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Interactive comment on "ASAM v2.7: a compressible atmospheric model with a Cartesian cut cell approach" *by* M. Jähn et al.

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Interactive Comment

Authors' response to interactive referee comment (15 September 2014)

18 September 2014

Thank you for your justifiable hints and critical remarks. Based on your and the referee comments, we will do a complete re-work of the 'Test cases' section (amongst others), where the focus lies on rigorous tests of the cut cell implementation in our model. From our understanding, this appears to be the main point of criticism – besides a more detailed description of the methods.

My co-authors and I do take the referee reviews very seriously, despite partially brief responses from our side. We already did a lot of changes in our manuscript and try to keep very close to the referee suggestions.

We would now like to present the analysis of a new set of test cases, which all include cut cells. The first test case is a modification of Straka et al. (1993), where a hill is added on the left side of the domain. The resulting structures from the descending bubble will then interact with the cut cell surface by the hill. Our second test case is also a modification of an existing test case. Here, the moist bubble benchmark case by Bryan and Fritsch (2002) is taken while a part of the domain center is cut out. This zeppelin-shaped obstacle interacts with ascending moist bubble. For these two test cases, an analysis on conservative properties of the model are done to show how the interpolation in the cut cells affect the accuracy. The last one is an idealized study by Kunz and Wassermann (2011) with a 1 km high mountain in the center of the three-dimensional domain. There, a turbulence scheme and multi-class microphysics are needed to obtain meaningful results.

Note that all figures are included in the supplement pdf-file.

1 Cold bubble with orography interaction

A first non-linear test problem is the density current simulation study documented in Straka et al. (1993). In this case, the computational domain extends from -18 to 18 km in horizontal direction and from 0 to 6.4 km in vertical direction with isotropic grid spacing of $\Delta x = \Delta z = 100$ m. Boundary conditions are periodic in x-direction and the free-slip condition is applied for the top and bottom model boundary. The total integration time is $t = 1800$ s. The initial atmosphere is in a dry and hydrostatically balanced state and there is a horizontally homogeneous environment with $\overline{\theta} = 300$ K. The perturbation (cold bubble with negative buoyancy) is defined by T={ $0\ .0\,\mathrm{C}\ if\ L > 1.0$, $-\ 15.0\,\mathrm{C}(\cos[\pi L] + 1.0)/2\ if\ L \leq 1.0$ where L=$\left(\left[(x - x_\mathrm{c})x_\mathrm{r}^{-1}\right]^2 + \left[(z - z_\mathrm{c})z_\mathrm{r}^{-1}\right]^2\right)^{0.5}$ and $x_\mathrm{c} = 0.0$ km, $x_\mathrm{r} = 4.0$ km, $z_\mathrm{c} = 3.0$ km and $z_\mathrm{r} = 2.0$ km. There is no fixed physical viscosity used like in the original test case (with $\nu = 75\,\mathrm{m}^2\,\mathrm{s}^{-1}$) since a conservation test regarding total energy is performed. For this test, two simulation runs are performed with a) the above described standard setup and b) a modificated setup where a mountain is added at the left part of the domain. The mountain follows the 'Witch of Agnesi' curve: h(x)={ $H\ /(1 + [(x - x_M)/a_1]^2)\ if\ x < x_M$, $H/(1 + [(x - x_M)/a_2]^2)\ if\ x \geq x_M$ with half-width lengths $a_1 = a_2 = 1$ km , mountain peak center position $x_M = -6$ km and mountain height $H = 1$ km.

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The potential temperature field after 900 s integration time is shown in Figure 1. The flow field on the right part of the domain has spread up to $x \approx 15.5$ km, which corresponds to maximum horizontal wind speeds of $|u|_{max,r} = 35\,\mathrm{m\,s^{-1}}$, whereas on the orography-influenced part the flow becomes decelerated with maximum horizontal winds of $|u|_{max,l} = 29\,\mathrm{m\,s^{-1}}$ at this part of the domain. Figure 2 shows the temporal evolution of the total energy error for both simulations. Since exact energy conservation is not expected due to the model design, there is some kind of energy loss for both simulations in the order of 10^{-3} % at the end of the integration time. However, this is still acceptable due to the fact that in the test case there are very sharp gradients in potential temperature and wind speeds. Also, the difference of the total energy error between the two cases is very small (10^{-4} %). This means that in this case, cut cells do not affect the conservation properties in the model at all. A check for total mass results in a relative error of 10^{-6} %, which is negligible small.

2 Moist bubble with mid-air zeppelin

The moist bubble benchmark case after Bryan and Fritsch (2002) is based on its dry counterpart described in Wicker and Skamarock (1998). There, a hydrostatic and neutrally balanced initial state is realized by a constant potential temperature. A warm perturbation in the center of the domain leads to the rising thermal. For the present test case, a moist neutral state can be expressed with the equivalent potential temperature θ_e and two assumptions: the total water mixing ratio $r_\mathrm{t} = r_\mathrm{v} + r_\mathrm{l}$ remains constant and phase changes between water vapor and liquid water are exactly reversible. The perturbation field takes the following form: $\theta_e' = 2\cos^2\left(\frac{\pi L}{2}\right)$ with L = $\sqrt{\left(\frac{x-x_\mathrm{c}}{x_\mathrm{r}}\right)^2 + \left(\frac{z-z_\mathrm{c}}{z_\mathrm{r}}\right)^2} \leq 1$. The parameters $x_\mathrm{c} = 10$ km, $z_\mathrm{c} = 2$ km and $x_\mathrm{r} = z_\mathrm{r} = 2$ km determine the position and radius of the moist heat bubble. The domain is 20 km long in x direction and the vertical extent is 10 km. Grid spacing is again isotropic

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with $\Delta x = \Delta z = 100$ m. Periodic boundary conditions are applied in lateral direction, whereas free-slip conditions are used for the top and bottom boundary. Again, a total energy test is performed by comparing two modifications of the present test case: a) A uniform horizontal wind speed of $U = 20\,\mathrm{m\,s^{-1}}$ is applied. With that, the center of the bubble is again located at $x = 0$ m at $t = 1000$ s after passing through the periodic boundaries. b) In the center of the domain, a zeppelin-shaped region is cut out and acts as an obstacle for the rising bubble. A similar test like this was already introduced in Klein et al. (2009) and Jebens et al. (2011). However, their tests were carried out with the dry bubble, which was also shifted 1 km to the left. The result for the first case is shown in Figure 3. The equivalent potential temperature field is very close to the benchmark simulation, despite the maximum value of θ_e is a little bit lower in our case compared to the literature values and there is a slight asymmetry at the top of the thermal due to lateral transport. The position of the rising thermal for the zeppelin case after $t = 1250$ s is shown in Fig. 4. Because of the centered obstacle, the bubble is split up into two parts and deformed, but still two typical rotors are formed by each bubble and the result remains symmetric.

Again, energy is not fully conserved, but the total relative energy error after 2000 s simulation time (there, in both cases, the bubbles reach the top boundary resulting in zonal divergence) stays in an acceptable range of 10^{-4} % (Figure 5), which is one order of magnitude smaller than in the cold bubble test case. The difference of the error in total energy between the zeppelin and the classical case is again very small. So even with very small cut cells (≈ 1 % of full cell volume) and microphysical conversions there is no indication that conservation properties are deteriorated. For all cases, total mass is conserved within the numeric accuracy. After Bryan and Fritsch (2002), both mass and energy conservation are required to obtain the benchmark result.

3 3-D mountain flow in a moist atmosphere

In this section, a test case described in Kunz and Wassermann (2011) is chosen. It includes forced lifting around a 1 km high mountain (see Figure 6), latent heat release and orographic precipitation. Compared to the first two test cases, this case is now three-dimensional and uses a more realistic initial profile, which mimic atmospheric conditions when it comes to orographically-dominated precipitation in the mountainous area of southwest Germany. In their work, they used the three-dimensional, non-hydrostatic weather prediction model COSMO with terrain-following coordinates to describe the orography of the idealized mountain. The model setup for the ASAM simulations is as follows: the domain extends 553 km $\times$ 553 km with a horizontal grid spacing of 2.765 km and 70 vertical layers with uniform spacing of $\Delta z = 200$ m. A Bell-shaped mountain is located at the center of the domain:

$$h(x,y) = \frac{H}{\left(\frac{x^2+y^2}{a^2}+1\right)^{1.5}} \tag{1}$$

with the mountain peak height $H = 1$ km and the half-width length $a = 11$ km. Inflow and outflow boundary conditions are set according to the initial conditions. A Rayleigh damping layer above 11 km is applied to suppress gravity wave reflections from the top boundary. Surface heat fluxes and Coriolis force are turned off. For turbulence parameterization, the standard Smagorinsky subgrid-scale model is used. Microphysics are parameterized by the warm (i.e. no ice phase present) two-moment scheme described in section 3.2. Initial profiles are obtained by assuming hydrostatic equilibrium, a near-surface temperature $T_s = 283.15$ K, a constant mean flow $U = 10$ m s^{-1}, a constant dry static stability $N_d = 11 \times 10^{-3}$ s^{-1} and a relative humidity profile, which is constant up to $z_m = 5$ km and rapidly decreases above this level according to

$$RH(z) = RH_{\mathrm{S}}\left[0.5 + \pi^{-1}\arctan\left(\frac{z - z_m}{500}\right)\right] \tag{2}$$

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with the near-surface humidity $RH_S = 95$ % (RH95 case). To compare the results with its dry counterpart, another simulation with $RH_S = 50$ % is performed (RH50 case). Figure 7 shows the wind field at 200 m height around the mountain for both cases. In the nearly saturated atmosphere, there is a more direct overflow over the mountain, which is caused by the reduced stability due to high moisture. These different flow characteristics also affect gravity wave structure (Figure 8). The resulting waves are steeper and have a greater wave length, which is in agreement with gravity wave theory and the results from Kunz and Wassermann (2011). Most notable differences in the numerical results are discrepancies in vertical wind strength in the lowest model layer near the mountain, which can be explained by the different surface coordinate systems of the models (Cartesian grid with cut cells in ASAM and generalized terrain-following coordinates in COSMO). Typical patterns of orographic clouds (one cloud upstream of the mountain and a larger cloud with a high amount of liquid water content (LWC) and precipitation in the lee of the mountain) are also reproduced (Figure 9). These resulting patterns as well as the cloud and rain water contents are comparable to the literature results.

4 Summary

Three test cases with different types of cut cells have been presented to prove that our cut cell implementation does work well. Also, conservation tests have been performed. If there is still a need for another test case, we suggest the one from Schmidli et al. (2011), which is a well documented model inter-comparison study for a valley system. The case design requires the usage of a subgrid scale turbulence model and land-use parameterization for surface fluxes in a three-dimensional domain. From our point of view, this could be an additional meaningful test case since the land-use model and the surface flux distribution around small cut cells (which are described in the 'Model physics' section) have not been covered yet by the other test cases. The 'Barbados'

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Fig. 1. Potential temperature isolines (contour interval 1 K, starting from 299.5 K) at t = 900 s for the density current test case with an 'Agnesi' hill (green color) on the left side of the domain.

Fig. 2. Time series of total energy error for the density current test case with and without the hill. The error is expressed as 10^{-4} % of the total energy at the beginning of the simulation.

Fig. 3. Equivalent potential temperature field for the moist rising bubble test case with background wind of $U = 20\,\mathrm{m\,s^{-1}}$. Snapshot taken at $t = 1000$ s simulation time.

Fig. 4. Equivalent potential temperature field for the moist rising bubble test including a zeppelin-shaped cut area in the center of the domain. Snapshot taken at $t = 1250$ s simulation time.

Fig. 5. Same as Figure 2, but for the zeppelin and the lateral transported moist bubble test cases.

Fig. 6. Computational grid around the mountain for an x-z cut plane at y =1.38 km (cell center)

Fig. 7. Horizontal cross-section of horizontal wind vectors at $z = 200$ m height for the RH95 case (black) and the RH50 case (grey). Surface grid cells around the mountain in green, circle lines represent 200 m orography intervals.

Fig. 8. Vertical cross-section (x-z plane) of vertical wind speed for the RH95 case (black) and the RH50 case (grey). Updrafts in solid lines (0.2 m s^{-1} contour interval, zero line included), downdrafts in dashed lines (0.2 m s^{-1} contour interval, zero line excluded).

Fig. 9. Vertical cross-section (x-z plane) of microphysical properties for the RH95 case. Liquid water content (shaded), contours of specific cloud water content q_c (red-yellow) and specific rain water content q_r (blue).

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