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The impact of a shadows scheme on a Mars mesoscale climate model

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ABSTRACT

Latitude and topography affect the amount of shadow cast on a landscape, which in turn can influence where water, ice or snow are stable. For martian climate models, whose output sometimes disagrees with observational data, we show that adding the ability to represent shadows generated by topography and understanding how they interact with relevant modelled variables can be important. We included a shadows scheme in a Mars mesoscale climate model and report on the impact that shadows had on surface temperature, and the resultant impact on one variable – surface water ice, and its accumulation or ablation in the study area of Lyot crater. Incorporating a scheme simulating shadows cast by topographical features had a measurable effect, increasing by up to 83% the amount of surface ice that the model predicted would be found in shadowed areas. The largest differences in ice content between simulations with and without shadows were found in those areas with the greatest amount of shadow.

1. Introduction

The amount of shadow cast on a landscape varies with latitude and topography, and can influence where water, ice or snow are stable (e.g. Leighton and Murray, 1966; Vincendon, 2015; Voelker et al., 2018). This is important for Mars, where morphological observations of landforms thought to be formed by ice or liquid water sometimes disagree with the outputs of existing climate models (e.g., Forget et al., 2006; Smith, 2001). Shadowing has an effect on data collected by instruments on the martian surface (e.g. Olsen et al., 2019; Petrosyan et al., 2011; Savijärvi et al., 2020), hence including shadows generated by topography, and having them influence relevant model variables, improves the output of Mars climate simulations.

Mesoscale climate models simulate local processes (<10 km scale) in limited domains that are too small to be efficiently represented by global models (e.g., Rafkin et al., 2001; Spiga and Forget, 2009; Toigo and Richardson, 2002; Wing and Austin, 2006). In mesoscale model studies, the impact of shadowing can be important if significant relief is present in the study area. Here, simulations running the Laboratoire de Météorologie Dynamique (LMD) Mars Mesoscale Model (MMM; Spiga and Forget, 2009) were used to assess whether incorporating a shadows scheme into the MMM had measurable effects on the output.

The study focused on Lyot crater, Mars, a ~215-km diameter impact crater centered at 50.5° N, 29.3° E. The crater floor is ~3000 m below the surrounding landscape and ~7000 m below Mars Orbiter Laser Altimeter (MOLA) datum, making it the lowest point in the northern hemisphere (Dickson et al., 2009). The crater's mid-latitude location means it experiences more persistent shadowing than equatorial sites of similar relief. Its topography includes low elevation areas within the crater, a high elevation inner ring and an even higher elevation crater rim (up to ~4500 m above the crater floor). The crater contains many geomorphological indicators of surface ice and ice melt, both past and present (Dickson et al., 2009), so we focus on the effect of shadowing on model surface variables relevant to surface water ice stability.

2. Methodology

The integration of a new shadows scheme to the MMM involved four steps. First, solar azimuth angles (horizontal coordinates which define the sun's relative direction along the local horizon; Kidder, 2003) were calculated at 30-min timesteps for the period for which the MMM was to be run, taking into account both planetary obliquity and the latitude of the center of the 2000 km study area.

Second, a 200 m/pixel MOLA digital elevation model (DEM) of the study area was ingested into ArcGIS software, along with the file listing solar elevation and azimuth. The ArcGIS Hillshade tool was used to determine where shadow cast by the landscape would occur for each time step (Kennedy, 2009; see also ArcGIS documentation). This tool
Fig. 1. Column 1 in each panel shows the baseline surface ice maximum depth during one martian sol from the simulation with no shadows. Column 2 shows the percentage difference between the two simulations of the surface ice maximum depth during one martian sol. Column 3 shows the maximum amount of shadow during one martian sol. Note the colorbar range varies in columns 1 and 2. These plots are centered on Lyot crater and do not display the full study area.
(e) $L_e = 130^\circ$

(f) $L_e = 190^\circ$

(g) $L_e = 230^\circ$

(h) $L_e = 320^\circ$

Fig. 1. (continued).
calculates shadow using a ray tracing algorithm where the illumination source is taken from the sun's position in the sky and assesses its effect on the landscape. The higher the resolution of the DEM, the more detailed the shadowing calculated, as the analysis considers the effects of the local horizon at each point.

Third, additional processing by the MMM was used to convert the Hillshade tool output into latitude-longitude maps of shadow, in the form of a shadow array file. The shadow array specified the proportion (a value between 0 – full shadow and 1 – no shadow) of each MMM grid box which experienced solar illumination, as the MMM grid box sizes contain areas for which the higher-resolution DEM had both shadowed and non-shadowed regions. Then the shortwave (SW) flux (the radiative energy from the sun arriving at the surface) was multiplied by this value at each location and time to determine how it was affected by the landscape's shadowing. If the grid box was in full sunlight (a value of 1) there was no change to the MMM SW flux but if the grid box was in full shadow (a value of 0) the SW flux was 0. Intermediate SW fluxes fell between 0 and 1, containing both shadowed and non-shadowed regions.

In the MMM, the total SW flux reaching the surface has three components: direct incoming flux, flux reflected by surrounding terrains, and flux scattered by atmospheric dust. A study of the parameterization of these variables (Spiga and Forget, 2008) noted that the value for reflected flux was lower than those for direct and scattered flux. Although they considered regolith covered surfaces, rather than ice-rich surfaces such as those found in some areas of Lyot crater (Dickson et al., 2009), a decision was made not to consider reflected flux's impact on shadowed areas in this study.

Finally, MMM simulations were performed for a duration of 10 days at various times during the martian year (at aerocentric longitudes (L_s) of 0° (vernal equinox), 30°, 70°, 90°, 130°, 190°, 230°, 320°) with and without the shadows scheme, to compare the results. Other than the inclusion or not of the shadows scheme, the simulations were identical. Boundary conditions were supplied at hourly intervals from a simulation run using the Open University version of the LMD Global Climate Model (GCM; for a full description of the model and its dust and water packages see Forget et al., 1998, 1999a, 1999b; Montmessin et al., 2002, 2004). The simulation was ‘spun-up’ (it was started using the input variables specified in the model parameter documents) for 12 years until the simulation was running with an equilibrated water cycle. The GCM had a resolution of 2.50° x 2.50° latitude and longitude, which was scaled to 6 km grid boxes in the MMM. Both dust and clouds were radiatively inactive. The GCM was forced using data reflecting a year when there was no global dust storm.

3. Results

As the shadows scheme determines the amount of SW flux over an area, this affects not only the surface temperature but also variables affected by surface temperature, such as water and CO₂ surface ice, wind speed and direction, and soil temperature. In this paper, the impact of shadowing and surface temperature on the accumulation (from the atmosphere) or ablation (by sublimation or melt) of surface water ice (referred to hereafter as simply 'ice') was assessed. The amount of ice in the simulations with and without shadows was calculated and the percentage difference between the two was plotted (data from simulations without shadows were subtracted from the shadowed simulations' data; Fig. 1). This reveals the impact of shadowing on surface ice abundance. The results show that areas which are in shadow have higher levels of ice when compared to the simulation without shadows.

The inclusion of shadows in the model nearly doubles the amount of ice seen (up to 83% higher) in some small areas south of the crater rim during the winter (L_s = 230° and L_s = 320°, Fig. 1g,h). The shadows cause colder surface temperatures (up to 7%, ~15 K colder) in these locations, allowing more ice to be deposited. Other areas of the crater at these times of year show lower percentage differences in ice amount due to both the varying amounts of shadow and surface temperature.

Large percentage differences of ice (between 41% and 44%) also occur in areas shaded by the inner ring before and after the summer solstice when temperatures are higher (L_s = 70° and L_s = 130°, Fig. 1c, e). The increased percentage of ice is found in areas inside the crater rim. In these shadowed locations, the reduced solar insolation and resultant lower surface temperature allows them to retain their ice, whereas in simulations without shadows the ice sublimates away.

The percentage difference of ice is smaller at other times of year, with the lowest maximum value of just under 8% at the spring equinox (L_s = 0°, Fig. 1a). Differences of ~15% can be seen just after the spring equinox (L_s = 30°, Fig. 1b), at summer solstice (L_s = 90°, Fig. 1d) and just after the autumn equinox (L_s = 190°, Fig. 1f). These are times of year when the temperatures are moderate and the shadows have less impact on the surface temperature (a difference of less than 1%, ~2 K), so there are low percentage differences of ice content.

The simulations with shadows also show small areas with increased ice sublimation near the shadowed areas at all times of year except winter (L_s = 230° and L_s = 320°, Fig. 1g,h). The percentage difference is generally only a few percent but in early summer (L_s = 70°, Fig. 1c) up to ~15% more sublimation occurs. This is due to the impact of the shadows scheme on the temperature and winds in surrounding areas, and particularly on nearby slopes, leading to small increases in ice sublimation. Some shadowed areas can also show no change in ice depth. This occurs in locations where the topography is steepest because the model's native slope insolation scheme was already reducing insolation on steep slopes facing away from the sun.

In summary, the results show, for example, that ice accumulates 40% more rapidly in areas where shadowing has a large effect, such as near the south crater rim at 48.5–49°N, 28–30°E, where there is heavy shadow in the winter (L_s = 230° and L_s = 320°, Fig. 1g,h). And ice is lost 42% more slowly south of the inner ring at 49–50°N, 28–30°E, where there is heavy shadow in the early summer (L_s = 70°, Fig. 1c). Although the difference in ice maximum depth is microns per annum, if this is extrapolated over the ~350,000 years when obliquity has been centered on 25° (Laskar et al., 2004), this can lead to differences of centimeters of ice retention between the two simulations.

4. Discussion and conclusions

Incorporating a scheme simulating shadows cast by topographical features into the MMM made a measurable difference in the amount of ice that the model predicted would be found in the shadowed areas. The largest differences in ice content are found in those areas with the greatest amount of shadow. Percentage surface ice difference is high (~40%) at times of the year when surface temperatures are warmer and solar insolation is stronger, with the shadows allowing ice to be retained in places where without shadows there would be sublimation. Our results demonstrate that the impact shadows have on the variables affected by surface temperature, both in and near the shadowed areas, can be quite large locally and at study-area scale can be large enough to play a significant role when summed over hundreds or thousands of years.

We note that if the DEM used to calculate the shadowed regions was downscaled to the same grid size as the MMM, the ‘smoothing’ of relief would lead to lower slopes and fewer shadows. Similarly, using higher resolution DEMs would lead to even more shadowed regions being included.

We suggest that incorporating a shadows scheme into mesoscale climate models is important in study areas that: (i) contain high relief at scales smaller than the mesoscale model grid; (ii) are located at moderate to high latitudes, and (iii) contain geomorphological evidence for processes linked to deposition and ablation of ice that are controlled mainly by surface temperature. All these conditions are met for Lyot crater and, given that Mars' obliquity has varied greatly over the last few million years (Laskar et al., 2004), including the effects of topographic shadowing of the surface for different obliquities can be even
more vital to understanding the long-term mass balance of surface and sub-surface ice in regions such as this. Given that a measurable difference in the amount of ice simulated has been found in or near the shadowed areas, future studies in such regions should include a shadows scheme in their climate model using the highest resolution topographic model possible to generate comprehensive shadows. Scaling modelled SW flux by the percentage of shadows found in each grid box will improve model outputs related to the behavior of temperature-affected variables at the surface.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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