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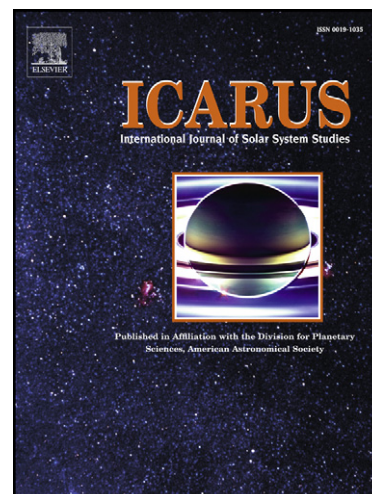
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Interfacial liquid water on Mars and its potential role in formation of hill and dune gullies.

Konrad J. Kossacki^a Wojciech J. Markiewicz^b

^a*Institute of Geophysics of Warsaw University,
Pasteura 7, 02-093 Warsaw, Poland*

^b*Max Planck Institute for Solar System Research,
Max-Planck-Str 2, D-37191 Katlenburg-Lindau, Germany*

Abstract

Gullies are among the most intriguing structures identified on the surface of Mars. Most common are gullies located on the slopes of craters which are probably formed by liquid water transported by shallow aquifers (Heldmann et al., 2007). Two particular types of gullies are found on slope of isolated hills and dunes. The hill-slope gullies are located mostly at 50° S, which is at the high end of latitudes of bulk of the gullies found so far. The dune gullies are found in several locations up to 65°S (Reiss et al., 2007), but the best known are those in Russel crater at 54° S. The hill-and dune gullies are longer than others making the aquifers explanation for their formation unlikely (Balme et al., 2006). Recently it has been noted that thin liquid films of interfacial water can play a role in rheological processes on the surface of Mars (Moehlmann, 2008; Kereszturi et al., 2009). Here we try to answer the question whether interfacial liquid water may occur on Mars in quantities large enough to play a role in formation of gullies. To verify this hypothesis we have calculated thermal models for hills and dunes of various steepness, orientation and physical properties. We find that within a range of average expected values of parameters it is not possible to have more than a few monolayers of liquid water at depths greater than a centimeter. To create subsurface interfacial water film significantly thicker and hence to produce conditions for the slope instability, parameters have to be chosen to have their extreme realistic values or an additional source of surface heating is needed. One possibility for additional heating is a change of atmospheric conditions due to a local dust storm. We conclude that if interfacial water is responsible for the formation of the hill-slope gullies, our results may explain why the hill gullies are rare.

Key words: Mars, Surface, Water

1 Introduction

Water has always been one of the central themes in studies of Mars. Stability of liquid water has been investigated by many authors. Some researches suggest, that water can be stable almost everywhere (Hecht, 2002), while others argue it is unstable everywhere (Mellon and Philips, 2001). There is however one form of liquid water which is undoubtedly stable under practically all conditions. This so called unfrozen or interfacial water is a thin liquid film separating frozen water ice and any mineral surface wherever these are present. The key question is how thick this layer can be. In recent studies it has been proposed that interfacial liquid water can be responsible for surface rheological processes on Mars (Moehlmann, 2008; Kereszturi et al., 2009). Here we attempt to model both the diurnal and the seasonal cycle of the interfacial liquid water in the context of a possible mechanism for formation of the so called hill gullies. If the subsurface liquid interfacial is thick enough it could destabilize the surface layers and produce the observed gullies.

Gullies are among the most intriguing structures identified on the surface of Mars (Malin and Edgett, 2000). Since the time of their discovery, gullies were investigated by many authors (e.g. Mellon and Philips (2001); Costard et al. (2002); Christensen (2003); Kossacki and Markiewicz (2004); Balme et al. (2006); Heldmann et al. (2007); Reiss et al. (2010)). To date these structures have been found in hundreds of locations in both hemispheres, incised into slopes in different types of terrain, impact craters, pits and valleys, hills and even dunes. In the current work we look only at the hill- and dune-gullies. In a survey of the southern hemisphere by Balme et al., (2006) the hill gullies were identified at latitudes about 30°S - 60°S , almost exclusively at the bottom of the Argyre basin and Gorgonum Chaos. These authors found that about 10% of gullied slopes visible in MOC images and about 23% in HRSC images are hill slopes. This in turn translates to nearly 100 hills identified to have gullies on their slopes. In Fig. 1 we show an example of a gullied hill, located in the South, approximately at 47.25°S , 330.1°E . This hill is about 2 km across, and about 1 km high. The dune gullies were found on numerous dark dunes in the southern hemisphere, up to 65°S (Reiss et al., 2007). According to Fenton (2006) flow features are observed on dune slopes inclined by about 30° , are up to hundreds of meters long and a few meters wide. Best known are probably the dune gullies in Russel crater at 54.5°S , studied by numerous authors (e.g. Mangold et al. (2003); Reiss et al. (2010)). These gullies have lengths of about 2 km and a relatively constant width of about 10 m. The channels are of sinuous shape and have branches, mostly in the upper sections. The listed set of features match scenario of the formation by viscous slurry flows (Mangold et al., 2003). Calculated velocities and viscosities are in the range of terrestrial

Email address: E-mail: kjkossac@fuw.edu.pl (Konrad J. Kossacki).

debris flows (Miyamoto et al., 2004). The channels are formed on the dune slope of the gradient only about 10° , too low for a debris flow (Mangold et al., 2003).

The physical processes involved in the formation of gullies are still under debate. In the literature various possibilities are discussed, mostly involving liquid water. Gullies located on the slopes of impact craters, by far the largest population, are most likely formed by liquid water, probably transported by shallow aquifers (Heldmann et al., 2007). The gullies found on the slopes of isolated hills, or dunes seem to be of different origin. The hill gullies are on average 50% longer than crater dunes, contradicting curving of gullies by water flowing from underground aquifer hypothesis, because only a small amount of water may be stored within an isolated hill (Balme et al., 2006). The same conclusion can be drawn for dune gullies. Here, we investigate the possibility that the slopes of gullied hills and dunes can become unstable due to interfacial melting of subsurface water ice, as suggested by observations of growing flow-like features on dunes (Moehlmann and Kereszturi, 2010; Kereszturi et al., 2010). Thickness of the water liquid film between a mineral grain and the ice layer is determined by the van der Waals force and is strongly dependent on the temperature. Theoretically one or two monolayers of this unfrozen water are present under any Martian conditions (Moehlmann, 2008). However, significant thickness of the water film can be expected only at temperatures close to the melting temperature of the ice. Thus, interfacial melting should be most important in locations where: a) the temperature does not reach melting point, but can be close to it; or b) ice is present mostly at night time, sublimates away before it can melt and later condenses again from the vapor phase.

The highest temperatures are encountered on surfaces illuminated at low zenith angle, but in such locations ice can be present only at some depth. To determine thickness of the interfacial water film realistic for the Martian regolith it is necessary to calculate distribution of the temperature and the water ice simultaneously. We have used such models in other contexts in the past (e.g. Kossacki and Markiewicz (2004)). Here we build on these models by including the equation for the interfacial liquid water. In the next section we briefly describe the model used and relevant range of the physical parameters. This is followed by results for hill slopes of different orientations and inclinations as well as a range of thermal and optical properties of the regolith. We conclude with discussion of the results.

77 2 Model description

78 2.1 Basic features

79 We used a numerical model that simulates evolution of the regolith temper-
 80 ature, as well as condensation and sublimation of H_2O and CO_2 ices. The
 81 model was previously used to investigate the possibility of seasonal ice melt-
 82 ing in Martian gullies (Kossacki and Markiewicz, 2004), to simulate the escape
 83 rate of subsurface ice (Kossacki et al., 2006), and to investigate possible frost
 84 formation in small trenches dug during the Phoenix mission (Kossacki and
 85 Markiewicz, 2009). In the current version we added formation of water film
 86 between the regolith grains and the water ice mantling the grains, see Sec-
 87 tion 2.2.

88 Our model describes diurnal and seasonal condensation and sublimation cycle
 89 of water and carbon dioxide ices on the surface and in the regolith below. The
 90 model regolith is composed of equal spherical sand, or dust grains mantled by
 91 ice, when it is present. The assumption of perfect sorting of the grains makes
 92 the model more appropriate for dunes than for hills of unknown origin. How-
 93 ever, for the diffusion of vapor in the regolith most important is size of small
 94 grains, filling gaps between larger ones. Hence, the size of grains composing our
 95 model hill can be considered as the size of smallest grains in a more realistic
 96 hill. In the numerical model are included: the time dependent illumination, in-
 97 frared emission from the surface, heat and vapor transport within the regolith
 98 as well as the heat exchange due to sublimation or condensation. The flux of
 99 absorbed light depends on the local orientation of the surface and on the cur-
 100 rent position of the sun. The latter evolves due to orbital motion and rotation
 101 of Mars. The model includes warming of the surface due to absorption of: (i)
 102 the solar light, direct and scattered in the atmosphere; (ii) the light scattered
 103 once within the considered trench, gully or crater; (iii) the IR radiation emit-
 104 ted by the atmosphere toward surface. The seasonal and diurnal variations of
 105 atmospheric pressure, humidity and atmospheric opacity can be taken either
 106 from the results of a general circulation model (GCM), or parameterized.

107 In the current work profiles of the atmospheric pressure, and the atmospheric
 108 humidity are taken from the results of GCM LMD/Oxford available at [http://www-](http://www-mars.lmd.jussieu.fr/)
 109 [mars.lmd.jussieu.fr/](http://www-mars.lmd.jussieu.fr/) (4 values per sol), for one location at the latitude where
 110 the hill-gullies are mostly observed i.e. 50° S. The IR flux emitted from the
 111 atmosphere toward the surface is either ignored, or taken from the results of
 112 GCM. In the latter case we take diurnal average values averaged over intervals
 113 30° L_s . For the atmospheric opacity use of the accurate current profile is not
 114 appropriate for our analysis. Opacity of the Martian atmosphere significantly
 115 changes from year to year, and the investigated gullies formed in an unknown

116 past. Given this uncertainty we decided to perform two types of simulations.
 117 First one with very low opacity of 0.05 resulting in that the solar flux reaching
 118 the surface is relatively high. Second keeping the opacity at the same low value
 119 but adding IR emission in the atmosphere as calculated for a normal dust at-
 120 mosphere with opacity taken from GCM simulations. This overestimates total
 121 flux of radiation absorbed at the surface and hence gives an upper estimate
 122 of the surface temperature.

123 The equations, except the formula for the instantaneous thickness of the liquid
 124 water film described below, were described in detail in our previous papers
 125 (Kossacki and Markiewicz, 2004; Kossacki et al., 2006). The main equations
 126 are those describing the diffusion of heat in the regolith, and the local energy
 127 input at the surface.

128 2.2 Interfacial melting

129 The actual melting temperature of ice covering regolith grains depends on
 130 the distance to the grain-ice interface. When micron scales or smaller are of
 131 interest, as they are here, effects of short range van der Waals forces need to be
 132 included. Following Moehlamann (2008) pressure resulting from presence of
 133 van der Waals force acting between a mineral grain and the ice layer mantling
 134 is,

$$135 \quad p_{vdW} = \frac{A_H}{6\pi d^3}, \quad (1)$$

136 where A_H is the Hamaker constant and d is the thickness of the liquid film
 137 separating ice layer and the mineral substrate. The excess of pressure resulting
 138 in the interfacial melting can be related to the actual melting temperature via
 139 (Dash et al., 2006),

$$140 \quad \Delta p = H \varrho_l \frac{T_m - T}{T_m}, \quad (2)$$

141 where H is the latent heat of melting, T_m is the standard melting temperature,
 142 and ϱ_l is density of liquid water. Combining the two above equations gives,

$$143 \quad d = \left(\frac{A_H T_m}{6\pi H \varrho_l (T_m - T)} \right)^{1/3}. \quad (3)$$

144 For more details see the two references above and Kereszturi et al. (2009).

2.3 Initial and boundary conditions

Since we are interested to solve the problem before a gully has formed we will assume the slope of the considered hill or dune to be a perfect inclined plane. It is than sufficient to solve heat and the vapor transport equations in one dimension in the direction perpendicular to the surface. In such case, most important boundary conditions are those at the surface of a slope: (i) the surface temperature satisfies heat balance through the energy equation (including heat of sublimation/condensation of a surface ice); (ii) vapor pressure at the surface (to calculate diffusion of vapor within regolith) is determined by the atmospheric humidity.

The initial volume fraction of ice is: (i) zero at the surface, (ii) linear function of depth z up to $z = 5$ cm (from 0 at the surface to $v_{i,0}$ at $z = 5$ cm), (iii) constant with the value $v_{i,0}$, when $z > 5$ cm. For the results presented below the value of $v_{i,0}$ is 0.30, or 0.01.

3 Parameters

Key model parameters are summarized in Table 6. The model slope is inclined by the angle γ toward the pole, or toward the equator. The values of γ are within the range $5^\circ - 45^\circ$. The regolith is composed of single size spherical grains whose radii r_g are within the range $50 \mu\text{m} - 0.5$ mm. If it is not stated otherwise, $r_g = 50 \mu\text{m}$. When the regolith is free of ice, it has the density $\rho = 1300 \text{ kg m}^{-3}$, the specific heat $c = 820 \text{ J kg}^{-1} \text{ K}^{-1}$, the porosity $\psi = 0.47$. The thermal conductivity λ of the regolith free of ice is $10 - 50 \text{ mW m}^{-1} \text{ K}^{-1}$. It is not known, what is the amount of the subsurface ice in locations, where the hill gullies and dune gullies are observed. It is likely, that dunes are almost free of ice, but within hills ice may be abundant. In our work we consider two initial values of the volume fraction of ice: 0.3, and 0.01. Presence of ice in the regolith enhances most significantly the efficiency of the heat transport. Thermal conductivity of the solid matrix of grains is determined by the contact areas of the grains, hence it is a strong function of the volume fraction of ice v_i . In addition, heat is transported within pore space. In our model the effective heat conductivity accounts for two processes: (i) heat conduction within the solid matrix of grains, and (ii) heat transport related to the sublimation and condensation of vapor in pores. The latter makes the effective conductivity very sensitive to the temperature. When $\lambda = 10 \text{ mW m}^{-1} \text{ K}^{-1}$, we have for example:

$$\begin{aligned} \lambda_{eff}(T = 230\text{K}) &= 0.1 \text{ W m}^{-1} \text{ K}^{-1}, \\ \lambda_{eff}(T = 250\text{K}) &= 1.5 \text{ W m}^{-1} \text{ K}^{-1}, \\ \lambda_{eff}(T = 270\text{K}) &= 7.8 \text{ W m}^{-1} \text{ K}^{-1}. \end{aligned}$$

Fig. 2 shows the temperature dependence of the various components of the thermal conductivity.

The albedo A of a surface free of frost is 0.15 - 0.25, and the emissivity e is within the range 0.5 - 0.8. For all the results below $A = 0.15$, and $e = 0.8$, maximizing the film thickness. The Hamaker constant A_H is most likely about $1.8 \cdot 10^{-19}$ J, but can be as high as 10^{-18} J (Moehlmann, 2008). Here we take this higher value to maximize the calculated thickness of the liquid layer. Thickness of a single monolayer of the water molecules is $\delta = 3.5 \cdot 10^{-10}$ m.

The simulations are performed with spatial resolution comparable to the diurnal thermal skin depth d_{th} . When the regolith is free of ice, the thermal skin depth is about 1 cm. However, when the regolith contains ice d_{th} becomes an order of magnitude larger. This change is due to influence of the presence of ice on the effective heat conductivity. At the temperature 230 K the thermal skin depths is 8 cm, while close to the melting point it becomes about 40 cm. The size of the grid itself is adjusted to have the vertical temperature gradient at the bottom boundary negligibly small. We performed tests and found, that 10 meters is sufficient. Resolution of our simulations is 1.25 - 10 cm and the time step is 2 - 30 seconds.

4 Results

In this section we present the simulated diurnal and seasonal cycles of the water film thickness in the regolith. The former is shown for $L_s = 271^\circ$, while the latter for $L_s = 180^\circ - 280^\circ$. Figures 3 - 5 show results of these simulations for slopes facing North and South. The values of other parameters are: the regolith dry thermal conductivity $\lambda = 50$ mW/m/K, the volume fraction of ice $v_{i0} = 0.3$, ice free surface albedo $A = 0.15$, and the emissivity $\epsilon = 0.8$. These values are chosen to maximize the film thickness meaning that all the values except albedo are at the high end of their possible range and albedo is low. Figure 3 shows diurnal profiles of the temperature of the regolith, while Figures 4 and 5 show diurnal profiles of the thickness of the interfacial water film. The curves are drawn for different depths beneath a flat slope inclined by either 25° or 35° (temperature profiles are shown only for 25°). The atmospheric humidity is taken from the GCM results for the present climate. The surface of the equator facing slope warms up in the afternoon up to 320 K, about 50 K above the melting temperature of pure water ice. At the depth of 2.5 cm temperature reaches nearly 270 K, which is reflected in growth of the interfacial water film to almost 10 monolayers (Figure 4, lower panel). This thickness persists for a time of several tens of minutes. At this depth the film of thickness of about 5 monolayers can be expected to be present for about 5 hours. The drop of the film thickness at about 4 pm is due to complete

sublimation of ice. Deeper below the surface the temperature is significantly lower throughout the whole day and thickness of the liquid layer is at the most 3 monolayers. When a slope is inclined toward the pole, all temperatures are lower and the maximum film thickness is only about 3 monolayers even at the depth of 2.5 cm. In Figures 4 - 5 we show diurnal cycle of the film thickness for slopes inclined by 35° (upper panels). The values are somewhat lower than for the case of 25° but the dependence on this parameter is not very strong.

In Figures 6, and 7 we show diurnal cycle of the interfacial water film thickness, when the model also includes absorption of the IR flux from the atmosphere. We see that this additional heating causes film thickness at depth of 2.5 cm on the equator facing slope to grow rapidly followed by complete sublimation of ice already at about 10:30 AM. Judging from the curve for 5 cm depth we can expect that the result at about 3 cm should be similar to that at 2.5 cm when atmospheric heating is not included.

In Figure 8 we show the seasonal evolution of the diurnal maximum of the liquid film thickness for both slope orientations. The profiles are shown for two values of slope inclination and with and without additional atmospheric heating. They are for depth of 5 cm for the equator facing slope and depth of 2.5 cm for the pole facing one. We see that the largest thickness of nearly 10 monolayers occurs on the equator facing slope and persists for about 40 martian days.

To investigate potential importance of liquid water films for the formation of dune gullies we have also calculated models with very low initial volume fraction of subsurface water ice of 0.01. We considered two locations, namely, (50°S , 50°E) and (50°S , 135°E). The former is in the Hellas basin, while the latter is on the southern highland. These locations differ in atmospheric pressure and humidity. For both locations during summer water ice is permanently present only at depths larger than 10 cm. Closer to the surface ice condenses at night (due to diffusion of the vapor from above or below, or freezing of water adsorbed on the mineral grains), and sublimates away during the day. The remaining model parameters are the same as in the case of Fig. 4. The diurnal maximum of the water film thickness obtained is always less than 4 monolayers and roughly the same for both locations. This indicates, that the atmospheric pressure and humidity have minor effect. Comparison with the profiles presented in Fig. 4 shows, that the water film thickness is at the depth of 2.5 cm is about 2 times smaller than predicted for the regolith rich in ice. The seasonal cycles are not significantly different for the two cases, only that ice poor regolith has never more than 4 monolayers film thickness. We have also looked at the dependence on grain and did not find this parameter to be in any way critical.

5 Conclusions

We attempted to answer the question, whether an interfacial water film of significant thickness may form in locations where the hill-gullies are observed. We investigated interfacial melting in the regolith beneath the sloped surfaces at a depth of few centimeters. We considered different initial volume fraction of the subsurface ice: high, possible for gullied hills, and low, likely for dunes.

When the regolith is rich in ice, our simulations suggest that under extreme conditions one may expect formation of a liquid film of water about 10 monolayers thick. Calculating stability of a slope in a presence of moisture is beyond the scope of the current work. However, quick estimate suggests, that 10 monolayers of liquid water could be sufficient to make the surface layer unstable. If we take thickness of the monolayer to be $3.5 \cdot 10^{-10}$ m, the whole liquid film is only $3.5 \cdot 10^{-9}$ m thick. We can compare this to the expected roughness of the grains within the regolith. The smallest grains are about 1 micron in size. Assuming the surface irregularities are 1% (10^{-8} m), we would require about 30 monolayers to fill them, which could allow films of neighbouring grains to connect. Although this is more than we observe in the model, we should note that: (i) it is of the same magnitude and given model limitations should be considered similar; and (ii) full separation of the adjacent grains may be not necessary for the material on a steep slope to become unstable. It should also be noted that gullies (of any type) found in mid-latitudes are mostly equatorial facing (Balme et al., 2006) orientation for which we also find thicker interfacial water films.

When the regolith contains low amount of ice, formation of a thick water film solely due to local interfacial melting is very unlikely. At the equatorward oriented slope interfacial water appears few centimeters beneath the surface only in the coldest season, in summer the regolith remains dry. At the poleward inclined slope interfacial water may appear the whole year but the liquid film is thin. Hence, only periodical sinking of water to a colder layer, freezing and melting seems to be able to produce significant amount of liquid water, as suggested by Kereszturi et al. (2010).

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374 Table 1 (File: I11326_table.tex)

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Fig. 1. Part of HRSC image h0155-000 showing gullies on slopes of a hill located approximately at 47.25°S , and 330.1°E . The hill is about 1 km across, and about 1 km high. North is up. The image comes from HRSCview. Freie Universitaet Berlin and DLR Berlin, <http://hrscview.fu-berlin.de/>. See also Neukum et al. (2004); Jaumann et al. (2007).

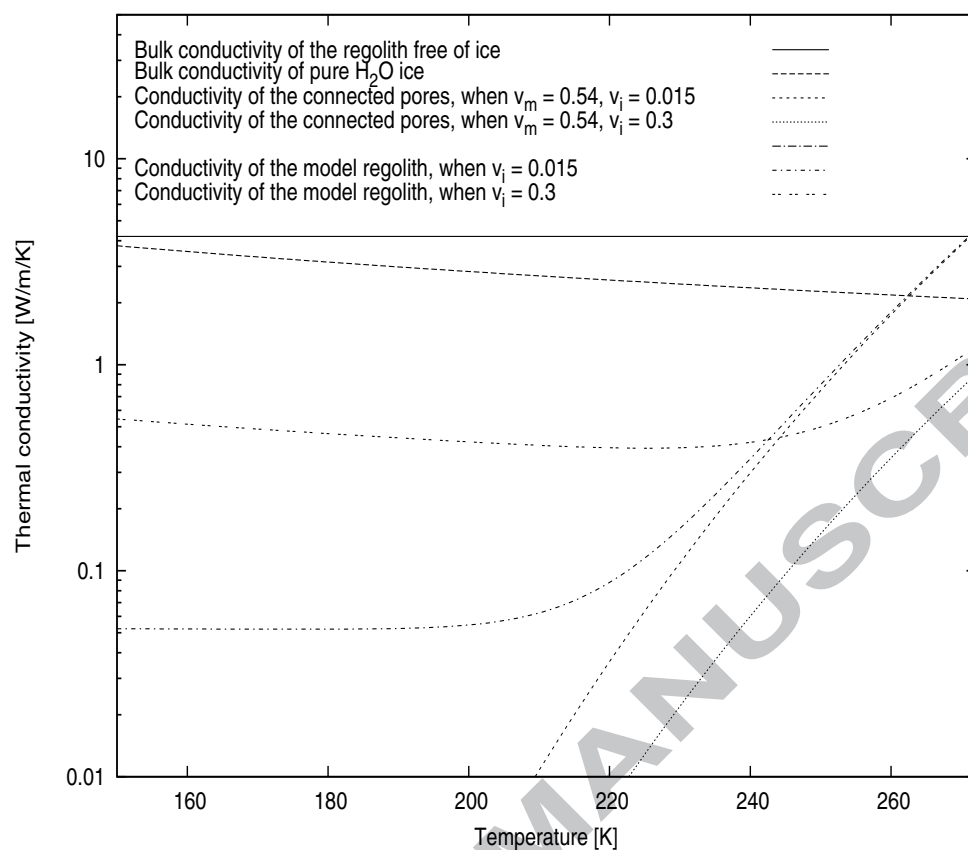


Fig. 2. Thermal conductivity of a regolith composed of grains covered by water ice.

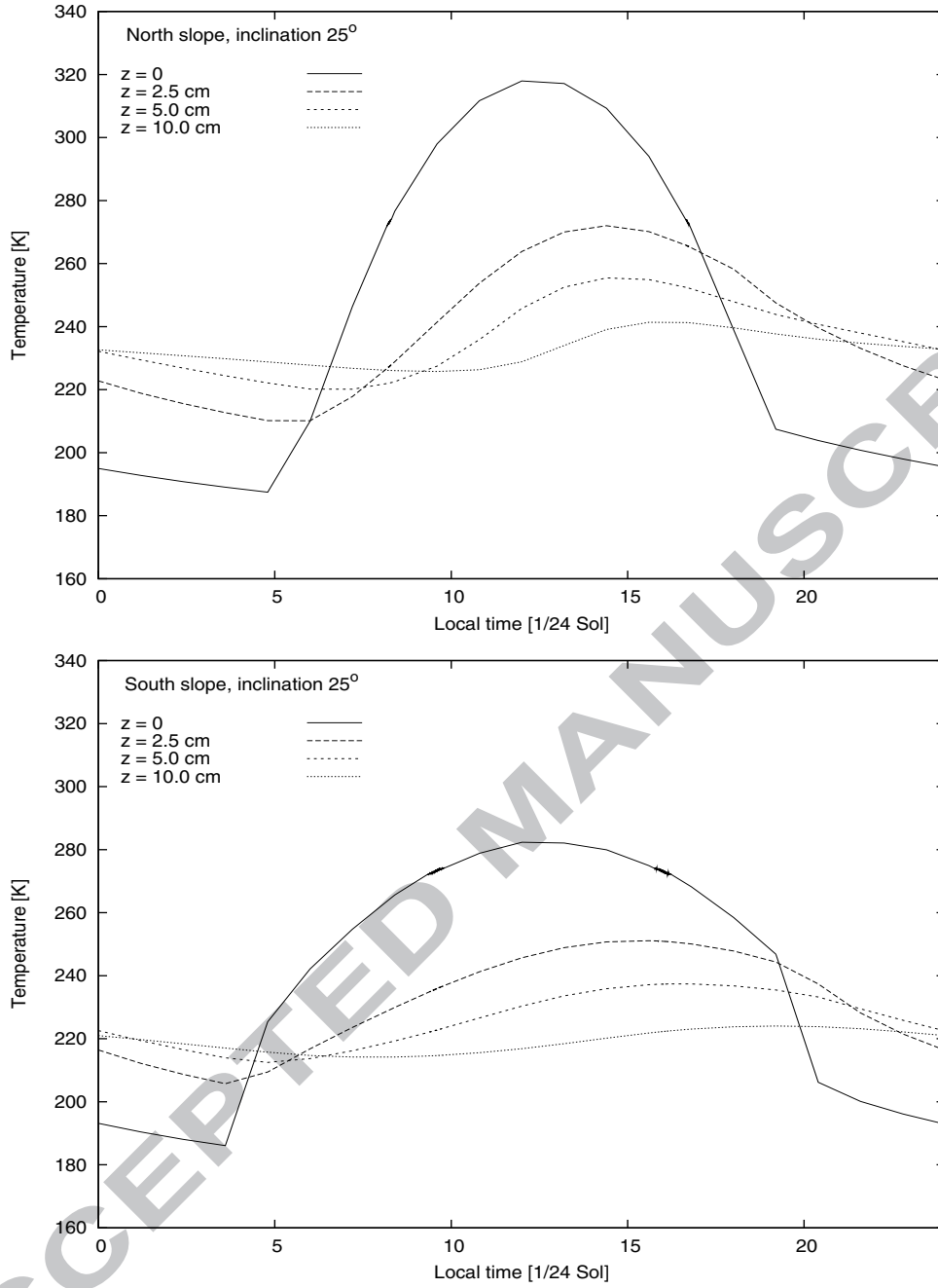


Fig. 3. Diurnal cycle of the temperature at different depth, when the slope is inclined toward North (upper panel), and toward South (lower panel). The profiles are drawn for $L_s = 271^\circ$.

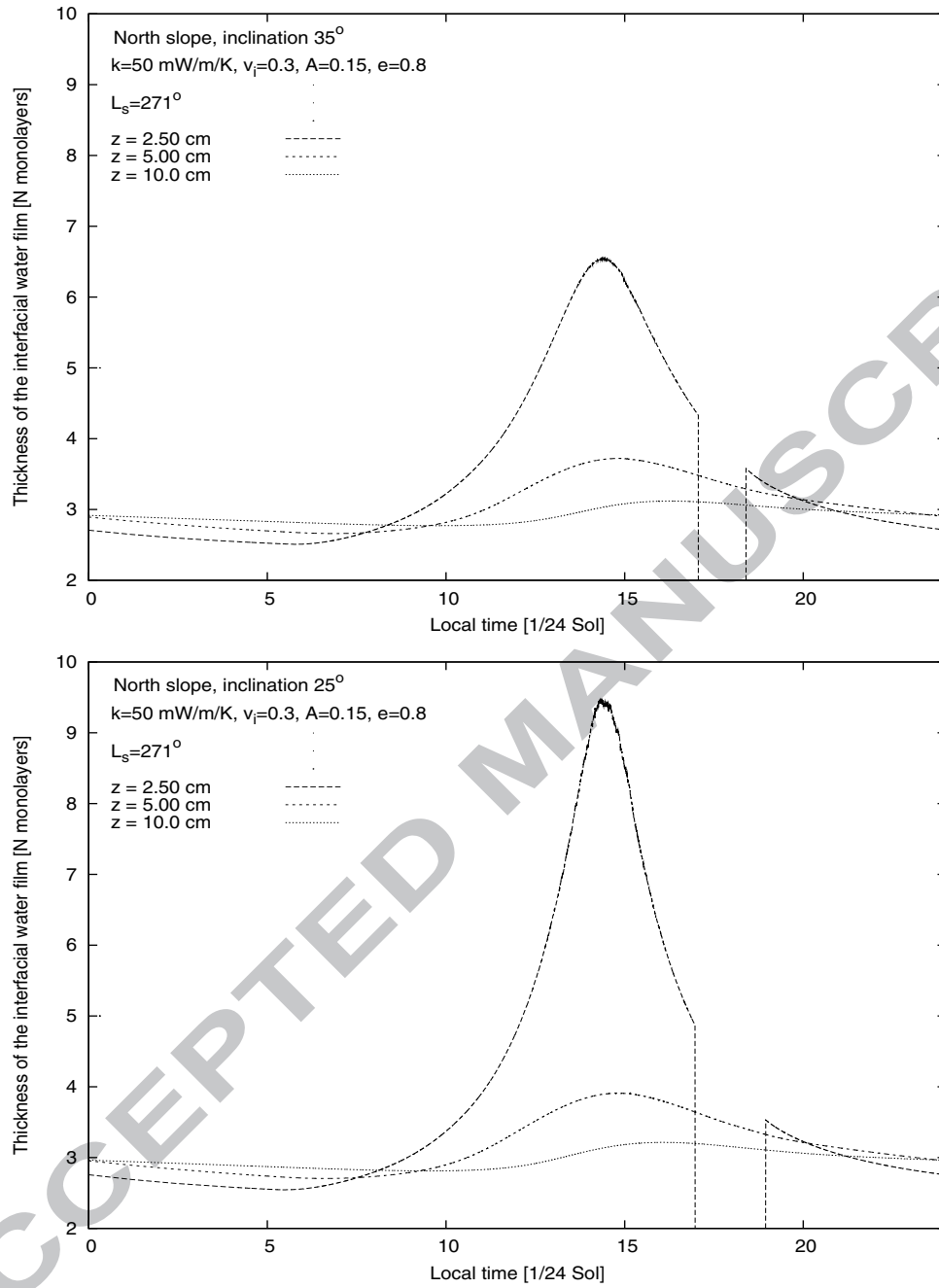


Fig. 4. Diurnal cycle of the thickness of the interfacial water film on regolith grains. The slope is inclined toward North by 35° (upper panel), and 25° (lower panel). The profiles are drawn for $L_s = 271^\circ$.

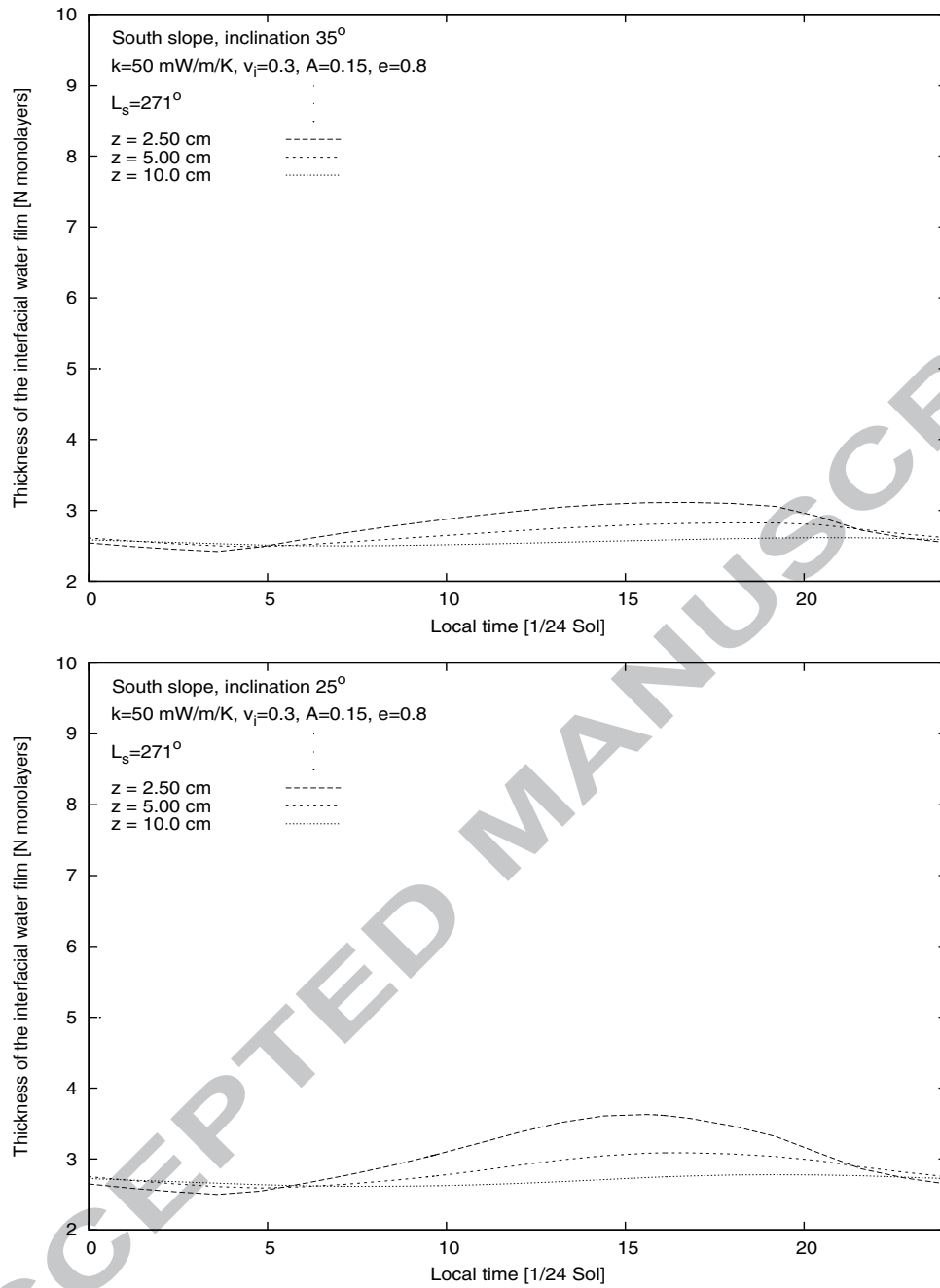


Fig. 5. The same as in Fig. 4, but for a south facing slope.

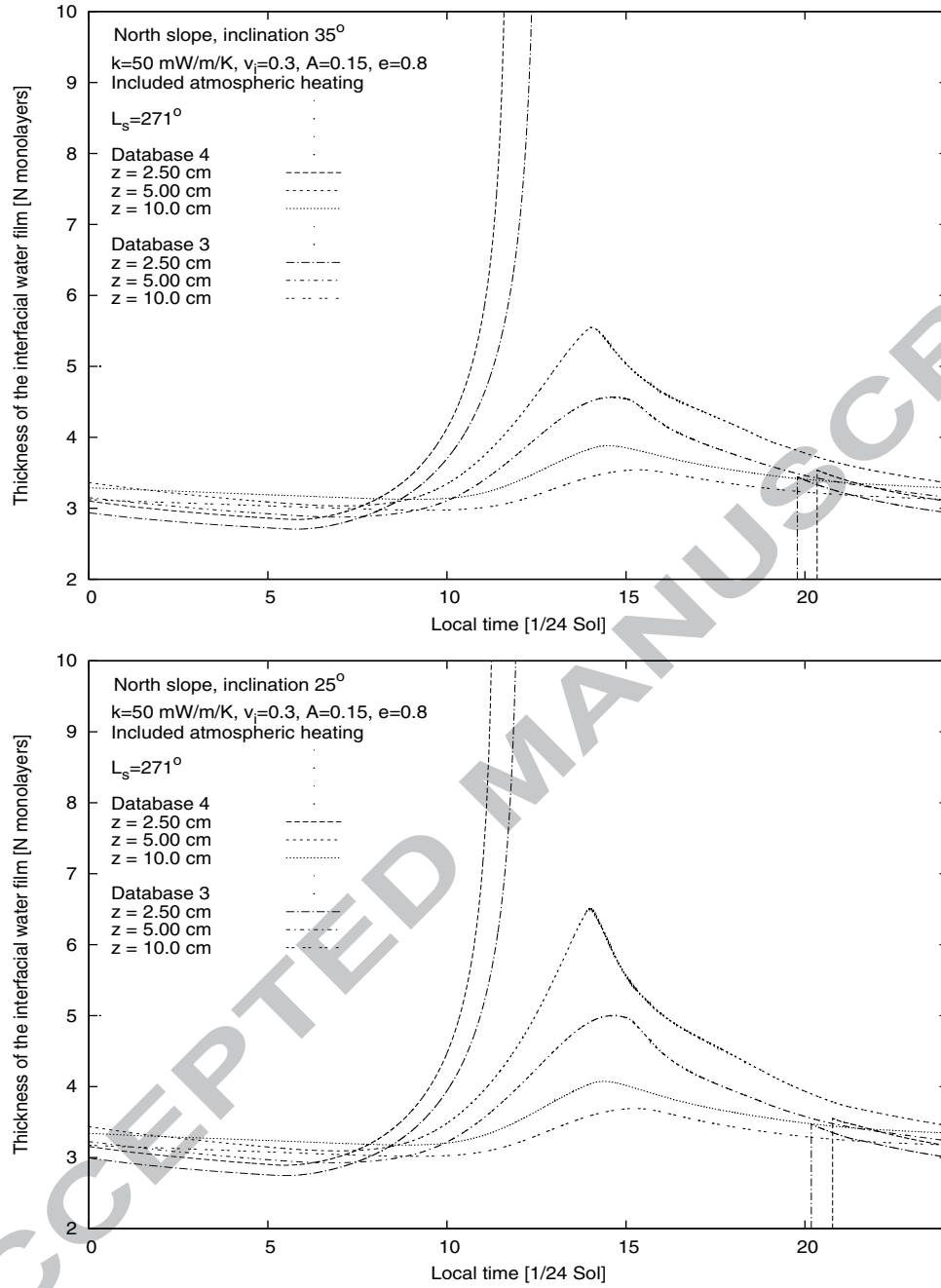


Fig. 6. Diurnal cycle of the thickness of the interfacial water film on regolith grains, as in Fig. 4, but including the IR flux from the atmosphere toward surface. The latter is taken from the results of the GCM LMD/Oxford, databases: 3 and 4. The profiles are drawn for $L_s = 271^\circ$.

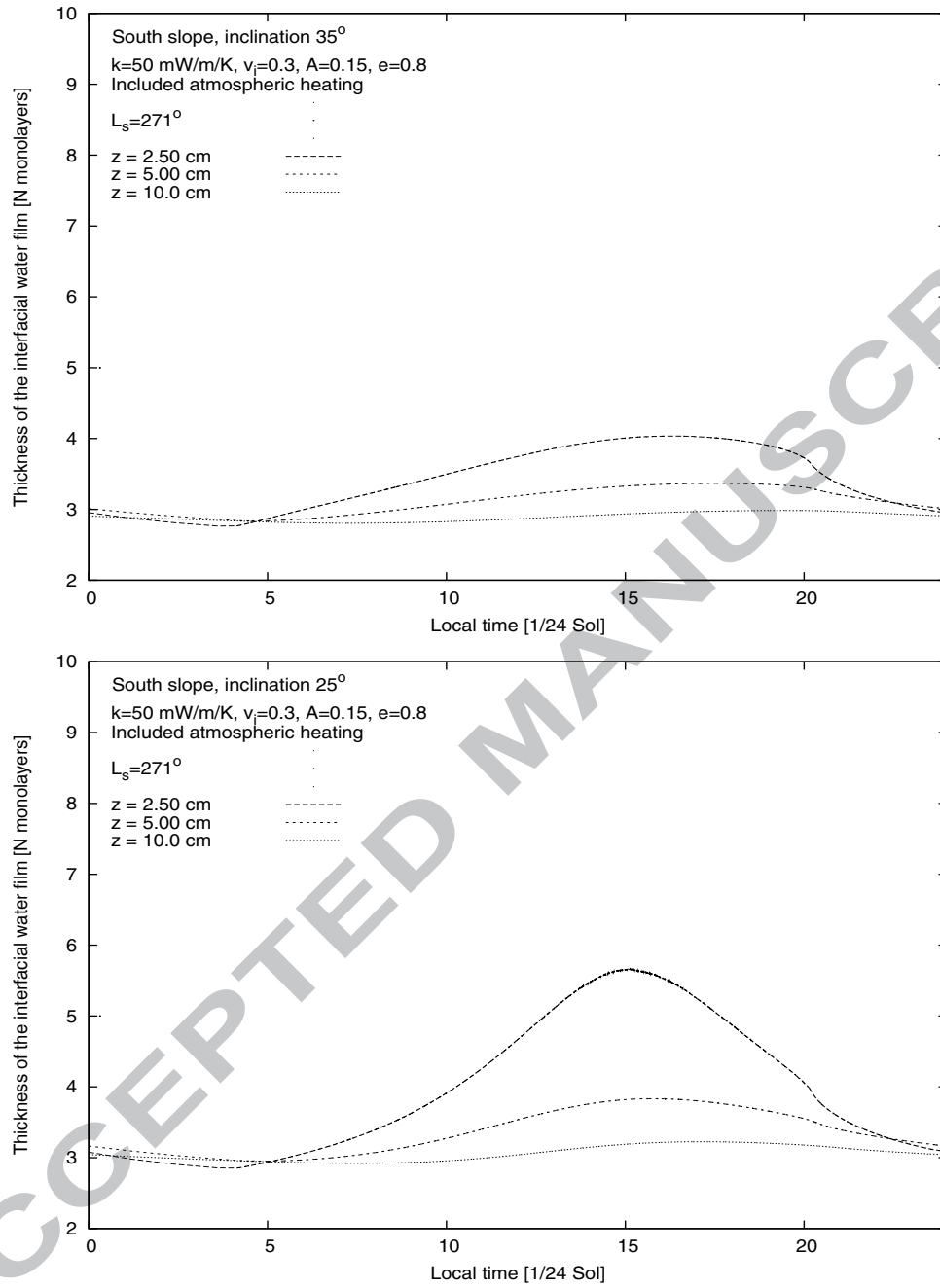


Fig. 7. The same as in Fig. 5, but including the IR flux from the atmosphere toward surface.

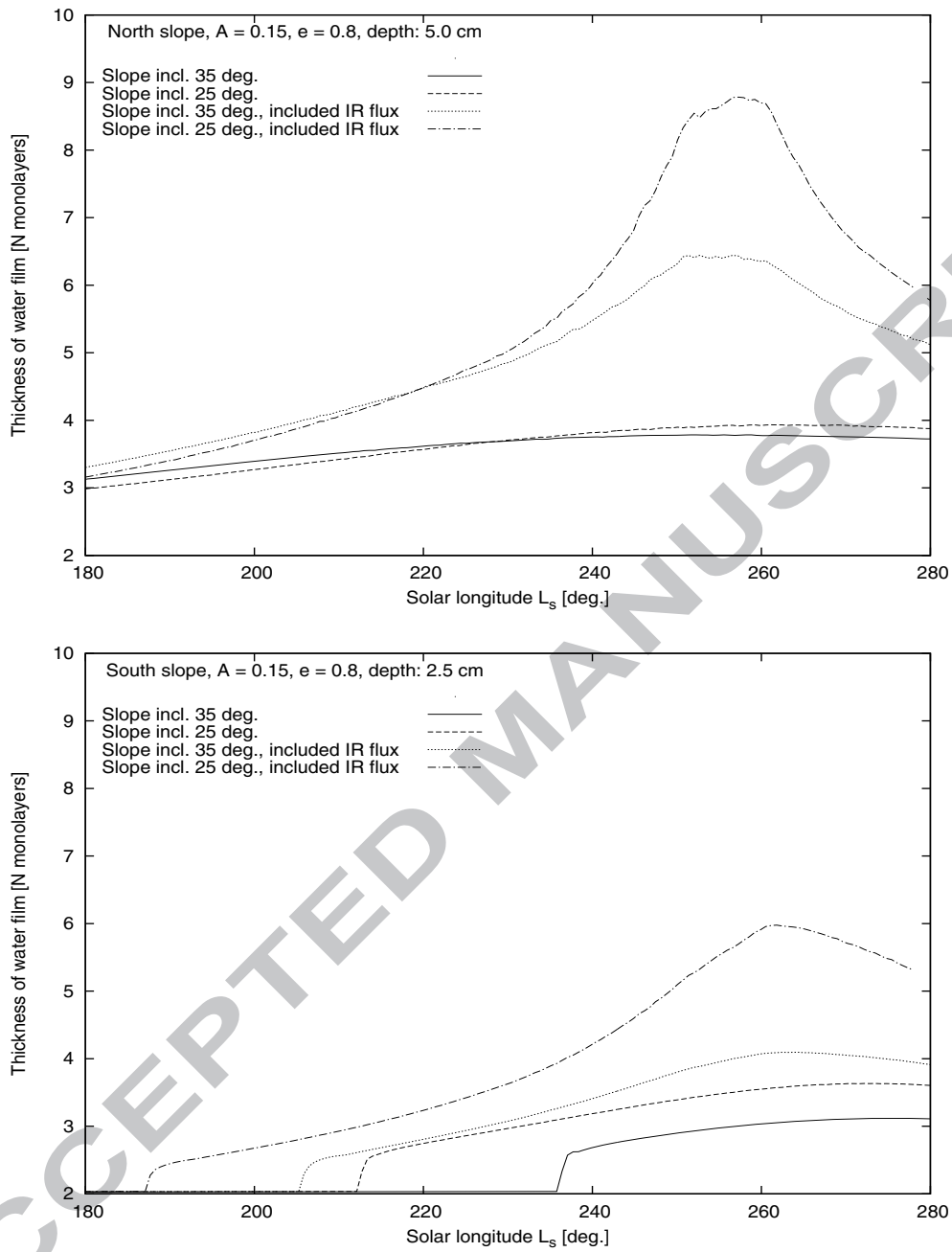


Fig. 8. Seasonal dependence of the diurnal maximum of the interfacial water film thickness, when: (i) equator facing slope, at depth $z = 5$ cm (upper panel); (ii) poleward facing slope, at depth $z = 2.5$ cm (lower panel).

Table 1
Model parameters

| Parameter | Symbol | Units | Value |
|---|------------------|---------------------------------------|-----------------------|
| Albedo of the regolith free of ice | A | | 0.15 |
| Albedo of the regolith covered by thick ice | A_i | | 0.35 |
| Emissivity of the regolith free of ice | ϵ | | 0.8 |
| Emissivity of the regolith covered by thick ice | ϵ_i | | 0.65 |
| Grain/pore radius free of ice | $r_g = r_p$ | [mm] | 0.05 |
| Density of the regolith | ϱ | [kg m ⁻³] | 1300 |
| Thermal conductivity of the regolith free of ice | λ | [W m ⁻¹ K ⁻¹] | 0.05 |
| Initial volume fraction of ice | v_{i0} | | 0.3, 0.01 |
| Porosity of the regolith when free of ice | $\psi = 1 - v_m$ | | 0.46 |
| Specific heat of the regolith free of ice | c_m | [J kg ⁻¹ K ⁻¹] | 820 |
| Hamaker constant | A_H | [J] | $10^{-19} - 10^{-18}$ |
| Thickness of a single monolayer of the water molecules | δ | [m] | $3.5 \cdot 10^{-10}$ |
| Inclination of a hill slope | γ | [°] | 15 - 35 |