Dynamics of Sand Ripples and Dunes

Hiraku Nishimori

Department of Mathematical and Life Sciences, Hiroshima University, Japan
E-mail address: nishimor@hiroshima-u.ac.jp

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1. How are Sand Ripples Formed?

Among various striped patterns formed in nature, ripple on sand beaches is one of the most easily sighted features. Let's step out in an windy beach where sand grains are jumping around your foots, you would see sand ripples with typically 10 cm of wave length. If you care individual sand grains at that time, you can find that each of them is alternately moving and resting, where no definite rule looks shared by a mass of grains. Then, what mechanism generates such beautiful undulation of ripple?

Various structures spontaneously organized in spatially-extended non-equilibrium systems are widely called "dissipative structures", among which roll patterns of clouds and striped skin patterns of tropical fishes have extensively been studied as typical examples of Benard cells and Turing patterns, respectively. Partial differential equations describing Turing patterns and Bernard cells formations have been derived under a strong assumptions that the temporal states of the system are described by a combination of spatially continuous field variables, and that the time evolution of them are kept smooth because of their local conservation.

On the other hand, the formation mechanism of sand ripples has not sufficiently been explained so far. This is because the sand bed on a beach consists of a mass of sand grains and every pair of neighboring grains keep interacting so strongly when they directly contact in the sand bed, whereas they move almost independently once released in the air and blown by the wind. In other words, both continuity and discreteness work as the intrinsic characters in the ripple formation dynamics. Moreover, jumps of sand grains break the local conservation of field variable (here, height of sand surface). In such situation, computational studies are considered feasible.

Actually, with the help of computational calculations, a great advance has recently been made in uncovering the basic mechanism of wind ripple formation (Fig. 1). The key process is as follows (Nishimori and Ouchi, 1993); The dominant mean of sand transport under strong wind sufficient for ripple formation is a short jump of grains called saltation. If a small bump or dip is occasionally formed at some location on a sand bed, the jump lengths of sand grains becomes nonuniform around the location, which causes the undulation of the influx of landing sand grains at the lee surface; thus the surface height undulation is produced too. The same processes propagate to the leeward direction. Once a long extending undulation of sand surface is formed, each location in the undulation is sustained by the grains coming from the just windward undulation.

In mathematical ecology, to describe the time evolution of number density of animals, differential equations (or difference equations) with time-delay are often used. For example, the amount of egg production in a year is reasonably modeled to directly determine the number of fishes in the next year. In modeling sand ripple formation, on the other hand, to incorporate the spatial-delay effect is essential, because, as explained above, the surface undulation at one place directly affects the undulation in the leeward surface. So far, the analysis of partial differential equations with spatial-delay has not remarkably been proceeded because of their highly nonlinear character, while a certain progress is expected hereafter accompanied by the development of computational mathematics. Through the progress, not only the research of ripple formation, but also studies on a wider category of pattern formation dynamics may reap unexpected benefits.

2. What Factors Determines the Shape of Dunes?

Next, let us shift our attention from ripples to dunes. Dunes are sand topographies having much larger scales than wind ripples, typically longer than 10 m in wind directional length and higher than 1 m. The largest dunes on the Earth is higher than 100 m. In addition, dunes exhibit various kinds of shapes. Even limited to only typical dune-shapes, the number of their variety exceeds ten, among which the barchan, linear and transverse dunes are easily recognized in desert fields. It was found that the shapes of these typical dunes are governed by small number of factors.

Examining previous observational reports of dune-shapes in various desert fields, Wasson *et al.* showed that only two environmental factors dominantly determine the shape of dunes (Wasson and Hyde, 1983). One of them is the thickness of available dry sand layer in each dune field, and, the other is the annual steadiness of wind direction blowing over dunes. In reality, numerous environmental factors potentially may affect the pattern selection of dunes;

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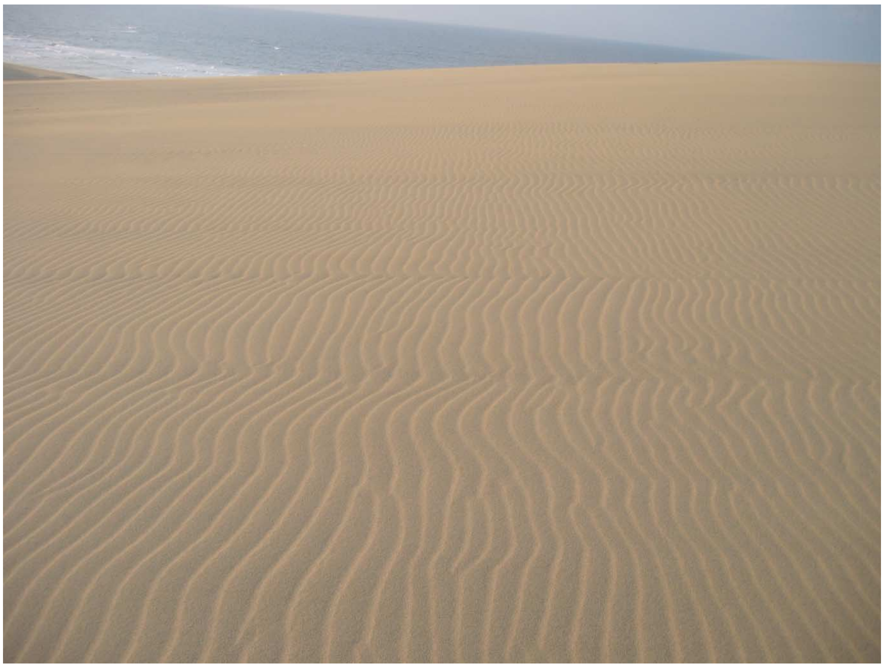
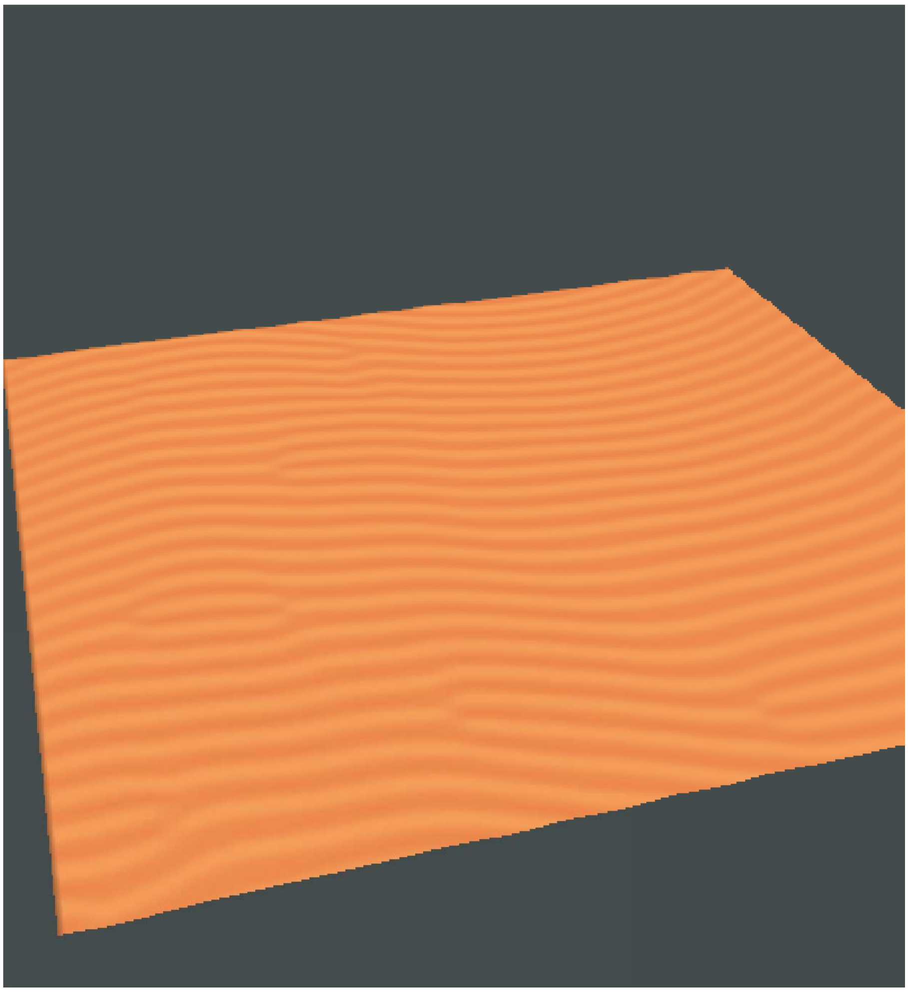


(a)



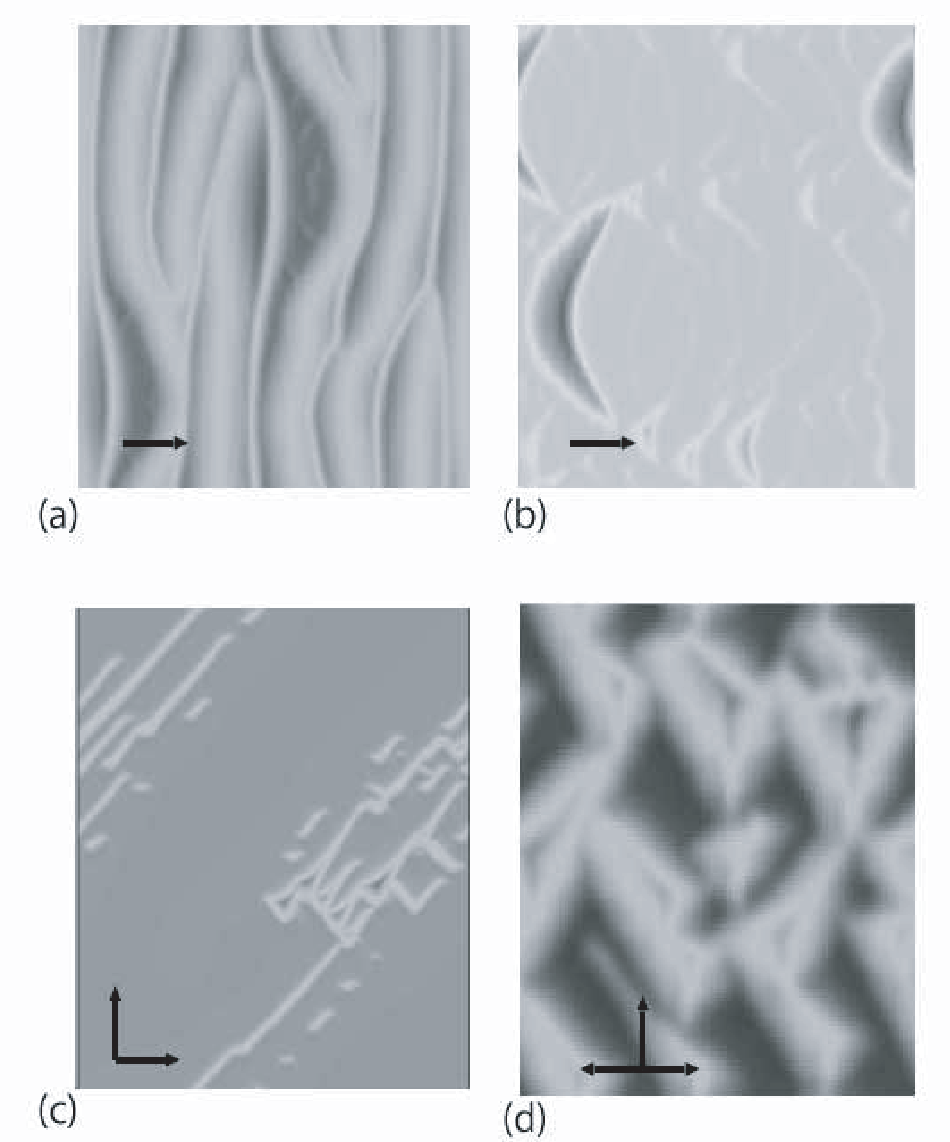
(b)

Fig. 1. (a) Sand ripples formed at the surface of sand dunes, and (b) those produced by computational simulation (Nishimori and Ouchi, 1993).

(a)

(b)

Fig. 2. Typical shapes of dunes: (a) barchans, (b) star dunes, and numerically produced dunes: (a) transverse demes, (b) barchan (c) linear dunes and (d) star dunes (Nishimori *et al.*, 1998). Arrows in figures indicate seasonal wind directions.



(c)

Fig. 2. (continued).

size and shape of sand grains, strength and steadiness of wind, vegetation cover, humidity of air and that in sand layer etc. Therefore, it is surprising that only two of them decisively affect the shape of dunes.

Because of such situation, two dimensional parameter space of the dominant factors is divided into several zones corresponding to respective shapes of dunes. This is just the idea of phase diagram widely used in statistical physics and nonlinear science. According to this basic idea, various types of numerical models have been introduced in recent years, and, have successfully simulated typical shapes of dune formation in each zone in the "phase diagram" (Nishimori *et al.*, 1998) (Fig. 2), most of which would have hardly be realized without computational power.

Still, computational study of dunes dynamics leaves many aspects to be investigated, while some problems are left as the next issues, such as pattern selection problems near the boundaries between different phases of dunes, and the elongation process of linear dunes etc.

Apart from dunes on the Earth, attempts to estimate the rough environmental situations on far distant planets, like Saturnfs moon Titan, from the satellite images of dunes-like patterns are attracting attention among a wide area of researchers, including geologists, planetary scientists, and physicists (Lorenz *et al.*, 2006; Burr *et al.*, 2015).

In these ways, studies of the dynamics of ripples and dunes from the viewpoint of shape-science preserve a great potential to develop new directional interdisciplinary collaboration among different fields of researchers.

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