Reexamine the effect of liquid humidity on the fluid threshold of wind-blown sand.

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Introduction: Previous experimental work in wind tunnels has demonstrated that the change of humidity could affect the fluid entrainment wind speed of sediments on Earth (e.g., Belly, 1964; McKenna-Neumann and Sanderson, 2008). If we take a look at the force balance of the grains, during the humidity change, gravity would not change, neither would the wind drag or lift forces change, so the change in the fluid entrainment speed must be coming from the change of the interparticle forces between the particles. The interparticle forces could have multiple components such as the van der Waals forces, capillary forces (when air is humid), and electrostatic forces. Here we would consider only the former two forces.

The final interparticle cohesion is a function of particle shape, roughness, and intrinsic cohesiveness. It can simply be expressed as: $F_i = \phi A$, where A is the contact area between the two grains, and ϕ represents the cohesiveness between the grains. The contact area A is a function of the shape and local roughness scale of the contact region between the grains. The change of humidity would vary both the contact area and the cohesiveness of the grain.

For a grain with non-zero roughness, under humidity, the liquid vapor layer could fill the indents and smooth out the bulges to reduce surface roughness, usually increasing the contact area. The liquid vapor could either increase or decrease the intrinsic cohesiveness of the grain depends on whether the cohesiveness of the liquid is larger or smaller than the cohesiveness of the solid. Here we use surface energy of the material as a measure for intrinsic cohesiveness.

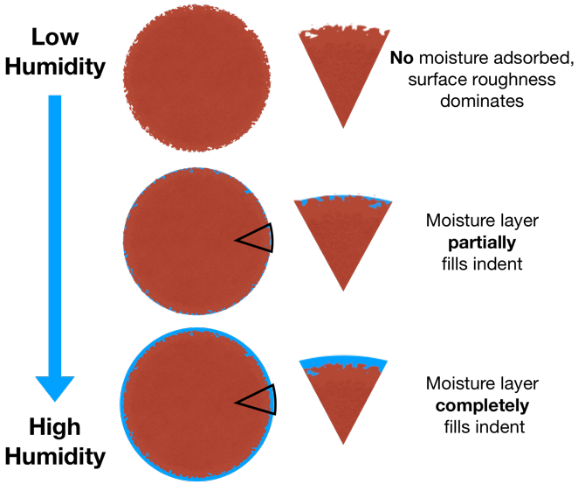

Figure 1: Particle liquid adsorption scheme from low humidity to high humidity.

On Earth, sand particles are made of mainly silicates, which have quite high surface energy in vacuum, of around 500 mJ/m^2. However, solid materials with high surface energy tend to adsorb liquids with low surface tension. High energy surfaces such as metals and silicates exposed in humid air would adsorb layers of hydrocarbons and water to achieve lower total free energy for the system (Wu, 1982). Because of the prevalence of water vapor in Earth's atmosphere and the lower surface tension of water (72 mN/m), silicate sand on Earth readily adsorbs a thin layer of water on its surface. Actually, silicates are converted from a high-surface-energy surface to a low-surface-energy surface at the adsorption of the first water layer, as low as when relative humidity (RH)=0.6% (Zisman, 1975). With increasing humidity, additional water layers are adsorbed on silicates, further reducing the surface energy of silicates.

However, what typically was observed in wind tunnel experiments is that the threshold wind speed decreases with increasing water humidity in the atmosphere, meaning that the total interparticle cohesion decreases with increases RH. There are two reasons for this observation. First, it is extremely difficult to achieve a completely dry experimental system, especially for wind tunnel experiments (e.g., Yu et al., 2017a), previous experiments are usually conducted starting from a certain humidity (Belly, 1964; McKenna-Neumann and Sanderson, 2008), thus the intial high surface energy period (when RH=0%) cannot be observed. The second reason is because of the particle shape and roughness devoid from perfect smooth and spherical grains. Local small-scale roughness would decrease the interparticle cohesion from a perfect smooth sphere because of the decreased contact area. The adsorbed water molecules, on the other hand, can smooth out the roughness by filling the indents/smoothing out bulges (Figure 1). Thus, with increasing humidity, more layers of water molecules would be adsorbed on the grain to decrease the roughness of the grain, thus increasing the local contact area. The response of the magnitude interparticle cohesion to humidity, after a certain amount of water is present, thus becomes a complex interplay between surface roughness of the grain and the amount of adsorbed water layer (or RH). On Earth, with humidity, the change in contact area would dominate over the change in cohesiveness between the grains, for the range of humidity commonly investigated in laboratory experiments (RH>5-10%).

Insights for other bodies:

Titan On terrestrial bodies, silicate sand is formed by mainly erosion from bedrocks, which has substantial roughness on their own, usually on the order of 1 μm (e.g., Alshibli et al., 2004). Looking at other planetary bodies, for example Titan, the surface sand is made mainly organics converted from the photochemical products of the atmosphere. The photochemical aerosol analogs produced in laboratory (so-called "tholin") has minimal roughness (e.g., Yu et al., 2017b), which suggests that it is possible that the surface sand on Titan could process lower roughness compared to Earth sand. The surface energy of tholin is measured to be around 60-70 mJ/m^2 (Yu et al., 2017; Yu et al., in prep) in air (which means in vacuum this value could be higher). While the surface tension of liquid methane under Titan's surface conditions is only 16 mN/m. Thus, the surface sand should readily adsorb methane when methane humidity is present. For Titan we investigated the interplay between roughness and methane humidity and how they are going to affect interparticle cohesion on Titan. If the roughness change of the grain is less important than that of the intrinsic cohesion of the material, then it is possible that interparticle cohesion is lower when it is "wetter" on Titan. This means a lower threshold wind speed is needed to saltate the sand grains, which is consistent with the GCM results that Titan dunes are more likely to form during equinox, when it is windy and "wet" (Charnay et al., 2015). We are compiling a relationship between the interparticle cohesion with root-mean-square (RMS) roughness and methane humidity. Figure 2 is the calculated liquid film thickness for methane on Titan and water on Earth. For example, for a tholin grain with RMS roughness of 1 nm, methane RH of 37% is sufficient to fill the roughness and keep the threshold wind speed low. The recently selected Frontier mission Dragonfly could potentially investigate the roughness of sand grains on Titan and validate our study.

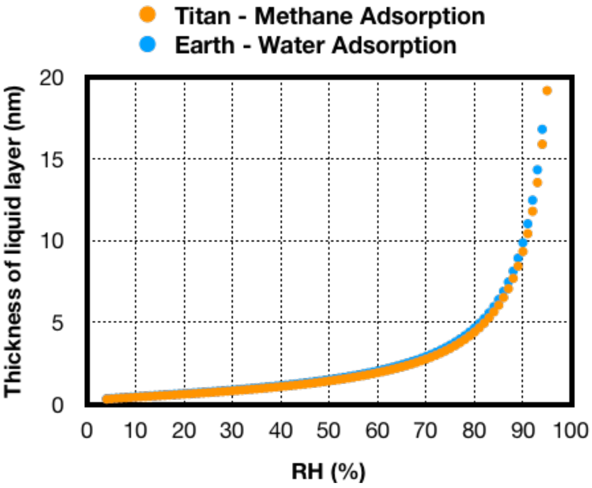

Figure 2: Liquid moisture layer thickness vs. relative humidity for methane on Titan and water on Earth.

Bodies with no moisture: For planetary bodies with no liquid moisture, the sediments would have cohesiveness equal to their surface energy in vacuum. For silicates, it is several hundreds mJ/m^2. If the sediments have the same roughness as sediments on Earth, the final interparticle cohesion would be several times larger, because sediments on Earth would adsorb water and become low surface energy surfaces. Thus larger wind speed would be needed for sediment transport on dry planetary bodies.

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