols as used and defined in Figure DR4). HiRISE orthoimage ESP_042224_1380; view is to the north.
Figure DR4. Bedform trends across the Hellespontus-Noachis Terra regions. (a) A subarea map with ripple migration results (white graduated circles) from Banks et al. (2018), dune field distribution (red polygons), and average slip face vectors (blue arrows), where dune morphology trends are provided by Hayward et al. (2014). Schematic arrows represent generalized wind patterns based on bedform migration. Base map is MOLA shaded relief colorized with MOLA elevation. Plots showing ripple migration rates vs. (b) increasing east longitude and, (c) increasing north latitude. Note the increasing mobility in the direction of Hellespontus. (d) A wider regional map that displays various gully monitoring results, where gully activity is largely
believed to be due to seasonal CO$_2$ frost. Note the anti-correlation between bedform mobility and seasonal CO$_2$ gully activity. Modified from Dundas et al. (2015).

Figure DR5. Dunes adjacent to the north polar layered deposit. (a) View of the broader area where the upwind layered deposit sand source is indicated (out of view, black arrows). White boxes indicate the locations of views in a and b. HIRISE ESP_036176_2640 centered on 233.672$^\circ$ and 83.9222$^\circ$. (b) Close up of mature barchans and barchanoid ridges downwind
where sand supply is high. (c) A view of sand patches forming protodunes, sand sheets, and downwind larger barchans. (d) Perspective view of the study site shown in other subimages adjacent to the layered deposit cliffs of Planum Boreum. White arrows indicate the inferred wind directions from bedform migration patterns and morphology. Mars Express HRSC data courtesy Google Mars.

Supplemental Animation Captions:

Animation DR1. An animated time-step sequence of moderate flux barchan dunes and megaripples (center) migrating to the WNW within Nili Fossae. Also see Fig. DR1.

Animation DR2. An animated time-step sequence of the high flux dunes within Nili Patera migrating to the WSW. Note the pristine bedrock A view of the swift Nili Patera dunes atop the heavily eroded bright fractured unit described by Fawdon et al. (2015).

Animation DR3. An animated time-step sequence of “barchan trains” in Hellespontus, migrating westward as driven dominantly by a unidirectional wind regime.

Animation DR4. An animated time-step sequence of Hellespontus high flux barch dunes migrating southwestward and radially away from the Hellas basin. These dunes are on the eastern edge of the field. Also see Fig. DR5.

Animation DR5. The same HiRISE (orthorectified) Hellespontus images as in DR4 but on the opposite, northwest edge of the ~5-km-wide dune field. These dunes and ripples are migrating to the east, demonstrating a reversing wind regime is occurring in these areas.

Animation DR6. An animated time-step sequence of a near-static barchan dune in Proctor crater. These bedforms are further south and west of Hellas where more active dune fields are present.

Animation DR7. An animated time-step sequence of north polar dunes over one Mars year. Note the large alcove development that has occurred as the result of over-steepening by migrating ripples and CO₂ ice over-burden.

Animation DR8. An animated time-step sequence of high flux dunes adjacent to the north polar cap boundary and nearest local sand sources. Note the development of proto-dunes and sand sheets into larger more mature barchans and barchanoidal ridges. Also see Fig. DR1.
References:


