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Unsteady saltation on Mars

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Saltation is an important process on Mars, as it contributes to dust raising, bedform dynamics, and aeolian abrasion. Lander measurements and mesoscale meteorological models suggest that winds in the Martian atmosphere rarely exceed the fluid threshold value that is necessary to aerodynamically initiate saltation, a fact in stark contrast to the existence of dunes and ripples on the planet, many of which are in an active state of migration. In an attempt to reconcile these observations, we perform an unsteady simulation with a simple turbulence model to calculate the saltation transport rate. Sinusoidal wind variations are imposed on the saltation layer. The numerical simulations verify that gusty transport is one of the main manifestations of Martian sediment transport events. A formula for the saltation transport rate is reported, $Q_m \sim (u_* - u_{*it})^p$, where u_* and u_{*it} are the friction velocity and impact threshold friction velocity. The power p varies in the range of 0.7–1.8 on Mars and ~1.5 on Earth, depending on the period and amplitude of the gusty inflow wind. Our results show that the law of Martian and terrestrial transport rate are not universal, and hence one should be cautious when trying to extrapolate existing terrestrial results to Mars.

1. Introduction

The surface of Mars is broadly characterized by abundant and varying concentrations of sand and dust. Dunes, ripples, and dust deposits are common, with active bedform migration, dust devils, and regional to global dust storms characterizing dynamic processes on the planet (Thomas and Gierasch, 1985; Bourke et al., 2008; Silvestro et al., 2010; Hansen et al., 2011; Chojnacki et al., 2011; Bridges et al., 2012a,b, 2013; Ayoub et al., 2014). It has long been noted that the fluid threshold wind speed required for particle detachment by the wind on Mars is very high (Greeley et al., 1982; Iversen and White, 1982), but wind speeds predicted by Martian atmospheric models and observed by landers seldom exceed the threshold value (Arvidson et al., 1983; Schofield et al., 1997; Fenton et al., 2005; Jerolmack et al., 2006). Saltation on Mars, as that on Earth, is one of the primary modes of aeolian transport and is believed to be responsible, among other factors, for the formation and evolution of aeolian geomorphology and dust entrainment (Greeley, 2002; Merrison et al., 2007). Therefore, knowledge of Martian saltation transport under modest wind speed, or even sub-fluid threshold conditions, is needed to understand aeolian sediment processes on Mars.

On Earth, the intermittency of aeolian transport has been widely observed in field measurements (e.g., Jackson, 1996; Stout and Zobeck, 1997; Davidson-Arnott et al., 2005; Pfeifer and Schönfeldt, 2012). It is found that the variability of sand transport rate in time and space are more than 20% (Jackson et al., 2006) and 100% (Baas and Sherman, 2006; Ellis et al., 2012) respectively, even on a relatively uniform upwind surface. Greatest variability has been found near the transport threshold and smallest variability occurs during the periods of high shear velocities (Baas and Sherman, 2006). Most importantly, sand transport could still be observed within long-time runs even though the fitted values of bed shear stress using conventional laboratory equations for mass transport predicted that there should be no transport (Rasmussen and Sørensen, 1999). By analyzing the observed data, many believe that the quasi-coherent structure in the turbulent wind in atmospheric surface layer is crucial to the intermittent saltation (e.g., Bauer et al., 1998; Baas, 2007; Martin et al., 2013), and the variability should be incorporated into the classical steady transport models. In the wind tunnel, Butterfield (1998) reported an obvious increase of induced transport which was much higher than the measured value in steady wind when imposing sinusoidal

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wind velocity variations with periods of 6–20 s. The results demonstrated the significant effects of unsteady wind on sand transport rate. Subsequently, numerical simulations of Spies et al. (2000) and Wang and Zheng (2014) successfully reproduced unsteady and sub-fluid threshold saltation transport. The simulated results showed that saltation transport rate driven by varying wind speed is larger than that driven by equivalent mean wind speed. The ratio of unsteady to steady transport rate depends on the frequency, amplitude and mean speed of inflow wind variations.

Because of the limitations of *in-situ* wind measurement, studies of Martian saltation have relied heavily on low pressure/density wind tunnel studies and numerical simulations. Greeley and co-workers (Greeley et al., 1976, 1980; Iversen et al., 1976) performed an extensive set of studies of sand/dust transport in a Mars simulation wind tunnel and found that the threshold friction velocity on Mars is much higher at low pressures than that on Earth. By numerical simulation, White et al. (1976) and White (1979) found that saltation trajectories on Mars are much longer than those on Earth. A universal function for mass flux estimation was also proposed. Employing FLUENT (software of computational fluid dynamics), Almeida et al. (2008) simulated two-dimensional saltation transport and proposed general expressions for saltation height, length and flux, respectively, under Earth and Martian atmospheric conditions. As for the puzzle that Martian saltation transport can be sustained at sub-fluid threshold wind speed, they believed that it should owe to the rather low impact threshold speed on Mars according to the simulation results. However, the model they used did not account for particle splash (Kok, 2010). By considering the hypothesis that once saltation is initiated by a localized wind gust, particle entrainment succeeds mainly through particle – soil collisions and saltation can be sustained at a smaller impact threshold u_{it} (Claudin and Andreotti, 2006; Almeida et al., 2008; Kok, 2010), Kok (2010) proposed a model to calculate the substantial probability of saltation transport by summing the probability of wind speed larger than fluid threshold u_{ft} needed to initiate saltation and the probability of $u_{it} < u < u_{ft}$. Subsequently, based on the model of Kok (2010), Huang et al. (2014), simulated the spatial and temporal evolution of wind-blown sand on Mars. They found that both the average saltation length and height are consistent with those calculated by Kok (2010), but substantially smaller than found by Almeida et al. (2008). The universal formulas describing the sand transport rate, average saltation length and height on Mars were also proposed.

Although these studies revealed some essential characteristics of wind-blown sand on Mars, the precondition was still that saltation transport would reach its steady state. Indeed, as shown by Mars missions, much of the observed soil erosion on Mars could have occurred in a few to several tens of seconds (Arvidson et al., 1983; Moore, 1985), while the simulations of Huang et al. (2014) had reported a response time of 7–8 s. This means that steady state transport could not last for a long time on Mars. In the extreme case, saltation might begin to attenuate before reaching the “equilibrium state”. This kind of ‘intermittent’ Martian saltation and its effect of transport rate prediction have not been studied before.

In this study, an unsteady model is applied to simulate saltation transport under Martian conditions. The one-dimensional wind field is solved with a finite volume method so that the varied wind can be imposed. Sand particles are traced individually. The aerodynamic lift and splash process are also included in the model. The simulated results are used to assess the dependence of transport rate on the characteristics of sand materials and varied wind velocity. Finally, the simulated transport rates are compared with those on Earth.

2. The model

A one-dimensional unsteady saltation model (Wang and Zheng, 2014) is used to simulate the saltation transport on Mars. The four key sub-processes (Anderson and Haff, 1991): aerodynamic entrainment, trajectory tracing, particle’s splash and rebound from the sand bed and wind modification are all included in the model.

For wind, the governing equation, $\rho \partial u/\partial t = \partial \tau/\partial z + f_x$, is solved based on the implicit finite volume method. ρ is the atmosphere density and f_x is the force per unit volume on the wind. The mixing length approximation is employed to calculate the effective viscosity and the shear stress $\mu_t = \rho k^2 z^2 |\partial u/\partial z|, \tau = \mu_t \partial u/\partial z$, where $k = 0.4$ is the *von Kármán*’s constant. Although the mixing length model employed to close the turbulent equation is relatively simple, the simulated results have proved to be comparable with the wind tunnel experiments for Earth saltation (Spies et al., 2000; Wang and Zheng, 2014). The upper boundary has a velocity-enforced condition, i.e., $u(H) = u(t)$ where $u(t)$ is the imposed wind variations and H is the height of the simulation domain. At the roughness height z_0, lower boundary condition, $u(z_0) = 0$, is applied, where $z_0 = D_p/30$ (Bagnold, 1941; Anderson and Haff, 1991) and D_p is the particle diameter.

Sand particles are presumed to travel only under the act of drag force $\mathbf{F}_D = C_D \pi D_p^2 \rho |V_r| \mathbf{V}_r/8$ and the gravity force $\mathbf{F}_g = g\pi\rho_p D_p^3/6$ (White et al., 1976), where ρ_p is the particle density. $C_D(Re)$ denotes the drag coefficient and is taken from empirical relations (Morsi and Alexander, 1972). Here, $Re = V_r \rho D_p |V_r|/\mu$ is the particle Reynolds number defined by particle diameter, the atmosphere density, kinetic viscosity μ and the relative velocity V_r between airflow (u, w) and the sand particle (u_p, w_p), $V_r = \left[(u-u_p)^2 + (w-w_p)^2\right]^{1/2}$.

The number flux N_a lifted vertically by the aerodynamic force, with a velocity $\sqrt{2gD_p}$, is proportional to the excess shear stress $N_a = \xi(\tau_s - \tau_c)$, where the constant is $\xi = 10^8$ according to Spies et al. (2000). τ_s is the instantaneous shear stress on the surface bed calculated from the wind profile and τ_c is the lowest shear stress defined as $\tau_c = \rho u_{*t}^2$, where $u_{*t} = C\sqrt{gD_p(\rho_p - \rho)/\rho}$ is the fluid threshold friction velocity (Bagnold, 1941). In the expression, C is an empirical coefficient which depends on interparticle forces, the lift force, ρ_p/ρ and the friction Reynolds number, $B = u_{*t}D_p/\nu$ (Iversen et al., 1976), where ν is the kinematic viscosity of atmosphere.

The models of ejection and rebound as saltation particles reach the bed surface are identical to those in Kok and Renno (2009). The probability of particle rebound is $p_{reb} = 0.95(1 - \exp(-\lambda v_{imp}))$, where v_{imp} is the impact velocity and the coefficient λ is assigned to be ~ 1 s/m. The number of splashed sand grains can be calculated by the expression, $N \approx a v_{imp}/\sqrt{gD_p}$ with $a = 0.02$. The rebound velocity is 0.55 times over the impact velocity, and the rebound angle is a normal distribution with a mean of 40° from horizontal. The ejection angles can be described by an exponential distribution with a mean of 50° from the horizontal direction.

3. The parameters

Diameter ranges assumed in past saltation studies of Mars were 0.1–0.6 mm (Kok, 2012) and those of Earth were 0.15–0.25 mm (Shao, 2008). We thus choose $D_p = 600$ μm and 250 μm respectively in order to compare simulated results with others. Atmosphere density, viscosity, gravity and particle density for Martian simulation are $\rho = 0.02$ kg/m^3, $\nu = 1.3 \times 10^{-5}$ kg/m s, $g = 3.71$ m/s^2 and $\rho_p = 3200$ kg/m^3. Those for Earth are