

Key Points:

- We use a novel evaporation rate parameterization method with the MarsWRF model
- Our results show the importance of wind speed variations on the evaporation rate variations
- We report strong seasonal variations up to a factor of 3 in the evaporation rate of liquid water

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Strong Seasonal and Regional Variations in the Evaporation Rate of Liquid Water on Mars

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Abstract We have investigated the seasonal and regional variations in the evaporation rate of both pure liquid water and liquid brine solutions on the surface of Mars. Our evaporation rate estimates are performed using a novel parameterization method taking into account the effects of concentration difference, between the evaporating liquid water solution and the atmosphere, in addition to the effects of near-surface winds. The method is based on atmospheric surface-layer calculations obtained from a global circulation model. We show that near-surface winds strongly enhance strong seasonal variability in the evaporation rate of liquid solutions on Mars. The evaporation rate of a liquid brine solution can vary seasonally up to a factor of 3 and changes by two orders of magnitude depending on the surface elevation and properties of the terrain.

Plain Language Summary The search for liquid water on modern-day Mars is one of the main drivers of exploration efforts because of its implications for habitability and value as an in-situ resource. Recent investigations have shown the plausible surface meteorological conditions for the existence of transient pure and saline water (brine) on the surface of Mars. The possibility of transient pure and briny water on the surface of Mars was suggested based on visual and spectroscopical evidence. A transient liquid water solution, pure or saline, can only exist on the surface of Mars, when the surface temperature and pressure permit its stability against boiling and freezing. The time duration that a liquid water solution can stay on the Martian surface depends on its evaporation rate. Here, we investigated the seasonal and regional variations in the evaporation rate of liquid water. We find that the residence time can vary up to a factor of 3 throughout a full Mars year with a higher geographical dependency that can cause the evaporation rate to vary by two orders of magnitude.

1. Introduction

Mars is a hyper-arid cold desert, where the surface temperature is mostly below the triple point of liquid water and atmospheric pressure is not high enough to sustain permanent liquid water on its surface. The surface meteorology of Mars exhibits strong diurnal variations, with temperature swings of up to 80 K from daytime to nighttime (Martínez et al., 2017; Schofield et al., 1997; Spanovich et al., 2006), due to its lower surface thermal inertia and thinner atmosphere with respect to the Earth (Mellon et al., 2000; Putzig & Mellon, 2007; Putzig et al., 2005). During daytime, surface temperatures can exceed the freezing point of water from mid to equatorial latitudes (McEwen et al., 2014; Pla-García et al., 2020; Savijärvi et al., 2004). Studies focused both on the surface meteorological conditions of present (Chevrier et al., 2020; Haberle et al., 2001; Pál & Kereszturi, 2017; Rivera-Valentín et al., 2020) and early Mars (Fukushi et al., 2019; Richardson & Mischna, 2005) show the possibility of transient liquid water on the surface of Mars. Different geological features have been suggested to be the result of past surface water flows (Borg & Drake, 2005; Gaidos, 2001; Head et al., 2008; McEwen et al., 2007; Schon et al., 2009) and present-day surface features hypothesized to be related to the existence of liquid water (Chevrier & Rivera-Valentín, 2012; Dundas et al., 2017; Martínez & Renno, 2013). The presence of salts decreases the melting point, allowing saline liquid water, or brine, to be stable under wider temperature and pressure conditions compared to pure water. Perchlorate salts, which have been detected both in polar and equatorial regions (Glavin et al., 2013; Hecht et al., 2009), can melt water ice and form brine near temperatures above their eutectic points, which can be as low as 199 K for pure salts found on Mars.

More recent studies on the stability of liquid water and brine have investigated their evaporation rate as a function of temperature and water activity, which vary with the composition of liquid brine solutions (Altheide et al., 2009; Hanley et al., 2012; Sears & Moore, 2005; Toner et al., 2014, 2015; Chevrier & Altheide, 2008). Two mechanisms were suggested for the formation of liquid brine. The first one is melting of water ice when the temperature exceeds the eutectic temperature of the brine (Brass, 1980; Clark & Van Hart, 1981; Fairén et al., 2009; Fischer et al., 2014). Nevertheless, a surface temperature higher than the melting point is a sufficient condition for liquid water, pure or saline, to exist. In order for liquid water to be stable against boiling, the surface pressure must also be higher than the saturation vapor pressure at the surface temperature. The second mechanism is the absorption of atmospheric water vapor by salts (i.e., deliquescence), when the surface temperature is above the eutectic temperature and relative humidity is higher than a threshold value (Clark, 1978; Davila et al., 2010; Gough et al., 2011; Nikolakakos & White-way, 2015, 2018; Nuding et al., 2015; Primm et al., 2020; Rennó et al., 2009; Toner & Catling, 2018). In addition to lowering the freezing/melting temperature of liquid solutions, the presence of salts also lowers the saturation vapor as a result of decreasing water activity. The effect of water activity manifests itself through changing the saturation vapor pressure, linearly. For a surface temperature of 273 K, the saturation vapor pressure is 610 Pa. For a liquid brine solution with a water activity coefficient, a_w , of 0.5, the saturation vapor pressure is 305 Pa (Akridge, 2008).

The possibility of transient liquid water on the surface of Mars can only be assessed if the surface temperature and pressure are known. The previous and currently operating landers and rovers (Banfield et al., 2020; Fischer et al., 2019; Guzewich et al., 2019; Hess et al., 1977; Martínez et al., 2017) provided information on the diurnal and seasonal evolution of surface meteorological conditions. However, a limited number of surface observations is insufficient to evaluate the liquid water potential of Mars on a global scale. Locations at the same latitude and similar elevations, having a similar seasonal radiative forcing, can have different diurnal temperature and pressure variations as a result of different surface properties, such as surface albedo, thermal inertia, and topographical differences. Remote sensing observations, such as from the Thermal Emission Spectrometer (TES) on the Mars Global Surveyor spacecraft (Christensen et al., 2001), are able to provide global daytime and nighttime surface temperature maps of Mars, but cannot provide the diurnal evolution of surface temperature, only daytime and nighttime temperatures at a specific local time. Therefore, atmospheric models, mostly global circulation models (GCMs), are also applied to investigate the transient liquid water potential of Mars (Chevrier et al., 2020; Haberle et al., 2001; Pál & Kereszturi, 2017; Richardson & Mischna, 2005; Rivera-Valentín et al., 2020).

One of the first GCM studies on the possibility of liquid water on Mars was performed by Haberle et al. (2001), showing that pure liquid water can only exist in equatorial regions; but when brine is considered, the regions, where the surface meteorological conditions permit the existence of transient liquid brine solutions, can cover the entire surface of Mars. Moreover, Richardson and Mischna (2005) investigated the effect of obliquity and surface pressure on the long-term liquid potential of Mars. Later, a GCM study was devoted to highlighting the time periods for observing possible transient liquid water activity at the landing site of the ExoMars rover (Pál & Kereszturi, 2017). Recently, Rivera-Valentín et al. (2020) provided estimates for the locations and properties of liquid brine solutions formed through deliquescence on present-day Mars using experimental constraints and GCM simulations. Following up this study, Chevrier et al. (2020) investigated the stability of liquid brine solutions, both on the surface and in the subsurface, providing evaporation rate estimates for an average Mars year using a GCM model.

The previous studies addressing the evaporation rate of liquid water on Mars, both experimentally and theoretically (Altheide et al., 2009; Chevrier & Altheide, 2008; Chevrier et al., 2009; Hanley et al., 2012; Hecht, 2002; Ingersoll, 1970; Sears & Moore, 2005), were carried out under idealized conditions without considering the effect of near-surface winds, atmospheric stability, and dust. It was suggested that the effect of wind on the phase change of water on Mars is negligible under a relative humidity larger than (30–35)%, but has an important effect for lower relative humidity conditions (Chittenden et al., 2008). In-situ observations on Mars show that with increasing surface temperature, the relative humidity becomes lower than 1% during daytime, when the surface temperature is most favorable for the existence of transient liquid water (Fischer et al., 2019; Savijärvi et al., 2015). For the sublimation of water ice under low relative humidity conditions, a linear relationship between sublimation rate and wind speed has been suggested, indicating

an increased sublimation rate of up to 40% for a mean wind speed of 10 m/s, compared to the case without any wind (Chittenden et al., 2008).

In this study, we focus on the seasonal variations in the evaporation rate of pure water and liquid brine solutions, affected by the near-surface winds, which are driven by the Martian dust cycle. We follow a similar approach to Chevrier et al. (2020), using the MarsWRF model (Richardson et al., 2007; Temel et al., 2021; Toigo et al., 2012). In order to represent the contribution of the Martian dust cycle to seasonal variations, we force GCM simulations with the observed atmospheric dust contents (Montabone et al., 2015). Additionally, we use a novel evaporation rate parameterization method (see Section 2), which includes the effects of atmospheric stability, near-surface density gradients, and near-surface winds in evaporation rates. Furthermore, we compare our estimates, based on this present method, with those obtained by Chevrier et al. (2020) using a variant of the parameterization presented by Ingersoll (1970). Finally, we assess both models' capability to represent seasonal variations in the evaporation rate of liquid water solutions on Mars (see Section 4). Our new evaporation model improves the model used by Chevrier et al. (2020).

We investigate the variations in the evaporation rate for pure liquid and saline water solutions on the surface for the regions, where and the time periods, when the surface pressure and temperature permit stability against boiling and freezing. These conditions are the bare minimum for a liquid solution to be present on the surface of Mars. In the case of brine formation through melting water ice, surface frost of a near sub-surface water ice reservoir must be present (Byrne et al., 2009; Carrozzo et al., 2009; Khuller et al., 2021; Mellon et al., 2004; Schorghofer & Aharonson, 2005). Also as noted, the relative humidity is a determining factor for the case of deliquescence. For both cases, these additional conditions can only be met for specific regions and seasonal conditions. These will, however, not be studied in this study, since our aim is to show the effects of seasonal and topography driven changes in the wind speed on the evaporation rate of liquid water solutions. We investigate the evaporation rate variations of liquid water solutions regardless of its formation mechanism for regions and time periods, where and when the surface conditions permit its transient stability.

The paper is organized as follows: We present our evaporation rate parameterization method in Section 2. This parameterization method is coupled with the outputs of GCM simulations as described in Section 3. In Section 4, we discuss the variability in the evaporation rates of liquid water, both pure and saline. Finally, we present our conclusions in Section 5.

2. Parameterization of the Evaporation Rate

When the surface meteorological conditions permit the presence of liquid water, and liquid water is available, evaporation starts to occur. The rate of evaporation is driven by two main related mechanisms. The first mechanism is diffusion driven by the vapor concentration difference between the brine and the atmosphere. The second mechanism is convection forced by the near-surface winds. As its speed increases, the wind carries more evaporated water vapor into the atmosphere so that the evaporation rate also increases. Both processes are affected by seasonal, geographical, and diurnal variations in the turbulent atmospheric surface layer (Jiménez et al., 2012), such as different turbulent regimes, and thus atmospheric stability conditions. After sunrise, convection starts to increase, with the increasing turbulent kinetic energy reaching its highest values around noon (Martínez et al., 2011; Spiga et al., 2010). In addition to diurnal variations, the Martian dust cycle plays an important role in the surface energy balance (Savijärvi et al., 2020). The presence of dust in the Martian atmosphere reduces daytime temperatures of the lower atmosphere and surface (Guzewich et al., 2019; Smith, 2004), and has significant effects on near-surface winds (Haberle, 1986). Furthermore, a lower surface temperature results in a lower saturation specific humidity, leading to a lower rate of evaporation. These effects will manifest themselves in surface layer fluxes of momentum, heat and volatile exchange between surface and the first layer of the atmosphere.

Atmospheric models use empirical relationships to determine the surface-atmosphere exchange of momentum, heat, or atmospheric volatiles (Garratt & Pielke, 1989; Kurgansky et al., 2011; Nickovic et al., 2001; Sharan & Piyush, 2016). The parameterization method that we adopt here to estimate the evaporation rate of liquid water on Mars for the first time, is based on Monin-Obukhov similarity theory (Katul & Parlange, 1992). The evaporation rate, E , is given by:

$$E = C_d^{0.5} u_* \rho (q^* - q_a) \quad (1)$$

where, C_d , the surface-atmosphere bulk transfer coefficient is defined as follows:

$$C_d = \left(\frac{\kappa}{\ln \left[\frac{z}{z_0} \right] - \psi_v \left[\frac{z}{L} \right]} \right)^2 \quad (2)$$

Despite that this term is not called as a “diffusion coefficient,” it has the same purpose of a diffusion coefficient modulating the amount of total transport. In Equations 1 and 2, κ is the von Kármán constant, taken as 0.4, u_* is the friction velocity, a reference wind velocity representing surface stress and used as a measure of near-surface winds (Foken, 2006), ρ is the atmospheric density, q_a is the near-surface atmospheric specific humidity, q^* is the saturation-specific humidity, z_0 is the aerodynamic roughness length, employed as a measure of surface terrain roughness, L is the Monin-Obukhov length, representing the atmospheric stability, and ψ_v is the stability correction term for surface flux formulation (see Katul & Parlange, 1992 and Martínez et al., 2009 for the calculation of these terms.). q_a , the ratio of the mass of water vapor to the total mass of the air parcel, is computed using the water vapor mixing ratio predicted by GCM simulations. The Monin-Obukhov length, which represents the relative roles of shear production and buoyancy production/destruction of turbulence, refers to the diurnally varying near-surface atmospheric stability, becoming negative during daytime (convective) conditions and positive during nighttime (stably stratified) conditions (Martínez et al., 2009, see their Section 3a for its detailed definition). Determination of the Monin-Obukhov length requires the knowledge of the surface temperature, near-surface temperature gradient, and near-surface winds, which are acquired by GCM simulations and used to calculate the Monin-Obukhov length, surface fluxes, and friction velocity as in (Martínez et al., 2009). To do that, we use the predicted wind speed at the first model layer of our GCM model (located at ~20 m) and interpolate it to lander altitude, 1.5 m, similar to (Newman et al., 2017). It must be noted that the Monin-Obukhov similarity theory is based on the theoretical formulation of the vertical fluxes of momentum, heat in the surface-layer. The turbulent fluxes and wind stress vary less than 10% within the surface layer (Stull, 1988). In other words, despite the wind speed will change if z is taken as another altitude, the resulting $u_* / C_d^{0.5}$ will be the same. Therefore, as long as the first model layer is located within the surface-layer, the choice of z will not affect our conclusions based on our evaporation rate estimates. The thickness of the surface layer can be approximated as $0.1 h$, where h is the height of the boundary layer (Petrosyan et al., 2011). The observational studies showed that the Martian boundary layer thickness can vary between 3 and 10 km (Hinson et al., 2008). Thus, our first model layer is sufficiently located deep in the surface layer for daytime conditions. Extensive observational and modeling studies are lacking for the nighttime Martian boundary layer. However, terrestrial studies showed that a shallow boundary layer, as thin as 50–100 m, can form under nighttime conditions with strong surface cooling when the surface temperature is coldest during the diurnal cycle (Chu et al., 2019; Liu & Liang, 2010). While this is probably the case for the nighttime Martian boundary layer. Such a shallow boundary layer will only form under very low nighttime surface temperatures and the liquid water solution will not be stable against freezing. For the stability correction term, we use the formulation as given in (Katul & Parlange, 1992, see their Equations 5–9). We note, though, that ψ_v has not been fully validated on Mars due to the lack of high-frequency (>1 Hz), simultaneous measurements of temperature, and wind speed at different heights. Nonetheless, Monin-Obukhov theory has been applied to Mars with reasonable success using in situ measurements and modeling (Davy et al., 2010; Martínez et al., 2009; Newman et al., 2019; Sutton et al., 1978; Tillman et al., 1994). Equation 1 includes both the effect of forced convection by winds and convection by density gradients, through u_* and $(q^* - q_a)$, respectively. Observational studies of the atmospheric surface-layer of Mars have shown that u_* varies diurnally, ranging from 0.5 m/s after the local noon to 0.05 m/s around sunrise and sunset (Martínez et al., 2009). The effect of temperature on the evaporation rate manifests itself through the saturation vapor pressure, and thus saturation specific humidity. The saturation specific humidity is computed as:

$$q^* = \frac{M_w p_{sat}}{M_a p_{surf}} \quad (3)$$

where M_w is the molecular weight for water and M_a for the atmosphere, which are 18.01 g/mol and 43.49 g/mol, respectively. P_{sat} and P_{surf} are the saturation vapor pressure and surface pressure. For P_{sat} , we use the Goff-Gratch equation (Smithsonian meteorological tables, 1984). In order to include the linearly lowering effect of water activity on the saturation-specific humidity (Akridge, 2008), we modify the saturation-specific humidity term as $a_w q^*$, where a_w is the water activity coefficient.

We incorporate Equations 1 and 2 into the MarsWRF model to estimate seasonal and regional variations in the evaporation rate, with the aim of searching the most plausible regions and seasons for the presence of liquid water. To validate this approach, we first compare our parameterization with the evaporation rate predictions obtained by experimental estimates for a wide range of surface pressures and for different temperature and water activity coefficients (Chevrier & Altheide, 2008). We perform the comparison based on the fact that despite the laboratory conditions and the simulation conditions, we acquire through GCM simulations, might differ, they should represent an average daytime behavior of near-surface conditions on Mars as the experimental conditions are designed using the similarity analysis by dimensional numbers (as in Hecht, 2002). So that, our chosen friction velocity and other parameters, corresponding to daytime conditions as observed by landers (Martínez et al., 2009), must be compatible with the experimental conditions. We use typical values of the Martian surface layer: $u_* = 0.55$ m/s, $z_0 = 0.02$ m, and $L = -5$ m (Charalambous et al., 2021; Martínez et al., 2009; Tillman et al., 1994). Atmospheric density is set to 0.02 kg/m³ and the specific humidity is 0.0001 kg/kg (Fischer et al., 2019; Martínez et al., 2017). The experimental results, focusing on the effect of pressure, were obtained in a pressure chamber, filled with nitrogen gas at room temperature and Mars-analog pressure conditions (Hecht, 2002). The evaporation rate was measured using a hygrometer and experimental results were scaled for Mars conditions. For both experimental results, we also include the evaporation rate estimates by a theoretical method (Ingersoll, 1970) that uses an empirical formulation as a function of a dimensionless number:

$$E = 0.17 \frac{D \Delta q}{x} Gr^{\frac{1}{3}} \quad (4)$$

Here, $Gr = \chi^3 \left[\frac{g \left(\frac{\Delta \rho}{\rho} \right)}{\nu^2} \right]$ is the Grashof number, where D is the mass diffusivity of water, $\Delta \rho$ is the density

difference between the surface and atmosphere, ν is the kinematic viscosity, and χ is the characteristic length scale. The Grashof number has been extensively used for free convection applications over a vertical wall or a heated sphere, and the diameter or length of the heated surface is usually taken as the characteristic length scale (Potter & Riley, 1980). We note that this method does not include the effect of convection driven by winds directly.

Our estimates for the evaporation rate show good agreement with the experimental results (see Figure 1). The good match between our estimates and experimental data proves that our methodology can be used to provide evaporation rate estimates using the outputs of GCM simulations.

3. GCM Simulations

3.1. Model Settings and the Dust Forcing Scenario

The MarsWRF model, using similar setups as we do, has also been widely validated against remote-sensing and in-situ observations (Guo et al., 2009; Newman & Richardson, 2015; Temel et al., 2021; Toigo et al., 2012). The model is run using a resolution of 5° in both longitude and latitude, with 52 vertical model levels, allowing us to resolve the boundary layer with a high resolution. A radiatively active water cycle (transported water vapor and water ice with a fixed particle radius) is included. Water vapor mixing ratio at the first model layer is used to calculate surface-specific humidity. Atmospheric radiative heating rates are calculated using a single scattering, two stream, Mars-specific, k-distribution radiation scheme (Mischna et al., 2012). Atmospheric dust content is specified using the average of derived optical dust thicknesses of Mars years (MY) without a global dust storm event between MY 24 and MY 33 (Montabone et al., 2015). The vertical distribution of dust is based on a variant of the classical Conrath profile as in Heavens et al. (2011). Turbulent mixing in the planetary boundary layer (PBL) is parameterized using a Mars-specific turbulence

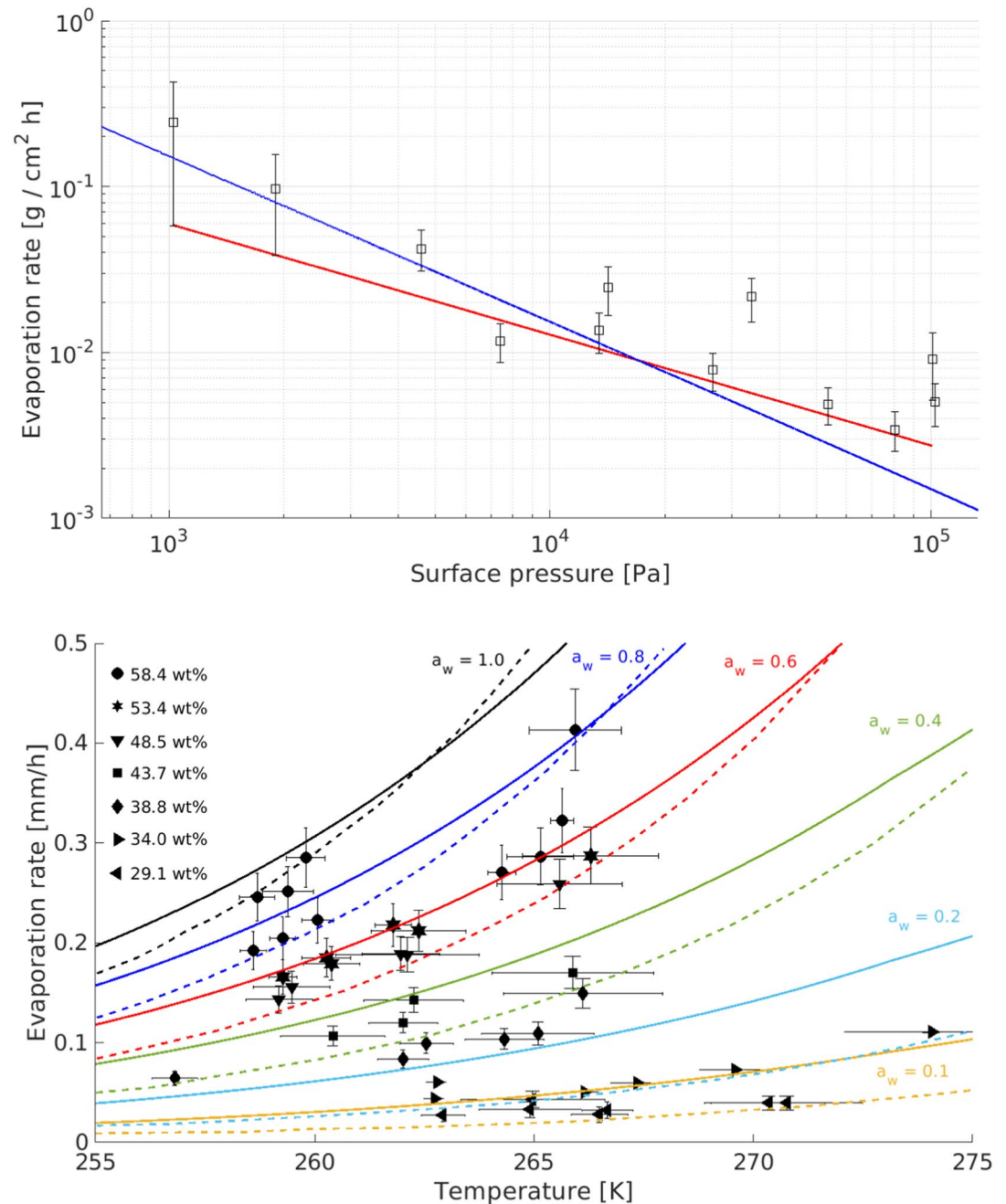


Figure 1. Top panel: Comparison of the present method (Equation 1) to estimate the evaporation rate of liquid water (blue) with another theoretical method (Ingersoll, 1970) (red) and with experimental results of Hecht (2002) (black). Experimental results and theoretical estimates are digitized from Figures 2 and 7 of Hecht (2002). Bottom panel: Comparison of the present method (solid lines) with experimental results of Chevrier and Altheide (2008) for various liquid brine solutions with different salt concentration (black) along with the theoretical estimations obtained by Chevrier and Altheide (2008).

closure (Temel et al., 2021). The lower boundary conditions for the vertical transport of state variables are obtained using a surface-layer parameterization scheme (Jiménez et al., 2012). This surface layer scheme is also used to provide the near-surface fluxes being used for the evaporation rate calculations.

Before investigating the seasonal and regional variations in the evaporation rate of liquid water solutions, we first briefly investigate how the friction velocity, which is one of the drivers of the rate of evaporation

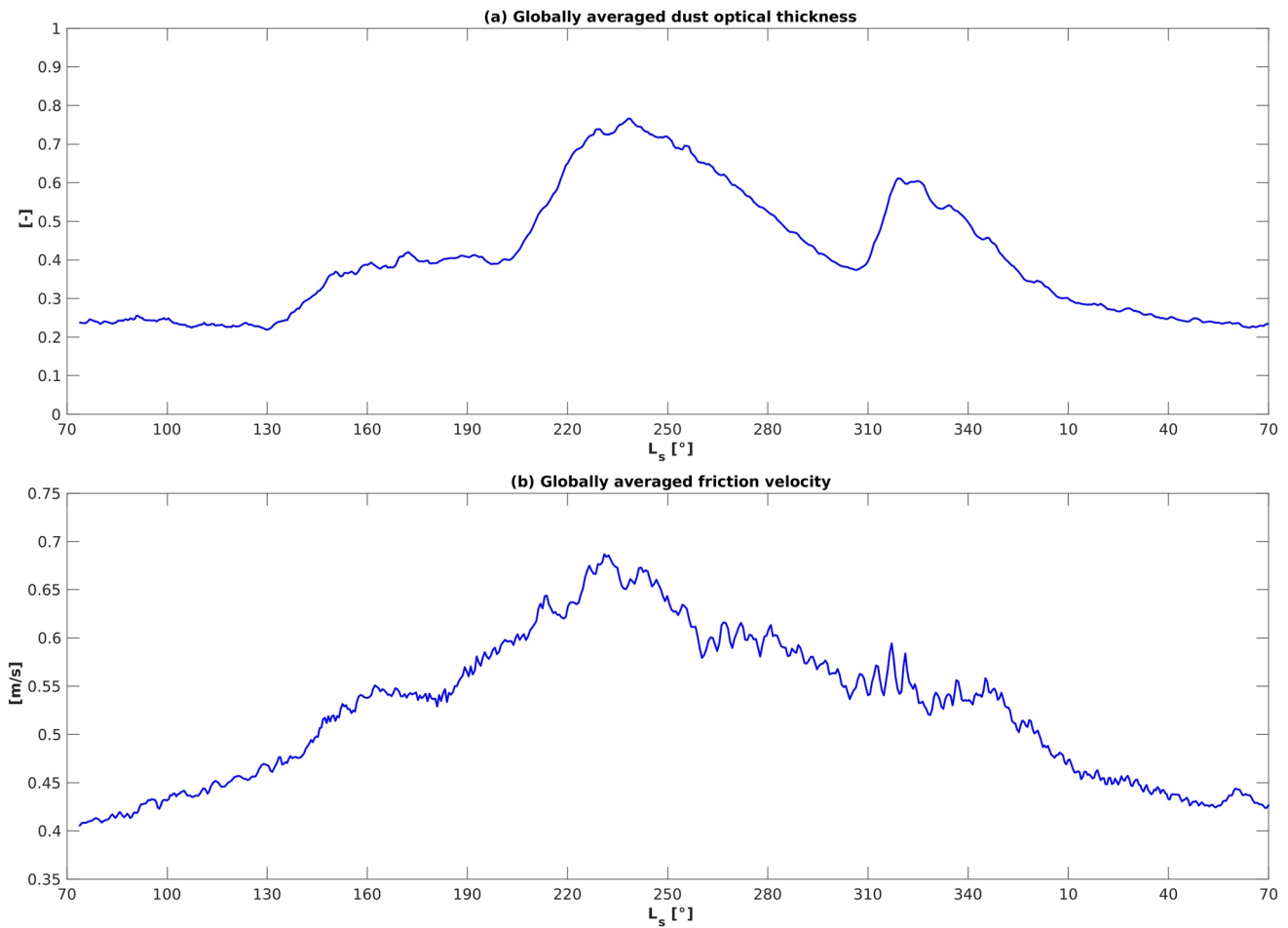


Figure 2. Globally averaged dust optical thickness as forced in our dust climatology scenario (top) and the seasonal evolution of the friction velocity (bottom).

according to Equation 1, varies in a full Mars year with respect to seasonal radiative forcing, boundary-layer meteorology, and dust forcing. The globally and daily averaged column integrated atmospheric dust opacity in our constructed dust forcing based on the observations and the resulting friction velocity, are presented in Figure 2. Figure 2 presents the annual variation of globally and daily averaged column integrated atmospheric dust opacity, as forced in our GCM calculations, and the resulting friction velocity. Despite our dust forcing scenario being obtained by using the average of years without a global dust storm, the atmospheric dust content still increases starting from $L_s = 130^\circ$ reaching its maximum value around $L_s = 230^\circ$. The averaged friction velocity starts to increase after $L_s = 160^\circ$, before the Southern hemisphere spring equinox at $L_s = 180^\circ$. This is mainly a result of the Martian topographic dichotomy, the elevation difference between the Northern and Southern Hemispheres. Both observational and numerical studies showed that lower daytime surface pressures lead to higher levels of turbulent mixing and PBL height (Spiga et al., 2010). Studies of the terrestrial PBL, which shares significant similarities with its Martian counterpart (Petrosyan et al., 2011), show the positive correlation between the PBL height and friction velocity (Gryning et al., 2007). After the Northern hemisphere autumn equinox at $L_s = 180^\circ$, surface temperatures at the Southern hemisphere start to increase and thanks to the lower surface pressure compared to the Northern hemisphere, the globally and daily averaged friction velocity becomes higher after $L_s = 180^\circ$ compared to the rest of the year. The other possible mechanism is related to the mixing of dust in the Martian atmosphere. The abundance of dust decreases the daytime surface temperature. However, the dust is not spread uniformly in the atmosphere, leading to strong thermal gradients on the surface. It might be possible that thermal gradients created by the heterogeneous distribution of dust after the onset of enhanced dust activity season, after $L_s = 130^\circ$, invoke higher near-surface winds globally. Such a possibility is consistent with the studies, which investigated the

seasonal variations of the dust lifting rate, a function of the friction velocity, and found that lifting rates increase after $L_s = 160^\circ$ (Haberle et al., 2003).

3.2. The Possibility of Liquid Water on the Martian Surface

In order to define where and when the liquid brine or pure water can be stable regardless of its source, we check the following conditions: (a) If the temperature is lower than the eutectic temperature of the brine solution, then the liquid solution will freeze. (b) Even if the surface temperature is higher than the eutectic temperature, the surface pressure must not be lower than the saturation vapor pressure. Otherwise, the liquid brine solution will not be stable against boiling. We use the hourly output of MarsWRF and calculate the total integrated amount of time, that liquid water can temporarily remain on the surface, through one full Mars year. We use a set of six eutectic temperatures and corresponding water activity coefficient, based on a temperature-water activity curve obtained by Chevrier et al. (2020) for various Mars-relevant salts (including sulfates, chlorides, perchlorates, and chlorates) (see their Figure 1): $(a_w, T_e) = (1.0, 273.15 \text{ K}; 0.9, 261.3 \text{ K}; 0.8, 249.4 \text{ K}; 0.7, 236 \text{ K}; 0.6, 217 \text{ K}; \text{ and } 0.5, 186 \text{ K})$.

Before investigating the seasonal variations in the evaporation rate of liquid solutions on Mars, we first calculate the total integrated amount of time, when the surface meteorological conditions may permit the existence of transient liquid water, both pure and saline. Figure 3 shows the total integrated amount of time over a Mars year and the corresponding regions for pure water ($a_w = 1.0$) and liquid brine solutions (from $a_w = 0.9$ to $a_w = 0.5$). The highest possible occurrence of liquid water is linked with low surface thermal inertia terrains, where the highest daytime temperatures occur (see the east of Amazonis Planitia and Arabia Terra in Figure 3a). Another region with a high potential for liquid water formation is Hellas Basin as a result of the higher surface pressures due to its low elevation. Since liquid brines can form under a much lower surface temperature, they can be present over a wider range of regions and for a much longer total integrated amount of time, spanning between 90 and 600 sols over one Mars year for the cases of the highest and the lowest considered water activity as in Figures 3b–3f. The estimated regions, and the integrated amount of time, where and when the transient pure liquid water can be stable on the surface of Mars, correspond to the same quadrangles in Richardson and Mischna (2005). Similar to the finding of Haberle et al. (2001), a liquid brine solution can be temporarily stable over the whole planet. It must be stated that a very high possible occurrence of liquid brine solutions, such as up to 600 sols over a full Mars year, does not mean that a liquid brine solution can remain on the Martian surface for such a long time. Despite the surface meteorological conditions allowing the existence of a temporarily stable liquid brine throughout the diurnal cycle, a liquid brine solution will freeze as soon as the surface temperature drops below its eutectic temperature or will boil when the surface pressure is not large enough to be stable against boiling.

4. Evaporation Rate Estimates

For the regions shown in Figure 3, we calculate annually averaged evaporation rates for pure water and brine solutions using Equation 1. As shown in Figure 4, the highest evaporation rates occur in the east of Amazonis Planitia, at 3.5, 1.0, and 0.5 mm/h for liquid brine with water activity of 1.0 (pure water), 0.7, and 0.5, respectively. With such an evaporation rate, a pure water spheroid of 1 cm in diameter, similar in scale to the purported briny spheroid observed on the robotic arm of the Phoenix lander (Rennó et al., 2009), would be fully evaporated in approximately 30 min. For a liquid brine solution with a water activity of 0.7, we obtained a residence time of 100 min. The evaporation rates calculated using Equation 1 is in $\text{kg}/(\text{m}^2 \text{ s})$. The residence time is computed by using the spherical area of a water droplet of 1 cm and its mass. Obviously, the residence time of a liquid brine on the Martian surface depends on the choice of the reference size. Chevrier et al. (2020) showed that a liquid brine layer of 10 μm with a water activity coefficient greater than 0.6 can only remain on the surface for a few minutes per sol. Consistently, we find that with an evaporation rate of 0.4 mm/h, which is the globally averaged rate for $a_w = 0.7$, such a liquid brine layer will be fully evaporated in 1.5 min. Hereafter, we define our residence time estimates using a droplet of 1 cm in diameter. Other regions with high evaporation rates are Arabia Terra, Hellas basin, and Elysium Planitia, more precisely to the west of Elysium Mons. The reason why we find higher evaporation rates for these

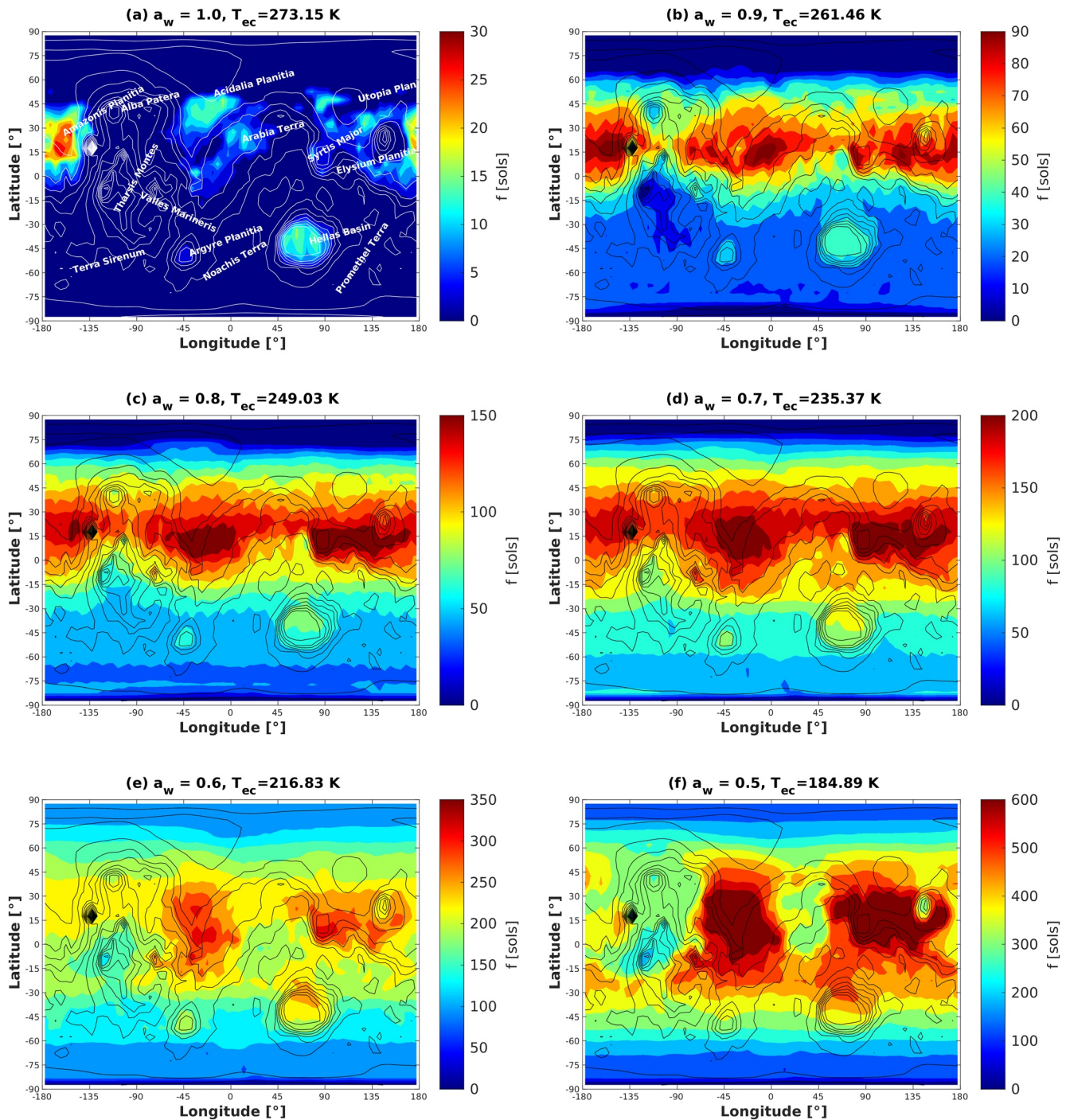


Figure 3. The total integrated length of possible residence time during a Mars year (sols) and location where surface meteorological conditions permit pure liquid water ($a_w = 1.0$ — panel (a)) and brine (with water activities from $a_w = 0.9$ to $a_w = 0.5$ (panels b–f) and eutectic temperatures as suggested by Chevrier et al., 2020).

regions is related to their topography and surface properties. For the Hellas basin region, strong downslope winds on its southern slope, leading to a strong meridional transport, have been reported (Ogohara & Sato-mura, 2008). It is also suggested that strong surface thermal inertia variations in the Amazonis Planitia region, similar to the Arabia Terra region, can result in strong near-surface winds (Fenton & Michaels, 2011). Moreover, the near-surface meteorology of the Amazonis Planitia region may be affected by the presence of

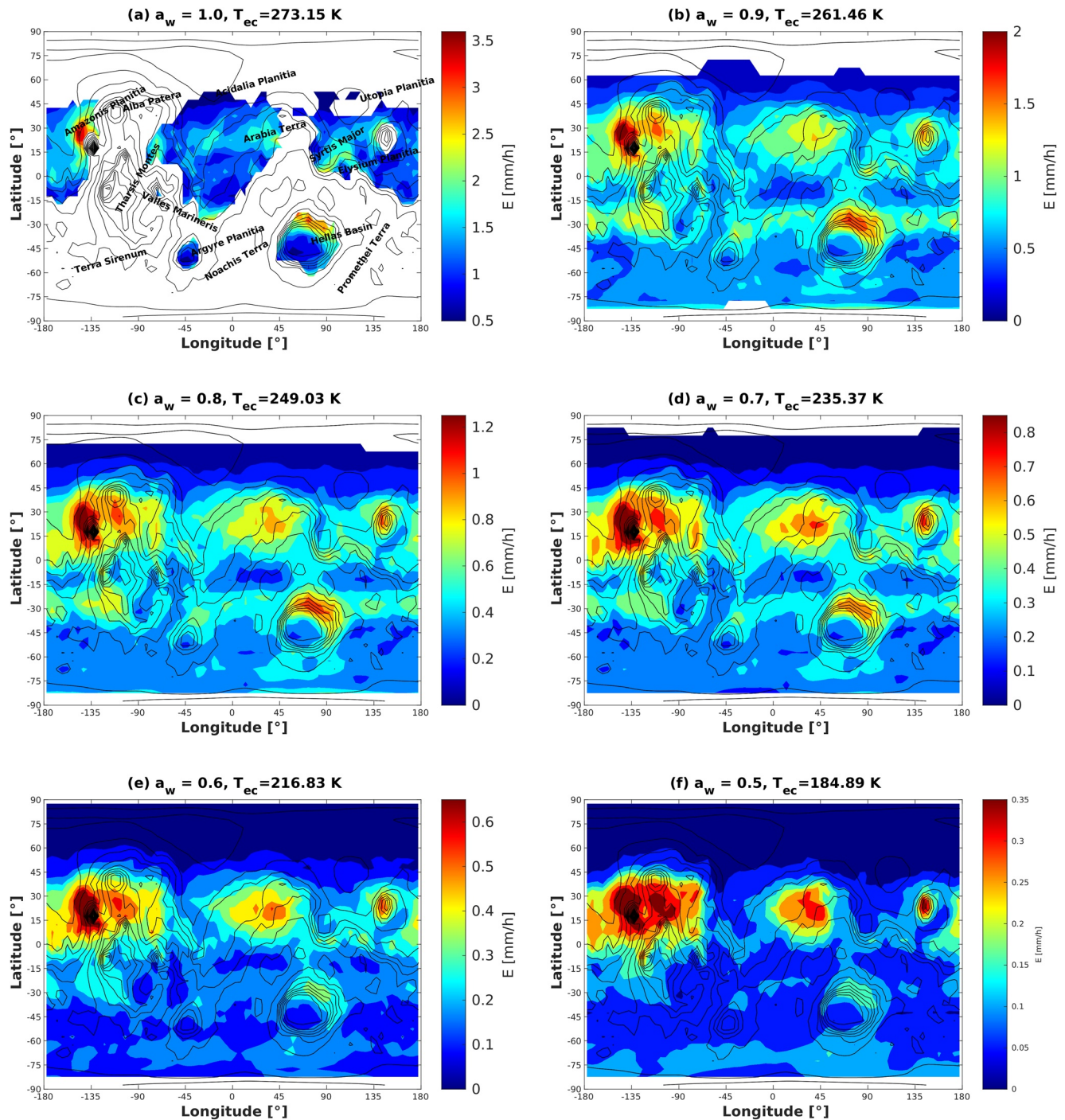


Figure 4. Annually averaged evaporation rate for pure liquid water (panel a) and liquid brine (panels b–f) with different water activity and eutectic temperatures (mm/h).

Tharsis Montes, with downslope winds generated by the elevation difference between mountainous highlands and flat lowlands. A similar surface meteorology is present for the Elysium Planitia region, resulting in high near-surface wind speeds and evaporation rates.

In terms of the effect of water activity, and thus the eutectic temperature, on the evaporation rate of liquid brine solutions, we find that a liquid brine solution can be stable for a much longer time period, as long as 3 h, even with the highest evaporation rate (for the case of water activity of 0.5). With the minimum

evaporation rates occurring in the poleward of the Northern midlatitudes, this residence time can be even longer than a whole diurnal cycle. However, it does not mean that a liquid brine solution can remain on the surface for such a long time, because even the globally averaged nighttime temperatures can fall below 170 K, lower than the considered eutectic temperature (Smith, 2004). Hence, the evaporation rate does not play an important role on the stability of liquid brine solutions with low water activity coefficients as suggested by (Chevrier et al., 2020). As illustrated in Figure 4, the evaporation rates start to fall in the northern midlatitudes and reach their minimum values, down to below 0.1 mm/h, in the northern polar region. This is a result of the elevation decreasing in the poleward direction, leading to a higher surface pressure, combined with the lower surface temperatures. As given in Equation 2, the saturation-specific humidity decreases with increasing pressure. In addition to the effect of decreasing temperature in the poleward direction, higher surface pressure leads to evaporation rates as low as 0.05 mm/h. With such a low evaporation rate, a briny spheroid of 1 cm can remain on the surface of Mars up to 6–7 sols as long as the surface meteorological conditions permit stability against freezing or boiling, which is not likely to happen as a result of either very low nighttime temperatures or daytime surface pressures in the northern high latitudes. The lowest evaporation rates in the Southern hemisphere correspond, similarly, to regions poleward of 60° S. Because of the higher elevation of the southern polar region compared to the northern polar region, the evaporation rates are higher in this region. Moreover, the lower surface pressure indicates that liquid water could exist during more brief periods, reducing the amount of nighttime that can permit its existence on the surface. As noted before, daytime near-surface conditions exhibit higher values of friction velocity and hence, higher values of evaporation rate. This is also another reason why higher values of evaporation rates are observed in the Southern hemisphere.

Figure 5 presents the seasonal evolution of evaporation rate of liquid solutions through one full Mars year using two different parameterizations: Our presently proposed method (Equation 1) and the one used by Chevrier et al. (2020) (see their Equations 1–7). Despite both parameterizations showing the gradual lowering of evaporation rate with lower water activity, evaporation rate estimates by Equation 1 exhibit strong seasonal variations in the case of all water activity coefficients unlike the latter. Evaporation rate estimates for $a_w = 0.6$ and $a_w = 0.5$ show that the highest evaporation rate can be three times higher than the lowest value in a full Mars year. For the case of $a_w = 0.8$ and $a_w = 0.7$, we find inconsistent evaporation rate estimates between our parameterization and the one used by Chevrier et al. (2020). As an example, our evaporation rate estimates by our method vary between 0.4 and 0.7 mm/h for $a_w = 0.8$, whereas the method of Chevrier et al. (2020) provides a seasonally independent diurnally averaged evaporation rate of approximately 0.85 mm/h, as calculated by using the meteorological predictions of our recent GCM calculations. It must be noted that this does not exclude the applicability of the method of Chevrier et al. (2020) to predict the extreme diurnal variations in the evaporation rate of liquid solutions. Chevrier et al. (2020) showed several orders of magnitude of difference between maximum and minimum evaporation rates by considering the annually maximum and minimum surface temperatures, including seasonal and also diurnal variations, which are stronger than the seasonal one. Here, we present the diurnally averaged evaporation rates, where the effect of strong diurnal temperature oscillations is excluded. Therefore, the evaporation rate estimates with our method are able to exhibit the seasonal variations caused by friction velocity variations, which is not taken into account by the method of Chevrier et al. (2020). The chosen eutectic temperature for $a_w = 0.8$, for which experimental studies for a chlorate-based brine solution report evaporation rates up to 0.6 mm/h (Hanley et al., 2012). This difference between our parameterization and the one used by Chevrier et al. (2020) can be a result of the chosen diffusion coefficient of water into gaseous CO_2 in the model of Chevrier et al. (2020), which formulates it as a function of temperature (Boynton & Brattain, 1929). Instead, Equation 1 is based on calculating a surface exchange coefficient using surface-layer relationships as a function of κ and z_0 , as in commonly used for modeling surface processes in Mars atmospheric models (see Equation 9 in Forget et al., 1999).

In terms of the results obtained from Equation 1, we observe two time periods when the evaporation rate changes remarkably. These two periods correspond to $L_s = 160^\circ - 220^\circ$ and $L_s = 260^\circ - 320^\circ$. As shown in Figure 2, the friction velocity increases as a result of the heterogeneous dust loading during $L_s = 160^\circ - 220^\circ$. The second time period covers the Southern hemisphere summer solstice ($L_s = 270^\circ$), when the shortwave radiative flux on the surface of the Southern hemisphere is the highest, thus leading to higher temperatures and lower atmospheric surface densities. Recalling that the forced convection term in Equation 1

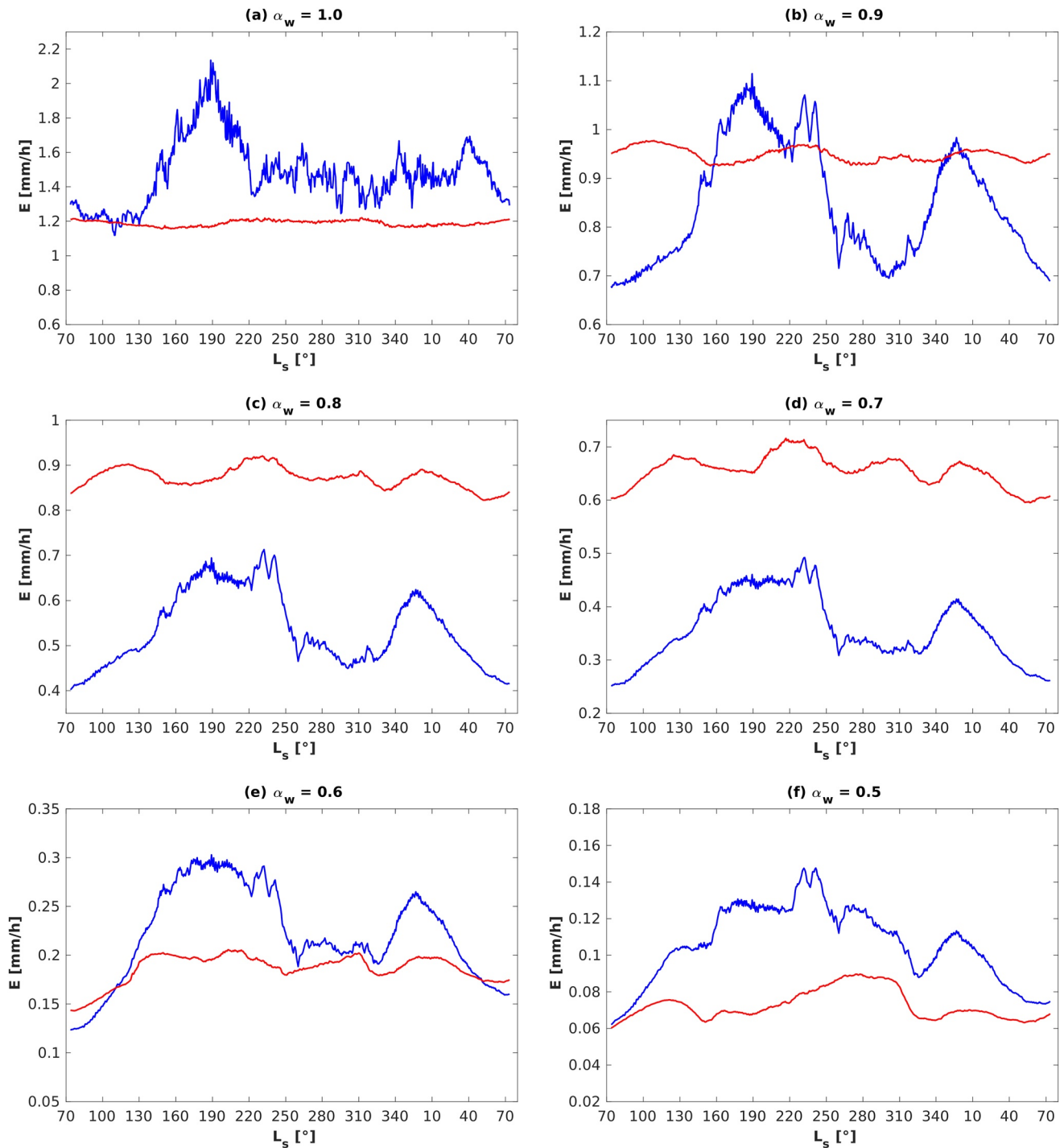


Figure 5. Globally and daily averaged evaporation rates for pure liquid water (panel a) and liquid brine solutions (panels b–f): predictions with Equation 1 (blue) and the method used by Chevrier et al. (2020) (red).

is formulated as ρu_* , it is reasonable to state that the forced convection decreases during this time period, leading to lower evaporation rates.

5. Conclusions

We obtain evaporation rates using the MarsWRF model with a parameterization that includes the effect of seasonally and regionally varying near-surface winds and atmospheric stability. To complement previous recent studies, we have focused both on the seasonal and regional variations in the evaporation rate of pure liquid water and liquid brine solutions. Furthermore, our results show that seasonal variations in the evaporation rate strongly depend on the effects of concentration difference of water vapor and near-surface winds, and therefore need to be considered.

We report strong seasonal variations in the evaporation rate of possible transient liquid brine on the surface of Mars. Our results show that globally averaged evaporation rates of liquid brine can vary by up to a factor of 2 for water activity coefficients higher than 0.6, and a factor of 3 for lower water activity coefficients through a Mars year. As an example, a briny liquid spheroid of 1 cm with a water activity of 0.8 and a eutectic temperature of 249.4 K would be fully evaporated in 140 min around $L_s = 220^\circ$, whereas it would remain on the surface much longer, up to 250 min, around $L_s = 70^\circ$.

We showed that variations in the evaporation rate caused by changes in the topography can be more significant than those caused by seasonal changes in the environmental conditions. Liquid brine solutions with water activity coefficients lower than 0.8 can evaporate at rates as low as 0.01 mm/h in the Northern Hemisphere high-latitudes, indicating that liquid brine solutions can remain on the Martian surface as long as the surface meteorological conditions permit stability against boiling and freezing. It must be noted that this is the case for brine formed through melting water ice. For the case of deliquescence, the absorption of atmospheric water vapor by salt solutions, the residence time will be a function of the efflorescence relative humidity of the solution. Here, we did not investigate the possible residence time of solutions formed by deliquescence specifically. Our lowest evaporation rate estimates correspond to the Northern high-latitudes, where the meteorological conditions can permit the formation of liquid brine solutions through deliquescence due to high atmospheric water vapor content during the Northern summer. Our finding shows that future studies on liquid solutions formed through deliquescence should focus on the diurnal variation of relative humidity to determine their possible residence time on the surface. Nevertheless, for the same water activity, evaporation rates can be two orders of magnitude higher, as high as 1.2 mm/h, in specific regions such as the east of Amazonis Planitia, leading a briny spheroid of 1 cm to be fully evaporated in 80 min.

Finally, our dust forcing is constructed to represent a Mars year without a major global dust storm event, which will increase the effect of seasonal variability. A major global dust storm can intensify the near-surface winds but would also result in lower daytime temperatures, leading to a lower saturation specific humidity. A comprehensive sensitivity analysis of atmospheric dust loading on the evaporation rate of liquid brine solutions on Mars will be the subject of a subsequent paper.

Data Availability Statement

The GCM data used to calculate the evaporation rates are available online (<https://doi.org/10.17605/OSF.IO/P9Z8J>) (Temel, 2021).

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