IMPROVING AVALANCHE FORECASTS BY EXTRACTING BOUNDARY CONDITIONS FROM MEASURED WIND DATA AND LOCAL WEATHER MODELS FOR SNOW DRIFT SIMULATION IN ALPINE AREAS

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ABSTRACT

Due to increasing development of Alpine environments by transport and tourism the forecasting of avalanche danger becomes more and more important. The protection of civil facilities and human lives is one major aim of avalanche forecasting. The accuracy of avalanche forecasting depends mainly on the precision of the provided initial conditions. Results close to reality can only be obtained by introducing real weather data. On the one hand these data can be extruded from local weather models such as Inca. Extra computational effort is needed to calculate boundary conditions based on this data. Comparison to calculation with constant average wind shall point out whether the implementation of the weather data provided by Inca is worth the extra costs or not. On the other hand weather data can be provided from station measurements by solving the open boundary conditions problem. In irrespective of the chosen methods, the operation has to happen fast enough to fulfill the requirements for the long-term objective, the forecast of avalanche danger. The results show significant differences in the deposition patterns and snow depth using a time averaged wind field or using a time varying wind field even after a 6 hours drifting period. Hence, using Inca for snow drift simulations prevails.

Keywords: snow drift, fluid dynamics, avalanche, INCA, open boundary conditions

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INTRODUCTION

Up to now the evaluation of avalanche danger depends on the knowledge of the properties of the snow cover, the available meteorological data and the interpretation of meteorological weather models. Following this approach it is possible to identify regional levels of avalanche danger, but the outcome is not sufficient for assessing the avalanche danger on small scales.

The determination of snow drift occurrences at critical local failure scars is limited by these common methods. Due to low visibility during snow storms it is not possible to evaluate the different snow layers. In fact the avalanche professionals are aware of the existence of a critical snow layer, but it is very difficult to examine from the valley the amount of accumulated snow at potential avalanche fracture zones.

The numerical simulation of snow drift supplies an area-wide distribution of the snow depth. The numerical approach includes time dependent geometries of the snow cover and complex particle transport phenomena. Additionally, the erosion and accumulation of snow particles leading to a deformation of the snow cover is determined by wall shear stress criteria. These deformations of the shape of the snow pack couple to the wind field and thus the flow is changed by the new geometry.

As an additional important issue the selection of appropriate boundary conditions for calculating the wind field has to be taken into account. In first place data from weather stations, which are located in the simulation area, can be used to determine the boundary conditions by applying a inverse approach. If there is no station data available, the boundary conditions can be provided by local weather models.

THE PHYSICAL CONCEPT OF SNOW DRIFT

Snow transport can be described as follows. If the wind shear exceeds a certain *threshold* grains will be entrained and set in motion. The so called *fluid threshold* (for reference see Bagnold 1941) is given by

$$\tau_{c_e} = (A_e)^2 (\rho_P - \rho_a) g d_P .$$

ρ_P and ρ_a are the densities of the snow particles and air. Furthermore g denotes the standard acceleration due to gravity, d_P the snow particle diameter and A_e a dimensionless empirical parameter, which is a function of the particle shape and particle cohesion. The exact underlying mechanism which is responsible for the initiation of the snow drift process is not completely known. Following Bagnold, Anderson and Haff (Anderson and Haff 1991) estimated that the number of entrained grains per unit time and unit area depends linearly on the excess shear stress

$$\frac{\partial N_e}{\partial t} = \xi\left(\tau_a - \tau_{c_e}\right)$$

where τ_a denotes the air induced shear stress. ξ is an empirical constant with the dimensions of (force x time)$^{-1}$. The entrained particles are easily accelerated by the wind because of their small mass and diameter. Already entrained grains contribute to the wind shear, i.e. they reduce the threshold. In addition, the wind influences the heights of the transport modes, e.g. the saltation layer height increases with increasing wind speed (for reference see Owen 1964).

Therefore, a higher amount of snow can be transported and more grains are entrained per unit of time. Due to the interaction between grains and wind the wind field is modified. However, if the wind shear is below a second *threshold*, the *impact threshold*, snow will be accumulated

$$\tau_{c_i} = (A_i)^2 (\rho_P - \rho_a) g d_P,$$

where A_i is again a dimensionless empirical parameter. Grains whose motion is directed towards the snow pack are deposited. The mass flux to the snow pack can be obtained by the change of volume fraction of the snow in an arbitrary control volume. In especially the change of mass inside the control volume has to be equal to the mass flux through the faces of the control volume by the principle of mass conservation.

Finally, it should be mentioned that only a certain amount of grains can be transported by the wind. This leads to deposition where the volume fraction exceeds a third *threshold*, the *saturation volume fraction*. In all cases, gravity acts as a body force. Due to the slope angle of the snow pack the snow grains are affected by a downhill-slope force. Since the shear stress thresholds mentioned above are only valid for flat plains a modification, which additionally incorporates the slope angle, is applied.

The transport processes discussed above cause a deformation of the snow pack. In deposition zones the snow cover is growing and thus the new shape influences the local velocity field. In addition, in erosion zones a reversed process takes place. Hence, due to the modification of the wind field the zones change with time and depend on the shape of the snow pack.

A MIXTURE MODEL APPROACH

The mixture model approach is based on the balance equations of a mixture for interpenetrating phases, where the phases are allowed to move with different velocities (Schneiderbauer 2006). In the model we consider three different phases:

- Air
- Drifting snow
- Precipitation.

Air acts as carrier phase and is observed as a wind field or primary phase. The transported grains are modeled by the secondary phases, which are observed as drifting snow. The saltation and the suspension layers are not separated as in Gauer 1999, but they are given by the behavior of the snow phase due to the flow field of air and due to the influence of gravity. This snow drift model is fundamentally based on Bagnolds impact and erosion criteria (Bagnold 1941), which distinguish between zones of erosion and zones of deposition. Additional empirical relationships, which are obtained from several measurements (for reference see, e.g., Naaim-Bouvet et al. 2001), such as the height of the saltation layer, which influences the saturation volume fractions in the finite control volumes, are of vital importance for computational calculations.

Precipitation is included by an additional secondary phase to incorporate the different physical properties of precipitating snow and drifting snow. In especially different grain sizes, densities and particle shapes are placed in the snow drift simulation.

As mentioned above in our mixture model approach the saltation and suspension layer are not treated separately in different calculation domains. The saltation layer is rather modelled by volume fractions of the snow phase in the volume cells adjacent to the snow cover. The mass fluxes are obtained from the flow field of the snow phase. Bagnold's "stick-slip" criteria are used to distinguish between zones of deposition and aerodynamic entrainment. To avoid unphysical effects in the flow field we introduced a saturation volume fraction. The deformations of the snow cover are predefined by the mass fluxes and the unit surface normals. A dynamic mesh model will remesh the domain if yield criteria are exceeded.

A PSEUDO INVERSE APPROACH FOR OPEN BOUNDARY CONDITIONS DETERMINATION

In many cases measured wind data from weather stations is available in the vicinity of the area of interest. But for the numerical simulation of the wind field we need the wind speeds at the boundaries of the area. The calculation of these so called "open boundary conditions" from measurement data is of vital importance for the modelling of wind fields.

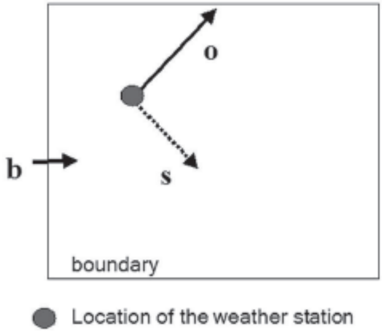

Fig 1: Illustration of the boundary, observation and solution vectors, which indicate the wind speed and wind direction.

In general, this inverse problem cannot be solved directly (e.g. Engl 2004) because of the non linear partial differential equations describing the fluid flow. Therefore, the computation of the wind speeds at the boundaries is considered as an optimization problem (e.g. Chu et al 1997). We define the cost function

$$I(\mathbf{b}) = \left\|\mathbf{s}(\mathbf{b}) - \mathbf{o}\right\|^2$$

where **b** denotes the wind speed and direction at the boundaries, **s** the wind speed and direction at the location of the weather station and **o** the measured wind speed and wind direction. These quantities are illustrated in figure 1. The coefficient α denotes a regularisation parameter and *T* the duration of the simulation. By minimizing the cost function the wind speed and wind direction at the boundaries can be computed iteratively.

If data from more than one weather station is available the cost function has to be rewritten as follows

$$I(\mathbf{b}) = \left\|\mathbf{s}_i(\mathbf{b}) - \mathbf{o}_i\right\|^2$$

where the subscript *i* stands for the i-th metrological station.

THE LOCAL WEATHER MODEL

INCA (Integrated Nowcasting through Comprehensive Analysis) is being developed at the Austrian ZENTRALANSTALT FÜR METEOROLOGIE UND GEODYNAMIK and used to obtain the time varying wind field conditions for the snow drift simulation. The fine output resolution of INCA 1 x 1 km is possible because of the use of several data sources during the calculation of the different meteorological fields (e.g. wind, pressure, humidity, …; for reference see Yong et al 2006 or Haiden et al 2007) as shown in figure 2.

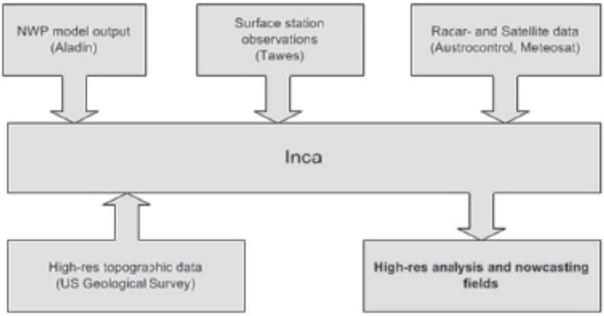

Fig 2: Inca uses several different sources for the calculation of metrological fields, the single most important data source is the network of about 150 automated surface stations called Tawes. The NWP (Numerical Weather prediction) model Aladin is used as first guess for the three dimensional analyses of temperature, humidity and wind

In this work, we take advantage of the nowcasting output of INCA to provide a forecast of the wind speeds and wind direction for the simulation of snow drift in alpine environments up to 6 hours. We concentrate on the appropriate integration of wind fields, but neglecting other meteorological data. Because of the significantly higher resolution of the computational domain for the snow drift simulation the overlay of the INCA velocities is done by a bidirectional interpolation onto the boundaries.

RESULTS

Snow drift distributions of fracture zones are very important for operational avalanche warning. In practice the assessment of those zones is a major problem for the present avalanche warning systems. We determined the snow drift distribution at the Birkgraben chute in Styria. In the vicinity of the chute the avalanche warning service of Styria operates a weather station (Planneralm, figure 3). We used these data to compute the boundary conditions for the snow drift simulation, which was performed within the dashed area (figure 3). At the station prevailing west-north-west winds were measured (figure 4, dash and dot lines). These conditions at the location of the station result in north-west-north winds at the Birkgraben chute by applying the pseudo inverse algorithm. In figure 4 the convergence history of the iterative solution of the optimization problem is shown.

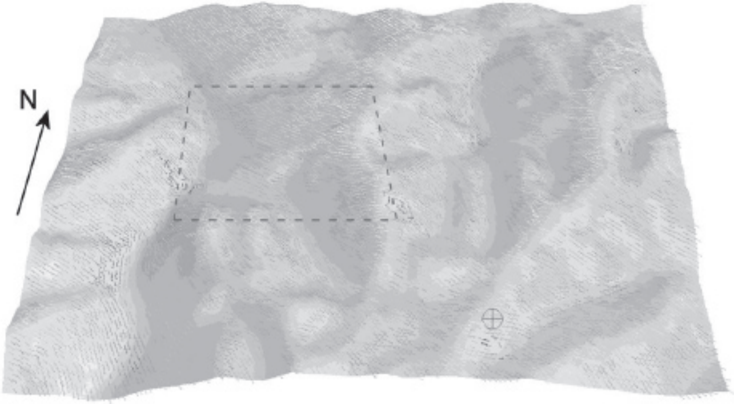

Fig 3: Wind field at 10 m height around the Birkgraben chute (dashed area). The Planneralm station is indicated by the cross.

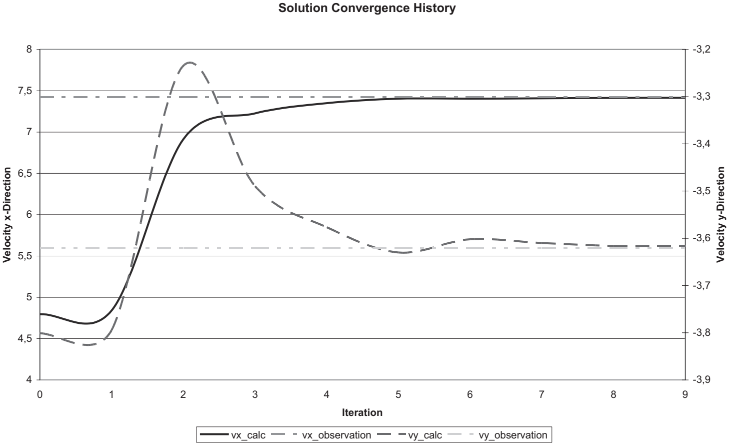

Fig 4: Convergence History of the pseudo inverse algorithm (velocities in m s^{-1})

Figure 5 presents the snow drift pattern including precipitation after a three days run (from the 31st Jan to the 2nd Feb 2005). At the upwind areas of the ridges snow is eroded and transported to the downwind areas, where it is deposited. Above a sea level of about 1600 m (indicated by the dashed line in figure 5) no wood inhibits the occurrence of drifting snow. Especially, at the Birkgraben chute where an avalanche released on the 2nd February. The maximum snow heights are located at the fracture zones of that avalanche. Hence, those additional snow loads in the chutes affect avalanche danger significantly.

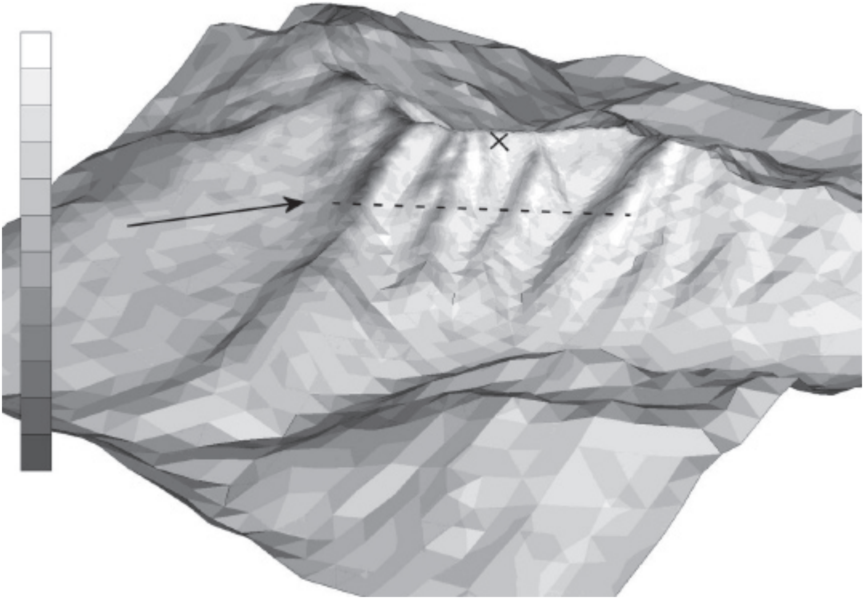

Fig 5 Snow distribution at the Birkgraben chute (indicated by the cross).White corresponds to additional snow loads due to snow drift and dark gray to erosion zones. The arrow indicates the wind direction. The maximum deposition height is about 1.6 m (white) and the maximum erosion is about 2 m (dark grey).

If no station data is available for the boundary conditions computation, these can be provided by the local weather model INCA. In order to justify the additional computational effort caused by the implementation of INCA, we computed the snow drift distribution at the mount Grimming (Styria) for a 6 hours drifting period. In figure 6 the resulting snow distribution using the time varying wind conditions provided by INCA is shown. In figure 7 the corresponding resulting snow drift distribution using the time averaged wind field is presented. The difference in snow heights caused by the use of real meteorological data is enormous. Using averaged wind fields less snow is eroded and therefore deposited (due to averaging high wind speeds disappear). Especially, winds crossing the ridge lead to enhanced snow transport in that region (figure 6).

In contradiction, the use of the INCA wind fields leads to more snow drift where snow is moved from mountain ridges towards chutes. The avalanche warning service of Styria observes the mountain channel (indicated by a dashed circle in figure 6) using radar measurements. The results based on INCA wind fields show clearly that enormous deposition of snow happens within those chute, whereas computations using an averaged wind field do not detect those potential avalanche fracture area.

Besides the higher accuracy, the time needed to obtain a solution rises because of lower convergence of the solver due to varying boundary conditions.

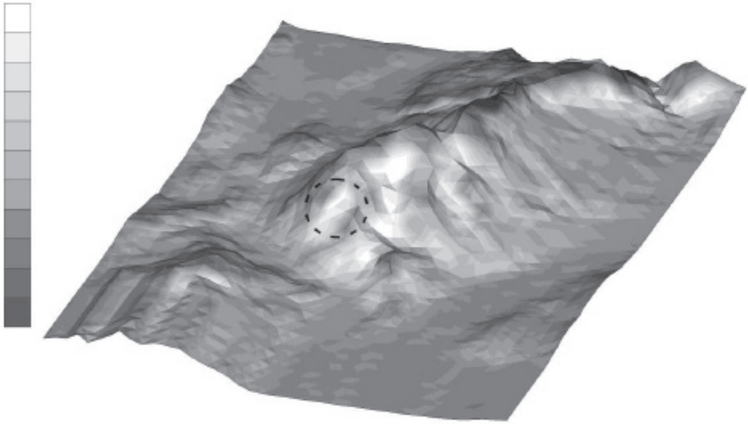

Fig 6 Snow distribution on mount Grimming after a 6h drifting period using the time varying wind field provided by INCA. White corresponds to additional snow loads due to snow drift and dark gray to erosion zones. The maximum deposition height is about 0.1 m (white) and the maximum erosion is about 0.1 m (dark grey).

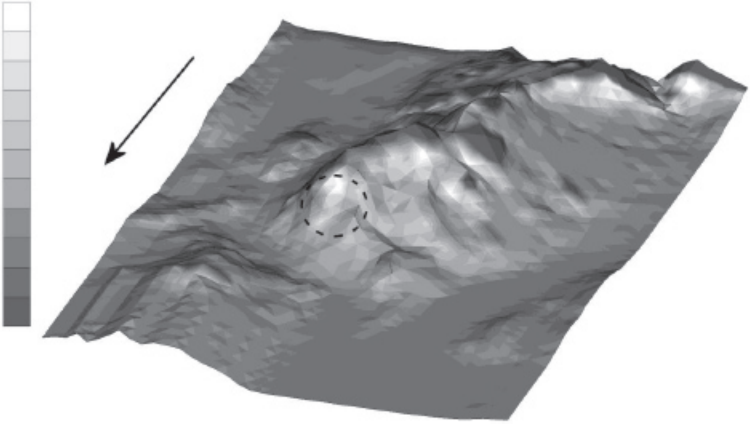

Fig 7 Snow drift on mount Grimming after a 6h drifting period using the time averaged wind field derived from the INCA dataset. The arrow indicates the average wind direction. White corresponds to additional snow loads due to snow drift and dark gray to erosion zones. The maximum deposition height is about 0.3 m (white) and the maximum erosion is about 0.3 m (dark grey).

CONCLUSIONS

The results of the snow drift simulations show the applicability of the novel simulation methods for whole mountain ridges. Therefore, snow drift simulations provide important information for the prediction of avalanche danger. The results demonstrate that it is necessary to apply measured wind data as boundary conditions, because of the high sensitivity of snow drift patterns to different wind conditions, which was clearly demonstrated on the mount Grimming example. Compared to punctual snow depth measurement the numerical simulation provides an area-wide distribution of the snow depth. Additionally, the result of snow drift simulations can be used as improved initial conditions for avalanche simulations. To sum up, it is of vital importance to consider real wind data for the prediction of snow depositions for operational avalanche warning.

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