Snow transport and deposition

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Abstract

The dynamics of snow erosion, transport and deposition due to the action of wind is still a controversial topic. Experts do not all agree on the mechanisms involved in this process and the field remains rather empirical compared to other domain of science. We propose a new description of the phenomenon, based on a simple and intuitive model in which wind and snow "particles" are the basic components. Our approach follows the cellular automata modeling techniques and provides plausible scenarios about the physical mechanisms present in snow transport. Our numerical simulations reproduce correctly a wide range of deposition patterns, showing the importance of our method as a prediction tool or to test theoretical concepts.

Snow transport by wind is still a domain where little understanding has been achieved. Many interesting phenomena occurs and give rise to diverse patterns of accumulation. For instance, when an obstacle is smaller than some characteristic scale, it rapidly gets buried by snow, whereas, if it is larger, the wind perturbation it creates are strong enough to prevent snow from accumulating. Patterns of quite different sizes (a few centimeters up to tens of meters) are observed: they range from the so-called zastrugis (kind of small oscillations of the snow surface similar to sand ripples but differently shaped) to large deposits past a mountain crest. In between these limits, there are also medium scale accumulations like the snowdrifts forming in the presence of a fence, or the deposit within a trench. As it grows, it is often observed that the shape of the deposit evolves in a non trivial way and no obvious scaling form can be found.

In addition to interesting academic problems, snow transport by wind raises important practical questions that strongly influences human activities. How can we prevent a road from getting buried under a snowdrift? Can we control the formation of wind slabs and cornices, which may dramatically increase the avalanche danger above a road or a ski trail? The crucial observation is that snow get transported where the wind is strong and it accumulates where the wind weak. Thus, building obstacles along the wind path influences the deposition pattern and may significantly reduce the drift by storing snow in the sheltered region or by accelerating the wind where the snow must not accumulate. Due to the lack of a theory and forecasting tools, experts still rely on an intuitive or empirical approach to decide on the shape and location of such wind obstacles.

Phenomenologically, snow transport (i.e. erosion and deposition) has been divided in three main processes, each corresponding to a different scale:

- *Creeping:* particles are "rolling" on the surface or making very little jumps.
- *Saltation:* in the first half meter above the surface, snow particles have been observed to be ejected vertically and follow a ballistic trajectory [1].
- *Suspension:* it accounts for transport over larger scales (often seen as white smoke by mountains crests).

To predict snow transport and obtain the snow erosion/deposition areas, both wind tunnel experiments (with fairly good accuracy over a mountain pass area by [2]) and numerical computations have been investigated. The numerical approach can be split in two kinds: statistical methods, based on comparisons with recorded data (they can be accurate on geometrically simple situations), and direct techniques, based on standard computational fluid dynamics (CFD) [3].

The latter approach is technically quite difficult: to compute the wind pattern, one has to solve the turbulent Navier-Stokes equation with dynamically changing boundary conditions (to account for the evolution of the deposition layer). Snow is usually added in some *ad hoc* way. Creeping, saltation and suspension are included separately and most of the time, one or two of these processes are neglected.

In this report we propose a new, radically different numerical approach to simulate snow deposition, free of the above complications and based on the cellular automata and lattice Boltzmann method. Instead of solving a differential equation, we propose a *model* of the phenomena. We consider a "microscopic" description, involving snow and wind "particles" and the essential basic interactions between them.

This approach relies on the fact that several levels of reality exist in physics[4]. On one hand there is the macroscopic level, where phenomena are expressed in terms of rather abstract mathematical objects such as the differential equations. On the other hand, there is the microscopic level of description where the interactions between the basic constituents are considered. An important results of statistical mechanics is that the macroscopic level of description depends very little on the details of the microscopic interactions. Rather, it depends on conservation laws and symmetries (most fluids obey the same equations of motion, though the molecular interactions differ). One can use this property to build a fictitious universe in which the microscopic interactions are particularly simple to simulate on a computer and whose macroscopic behavior is just that of the real system[5].

The first step in this direction was the so-called FHP lattice gas model, a two-dimensional cellular automata fluid proposed by Frisch, Hasslacher and Pommeau [6] in 1986. The fluid is modeled as a large population of boolean particles moving synchronously, according to discrete time steps, along the links of a regular lattice and changing their direction when bouncing into each other. Cellular automata fluids are typically described by occupation numbers $n_i(\vec{r},t) \in \{0,1\}$ indicating the absence or presence of a particle entering site $\vec{r}$ at time t, with a velocity $\vec{v}_i$ pointing along lattice direction i

(for instance i designates the direction up, left, down and right on a square lattice). The equation of motion reads

$$n_i(\vec{r} + \tau\vec{v}_i, t + \tau) = n_i(\vec{r}, t) + \Omega_i(n(\vec{r}, t)) \tag{1}$$

where τ is the time step and Ω_i the collision term defined as a nonlinear combination of the n_i and expressing the balance of particle in direction i after the collision takes place. It is tailored so that *mass* (defined as $\sum_i n_i$) and *momentum* ($\sum_i n_i\vec{v}_i$) are locally conserved by the interaction. Note that boundary conditions are easily implemented in this approach, due to the level of description in terms of particles.

These types of models, despite their artifacts and limitations, captures the main essence of fluid dynamics, in the sense that the local average density $\rho =< \sum_i n_i >$ and local average velocity field $\vec{u} = (1/\rho) < \sum_i n_i\vec{v}_i >$ obey, within certain limits, the Navier-Stokes equation with built-in viscosity and pressure term.

Many progresses have been made to simulate three dimensional fluids and remedy the early deficiencies (lack of Galilean invariance, statistical noise). A key improvement was to simulate the probability of presence $f_i =< n_i >$

of a particle rather than the particle itself. This gives much more flexibility to define the collision rule and the so-called lattice BGK models[7] recover all the expected physical behaviors, have no statistical noise and contains a free relaxation parameter $\tau_r > 1/2$ to tune the viscosity $\nu = (1/6)[2\tau_r - 1]$ (a review of this evolution is summarized in[8]). The dynamics reads

$$f_i(\vec{r} + \tau\vec{v}_i, t + \tau) - f_i(\vec{r}, t) = \frac{1}{\tau_r}\left[f_i^{(0)} - f_i\right] \tag{2}$$

where $f_i^{(0)}$ is the local equilibrium distribution which is a known function of the actual local velocity field $\vec{u}$ and particle density ρ.

Recently, subgrid techniques have also been used in lattice BGK models by adjusting dynamically and locally the relaxation time τ_r according to the local gradients in the fluid

$$\tau_r = \tau_0 + C\left[\partial_\beta u_\alpha + \partial_\alpha u_\beta\right]^2 \tag{3}$$

where C is a constant and τ_0 the bare relaxation time. The indices α and β label spatial coordinates and summation over repeated indices are assumed. Having an effective relaxation time (and thus an effective viscosity) allows one to extrapolate unresolved scales and simulate high Reynolds number flows ($\sim 10^6$)[9].

This latter model is far more elaborate than the original FHP but it keeps its main advantages: one deals directly with fluid "particles," the algorithm is simple, local and fits very well on massively parallel computers.

The main contribution of our work is to add snow particles on the top of such a lattice BGK model for wind and to propose simple erosion and deposition mechanisms. Snow particles can be injected in the simulation (snow fall) or eroded from the ground, deposited and transported according to the combined effect of gravity and wind direction.

It would be far too pretentious (and against our working hypotheses) to include all the complication of the erosion/transport phenomenon (exact number of snow particles, their geometrical structures, the correct inter-particle cohesion, and the evolution of the chemical properties and the temperature...). Following the philosophy of the cellular automata approach, we restrict ourselves to what we identify as the most significant processes and express them in simple rules. The macroscopic behavior will be captured provided that these ingredients are indeed the relevant ones and that enough scale separation exist between the different levels of description. For or the time being, no mechanism is included to compute the strain inside the snow deposit and no realistic cornices can be modeled. The rules we consider are:

Transport: an arbitrary number of snow grains may reside at each lattice site. During the updating step, they synchronously move to the nearest neighbor sites. The amount of grains that reach each neighbor is computed according to a random algorithm which ensures that the average motion satisfies the local wind speed and gravity (i.e the falling speed). No effort is made to split the transport in creeping, saltation or suspension since a particle is not aware of its elevation above the snow ground level. An important ingredient, however, is to make the C constant in equation (3) space dependent so that it decreases from 1 to 0 as the distance to the ground (top of the deposition layer) increases. This is a way to account for a boundary layer and impose a length scale to the system by adjusting the number of lattice sites necessary for C to go to zero.

Deposition: lattice sites can be either solid (original landscape or deposited snow) or free (air). Snow particles on a free site may "freeze" if the neighbor site they want to jump to is a solid site. When the number of frozen particles exceed some pre-assigned threshold, they become solid snow on which subsequent incoming wind particle will bounce back. This threshold gives a way to assign some size to the snow flakes. When a site solidifies the wind particles that may be present get trapped until erosion frees them again.

Erosion: deposited particles may be eroded under some conditions. The erosion rate is not trivial: it seems to be related [10] to the wind speed above the solid site, the concentration of snow being transported, the saturation concentration and the efficiency of the transport. In our model, erosion means that snow particles are ejected with a vertical speed. This happens with some (low) probability $p(u)$ when the local wind $\vec{u}$ is faster than a threshold. This ejection probability is related to the "efficiency" of the transport which, in turns depends on the kind of snow we are dealing with.

Since no first principle theory is available, the only and most convincing way to assess the validity of our model is to compare its predictions with the outdoor observations which can be found in the literature. Our simulations has been tested against a wide range of situations and has shown to catch realistic phenomena at very different spatial scales, using a coherent set of parameters (we only modify the space dependence of C). The situations we have considered are the following and are detailed in figures 1 to 4.

- Snow deposit along a mountain crest (fig.1), at different position, to compare the influence of the landscape profile on the deposit.

- Snow accumulation around a fence (fig.2). Fences are commonly used to store snow downwind. One may observe the influence of a bottom gap on the deposit length.

- Filling of a trench (fig.3) excavated in a large flat area, to observe the non-intuitive deposition pattern and its time evolution.

- Micro snow transport, creating zastrugis (fig.4) (or ripples).

All these simulations are two-dimensional and have been performed on a massively parallel computer (a 8192 processors CM-200) which is very well suited to the present approach.

In conclusion, our model not only produces quantitatively realistic deposits, it also provides, through the simple and intuitive rules we have used, a better understanding of the basic (and quite controversial) mechanisms that occur in snow transport. It shows that the various patterns of deposition result from the emergence of a collective effect rather than from mechanisms that have yet not been identified. Creeping, saltation or suspension are no longer three different phenomena, each requiring special treatment, they are all captured by the same erosion/transport mechanisms. Thus, our model results in an unified view of the basic laws governing the formation of snow deposition pattern.

Note that the same approach can be extended to simulated sand dune formation or sedimentation problems. To model dry sand deposit, one could neglect cohesion and allow a particle to deposit only if it occupies a stable position with respect to the solid sites underneath.

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Figure captions

Figure 1: Snow deposit over mountains crests, where the wind blows from left to right (different positions along the same crest - the Schwarzhorngrat near Davos). Our results can be compared with terrain observation by [11]. The agreement is fairly good, excepted for the steeper (furthest) slope, where a cornice has been observed. Our model does not catch this feature as there is no rule dedicated to the growth of cornices.

Figure 2: Snow deposition around a fence without or with a ground clearance. The shape of the deposit and the influence of the bottom gap are in good agreement with observations[12]. The purpose of the gap is to prevent the fence from being buried quickly and lose its efficiency. In theses simulations, the lattice spacing is 0.2m.

Figure 3: A trench (0.7x1.6m, lattice spacing 0.03m) is getting buried under snowdrift. Field observations have been achieved by [1]. Good agreement is observed between the model and reality, mainly for the first part of the experiment (growth of two depositon peaks), before the wind has slowed down in the outdoor experiment.

Figure 4: Zastrugis are observed under special conditions (fresh mobile snow fallen without wind followed by a wind episode inducing a high creeping flux). Little bibliography exists on this subject, but the ratio between the height the and the spacing of the oscillation is about the same as written in [2]. Field zastrugis height has been observed between a few centimeters up to one meter. We also observe the same shape as in reality (much steeper windward than leeward, as opposed to sand ripples because sand has no cohesion like snow). The slow downwind motion of the zastrugis is also captured in our model, though not visible in this figure.

FIGURE 1

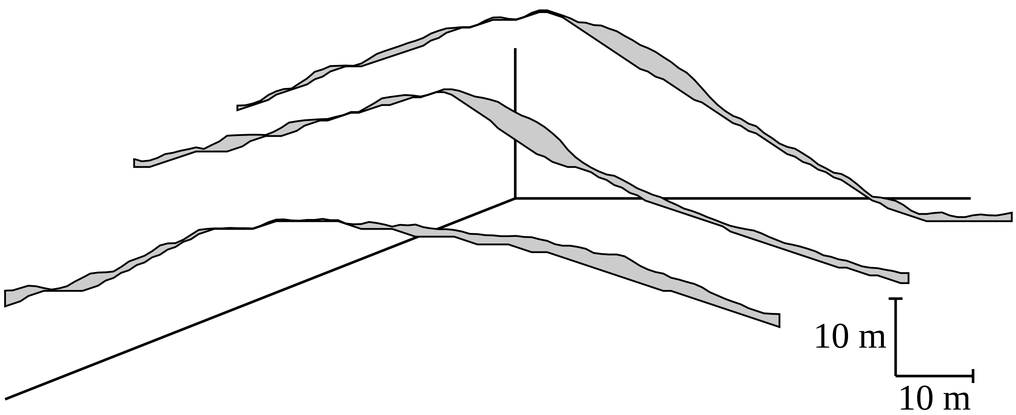

FIGURE 2

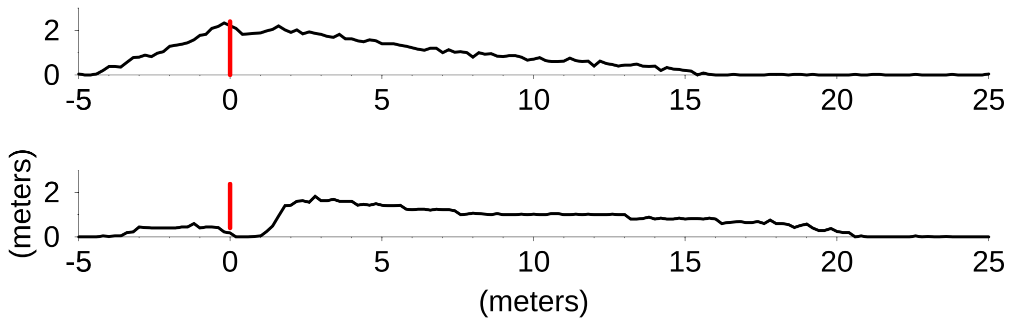

FIGURE 3

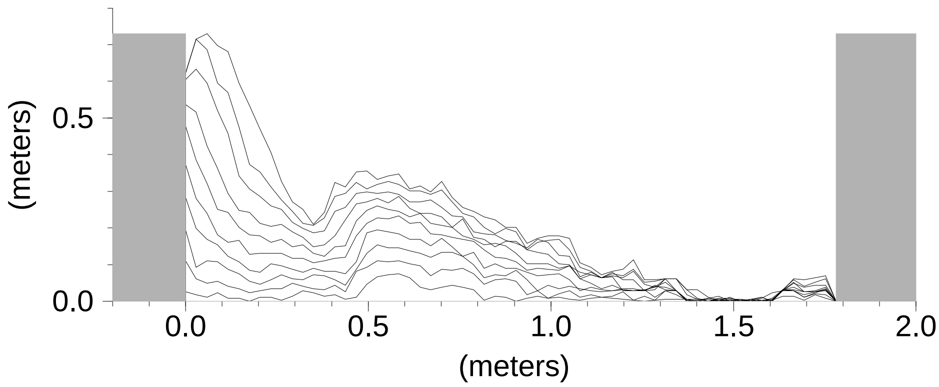

FIGURE 4