Current mass flows in Martian gullies driven by CO\textsubscript{2} sublimation

Supplementary materials

Supplementary material to: How, when and where current mass flows in Martian gullies are driven by CO\textsubscript{2} sublimation.
Current mass flows in Martian gullies driven by CO$_2$ sublimation

Flow depth data of the four main experiments

Supplementary Figure 1 Flow depth of the two mechanisms in the four experiments (see Fig. 3). Measured by the two laser distance sensors; flow depth for the experiment testing mechanism 1 (a.), mechanism 2 (b.), reference experiment without CO$_2$ (c.) and reference experiment under Earth atmosphere with CO$_2$ (d.).
Supplementary Notes 1 - Additional reference experiments under Earth atmosphere and duplicate experiments

We performed duplicates for the experiments presented in Figure 3 and an extra reference experiment under Earth’s atmospheric conditions. The results of these duplicates are presented in Supplementary Figure 2. Comparison with Supplementary Figure 2 shows that the experiments are reproducible and that the natural variability in results is small for the reference experiment without CO$_2$ ice, the experiment testing mechanism 1 under Martian atmosphere, and for the experiment testing mechanism 1 under Earth’s atmosphere. The variability in the experiments testing mechanism 2 is larger. Especially the frontal velocity and outflow length differ. Nevertheless, the phenomena are robustly reproduced as the general mode of transport of the sediment is similar and the final morphology of the deposits have comparable features.
Supplementary Figure 2 Overview of the results of the duplicate experiments under Martian atmospheric pressure. The first column shows the orthophotos whereas the second column displays the DEMs of the duplicate experiments. Panel a.-b. show the duplicate experiment for testing mechanism 1, panel c.-d. display the duplicate for mechanism 2. Panel e.-f. show the duplicate of the experiment under Martian atmosphere without CO$_2$ and panel g.-h. depict the result of the duplicate experiment for mechanism 1 under Earth’s atmosphere. The results from these duplicate experiments show similar results as the originals in Figure 3. Fluidization of the sediment occurs in the duplicate experiments testing mechanism 1 (b.) and mechanism 2 (c.) under Martian atmosphere.
Supplementary Notes 2 - Sensitivity analysis of the presence of CO$_2$ ice on slopes with different TIs

To make sure the temperature and presence of CO$_2$ ice on slopes in our model matches observation we executed a sensitivity analysis studying the presence of CO$_2$ ice on south and north facing slopes of 35° slope for different TIs. We tested TIs ranging from 250 to 2120. As is evident from the results in Supplementary Figure 3, the predicted observations of CO$_2$ frost from the model match the observations of actual frost best when the TI of the slope is 750 or 1000. This justifies our choice for using these TIs to test our mechanisms.
Supplementary Figure 3  Overview of the results of the sensitivity analysis studying the presence of CO$_2$ frost on north and south facing slopes of 35° of different TIs. The left column shows results for slopes facing north (0°), the right column shows results for slopes facing south (180°). TIs are given on the left in the figure. Diamonds are data from a HiRISE image survey [28]. Solid gold dots are where no frost was present. Hollow dark blue dots are when frost is present in a HiRISE image as evidenced by bright frost or the presence of defrosting spots or flows as described in [28]. Note that this frost may be H$_2$O or CO$_2$ frost. Purple line is the northern limit of CO$_2$ frost as found in CRISM data [45].
Supplementary Notes 3 - Additional 1D Mars Planetary Climate Model results for different TIs, slope angles and orientations

In addition to the model results presented in Figure 4, we present results from model runs with different thermal inertias (TIs) of the involved surface, different involved slope angles, and different slope orientations. Furthermore, we provide a more in-depth explanation of the conceptualisation of the two CO$_2$ driven mechanisms discussed in the main paper.

Mechanism 1 is based on the following conceptual model. Considering a typical simple bowl-shaped impact crater and assuming entirely uniform thermal inertia, its topography dictates that the equator-facing slope should defrost from the rim progressing down-slope. The surrounding terrain will remain frosted as will the crater floor. Next, the crater floor and surrounding terrain will defrost. Due to the slight asymmetry of the diurnal insolation there will be a slight delay in the defrosting of the east- and west-facing slopes with respect to each other and they will defrost slightly before the flat terrain [15]. Then the frost will retreat from the bottom to the top of the pole-facing slope. Typically, pole-facing steep slopes are the last to retain their frost. Therefore, these slopes are those where CO$_2$ frosted terrain can detach as a mass movement. This was seen at Matara crater dune field [23] (Figure 2.a–e). In Supplementary Figure 4 we show the model results for the scenario comparing the temperatures of a 35° slope with a flat zone when the 35° slope hosts CO$_2$ frost for thermal inertias of 750, 1000, and 1250. Supplementary Figure 5 presents the TI=1000 results from Supplementary Figure 4.b alongside the results when the temperature difference is calculated between the 35° frosted pole-facing slope and any defrosted neighbouring 35° slope. This simply widens the period over which
Current mass flows in Martian gullies driven by CO$_2$ sublimation

this mechanism could be active, so we consider the comparison to a flat surface as a reasonable conservative estimate and is thus presented in the main text.

Alongside these model outputs, the presence of frost is plotted, which is detected from visible images (which could be both CO$_2$ and H$_2$O frost) [28] and the extent of CO$_2$ detections in CRISM [45]. The TI of 1250 provides the best fit to these frost observations at the lowest latitudes, yet fits poorly at the highest latitudes, predicting an earlier retreat of the frost than observed. The TI 750 provides the best fit to the high latitude observations, but predicts an unrealistically low latitude extent of frost; condensation occurs too early and defrosting too late. TI 1000 seems to present the best compromise. This seems to suggest that the TI of the alcoves decreases poleward, and we think this could be likely, because near-equator alcoves tend to expose bedrock, whereas polar alcoves are almost universally deeply mantled with what is expected to be a dust-ice mix [4, 28, 59, 60]. Important to note are the coloured bars that represent linear and classic dune gullies – these bars represent ongoing activity, rather than the black bars that only represent the time interval during which the activity occurred. The duration of the temperature contrast and the activity of these gullies matches extremely well with the TI 1000 result – even predicting the ongoing gully activity in winter on the Kaiser dune field [61].

It should also be noted that mechanism 1 is not restricted to pole-facing gullies, but to gullies with pole-facing slope facets. Indeed, the classic gully in Matara dune field is east-facing, yet it is the pole-facing flanks that supply the material. In Hale crater the west-facing gullies have pole-facing flanks that have also been observed to fail and provide material for flows [12]. It is less likely that equator-facing gullies could be active via this mechanism.
For mechanism 2 we are seeking to understand where and when on Mars hot materials in the alcove area can fall upon a more flat frosted unconsolidated surface, this could be a fan surface or a part of the gully channel where material is deposited. Unconsolidated material retains frost longer than the alcoves as the TI of the material is often lower [62], this counters the slope-effect discussed for mechanism 1. Fans remaining frost later than the surrounding terrain are observed in imaging data from HiRISE and CaSSIS [15] (Supplementary Table 1) and are plotted as the black dots in Figure 4 in the main paper. In the main paper, we only plotted pole-facing slopes, yet unlike mechanism 1 this mechanism can act on fans with any orientation (not just pole-facing). In Supplementary Figure 6 the results are shown for TI=750 on 15° fans and TI=1250 on 35° alcoves for all orientations. On the southern hemisphere of Mars, the observations of activity and frost best match the predictions for temperature differences on south-facing slopes. This is due to the larger temporal and spatial extent of the required temperature differences for south-facing slopes on the southern hemisphere. However, certain specific activities and observations of frost in the northern hemisphere, correlate best with our model results on north, west, and east facing-slopes. This shows that subtle differences in topography are key in understanding the boundary conditions for CO$_2$-driven flows, and thus the accurate representation of topography in climate models when they are used for understanding surface processes.
Supplementary Fig. 4 Rest of the figure and the figure caption follow on the next page.
Supplementary Figure 4  Model results showing the maximum daily temperature difference (in °C) between frosted 35° slopes and unfrosted flat surfaces under the boundary conditions of mechanism 1, for different thermal inertias (a. TI 750, b. TI 1000, c. TI 1250). Temperature differences in °C between slopes are projected as different colors. Black lines are the intervals of time during which a change occurred between two images of a gully, where that interval could be narrowed down to less than 120° Ls [14, 24]. Blue lines represent activity in classic dune gullies [21], where the dashed line indicates ongoing small-scale activity in Kaiser crater[61]. Green lines represent activity in linear dune gullies [21, 63]. Black dashed lines represent the lowest latitude activity [14], but no precise season could be ascertained because of the interval between the before and after images. Purple line is the northern limit of CO₂ frost as found in CRISM data [45]. Dots are data from a HiRISE image survey [28]. Solid gold dots are where no frost was present. Hollow dark blue dots are when frost is present in a HiRISE image as evidenced by bright frost or the presence of defrosting spots or flows as described in [28]. Note that this frost may be H₂O or CO₂ frost.
Supplementary Figure 5 Model results showing the maximum daily temperature difference (in °C) between frosted 35° slopes and unfrosted flat surfaces (a.) and any unfrosted surface (b.) under the boundary conditions of mechanism 1, for different Martian latitudes over a Martian year. Temperature differences in °C between slopes are projected as different colors. For the description of the symbols, see caption of Figure 4. For the description of the symbols, see caption of Figure 4.
Supplementary Figure 6 Model results showing the maximum daily temperature difference (in °C) between frosted and unfrosted surfaces under the boundary conditions of mechanism 2 for south, west, north, and east-facing slopes, for different Martian latitudes over a Martian year. Temperature differences in °C between slopes are projected as different colors. For the description of the symbols, see caption of Figure 4. In this figure the black lines are shown in the same orientation classes as the corresponding model results, the other symbols are simply placed on every plot.
**Current mass flows in Martian gullies driven by CO$_2$ sublimation**

**Supplementary Table 1** Images wherein fans remained frosted later than the surrounding terrain.

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