WG2 – recommendation document

M. Baldauf, 29.07.2021

Short- to mid-term developments

Better adaptation of the ICON dyn. core for convection-permitting applications

The ICON model is running in the global setup with EU-nest since 2015. At 25. Nov. 2019 the convection-permitting setup with a model grid mesh size of about 2.1 km (ICON-D2) was started at DWD. Similar setups will be run soon also by other members of COSMO. Therefore, because this setup is relatively new, there is still a certain lack of experience how to tune some of the damping mechanisms in the dynamical core for this purpose. Maybe slight changes in the related parameters can be beneficial for this application.

In particular the following processes should be investigated:

- Off-centering in the solver for vertically propagating sound waves can almost completely be switched off in pure dyn. core tests. Since the deep convection parameterization is switched off in these applications, a stronger source for perturbations is omitted and the off-centering might be slightly reduced.
- The strength of the fourth order divergence damping in the horizontal momentum equation should be investigated.
- Horizontal fourth order artificial diffusion in the vertical momentum equation seems to be necessary especially for higher resolutions.
- Similarly, the Smagorinsky second order diffusion mechanism might be even more important for numerical stability in small scale applications.
- The coefficient α for temporal extrapolation of the Exner pressure in the vertical acoustic solver part is obviously dependent from the spatial resolution and should be optimized, too.
- Currently, an alternative 3D divergence damping has been developed, which shall avoid strange mass sources/sinks in deep convective events (M. Langguth, Univ. Bonn, publ. in preparation). It might be worth to support this new development.

In general, such investigations could be done by looking to spectra of kinetic energy, vertical velocity, precipitation, and of other variables. Of course, case studies should be carried out, with a careful look into the structure of the single fields, and furthermore the usual verification by longer periods. Idealized tests (e.g. single high mountains) also might be a valuable tool for such investigations.

Numerical implementation of the 3D diffusion

Baldauf, Brdar (2016) describe a method to implement 3D diffusion in a stable manner also in steep terrain. Additionally, a testing procedure both for scalar diffusion and for vector diffusion (i.e. diffusion in the momentum equation) is given. While both scalar and vector diffusion works in COSMO, unfortunately, vector diffusion is still not correctly implemented in ICON. This problem should be solved and tests against the idealized solution should be carried out.

Physics-dynamics-coupling for convection-permitting applications

There are hints that precipitation spectra are quite different for the convection-permitting setups of ICON and COSMO. The effect is visible already in simple hindcast runs during summer months. This should be further investigated and possible explanations should be extracted.

Change of the continuity equation

Some work has been spent in the formulation and implementation of a continuity equation of dry air instead of the current moist air (mostly by D. Reinert, DWD). Obviously, the ICON code must be adapted at several places in the dynamics, in the physics-dynamics coupling and also in the boundary conditions. Unfortunately, this work was not successful until now, indicating that not all places for code changes have been identified.
The benefit of this work would be the elimination of small inconsistencies in the formulation for moist air.

Literature:
G. Zängl, D. Reinert, P. Ripodas , M. Baldauf (2015): *The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core*, Quart. J. Royal Met. Soc.,141, 563-579

M. Baldauf and S. Brdar (2016): *3D diffusion in terrain-following coordinates: testing and stability of horizontally explicit, vertically implicit discretizations*, Quart. J. Royal Met. Soc., 142, 2087-2101

Mid- to long-term developments

The current dynamical core of ICON possess a lot of positive properties that we didn't had before (neither in GME nor in COSMO):

- It is exactly mass and tracer mass-conserving.
- It is a true second order scheme (as long as no parameterizations are switched on).
- It is stable in very steep mountainous regions.
- It is useable both for global and regional applications.
- It is computationally very efficient.

Any development of a new dynamical core must at least fulfill these positive properties and in the best case should add more.
The **Discontinuous Galerkin (DG)** method promises to fulfill at least several of these requirements:

- It offers even more local conservation properties: additionally momentum conservation is achievable, which is most welcome for small scale applications. Total energy conservation might be achievable (but most probably it is preferred ‚only' to conserve internal energy for adiabatic processes).
- Furthermore, higher order discretizations are achievable. This would proceed a development started with the higher order advection schemes in COSMO, but now in a much more concise manner and encompassing all dynamical processes.
- First tests seem to indicate that higher order also helps in dealing with steeper terrain (but this must be investigated in more detail).
- It delivers optimal parallelization due to compact data transfer without using large halos.

However, DG methods are computationally expensive, and the final question will be, if these positive properties still outperform the current dyn core, when higher order in combination with larger grid cells are used. This point is currently seen as the main risk in this whole development.

At the current state, we have made investigations how to develop an explicit DG discretization that both works for global models (also for non-spherical bodies, Baldauf (2020)) and for regional models. Furthermore, experience has been gained in the development of HEVI-DG schemes for the Euler equations (Baldauf, 2021). Therefore, the basic ingredients in constructing a full fledged 3D DG solver of the Euler equations are available.

Next steps consist in the development of a 3D prototype (this will be not a direct ICON implementation, but it will use several ICON infrastructure modules, like icosahedral triangle grid generation, basic I/O, and data exchange for parallel computing).
Later on, coupling of positive definite and mass-consistent tracer advection must be investigated and the best way in coupling of the particular parameterizations.

Literature:
Schuster, D., Brdar, S., Baldauf, M., Dedner, A., Klöfkorn, R., Kröner, D. (2014): *On discontinuous Galerkin approach for atmospheric flow in the mesoscale with and without moisture*, Meteorol. Z., 23, 449-464

M. Baldauf (2020): *Discontinuous Galerkin solver for the shallow-water equations in covariant form on the sphere and the ellipsoid*, J. Comput. Phys. 410, 109384

M. Baldauf (2021): *A horizontally explicit, vertically implicit (HEVI) Discontinuous Galerkin scheme for the 2D Euler and Navier-Stokes equations using terrain-following coordinates*, accepted by J. Comput. Phys. 446