Snow avalanche dynamics: observations and experiments

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ABSTRACT. In order to investigate the dynamics and the detailed structure of snow avalanches, we have made systematic observations in the Shiai-dani, Kurobe Canyon since 1989. Velocities of the lower flowing component were calculated by differencing measurement of impact pressure. A ultra-sonic anemometer or a new device to measure static pressures was used to estimate velocities in the snow cloud that develops above the flowing component of avalanches. Both recordings of flowing part and snow cloud changed with a similar trend and suggests a close interaction between the two layers.

On the other hand, we have started the snow avalanche experiments at a ski jump. In winter, natural snow 300 kg in weight at maximum was released and flow velocities, impact pressures, induced wind velocities, and dynamic friction coefficients were measured. The observation setup is almost the same as the one installed in Shiai-dani. Instead of snow itself, in summer, we have used 350,000 ping-pong balls. Since the air drag was a large effect, the flow arrived at a steady state within a short distance. The terminal velocities attained increased with the number of released balls. In addition, the flow formed a distinct head and tail structure, which has often been observed in large-scale geophysical flows in nature. Similarity analysis is used to show that the experiment corresponds to a natural powder snow avalanche that runs for several kilometers.

Computer simulation of 3-dimensional, inhomogeneous two-phase flows that uses the DEM (Discrete Element Method) for the particles and the Reynolds-averaged Navier Stokes Equations for the fluid are currently also in progress. The unique nature of the ping-pong ball experiment provides a wonderful opportunity for testing a theory and simulation of strongly coupled two-phase flows.

INTRODUCTION

Since the winter tends to be milder year by year in general, the government office, the resident and even the research institute look as if they forgot the natural disaster due to the snow avalanche. In Japan, however, we should notice that 143 avalanche disasters have been reported last five years and they caused fifty fatalities. In particular, it should be stressed that seventy-seven accidents happened and thirteen people were killed in the winter from 1995 to 1996, in which we had only an average snow fall.

In order to increase our knowledge of the avalanche dynamics and contribute to an avalanche zoning and the design of structures, we have been carried out not only the avalanche measurements in nature but also the experiments at ski-jump.

In this paper we introduce both approach and the obtained data including the numerical simulation results briefly.

MEASUREMENTS IN NATURE

A Japanese-Norwegian joint project has been organized since the winter of 1990 to 1991 and systematic investigations have been made at Ryggfonn. Although we succeeded in obtaining some sets of valuable data, for example, internal velocity, velocity shear, growth rate of snow cloud (Nishimura et al., 1993, 1995), we leave it there and focus on the measurements at Shiai-dani, Kurobe Canyon, Japan.

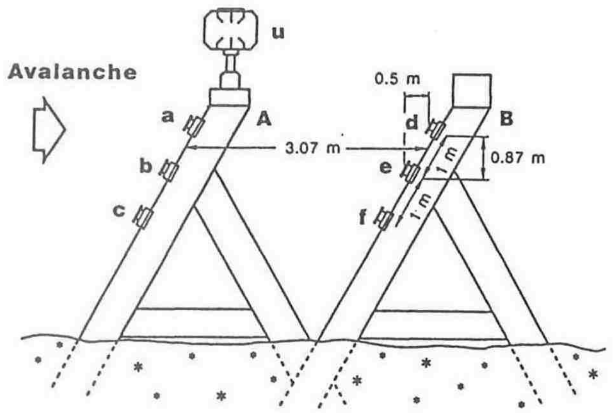

Figure 1 Measuring apparatus set in the Shiai-dani. The a-f, impact pressure sensors and u, an ultrasonic anemometer.

In the Shiai-dani, a systematic investigation of natural powder snow avalanche has been under way since 1989. In winter, snow usually accumulates to more than 20 m in the valley and the air temperature falls to below -15 ℃ (Kawada et al., 1989). Shiai-dani starts at an elevation of 1600 m a.s.l. and at the junction with the Kurobe River at the elevation is 600m; its length is about 2000 m, the vertical drop is 1000 m, and angle of inclination is 33 deg.. At the main observation site at the midpoint of the avalanche path, instruments were set to measure avalanche impact pressures, wind velocity, wind pressure, atmospheric pressure, temperature and ground vibration. Avalanche movement was recorded with three video cameras. Most of the equipment was installed on two steel mounds of cylinders 0.3 m in diameter and 5 m in height (Figure 1). Data were recorded at a rate of 1 kHz by the data acquisition system in an underground room. Detailed information on the measurement system can be found in Kawada et al. (1989) and Nishimura et al. (1989).

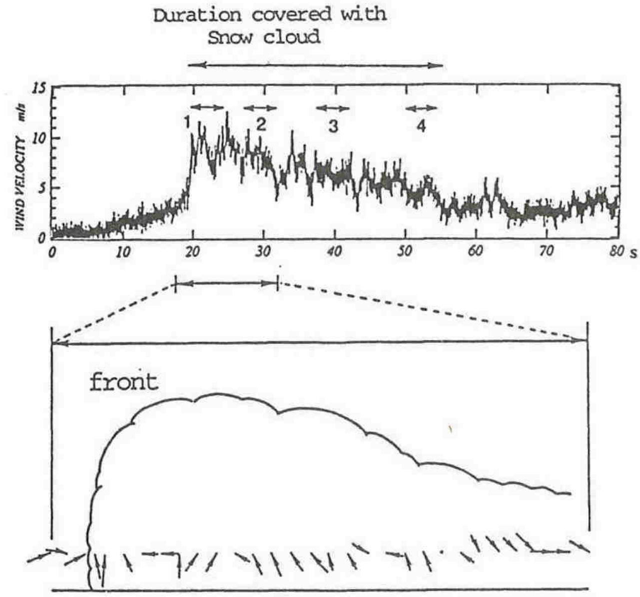

Figure 2 Air velocities in avalanche on 9th February 1991 in the Shiai-dani. and a schematic picture of internal structures near the front.

Figure 2 shows the recording of ultrasonic anemometer on 9th February 1991. The dense flowing part of the avalanche was observed to stop about 200 m in front of the observation site and only the snow cloud passed by. The period indicated with arrow in the figure shows the duration of time covered with snow cloud. The wind velocity became large gradually before the front and increased rapidly in the snow cloud region and came up to about 12m/s, 4 seconds later. In the following 30 seconds it declined gradually. Although some fluctuations appeared, the average wind direction was nearly 360° which corresponds to the upstream of the valley. Since the wind blew down the valley, the vertical component of the wind velocity was negative in general, but it became positive near the front. In addition, both the wind velocity and direction showed the periodic change which implied ordered, vortex-like structures existed in the snow cloud (Nishimura et al., 1993). To investigate more detailed structures near the front, the recordings in Figure 2 were analysed to show the air flow relative to the avalanche front movement. It should be noted that rising current exists near the front. On the contrary, air moves downwards in the trail.

Friction velocity and the root-mean-square values of the vertical component of the eddy velocity were calculated by means of the wind records and shown in Table 1. Numbers from 1 to 4 in table 1 corresponds to the part indicated in Figure 2 respectively. It is reasonable to consider that snow particles on the surface are entrained in the air in the region from 1 to 3 because threshold friction velocity for the drifting snow is usually known as less than 0.3 m/s. On the other hand, if terminal fall velocity is of the same order of the magnitude as the root-mean-square values of the vertical component of the eddy velocity $\sqrt{\overline{w^2}}$, the particle also can be taken into suspension. Table 1 indicates that $\sqrt{\overline{w^2}}$ obtained near the front is much larger than the terminal fall velocity of snow particles which is considered to be 0.5 to 1 m/s. Thus we can conclude that near the avalanche front snow particles on the surface are entrained in the cloud due to the high friction velocity and are kept in suspension. On the contrary, in the tail which corresponds the region 4 turbulence was not enough to suspend particles and the deposition was taking place.

Table 1 Turbulence structure in the snow cloud
Mean wind velocity: U (m/s), Friction velocity: u_* (m/s), and Vertical component of eddy velocity: $\sqrt{\overline{w^2}}$ (m/s).

	U	u_*	$\sqrt{\overline{w^2}}$
1	8.6	0.80	1.60
2	7.4	0.13	0.93.
3	6.3	0.12	0.90
4	4.7	0.01	0.41

As shown above, the ultra-sonic anemometer could reveal the internal structure of the snow cloud of one small avalanche (Nishimura et al. 1995). However, there are a couple of limitations in this method: First, it is expensive and large avalanches can sometimes destroy the sensor; Second, it often gives ambiguous signals when the density of the snow cloud is relatively high. Then we applied the measurements of the static pressure depression in the flow and use these measurements to estimate the air velocity in the snow cloud.

In general, we can expect that air flow velocity u (m/s) is related to the static pressure depression ΔP (Pa) in the flow. It can be expressed by the equation:

$$\Delta P = \frac{1}{2}\rho u^2 \qquad (1)$$

where ρ is the density of the air. However, the diameter (0.01m) and the length (40m) of piezometer tube substantially affect Equation 1. Wind tunnel experiments were performed to calculate the exact relation and the method of least squares were used to calculate the empirical equation $\Delta P = 0.44\ \rho u^2$. The effect of snow particles may be not negligible, our snow flow experiments at the Miyanomori ski jump proved the reliability of this measurement (Nishimura and Ito, 1997). A piezometer tube to measure the static pressure depression in the snow cloud was added to the instrument tower in Shiai-dani for the 1995-96 winter.

Figure 3 shows the air velocities calculated from the static pressure difference between in an avalanche cloud and in the underground room during the passage of four dry snow avalanches. Since the snow cover was observed to be about 2 m deep, it presents the recording at around 3 m high from the snow surface. The avalanche at 1337 on 29 January (Figure 3 d) was the largest one in seven years, and was strong enough to damage the observation tower and to destroy some instruments. The velocity of the snow cloud showed rapid increase to more than 56 m/s, the limit of measurement with this system. The velocity then declined gradually with periodic fluctuations.

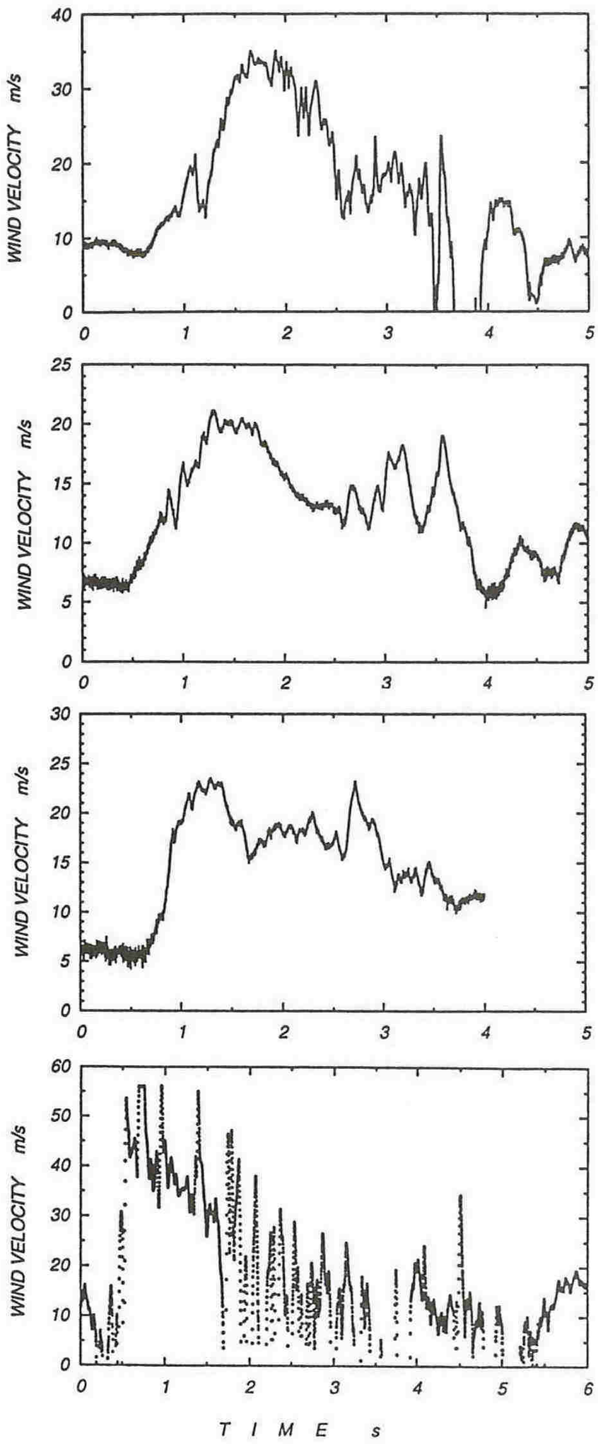

Figure 3 Air velocities in a snow cloud calculated with the recordings of the static pressure depression in the Shiai-dani. A: 0118 LT, B: 0510 LT, C: 1456 LT on 26th, and D: 1337 LT on 29th January, 1996.

Velocities of the lower flowing layer were also calculated by differencing measurement of impact pressure. The cross-correlation function was calculated at 0.25 s intervals from a time series of impact data to find the average internal snow flow velocity. The velocity was obtained every 0.25 s from a combination of the lag time that gave the highest correlation and the distance between the two measuring points. Further details of the method have been given in Nishimura et al. (1989). Calculated velocities for the pair of b and e in Figure 1 are presented in Figure 4 which shows that the magnitude and the variation of the velocity in the snow cloud are in approximate agreement with the one of snow layer, which suggests a close interaction between the two. Since the interval of calculation here is much coarser than the sampling rate of static pressure depression (10^3 s^{-1}), we cannot compare the data directly. However, it is noteworthy, that the velocities of the snow flow also show a periodic change with a dominant frequency of around 1 Hz. Such longitudinal wave-like characteristics were also found by McClung and Schaerer (1985) for both wet and dry avalanches.

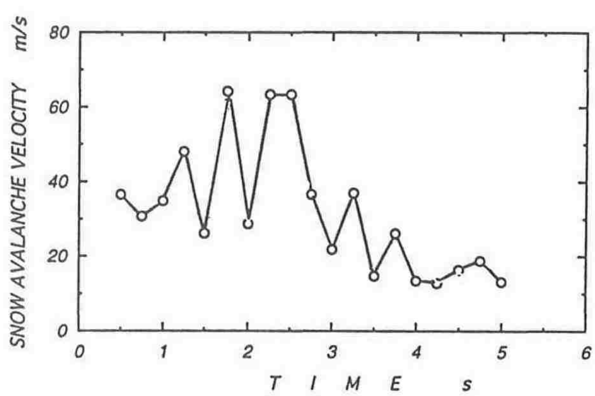

Figure 4 Internal snow flow velocities of the avalanche at 1337 LT on 29th January, 1996. calculations were carried out for the pair of b and e in Figure 1.

EXPERIMENTS AT SKI JUMP

Perhaps it is right to say at the outset that snow avalanches are made up of granular materials. After a dry snow avalanche starts, the snow blocks are broken into smaller lumps or even ice particles. On the other hand, after a wet snow avalanche stops we find a number of snow balls in the debris. Hence, some of the results from studying granular flows can be applied to snow avalanche modeling (Savage, 1983), but unfortunately most of the theories and numerical simulations developed so far appear too simplified to realistically decide the snow avalanches. To investigate granular flows, we carried out inclined chute experiments with snow and ice spheres in a cold laboratory and obtained the profiles of density and velocity as functions of inclination and temperature (Nishimura et al., 1993). However, it was unclear whether the flow reached the steady-state in the 5.4 m long. Thus, as a next step, we have started avalanche experiments on the Miyanomori ski jump in Sapporo, because it offers the longest inclined plane under controlled conditions. In winter, natural snow 300 kg at maximum was used. In summer, on the other hand, we have released up to 300,000 ping-pong balls to perform three dimensional granular experiments (Nishimura et al., 1997). In this paper, experimental procedures and some results obtained by the ping-pong experiments are shown.

The ping-pong balls used in this study were 37.7 mm in diameter and weighted 2.48 g. Since the effect of the air drag acting on such a light ball is fairly large, the flow velocities were expected to arrive at steady state within a short distance. In fact, Nohguchi et al. (1996) found in their 22 m long chute experiments that the front velocity of ping-pong ball flow became nearly constant at 10m downstream of the starting point. Furthermore, Nohguchi (1996) concluded with his similarity analysis that the ping-pong flow on the 100 m long slope corresponded to the natural powder snow avalanches which run down for a few kilometer distance.

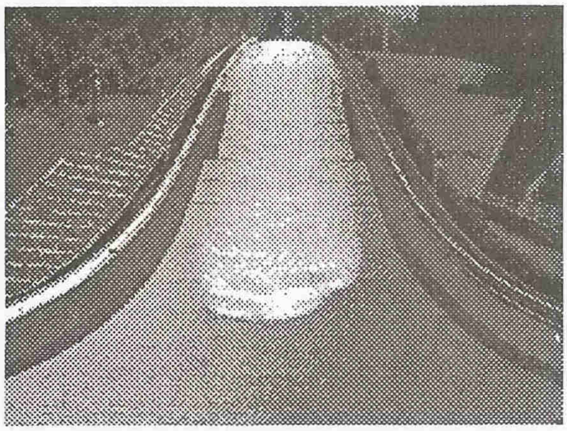

Figure 5 250,000 ping-pong ball flow along the ski jump.

In the experiments, up to 300,000 ping-pong balls were stored in a large container set on top of the landing slope. They were released simultaneously by opening the gate of the container. The flow accelerated down along the 150m long and 30 m wide slope, the floor of which was made with an artificial grass and its inclination amounted to 36 deg. from K to P point. The individual movements of the balls and the behavior of the flow were recorded with several video cameras (Figure 5).

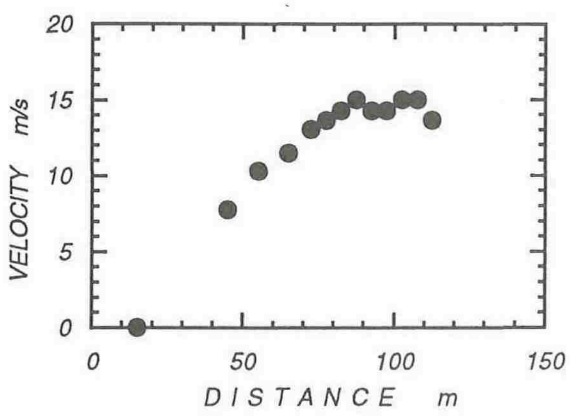

Figure 6 The leading edge velocity of the ping-pong ball flow.

Figure 6 shows the leading edge velocity as a function of runout distance when 250,000 ping-pong balls were released from 15 m down the top. The flow accelerated linearly with the distance down the inclined artificial grass floor and its velocity eventually amounted to 15 m/s 65 m down from the starting point. Then the flow kept the

velocity almost constant for 30m until the inclination started to decrease; that is a steady granular flow moving at its inherent terminal velocity was obtained. The flow spread out laterally and longitudinally as it moved down the slope (Figure 6) and, after passing the steepest part, the flow came to a stop on the braking track.
The flow velocities and run out distance strongly depended on the number of released balls. The leading edge velocities measured from K to P point are given in Figure 7 as a function of the number of released balls. The velocity showed a remarkable growth from 2.8 to 15 m/s as the number of ping-pong balls increased from 2 to 300,000. Generally not only air drag but also particle-particle and particle-floor collision act to reduce the velocity. In fact, when two balls were released the velocity was only 2.8 m/s; each ball ran down individually without interaction. This velocity is much less than the free fall velocity of a ping-pong ball, which is U_t = 9.4 m/s. However, with an increasing numbers of balls the free fall velocity was reached and surpassed. In fact the largest velocity 15 m/s which is 1.5 times larger than the free fall velocity.

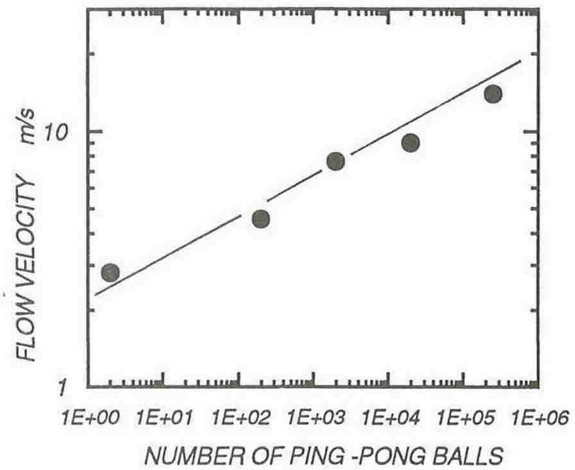

Figure 7 The leading edge velocities from K to P point as a function of released ball numbers. The line was derived theoretically by Nohguchi (1996).

In the experiments, as the number of balls increased, the head and tail structure became clearer and clearer. When 250,000 balls were released, the thickness of the head became higher than 60 cm which corresponds to about 16 particles diameters. Although the individual balls changed positions rapidly, the leading edge flowed like a consolidated body. Hence, it is reasonable to say that the size of the head gives a strong effect on the flow velocity change listed in Figure 6. In addition, it should be noteworthy that the head and tail structure shown this experiments had been often observed not only the snow avalanche but also other large-scale natural geophysical flows in nature.
A video camera positioned above the flow allowed the measurement of the location and the distance of a single ball, which finally leads to its velocity. Different profiles in head and tail as well as other properties are obtained. The static pressure depression measurement in and above the flow led the air velocity profiles qualitatively (Figure 8).

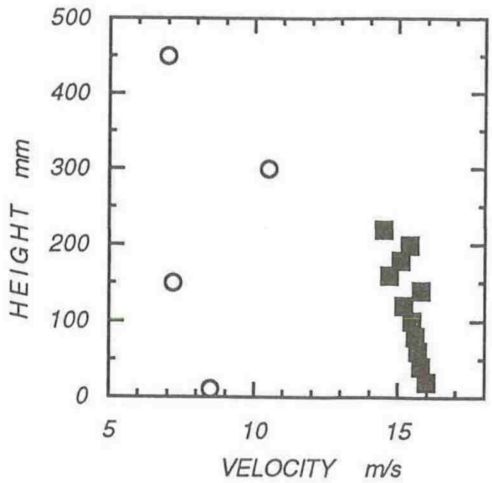

Figure 8 Vertical profiles of the downslope velocity components of the ping-pong ball (squares) and of the air in the tail(circles).

NUMERICAL SIMULATION

Particle/gas two-phase flows are at the heart of many industrial processes as well as snow avalanches and snow drifting/saltation. Until recently however, mathematical modeling has not been particularly successful. Many people have studied the equations but due to their extreme complexity little progress has been made. In recent years 2-dimensional DEM (Discrete Element Method) simulations have increased the understanding of granular flows and progress has also been made towards simulating two-phase flows, though as yet these simulations do not accurately deal with particles strongly coupled to fluids nor do they deal with 3-dimensional and/or anisotropic flows. We are developing a system for the simulation of 3-dimensional, inhomogeneous two-phase flows that uses the DEM (Discrete Element Method) for the particles and the Reynolds-averaged Navier Stokes Equations for the fluid that will run on Hokkaido University's Hitachi SR2201 massively parallel supercomputer.
The first stage of the project is to complete the system design for simple, well understood particles (ping-pong balls) and test the theoretical predictions. By analyzing the data of ping-pong ball experiments from video cameras, seismic sensors and air pressure sensors a great deal of information is available about the individual particle trajectories and air flow that is not available from laboratory experiments. The initial stage of our project is to attempt to quantitatively reproduce the results of these experiments. The unique nature of this experiment provides a wonderful opportunity for testing a theory and simulation of strongly coupled two-phase flows.
The flow itself has a complicated three dimensional structure, similar to powder snow avalanches, and none of the usual approximations in two-flow phase theory are appropriate since the flow is highly inhomogeneous and the volume fraction of the particles is large. The second stage of this project is to extend the system to include the more

complicated inter-particle interactions of snow and ice particles as well as different geometries.

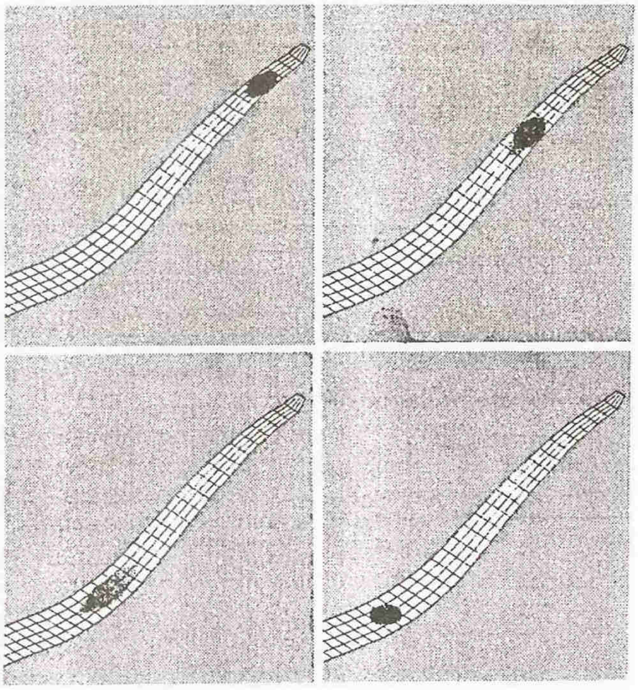

Figure 9 Numerical simulation of the 1000 ping-pong ball flow at the Miyanomori ski jump.

By using the data from snow saltation experiments to check the validity of the system it will be possible to predict wind profiles and trajectories, and describe non-stationary saltation in the drifting snow. This will lead to a better understanding of saltation that is unavailable with present experimental techniques. If the approximations of Reynolds averaging are valid and suitable closure conditions can be found we will then extend the system to look at the saltation/suspension transition that occurs when turbulent velocities exceed the particle terminal velocity. This transition is at present very poorly understood but is crucial for predicting and controlling drifting snow. The transition also occurs on the top of a dense snow avalanche as it gains speed and transforms into powder snow avalanche and is important for understanding the genesis of powder snow avalanches as well as mass/momentum balance between the dense flowing part and the powder part.
The four figures shown in Figure 9 show different times in a small 1000 ball simulation of the Miyanomori ski jump ping-pong ball experiments.

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