INDICATIONS THAT TRAPPED GRAVITY WAVES HAVE A POTENTIAL FOR GENERATING EXTREME FOEHN WINDSTORMS

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Abstract: We present high-resolution numerical simulations of an Alpine south foehn case (14–16 November 2002) during which extremely strong surface winds occurred in several regions of the Alps. The specific focus is on a storm event in the upper Isar Valley in the Bavarian Alps, where gusts reached an estimated speed of about 45 $\mathrm{m\,s^{-1}}$. Our simulations indicate that the extreme low-level wind speeds were related to a large-amplitude trapped gravity wave, contrasting previous findings that violent surface winds are usually related to vertically propagating gravity waves, especially in the presence of low-level wave breaking, or to shooting hydraulic flow. According to the model results, gravity waves were excited over the mountain ranges adjacent to the valley and propagated towards the valley axis due to their three-dimensional dispersion characteristics, and wave trapping was caused by a deep neutral layer in the upper troposphere. A sensitivity test in which the neutral layer was removed exhibits significantly weaker surface winds in the region of interest, suggesting that wave trapping made an important contribution to this windstorm event.

Keywords: *Downslope windstorms, gravity-wave dynamics, foehn, numerical modelling*

1. INTRODUCTION

In the literature on mountain flow dynamics, violent windstorms in the lee of mountain ranges are usually either attributed to the formation of orographic gravity waves or to a transition from subcritical to supercritical hydraulic flow. Vertically propagating orographic gravity waves are known to be associated with a wind maximum over the lee slope, but the wind amplification reached in linear or quasi-linear waves is too small to explain the speeds observed in occasional severe storms. However, as first discovered by Clark and Peltier (1977), the occurrence of low-level gravity-wave breaking leads to a massive intensification of the winds, consistent with observed speeds in severe events. Hydraulic theory was first used by Schweitzer (1953) to explain the dynamics of downslope windstorms. For a downslope windstorm to develop, the local Froude number has to be equal to 1 at the mountain crest or, more generally, at a pass in the presence of three-dimensional topography. The atmospheric stratification most conducive to hydraulic-type flow is marked inversion separating the near-surface flow from a dynamically more or less passive upper layer. Real-case studies corroborate that lee-side windstorms are usually related to either vertically propagating gravity waves or hydraulic dynamics. Only a few recent studies on trapped lee waves, focusing mainly on the associated formation of rotors, provide evidence that marked local wind maxima can also occur beneath the wave troughs of trapped waves (e.g. Doyle and Durran, 2002; Hertenstein and Kuettner, 2005). However, these maxima tend to be significantly weaker than the primary maximum forming over the lee slope beneath the vertically propagating wave, and there appears to be no mention in the literature that trapped waves are particularly conducive to damaging winds. The goal of this study is to present an example in which high-resolution numerical simulations do indicate that a trapped gravity wave triggered a localized extreme wind maximum in an Alpine valley. The event under consideration occurred on 16 November 2002, the last day of an exceptional three-day south foehn period (Zängl and Hornsteiner, 2007). Our focus is on a small region of the Bavarian Alps in which a dense network of surface stations happened to be available for validating the simulated wind field. The remainder of this paper is structured as follows. Section 2 gives a brief description of the model setup, followed by a discussion of the results in section 3. A set of conclusions is drawn in section 4.

2. MODEL AND SETUP

The numerical simulations discussed here have been conducted with the Penn State–National Center for Atmospheric Research mesoscale model MM5 (Grell et al., 1995). Five two-way nested domains are used, having mesh sizes of 27 km, 9 km, 3 km, 1 km and 333 m, respectively. The first domain covers a large fraction of Europe, and domain 3 covers the east-west-oriented part of the Alps. The topography of domain 4 is shown in Fig. 1 together with the position of domain 5. In the vertical, 39 unevenly spaced full-sigma levels are used, the lowermost one being about 11 m above ground. At the upper model boundary (100 hPa), a radiative boundary condition is used in order to prevent spurious reflections of vertically propagating gravity waves. Moreover, sophisticated physics parameterizations are used for cloud microphysics, subgrid-scale convection, radiation and boundary-layer processes. To minimize the numerical errors over steep topography, a truly horizontal numerical diffusion scheme (Zängl, 2002) and a generalized coordinate definition (Zängl, 2003) are used. The initial and boundary conditions are taken from the operational ECMWF (European Centre for Medium Range Weather Forecasts) analyses. The initialization date is 12 UTC 15 November 2002 except for the fifth domain which is opened 12 h later, and the simulation terminates at 00 UTC 17 November.

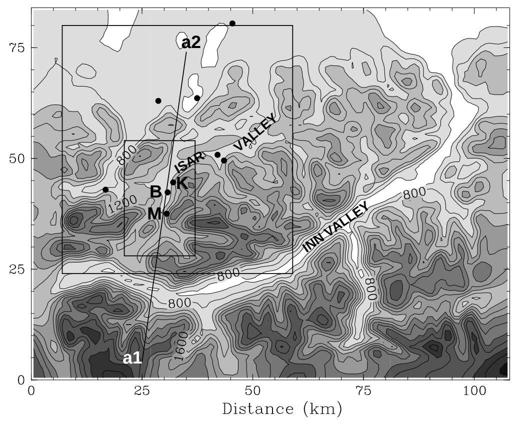

Figure 1: Topography of the fourth model domain with a contour interval (shading increment) of 200 m (400 m), no shading below 600 m. The boxes indicate the subdomain shown in Fig. 3 (outer box) and the location of model domain 5 (inner box). Line a1-a2 indicates the position of vertical cross-sections, and locations of surface stations are Mittenwald (M), Buckelwiesen (B) and Krün (K).

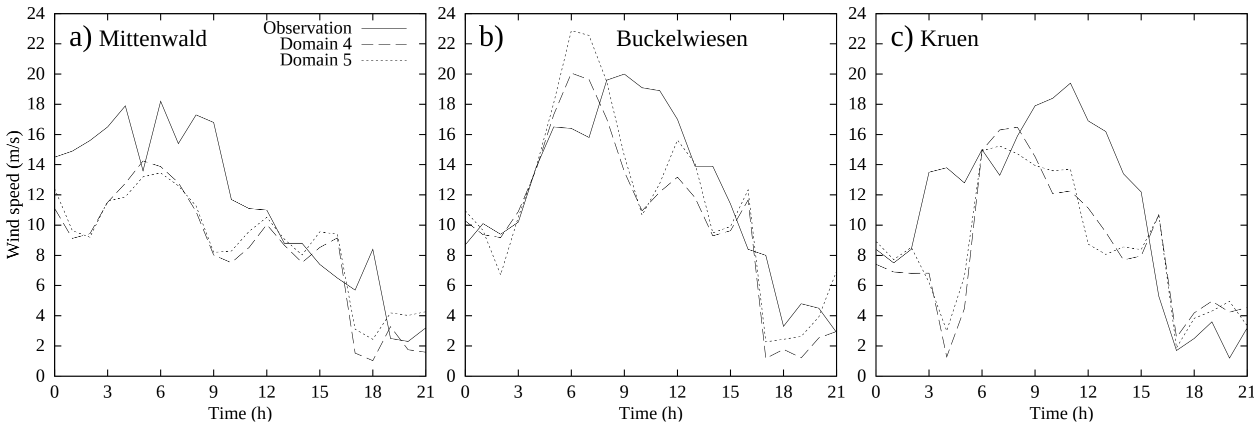

Figure 2: Time series of simulated and observed surface wind speeds for the stations indicated in Fig. 1. All times refer to 16 November 2002. The line key given in (a) is valid for all panels.

3. RESULTS

3..1 Evolution of surface winds

Fig. 2 displays the observed and simulated surface wind evolution for the three stations in the upper Isar Valley where the strongest winds occurred (Mittenwald, Buckelwiesen and Krün, see Fig. 1 for location). The surface measurements indicate exceptionally strong winds in the morning of 16 November, reaching up to $20\,\mathrm{m\,s^{-1}}$ on an hourly average. The wind maximum slowly propagated northward from Mittenwald to Krün. Surface winds started to weaken in the afternoon, and a cold-front passage near 16 UTC terminated the storm. The corresponding model results show that the simulations are in reasonable agreement with reality, but the wind maximum propagates northward too rapidly. Specifically, the simulated wind maximum reaches Buckelwiesen two hours too early and Krün three hours too early. The timing at Mittenwald is in better agreement with observations, but the simulated wind maximum is too short. The magnitude of the simulated wind maxima is somewhat lower than observed at Mittenwald and Krün. At the Buckelwiesen station, the simulated speed maxima are very close to the observation at a resolution of 1 km and somewhat higher at 333 m.

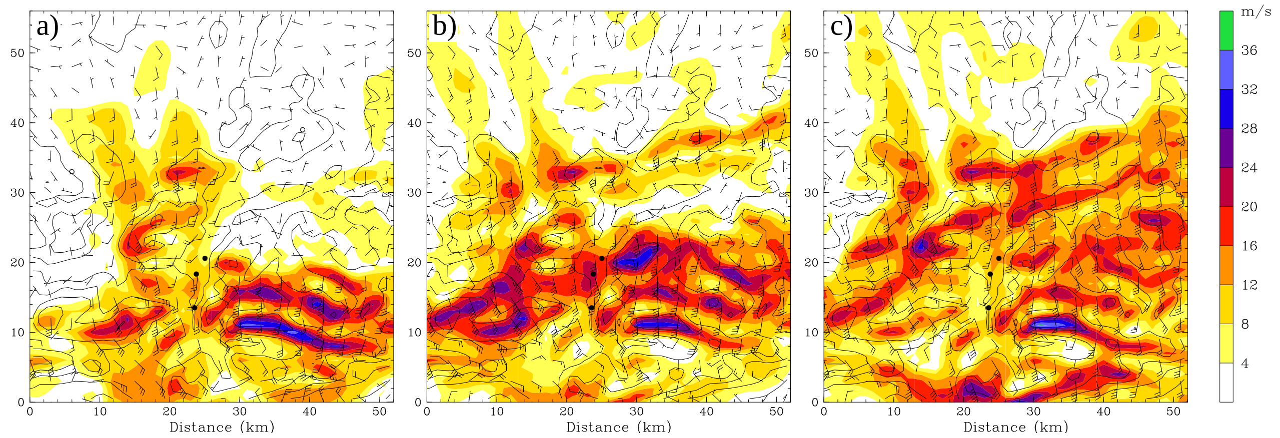

Figure 3: Simulated surface wind fields (full barb = 5 $\mathrm{m\,s^{-1}}$) for the subdomain indicated in Fig. 1b at (a) 03 UTC, (b) 06 UTC and (c) 10 UTC on 16 November 2002.

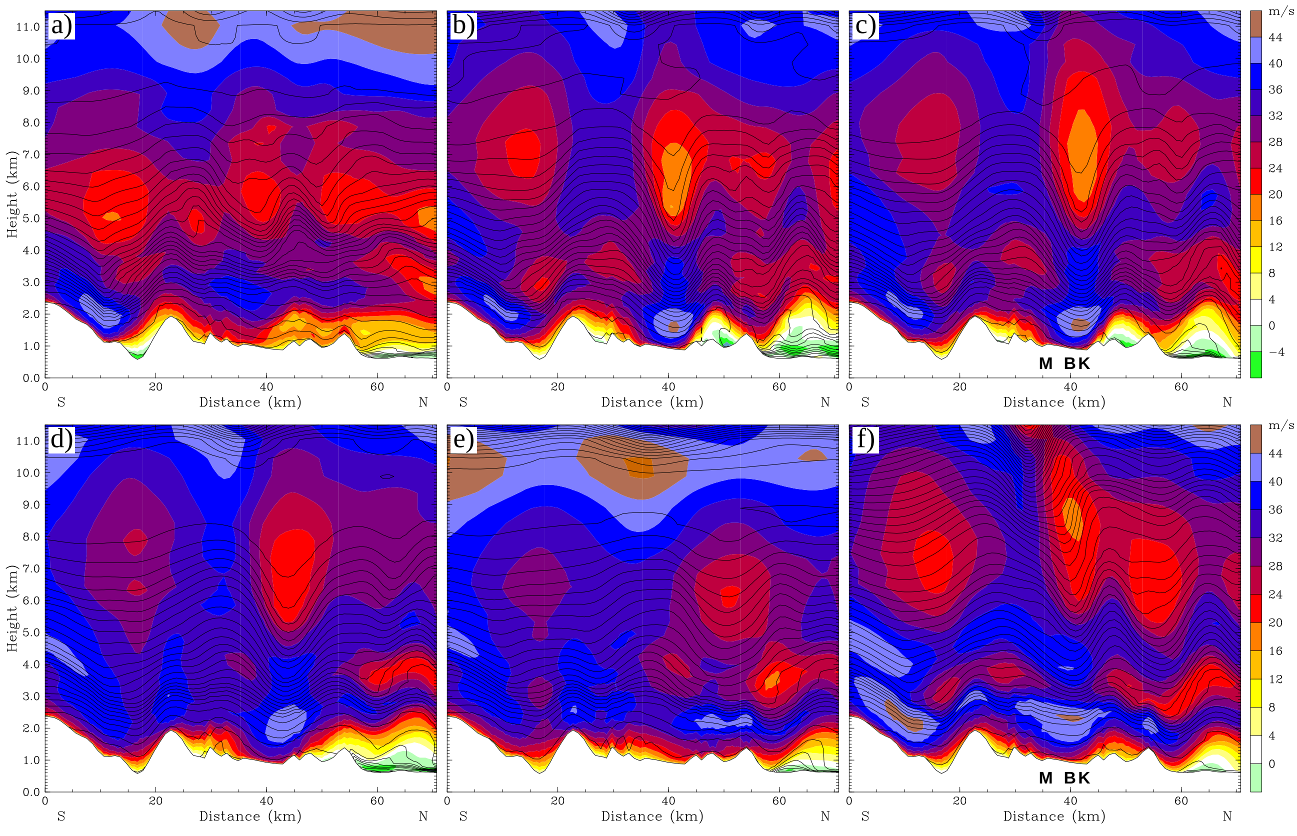

Figure 4: Vertical cross-sections of potential temperature (contour interval 1 K) and wind speed (see colour key) along line a1-a2 indicated in Fig. 1. Results are shown for the reference experiment at (a) 03 UTC, (b) 06 UTC, (c) 07 UTC, (d) 08 UTC and (e) 10 UTC, and for the sensitivity test with modified stratification at 07 UTC (f). In (c) and (f), the locations of Mittenwald (M), Buckelwiesen (B) and Krün (K) are indicated.

Simulated surface wind fields are illustrated in Fig. 3 for 03, 06 and 10 UTC. While violent winds were mainly restricted to the mountain ridges at 03 UTC, surface maxima in excess of $20\,\mathrm{m\,s^{-1}}$ appear in the upper Isar Valley at 06 UTC. By 10 UTC, the storm front has reached the northern rim of the Alps.

3..2 Gravity-wave structure

To provide some insight into the underlying gravity-wave dynamics, Fig. 4 presents vertical cross-sections of wind speed and potential temperature along line a1-a2 (see Fig. 1). At 03 UTC on 16 November (Fig. 4a), moderate gravity-wave activity is present in the middle troposphere, but its impact on the low-level wind field in the upper Isar Valley is still quite moderate. During the subsequent hours, a trapped gravity wave amplifies above Mittenwald and generates a marked low-level wind maximum by 06 UTC (Fig. 4b). The wave is generated over the adjacent mountain ridges and propagates towards the valley axis due to the three-dimensional dispersion characteristics of orographic gravity waves. Wave trapping is caused by a deep neutral layer in the upper troposphere, which reflects a large fraction of the upgoing wave energy. As a consequence, the axis of the wave trough is oriented almost vertically, and the wind perturbations are in phase or anti-phase with the temperature perturbations (in contrast to vertically propagating waves for which wind and temperature perturbations are in quadrature). Farther downstream, the wave amplitude decays rapidly, presumably because the stagnant cold-air pool in the Alpine foreland absorbs the wave energy quite effectively.

During the subsequent hours, the trapped wave and the associated low-level wind maximum propagate northward and reach the northern rim of the Alps by 10 UTC (Fig. 4b–e). The strongest low-level winds are attained between 06 UTC and 07 UTC (Fig. 4b,c), reaching almost 45 $\mathrm{m\,s^{-1}}$ between 600 m and 900 m AGL. Compared to 03 UTC and earlier, the low-level wind speed has amplified by about a factor of two beneath the trough of the trapped wave, which is consistent with the evolution of the surface wind speed displayed in Fig. 2b,c. After 07 UTC, the trapped wave gradually decays (Fig. 4d,e).

To further elucidate the dynamical role of the upper-tropospheric neutral layer, a sensitivity experiment with artificially modified large-scale data has been conducted. In this simulation, the neutral layer has been removed by increasing the temperature in the upper troposphere and stratosphere. During the growing phase of the wave, this modification turned out to have only a minor impact on the wave pattern and the associated wind speeds (not shown). However, a significant difference is found during the phase of strongest winds (Fig. 4f). Due to the altered wave dynamics, the wind maximum over the upper Isar Valley weakens by about $2.5\,\mathrm{m\,s^{-1}}$ (compared to the reference run) and is shifted upward by 500 m. Also, the region of largest wave amplitude is shifted upward. At the lowermost model level, the peak winds in the upper Isar Valley weaken by about $4\,\mathrm{m\,s^{-1}}$, which can be regarded as quite significant in terms of the expected storm damages.

4. CONCLUSIONS

Our simulations indicate that an extreme surface windstorm encountered on 16 November 2002 in the upper Isar Valley in the Bavarian Alps was related to a large-amplitude trapped gravity wave. Beneath the trough of the trapped wave, a low-level wind maximum with a speed of about 45 $\mathrm{m\,s^{-1}}$ was established, and surface winds exceeded 20 $\mathrm{m\,s^{-1}}$ even at valley locations. A sensitivity test in which the upper-tropospheric neutral layer was artificially removed indicates that wave trapping contributed about 4 $\mathrm{m\,s^{-1}}$ to the simulated surface wind maxima, mainly due to shifting the wave-induced low-level wind extremum closer to the surface.

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