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# Simulation of the meteorological conditions during a winter smog episode in the Inn Valley

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With 8 Figures

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**Summary**

A state-of-the-art numerical non-hydrostatic model is applied to simulate meteorological conditions during a winter smog episode in a large Alpine valley. This case study illustrates what such models are capable of and where there are limitations. The PSU/NCAR mesoscale model known as MM5, version 3.7, is used to simulate the period 31 January 2004 until 9 February 2004, when elevated pollution levels were observed in the Inn Valley. The MM5 model was used with the modifications provided by G. Zängl and with two different boundary layer schemes. Simulation results of five different model runs are compared with wind and temperature observations in the valley, at mountain stations and outside the Alps. A comparison of the results of the runs using a resolution of 2.4 km in the innermost nest with a run with 0.8 km resolution shows that 2.4 km is insufficient for acceptable results, while with 0.8 km the characteristic features could be reproduced. This concerns mainly the temperature and stability inside the Inn Valley whereas conditions in the Alpine foreland are simulated reasonably even at the coarser resolution.

## 1. Introduction

Local meteorology and the orography play a major role in transport and dilution of pollutants in Alpine valleys. Stagnation and recirculation, valley and slope wind systems, and temperature inversions reduce the dispersion of pollutants. Especially in autumn and winter, persistent and strong inversions with low wind speeds are often found in Alpine valleys, causing unfavourable dispersion conditions. Pollutants emitted tend to accumulate near the valley floor and may cause exceedances of air pollution limits. Numerical models are one possibility to investigate such situations and the impact of emission-side measures. However, in the Alpine topography it is difficult to achieve realistic simulations of the flows. Zängl's Alpine version of MM5 (Zängl 2003) has opened new possibilities for such simulations. Many high-resolution simulations of local wind systems and flows over mountains have been carried out with MM5, e.g. by Hornsteiner and Zängl (2004), and Zängl (2002). The MM5 model has been used also in other mountainous areas as in Titov and Sturman (2008) who used MM5 and CAMx to evaluate reduction strategies for PM10 in the area of Christchurch, New Zealand, or Regmi et al. (2003) who used MM5 in the Kathmandu Valley to simulate local flows. Zängl et al. (2001) simulated the valley wind system in the Himalayan Kali Gandaki Valley, where an extremely strong diurnal up-valley flow can be observed. Panday (2006) simulated two periods in February and May 2005 in the

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Kathmandu Valley, Nepal, and used the simulated meteorology as input into the CAMx model.

Also other mesoscale models have been used in alpine terrain. Brulfert et al. (2005) used in addition to the MM5 model the Advanced Regional Prediction System (ARPS) for grids spaced at less than 1 km for a study on photochemistry in French Alpine valleys. Song et al. (2007) used the ARPS model to simulate and investigate down-valley flows in the Himalayan Rongbuk Valley. De Wekker et al. (2005) used the Regional Atmospheric Modeling System (RAMS) to compare measurements obtained from a campaign in the Riviera Valley, southern Switzerland, with numerical simulations. A modelling system composed of the RAMS model, the Lagrangian dispersion model SPRAY, and the interface code between these two modelling system, MIRS, has been used by Carvalho et al. (2002) to study transport and diffusion in the area of the Rhine Valley, France and Germany, and compare the simulations to observations of the TRACT experiment. Dosio et al. (2001) compared campaign measurements with model output of two non-hydrostatic models, MM5 and TVM, for South Tyrol in northern Italy.

Publications treating the evolution of the boundary layer, and atmospheric and hydrological processes over mountainous terrain have been produced in context of a variety of other projects, e.g. during the MAP programme (*http://www.map.meteoswiss.ch*). Other models used in simulation of mountainous terrain are the Lokal-Modell (LM) which is part of the numerical weather prediction system of the German weather service (DWD) and the successor of the MM5 model, the Weather Research and Forecast (WRF) model.

In the present study we concentrated on simulating winter conditions in an Alpine valley. The study was carried out in the context of the ALPNAP project (*http://www.alpnap.org/*, Heimann et al. 2007) which was part of the EU Alpine Space Interreg programme. It was devoted to the demonstration of scientific methods for air pollution and noise investigation along major Alpine transit routes (Seibert et al. 2005). Results of two of the five simulations presented here have been used as input for a dispersion and atmospheric chemistry simulation with the Eulerian photochemical model CAMx (Environ 2006). These results are not presented in this paper.

## 2. Area of interest

The area studied is a section of the Inn Valley, Tyrol, in Austria. This is one of the major Alpine valleys leading from Switzerland through Austria into Germany. The section considered, going from west to east, parallel to the Alpine main ridge and to the northern border of the Alps, is surrounded by mountain tops around 2500 m asl and has a height of the valley floor from 500 to 600 m asl. It is influenced by tributary valleys from the north and more importantly from the south. One of the tributary valleys is the Wipp Valley which reaches the Inn Valley at Innsbruck.

## 3. Model setup

The PSU/NCAR mesoscale model MM5 version 3.7.4 (Dudhia 1993; Grell et al. 1996) was used in this study with the modifications based on Zängl's Alpine MM5 version (Zängl 2003). A 10-day episode during February 2004 was simulated.

Five different runs were carried out. They differ with respect to the atmospheric boundary layer (ABL) schemes, the number of nests and the location of the innermost nest. Runs 1 and 2 use four domains with a smallest grid size of 2.4 km, runs 3 and 3a have five domains and 0.8 km grid size in the innermost domain, run 4 has six domains with a different setup of domain 5. The simulation period for run 4 is much shorter than in the other three runs with 60 hours only because higher frequency temporal output, every 5 min, and a spatial resolution, 0.27 km, in domain 6 did not allow more with computer hardware presently available to us. In addition to these 4 runs, 2 test runs using the ETA scheme with the 2 versions of the implemented $\sigma$-diffusion for 4 domains have been carried out.

In runs 1 and 3a, the MRF ABL scheme (Hong and Pan 1996), based on the nonlocal-K, first-order closure scheme using the bulk Richardson number described in Troen and Mahrt (1986), has been applied. For the unstable boundary layer it is based on a countergradient transport term which incorporates contributions of large-scale eddies to the total flux, in the stable atmosphere

**Table 1.** Overview of specifications for model runs. Domain sizes are given of the innermost nest

| Run ♯ | ABL | | Domain Size | Grid spacing in km | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scheme | No. | | D1 | D2 | D3 | D4 | D5 | D6 |
| Run 1 | MRF | 4 | $276 \times 340.8\,km^2$ | 64.8 | 21.6 | 7.2 | 2.4 | – | – |
| Run 2 | ETA | 4 | $276 \times 340.8\,km^2$ | 64.8 | 21.6 | 7.2 | 2.4 | – | – |
| Run 3 | ETA | 5 | $70.4 \times 135.2\,km^2$ | 64.8 | 21.6 | 7.2 | 2.4 | 0.8 | – |
| Run 3a | MRF | 5 | $77.6 \times 140\,km^2$ | 64.8 | 21.6 | 7.2 | 2.4 | 0.8 | – |
| Run 4 | ETA | 6 | $35.1 \times 54.54\,km^2$ | 64.8 | 21.6 | 7.2 | 2.4 | 0.8 | 0.27 |

moist vertical diffusion in clouds is included. In runs 2, 3 and 4 the ETA ABL scheme (Mellor and Yamada 1982; Janjic 1990, 1994; Gayno et al. 1994) based on the Mellor–Yamada level 2.5 closure scheme is used. In this scheme turbulent kinetic energy (TKE) is a 3D prognostic variable and it uses standard stability functions for the surface layer, which makes it computationally more expensive than the simpler MRF scheme. Taking into account the region of interest, a scheme designed for steep mountainous regions such as the ETA model is more applicable.

In Table 1, a summary of the runs is given. For all five simulations 2-way nesting was applied. The Noah land surface model (Dudhia 1996; Chen and Dudhia 2001a, b) was used with the built-in land-use and the USGS 30″ elevation data (∼1 km). Using a grid size of 0.8 km in the innermost nest therefore means a slightly smoothed terrain representation compared to what would be obtained with better terrain elevation data. The Reisner 1 moisture scheme (Reisner et al. 1993; 1998) has been used in addition to the Betts–Miller cumulus scheme (Betts 1986; Betts and Miller 1986) in the outermost nest, the Grell cumulus parameterisation in the second nest and no cumulus parameterisation in nests 3–5. The cloud radiation scheme was applied in all model runs. Model top was at 50 hPa, and in the vertical 35 sigma levels were used,

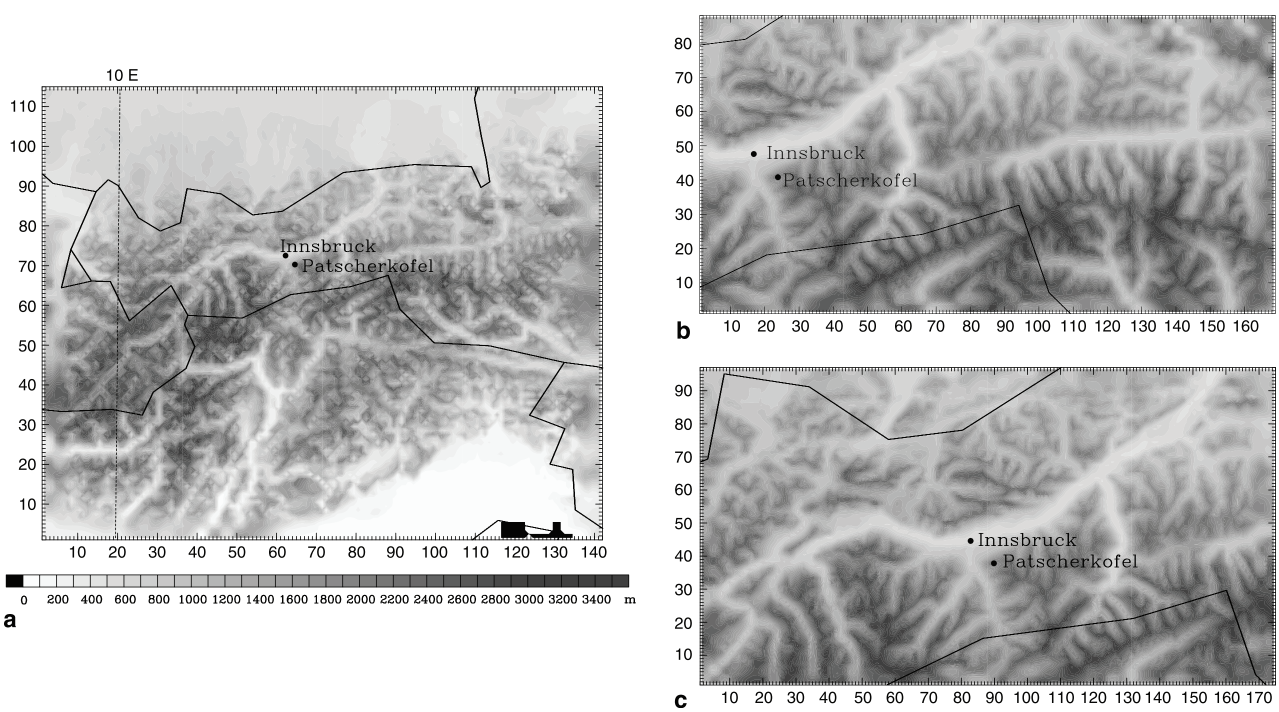


**Fig. 1.** Model topography of (**a**) domain 4, (**b**) domain 5 for the simulation runs 1, 2 and 3, and (**c**) domain 5 of run 3a, 4. The axes are annotated with grid point numbers. Altitudes of the stations used for comparisons are: Innsbruck 577 m, Patscherkofel 2247 m, Munich 520 m, and Hohenpeißenberg 977 m

four of them below 100 m. Zängl's $z$-diffusion scheme (Zängl 2003; 2002) and orographic shadowing is also taken into account. There, the solar part of the scheme is modified to take the sloping orography and topographic shadowing into account. With the generalised $\sigma$-coordinate implemented by Zängl (2003), based on the work by Schär et al. (2002), a rapid decay with height of small-scale topographic features is achieved. It allows an improvement over steep terrain of the accuracy of the horizontal advection at higher levels. The $z$-diffusion calculates the numerical diffusion truly horizontally, and a recursive coarse-to-fine-mesh nesting of the radiative boundary condition is applied. At model levels where truly horizontal computation without intersecting the lowermost half-sigma surface, the intersecting level, is not possible, a combination of an orography-adjusted diffusion along the sigma surfaces and a one-sided truly horizontal diffusion is used for the moisture variables. The one-sided truly horizontal diffusion is not used for the temperature because the slope wind circulation would be damped in an unphysical way (Zängl 2002). Lower-level temperatures are calculated using a transition to an orography-adjusted sigma diffusion and additionally a temperature gradient correction. For model levels above this intersecting level, which depend on the steepness of the orography, the truly horizontal computation of the diffusion is used.

The MM5 model runs were initialised with and, on the outermost domain, nudged towards ECMWF analyses having a horizontal resolution of 1° and which were available at full vertical resolution every 3 hours.

Domain sizes (Table 1), especially in the innermost nests shown in Table 1, in the MM5 runs are relatively large due to the special requirements of domain settings in the CAMx chemistry-transport model. Figure 1a and b shows the terrain in the two innermost domains, 4 and 5, of runs 1, 2 and 3 whereas Fig. 1c shows the changes of the location of domain 5 in runs 4 and 3a.

## 4. Selection and description of the episode

The simulation period was selected to represent a winter smog episode in the Inn Valley. Selection criteria were that it should be associated with elevated, but not necessarily extreme levels of air pollution and it should be in the cold season. A period in February 2004 in the Inn Valley as well as in the other target areas of the ALPNAP project in the Southern and Western Alps fulfilled these conditions. We used this period, defined as 31 January to 6 February, 2004. In order to include the build-up and dissolution phases and to allow for some spin-up especially in the CAMx model, the simulation starts on 27 January, 12 UTC, and ends on 9 February, 00 UTC. In run 4 the period 3 February 12 UTC–6 February 00 UTC 2004 was used.

Weather during the simulation period includes a typical high-pressure situation with stable stratification in the Inn Valley. Table 2 gives an overview of the prevailing weather during the simulation period.

Figure 2 displays the conditions during the simulation period at the station Innsbruck University (meteorology) and the down-town mea-

**Table 2.** Prevailing weather and cloud coverage during the simulation period starting on 27 January, 12 UTC and ending on 9 February, 00 UTC

| Date | | Synoptic conditions | Cloud coverage |
|---|---|---|---|
| 27–28 | January | cyclonic influence | partially clouded |
| 29 | January | NW flow, snow showers | partially clouded |
| 30 | January | anticyclonic influence | mostly clear sky |
| 31 | January | westerly flow, cold air at valley bottom remains | mostly clear sky |
| 1 | February | SW flow | mostly clear sky |
| 2–3 | February | SW flow | partially clouded |
| 4 | February | anticyclonic influence, cold air at valley bottoms | partially clouded |
| 5–6 | February | anticyclonic influence, cold nights, cold air at valley bottoms | cloud free |
| 7–9 | February | W flow, rainfall, decreasing temperatures<br>NW flow and snow fall | overcast |

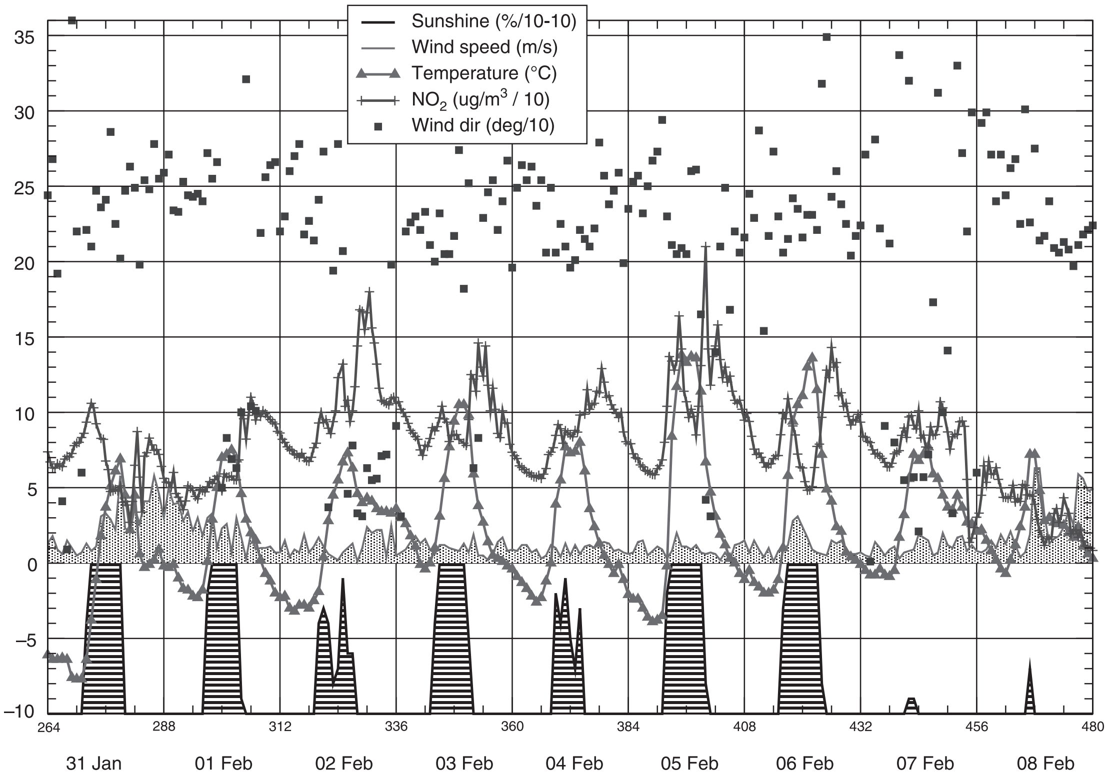


**Fig. 2.** Observed temperature in °C, wind speed in m/s, wind direction in tens of degrees and relative sunshine duration in tens of percent shifted by $-10$ (strip-filled curve) at Innsbruck University, and $NO_2$-concentration in $\mu g/m^3$, scaled by a factor of 10, at Innsbruck–Fallmerayerstrasse during the simulation period. Axis spacing is given in date on the x-axis and in the corresponding values for quantities on the *y*-axis

surement site Innsbruck–Fallmerayerstraße (pollution), located at a parking lot between a street and a small park.

## 5. Results

### *5.1 Discussion of resolution effects*

First results of the comparison between run 1 and run 2, which will be discussed in detail in section 5.2, have shown that a resolution of 2.4 km in a valley with a width of approximately 5 km is not sufficient enough to resolve the valley atmosphere properly. Also other studies, e.g. Hornsteiner and Zängl (2004) and Gohm et al. (2004), have shown that a higher resolution in the Inn Valley is needed. Therefore, simulations using higher spatial resolution, run 3 and 3a with a resolution of 0.8 km in the innermost nest, and run 4 (Schicker et al. 2008) with high spatial resolution (0.27 km in the innermost nest) at a high temporal frequency of 5 min were performed. Results of run 4 should account for our feelings that probably a higher resolution than 0.8 km would deliver better nocturnal temperature results at the valley bottom. For this run, the same domain size for domain 5 has been used as in run 3 but it has been shifted to the west, starting now near the Arlberg Pass (see Fig. 1c) with Innsbruck and Patscherkofel located in the middle of the domain. Comparisons between run 2, run 3, run 4 and the observations have been carried out for these two stations only.

Results of run 3a (Fig. 3a), with the same domain setting as in run 4 but with the MRF ABL scheme, confirmed that the ETA scheme performs better at the valley bottom, which is the area we were interested in. A comparison between runs 3a and 3 for temperatures at Innsbruck (Fig. 3a) show that the MRF run underestimates the amplitude of the diurnal cycle at the valley bottom. Temperatures during daytime are about 6 K too low. Nocturnal temperatures are better simulated than in run 3 but still overestimated by 1–2 K. The correlation coefficient between observed and run 3 temperature values is 0.79,

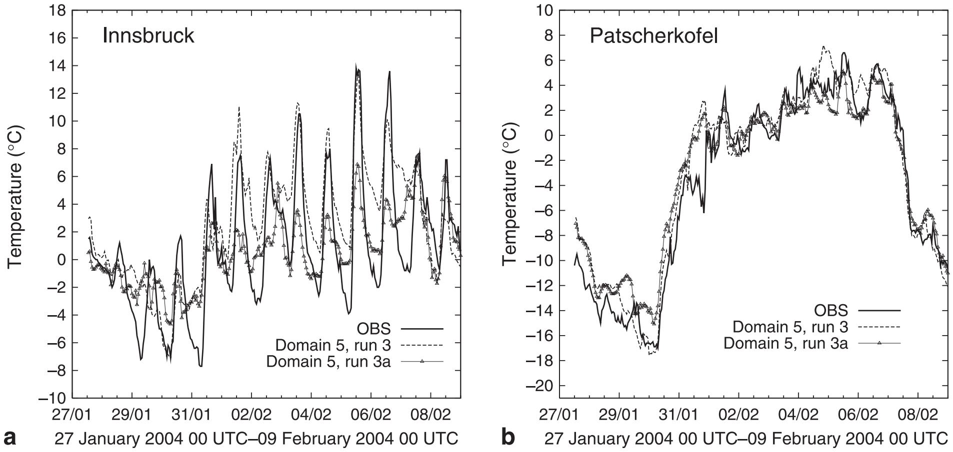


**Fig. 3.** Comparison of observed (OBS) and modelled temperature for (**a**) Innsbruck University (577 m), and (**b**) Patscherkofel (2247 m). Modelled values are taken from the runs 3 and 3a

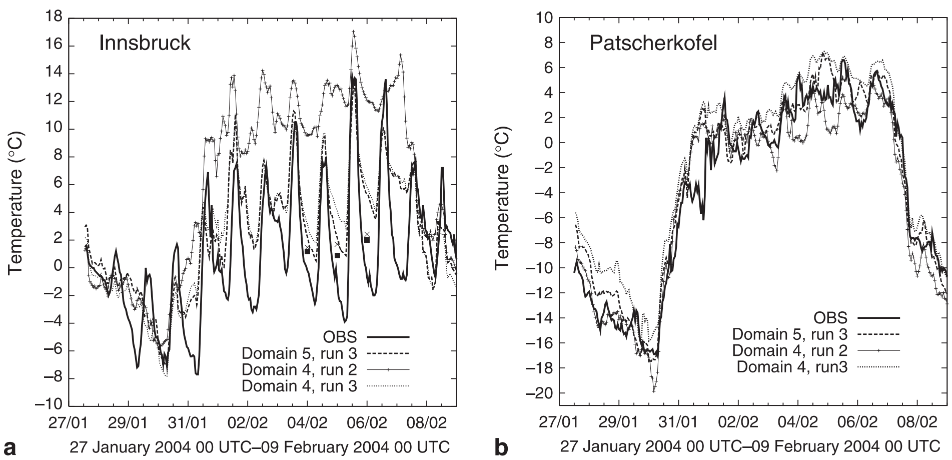


**Fig. 4.** Comparison of observed (OBS) and modelled temperature for (**a**) Innsbruck University (577 m) and (**b**) Patscherkofel (2247 m). Modelled values are taken from the runs 2, 3 and 4. Of run 4, only the 00 UTC values for Innsbruck are shown here, domain 5 with 0.8 km resolution as × and domain 6 with 0.27 km resolution as a filled square

between run 3a and observations it is 0.76, the correlation coefficient between run 3 and run 3a is 0.79. Still, results of run 3 using the ETA scheme are much better compared to run 3a using the MRF scheme. At Patscherkofel (Fig. 3b), differences between run 3 and run 3a are small. As a consequence of these findings, results of run 3 will be discussed in the following. Limitations related to the CAMx model unfortunately prevented the inclusion of Munich and Hohenpeißenberg in domain 5 of both runs, 3 and 3a, but results of run 1 and run 2 (Sect. 5.2) are already in good agreement with observations.

The temperatures in Innsbruck and its diurnal cycle are vastly better reproduced in run 3 than in run 2 (Fig. 4a). Thanks to two-way nesting, even results in domain 4 are improved. During daytime, differences between the results of domain 4 and domain 5 in run 3 (Fig. 4) are not large. Comparing nocturnal temperatures, the simulated values are still too high. Still, the amount of cooling and the time of the minimum temperature is simulated better compared to runs 1 and 2 in domain 5. After the initialisation period, daytime values are accurate to 0.2 K on 2, 3, 5 and 7 February, while larger errors up to 2.5 K can be found on 31 January, 1, 6 and 8 February. Modelled and observed nocturnal temperatures still are 2 K to 5 K too high in the simulation (run 3) in most nights, except during the night from 7 to 8 February when results were better. While run 3 with its 0.8 km grid brought a very significant improvement compared to runs 1 and 2, it still overestimated nocturnal temperatures in the valley. The three 00 UTC values of run 4 of domain 5 and 6 included in Fig. 4a

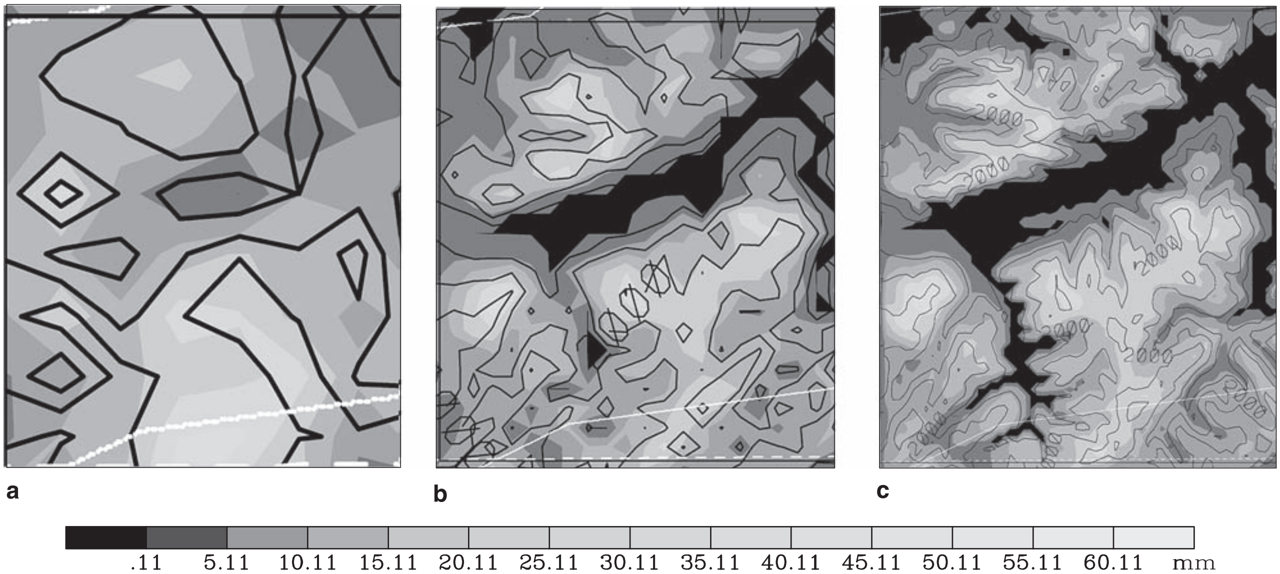


**Fig. 5.** Modelled snow cover water equivalent in run 3 for 1 February 12 UTC in (**a**) domain 3, (**b**) domain 4, and (**c**) domain 5. In all three panels the area shown represents the westernmost part of domain 5

show that a resolution of 0.27 km has some potential to further improve the nocturnal temperatures at the valley bottom but still falls short of simulating the observed nocturnal minima. At Patscherkofel (Fig. 4b), simulated temperatures in run 3 were already in good agreement in domain 4 and show no major improvements. The decreasing temperature during the night of 28/29 January, especially in Innsbruck but also at Patscherkofel, is not well simulated in all three runs (1–3). Starting on 30 January, the simulation captures well the temperature increase at the beginning of the high-pressure period, and the higher temperatures between 30 January and 7 February are well simulated. The temperature drop with the passage of a cold front on 7 February was simulated well for both Innsbruck and Patscherkofel.

The daily maximum temperatures occur too early in the simulations. For example, on 3 February, the temperature maximum in Innsbruck was modelled at 13 UTC (14 LST), but observed at the rather late time of 15 UTC at Innsbruck University as well as at Innsbruck Airport.

Snow cover, wind speed and wind direction are not well simulated in runs 1–3. Snow cover observations of Innsbruck and other valley stations show that during the whole period a snow cover of 5–10 cm was present and much more of course at the mountains. In the model in domain 3, here for run 3 (Fig. 5), there is no snow at Innsbruck after initialisation and a very shallow snow cover forms only as a consequence of modelled snow fall and disappears after four days at the valley bottom, which is in fact not really a valley in domain 3 (7.2 km resolution) but more like a plateau (Fig. 5a). Therefore, snow cover is present due to the smoothed orography leading to higher elevation of the valley bottom. In domain 5, large valleys such as the Inn Valley, the Wipp Valley, and the Ziller Valley, generally do not have any snow cover at all during the simulation. Lower mountains and smaller valleys are snow-covered in domain 5, but this snow cover breaks up in the small valleys, too, in the course of the simulation. Also in domain 4, there is no snow cover at the bottom of the valleys especially in the region of Innsbruck and the lower Inn Valley. Modelled snow cover water equivalent values are generally unreasonably low (Fig. 5). A major reason why the snow cover in the model is underestimated is probably the fact that the soil temperature is downscaled down from the ECMWF input using a temperature gradient of 0.6 K/100 m at initialisation. Another possibility for improving snow cover and in the following also the modelling results would be using snow cover fraction from satellite data.

Wind speed and wind direction are important meteorological parameters in relation to

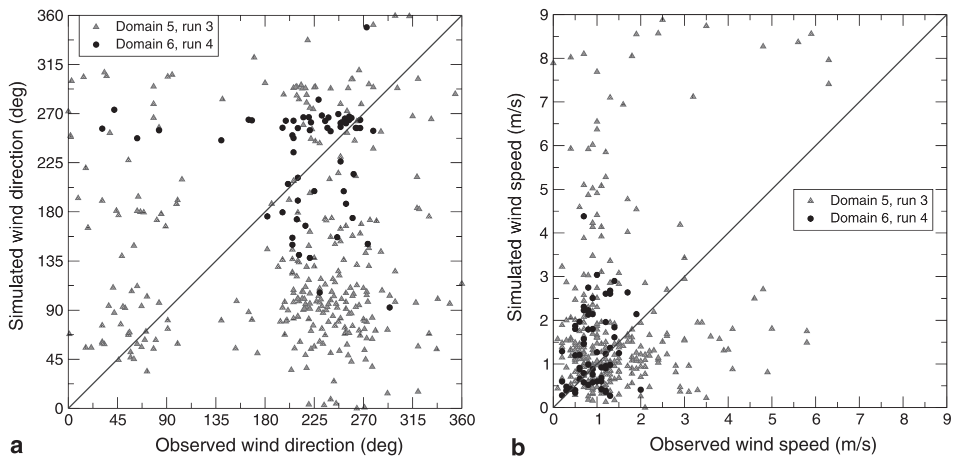


**Fig. 6.** Scatter plot of runs 3 and 4 of observed and modelled wind direction (**a**) and speed (**b**) at Innsbruck University

air pollution. These two parameters were found to be difficult to simulate in mountainous terrain, particularly at the valley floor. Due to the close grid-domain boundary near Innsbruck (Fig. 1) in domain 5 of run 3 (Fig. 6) and the too high simulated temperatures, wind direction and speed is not well reproduced by the model especially during the high pressure period at Innsbruck. At Patscherkofel it seems that modelled wind directions and speed are also influenced by these boundary effects observed at Innsbruck. As wind direction and wind speed are crucial parameters in dispersion and dilution of pollutants especially in Alpine valleys and the results of run 3 have been used as input into a chemistry model, a better layout of the domains was tested in run 4. These investigations of run 4 (Fig. 6), with a better domain layout, show large improvements of the modelled wind direction. Still, wind speed is overestimated and not in good agreement with the observations. At Patscherkofel, wind speed is underestimated, wind direction of run 4 is simulated in good agreement with observations.

Two reasons for the badly simulated wind speed and wind direction at the two stations in run 3 can be identified. One is the previously mentioned too close grid-domain boundary, or in other words a bad choice of domain layout. The other reason is that in valleys the nocturnal cooling is a result of radiation cooling and, under anticyclonic conditions, horizontal temperature gradients whereas over flat terrain wind is the governing parameter for the nocturnal decrease of temperature.

### *5.2 Comparison between the ETA scheme and the MRF scheme*

For the comparison between run 1 and run 2, the station Innsbruck University in the Inn valley and the nearby mountain station Patscherkofel, situated on a ridge south of the Inn valley, as well as the two Alpine foreland stations Munich and Hohenpeißenberg were used. The Patscherkofel observation site is located at the pyramidal mountain peak at a height of 2247 m. Munich is a large city located 45 km north of the Alps at 515 m asl. The station is located in the city. The meteorological observatory Hohenpeißenberg is situated 20 km north of the Alps on an isolated low mountain at a height of 977 m; the surrounding area is at 550 m to 700 m asl. During stable winter conditions, Hohenpeißenberg is usually above the boundary layer while for conditions with stronger mixing it will be within the ABL.

Both of the MRF (run 1) and ETA (run 2) ABL schemes reproduce well the general course of the temperature, e.g. warming on 30/31 January and cooling on 7 February (Fig. 7). Simulated and observed temperatures are in good agreement at the stations Hohenpeißenberg, Munich and Patscherkofel. At Innsbruck (Fig. 7b), however, simulated temperatures are much too high, especially during night when the deviation exceeds 10 K, and the diurnal range is strongly damped compared to the measurements. At Innsbruck, temperatures in run 2 (ETA scheme) are slightly better than in run 1 (MRF scheme), and also winds are simulated better (not shown). On the other hand, at Munich (Fig. 7a), the diurnal tem-

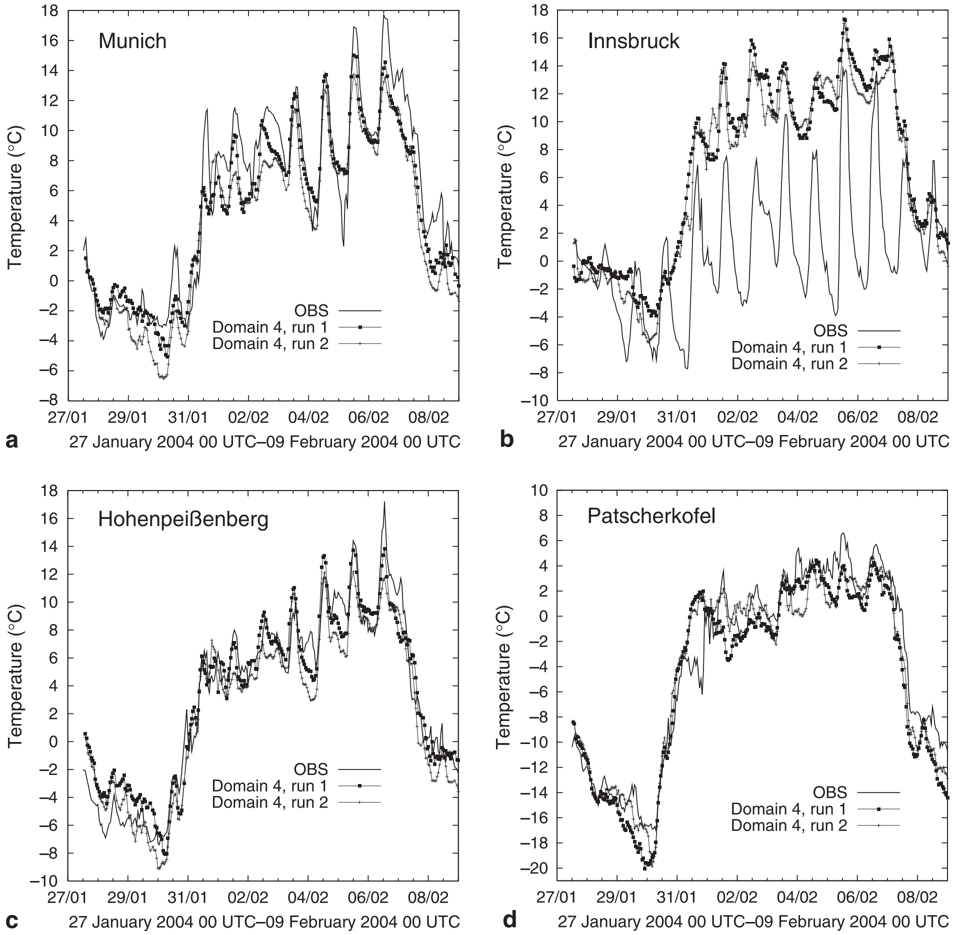


**Fig. 7.** Comparison of observed (OBS) and modelled temperature for (**a**) Munich, (**b**) Innsbruck University, (**c**) Hohenpeißenberg, and (**d**) Patscherkofel of run 1 (MRF ABL scheme) and run 2 (ETA ABL scheme). Both model results are for the innermost domain with a resolution of 2.4 km

perature cycle is simulated slightly better in run 1. One can also see that the diurnal range of the modelled temperatures of both runs at Munich is much more realistic as in Innsbruck. At the two mountain stations, both runs give nearly identical results. The general circulation, though, is reproduced well by both ABL schemes.

### 5.3 Stability

As stability in the lower atmosphere, expressed as potential temperature differences between mountain station and valley station, is crucial for the trapping of pollutants in the valley, and it is a major difference between Alpine valleys and basins,

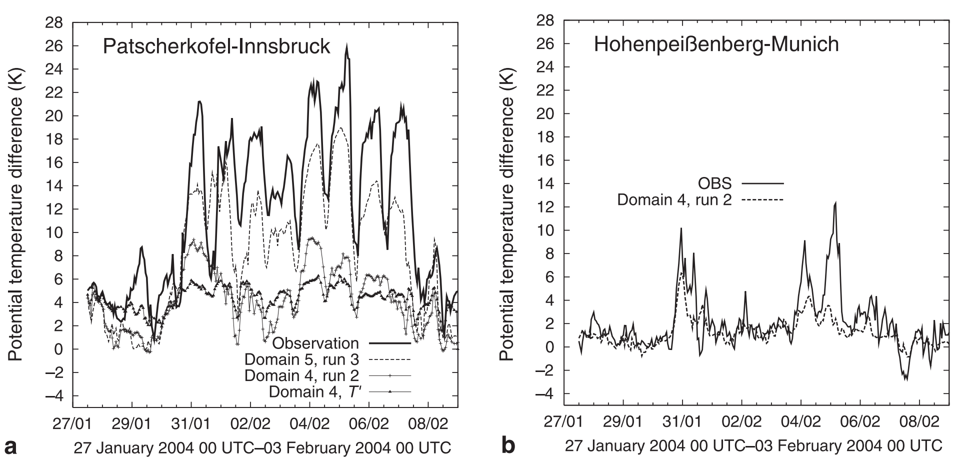


**Fig. 8.** Observed and modelled stability (potential temperature difference) for the station pairs (**a**) Patscherkofel–Innsbruck of run 3 (dashed), run 2 (plus) and a test run (triangles) using the $\sigma$-diffusion option with $T'$, (**b**) Hohenpeißenberg–Munich (run 2, domain 4)

where stability is influenced by the valley temperatures, on one hand and the Alpine foreland or other flat regions on the other hand, it has been investigated, too. The diurnal cycle of the stability is well reproduced but still underestimated compared to the observed strong stability in domain 5 of run 3 (Fig. 8a). The simulated stability in both four-domain runs, run 2 and run 1, is far from being realistic in the Inn valley thus not shown here. Over the Alpine foreland stability is much better simulated (Fig. 8b). Interestingly, in the coarser simulations the stability modelled inside the valley is similar to that outside. According to Zängl (personal communication), this is typical for simulations without the $z$-diffusion option activated. This means that the $z$-diffusion scheme, designed to have horizontal diffusion truly horizontal and not along the model levels (which means vertical mixing in steep terrain) works only if a minimum number of grid points is available to represent the valley floor. For comparison, two simulations with the standard $\sigma$-diffusion, as implemented in MM5, and 2.4 km resolution were also carried out. Land use, radiation and cumulus parameterisation scheme where chosen like in run 2. Zängl (2002) describes that the $\sigma$-diffusion option using temperature $T$ tends to heat mountains and cool valleys whereas the option $\sigma$-diffusion using perturbation temperature $T'$ uses a vertical temperature gradient of $-6\,\mathrm{K/km}$ which warms the valleys compared to the option $T$. In our test we found the same results. In the case using $T$, simulated temperatures and stability in the Inn Valley were not at all realistic (e.g., simulated temperatures close to $-20\,^{\circ}\mathrm{C}$ compared to observed temperatures of $-8\,^{\circ}\mathrm{C}$). Temperatures and stability variations of the test run using $T'$ (Fig. 8a) are more damped compared to the simulated values of runs 1 and 2(not shown here), though they do not differ much at a resolution of 2.4 km. Results of these test runs using $\sigma$-diffusion compared to results of runs 1–3 confirm our findings that $z$-diffusion works only with a minimum number of grid points for resolving a valley atmosphere.

## 6. Conclusions

Simulations of a 10 day winter smog episode in the Inn valley have been carried out using MM5. Five different runs were made using two different boundary layer schemes and four or, respectively, six domains. Run 1 used the MRF ABL scheme and four domains with a resolution up to 2.4 km, runs 2 and 3 used the ETA ABL scheme with four domains in run 2 (2.4 km resolution) and five domains in run 3 with 0.8 km resolution in the innermost nest. Run 3a was performed using the setup as run 3 but with the MRF ABL scheme, and changed domain settings which are the same as in run 4. Run 4 used the same ABL scheme as runs 2 and 3 though only 60 hours have been simulated using 6 domains with a spatial resolution of 0.27 km in the innermost nest and a temporal resolution of 5 min.

Comparisons of run 3 with run 3a have shown that the ETA scheme proved to be the better scheme in the Inn Valley. The grid resolution is a key parameter in representation of the diurnal cycle and general level of the temperatures and thus also the stability inside the Inn Valley, which we consider as representative for large Alpine valleys. While the temperature is simulated well on the mountain stations Patscherkofel and Hohenpeissenberg and at the foreland station Munich in runs 1 and 2 (four domains, 2.4 km grid size), the results for Innsbruck and thus the stability inside the Inn Valley were unacceptable at this resolution. The addition of a further nest with 0.8 km grid spacing achieved realistic simulation results also at the valley bottom. However, nocturnal temperature minima and stability are still underestimated.

This could be caused by a too thin snow cover which melted in the valley during the simulation, while observations show that the valley was snow-covered throughout the period. Comparisons with test runs using $\sigma$-diffusion show that the $z$-diffusion scheme needs a minimum number of grid points to resolve a valley atmosphere. Snow cover in the model is melting too fast due to soil temperature downscaling of 0.6 K at initialisation. This also influences the stability and the temperatures in the valley.

Wind direction and wind speed are better represented in the ETA scheme, but both schemes need higher resolution than 1 km in space to represent the valley wind system. Results of run 4 have shown that a resolution of at least 0.27 km grid size and a frequencey output of 5 min is needed to simulate wind direction and wind speed in qualitative good agreement with the observations.

Simulations with even higher resolution, with a better placed domain 5 including more of the upper Inn Valley and with a corrected initial snow cover should be done in the future to find out how the nocturnal temperature in the valley and the cold-air outflow could be optimised. Additonally, terrain data and land-use data with higher resolution should be used as input to the model. With these improvements, air pollution simulations should have the necessary input data to realistically consider the especially unfavourable dispersion conditions in Alpine valleys.

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