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# Mechanisms limiting the growth of aeolian megaripples

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**Key Points:**
- Two mechanisms which limit the size of megaripples
- Both mechanisms depend on grain size, megaripple height, and wind speed
- For a given wind and grain size, there exists a limit on megaripples size

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**Abstract** Megaripples are distinguished from regular ripples by their larger size and bimodal sediment distribution. The interplay between wind, grain size, and morphology controls their development, but the exact mechanisms that limit the size of megaripples have been unclear. Using wind tunnel experiments, we found two main mechanisms that limit the height of megaripples. The first mechanism is megaripple flattening due to strong enough winds that drive the coarse grains into saltation; the second mechanism is megaripple deflation by impacts of faster saltation grains. In this latter mechanism, the coarse grains are propelled by the impacts of fine saltating grains. The occurrence of both these mechanisms depends on the grain size distribution and increases with both megaripple height and wind speed. Thus, for a given wind environment and grain size distribution, there exists a limit on the size of megaripples, which is determined by these two mechanisms.

## 1. Introduction

Aeolian megaripples form when a bimodal sand distribution is blown by wind and have been described in many places throughout the world [*Cornish*, 1914; *Bagnold*, 1941; *Sharp*, 1963; *Tsoar*, 1990; *Jerolmack et al.*, 2006; *Yizhaq*, 2008; *Milana*, 2009; *Zimbelman et al.*, 2009; *Lorenz and Valdez*, 2011; *Isenberg et al.*, 2011; *Qian et al.*, 2012]. Megaripples are also abundant on Mars [*Sullivan et al.*, 2005; *Jerolmack et al.*, 2006; *Yizhaq et al.*, 2012b].

Megaripple growth starts with the coalescence of small ripples. During this growth process, coarse and fine grains begin to segregate. This occurs because coarse grains are moved by the impacts of bouncing "saltating" fine grains, and fewer fine grains impact beyond the crest. Consequently, an armoring layer of coarse grains develops on the crest, with the finer grains concentrating in the troughs [*Isenberg et al.*, 2011; *Yizhaq et al.*, 2012a]. The coarse grains on the megaripple crest allow the ripples to grow higher as strong winds are needed to destroy the armoring layer. In contrast, normal ripples, which are composed only of fine grains, cannot grow as high since weak winds may drive the fine grains at the crest into the saltation cloud [*Manukyan and Prigozhin*, 2009]. The final wavelength of the ripples is not simply correlated to the mean saltation length but rather evolves through interaction between ripples with different sizes. Normal ripples and megaripples are thus a product of self-organization, where ordered spatiotemporal structures spontaneously emerge through positive feedback operating at smaller scales [*Anderson*, 1990; *Hallet*, 1990; *Yizhaq*, 2008].

According to *Bagnold* [1941], the difference between normal ripples and megaripples is that normal ripples cease to grow whereas megaripple (ridges in his terminology) never cease to grow, because the wind is too weak to carry away the coarse crest grains. In his own words [*Bagnold*, 1941],

"The essential difference between ripples and ridges lies in the relative magnitudes of the wind strength and the dimensions of the crest grains. In the ripple, the wind is strong enough to carry away the topmost crest grains whenever the crest rises above a limiting height. In case of the ridge the wind is too feeble, relatively to the size of the crest grains, to do this. The wind condition favorable to ridge formation may be looked upon as an extended range of strengths lying between the impact threshold and fluid threshold."

Note that Bagnold referred to the impact threshold (the minimum wind speed at which saltation can be sustained) of the fine grains and to the fluid threshold (the minimum wind speed required to initiate saltation) of the coarse particles. The range between these two wind velocities is the range of winds that is favorable for the formation of megaripples [*Jerolmack et al.*, 2006].

There is a correlation between the wavelength and the maximum grain size at the megaripple crest although the exact functional dependence varies between different studies [see *Williams et al.*, 2002, Figures 3 and 4 ; *Stone and Summers*, 1972; *Milana*, 2009; *Pelletier*, 2009]. During our 7 year field study in Nahal Kasuy in the southern Negev, Israel [*Isenberg et al.*, 2011], the average size of the magaripples changed several times but never exceeded 7 cm. These observations revealed a correlation between megaripple wavelength ($\lambda$) and ripple height ($h$), quantified by the ripple index (RI), which denotes the ratio between wavelength and ripple height which is around 15 [*Qian et al.*, 2012] although it can vary between specific sites. Wind storms (defined here as winds much above the fluid threshold of fine particles) can build megaripples [*Sakamoto-Arnold*, 1981] but can also destroy them [*Isenberg et al.*, 2011; *Yizhaq et al.*, 2012a]. *Bagnold* [1941] argued that it may take decades or centuries to form a huge megaripple in the Libyan Desert (20 m wavelength and height of 60 cm), whereas it took about 2 years to build megaripples at Nahal Kasuy (70 cm wavelength and 5 cm height) [*Isenberg et al.*, 2011]. These observations revealed that interactions between wind, grains, and ripple size limits the megaripple growth. In the absence of these interactions, megaripples would continue to grow as suggested by *Bagnold* [1941], such that a correlation between the morphometry of megaripples from different locations would not be realistic.

The processes that control megaripple evolution and whether they grow indefinitely are still poorly understood. The basic questions which we address in this work are (i) whether megaripples reach a steady state like normal ripples or (ii) whether they grow indefinitely as suggested by *Bagnold* [1941]. If the former is true then what are the basic mechanisms that limit the size of megaripples? We present results from field experiments, wind tunnel experiments, and numerical simulations, which indicate that megaripples, in fact, do not grow indefinitely, contrary to what Bagnold inferred. Rather, we find that there are two main processes that control megaripples growth. The first is a complete destruction or flattening [*Isenberg et al.*, 2011], which occurs once the wind speed at the crest exceeds the fluid threshold of the coarse grains for a sufficient amount of time. The second mechanism, which occurs at lower wind speeds (below the fluid threshold of coarse grains) is crest deflation due to splashing (ejection) of coarse grains by the impacts of energetic fine saltating grains [*Ungar and Haff*, 1987; *Kok and Renno*, 2009; *Werner*, 1990]. The efficiency of this second mechanism also increases with megaripple height as the speed of saltating particles increases with height in the saltation layer [*Kok et al.*, 2012]. Since the occurrence and efficiency of both these mechanisms depend on the height of the megaripple, we find that there is a maximum crest height at which megaripples are stable for a given particle size distribution and wind conditions.

The two growth-limiting hypothesized mechanisms are discussed in detail in section 2. In section 3 we then describe the results of wind tunnel experiments designed to test whether these two mechanisms indeed limit the growth of megaripples. In section 4 we discuss the results and present a conceptual mathematical model that describes the complex interplay between grains size, wind intensity, and megaripple height.

## 2. Hypothesized Mechanisms Limiting Megaripples Growth

The first mechanism (mechanism 1) limiting the growth of megaripples is a complete destruction or flattening [*Isenberg et al.*, 2011], which would occur once the wind speed at the crest exceeds the fluid threshold of the coarse grains for sufficient amount of time. When this happens, the armoring layer at the crest is destroyed, and the bulk fine material of the megaripple is exposed to wind deflation. In our previous works in Nahal Kasuy we documented megaripples flattening due to strong storms [*Isenberg et al.*, 2011; *Yizhaq et al.*, 2012a].

The second mechanism that we hypothesize that limits the growth of megaripples is crest deflation due to splashing of coarse grains by energetic fine saltators. We hypothesize that this mechanism produces a net erosion when (i) the ripples are higher than their steady state height, which is reached by applying a given wind velocity (below the fluid threshold of the coarse grains) or (ii) when the wind velocity exceeds the wind velocity that created them. Crest erosion is maintained due to the impacts of high-speed fine-grained saltators. At higher wind speed or high megaripples height the impacts are sufficiently energetic and they can drive the coarse grains into saltation. In the latter case, it should cause a gradual decrease in ripple's height. The horizontal velocity of saltating grains increases with height from the surface [see *Kok et al.*, 2012, Figure 2.11]. The increasing wind speeds near the top of the saltation layer cause the population of fast-moving grains to grow; thus, the occurrence of the unusually high saltator impact speeds required to splash coarse grains into saltation (assuming > 5 m/s) increases drastically with the wind speed

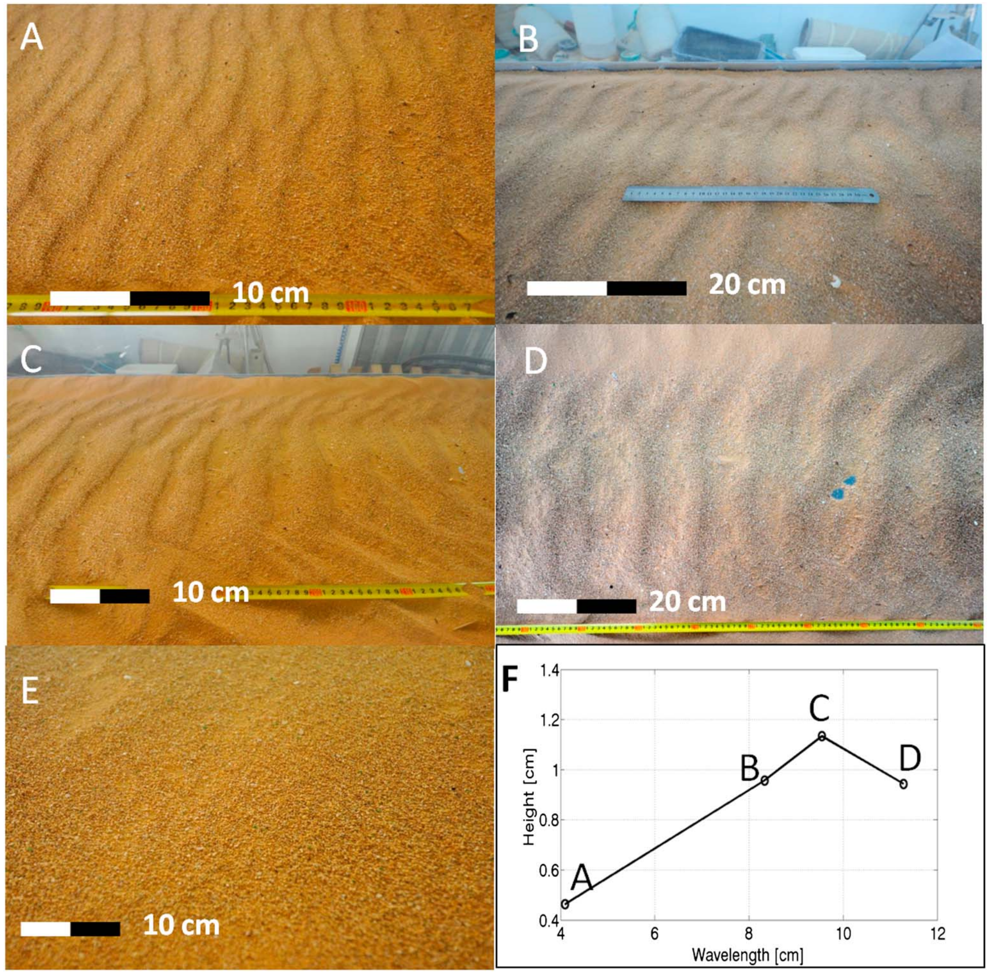


**Figure 1.** Series of images illustrating the sequence of the wind tunnel experiment. (a) Phase A: Initial ripples after applying 19 min of 6.5 m/s winds. (b) Phase B: Continued growth of the megaripples is seen after subsequently applying 12 min of 7.5 m/s winds. (c) Phase C: Ripples after subsequently applying 78 min of 6.5 m/s winds. (d) Phase D: Ripples after subsequently applying 2 min of 9 m/s winds. (e) Phase E: Final bed form (the ripples have been destroyed) after applying another 1 min of 12 m/s winds. (f) Average height versus average wavelength during the experiment (phase E is not included in the graph since the ripples disappeared).

[see *Isenberg et al.*, 2011, Figure 19]. Numerical simulations indicate that the fraction of the stream-wise mass flux that is due to the coarse grains increases nonlinearly with wind speed [*Isenberg et al.*, 2011, Figure 18].

## 3. Experimental Methods

We studied the evolution of megaripples using controlled experiments conducted at the stationary boundary layer wind tunnel of the Aeolian Simulation Laboratory (Ben-Gurion University of the Negev) [*Pye and Tsoar*, 2009]. The wind tunnel is an open circuit tunnel configured for air suction mode, allowing maximum wind speed of 25 m/s (measured at 0.15 m). The cross-sectional area is $0.7 \times 0.7$ m, and the working length is 12 m (7 m of test section). The tunnel has a feeder section to control sand supply in space and time and thus the occurrence of saltation in the test section. We used natural sand collected from the megaripple field in Nahal Kasuy that is characterized by a bimodal distribution typical of moderate-sized megaripples. During the experiments the sand in saltation was sampled using a vertical array of traps oriented in the along-wind direction. The traps were placed at heights of 1, 3, 4.5, and 6.5 cm above ground, and each trap had (a cross section of $2 \times 1$ cm). Analyses of grain size distribution (GSD) of the samples were performed in the laboratory by a laser difractometer (ANALYSETTE 22 MicroTec Plus), which measures GSD over the range of 0.08 to 2000 $\mu$m [*Isenberg et al.*, 2011].

In order to test the hypothesis of *Isenberg et al.* [2011] that the growth of the megaripples is limited by both fluid lifting of coarse grains from the crest (mechanism 1) and splashing of coarse grains by fine saltators

  

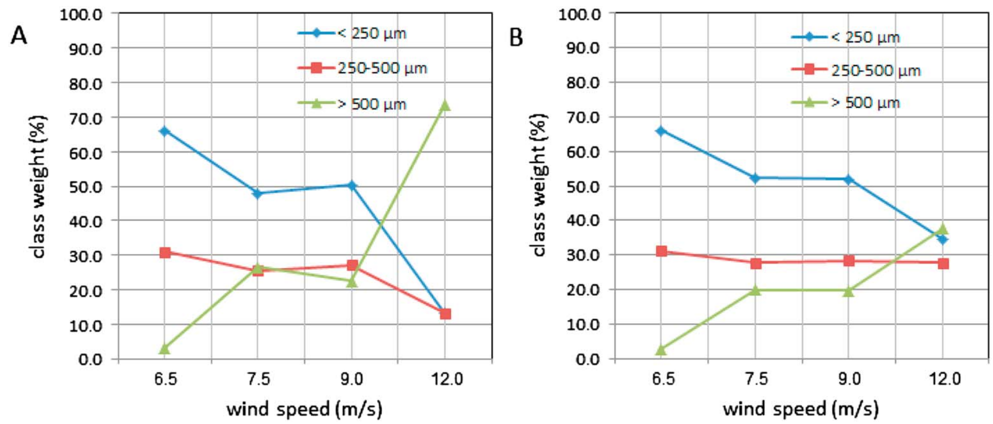


**Figure 2.** Sand fraction distribution at a sequence of wind speeds applied in the tunnel. Shown are sand collected from the two lower traps (a) T1 and (b) T2 at heights of 1 and 3 cm, respectively.

(mechanism 2), we varied the wind speed in phases during the experiment. Specifically, in phase A small megaripples were allowed to form from the initial state of a flat surface of mixed sand by applying wind speed of 6.5 m/s (measured at 15 cm above the wind tunnel surface), which exceeds the fluid threshold of the fine grains but is below the impact threshold of the coarse grains. Then, in order to check if wind speeds just above the fine's fraction fluid threshold (~ 5.5 m/s [*Bagnold*, 1941]) will allow ripples to grow, we applied a succession of wind speeds as follows: wind speed was increased to 7.5 m/s in phase B (still below the impact threshold of the coarse grains (Figure 1b)), after which wind speed was lowered to 6.5 m/s in phase C for 78 min (Figure 1c). Subsequently, we investigated the stability of the formed megaripples with respect to wind speed above the impact and the fluid thresholds of the coarse grains, respectively, by applying 2 min of wind speed of 9 m/s in phase D (Figure 1d) and 1 min of 12 m/s (Figure 1e) in phase E. For each of the experimental phases, we documented the response of the megaripples by using high-resolution photography, morphometry, and GSD analysis of sand collected in the traps.

## 4. Results and Discussion

Figure 1 shows snapshots of the sand bed during the experiment and the height versus wavelength of the ripples. For wind speeds of 6.5 and 7.5 m/s (phases A, B, and C) the ripples continue to grow whereas for wind speed of 9 m/s (phase D) their height decreased. Note that the ripples were flattened when wind of 12 m/s (phase E) was applied in the wind tunnel.

Figure 2 shows the fraction distribution of sand in traps T1 and T2 (heights 1 and 3 cm, respectively) during the different phases of the experiment. We found an increase of 40% in the coarse sand fraction at the T2 trap during experiment phase E (wind of 12 m/s, Figure 1e) relative to the measurement at the low wind speed (Figure 2), indicating that the coarse grains moved in saltation.

From the experimental results we conclude that megaripples grow, unless the wind speed exceeds a certain threshold. Since the results presented in Figure 2 indicate that coarse grains saltate when the megaripples erode, we hypothesize that this threshold is the coarse grain impact threshold, which is the minimum wind speed at which coarse grains can saltate. Furthermore, our results show that when wind speed increases even further, the megaripples are flattened, presumably because of extensive saltation of the coarse particles, which we hypothesize occurs above the coarse grain fluid threshold. These two thresholds depend on (i) the size of coarse grains constituting the armoring layer and (ii) on the megaripple height since the wind speed is modified due to the megaripple topography. Specifically, because the wind stress at the ripple crest exceeds that at the ripple trough [*Bagnold*, 1941], the minimum total wind stress at which coarse grains are lifted by wind reduces with megaripple height.

We can use these observations to quantify a "phase diagram" of megaripples growth based on the two hypothesized mechanisms, which we do below. The interplay between wind velocity and ripple morphology can be addressed by estimating the threshold velocity $u_t$ as a function of the grain diameter $D$ and the megaripple height $h$. This estimation should be regarded more as a conceptual model rather than an exact calculation since it is based on approximations and simplifications of the complex coupling between sand transport, ripple morphology, and the wind profile. The shear velocity at the fluid threshold $u_{*t}$ is approximately given by [*Bagnold*, 1941]

$$u_{*t} = A\sqrt{\sigma g D}, \tag{1}$$

where $\sigma = (\rho_s - \rho)/\rho$, $\rho_s$ is the grain density (taken as 2710 kg/m$^3$ [*Yizhaq et al.*, 2009]), $\rho$ is the air density (taken as 1.2 kg/m$^3$), $g$ is acceleration due to gravity, and $A$ is an empirical constant ($A \approx 0.1$). Equation (1) is not valid for grains smaller than 0.1 mm due to cohesive forces between the grains. The wind profile when $u_* < u_{*t}$ is given by the law of the wall for wind in the boundary layer [*Kok et al.*, 2012]:

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{z}{z_0}, \tag{2}$$

where $\kappa = 0.4$ is von Karman's constant, $u$ is the wind speed at height $z$, $u_*$ is the shear velocity, and $z_0$ is the aerodynamic roughness of a flat surface. Combining equations (1) and (2) gives the threshold velocity $u_t$ at height $z$ required to initiate sand transport,

$$u_t = \frac{1}{\kappa}A\left(\sigma g D\right)^{0.5}\ln(z/z_0). \tag{3}$$

It is important to note that equation (3) is only an approximation since equation (2) is valid only for a flat surface whereas the streamlines of the flow will follow the ripple profile. This approximation will thus underestimate the value of the shear velocity needed to move particles at the crest into saltation. The roughness $z_0$ needs to account for the effects of both saltation and ripples topography. First, we take into account the effect of saltation. On a flat surface, $z_0$ is a function of both the grain diameter and the excess shear velocity and can be approximated by [*Sherman and Farrell*, 2008]

$$z_s = \frac{D}{15} + C_m\frac{(u_* - u_{*t})^2}{g}, \tag{4}$$

where $C_m$ is an empirical constant, $C_m = 0.132$ for field conditions, and $C_m = 0.025$ for wind tunnel conditions [*Pelletier*, 2009]. Taking into account the rippled surface, assuming sinusoidal topography, the effective roughness length $z_e$ can be approximated by [*Pelletier*, 2009]

$$z_e = z_s\exp\left[\frac{1}{2}\left(\delta\ln\left(\frac{L}{z_s}\right)\right)^2\right], \tag{5}$$

where $L$ is the half width of the ripple at half-height position and $\delta$ is the maximum slope of the ripples, which can be approximated by $h/L$ where $h$ is the ripple height and $z_s$ is given by equation (4) with the presence of saltation. Thus, the threshold velocity at height $z$ on a rippled surface with height $h$ can be approximated by

$$u_t = \frac{1}{\kappa}A\left(\sigma g D\right)^{0.5}\ln(z/z_e). \tag{6}$$

It is important to note that equation (6) is not accurate within the saltation layer since the wind stress near the surface decreases with $u_*$ due to momentum absorption by saltating particles [*Kok et al.*, 2012]. Thus, $u_*$ in equation (4) may be lower inside the saltation layer leading to an increase in the threshold velocity inside the saltation layer. The saltation layer height increases only slightly with wind speed [*Kok et al.*, 2012]. This effect will favor the flattening of megaripples whose crests extend above the saltation layer, because these megaripples experience substantially higher wind shear stress at their crests than in their troughs.

Using the grain diameter of the coarse sand denoted as $D$ in equation (6) will give the threshold velocity above which megaripples will be flattened considering that this process is dominated by saltation of coarse grains. Figure (3) shows the threshold velocity needed for flattening megaripples of 5 cm height and $L = 20$ cm under different storms (defined by different shear velocities). The inset shows the threshold velocity for the wind tunnel experiment (using $C_m = 0.025$). The stronger the storm the lower is the threshold velocity at a specific height due to the increase in the roughness $z_0$ according to equation (4).

Figure 4 shows the effects of the height and grain diameter (inset) on the threshold velocity for $u_* = 0.5$ m/s (keeping $L$ constant). Higher megaripples are more susceptible to flattening as the threshold velocity at their crests needed to drive the coarse grains into saltation is lower than that for smaller ripples. This effect

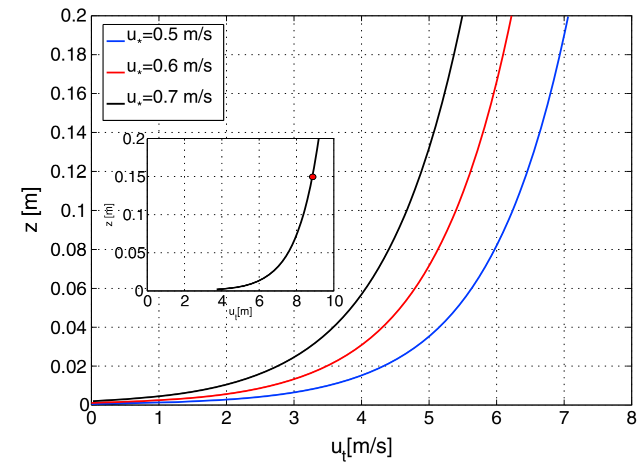


**Figure 3.** Fluid threshold velocity for a coarse grain size of $D_c = 1$ mm for different shear velocities, with a rippled topography ($h$ =5cm, $L$=20 cm), $z$ is the height above the surface. The inset shows the threshold velocity at wind tunnel conditions for $u_* = 0.5$ m/s, $h = 1$ cm and $L = 10$ cm. It shows (marked with a red circle) ripples flattening when the wind velocity calculated at 15 cm is close to 9 m/s, which is in the range we measured in the wind tunnel experiment.

can explain the observations of *Isenberg et al.* [2011] and *Yizhaq et al.* [2012a] that large megaripples were flattened during a strong windstorm of $u_* = 0.55$, whereas smaller megaripples were not. As expected for coarser grains at the crest, stronger winds are needed to flatten the megaripples (inset of Figure 3).

Figure 5 summarizes our hypothesized processes that control the evolution of megaripples. It shows the impact threshold of the fine grains $u_{imp}$, the impact threshold of coarse grains $u_{impc}$, and the fluid threshold of the coarse grains $u_{tc}$ as a function of wind velocity for specific grains sizes and shear velocity. The ripples response to the wind will thus depend on the wind velocity just above the crest compared to the critical thresholds. The problem is that this velocity is still not fully known. Computational fluid dynamic modeling of boundary layer flows over ripples of various shapes and sizes will be needed to more precisely quantify the wind velocity over natural megaripples. For $u < u_{imp}$ ($u_{imp}$ is the impact threshold of the fine grains) there would be no saltation of fine grains (we used fine grains with diameter of 0.2 mm), and thus, the megaripples will not evolve. For $u_{imp} < u < u_{impc}$ ($u_{impc}$ is the impact threshold of coarse grains) taken as 80% of the fluid threshold of the coarse grains $u_{tc}$ [*Bagnold*, 1941], the megaripples will grow, since the wind speeds are sufficient to drive fine grains into saltation and thus produce reptation of coarse grains, yet they are insufficient to sustain coarse grains in saltation. For stronger winds $u_{impc} < u < u_{tc}$, wind strengths

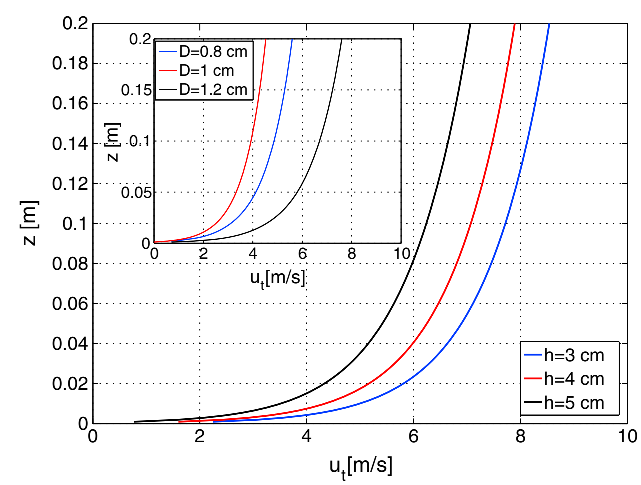


**Figure 4.** Threshold velocity for $D_c = 1$ mm and $u_* = 0.5$ m/s for ripples with different heights; $z$ is the height above the surface. The inset shows the threshold velocity for different values of grain diameter (the other parameters are the same).

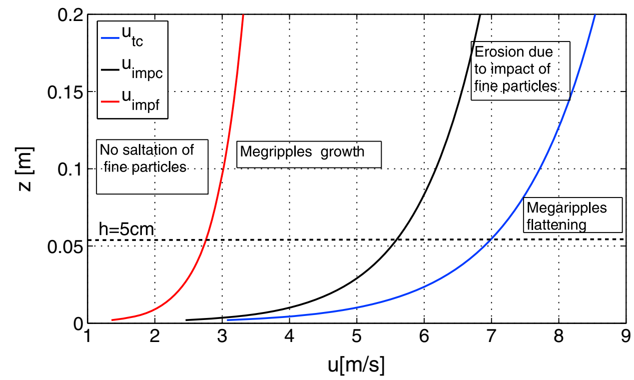


**Figure 5.** The different processes in megaripples evolution dictated by wind velocity at different height above the surface ($z$). Parameters: $h = 5$ cm, $L = 0.2$ cm, $D = 1$ mm, and $u_* = 0.5$ m/s.

are strong enough to put some of the ejected coarse grains in saltation, producing a gradual erosion of the megaripple crests.

For $u > u_{tc}$ direct fluid drag produces a substantial population of saltating coarse grains. The transfer of their momentum upon impact can be sufficient to drive other coarse grains into saltation. As the crests continue to erode, direct fluid lifting of coarse grains will become increasingly difficult (Figure 4), and eventually will cease. However, at this point, there is a substantial population of saltating coarse grains that continue to eject other coarse grains into saltation. Therefore, unless the wind quickly drops below the coarse grain impact threshold, this continued ejection of coarse grains from the crests will usually result in the flattening of the megaripples. Figure 5 was plotted for specific megaripple dimensions and specific shear velocity, but the same principles apply for megaripples with other dimensions and for other shear velocities.

Notably, winds that are just above the impact velocity of the fine grains will maintain megaripples growth until the effect of ripple height becomes significant resulting in a lower fluid threshold velocity for coarse grains at the crest (Figure 3). Unlike *Bagnold* [1941], our results thus indicate that megaripples growth is, in fact, limited by two mechanisms that determine specific maximum heights of megaripples for a given wind strength and particle size distribution. The final wavelength is a result of the complex relationships among coarse-grain size, wind regime, and ripple height.


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