Formation of recurring slope lineae by liquid brines on present-day Mars

Vincent F. Chevrier[1] and Edgard G. Rivera-Valentin[2]

Received 4 October 2012; accepted 5 October 2012; published 10 November 2012.

[1] Recurring Slope Lineae (RSL) are small scale seasonal flow features identified by Mars Reconnaissance Orbiter that present several interesting characteristics such as an albedo contrast, seasonal dependence, and a strong preference for equator-facing slopes. All of these characteristics strongly suggest a thermally driven mechanism such as a liquid triggered or dominated flow. Here we investigate the possibility that these features are formed by melting of brines of various compositions via a combination of thermodynamic and kinetic numerical models. Results suggest that a solution with a freezing temperature of ~223 K can best reproduce the observed seasonality. Relatively high surface evaporation rates at the RSL locations make the flows quickly disappear over a single season. Our model reproduces well the seasonality of RSL and can explain the preference for equator-facing slopes suggesting that brine flows, and therefore liquids, are possible on a small time and space scale today on Mars. However, if the RSL are indeed formed by brines, it may indicate that a recharge mechanism is active in order to maintain a source of brine over even short geological timescales, which would have important implications for the Martian water cycle. **Citation:** Chevrier, V. F., and E. G. Rivera-Valentin (2012), Formation of recurring slope lineae by liquid brines on present-day Mars, *Geophys. Res. Lett.*, *39*, L21202, doi:10.1029/2012GL054119.

1. Introduction

[2] The occurrence of liquid water on Mars is one of the most controversial research areas in planetary science. Direct observations of possible liquids have been so far limited to a few droplets on the feet of the Phoenix lander [*Rennó et al.*, 2009]. Various Martian geomorphological features have been attributed to liquid water such as gullies [*Malin et al.*, 2006] or slope streaks [*Kreslavsky and Head*, 2009], the latter of which do not evidence any seasonality despite years of observations. Gully activity, on the other hand, has been found to occur mostly during winter and are thus most probably not triggered by liquid water [*Dundas et al.*, 2012; *Dundas et al.*, 2010; *Diniega et al.*, 2010]. Recently, the Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) identified small scale flow features termed Recurring Slope Lineae (RSL) [*McEwen et al.*, 2011]. They present several unique characteristics such as an albedo contrast, a strong preference for equator-facing slopes, are associated with channels, and they appear mostly during the spring and summer seasons, slowly fading and disappearing during the autumn and winter. Such characteristics and their small size suggest that these features could result from melting of frozen liquid solutions.

[3] The identification by various orbiter and lander missions of large amounts of salts as sedimentary deposits or dispersed in the regolith [*Gendrin et al.*, 2005; *Squyres et al.*, 2004; *Wang et al.*, 2006] has raised the possibility for abundant brines on the surface of Mars. Pure water is highly unstable in present-day surface conditions [*Chevrier and Altheide*, 2008], but brines exhibit lower water activity, which quantifies their deviation from ideal solutions (water activity of 1), resulting in lower freezing temperatures and evaporation rates, making them potential liquid phases on the surface of Mars [*Altheide et al.*, 2009; *Brass*, 1980; *Chevrier and Altheide*, 2008; *Sears and Chittenden*, 2005].

[4] It has been suggested by *McEwen et al.* [2011] that brines near the surface may trigger these events; therefore, we investigate the possibility of brine formation at RSL locations. Assuming there exists buried ice and/or a subsurface source of H_2O on the crater slopes and salts intermixed within the regolith, brine formation may be possible depending on the subsurface temperature and the abundance of salts [*Chevrier and Altheide*, 2008; *Kreslavsky and Head*, 2009]. Here, via a combination of thermodynamic and kinetic numerical models, we simulate the stability of these salt systems along with the expected melt production and its seasonality for various compositions. We compare the simulated seasonality to the RSL observations in order to approximate the characteristics of the possible brine forming these features.

2. Model Description

[5] A heat transfer model for the surface and subsurface of Mars [*Keresztūri and Rivera-Valentin*, 2012; *Rivera-Valentin et al.*, 2011; *Ulrich et al.*, 2010] was combined with a kinetic model of water evaporation [*Chevrier and Altheide*, 2008], as detailed in the auxiliary material.[1] Temperatures were modeled to a depth of 10 m, which is well below the annual skin depth, as a function of latitude and slope [*Aharonson and Schorghofer*, 2006]. For the regolith properties, the thermal inertia and albedo measured around the RSL [*McEwen et al.*, 2011] were used along with the heat capacity and thermal conductivity of the Phoenix regolith

[1]Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, Arkansas, USA.
[2]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.

Corresponding author: V. Chevrier, Arkansas Center for Space and Planetary Sciences, University of Arkansas, FELD 202, Fayetteville, AR 72701, USA. (vchevrie@uark.edu)

0094-8276/12/2012GL054119

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL054119.

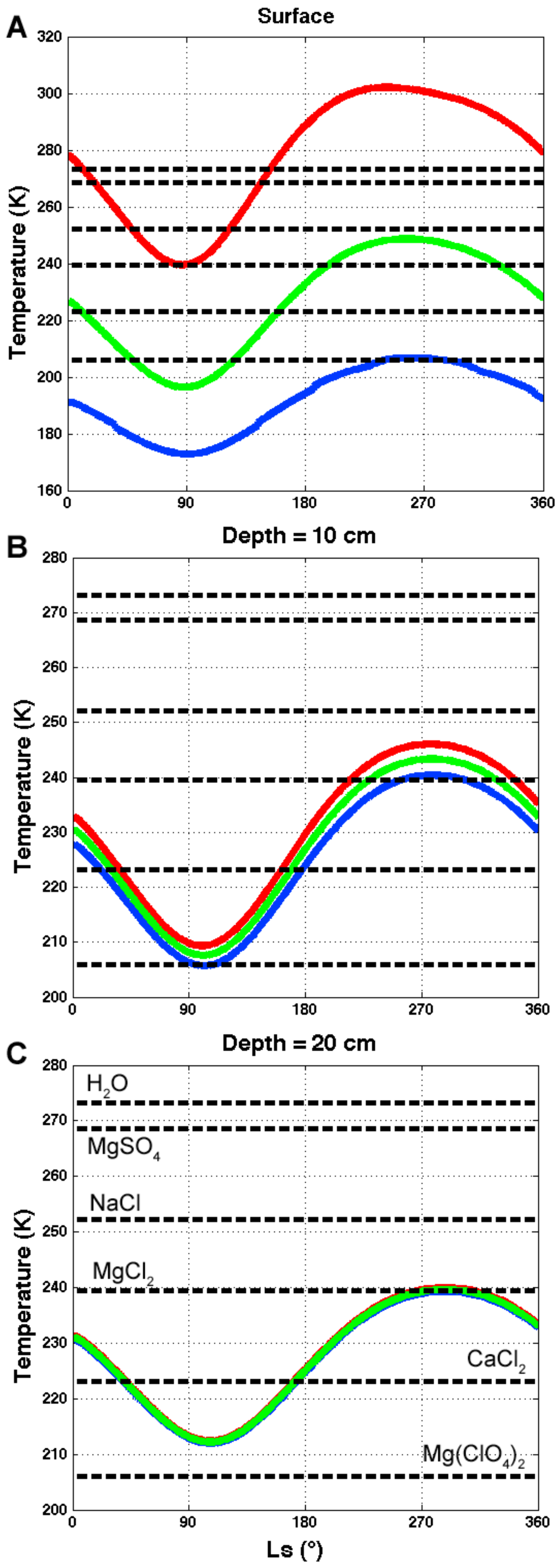


Figure 1. Modeled temperatures of surface and shallow subsurface as a function of depth, and solar longitude at latitude 40° south and for a 35° equator-facing slope: (a) surface, (b) 10 cm deep, and (c) 20 cm deep. Figures 1b and 1c were made with ice cemented soil at the given depth. Red: maximum, blue: minimum and green: average yearly temperatures. Horizontal dashed lines represent eutectic temperatures for several salts, from top to bottom: Water (T_E = 273.16 K), $MgSO_4$ (T_E = 268.6 K), NaCl (T_E = 252.2 K), $MgCl_2$ (T_E = 239.5 K), $CaCl_2$ (T_E = 223.2 K) and $Mg(ClO_4)_2$ (T_E = 206 K).

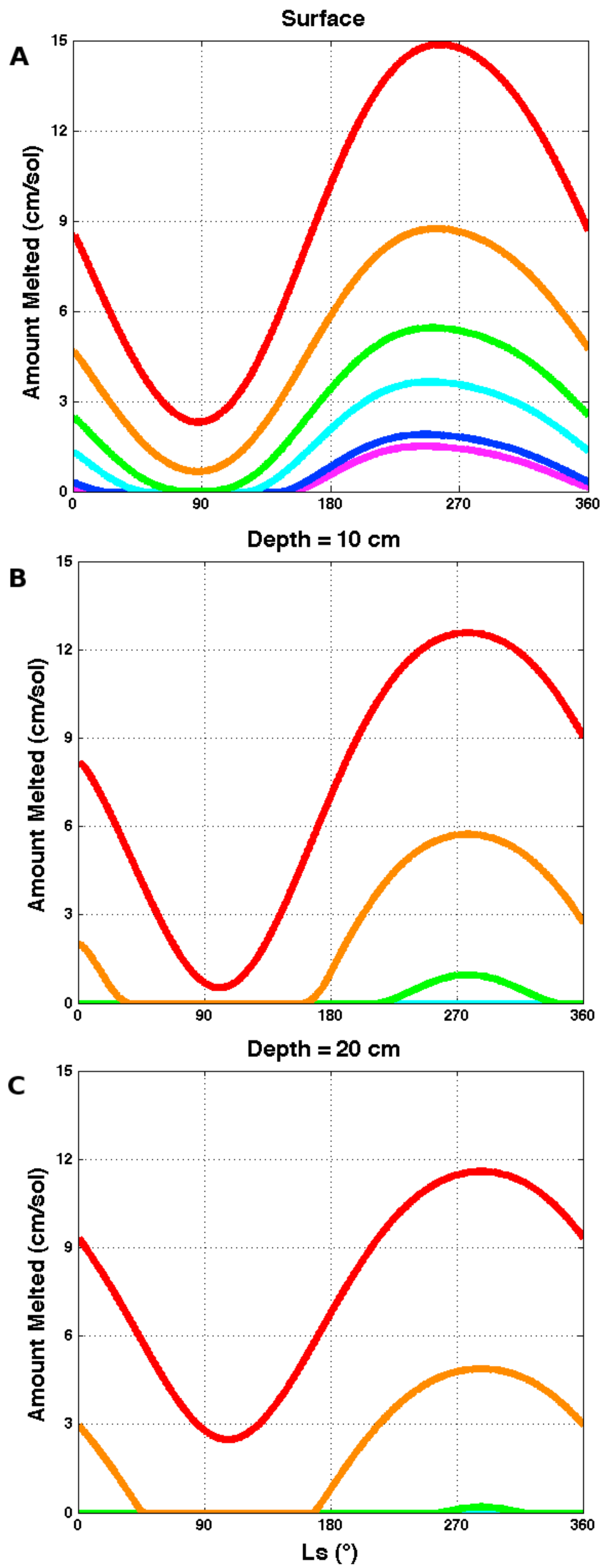
[*Zent et al.*, 2010]. A soil-ice mixture is assumed to exist at varying depths using the properties from *Keresztúri and Rivera-Valentin* [2012] following the method of *Mellon et al.* [2004]. Surface evaporation rates were modeled using a diffusion-buoyancy equation [*Ingersoll*, 1970], modified to include the effect of water activity [*Altheide et al.*, 2009; *Chevrier and Altheide*, 2008; *Chevrier et al.*, 2009]. Evaporation in the subsurface includes the effects of diffusion-advection in the regolith [*Ulrich*, 2009].

[6] Results were compared to the eutectic temperatures of various salts relevant to Mars: $MgSO_4$ (a_{H2O} = 0.96, T_E = 268.6 K), NaCl (a_{H2O} = 0.82, T_E = 252.2 K), $MgCl_2$ (a_{H2O} = 0.72, T_E = 239.5 K), $CaCl_2$ (a_{H2O} = 0.62, T_E = 223.2 K), $Mg(ClO_4)_2$ (a_{H2O} = 0.55, T_E = 206 K). Magnesium sulfate has been widely observed on Mars [*Gendrin et al.*, 2005], whereas chlorides have been identified in the southern highlands [*Osterloo et al.*, 2008], where the RSL are observed. Finally, perchlorate has recently been identified by the Phoenix lander and magnesium perchlorate exhibits one of the lowest eutectic temperature of all salts [*Chevrier et al.*, 2009; *Hecht et al.*, 2009]. Although this is not an exhaustive selection, we focused on a wide range of water activities and corresponding eutectic temperatures. Most other possible salts have eutectics similar to those studied here. For example, the eutectic of ferric sulfate is very close to Mg-perchlorate, whereas ferrous sulfate's is similar to Mg-sulfate.

3. Results

[7] Latitudes between 30° and 50°S were modeled recording results for depths of 0 (surface) 10, and 20 cm to allow for temperature cycling. Modeled temperatures for equator-facing slopes reach a maximum of ~300 K at 30°S and 270 K at 50°S, while poleward slopes reach only 210 to 180 K respectively (auxiliary material, Figures S1a–S1c). Hence, equator-facing slopes experience maximum temperatures high enough for various salt-ice mixtures to melt, even at depth. Poleward slopes are too cold for seasonal melting to occur except for the lowest eutectics. These results correlate well with observations of RSL on equator-facing slopes, whose surface brightness temperatures were as high as 300 K [*McEwen et al.*, 2011].

[8] Diurnal variations in surface temperature allow melting and freezing for virtually any brine; however, at lower depths, only $MgCl_2$, $CaCl_2$, and $Mg(ClO_4)_2$ solutions can melt (Figures 1a–1c). Water, $Mg(SO_4)$, and NaCl systems only melt if close to or on the surface. All salt systems are frozen for at least part of the winter, so melting is only a seasonal process, except for some limited diurnal melting on the surface. Most of the confirmed RSL were observed in



the range Ls 250°–350° [*McEwen et al.*, 2011] with some candidate RSL occurring early in the year near Ls 10°. This Ls range correlates well with the simulated seasonality of $CaCl_2$ (Figures 1a–1c). $MgCl_2$ brine is slightly less stable so it melts over a shorter range of Ls and does not produce much melt at depth. $Mg(ClO_4)_2$ remains liquid most of the year, which limits seasonality.

[9] The total amount of melt per sol is slightly dependent on the depth and strongly on the season and type of salt (Figure 2), where the lower the eutectic the larger the amount of melt. Mg perchlorate, and Mg, Ca chlorides are the only salts forming melts at all three depths, with melt rates from 1 to 15 cm/sol. Such melting rates are relatively high and represent significant volumes of liquid depending on the affected surface area. Integrated melting rates over one year range between 4 meters for pure water and 60 meters for $Mg(ClO_4)_2$ on the surface, with most salt systems around 10–20 meters. In the subsurface, melting only occurs for salts with freezing temperature <240 K. As is seen from Figure 2, maximum melt productions per sol for melting salt systems range from 15 cm/sol to 0.2 cm/sol.

[10] Once melting has occurred at depth, it may wick to the surface where it will experience high evaporation rates. As shown in Figure 3, evaporation rates are slightly dependent on the water activity but strongly on the depth, because of the diffusive barrier created by the overburden [*Chevrier et al.*, 2007; *Chevrier and Altheide*, 2008; *Ulrich*, 2009]. The evaporation rate is about 2–3 m yr^{-1} on the surface and drops by about 3 orders of magnitude at 10 and 20 cm deep. Therefore, once on the surface, liquids evaporate very quickly. Moreover, the decrease of albedo resulting from the presence of liquids on the surface would result in higher local temperatures and faster evaporation rates. At 10 or 20 cm deep, though, brines experience lower evaporation rates (10^{-3}–10^{-4} m yr^{-1} in the summer) due to the attenuated temperature wave allowing for liquids at depth to be sustained perhaps even surviving from one year to another since subsurface liquids are completely frozen during winter when sublimation is inhibited by the overburden and low temperatures.

4. Discussion

[11] Our model suggests that RSL could result from episodic melting of brine and their seasonality would result from melting, freezing, and evaporation. Modeling confirms their preference for equator-facing slopes. Slope effects have been previously demonstrated for the formation of gullies by pure water during obliquity changes [*Costard et al.*, 2002]. Once melting occurs in the subsurface, either liquid dominated or triggered flows are possible under present-day conditions provided they are constituted of concentrated salt solutions. Although most brines and even pure water may produce RSL, lower eutectic salts like magnesium or calcium chlorides are the best candidates for episodic seasonal

Figure 2. Calculated melt rate for the studied brines as a function of solar longitude at latitude 40°S and for a 35° equator-facing slope: (a) surface, (b) 10 cm deep, and (c) 20 cm deep. Figures 2b and 2c were made with ice cemented soil at the given depth. Colored lines represent the various salts tested in this study: purple: water, blue: $MgSO_4$, light blue: NaCl, green: $MgCl_2$, orange: $CaCl_2$ and red: $Mg(ClO_4)_2$.

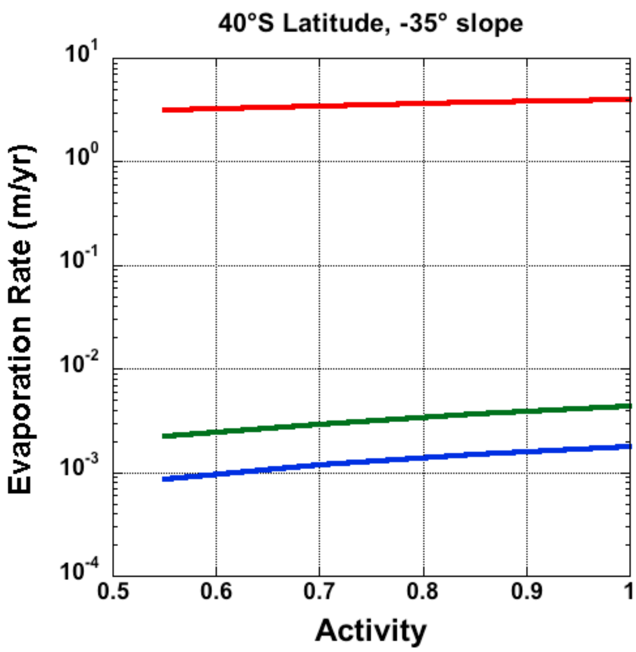


Figure 3. Modeled evaporation rates as a function of the water activity of the brine at latitude 40°S and for a 35° equator-facing slope. Red: surface, green: 10 cm deep and blue: 20 cm deep. Results at depth were made assuming ice cemented soil at the studied depth.

melting. Furthermore, high surface evaporation rates explain why they disappear relatively quickly and why MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) could not identify water signatures. This instrument is only sensitive down to about 100 μm deep. It would take only a few hours for the liquid brines to evaporate down to such a depth. Therefore, unless the instrument caught the liquid while flowing, there is only a small chance for the signal to show any evidence of liquid water.

[12] Figure 4 illustrates the diurnal and depth dependence of $CaCl_2$ brine melt at 40°S latitude on an equator-facing 35° slope at Ls 270°, when maximum annual temperatures are expected. Although surface melt occurs during daylight hours, melting at depths may occur throughout the entire day and night. Melting rates in the subsurface are small (2 mm/hr versus 9 mm/hr on the surface), with the total amount of liquid produced decreasing from about 8 cm to 5 cm formed that sol. Surface melting could possibly trigger a granular flow of low liquid content, while subsurface melts could accumulate over several days until triggering a more liquid dominated mass movement event.

[13] Recent work has shown that deliquescence is an efficient mechanism to form liquid brines on Mars, especially since lower hydrates prefer to form liquid, even below the eutectic, instead of increasing their hydration [*Gough et al.*, 2011]. The major problem with RSL is the amount required to form flowing liquids. During the favorable season, the maximum water vapor amounts in the atmosphere does not exceed 100 precipitable μm [*Smith*, 2002]. This is far too low for significant liquid features to form, even if all the water vapor in the atmosphere was condensed, which is highly unlikely.

[14] Though our model can accurately reproduce several RSL key characteristics (e.g. preference for equator-facing slopes and observed seasonality), it requires the presence of buried ice within the regolith column, which in the southern hemisphere is only considered stable for latitudes >40°S [*Mellon et al.*, 2004]. Equator-facing slopes further exasperate this issue by increased solar insolation with respect to

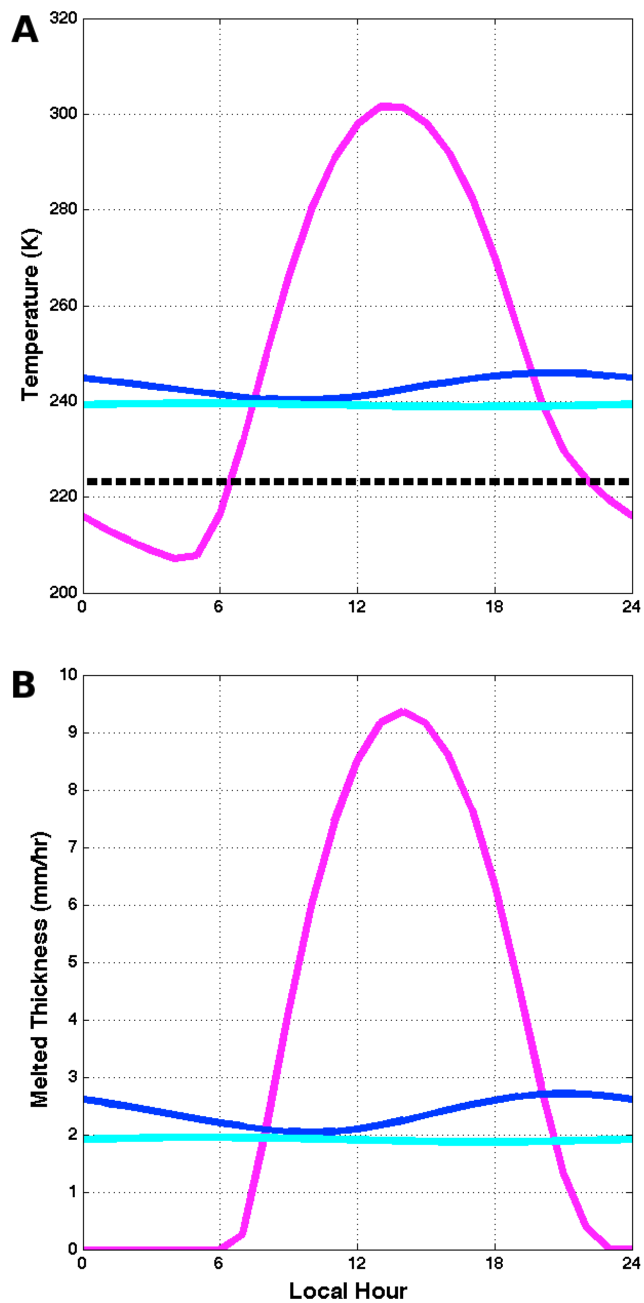


Figure 4. Diurnal results for $CaCl_2$ at 40°S on an equator-facing 35° slope at Ls = 270. (a) Temperature results for local hour on the surface (magenta) and at 10 (blue) and 20 cm (cyan). The dotted black line is the eutectic temperature of $CaCl_2$ (223.2 K). (b) Thickness melted in mm per hour on the surface (magenta) and at 10 (blue) and 20 cm (cyan). Results at depth were made assuming ice cemented soil at the studied depth.

flat terrain. However, our primary assumption is that there exists salts intermixed within the regolith column, which has been shown to reduce the diffusivity of water vapor by a factor of 10 [*Hudson and Aharonson*, 2008]. Moreover, these salts and ice mixtures would be more resistant to sublimation, since they would preferably melt and then possibly evaporate, but with a lower equilibrium pressure due to the activity of water in the liquid phase [*Chevrier and Altheide*, 2008]. This may increase the stability of buried ice and their modeled stability zone. Also, some RSL have been observed from one year to the next on the same spot following the same channels [*McEwen et al.*, 2011]. If our model is correct, this would imply that not all of the melt produced goes to form the features and is sustained from one year to the next due to limited sublimation and evaporation in the subsurface or that a recharge mechanism exists.

5. Conclusions

[15] The presented model reproduces accurately the distribution, and seasonality of the RSL observed by MRO HiRISE. More observations covering their diurnal and seasonal time constraints are necessary to identify the precise brine or brine mixture responsible for their formation. An interesting feature of the RSL that cannot be well reproduced is that they have been primarily found in the southern hemisphere. Melting should also occur on steep slopes in the northern hemisphere; however, this may imply that the salts are not as readily available in the north. Alternatively, the difference of insolation between the northern and southern hemispheres could also have created a transfer of water to the north, forcing salt ice mixtures towards increasing salt concentration in the south, thus favoring melting, which may also explain observations of shallow metastable "pure" ice at mid latitude in the northern hemisphere [*Byrne et al.*, 2009]. Although we do not rule them out, dry models do not explain the seasonality of the RSL and preference for equator facing slopes. Seasonal melting and freezing of salt-ice mixtures represent so far the best process to form these features, in agreement with *McEwen et al.*'s [2011] observations. However, if the model presented here is confirmed by future observations, it may indicate that a recharge mechanism is active in order to maintain a source of brine over even short geological timescales, which would have important implications for the Martian water cycle.

[16] **Acknowledgments.** We thank Shane Byrne, Alfred McEwen, and an anonymous reviewer for their comments which significantly improved our manuscript.

References

Aharonson, O., and N. Schorghofer (2006), Subsurface ice on Mars with rough topography, *J. Geophys. Res.*, *111*, E11007, doi:10.1029/2005JE002636.

Altheide, T. S., V. Chevrier, C. Nicholson, and J. Denson (2009), Experimental investigation of the stability and evaporation of sulfate and chloride brines on Mars, *Earth Planet. Sci. Lett.*, *282*, 69–78, doi:10.1016/j.epsl.2009.03.002.

Brass, G. W. (1980), The stability of brines on Mars, *Icarus*, *42*, 20–28, doi:10.1016/0019-1035(80)90237-7.

Byrne, S., et al. (2009), Distribution of mid-latitude ground ice on Mars from new impact craters, *Science*, *325*, 1674–1676, doi:10.1126/science.1175307.

Chevrier, V., and T. S. Altheide (2008), Low temperature aqueous ferric sulfate solutions on the surface of Mars, *Geophys. Res. Lett.*, *35*, L22101, doi:10.1029/2008GL035489.

Chevrier, V., D. W. G. Sears, J. Chittenden, L. A. Roe, R. Ulrich, K. Bryson, L. Billingsley, and J. Hanley (2007), The sublimation rate of ice under simulated Mars conditions and the effect of layers of mock regolith JSC Mars-1, *Geophys. Res. Lett.*, *34*, L02203, doi:10.1029/2006GL028401.

Chevrier, V., J. Hanley, and T. S. Altheide (2009), Stability of perchlorate hydrates and their liquid solutions at the Phoenix Landing site, Mars, *Geophys. Res. Lett.*, *36*, L10202, doi:10.1029/2009GL037497.

Costard, F., F. Forget, N. Mangold, and J. P. Peulvast (2002), Formation of recent Martian debris flows by melting of near-surface ground ice at high obliquity, *Science*, *295*, 110–113, doi:10.1126/science.1066698.

Diniega, S., S. Byrne, N. T. Bridges, C. M. Dundas, and A. S. McEwen (2010), Seasonality of present-day Martian dune-gully activity, *Geology*, *38*, 1047–1050, doi:10.1130/G31287.1.

Dundas, C. M., A. S. McEwen, S. Diniega, S. Byrne, and S. Martinez-Alonso (2010), New and recent gully activity on Mars as seen by HiRISE, *Geophys. Res. Lett.*, *37*, L07202, doi:10.1029/2009GL041351.

Dundas, C. M., S. Diniega, C. J. Hansen, S. Byrne, and A. S. McEwen (2012), Seasonal activity and morphological changes in Martian gullies, *Icarus*, *220*, 124–143, doi:10.1016/j.icarus.2012.04.005.

Gendrin, A., et al. (2005), Sulfates in Martian layered terrains: The OMEGA/Mars Express view, *Science*, *307*, 1587–1591, doi:10.1126/science.1109087.

Gough, R. V., V. F. Chevrier, K. J. Baustian, M. E. Wise, and M. A. Tolbert (2011), Laboratory studies of perchlorate phase transitions: Support for metastable aqueous perchlorate solutions on Mars, *Earth Planet. Sci. Lett.*, *312*(3–4), 371–377, doi:10.1016/j.epsl.2011.10.026.

Hecht, M. H., et al. (2009), Detection of perchlorate and the soluble chemistry of Martian soil at the Phoenix Lander Site, *Science*, *325*, 64–67.

Hudson, T. L., and O. Aharonson (2008), Diffusion barriers at Mars surface conditions: Salt crusts, particle size mixtures, and dust, *J. Geophys. Res.*, *113*, E09008, doi:10.1029/2007JE003026.

Ingersoll, A. P. (1970), Mars: Occurrence of liquid water, *Science*, *168*(3934), 972–973, doi:10.1126/science.168.3934.972.

Kereszturi, A., and E. G. Rivera-Valentin (2012), Locations of thin liquid water layers on present-day Mars, *Icarus*, *221*, 289–295, doi:10.1016/j.icarus.2012.08.004.

Kreslavsky, M. A., and J. W. Head III (2009), Slope streaks on Mars: A new "wet" mechanism, *Icarus*, *201*, 517–527, doi:10.1016/j.icarus.2009.01.026.

Malin, M. C., K. S. Edgett, L. V. Posiolova, S. M. McColley, and E. Z. Noe Dobrea (2006), Present-day impact cratering rate and contemporary gully activity on Mars, *Science*, *314*, 1573–1577, doi:10.1126/science.1135156.

McEwen, A. S., L. Ojha, C. M. Dundas, S. S. Mattson, S. Byrne, J. J. Wray, S. C. Cull, S. L. Murchie, N. Thomas, and V. C. Gulick (2011), Seasonal flows on warm Martian slopes, *Science*, *333*, 740–743, doi:10.1126/science.1204816.

Mellon, M. T., W. C. Feldman, and T. H. Prettyman (2004), The presence and stability of ground ice in the southern hemisphere of Mars, *Icarus*, *169*, 324–340, doi:10.1016/j.icarus.2003.10.022.

Osterloo, M. M., V. E. Hamilton, J. L. Bandfield, T. D. Glotch, A. M. Baldridge, P. R. Christensen, L. L. Tornabene, and F. S. Anderson (2008), Chloride-bearing materials in the southern highlands of Mars, *Science*, *319*, 1651–1654, doi:10.1126/science.1150690.

Rennó, N. O., et al. (2009), Possible physical and thermodynamical evidence for liquid water at the Phoenix landing site, *J. Geophys. Res.*, *114*, E00E03, doi:10.1029/2009JE003362. [Printed *115*(E1), 2010.]

Rivera-Valentin, E. G., D. G. Blackburn, and R. Ulrich (2011), Revisiting the thermal inertia of Iapetus: Clues to the thickness of the dark material, *Icarus*, *216*, 347–358, doi:10.1016/j.icarus.2011.09.006.

Sears, D. W. G., and J. D. Chittenden (2005), On laboratory simulation and the temperature dependence of the evaporation rate of brine on Mars, *Geophys. Res. Lett.*, *32*, L23203, doi:10.1029/2005GL024154.

Smith, M. D. (2002), The annual cycle of water vapor on Mars as observed by the Thermal Emission Spectrometer, *J. Geophys. Res.*, *107*(E11), 5115, doi:10.1029/2001JE001522.

Squyres, S. W., et al. (2004), In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars, *Science*, *306*, 1709–1714, doi:10.1126/science.1104559.

Ulrich, R. (2009), Modeling diffusion advection in the mass transfer of water vapor through Martian regolith, *Icarus*, *201*, 127–134, doi:10.1016/j.icarus.2008.12.035.

Ulrich, R., T. Kral, V. Chevrier, R. Pilgrim, and L. A. Roe (2010), Dynamic temperature fields under the Mars landing sites and implications for supporting microbial life, *Astrobiology*, *10*(6), 643–650, doi:10.1089/ast.2010.0472.

Wang, A., et al. (2006), Sulfate deposition in subsurface regolith in Gusev crater, Mars, *J. Geophys. Res.*, *111*, E02S17, doi:10.1029/2005JE002513.

Zent, A. P., M. H. Hecht, D. R. Cobos, S. E. Wood, T. L. Hudson, S. M. Milkovich, L. P. DeFlores, and M. T. Mellon (2010), Initial results from the thermal and electrical conductivity probe (TECP) on Phoenix, *J. Geophys. Res.*, *115*, E00E14, doi:10.1029/2009JE003420.