12.2 BOUNDARY LAYER WIND FIELD OVER STEEP, SNOW COVERED, HIGH ALPINE TOPOGRAPHY

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1 Introduction

Surface properties and meteorological parameters are the key factors influencing the seasonal build-up of the snow cover in mountainous terrain. Over non uniform terrain blowing and drifting snow is the main reason for a spatially and temporally inhomogeneous snow cover. Avalanche activity is directly linked to the additional snow loading in the slopes of accumulation. Furthermore, drifting snow can be a major problem for infrastructure such as roads and habitation. Therefore the investigation of blowing and drifting snow in Alpine terrain is an important topic. Despite of the progress that has been made in understanding and modeling of snow drift over the last few decades, an adequate model system to assess and finally predict snow redistribution in steep terrain is missing. A numerical, three dimensional snow drift model, has been developed at the SLF (Lehning et al., 2000), which combines an atmospheric model analysis of the high resolution wind field, a novel snow drift formulation, (Doorschot et al., 2001), and a snow cover model. This article deals in particular with the modeling of the high resolution wind field over steep topography. The small scale flow features such as flow separation, recirculation and turbulence are the driving mechanisms behind inhomogeneous snow distribution.

Current knowledge about the micro scale modeling of the boundary layer wind field and the modeling of turbulent fluxes of momentum over steep terrain is limited. Calculation of the atmospheric flow on the meso to micro scale request nonhydrostatic and compressible models. In the current study the Submeso version of the Advanced Regional Prediction System (ARPS) is used to calculate high resolution wind fields over steep terrain. The ARPS model has been developed at the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, (Xue et al., 2000). The Submeso version of the model has been created at the University of Grenoble to adapt the ARPS model to steep terrain (Anquetin et al., 1998). The modifications concern the calculation of the surface fluxes and the turbulent mixing parameters.

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2 ARPS model description

Realizing small scale modeling of the atmospheric flow in complex terrain the non hydrostatic, compressible atmospheric prediction model ARPS has been employed in the current study. Originally the ARPS model has been developed to study and predict storm scale phenomena like supercell storms, squall lines and tornados. Extensive verification of the model has been performed comparing the model computations with analytic solutions of linear and nonlinear mountain waves for flow over idealized topography and with observed small scale weather phenomena like thunderstorms and windstorms on the lee of mountains. End of the 1990s the Submeso version of the ARPS model has been advanced at the University of Grenoble, to study thermal driven flow in steep Alpine valleys.

A generalized terrain following coordinate system is used in the Submeso model to solve the nonhydrostatic and compressible Navier-Stokes equations on a staggered Arakawa C-grid. The sound wave containing equations are integrated applying a split explicit time integration scheme. The conservation equation for momentum, heat, mass, water substances, turbulent kinetic energy (TKE) and the equation of state of moist air are solved. The model variables Ψ are defined as the sum of base state variables $\overline{\Psi}$ and the deviations from the base state $\Delta\Psi$.

$$\Psi(x,y,z,t) = \overline{\Psi}(z) + \Delta\Psi(x,y,z,t) \quad (1)$$

The base state $\overline{\Psi}$ is by definition horizontally homogeneous, time invariant and hydrostatically balanced. Neglecting the ellipticity of the earth and assuming the atmosphere to be thin are the main approximations made in the original model equations. The horizontally homogeneity of the base state assures that the pressure gradient terms vanish. This reduces the computational error associated with the terrain following coordinate system. The computational grid can be arbitrary and time dependent because it is defined numerically. Also the Jacobians of the transformation are computed numerically.

The ARPS model has been set up as a Large Eddy Simulation (LES) model. Applying the LES approach, the large scale turbulent motions are computed explicitly with a three dimensional numerical model whilst the small scale turbulent motions are parameterised via a subgrid scale (SGS) model. The SGS model of the ARPS is based on the work of Smagorinsky (1962). The turbulent mixing terms in the momentum equations, describing the turbulent flux of momentum $u_i u_j$, are expressed in terms of the Reynolds stress tensor. Therefore the turbulent flux of momentum $u_i u_j$ is assumed to be proportional to the deformation of the wind:

$$u_i u_j = \frac{2}{3} e \delta_i j - K_m \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right). \quad (2)$$

A 1.5 order TKE based turbulent closure model is used to complete the set of model equations. The turbulent mixing coefficient are herein related to the mixing length of the subgrid scale model l and the subgrid scale turbulent kinetic energy (TKE),e,

$$K_{mj} = 0.1 e^{\frac{1}{2}} l_j. \quad (3)$$

For anisotropic turbulence, the length scales l_j are defined as

$$l_1 = l_2 = \Delta_h \quad (4)$$

and

$$l_3 = \begin{cases} \Delta_v & for\ unstable/neutral\ case \\ min(\Delta_v, l_s) & for\ stable\ case \end{cases} \quad (5)$$

where $l_s = 0.76 e^{\frac{1}{2}} N^{-1}$; Δ_h and Δ_v are the horizontal respectively vertical grid spacing.

3 Model setup

An area of (1.5 x 1.5) km in the horizontal and a height of the domain of approx. 3000 m above ground has been chosen to resolve the largest turbulence eddies in steep mountainous terrain. Using a horizontal resolution of 25 m, 61 grid points in each direction are necessary to cover the whole area. In the vertical a grid stretching leads to a resolution of approx. 1.5 m near the ground and approx. 300 m close to the top of the model domain.

The model is initialized via a vertical sounding of the atmospherical parameters taken by the MeteoSwiss (Swiss Meteorological Institute). The conditions near the snow covered, alpine surface are added using measurements taken on meteorological stations on our experimental site, the Gaudergrat. Hence the ARPS model computes the horizontal homogeneous base state. The acoustic wave modes has been integrated using the small time step of $0.001s$. The Integration of the acoustic not active wave modes has been undertaken using the big time step o $0.01s$. For the lateral and top boundary conditions the zero gradient formulation has been chosen. The bottom boundary has been taken as an rigid wall. Below the top boundary a 1000 m thick upper level Rayleigh dumping layer has been introduced.

4 Model results

The results presented in this study are from computations of the wind field over the Gaudergrat, our experimental site in the Weissfluh area near Davos. The Gaudergrat is a quasi 2 dimensional mountain ridge with slopes up to 38 degrees. The rather sharp crest reaches a high of approx. 150 m above the surrounding topography. The prevailing wind direction during strong precipitation events is northwest and thus perpendicular to the crest line. The Gaudergrat site is equipped with six masts carrying instruments measuring wind profiles and other meteorological parameters with a temporal resolution up to 1 Hz at different heights. The wind masts are situated in a line perpendicular to the crest line. The two masts upstream and downstream of the crest are positioned in a horizontal distance of approx. 500 m from the crest line. The masts in both slopes have a horizontal distance of 20 m from the crest line.

A drift period between 18 und 22 March 1999 has been chosen to compare the model results with measurements. Starting with a horizontal homogeneous base state generated by the Submeso model using a single input sounding, the model has been run till a quasi steady state has been reached. No time development but the adaptation of the wind field to the terrain has been calculated. It takes 12 000 time integration steps or 120 s till a quasi steady state is reached.

Fig. 1 shows a section of a snapshot of the computed wind field for the first grid level after 120 s time integration.

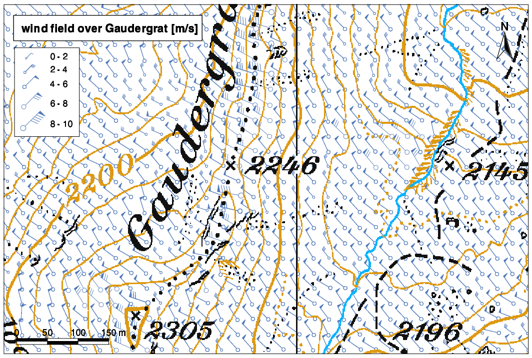

Figure 1: Wind field over the Gaudergrat ridge at the first vertical grid level.

A north west wind of 5 m/s at the first level above ground has been used to initialize the model. The adaptation of the wind field to the steep terrain is clearly visibly. The overall pattern of the wind field agrees quite well with the measurements. The measurements, (Fig 2) have been undertaken and analyzed by Gauer (1999).

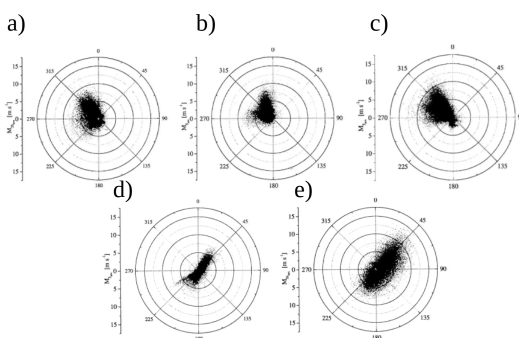

Figure 2: Measurement of the wind speed and wind direction on the Gaudergrat experimental site. a) upstream of the crest; b) in the luff slope; c) on the crest line; d) in the lee slope; e) downstream of the crest.

Upstream of the crest the wind direction is northwest and the wind speed is 5 m/s. Over the luff slope the wind speed is 20% lower and the direction changes more to the north. At the crest line a speed up of 1.5 to 2.0 was found both for measurements and for computation. The wind direction changes back to west-northwest and is therefore perpendicular to the crest line.

Most difficulties in modeling the wind field arise downstream of the crest in the separation region of the flow. In the lee slope the Submeso model overestimates the wind speed slightly. The measurements show a 30 % lower wind speed than upstream of the crest. The wind direction is poorly reproduced. In the separation zone downstream of the crest northeast and southwest wind directions are recorded. The model shows only a small change of the wind direction to the north. At the downstream mast again stronger winds from the northeast and southwest are measured.

Fig. 3 shows a vertical slice of the first ten grid levels of the model calculation. The slice is taken nearly perpendicular to the crest line at the region where the masts are situated.

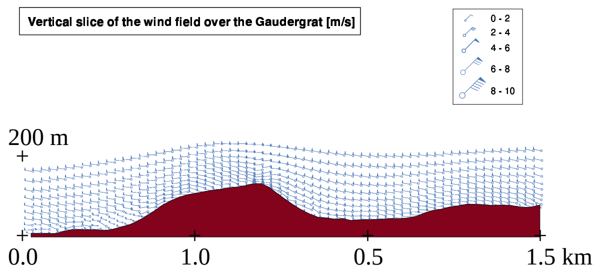

Figure 3: Vertical slice of the wind field over the Gaudergrat for the first ten grid levels.

In the vertical slice no recirculation pattern can be found, which would have been expected in the separation region. The model is calculating a wave structure wind field starting at the first steep upstream slope. The speed up region is nice reproduced followed by a down slope wind over the lee slope. In agreement with the theory the influence of the small scale topography reaches up to 200 m above the ground.

Pattern of turbulent kinetic energy (TKE) near the Gaudergrat are shown in Fig. 4. The snapshot of the TKE pattern indicates a wave structure. Small areas of high values of TKE are surrounded by bigger areas of low TKE. The region of low TKE downstream of the crest line is essential to make flow separation possible. Fourier analyses of the wind measurement data have shown, that the eddy spectrum reaches from 0.05 Hz down to 0.001 Hz. With the horizontal model resolution of 25 m the distinction between the large scale and the subgrid scale motions falls within the internal subrange of the turbulence energy spectrum.

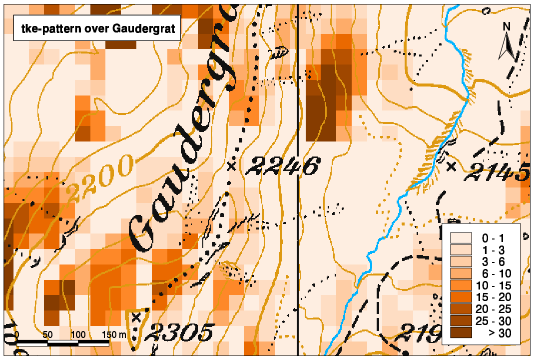

Figure 4: Pattern of the turbulent kinetic energy over the Gaudergrat.

5 Conclusions and outlook

Using a horizontal resolution of 25 m for submeso scale modeling of the wind flied close to complex terrain we are breaking new ground into this research field. The overall structure of the wind field close to steep Alpine topography can be well reproduced with the Submeso model. Problems arise in the separation part of the flow directly downstream of obstacles. With the currently used model configuration we are not able to compute adverse pressure gradients in this region which are essential for the development of recirculation. Future work will include calculations with a higher spatial resolution over a longer time period to make sure that separation can develop. As a supplementation the subgrid closure model will be improved. The currently used Smagorinsky SGS model causes difficulties near the bottom boundary of the domain where the velocity gradients are great. In the region near a solid wall the size of the turbulent eddies varies in proportion to the distance from the surface. In consequence the characteristic scale of the turbulence reduces to values less then the size of the mesh spacing. Another critical point is the parameterization of the turbulent mixing in the model. The currently used default values for the fourth order computational mixing may cause too strong diffusion of momentum. Further studies will additionally concentrate on the influence of the stratification of the atmosphere on the wind field development.

Also there are some challenging problems left in reproducing the small scale wind field over steep topography the model results are useful to serve as input for the snow drift model (Lehning et al., 2000).

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