HIGH RESOLUTION NUMERICAL STUDY OF THE 19 NOVEMBER 2004 WINDSTORM

André Simon, Jozef Vivoda

The study presents the results of the numerical simulation of the 19 November 2004 windstorm using several models with high horizontal resolution. Effects of the hydrostatic and non-hydrostatic dynamics were compared, as well as the method of the so called dynamical adaptation. The nature of the event that is considered as a downslope windstorm is evaluated with help of diagnostic parameters as the Froud number and with vertical cross-sections of potential temperature and vertical velocity fields. It is concluded that windstorms of this kind can be forecasted by numerical models of 2.5 km resolution with higher precision than by using the current operational models. It is shown that computationally effective hydrostatic models based on dynamical adaptation approach can be sufficient in forecasting extreme non-convective wind, similar to the evaluated event. Nevertheless, the results are strongly dependent on the physical parameterisation of the model (turbulence, orographic drag, etc.). Hence, future versions of both hydrostatic and non-hydrostatic numerical models should be carefully examined and tested to keep the performance of forecasting severe downslope windstorms.

Key words: windstorm, numerical model, high resolution, downslope windstorm

Výskum víchrice z 19.11.2004 pomocou numerických modelov s vysokým rozlíšením. *Článok informuje o výsledkoch numerickej simulácie víchrice z 19. novembra 2004, pri ktorej boli použité modely s vysokým horizontálnym rozlíšením. Porovnávali sa vplyvy hydrostatickej a nehydrostatickej dynamiky, rovnako aj metóda tzv. dynamickej adaptácie. Fyzikálna podstata javu, ktorý je považovaný za prípad bóry, bola skúmaná pomocou diagnostických parametrov ako je Froudovo číslo a pomocou vertikálnych rezov cez polia potenciálnej teploty a vertikálnej rýchlosti. Konštatuje sa, že víchrice tohto typu je možné predpovedať s numerickými modelmi pri rozlíšení 2,5 km s vyššou presnosťou ako pomocou súčasných operatívnych modelov. Ukázalo sa, že výpočtovo efektívne hydrostatické modely založené na dynamickej adaptácii môžu v podobných prípadoch postačovať pri predpovedaní extrémneho vetra, ktorý nie je spojený s konvekciou. Napriek tomu sú výsledky veľmi závislé od fyzikálnej parametrizácie v modeli (schéma turbulencie, parametrizácia účinkov orografie a pod.). Preto budúce verzie hydrostatických aj nehydrostatických numerických modelov budú odskúšané a testované aj s ohľadom na zachovanie schopností predpovedania extrémnych prípadov bóry.*

Kľúčové slová: víchrica, numerický model, vysoké rozlíšenie, bóra

---

1. INTRODUCTION

The 19 November 2004 windstorm was a severe weather event that caused considerable damages in Slovakia, above all in the region of High and Low Tatras. The forest in High Tatras was reported to be destroyed on area of 120 km^2 in a belt 40-50 km long and 2-5 km wide (WWF position paper, 2004). Daily maximum of the mean hourly wind speed exceeding 21 m/s has average occurrence frequency 5 ‰ (what means two-three days in a year in average) at high altitudes of High and Low Tatras. Orographical strengthening and high gustiness of the wind are frequently observed at lee sides of mountain passes. Climatological studies for years 1951-1960 showed that at some places (e.g. Skalnaté Pleso, 1778 m above sea level) daily maxima of wind gusts overlapping the speed of 105 km/h (29.2 m/s) can have occurrence frequency of 20% (Otruba, 1964, Otruba and Wiszniewski, 1974). In the evaluated case, wind gusts of speed over 160 km/h (44.4 m/s) were recorded in the southern (lee) slopes of the mountains even at altitudes of 800 – 1200 meters above sea level what can be considered as a rare event. In the past, windstorms of considerable destructive consequences for High Tatras were referenced in the years 1915, 1919, 1941 (Konček, 1944), in 1964 (Rak, 1967) and 1981 (Koreň, 2005) as well. Wind blowing from northern direction and accelerating along the slopes of Tatras was considered as a possible reason for such extreme events. This knowledge was based mainly on damage surveys and records of meteorological stations situated in the region of High Tatras.

More information about the character of severe downslope winds are available from research of bora winds in Croatia (Picek and Tutiš, 1996, Jurčec and Brzović, 1995, Klemp and Durran, 1987) and of similar events appearing in the United States (Lilly, 1978). It was shown that the phenomenon of downslope windstorm can be described analytically (see e.g. textbooks of Holton, 1992 and Stull, 2003). Numerical simulations proved that the wind of this kind is induced by mountain waves of large

amplitudes and by breaking of mountain waves (Clark and Peltier, 1977, Laprise and Peltier, 1989). Another works examined both wavy and hydraulic origin (Smith, 1985) of the wind amplification giving a unified concept of downslope windstorms (Durran, 1986). Currently, limited area models as ALADIN or MM5 provide operationally mesoscale analysis and forecasts of wind and pressure. This enabled to forecast severe bura events in Dalmatia by using the so called dynamical adaptation (Ivatek-Šahdan and Tudor, 2004, Kraljević and Tudor, 2005).

The study presented in this paper shows the possibility of high resolution numerical simulation and forecasting of the 19 November 2004 windstorm. The main motivation of the research was to see, how much a hydrostatic model can improve the forecast of this event and if a non-hydrostatic approach produces forecasts of better quality. Another point was the effectiveness of several computational approaches including the dynamical adaptation of the ALADIN model. Finally, numerical analysis and forecasts of several meteorological parameters at high resolution grid were expected to provide more information about the nature of the event.

The paper is divided in seven parts. The next section gives a brief description of the macro-synoptic situation and local meteorological conditions inferred from surface observations. Section 3 is an overview of research methods and used versions of numerical models. Section 4 presents the results of the model ALADIN operational at 19 November 2004 which are compared with outputs of both hydrostatic and non-hydrostatic high resolution runs in section 5. Section 6 shows the availability of mesoscale diagnostics of downslope windstorms. Future plans and consequences for operational forecasting are discussed in the conclusion (section 7).

2. OBSERVATIONS AND SYNOPTIC ANALYSIS

In the morning of 19 November, 2004, the territory of Slovakia was situated in polar air-mass with prevailing westerly flow between the area of low pressure over Baltic Sea and Scandinavian Peninsula and the area of high pressure over Mediterranean. In the upper troposphere a jet stream was spread from Northern Atlantic over British Isles and exiting over France and Germany with north-westerly wind of speed exceeding 50 m/s along the axis. Between 00 and 06 UTC a cyclone started to develop in elongated trough of low pressure over Germany and Benelux. It deepened quickly and moved over northern part of Czech Republic and southern Poland eastwards. A cold front was quickly passing the territory of Slovak Republic between 11 and 16 UTC when the centre of the low was propagating through southern Poland. The passage of the front was associated with remarkable advection of cold air-mass and with turn of the wind direction from south-westerly to westerly and north-westerly, respectively.

The majority of the stations measured the maximum wind speed during or shortly after the passage of the front. For instance, the peak wind gust was recorded at Poprad station at 1321 UTC (34 m/s from west). However, the start of the windstorm according to observations in High Tatras (Stará Lesná station, 810 m above sea level) can be placed after 1420 UTC. It was marked by sudden increase of both average wind speed and speed of the wind gusts and by turn of the wind from westerly to north-westerly direction. At that time the region of High and Low Tatras was already situated on the rear side of the low. The north and north-western flanks of the mountains were windward and the south and south-eastern flanks leeward according to the mean low and middle tropospheric flow. The gusty character of the wind is underlined by big difference between the hourly mean wind speed (almost 20 m/s) and maximum measured wind gusts (45 m/s at Stará Lesná at 1628 UTC and 54 m/s at Skalnaté Pleso at 1754 UTC). Wind gusts were accompanied by fast oscillations of the atmospheric pressure in order of 3 hPa (from records of the station Stará Lesná belonging to the Geophysical Institute of Slovak Academy of Sciences). The speed of the wind gusts in the Poprad Valley remained during the event mostly below 30 m/s (station Poprad airport and station Poprad Gánovce). The wind speed was even continuously decreasing during 15 and 17 UTC because this region was not directly affected by the windstorm. The end of the event at High and Low Tatras can be situated to 20 UTC. Later the speed of the gusts at most of the stations decreased below 30 m/s and the wind has lost its severity.

3. NUMERICAL WEATHER PREDICTION TOOLS

The limited area hydrostatic model ALADIN used at SHMÚ was operationally running on 19th of November 2004 with the ALADIN cycle 25t2. Horizontal resolution was 9km with 37 vertical levels. The model takes the initial and boundary conditions from global model ARPÈGÈ with 3 hour coupling frequency. Model is initialised via digital filter (see more details about ALADIN model in Radnóti et al., 1995). After the event, the test with 2.5 km horizontal resolution was carried out with hydrostatic version of the model ALADIN (further denoted as DADA). It used the physical parameterisation from reference operational model version with convection parameterisation switched off. The initial and boundary conditions were taken from the operational run with 1 hour coupling frequency.

The second experimental run used the non-hydrostatic ALADIN dynamics and the physical parameterisation of the ALADIN model from cycle 29. Here the coupling strategy was the same as in the DADA experiment. All experimental runs were based on 19 November 2004 00 UTC analysis and the evaluated forecasting period was 0 to 36 hours (valid for short range and very short range forecasting).

The last test was performed with the so called dynamical adaptation approach. The model was running for 30 minutes and for 60 minutes, respectively, using only 15 vertical levels adjacent to the model surface. It was expected that even simplified and computationally effective hydrostatic simulation at short time ranges keep a good representation of interaction of atmospheric flow with the terrain. This approach enables to forecast the mesoscale distribution of wind field, except of events, where explicit non-hydrostatic simulation and more sophisticated physical parameterisation are necessary (for instance by convection). By dynamical adaptation, the model is integrated from forecasts of the operational 9.0 km ALADIN model at every hour (e.g. at times 00, 01, 02 UTC …). The 30 minute integration with time constant coupling is time inconsistent because its final output is approximated as the state of the atmosphere at the beginning of the integration. The 60 minutes integration is time consistent, hence, providing better estimates for minimal and maximal values in the given period.

4. RESULTS OF THE OPERATIONAL FORECAST

The forecasts of the ALADIN model with cycle 25t2 provided very satisfying results for the case of the 19 November 2004 windstorm. The situation was well forecasted already by the run based on 18 November 2004 00 UTC. Forecasts of the 10 m wind and wind gusts from this run enabled to issue warning on wind speed exceeding 100 km/h more than 36 hours in advance. The reference run in this study based on 19 November 2004 00 UTC forecasted peak wind gusts of 40 m/s with maximum situated in the region of High Tatras. Time course of the values forecasted and interpolated to the locality of Lomnický štít (2635 m above sea level) were compared with records of the meteorological station (Fig.1). The start of the event was predicted with small time shift (1 hour) but the overall tendency fits very well the observations. The horizontal distribution of wind field was less precise – overestimating the magnitude of the wind in Poprad Valley and underestimating certain regions, e.g. Low Tatras (Fig.2). Generally speaking, this forecast gave a good possibility to estimate severe wind occurrence. However, at 9 km resolution it was not possible to sufficiently localise the position of the event (e.g. to distinguish if the wind maximum is more likely on the peaks or on the slopes of the mountains).

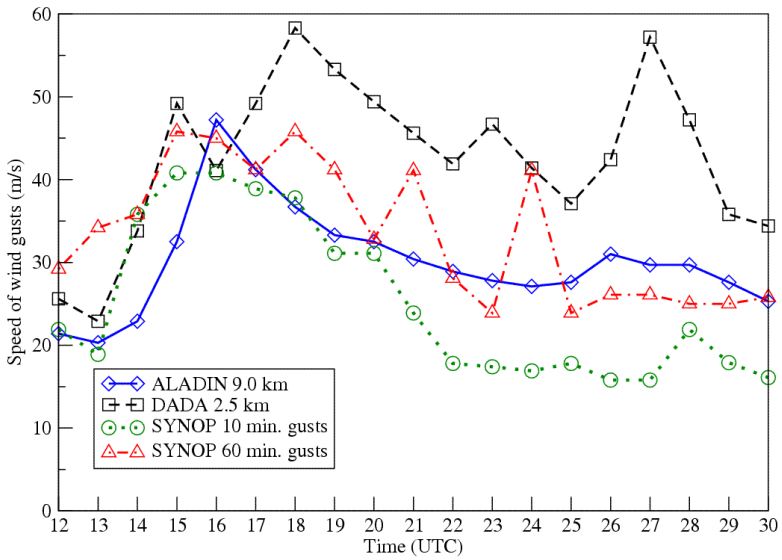


Fig. 1 Time course of ALADIN model forecast of wind gusts for operational run (solid line) and for the experimental run DADA (dashed line) as approximated for the Lomnický štít station (2633 m above sea level). Dotted and dash-dotted lines are maximum wind gusts recorded for the previous 10 minutes and 1 hour, respectively (SYNOP observations).

Obr. 1 Časový priebeh predpovede nárazov vetra modelu ALADIN z operatívnej integrácie (plná čiara) a z experimentu DADA (prerušovaná čiara) aproximovaný pre stanicu Lomnický štít (2633 m.n.m.). Bodkovaná čiara znázorňuje maximálny náraz vetra zaznamenaný za predchádzajúcich 10 minút a bodko-čiarkovaná čiara vyznačuje priebeh maximálnych nárazov vetra za predchádzajúcu hodinu (zo správy SYNOP).

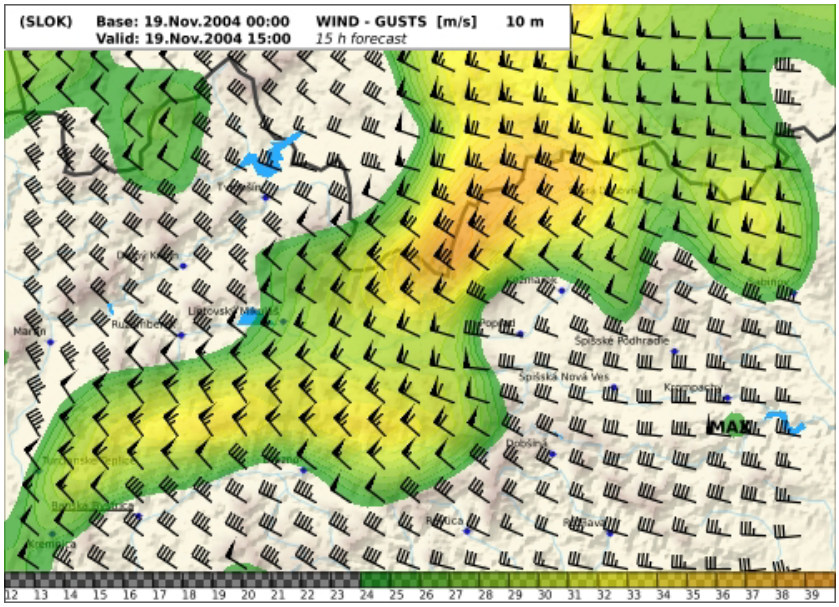


Fig. 2 Operational forecast of ALADIN SLOVAKIA model of the wind gust field at 10 m height AGL (wind barbs) and of the wind gust magnitude (in colour) based on 19 November 2004, 00 UTC and valid for 19 November, 15 UTC. Unit is m/s.

Obr. 2 Operatívna predpoveď nárazov vetra z modelu ALADIN SLOVAKIA pre výšku 10 m nad terénom. Pole vetra je znázornené šípkami a veľkosť rýchlosti je vo farebnej škále. Predpoveď bola iniciovaná 19. Novembra 2004 o 00 UTC a platí pre 19. November 15 UTC. Jednotkou je m/s.

5. HIGH RESOLUTION FORECASTS

The resolution of the horizontal grid is very important by numerical simulation of small scale events. In the operational model configuration at 9 km resolution, the area of High Tatras is represented only by few grid points. Hence, models with higher resolution should describe better the spatial distribution of the wind and should localize the wind speed maxima with higher precision. Outputs of the hydrostatic run at 2.5 km fulfilled these expectations. The distribution of the wind gust field (Fig. 3a) coincides with the stationary observations and information from damage survey better than the operational run with lower resolution. Maximum predicted wind gust at south-eastern flank of High Tatras was 50 m/s what was observed at some locations (e.g. Skalnaté Pleso). Better is the representation of Poprad Valley, where the wind is weaker against the reference outputs and the second maximum located at southern slopes of Low Tatras seems to be realistic as well (it corresponds with reports about damages observed in this region). Forecasts of the high resolution model show very interesting features in the field of mean sea level pressure and wind at 10 m height (Fig.3b). A mesoscale cyclone forms on the lee side of High Tatras and a ridge of high pressure on the windward side. This configuration creates significant pressure gradient on the southern slopes of the mountains. The wind in this region is cross-isobaric, hence, the forcing is characterized by strong pressure drag what is typical for downslope windstorms (Tutiš and Picek, 1991, Picek and Tutiš, 1995).

Vertical cross-sections of wind and potential temperature field in direction perpendicular to the ridge of High Tatras show other evidence about the presence of an intense downslope wind. Areas with wind speed exceeding 30 m/s are located in the close vicinity of the south-eastern slopes of mountains. Analysis of potential temperature shows a deformation of isotherms in this region (Fig.4a). If we expect an adiabatic motion of the air parcel following the surfaces of constant potential temperature, intense downward vertical motions are necessary on the lee side of the mountain. This is accompanied by shrinking of the vertical air column, hence, with large increase of the static stability. Further downstream, the parcel is forced to rise, what is related to decrease of static stability. Diagnostics of the vertical velocity field indicates downward motions faster than 50 Pa/s and upward motions of velocity higher than 25 Pa/s. This is much in excess of usual vertical wind speed in non-convective environment (in order of 0.1-1 Pa/s). The effect of creating strong vertical motions by airflow over obstacle is called hydraulic jump (see e.g. Holton, 1992) and it is discussed with more details in the next section.

Non-hydrostatic simulation of the 19 November wind storm showed qualitatively similar results as the DADA experiment according to the vertical profiles of potential temperature and simulation of the hydraulic jump (Fig. 4b). However, the start of the event is shifted forward almost by three hours against the reference operational run. This leads to differences in the wind field distribution of the 15 hour forecast and weaker wind gusts (maximum speed of 35 m/s). The forecast valid for 18 UTC shows already results similar to 2.5 km hydrostatic run and higher speed of wind gusts up to 50 m/s (Fig.5a). The reason of this time shift is not yet completely understood. Probably it is related to physical parameterisation used for the experiment with non-hydrostatic run that was different from the reference run of cycle 25t2. Tests with current operational configuration (cycle 28) showed a considerable dependence of the forecasted wind field on the used version of the model including changes in physical parameterisation, diagnostic scheme of wind gusts, and representation of the model orography (Simon and Vivoda, 2005, Drvar et al., 2005).

The dynamic adaptation of the ALADIN model forecasted strongest wind gusts (58 m/s) from all high resolution runs (Fig.5b). The distribution of this parameter is in principle equal to the output of the DADA experiment. Despite of the time inconsistency, the dynamical adaptation using 30 minute integration valid to 15 UTC described the situation better than the time consistent version with one hour integration valid for the same time. In the latter case, the start of the windstorm was predicted with one hour delay. This experience suggests that the dynamical adaptation is very dependent on the initial and boundary conditions obtained from the reference run. Hence, the one hour integration of dynamical adaptation is probably not able to give a good forecast until the mesosynoptic conditions for the windstorm are not established in the initial input file taken from the reference run.

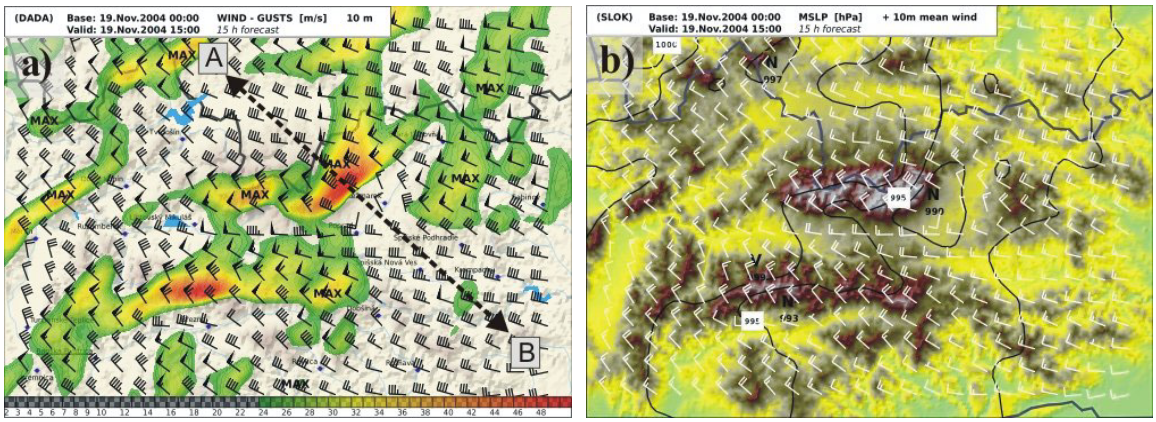


Fig.3 a) The same as in Fig. 2 except for the experimental model DADA. The AB line denotes the sense of the cross-section in Fig. 4.

b) Forecast of the wind field at 10 m height AGL (wind barbs) and of the mean sea level pressure in hPa (thin black line). The background shows the orography in the region of High Tatras (centre of the figure) and Low Tatras (southerly from High Tatras). Border with Poland is marked by thick grey line. Note the mesocyclone at south-eastern flank of the High Tatras (990 hPa in the centre of the low).

Obr. 3 a) To isté ako v obrázku 2 ale pre experimentálny model DADA. Čiara AB znázorňuje smer vertikálneho rezu na obr. 4.

b) Predpoveď poľa vetra vo výške 10 metrov nad terénom (šípky) a poľa prízemného tlaku vzduchu v hPa (tenká čierna čiara). Pozadie znázorňuje orografiu v okolí Vysokých Tatier (v strede obrázku) a Nízkych Tatier (južne od vysokých Tatier). Hranica s Poľskom je znázornená hrubou šedou čiarou. Za zmienku stojí mezocyklóna situovaná na juhovýchodnom okraji Vysokých Tatier (990 hPa v strede níže).

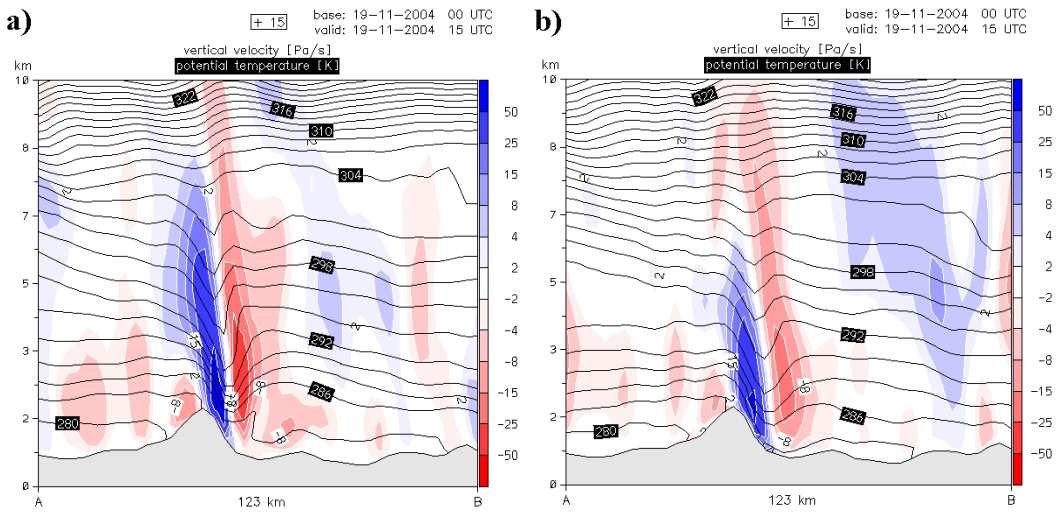


Fig. 4 a) Vertical cross section through the field of potential temperature in Kelvins (solid lines) and vertical velocity in Pa/s (in colour) as derived from the forecast of the DADA experimental model based on 19 November 2004 00 UTC and valid for 19 November 2004 15 UTC. The sense of the AB cross section is from north-west to south-east (marked in Fig. 3a).

b) The same as in a) except for the non-hydrostatic model.

Obr. 4 a) Vertikálny rez poľom potenciálnej teploty v Kelvinoch (plné čiary) a vertikálnej rýchlosti v Pa/s (farebné odtiene) odvodený z predpovede experimentálneho modelu DADA iniciovaného 19. novembra 2004 00 UTC a s platnosťou pre 19. November 2004 15 UTC. Rez AB je vedený od severozápadu na juhovýchod (znázornený na obrázku 3a).

b) to isté ale pre nehydrostatický model

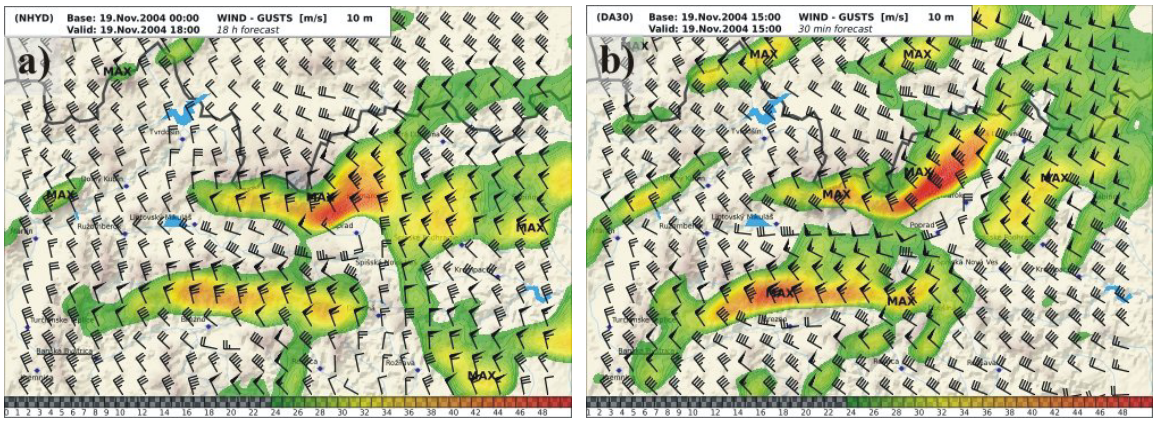


Fig. 5 a) The same as in Fig. 2 except for the non-hydrostatic model and for 18 UTC.
b) The same as in Fig. 2 except for the time inconsistent dynamical adaptation valid for 15 UTC.

Obr. 5 a) To isté ako v obrázku 2 ale pre nehydrostatický model a s platnosťou pre 18 UTC.
b) To isté ako v obrázku 2 ale pre časovo nekonzistentnú dynamickú adaptáciu s platnosťou pre 15 UTC.

6. MESOSCALE DIAGNOSTICS

Several analytical models describe the onset and characteristics of downslope windstorms. The simplest possible solution can be obtained from the shallow water equations (Holton, 1992). It can be shown that by certain ratio of the wind speed and mean static stability, the air starts to flow over the obstacle and to create mountain waves. The amplitude of the waves is increasing when the mean kinetic energy of the air parcels on the windward side of the mountain is approaching the potential energy needed to overcome the mountain. The ratio of the mentioned kinetic and potential energy is the square of the so called Froud number.

When the Froud number is higher or very close to one, the flow is called supercritical. In this case the potential energy is converted into kinetic energy during the entire period that the air column flows over the crest of the mountain and falls down on its lee side (Durran, 1986). In the upslope part of the wave, the flow is adjusted to ambient subcritical conditions via turbulent (hydraulic) jump.

The Froud number can be expressed in several ways, according to the used analytical model. In this study a linear approximation of shallow water model was evaluated with Froud number defined

$$F_r = \frac{U}{NH} \tag{1}$$

where F_r is the Froud number, U is the component of the mean speed of the flow in direction perpendicular to the mountain ridge, N is the mean Brunt-Väisälä frequency and H is the height of the obstacle (considered as a variable depth over the surface in this computation). The means of the wind speed and static stability were computed for the layer of depth H. The Froud number was evaluated over selected point in the windward side of High Tatras in order to make diagnostics of conditions to create downslope windstorm (Fig.6). The Froud number is decreasing with increase of the height of the obstacle. However, by corresponding wind speed and stratification of the atmosphere the air parcels would be able to rise along the slopes of the mountains even to heights of 3000 m above the sea level. From this point of view, conditions for downslope windstorm were fulfilled.

Visualization of the horizontal distribution of the Froud number is computationally more difficult (because of subtracting the wind component); however, by replacing U with the magnitude of the wind vector we obtain at least a simplified version, partially useful as a precursor of downslope wind generation. Horizontal distributions of the mean Brunt-Väisälä frequency of the layer 1200 m over surface were also examined and showed considerable increase of the static stability on the lee side of High Tatras replaced by decrease of this parameter further downstream in the area of the hydraulic jump. Similar parameters could help the forecasters to recognize the features of the downslope windstorm.

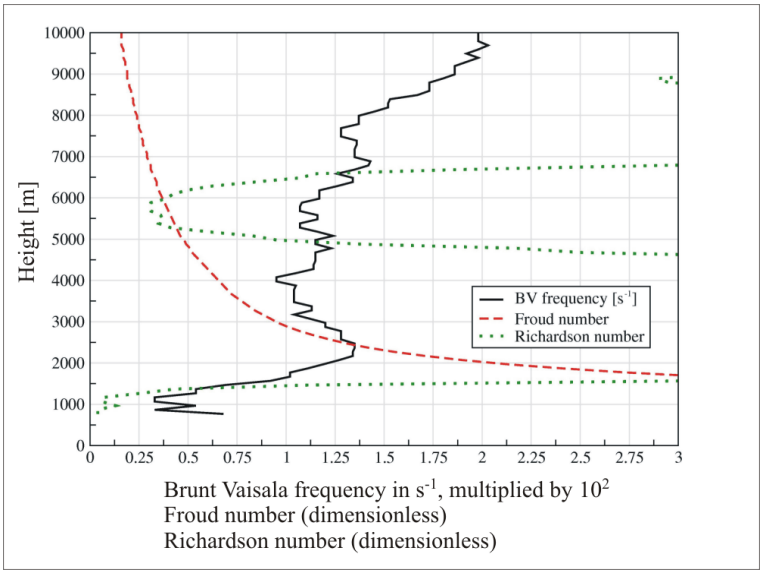


Fig. 6 Vertical course of several stability parameters derived from the forecast of the DADA experimental model valid for 19 November 2004 15 UTC and for the point over Zakopane (in Poland, at windward side of High Tatras). Solid black line denotes the Brunt Väisälä frequency (in s^{-1}, multiplied by 10^2), dashed red line is the dimensionless Froud number and dotted green line the dimensionless Richardson number. The vertical axis indicates height above sea level (in meters).

Obr. 6 Vertikálny priebeh niekoľkých parametrov stability vypočítaný z predpovede experimentálneho modelu DADA s platnosťou pre 19. november 2004, 15 UTC, pre bod nad Zakopane (v Poľsku, na náveternej strane Vysokých Tatier). Plná čierna čiara reprezentuje Brunt Väisäläovu frekvenciu (v s^{-1}, vynásobená 10^2), prerušovaná červená čiara je bezrozmerné Froudovo číslo a bodkovaná čiara bezrozmerné Richardsonovo číslo. Vertikálna os ukazuje výšku nad hladinou mora (v metroch).

7. SUMMARY AND CONCLUSION

Results of the study presented in this paper imply several consequences for future development and for the operational suite in numerical weather prediction. It was shown that models with sufficiently high resolution are able to forecast extreme mesoscale event as was the 19 November 2004 windstorm. Further, hydrostatic approximation seems to be fully sufficient to simulate the effect of intense downslope winds. It turned out that already the dynamical adaptation of the ALADIN model provides at 2.5 km resolution satisfying outputs and better horizontal distribution of the wind field in comparison to the reference run on lower resolution. This is important for the operational suite, because the dynamical adaptation is computationally more effective than conventional integration of the model with full number of vertical levels. On the other hand, the results of high resolution runs are dependent on the performance of the model giving the initial and boundary conditions. It was shown that the success of the reference run was linked with optimal setup of physical parameterisation used in the cycle 25. Different schemes of horizontal diffusion or the parameterisation of turbulence might have considerable influence on both low and high resolution simulations. Hence, the case of the 19 November 2004 should be used to test the future versions of model dynamics and physics to keep the performance of forecasting windstorms of these types.

From the forecasters point of view it is important that all model forecasts with high resolution showed typical features of a downslope windstorm (e.g. the hydraulic jump). Forecasters in Slovakia do not have many experiences with extreme events similar to the 19 November 2004 windstorm, because downslope wind of this intensity occurs rarely in Slovakia. The density of available surface observations is also not sufficient to get complete information from scales less than 10 km in horizontal. Hence, forecasters are forced to accept and rely on the model results what is easier if the dynamical reasons of the windstorm are known and better understood.

Results of the mesoscale diagnostics should be considered as very preliminary. Computation of the vertically averaged Froud number or Brunt-Väisälä frequency could be useful in forecasting praxis; however, more sophisticated diagnostic parameters are required to identify the events as the 19 November 2004 windstorm.

Future activities related to study of downslope windstorms will continue with more detailed sensitivity tests in different parts of the physical parameterisation (e.g. on the influence of the mixing length and critical Richardson number in parameterisation of the turbulent fluxes). Several available analytical models will be carefully examined to find appropriate parameters for fast diagnostics of downslope windstorms or mountain waves phenomena. It can be concluded that high resolution models are necessary to provide early warnings on extreme weather events with sufficient precision. Because of computational limitations, models with hydrostatic dynamics will be used in the near future. However, realistic simulations of windstorms in general, will require further development of non-hydrostatic models.

References

Clark, T.L., Peltier, W.R. (1977): On the Evolution and Stability of Finite-Amplitude Mountain Waves, *J. Atmos. Sci.*, 34, 1715-1730

Drvar, D., Stiperski, I., Tudor, M., Tutiš, V. (2005): ALADIN/HR: Testing the New Sub-Grid Scale Orography Representation on Bura Cases, *Croatian Meteorological Journal* 40, 304-307

Durran, D.R. (1986): Another look at downslope windstorms. Part I: The development of analogs to supercritical flow in infinitely deep continuously stratified fluid. *J. Atmos. Sci.*, 43, 2527-2543

Holton, J.R. (1992): *An Introduction to Dynamic Meteorology*, ACADEMIC PRESS, third edition, 282 – 287

Ivatek-Šahdan, S., Tudor, M. (2004): Use of high-resolution dynamical adaptation in operational suite and research impact studies, Meteorol. Z., 13, 99-10

Jurčec, V., Brzović, N. (1995): The Adriatic bora: special case studies, *Geofizika*, 12, 15-32

Klemp, J.B., Durran, D.R. (1987): Numerical Modelling of Bora Winds, *Meteorol.Atmos.Phys.*, 36, 215-227

Konček, M. (1944): *Meteorologické podmienky katastrofálnej víchrice na Slovensku v jeseni roku 1941* (Die meteorologischen Vorbedingungen des katastrophalen Sturmes in der Slowakei im Frühherbst 1941. Meteorological circumstances of catastrophic windstorm in Slovakia during autumn of 1941. In Slovak, with abstract in German language), Prírodovedecká fakulta Slovenskej university, Bratislava, 44 pp.

Koreň, M. (2005): Vetrová kalamita 19. novembra 2004 – nové pohľady a konsekvencie (Wind calamity of 19 November 2004 – new points of view and consequences, in Slovak), *Vysoké Tatry*, special issue, 15, 6-28

Kraljević, L., Tudor, M. (2005): High Resolution Simulation of a Severe Bura Event – an Intercomparison of Two Models, presentation, 15th ALADIN workshop, Bratislava

Laprise, R., Peltier, W. R. (1989): The structure and energetics of transient eddies in a numerical simulation of breaking mountain waves. *J. Atmos. Sci.*, 46, 565-585

Lilly, D.K. (1978): A Severe Downslope Windstorm and Aircraft Turbulence Event Induced by a Mountain Wave, *J. Atmos. Sci.*, 35, 59-77

Otruba, J. (1964): *Veterné pomery na Slovensku* (Wind conditions in Slovakia. In Slovak), SAV, Bratislava, 130-134

Otruba, J. and Wiszniewski, W. (1974): in: *Klíma Tatier* (Climate of Tatras. In Slovak, edited by Konček, M.), Veda, Bratislava, 328-339

Picek, B.I., Tutiš, V. (1995): Mesoscale Bora flow and mountain pressure drag, *Meteorol. Zeitschrift*, 4, 119-128

Picek, B.I., Tutiš, V. (1996): A case study of a severe Adriatic bora on 28 December 1992, *Tellus*, 48A, 357-367

Radnóti, G., Ajjaji, R., Bubnová, R., Caian, M., Cordoneanu, E., et al. (1995): The spectral limited area model Arpègè-Aladin. In: PWPR report series n.7 – WMO TD n. 699, pp. 111-118

Rak, J. (1967): Víchrica v oblasti Tatier v novembri 1964 (The gale in the Tatra region - in November, 1964. In Slovak, with abstract in Russian, English and German language.), *Sborník prác o Tatranskom národnom parku*, 10, 49-64

Simon, A., Vivoda, J. (2005): Downslope windstorm in High Tatras 19 November 2004, presentation, 15th ALADIN workshop, Bratislava

Smith, R.B. (1985): On Severe Downslope Winds. *J. Atmos. Sci.*, 42, 2597-2603

Stull, R.B. (2003): *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, 601-609

Tutiš, V., Picek, I.B. (1991): Pressure Drag on the Dinaric Alps During the ALPEX SOP, *Meteorol. Atmos. Phys.*, 47, 73-81

WWF position paper (2004): *Storm in Tatras National Park (Slovakia)*, web page of WWF organisation

Authors

André Simon, Jeséniova 17, 833 15 Bratislava, andre.simon@shmu.sk
Jozef Vivoda, Jeséniova 17, 833 15 Bratislava, jozef.vivoda@shmu.sk