Dune Morphology and Sand Transport

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(Received November 26, 1999; Accepted January 23, 2001)

Keywords: Pattern Formation, Geomorphology, Monte Carlo Simulation

Abstract. We performed a computer simulation on patterns and dynamics of desert dunes. Dune patterns observed in deserts were reproduced. From the initial random state, barchans and linear dunes are produced, depending on the variability of the wind direction. The efficiency in sand transport is calculated through the course of development. We found that the sand transport is the most efficient in the linear transverse dune, barchans next, and the least when no pattern is formed. The efficiency in sand transport always increased through the evolution, and the way it increase was stepwise. We also found that the shadow zone, the region where the sand wastes the chance to move, shrinks through the course of evolution.

1. Introduction

There are various types of dunes in arid regions of the world. Barchans (crescent-like dunes), transverse dunes (a kind of linear dunes that align in stripes, vertically to the main direction of wind), longitudinal dunes (another kind of linear dunes that align parallel to wind), network dunes (connected dunes like a fishnet), and star dunes are some of the examples. Most of the dune types are observed in deserts all over the world, and some types even on the Mars. It would be an interesting problem to explore how these dunes are formed and what factors determine their shapes. So far, several studies have done on this subject. From field observations, how the patterns of dunes relate to the wind direction was studied. It was found that transverse linear dunes and barchans are formed when the wind blows mainly from one direction, and star dunes from various direction (LIVINGSTONE and WARREN, 1994; LANCASTER, 1995). From experimental studies, how the crests of dunes align with regard to the wind direction was studied (RUBIN and HUNTER, 1987; RUBIN and IKEDA, 1990). In lab-scale experiments, they found that the crests align so that the gross sand transport across the bedform is maximized. In the present study, we investigate the relation between sand transport and dune patterns. We use computer simulation of dune formation. It is suitable for seeing the quantity of transported sand precisely.

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Before explaining the details of the simulation, let us review basic processes of sand transport. Sand grains in deserts are moved by (i) transport by wind (creeping, saltation, and reptation) and (ii) avalanching (Bagnold, 1941; Livingstone and Warren, 1994). A sand particle is moved by wind in three modes: creeping, saltation, and reptation. Creeping is rolling of sand grains on surfaces. Saltation is a “hop” of a grain along the surface, propelled by wind on long, low-angle trajectory. Reptation is the splash of surface grains when a saltating particle hits the ground. The distance of the grain movement due to reptation is generally less than that due to saltation. Larger grains are transported through this mechanism. Smaller grains are transported through saltation and reptation. When a region of a sand surface becomes too higher than its neighbors, an avalanche occurs to smooth the rough surface. The critical value in the height difference is determined by the angle of repose.

2. Model

We investigate the dune formation and its sand-transport properties with a model of Werner (1995). We describe it below briefly. In this model, dunes are built of sand slabs stacked on a two-dimensional lattice. The height of the dune is proportional to the number of sand slabs at the site. Figure 1 shows the procedure. We choose a slab randomly from all the slabs on the surface. The slab is transported by “wind”, in a specific direction over a specific distance. We call it a “hop”. After one hop, the slab is deposited with the probability \( p \), but otherwise (with the probability \( 1 - p \)) hops again, and repeats the process until it is deposited. This constitutes one time step. The magnitude and the direction of wind is fixed during the step. The probability \( p \) depends on the materials underneath; if there is sand on the site, the moving slab is more likely to be deposited with the probability \( p = P_{\text{sand}} \). On the other hand, if the site is the bare surface, the slab is more likely to hop again \( (p = P_{\text{surface}}) \). In the present study we assume two-directional wind described by two parameters \( u \) and \( v \). For example, we define the case \((u,v) = (1,3)\) as that wind takes the value either \((1,3)\) or \((-1,3)\) at each time step. The simulations are carried out by changing the values of \( u \) and \( v \) from 1 to 6.

A region called the “shadow zone” is defined as in Fig. 1. A slab in the shadow zone cannot be picked up by wind. Once a moving slab is dropped in the shadow zone, it is always
deposited at that location. Therefore the shadow zone works to stabilize the sand. Avalanching is also taken into account. When the height at a site becomes higher by $\Delta H_e$ than four neighboring sites, the slab at the top falls down to the lowest neighbor’s site. Other computer models are given by Nishimori and his group (NISHIMORI and OUCHI, 1993; OUCHI and NISHIMORI, 1995; NISHIMORI et al., 1998).

The initial condition is a random distribution with the average height $H$. The boundary condition is periodic. The lattice size is $100 \times 100$ in our simulation. We use the following parameters: $P_{\text{sand}} = 0.6$; $P_{\text{surface}} = 0.4$; $\Delta H_e = 2$; and $H = 3$.

3. Simulation Results

In the simulation results, we observed patterns of real dunes: barchans, linear transverse dunes, and linear longitudinal dunes. Simulated patterns are given in Fig. 2. Clear two barchans with different size can be seen in Fig. 2(a), a transverse dune in Fig. 2(b), and a longitudinal dune in Fig. 2(c). The final pattern in the present study was either Fig. 2(b) or (c), depending on the open angle of the wind direction.

The results regarding the wind direction are summarized in Fig. 3 as the phase diagram. Figure 3 is divided into three regions with regard to $\theta$, the variability in the wind direction. In Region A, where the wind variability is small ($\theta$ is less than $57^\circ$), the final pattern is the transverse dune. In Region B, where $\theta$ is larger than $127^\circ$, the final pattern is the longitudinal dune. This result agrees with field observation, which the transverse dunes tend to appear in uni-directional wind regime, and the longitudinal dunes tend to appear under alternating wind direction. When $\theta$ is not in either of the two regions, no dune

Fig. 2. Patterns generated by the simulation. (a) two barchans; (b) a transverse dune; (c) a longitudinal dune.
is formed. The sand profile looks random throughout the simulation; the initial random profile does not seem changed. Incidentally the initial profiles did not affect the final patterns. Whether the system finally produce to the longitudinal/transverse dunes (or remains random) can not be changed by the initial profiles. Even if we use the initial profile which different from its final pattern, the result is the same.

In doing the simulation, we found that there are different types on how the final pattern is produced. In most cases the final pattern is made directly from the initial random state, but there is a case where a different pattern appears transiently. The result suggests that there are at least three types of evolution. Type (i) is the simplest evolution, the cases where the final pattern develops directly from the initial random state. Type (ii) evolution denotes the cases where a transient pattern appears on the way to the final pattern. Type (iii) is another type. In these cases, the number of dunes changes with their shape unchanged; for example, when four transverse dunes are formed, they began to merge together at a specific time, to be two dunes of the same shape.

In Region A of Fig. 3, most cases are Type (i); a transverse dune developed directly from the initial state. Type (ii) evolution is the case of \((u,v) = (1,6)\) and Type (iii) is the case of \((u,v) = (1,2)\). Snapshots of Type (ii) evolution in Fig. 4 show how a transient pattern appears. In this figure, during \(t = 200\sim400\), two barchans were observed. Around \(t = 600\) these two barchans merged and changed into a transverse dune. The barchans were not one of the final patterns; they appeared only transiently. On the other hand, For \((u,v) = (1,2)\), Type (iii) evolution was observed (Fig. 5). The number of dunes decreased from four to two around \(t = 400\), and decreased another time from two to one for \(t = 900\sim1000\). We can see one of the dunes was shrinking at \(t = 900\). During the transition, the shape of the dunes was the same.

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**Fig. 3.** The final patterns and wind variability. “—”: transverse dune; “|”: longitudinal dune; “×”: no pattern.

Types of evolution is also shown by numerics on the marks. Cases of Type (i) evolution have no numerics.

2: Type (ii) evolution; 3: Type (iii) evolution.
In Region B, we observed other cases of Type (iii). For both \((u,v) = (2,1)\) and \((3,1)\), dune number decreased in the course of development. Snapshots for \((u,v) = (3,1)\) are given in Fig. 6, where two longitudinal dunes changed into one large dune. At \(t = 400\), we saw two dunes. One of the dune was shrinking during \(t = 600\)–800, until they change into one large dune. This is another case where small dunes merge into a larger dune of the same shape.

4. Sand-Transport Properties and Discussion

In the previous section, it was shown that the wind variability \(\theta\) was important for determining the final pattern. More essentially the factor that really affects the dune
Formation should be the quantity of transported sand, rather than $\theta$. Thus we discuss the sand transport next. We first define the quantity, the flux transport rate (FTR) as the total distance which all the slabs migrated during a time step. We consider only the transport in the $y$ direction, since the gross transport in the $x$ direction should be negligible, due to the setting of the wind direction. We calculate FTR for all the cases.

Let us begin with the cases where a transverse dune is formed. Figure 7 is FTR for the cases of $(u,v) = (2,6), (3,6)$ (Type (i) evolution) and for the case of $(u,v) = (1,6)$ (Type (ii)).

In Type (i), as a transverse dune is formed directly from the initial state, FTR increases quickly in the beginning and achieves a constant value soon. It is the time when a distinct

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Fig. 5. Snapshots in the case of $(u,v) = (1,2)$. (a): $t = 100$; (b): $t = 400$; (c): $t = 700$; (d): $t = 800$; (e): $t = 900$; (f): $t = 1000$. Four transverse dunes at $t = 100$ grow into two larger ones at $t = 400$. One of the two dunes shrinks gradually until it becomes small ($t = 900$). At $t = 1000$, the smaller one is totally absorbed and a large transverse dune is formed.
linear dune appears. The sand transport is more efficient in the single transverse dune than in the random state.

On the other hand, FTR of Type (ii) increased stepwise for two times. The first increase corresponds to the creation of two barchans (around $t = 100$). The second increase is when these barchans are being transformed into a single transverse dune ($t = 600$–$700$). Thus the sand transport is more efficient in the transverse dune than in the two barchans.

Figure 8 shows the flux transport rate for the case of $(u,v) = (1,2)$ (Type (iii)). We observed that four transverse dunes were transformed into two dunes, then two dunes into one. These dunes were the same in shape. The stepwise increase in FTR was the time when the dunes is being merged together. In this case, too, FTR always increased in the course of evolution. As the number of dunes decreased, the transport became more efficient.
Fig. 7. The flux transport rate for the evolutions of Type (i) and (ii).

Fig. 8. The flux transport rate for Type (iii) evolution.
The observation above is the same in Region B. Figure 9 shows the flux transport rate for cases \((u, v) = (2, 1), (3, 1), \) and \((4, 1)\). For Type (i) evolution \((u, v) = (4, 1)\), FTR increased quickly and achieved a constant value. For Type (iii) \((u, v) = (2, 1)\) and \((3, 1)\), FTR decreased when number of dunes changed. Again, we clearly see that the efficiency in sand transport always increased along the course of evolution.

A question to be raised here is that which factor contributes to the increase in FTR: (a) the increase in the migration length of each slab, or (b) the increase in the number of slabs which were moved. To answer this, we calculate (a) and (b) and found that the increased number of moved slabs (namely (b)) was the reason for the increase in FTR. The migration length (namely (a)) was scarcely changed throughout the simulation.

Then we use the quantity, the shadow zone, which is expected to indicate the system’s evolution more explicitly than FTR. As explained in Section 2, the shadow zone makes the slabs in it immobile. During a time step, slabs are chosen by the wind one by one systematically from the point \((x, y) = (1, 1)\) to \((x, y) = (100, 100)\). When a slab in the shadow zone is chosen, nothing happens, and the next slab comes to its turn. Therefore, the decrease in the shadow zone means the decrease of lost chance to move the sand. Moreover, the shadow zone directly depends on the shape of dunes, it should be a more intrinsic index for pattern formation.

In Fig. 10 we plot the area of the shadow zone for some cases in Region A. We see the shadow zone shrinks in the course of evolution. Naturally, the shadow zone converges to the same value for these cases (FTR does not, even the final pattern is the same). For the case of \((u, v) = (1, 6)\), where two barchans appear transiently around \(t = 100\sim600\), the area of the shadow zone is the same as the final pattern. Thus, in this case, two barchans and a
transverse dune are at the same extent in wasting the chance to move the slabs. In any case (including Region B), we found that the area of the shadow zone decreased during evolution.

In the following we examine why FTR changes stepwise. From the initial random state, small linear dunes appear first. These dunes are different in their size, because of the randomness of the initial state and the wind direction. Since the smaller linear dunes travel faster than the larger linear dunes, smaller ones catch up larger ones after a long enough time. During this process, FTR is almost constant. When the smaller dune comes close enough that one hop of a slab from the smaller dune reaches the other, merging of two dunes begins. Slabs transported quickly from the smaller one to the other, because a slab originated from the smaller dune is deposited on to the other with a large probability. Thus FTR changes stepwise.

Our simulations agree with field observations in that the linear dunes migrate themselves and grow larger (Bristow et al., 2000). Considering our result that the random state is the least effective mode of sand transport, we may expect that the sand in deserts can be transported more efficiently by forming the dune patterns.

5. Summary

We performed a computer simulation on desert dunes to investigate how the sand transport affect the dune shapes and development. Actual dune patterns were reproduced from the initial random state. Three types of evolution were found. Type (i) is a course
where the final pattern is formed directly from the random state; In Type (ii) a transient pattern appears on the way to the final state; the pattern is altered in the middle of evolution. Finally in Type (iii) the number of dunes changes but their shapes are similar. In every course of the evolution the sand transport always increased, and larger dunes made the sand transport more efficient. The shadow zone shrank through the course of evolution, which means that the loss of the chance to move the sand becomes smaller.

This study is partly supported by Sumitomo Funds.

REFERENCES