Response to reviewer #2 comments (of gid-2-737.2012.pdf)

Dear reviewer #2,

Thank you for your comments. We have considered them carefully and found them to be helpful. Please find below replies to the scientific and technical comments. At the end of the document please find some new text and a new figure that has been added to the paper.

Reply to scientific comments

1. The ability of the model to use temperature dependent thermal properties is mentioned several times, but no examples are given (e.g. specific heat capacity and thermal conductivity).

We agree that this needs to be demonstrated so the reader can asses its importance and it is also a good test for the model

- In section 2, Thermal properties of the Martian subsurface, we include some discussion of the temperature dependence of the thermal properties of the Martian subsurface with references

- In section 5, Validation of the model, we include a figure comparing the surface temperatures produced by models with and without temperature dependent thermal properties

- In section 5, we describe in detail the thermal properties and their relation to temperature and discuss the results, comparing the results to published work and discuss the results qualatively in terms the expected behaviour of the models

2. As well as "slab" models, continuously varying physical properties with depth would also be of interest (e.g. allowing for a dust layer with increasing density with depth)

- this is possible and this potential is hopefully made clear in additions to the text in the final section 6, Effects of layered material on the surface temperature

- Further work planned and underway with this model would include further simulations that are relevant for specific investigations that could include the investigation of varying physical properties with depth

3. Ice and dust-ice layers are mentioned several times, but it is not clear how these would be included in such a model (and how this would affect the stability of the numerical method)
– in particular sublimation/condensation processes
– no mention of the volatile transport within the subsurface is mentioned
– if the model can handle such cases this should be mentioned, or otherwise clarified
– perhaps this just means expanding on the sentence "Surface sublimation is modeled using a constant soil moisture fraction."?

- Agreed, sentence has been expanded upon. Only sublimation/condensation at the surface is modelled.

4. Thin "slabs" (i.e. a fine grid) are needed where the temperature gradient is steep, i.e. close to the surface or boundaries where sublimation/condensation might take place, but not everywhere. Could a variable (e.g. exponential) step size not have been used?

- We use the finest grid spacing for all the levels. Sublimation/condensation only occurs at the surface (top layer). A variable step size could be used to perhaps save on computer processing time but at the moment the code is rather efficient and time management of running the simulations is not an issue.

Reply to technical comments

The page and line numbers on the left refer to the discussions document gid-2-737.2012.pdf. After the replies are some numbers which refer to pages and lines in our working document.

Page	Line	
		1. Some references are to "Fig. n" and some to "Figure n"
745	24	figure -> Fig.
747	13	figure -> Fig.
747	22	figure -> Fig.
747	26	figure -> Fig.
748	11	figure -> Fig.
749	20	figure -> Fig.
		2. Eq.1: it might be worth showing the dependencies of e.g. k (on temperature, depth etc.)
741	7	Updated equation showing temperature and depth dependencies P3 L30
		3. "On Earth the surface temperature may vary only a few degrees during the day for locations in, or surrounded by, an ocean to variations of up to 50 K in desert regions" - perhaps this could be worded "On Earth the diurnal temperature variation may be only a few degrees in oceanic regions and up to 50 K in desert regions" or similar.
742	23	Rewrote sentence, "On Earth the diurnal temperature variation may vary a few degrees in regions, surrounded by ocean, and up to 50 K in desert regions (Price, 1977)." P4 L23
		4. "framework material" – matrix material or similar?
742	26	Removed the word "material" P5 L9
		5. "which is representative from vertically homogeneous dust, sand, solid rock to ices" - meaning that the range of thermal inertia covers this range of materials, respectively?
743	5	Rewrote sentence, "The thermal inertia of the surface of Mars ranges from 30 to 3000 J m^{-2} K^{-1} $s^{0.5}$ (Jakosky et al., 2000) which represents surface types, in order of increasing thermal inertia, of dust, sand, solid rock and ices." P5 L10
		6. "Most trenches were typically around a few centimtres in 11 depth that uncovered water-ice bearing soils" - meaning is not clear - most trenches were 11 cm deep, or most trenches that uncovered water-ice were 11 cm deep?
743	5	Rewrote sentences, "The Phoenix lander dug trenches to depths of a few centimetres in a polygon and dug a trench down to 18 cm in a trough between polygons. Trenches in the polygon uncovered water-ice bearing soils under crusty to cloddy solis but no icy soils were found in the trough between polygons (Ardvidson et al., 2009)." P5 L19
		7. Also centimtres -> centimetres.
743	5	Corrected P5 L20
		8. "The subsurface thermal scheme" - as before, "thermal scheme" is not very descriptive
743	13	Modified subtitle, "3. A numerical scheme for thermal modelling of the subsurface" P5 L28

		Modified sentence, "heat transfer scheme" -> "numerical heat transfer scheme" P5 L29
		9. "surface layers" -> "subsurface layers"?
745	21	surface->subsurface P7 L13
		10. "level thickness" = layer thickness? Or rather the vertical spacing of control volume cells in your model?
746	25	level->layer P7 L18
		11. "the results from the altered model was subtracted from" - either "results were subtracted from" or "result was subtracted from"
746	2	Modified sentence (from->of), i.e. "Each parameter was varied in turn and the results of the altered model was subtracted from the control model." P7 L19
		12. "stability criteria for the explicit scheme are" or "stability criterion for the explicit scheme is"
747	4	Criteria->Criterion P8 L20
		13. conductiviy -> conductivity
747	6	conductiviy->conductivity P8 L21
		14. give units for conductivity, as other values
747	7	Added units for conductivity W m^{-1} K^{-1}
		15. "This corresponds to the lower value of the level thickness found in the simulations featured in figure 4." - meaning 100 cm? or 200 cm? please specify.
747	8	Rewrote sentences, "This result was used to initialise the simulations featured in Fig. 4, except the lower boundary which was set to a depth of 2 m. This then allowed us to explore the effect of increasing the layer thickness and the depth of the lower boundary. Consequently all the simulations of the Martian atmosphere and subsurface in this paper were made with a layer thickness of 2 mm, allowing us explore the effect of dust layers on rock, and to maintain stability when simulating the atmosphere." P8 L23
		16. "The surface temperatures calculated with the atmosphere present results": either "calculated temperatures result in" or "calculate temperature results in"
747	16	Rewrote sentence, "The calculated temperatures results in a reduced amplitude compared to the results under the assumption that no atmosphere is not present." P8 L25
		17. "assumed in figure 6." -> "assumed." (the figure has already been mentioned in this sentence)
747	26	Rewrote sentence, "Fig. 6 shows that the new model produces more or less identical results to the previous version of the previous version of the model with less layers." P9 L10
		18. "(i.e. summer, autumn and spring)" - Figure 7 has four panels, including winter
748	12	Inserted "winter" in the brackets P9 L24
		19. " The lag of the temperature maximum is not significantly affected until the dust layer is about 1 cm" - the graph shows only 0 and 1 cm, what intervals were tested in between? And what was the grid resolution for these tests?
749	23	See new text and figure for section 6 (included after this table). We agree it is not clear that a decrease in the thickness of the dust layer is related to an increase in the time of maximum temperature. The grid resolution for these tests was originally set to 5 mm between all grid points as it produced stable results for the dust layer and rock substrate. We have redone the tests with the grid points reduced to 2 mm for the dust layers for a greater resolution of the subsurface temperatures. We have updated the program to include variable layer thickness and updated the equation on Page 743, Line 20, to

		reflect this, following Patankar (1984). The main change is updating the calculation of the conductivity between the interface between the control volumes. $k_s=f_s k_P+(1-f_s)k_S$ where $f_e=(\delta z)_{s+}/(\delta z)_s$ where $(\delta z)_{s+}$ is the distance between the grid interface and the grid point below and $_{+}/(\delta z)_s$ is the distance between the grid point, of the control volume under consideration and the grid point of the control volume below. P11 L1
		20. general: spelling seems to be mostly British, but there are some exceptions (e.g.“modeled”).
739	2	habitibility->habitability P2 L5
739	7	modeling->modelling P2 L10
740	3	modeled->modelled P3 L2
740	13	transfered->transferred P3 L11
742	23	sulfate->sulphate P5 L9
743	4	sulfate->sulphate P5 L19
743	14	modeling->modelling P5 L29
747	4	realisitc->realistic P8 L19
748	1	discrepency->discrepancy P9 L13
756		modeling->modelling P18 L9
		Comments on figures
		Figure 4: "sensitivity of the model on the depth of the fixed temperature" might be better "sensitivity of the model to variations in the depth of..."
758		Rewrote sentence, "The sensitivity of the surface temperature to variations in the depth of the fixed temperature lower boundary condition (left) and the sensitivity of the model on the thickness of the layers (right)." P20 L10
		Figure 4: add that this is the temperature difference at the surface.
758		Inserted "surface" between "in" and "temperature" P20 L10
		Figure 4: it would be interesting to also plot the solar input (forcing function) here, for comparison
758		Added figure showing the solar input P20
		Figure 5: text states 14 mm and 50 mm depth, figure legend shows 14 cm and 50 cm
759		Updated legend in figure 6 from m to mm P22
		Figure 6: change legend "Model" to "New model" or similar, for clarity
760		Updated legend in figure 6 to add "New model" P22

Updated text to be included in the paper

2. Thermal properties of the Martian surface

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The thermal inertia of the Martian surface shows a clear temperature dependence (e.g. Piqueux and Christensen, 2011). The temperature dependence of the conductivity of particulate basalt in a Lunar environment is significant, however on Mars the gas phase tends to reduce this effect (Fountain and West, 1970). The heat capacity for basalt, in a Lunar environment, varies significantly with temperature (Robbie et al., 1970). On Mars the heat capacity It depends less on the gas phase so the heat capacity will contribute more to the temperature dependence of the thermal inertia in a Martian environment. This may cause errors in interpretation of observations of surface temperatures on Mars (Piqueux and Christensen, 2011)

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5. Validation of the model

(text start after Fig. 7)

To further confirm the model behaviour was stable and producing realistic results the temperature dependent thermal properties (TDTPs) were activated in the subsurface thermal numerical scheme and tested. This allowed us to explore if TDTPs present any numerical stability issues and to compare with other published works in this area. The temperature dependent thermal conductivity (TDTC) was modelled using a linear relationship that approximates the trend of increasing thermal conductivty with increasing temperature that can be seen in the data for particulate basalt with a particle size between 37 and 62 μm and a bulk density of 1.5 kg m^{-3} in a simulated Martian environment obtained by Fountain and West (1970). The linear relationship for thermal conductivity is, k_T=T/60000+1/115, which gives a conductivity value of 0.012 W m^{-1} K^{-1} at a temperature of 200 K and and a conductivity value of 0.014 W m^{-1} K^{-1} at a temperature of 320 K. This amounts to about a 10% to 20% change in thermal conductivity over the temperature ranges we are calculating. The temperature dependent heat capacity (TDHC) was modelled using a linear relationship fitted to data obtained from by Robbie et al. (1970) for basalt in a simulated Lunar environment. The linear relationship for TDHC used here is, c_T=2T+120, which gives a TDHC of 520 J kg^{-1} K^{-1} at 200 K and 760 J kg^{-1} K^{-1} at 320 K. This amounts to a 25% to 50% change in heat capacity over the range of temperatures we are calculating. The thermal inertia, using these equations and a bulk density of 1.5 kg m^{-3}, ranges from about 100 to 130 J m^{-2} K^{-1} $s^{-0.5}$ which would correspond to a dusty surface.

Fig. 8 compares the surface temperatures from a model with and without TDTPs for dusty, sandy and rocky surfaces. To obtain thermal inertias appropriate for sandy and rocky surface, as published relationships are unavailable, the equation for TDTC was multiplied by a factor of 15 for a sandy surface and for a factor 330 for a rocky surface. The equation TDHC remained unchanged as the effect of gas phase of the specifi heat is probably negligible. The model results shown using temperature independent thermal properties (TITPs) used a model with thermal properties values calculated using the equations for TDTPs but keeping the temperature fixed so the temperatures at 2 am conincided. This was done so the temperature difference could be easily seen. The time was chosen because this is commonly used time for fitting model diurnal temperature curves to observed temperature from Mars to determine the surface properties such as grain size. As can be seen there is a non-negligible difference in temperatures for dust and sandy surfaces.

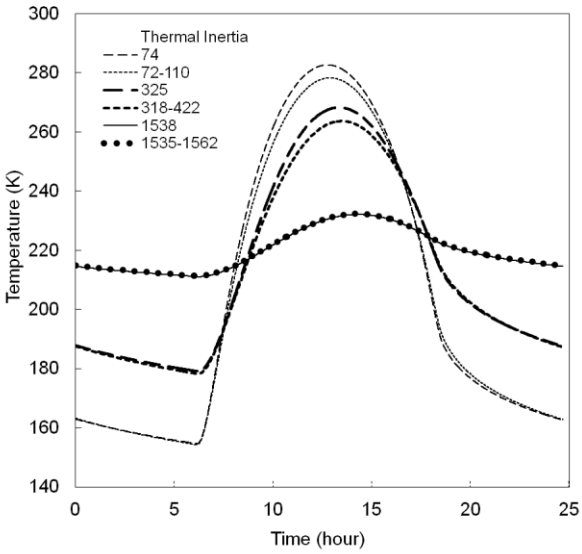

Figure 8. Surface temperature differences for temperature dependent and temperature independent thermal properties for dust, sandy and rocky surfaces. For a model using constant thermal properties there is a single value of thermal inertia in the legend. This corresponds to the value at 2 am. For a model using temperature dependent thermal inertia there are two valuesin the legend. The minimum value corresponds to the minimum temperature and the maximum value corresponds to the maximum temperature. The units of thermal inertia for the values in the legend are J m^{-2} K^{-1} $s^{-0.5}$.

The maximum difference bewtween temperatures calculated using a model with TITPs and a model with TDTP is around 4-5 K for dusty and sandy surface. This agrees well with more realistic simulations by Piqueux and Christensen (2011). The model with TITPs produces higher temperatures, during the day, than produced by the model with TDTPs because as the temperature goes up the thermal inertia increasess which in turn tends to cause the material to resist further temperature changes. For the rocky surface the difference between a model with TDTP and a model with TITP is about 0.2 K. This is small because the the temperature variation through the diurnal cycle is also small. We do not discuss the problem of interpretation of Martian temperature observations of the surface here and only note that there is a significant difference between models with and without TDTP. The problem of determining Martian surfaces properties such as grain size, fitting models with TITP to observations of the Martian surface is discussed in detail by Piqueux and Christensen (2011). They conclude that because the models used for this task use TITPs obtained from laboratory measurements of analogue materials above room temperature the grain sizes can be underestimated.

6. Effects of layered material on the surface temperature

(text starts after second paragraph)

The updated model was used to investigate the effect of a layered subsurface on the surface and near-surface temperatures. Dust layers of varying thickness were placed on top of rock that was composed of the same rocky material as the grains in the dust. Table 1 lists the thermal properties used to calculate the thermal parameters for the dust layer simulations. The dust layer was composed of modelled slabs, each 2 mm in thickness. So for a dust layer of 1 cm thickness there would be five slabs in the model and for a dust layer of 2 cm thickness there would be ten slabs.

The rock substrate was modelled with slabs of 5 mm in thickness. The dust layer was varied from a thickness of 0 cm to 6 cm in steps of 2 mm over a diurnal cycle. Diurnal surface temperatures were then plotted for dust layers varying from 0 cm to 6 cm in 1 cm steps. The maximum temperature was plotted, in 2 mm steps, to make clear the variation in the lag of the maximum temperature as the dust layer decreases in thickness.

TABLE 1 (unchanged)

Fig. 9 shows the results from the simulations with the dust layers. The figure demonstrates how the temperatures vary for a range of dust layer thicknesses on a rocky substrate underneath. Notice that the surface temperature diurnal range is greatly affected by the thickness of the dust layer while the atmospheric temperature ranges less. The lag of the temperature maximum is not significantly affected until the dust layer is about 2 cm thick. The time of maximum temperature for both the surface and the atmospheric calculations varies over a period of about 1.5 hours. This is clearer in the atmospheric temperatures because the curves are closer together.

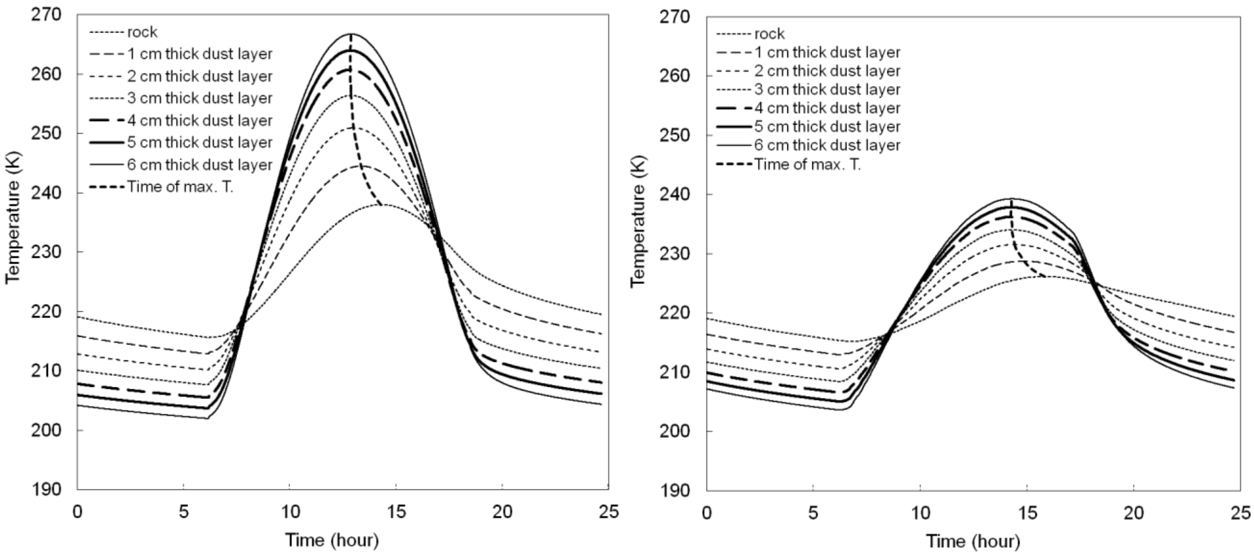

Figure 9. Diurnal temperature profiles at 0 m and 2 m altitude for a range of dust layer thicknesses on solid rock. Seasonal variation of thermal inertia is to be expected due to a varying amount of dust on the surface and also exchange of volatiles between the regolith and the atmosphere (not simulated here).

In Fig. 10 the dust-layer model where the dust layer is set to 2 cm, is compared to a homogeneous material or 'rock' which has constant thermal properties in the vertical direction. Even though the amplitude of the temperature variations is similar in all cases there is a significant lag between the layered material and the solid material. This is presumably due to the larger volumetric heat capacity of the 'rock' and its ability to store the heat for later release in the afternoon.

FIGURE 10 (was figure 9 and is unchanged)