A modified diffusion scheme for simulations over complex terrain

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1. Introduction

An appropriate implementation of explicit horizontal diffusion is very important for simulations over mountainous topography. Calculating this diffusion along the coordinate surfaces, as is done in the MM5 model, may introduce serious errors, particularly for atmospheric properties having a strong vertical gradient. Temperature diffusion along sigma surfaces, for example, tends to cool valleys and to heat mountains. Likewise, diffusion of the water vapor mixing ratio along sigma surfaces tends to dry valleys and to moisten the atmosphere above mountains.

To prevent spurious temperature or moisture tendencies, diffusion should be computed truly horizontally. This can be accomplished with vertical interpolation between the sigma levels. However, truly horizontal computation is not always possible without intersecting the ground. Thus, a special treatment is needed for the model levels close to the ground. Switching back to diffusion along the sigma surfaces (henceforth referred to as sigma-diffusion) is certainly not adequate because this retains the diffusion-induced errors noted above. A more promising method is to use one-sided, truly horizontal diffusion, as suggested by Li and Atkinson (1999). However, applying one-sided diffusion to temperature damps slope winds in an unphysical way because the radiatively cooled (or heated) air above the slope is mixed with the warmer (cooler) air over the interior of the valley. In this paper, a more effective method to reduce diffusion-induced errors in the lower model levels is presented.

2. The modified diffusion scheme

In the modified diffusion scheme, diffusion is computed truly horizontally at all model levels where this is possible without intersecting the topography at any grid point. This is accomplished by linear vertical interpolation between the coordinate surfaces. It has been found that higher-order interpolation does not yield a significant further improvement but is substantially more expensive than linear interpolation.

In the lower model levels, diffusion is treated differently for momentum, temperature and the moisture variables. For momentum, a simple linear transition to diffusion along the coordinate surfaces (henceforth referred to as sigma-diffusion) is chosen. Since the influence of surface friction essentially follows the orography, this way is thought to be better justified than a transition to one-sided, truly horizontal diffusion. A more sophisticated method does not appear to be necessary here because the sensitivity to the implementation of momentum diffusion is rather weak. In many situations, momentum diffusion may even be calculated everywhere along the sigma surfaces without significant impact on the results.

For the moisture variables (the mixing ratios of water vapor, cloud water etc.), a combination of one-sided truly horizontal diffusion and orography-adjusted sigma-diffusion (to be described below) is used. The transition is implemented with weighting functions for sigma-diffusion (w_σ) and for one-sided truly horizontal diffusion extending to higher and lower indices, respectively (w_{h+} and w_{h-}). At the top of the transition layer, w_{h+} and w_{h-} are set to 1, corresponding to centered truly horizontal diffusion (see Eq. 1 below). These coefficients decrease linearly with height to 0.5 at the surface provided that the ground is not intersected. If the latter condition is not met, the respective coefficient is set to zero. w_σ is set to $1-(w_{h+}+w_{h-})/2$. Note that this weighting is done for each horizontal direction separately. One-sided diffusion is discretized using the "half" of the centered difference scheme for the fourth derivative

$$\left(\frac{\partial^4 u}{\partial x^4}\right)_i \approx \frac{3u_i - 4u_{i+1} + u_{i+2}}{\Delta x^4}\,, \qquad (1)$$

Δx being the grid increment. Thus, applying one-sided diffusion on both sides of a grid point yields centered diffusion.

Orography-adjusted sigma-diffusion follows the idea that sigma-diffusion may be applied along the axis of a valley without inducing spurious tendencies. However, in the direction across the valley axis, sigma-diffusion should be switched off. To determine which direction is along and across the valley axis, respectively, the height difference between the actual grid point and the surrounding grid points is considered. Specifically, the diffusion coefficient in i-direction (denoting one of the horizontal directions) is reduced by a factor of $5(5 + \Delta h_{i,1}^6 + \Delta h_{i,2}^6)^{-1}$, where

$$\Delta h_{i,1} = \frac{h_{i+2} + h_{i-2} - 4(h_{i+1} + h_{i-1}) + 6h_i}{100\,\mathrm{m}} \quad (2)$$

and

$$\Delta h_{i,2} = \frac{h_i - 0.25(h_{i+1} + h_{i+2} + h_{i-1} + h_{i-2})}{100\,\mathrm{m}}. \quad (3)$$

Note that (2) has the same structure as the discretization of the fourth derivative. This reduction has been found to eliminate the unphysical behavior of sigma-diffusion very effectively. However, for very complex topography, there may still be a few grid points where there is essentially no diffusion. Since numerical noise tends to develop at such grid points, a subsidiary second-order sigma-diffusion is applied where one-sided horizontal diffusion is switched off in all directions and fourth-order sigma-diffusion is reduced strongly. The second-order diffusion is reduced in a similar manner as described above when the grid points involved are not at the same height. However, since the discretization of the second derivative involves only three instead of five grid points, it is easier to apply in narrow valleys.

For temperature, one-sided truly horizontal diffusion is not used because it damps the slope wind circulation in an unphysical way. Instead, a transition between centered horizontal diffusion and orography-adjusted sigma-diffusion is used in the lower model levels. It follows the same weighting functions as moisture diffusion except that $(w_{h+} + w_{h-})/2$ is replaced by w_h. w_h is set to zero if centered horizontal diffusion intersects the ground.

In addition, a temperature gradient correction is applied to sigma-diffusion in the lowermost model levels. Based on the vertical temperature gradient at the local grid point, this correction ensures that sigma-diffusion behaves neutrally with respect to this temperature gradient. If, for example, a dry adiabatic temperature gradient is diagnosed, the corrected diffusion is essentially equivalent to using potential temperature for the computation of diffusion. Overadiabatic temperature gradients and gradients exceeding $+30\,\mathrm{K\,km^{-1}}$ are not allowed in order to avoid unphysical positive feedback effects. The correction is applied to the standard fourth-order diffusion and to the subsidiary second-order diffusion. It improves the model's capability of reproducing the nocturnal ground inversion.

3. A test simulation

Idealized numerical simulations of the valley wind system of the Alpine Inn Valley have been performed in order to test the modified diffusion scheme. The Inn valley has been chosen because a large amount of detailed measurements is available for this valley (e.g. Pamperin and Stilke 1985, Vergeiner and Dreiseitl 1987). Since these measurements show a lot of characteristic features recurring every fine weather day, the simulations could be based on a highly idealized setup, only orography being taken from data.

a) Setup of the simulations

The test simulations have been computed on five interactively nested model domains, the finest horizontal resolution being 800 m. The innermost model domain covers the lower Inn valley together with its tributaries. In the vertical, 39 sigma levels are used, corresponding to 38 half-sigma levels where most of the variables are computed. The lowermost half-sigma level is located at about 18 m above ground. The vertical resolution is about 50 m close to the ground and decreases up to 800 m near the upper boundary, which is chosen to be at 100 hPa.

To keep the setup as simple as possible, the absence of any horizontal pressure and temperature gradients is assumed. This corresponds to vanishing large-scale winds. For consistency, meridional gradients of solar radiation have also been switched off. A constant latitude of 47.5°N is used to compute radiation. The simulation starts at a fictitious date of 15 October, 00 UTC (the date being relevant for radiation only) and is carried out for 30 hours. Temperature and moisture are specified according to what is typical for mid-October in the presence of continental air.

Three simulations based on the same initial conditions are considered. Two of them use existing model

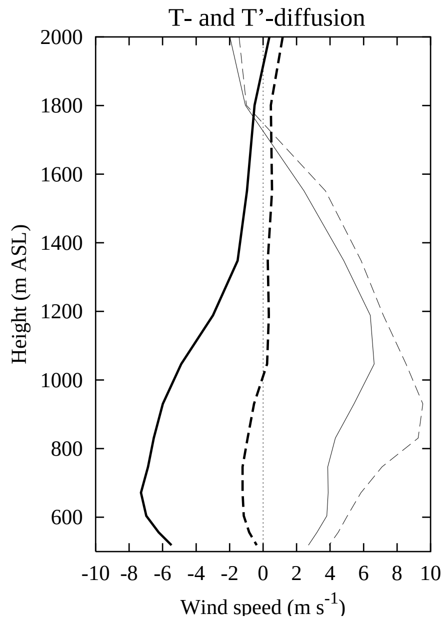

Figure 1: Simulated wind profiles, $t = 16$h (solid lines) and $t = 30$h (dashed lines). Note that positive (negative) values denote downvalley (upvalley) wind. Simulations are performed with T-diffusion (thin lines) and T'-diffusion (bold lines).

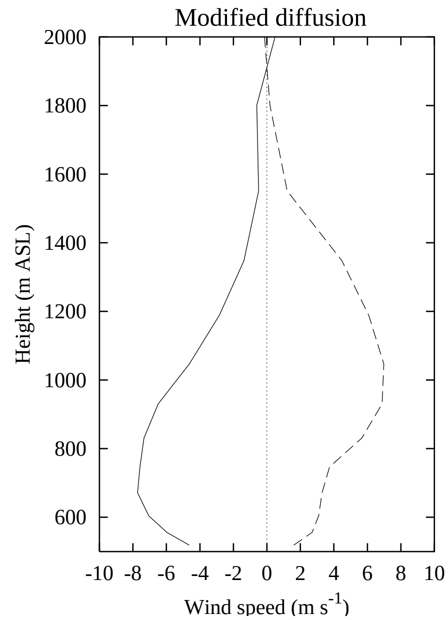

Figure 2: Same as Fig. 1, but for simulation with modified diffusion.

options. First, actual temperature (T) is used for computing the diffusion along the sigma levels. Since sigma-diffusion tries to equalize temperature differences on a model surface, this option tends to cool valleys and to heat mountains. In the second simulation, the so-called perturbation temperature (T') is used for computing the diffusion. T' the difference between the actual temperature and a reference temperature profile that usually has a vertical gradient around $-6\,\mathrm{K\,km^{-1}}$ in the lower troposphere. Thus, the second option tries to establish a vertical temperature gradient of $-6\,\mathrm{K\,km^{-1}}$ within valleys. Consequently, valleys tend to be warmer than with the first option. In the following, these two versions of sigma-diffusion will be referred to as T-diffusion and T'-diffusion, respectively. In the third simulation, the modified scheme described in section 2 is used.

b) Results

Simulated vertical wind profiles at a location where measurements are reported by Pamperin and Stilke (1985) are displayed in Figs. 1 and 2 for $t = 16$ h (solid lines) and $t = 30$ h (dashed lines). In each case, negative (positive) values denote upvalley (downvalley) wind. From the measurements, we expect upvalley wind in the afternoon and downvalley wind in the night. At the location considered here (Niederbreitenbach), the upvalley wind maximum is observed significantly closer to the ground than the downvalley wind maximum.

It is obvious that the model fails to reproduce the observed valley wind circulation with the original sigma-diffusion scheme (Fig. 1). With T-diffusion, downvalley wind is simulated throughout the day. It is only slightly weaker in the afternoon than during the night. On the other hand, permanent upvalley wind is obtained with T'-diffusion. It is rather weak at the end of the night and of realistic strength in the afternoon. Briefly spoken, the variable used for computing the temperature diffusion determines the direction of the valley wind. With the modified diffusion scheme, however, the simulated valley wind circulation is rather close to reality (Fig. 2). The wind maxima of both the upvalley wind and the downvalley wind are well within the observed range of values. Moreover, the day-night asymmetry of the height of the wind maximum is captured well by the simulation.

To explain the differences between sigma-diffusion and the modified diffusion scheme, the vertical temperature profiles at Niederbreitenbach are considered (Fig. 3). With the modified scheme (solid lines), a re-

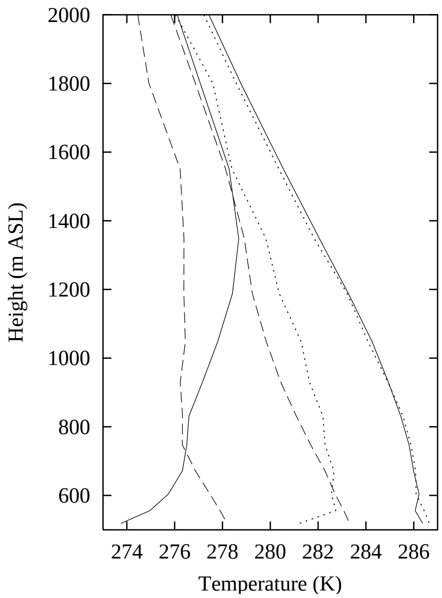

Figure 3: Simulated temperature profiles for modified diffusion (solid lines), T-diffusion (dashed lines) and T'-diffusion (dotted lines). In each case, the colder (warmer) profile refers to $t = 30\text{h}$ ($t = 16\text{h}$).

alistic diurnal temperature range is obtained. In particular, enhanced nocturnal cooling is evident up to a height of 1000 m above ground. Such a nocturnal temperature profile is rather typical for the Inn Valley (e.g. Vergeiner and Dreiseitl 1987). It is a consequence of the slope wind circulation that is associated with weak upward motion over the interior of the valley, leading to adiabatic cooling. Over the plain, nocturnal cooling is usually confined to a more shallow layer above the ground. This difference in the depth of nocturnal cooling is the primary reason for the development of nocturnal downvalley winds since a cooler air column above the valley is related to higher surface pressure.

However, with sigma-diffusion, a realistic simulation of the diurnal temperature range is impossible. In both cases, the day-night difference of the surface temperature is several times too weak. Comparing the profiles for T-diffusion (dashed lines) and T'-diffusion (dotted lines), it becomes clear why the direction of the valley wind is opposite for these two options. With T-diffusion, the whole valley atmosphere is several degrees colder than with T'-diffusion. This results from the fact mentioned above that sigma-diffusion attempts to establish a certain vertical temperature gradient within a valley.

4. Further improvements needed for simulations over mountainous terrain

Test simulations have also been performed for flow configurations associated with stronger winds in the Alpine valleys. They indicate that mechanical turbulence in narrow valleys is strongly underestimated by the PBL parameterizations currently available in the MM5. Since present PBL theories have been developed for flat terrain, one is lead to infer that the influence of the surrounding topography should be taken into account in some way. For example, turbulent kinetic energy produced along the side slopes of a valley must be transported more effectively into the interior of the valley. It is likely that this transport cannot be parameterized adequately with “normal” diffusion. Moreover, investigations are needed whether the vertical diffusion approach adopted in current PBL parameterizations is appropriate for deep, strong turbulence. From the test simulations, one gets the impression that vertical diffusion works too slowly in this situation.

References

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