SMALL SCALE WIND FIELD SIMULATIONS FOR THE STEEP GAUDERGRAT RIDGE USING CFX-4 AND ARPS; INFLUENCE OF THE BOUNDARY CONDITIONS AND COMPARISON WITH MEASUREMENTS

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Abstract: Two meso-scale numerical models, the Advanced Regional Prediction System ARPS, and a model based on the computational fluid dynamics model CFX-4, were used to simulate very high resolution wind fields above the complex mountainous topography of an Alpine ridge. Using an horizontal mesh resolution of 25x25 m, both models were able to reproduce qualitatively important flow features (change in direction and separation) that had been observed in the field. However, it could also be shown that the boundary conditions strongly influence the results.

Keywords – *Wind, simulation, CFD, Snow drift, Measurements, Steep terrain, micro-scale, flow separation.*

1. INTRODUCTION

Snow drift is an essential parameter when it comes to assessment and mitigation of avalanche hazard in mountainous environments. An accurate simulation of transported snow quantities is only possible with an appropriate knowledge of the wind forcing of the snow transport. A mountain ridge located close to Davos in Switzerland, the Gaudergrat, has been used as a test site for wind and snow drift for many years. It is oriented North-South with prevailing winds blowing from West to North-West which makes this site ideal to study flow features in complex terrain. In a previous study conduced at the Swiss Federal Institute for Snow and Avalanche Research (SLF) an attempt to couple high resolution wind field simulation results with a newly developed snow transport model showed promising results. It became clear however that boundary layer wind field had to be further investigated in order to define applicable guidelines for the initialisation of the wind simulations (Lehning et al. 2000). Experimental data necessary to drive and validate the numerical models were also needed. In summer 2003 an experiment, GAUDEX, took place there with a total of 33 measurement stations. The data gathered during the experiment provide an incomparable set of information that is used to improve the wind models used for the snow drift related problem and also for our understanding of flow processes in complex terrain.

Using two different meso-scale wind models, the meteorological model ARPS and a version of the computational fluid dynamics model CFX-4 modified at the Swiss Federal Institute of Technology EPFL, a study has been undertaken aiming at the reproduction of the phenomena observed in the nature. In order to make an accurate comparison, based on the most identical situations, both models were run on the same domain with the same boundary conditions and the same horizontal grid resolution.

2. WIND MODEL DESCRIPTIONS AND SIMULATION SETUP

CFX-4 is a computational fluid dynamics model (AEA Technology 2001). The core of the model is able to solve the Reynolds averaged Navier-Stokes equations for different kind of problems in the world of fluid dynamics. It uses a finite-volume discretisation scheme on a structured grid. Based on the possibility to add user-defined equations to the solver, the model has been adapted to atmospheric flows (Montavon 1998).

The Advanced Regional Prediction System (ARPS) has been developed in the 1990's as a new meteorological model. Its first goal was to predict storms in the North-American Mid-West. The model has been upgraded with time and is now able to solve airflow over complex terrain. It also solves the

Navier-Stokes equation but is set-up as a Large-Eddy Simulation model (LES) where larger scales are solved explicitly and sub-grid scales are parameterised (Xue et al. 2000). The grid is defined in terrain following coordinates and the solution is based on finite-differences.
Both models resolve the same base set of equations with conservation equations for mass, momentum, heat, potential temperature. An equation of state for the air completes the system. ARPS also includes several models specific to the atmospheric flows. Conservation of rain content, radiation model, and a complete multi-layered soil model can be activated and improve their prediction. A model of water micro-physics is also implemented in the modified version of CFX-4.
The main difference between both models is the turbulence modelling: CFX-4 is formulated using averaged values for variables. The k-ε model, modified to account for atmospheric stability, provides the turbulence closure model. ARPS is set up as a LES code using the 1.5 order TKE closure for the current study.
Both models can be initialised using external sounding data. For CFX4, an initial hydrostatic state is calculated first and the model is then launched with constant boundary conditions. ARPS uses a horizontally homogeneous time invariant base state, also hydrostatically balanced, and is run using periodic boundary conditions. The models are then run until a quasi-steady state is reached.

The simulation domain for the Gaudergrat ridge is 1500x1500 m. In order to reproduce the complex mountainous topography a horizontal resolution of 25 m has been used. This corresponds to the digital elevation model data currently available from the Swiss Topography Service. More accurate data would have to be acquired in order to increase the accuracy of the results. With the chosen resolution, 61 points in each direction are needed to include the area around the Gaudergrat. The domain extends approximately up to 3 km above the ground. The vertical grid spacing used with CFX-4 in the models ranges from 5 m close to the ground up to 80 m at the top of the domain leading to 52 cells in this direction. The grid stretching in ARPS is much larger since cell height goes from 3 m to 300 m with only 31 divisions. The ridge is 150 m above the surrounding landscape with slope up to 40°, and is approximately 1 km long. Simulations were run using sounding data to provide information for the velocity profiles and potential temperature; the same data was used with both model in order to allow comparison. The profiles were designed based on typical meteorological situations and using a log-law relation for velocity intensity in boundary layer.

3. RESULTS

Three flow phenomena, presented in the companion paper "Surface Observations During GAUDEX 2003" were investigated (separation from the ridge crest with an horizontal eddy in the lee, separation from the end of the ridge associated with a vertical stable eddy, and a new phenomenon in which the flow is along the ridge everywhere except close to the crest where a strong cross-ridge flow is present).

The inflow wind direction plays a very important role for the features that were investigated. Figure 1 shows two situations. On the left, the wind is blowing from South-West and the ridge forms an obstacle. This blocking is less important for the second case (b).
The observation of wind direction before, above and after the ridge shows interesting features (Figure 1a). On the luff side, the airflow approaches the ridge without any large change in direction. Above the ridge the flow becomes perpendicular to the ridge and shows a strong speed-up. Velocity above the ridge is up to 50 % higher than in the inflow region. After the ridge the direction changes again and turns toward North-East, where the topography is lower. With South-West wind, no separation could be created on the domain with the velocity used for the simulation. If the inflow direction changes to West, i.e. perpendicular to the ridge crest, the same velocity is sufficient to create one main vertical vortex located near the northern-end of the ridge on the downwind-side (Figure 1b). At the same time, a large separation could be observed behind the ridge. The position of this eddy remained stable. The change in wind direction for this situation does not occur on the ridge but only later when the flow reaches the bottom of the lee side slope where the wind turns again to West-South-West flowing to the lower part of the topography.
ARPS simulation results showed similar patterns with both the eddy in the lee slope and the separation zone (Figure 2). Eddies predicted by ARPS seem however to have a slightly smaller extension. The change in direction toward North is not as strong here as with CFX-4.

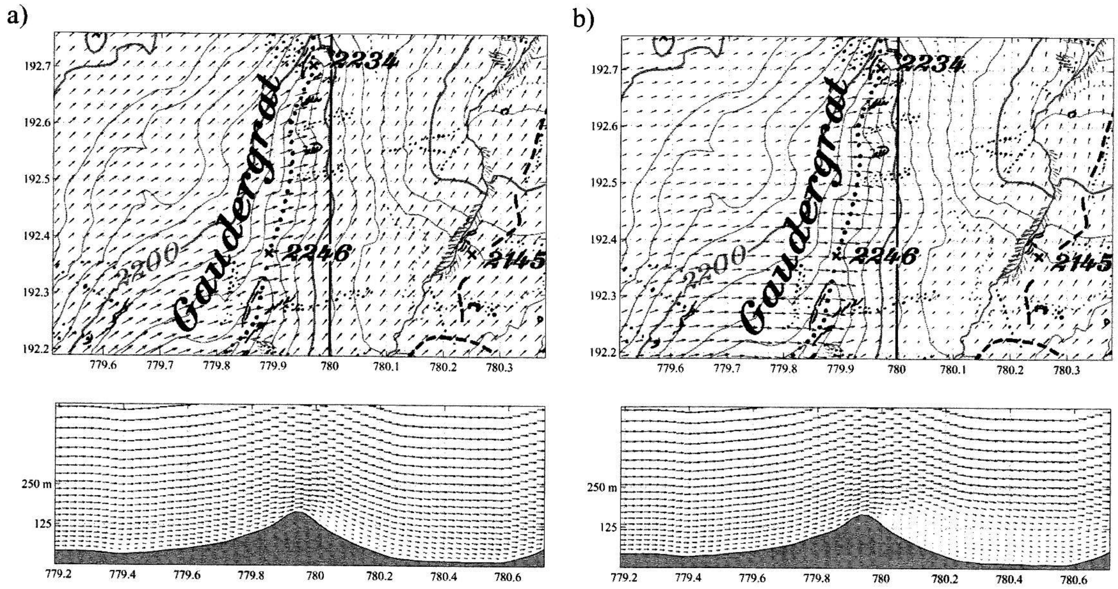

Figure 1. CFX-4; Top view and vertical cross section of the wind field over the Gaudergrat Ridge after 480 s simultation time. *(Horizontal units are in the Swiss Official Coordinate System [km])*
a) South-west inflow wind condition (240°), b) West inflow wind conditions (270°)
Cross-sections are taken at coordinate 192.6.

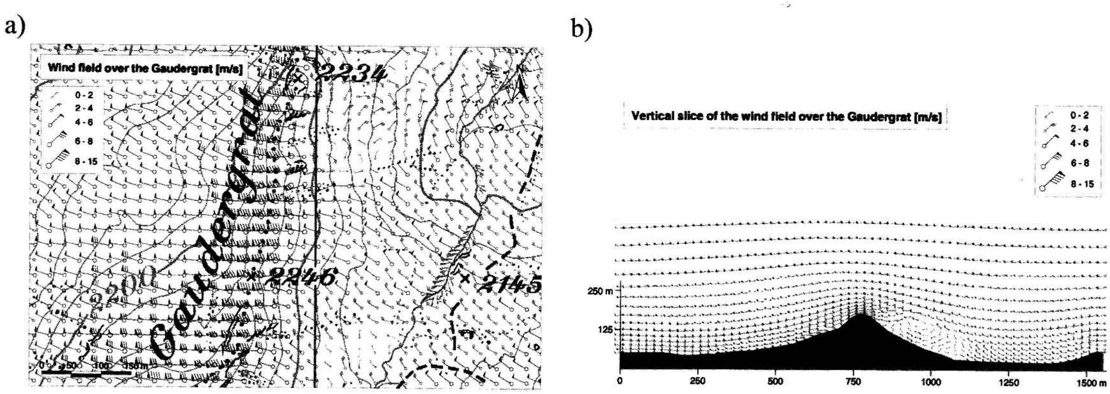

Figure 2. ARPS; a) Top view and b) vertical cross section of the wind field over the Gaudergrat Ridge after 480 s simulation time for West wind (270°). Situation similar to Figure 1 b).

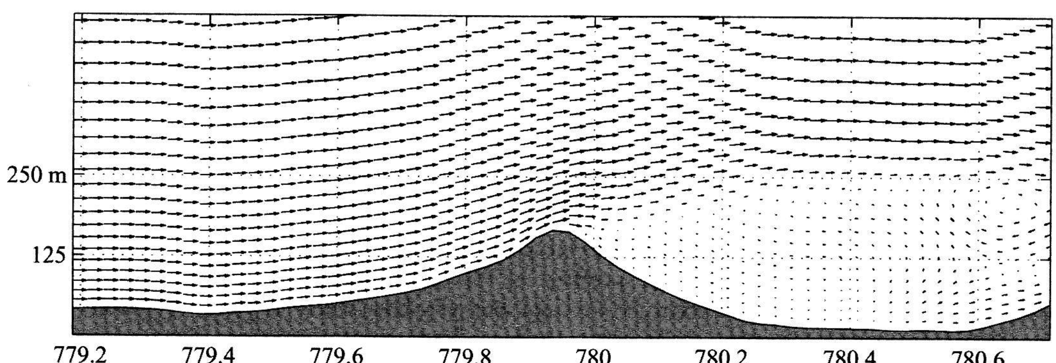

Figure 3. CFX-4; Separation eddy behind the ridge using inappropriate boundary conditions. The eddy becomes too large and extends to the entire valley located on the lee-side.

These results were obtained using boundary conditions chosen to recreate adequate flow around the Gaudergrat ridge. Attempts to use non-treated measured sounding data to initialise the models lead to unsatisfactory results. The separation eddies become much too large with CFX-4 (Figure 3) and chaotic flows were observed with ARPS.

4. CONCLUSIONS

Two numerical meso-scale meteorological models, ARPS and the modified CFD flow solver CFX-4, were used to reproduce wind fields at the Gaudergrat.
The computational fluid dynamics model CFX-4 applied to atmospheric flow is able to reproduce the near ground wind field over complex alpine terrain. It appears nevertheless that some critical features such as separation can be over-predicted by the model for certain inflow conditions. At the same time the role of the atmospheric stability is very important and strongly influences CFX-4 simulation results. The qualitative comparison between the meteorological model ARPS and the CFD model CFX showed that the main flow features are predicted in similar ways by both models. For prediction of avalanche danger CPU time is important, as simulations have to be coupled to snowdrift models. In a standard configuration, both models require comparable simulation times.
In order to reduce the effect of initial and boundary conditions, two different approaches are to be investigated in parallel. One will be to initialise and update the model with external data from measurements or computations results. For this purpose ARPS could already be coupled with the aLMo model (7 km gridsize) from the Swiss Meteorological Service (Spreitzhofer & al. 2004). Moreover the Gaudergrat ridge is surrounded by higher mountains which may have a significant influence on the air flow conditions especially those upwind of the ridge. To make the boundary conditions of the current 1500x1500 m domain more realistic, another way will be to extend the domain to the mountain region scale. This should allows us to compute more realistic boundary layer wind fields that could be coupled to the snow drift models and thus predict the snow distribution.

Acknowledgements: *This work as been partially funded by the Swiss Academy for Technical Sciences (SATW). We thank J. Rhyner for his helpful remarks. CFX Simulations were run on the central computers of the Civil Engineering Section of the Swiss Federal Institute of Technology in Lausanne EPFL. The Advanced Regional Prediction System (ARPS) is developed at the Centre for Analysis and Prediction of Storms (CAPS), University of Oklahoma. CAPS is supported by the National Science Foundation and the Federal Aviation Administration through combined grant ATM92-20009*

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