Dust Devil Dynamics Observed from Orbit as a Tool to Quantify Atmospheric Dust Sourcing on Mars.

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Introduction: Dust devils and near-surface winds are responsible for the sourcing and atmospheric injection of dust on Mars, representing a vital part of the martian dust cycle that affects surface processes, weather, climate, and exploration missions [1-6]. Yet, direct observations of wind speed and direction are mostly limited to static landers and constrained to short periods of time. In addition, in-situ observations of wind speed rarely indicate conditions suitable for the initiation of particle saltation and dust lifting, termed the 'Mars sand transport puzzle' [7,8].

Here, we use observations of dust devil migration velocity and azimuth ('dynamics') in Trace Gas Orbiter CaSSIS (Colour and Stereo Surface Imaging System) and Mars Express HRSC (High Resolution Stereo Camera) images as a tool to characterize the dynamics of the lowermost martian atmosphere between MY27-37 (2004-2024) in space and time, directly addressing the Mars sand transport puzzle.

Methods: Using a well-established workflow [9-11], we train, evaluate, and deploy two YOLOv5x object detection models to identify dust devil vortices in CaSSIS color-infrared NPB (Near-Infrared, Panchromatic, Blue, >40,000 images with pixel scales of ~4 m [12]) and HRSC nd3 images (nadir channel, >5000 images with pixel scales between 12.5 and 50 m [13]). Both detectors achieve average precisions (AP) of 84 and 98 %, respectively, and are expected to identify between 70 to 80 % of all resolved dust devils in the CaSSIS and HRSC datasets. All detections are manually reviewed by human experts to ensure the integrity of the resulting catalog.

Depending on the availability of data products, we use three different methods to extract dust devil speed and azimuth, using the displacement of dust devils between 1) two CaSSIS stereo pair images (Δt ~45 s), 2) three to four CaSSIS color channels (Δt ~1 s), and 3) five HRSC stereo images (1x nadir, 2x stereo, 2x photometry, Δt ~9 to ~19 s). We cross-validate those measurements (CaSSIS-CaSSIS-HRSC) and compare them with measurements derived by landed missions, such as Viking and InSight [14], as well as the outputs produced by current Global Circulation Models (GCMs), such as the Mars Climate Database [15].

Lastly, we compute information about the second-scale variations of dust devil velocity and azimuth as recorded by the 5 HRSC stereo images, convert all measured wind speeds to shear velocities [16], derive new global dust lifting estimates, and compare the spatiotemporal dynamics of our dataset with the occurrence of dust lifting events and storms, such as reported by [17,18].

Results: Our deep learning detectors identify a total of 1039 active dust devils in the CaSSIS and HRSC image datasets (Fig. 1). We are able to derive speed and azimuth measurements for hundreds of those dust devil detections, using the three different measurement techniques. In addition, we derive the first observations of second-scale variations of dust devil dynamics (speed and azimuth).

This dataset provides unprecedented, global- and decade-scale insights into the seasonal and diurnal dynamics of dust devil distribution and migration. In addition, our data represent the first global-scale observations of the dynamics of near-surface winds on Mars. We use this dataset to pinpoint where and when dust devils and near-surface winds source dust off the martian surface, understand where and when current GCMs succeed or fail to capture these dynamics, examine how dust devils and near-surface winds are connected to small and large dust lifting events/storms, and investigate how the dynamics of the lowermost atmosphere could affect or benefit future missions to Mars, such as the ExoMars rover. The dust devil catalog from this work, along with additional works [19], is being used as the basis for a new coordinated observation campaign between CaSSIS and HRSC to target further observations of dust devils and other atmospheric phenomena.

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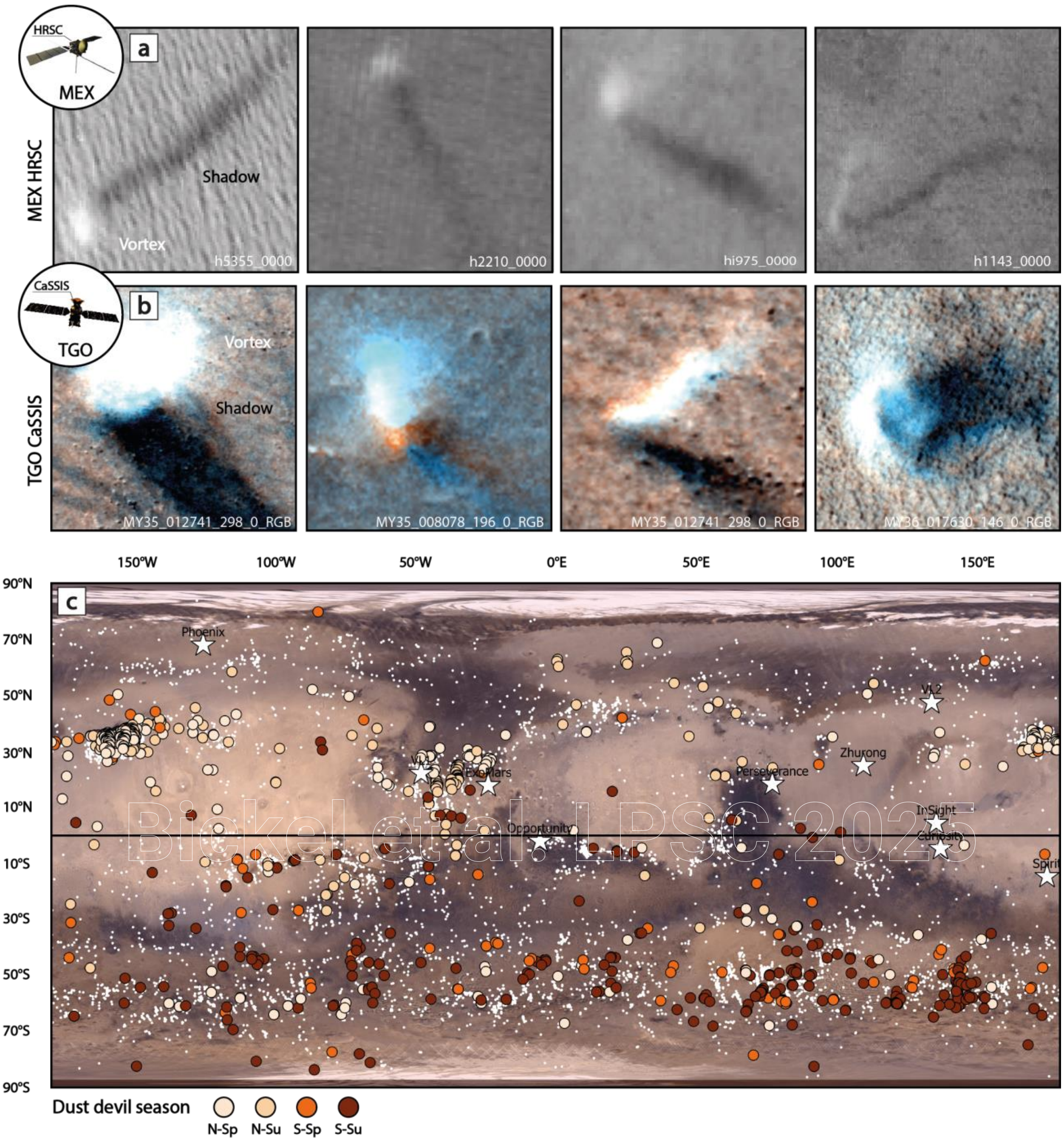

Fig. 1. Examples of dust devils imaged by (a) HRSC and (b) CaSSIS, note the dust-bearing vortex and associated shadow. (c) Spatiotemporal distribution of dust devils as imaged and detected in the CaSSIS and HRSC datasets MY27-37 (n = 1039); shape color indicates season of occurrence; small white dots represent dust devil detections made in CTX data by [19]. Locations of landed missions (white stars) indicated. Viking color mosaic in the background. Image credit: ESA/TGO/CaSSIS CC-BY-SA 3.0 IGO, ESA/DLR/FU Berlin CC-BY-SA 3.0 IGO.