

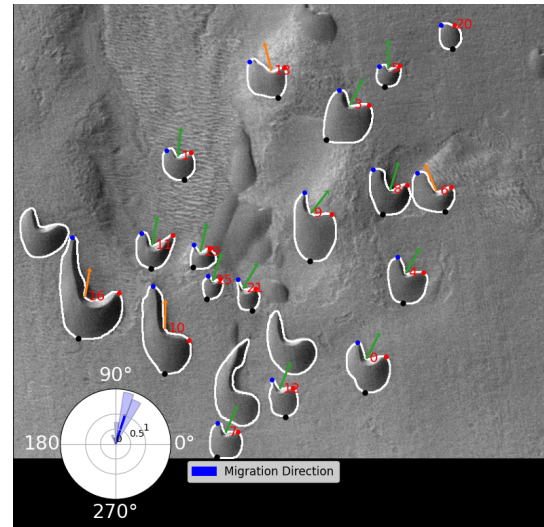
# WINDS ON MARS INFERRED FROM THE GLOBAL DISTRIBUTION OF BARCHAN DUNES USING A CONVOLUTIONAL NEURAL NETWORK.

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**Introduction:** The morphology of barchan dunes is a proxy for the environmental conditions that form them [e.g., 1]. The center of the slipface is in many cases transverse to the prevailing wind direction, while horn asymmetry or elongation may be caused by a secondary wind component [2,3]. On Mars, where meteorologic data are scarce, spacecraft observations of barchan dunes have been employed to study local circulation patterns and constrain physical laws governing sand mobility [4–7]. Measuring slipface orientation and horn asymmetry can therefore shed light onto the time-integrated evolution of barchan dunes, reflect the change of seasons, and potentially provide insight into Mars' recent climate [8].

Here we analyze over a million barchan dunes automatically outlined in images obtained by the Mars Reconnaissance Orbiter Context Camera (MRO CTX) with a convolutional neural network. We derive dune morphometrics from their outlines and use dune shapes to compile a global map of barchan-dune migration directions. By correlating wind dispersion and horn asymmetry with topography, dune wavelength and predictions from a global climate model (GCM), we isolate regions suspected to be influenced by wind seasonality and past global circulation patterns.

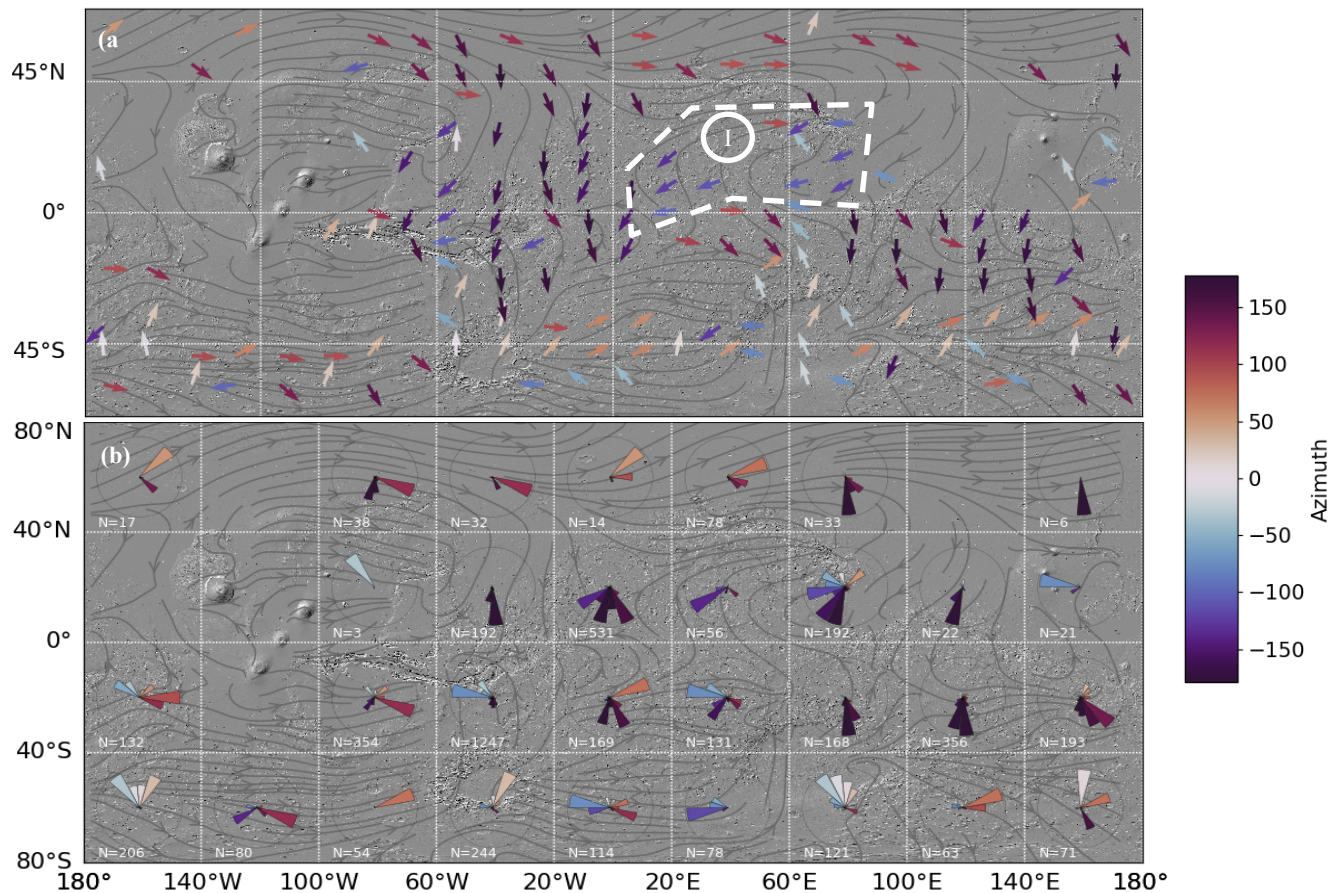
**Methods:** To outline barchan dunes globally on Mars, we employ *Mask R-CNN*, a state-of-the-art convolutional neural network (CNN) that excels at outlining objects in images [9,10]. The CNN was trained on 1,008 images obtained from a MRO CTX global mosaic [11], located using the global dune field catalog [12,13]. The CNN reviewed 137,111 images – 55,674 of which were found to contain at least one instance of a barchan dune. To increase the robustness of our results, we filtered the dataset by only selecting objects whose outlines are characteristic of barchan dunes [4]. Additionally, because the model erroneously identified sublimation-related features as barchan dunes near the south pole, we elected to focus on latitudes -70°N to 90°N in this work. Next, we measure the morphometrics of each dune detected by the CNN by identifying six reference points along its outline: the slipface center, the horns' apexes, the tail, and the dune sides (Fig. 1). The migration direction of symmetric dunes (horns-length ratio < 2) is set as the bisector vector of the horns, and the migration direction of asymmetric dunes (horns-length ratio > 2) is set as the vector emerging from the dune tail to the dune slipface (Fig. 1). For each CTX image, we assign a migration



**Figure 1:** Automatically detected barchan dunes (white outlines), and their respective migration directions (green and orange) calculated from the center of the slipface, the apexes of the horns (red dots), and the vector connecting the tail (black dot) to the center of the slipface. Rose plot shows the average migration direction, weighted by the detection confidence of each dune.

direction by averaging the migration directions of all dunes in the image, weighted by the outline detection confidence (output of the neural network) and the slipface detection confidence (estimated from the convexity defect depth of the dune).

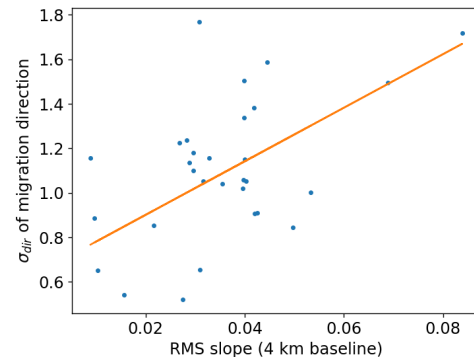
**Results:** We map the global migration directions of barchan dunes on Mars – a proxy for present-day and recent prevailing surface wind directions – by binning the migration directions within each CTX image in bins of 10° between -70°N and 70°N (Fig. 2a). Dunes migrate mainly towards the east in mid-latitudes (±45°N) and towards the south in equatorial regions. Additionally, we find that dune migration directions follow consistent vectors for up to thousands of kilometers, which are themselves mostly consistent with the direction of yearly net sand fluxes computed by a GCM [14], except for the region between Arabia Terra, Terra Sabaea, and Meridiani (marked by I in Fig. 2a), where GCM predictions are opposite to measured dune migration directions. To show the magnitude of dispersion in migration directions across the surface of Mars, we report migration-direction roses in bins of 40° (Fig. 2b), showing for the most part low dispersion on meso-scales. However, topographic “obstacles” (such as Valles Marineris or the dichotomy boundary) correlate with higher variance. The link between topography and wind dispersion is also evident in the positive correlation between Mars Laser Altimeter (MOLA)



**Fig. 2:** Global maps of barchan-dune migration directions. (a) Average migration directions binned in 10°x10° (arrows) overlaid on net sand-flux direction, as computed from a global climate model [11]. (b) Dispersion in inferred migration direction in bins of 40°x40°.

RMS slope at the 4 km baseline and the directional standard deviation in migration direction (Fig. 3).

**Discussion:** The strong autocorrelation between the migration directions along flow lines, the agreement with GCM predictions and the relatively low wind dispersion at the mesoscale indicate that dune migration on Mars is largely controlled by the planet's global circulation. Locally, the dispersion in dune migration directions may be explained by sharp topography. However, the region between Arabia Terra, Terra Sabaea, and Meridiani, west of the Isidis Basin, is characterized by long wind-flow lines which are opposite the wind directions predicted by the GCM. This discrepancy, which occurs in a region near Jezero Crater (the landing site of NASA's Perseverance rover), could potentially be explained by local effects not captured by the GCM, seasonality or the convolved relationship between dunes migration and the winds that drive it. However, the consistency of dune-migration directions along long streaks that resemble flow lines from global circulation and extend from Isidis Basin to Meridiani, could also potentially reflect relict migration directions from a past wind regime.



**Fig. 3:** Correlation ( $\rho = 0.54$ ,  $p < 0.01$ ) between RMS slope (4 km baseline) and Yamartino standard deviation of migration direction, binned at 40°x40°.

**References:** [1] Long & Sharp (1964), *GSA Bulletin*. [2] Lv et al (2016), *EES*. [3] Fenton et al. (2003), *JGR: Planets*. [4] Rubanenko et al., (in review). [5] Bourke (2008), *Icarus*. [6] Parteli et al. (2013), *AR*. [7] Ayoub et al. (2014), *Nat. Com.* [8] Courrech du Pont et al. (2014), *Geology*. [9] He et al., *IEEE CV* (2017). [10] Rubanenko et al., *IEEE: JSTARS* (2021). [11] Dickson et al. (2018), *LPSC*. [12] Hayward et al., *Icarus*, 2014. [13] Fenton, *Icarus* (2020). [14] Forget et al., *JGR: Planets* (1999).