Aeolian sand ripples around plants

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Plants in the desert may locally change the aeolian process, and hence the pattern of sand ripples traveling nearby. The effect of plants on ripples is investigated using a coupled map lattice model with nonuniform coupling coefficients.

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I. INTRODUCTION

Plants are now accepted as playing an important role in arid region geomorphology and are of considerable practical use in sand stabilization, rehabilitation, and ecology restoration [1–3]. As they locally change the aeolian process, plants may display obvious impacts on sand ripples in their vicinity [1,4,5].

Previous computer simulations of aeolian sand ripples relying on tracing the trajectories of individual sand grains have achieved great success [6–9]. Despite the fact that few deserts are completely devoid of vegetation [1,3,4], little attention has been paid to the effect of plants on ripples, the smallest bedform unit, in the numerical studies. In this paper, we investigate the influence of desert plants such as grasses or shrubs on aeolian sand ripples using a coupled map lattices (CMLs) model, which describes macroscopic behavior rather than microscopic details [10].

II. THE CMLs MODEL FOR RIPPLES AROUND PLANTS

A. Aeolian sand ripples

In the aeolian process, most of the sand grains are driven along the ground by the impact of saltating grains [11]. For a small sand bump, two processes happen simultaneously: (a) with upwind side bombarded by more saltating grains, the bump moves downwind; (b) as an obstacle to the slowly flowing surface grains, the bump grows.

The change of surface height at a lattice (i,j) in process (a) can be written as

$$\Delta_1(i,j)=D[h_t(i,j-1)-h_t(i,j)], \tag{1}$$

where h is surface height, t is time step, D is a positive constant, and $(i,j-1)$ is the upwind lattice of (i,j). Furthermore, because of the lateral dimension of collisions [8,12] and the surface creep due to gravity, the influences of other connecting neighboring lattices should also be taken into account, although such influences are much smaller compared with that of the upwind lattice $(i,j-1)$. Then Eq. (1) becomes

$$\Delta_1(i,j)=D\left[\sum_{\substack{k,l\in\{\pm 1,0\}\\ k^2+l^2\neq 0}} a_{kl}h_t(i+k,j+l)-h_t(i,j)\right], \tag{2}$$

where

$$\sum_{\substack{k,l\in\{\pm 1,0\}\\ k^2+l^2\neq 0}} a_{kl}=1, \quad a_{kl}>0. \tag{3}$$

Process (b) means the height of the bump will increase with time. However, the bump will protrude into zones of higher wind speeds in the atmospheric boundary layer as it grows. Its height is limited by this as sand grains at the crest are easier to be moved forward under the influence of the wind (Ref. [13], and references therein). So this change can be simply described as

$$\Delta_2(i,j)=\beta\tanh[h_t(i,j)]-h_t(i,j), \tag{4}$$

where β is a positive constant.

Combining Eqs. (2) and (4), the increment of lattice (i,j) is

$$I(i,j)=\Delta_1(i,j)+\Delta_2(i,j). \tag{5}$$

It should be noted that the height increment $I(i,j)$ depends on the grains coming from its neighbors. Meanwhile, some grains at lattice (i,j) would be transported to its neighbors as these neighbors have their own increments. So (i,j) need to "compete" for sand grains, and the strongest competition occurs between (i,j) and its upwind neighboring lattice $(i,j-1)$. Then, lattice (i,j) has a net height increment

$$\Delta(i,j)=I(i,j)-\sum_{\substack{k,l\in\{\pm 1,0\}\\ k^2+l^2\neq 0}} a_{kl}I(i+k,j+l). \tag{6}$$

Thus, the final expression for the CMLs model for aeolian sand ripple formation is

$$h_{t+1}(i,j)=h_t(i,j)+\Delta(i,j). \tag{7}$$

Different from the CMLs model introduced by Oono and Puri [10] for the study of phase separation dynamics, here the coupling coefficients a_{kl} are nonuniform. This is very important for ripple formation. Because of the dominant a_{kl} of the upwind lattice, the information of local topology is

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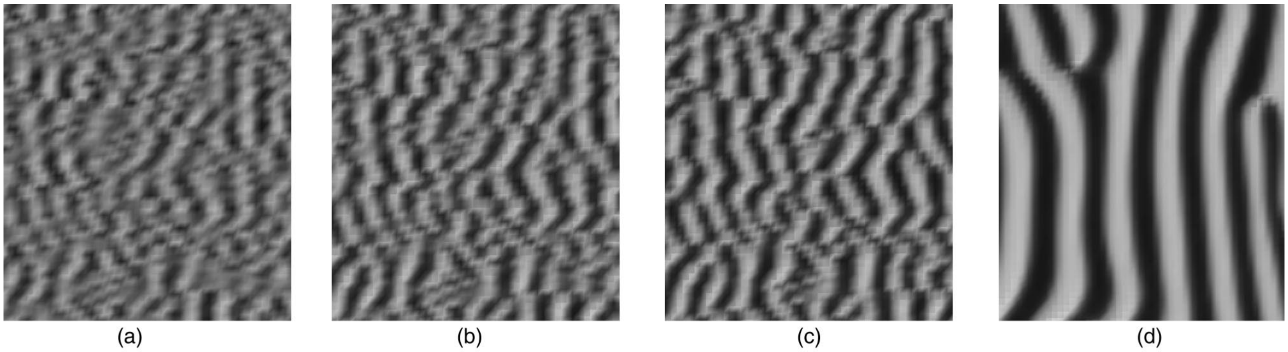

FIG. 1. The development of sand ripples from a flat (with small irregularities) sand bed. Only 50×50 lattices are showed. Wind is from left to right. $D=0.25$, $\beta=1.2$, $a_{0,-1}=0.79$, and $a_{kl}=0.03$. (a) $t=30$, (b) $t=40$, (c) $t=50$, and (d) $t=500$.

transmitted downwind; the other a_{kl} provide lateral information exchange in the sand bed. This effect can be seen in Fig. 1.

B. Effect of plants on ripples

Plants function as an obstacle in wind or air flow and hence influence sand mobility. In this paper, we only study the effect displayed by grasses and shrubs. In fact, they are the most effective at reducing wind erosion because most sand transport takes place along ground level [1]. They usually have a loose global or cylindrical silhouette. This structure causes a decrease in wind velocity within the plant canopy, thus leading to the accretion of fine sand among the stems, and to the formation of nebkas. There is no evident increase in wind speed at the plant's margins, and thus there is no wind erosion in this microhabitat [4].

Here we assume two effects of grasses and shrubs on aeolian processes which are most important. First, plants protect the sand grains beneath them from erosion [14]; second, the local flow direction and flow speed are changed [4,14].

Actually, the flow in or around the plant canopy is turbulent [15]. Following Ref. [16], we assume an effective sheltered area in which the influence of plant can not be ignored, see Fig. 2. The sheltered area depends on the local wind velocity, canopy density, height, flexibility, lateral cover (plant silhouette), and so on. In Fig. 2, the surface covered with plants is represented by a black circle; in the dark gray area at the plant's margin, the wind speed is heavily reduced and the wind direction is severely changed; while in the light gray area some distance away, the wind is near normal.

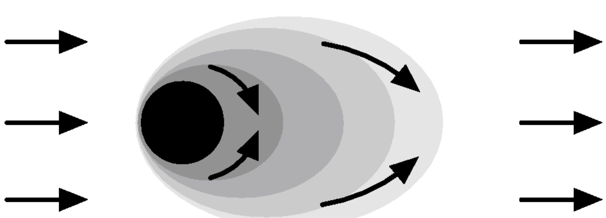

FIG. 2. Wind direction and speed around a plant. The normal wind speed area is white; absence of wind inside the plant is indicated by black; transition areas are shades of gray. Wind directions are indicated by arrows. While this only crudely approximates real flows, it captures the essence of the flow pattern around a plant.

In the simulation, the lattices beneath plants would transport no sand grains to other lattices. For simplicity, the varying wind speed is represented by D. In a zone of low wind speed, the sand mobility is reduced, a small value of D is given. The varying wind direction is represented by a_{kl}. As mentioned above, a_{kl} corresponding to an upwind neighboring lattice will have a much large value, see Fig. 3.

Although it is difficult to determine parameters in this model, a rough estimate of the lattice spacing and time step can be obtained through comparing our simulation of ripple growth with field observation or the wind tunnel experiment. For example, with wind speed of 25–30 mph, when smoothing out a patch of sand in an area of actively moving ripples, Sharp observed that [5]: within 1 min, small piles or ridges form; then, within 2–3 min, grow short, curved small ripples with greater lateral extend, wave length about 1 inch; 10–12 min later, large, regular and continuous ripples grow, and the original ripple pattern is reestablished on the smoothed patch. From this, a single lattice spacing and time step in our simulation are about 0.4 cm and 1 sec in Sharp's field test, respectively [17].

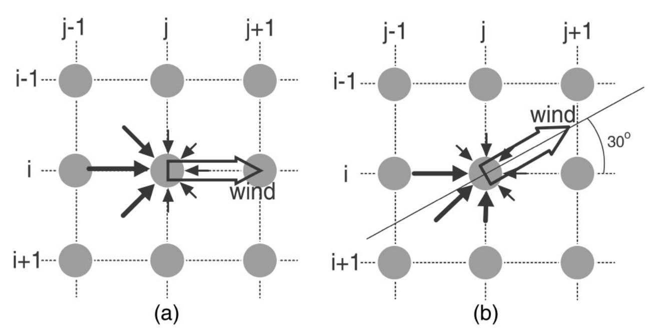

FIG. 3. Wind direction can be represented by the nonuniform coupling coefficients a_{kl}. The values of a_{kl} are indicated by the length of the black arrows. We can simply take each a_{kl} as the ability of transport from the corresponding neighboring lattice to the centering lattice. If we choose suitable a_{kl}, the resulting transport direction will be in the wind direction. (a) $a_{0,-1}=0.5$, $a_{-1,-1}$ and $a_{1,-1}$ are 0.15, other five $a_{kl}=0.04$; (b) $a_{0,-1}=0.39$, $a_{1,-1}=0.27$, $a_{1,0}=0.14$, other five $a_{kl}=0.04$.

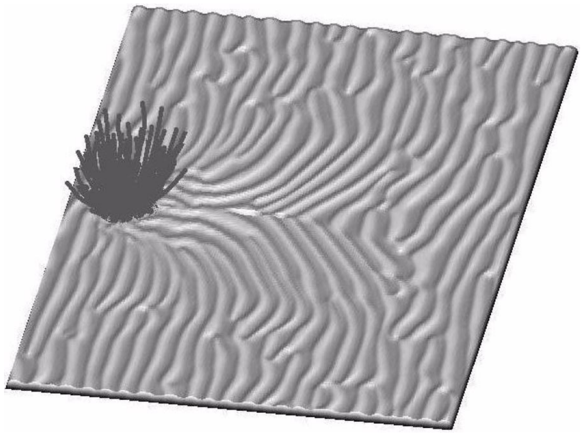

FIG. 4. Ripples around a clump of dense grasses. Wind is from left to right. The area covered by the plant is 325 lattices, or 52 cm^2. The effective sheltered area is 5030 lattices, or 805 cm^2. $D=0.25$, $\beta=1.2$, $t=400$.

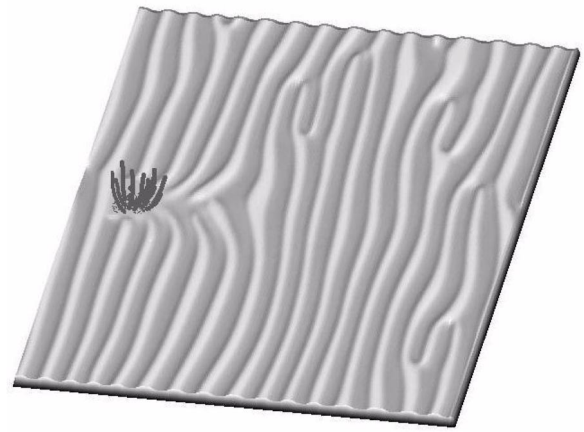

FIG. 5. Ripples around a clump of loose grasses. The area covered by plants is 200 lattices, or 32 cm^2. Wind is from left to right. $D=0.25$, $\beta=1.2$, $t=400$.

In this paper, simulations start with a sand bed (200×200 lattices) bearing uniformly distributed random irregularities $|h(i,j)|<0.05$. Periodic boundary conditions are given in order to minimize edge effects.

III. RESULTS

The general results show that, as in the nature (see pictures in Ref. [1], p. 119 and Ref. [4], p. 7), the directions of ripples close to plants are influenced remarkably. With wind speed of 25–30 mph, after 6–7 min, the ripples around the plant that covers an area of 52 cm^2, form a pattern of distinctive characteristic, similar to the arrangement of magnetic field lines around a pole of a bar magnet, see Fig. 4. The wavelength is not obviously changed.

When it is very loose or small enough, plants have such a small influence that the local wind speed will barely be reduced and wind direction almost as normal. In this case, the effective sheltered area is exactly a covered area of the plant. So only the effect that the area beneath the plant is protected from erosion is considered in the simulation. We found that the plants display some influence on the ripples, see Fig. 5. In order to see the effect more clearly, we let mature ripples grow at first ($t=1000$), then the influence of plants is calculated. So the ripples in Fig. 5 are larger and less sinuous than those in Fig. 4.

Another important effect of vegetation on aeolian processes is that it can act as a trap for migrating sand grains [1,3,14]. As time goes by, sand accumulation will take place and a small sand mound will be built by the plant. In our opinion, this accumulation has little impact on the direction and shape of sand ripples. So we have not taken this into account in the simulation.

We only study the ripple pattern around a clump of grasses, as vegetation in a desert is commonly sparse but spatially aggregated. With decrease in spacing, the wakes of individual plants can interact with one another [1]. There is no essential difference between them by using the CMLs model to simulate the impact on sand ripples. Rather than the microprocess as the trajectories of each sand grain being calculated, only the dynamics properties of much larger scale are considered. Our numerical results show that the CMLs model has great computational efficiency in modeling sand ripples in complex flow conditions with varying flow direction and speed.

IV. SUMMARY

This paper presents a CMLs model for aeolian sand ripples around plants. As plants are used as a means of stabilizing mobile sand surface and ripple is an indicator of sand mobility [3,4], such a study may be of some practical importance. The results show that, as in the Nature, plants display substantial impact on the nearby sand ripples. The presented model, simular to the model for wave dynamics in vertically vibrated granular materials [18], mainly composes two processes: local accumulation and surface diffusion of the grains. This suggests that there may be some common mechanics behind the pattern formation of granular materials.

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