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Interactive comment on "The ICON-1.2 hydrostatic atmospheric dynamical core on triangular grids – Part 1: Formulation and performance of the baseline version" *by* H. Wan et al.

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We thank referee #2 for the helpful comments and suggestions. Our reply is given below.

1) Grid choice

– It would be interesting to see motivations regarding the choice of the triangular icosahedral grid and the type of staggering.

– What are the potential advantages/disadvantages of this choice when comparing to other icosahedral models such as GME, NICAM, MPAS and OLAM?

The introduction of the paper is revised to provider a clearer explanation of the goals of the ICON development and the motivation for the presented model configuration.

2) Grid optimization

– The authors are using an optimized version of the icosahedral grid, using spring dynamics. This kind of optimization is sensible to the choice of some parameters and implementation. I recommend that the paper could contain more details about the grid used. For example, why was beta=0.9 used? Was it implemented with linear or non-linear spring?

– From table 1, it seems that the ratio of max/min areas is growing with resolution, indicating that, on finer grids, some loss of uniformity is happening.

– This optimization method is designed to perform well on hexagonal/pentagonal grid cells, minimizing their distortions. Are there any guarantees that it will improve quality of triangular grids as well?

– The discretization and interpolation methods used are sensitive to grid properties, this is mainly why I recommend commenting a bit more on the grid properties.

Through idealized tests, it was noticed that two particular features of the unoptimized icosahedral grids have largest impact on the quality of the numerical solutions obtained with our dynamical core. The first one is related to the fact that the velocity points, which bisect the triangle edges, do not coincide with the midpoints of the dual edges (i.e., the arcs that connect the centers of two neighboring triangles). This off-centering causes first order error in our gradient operator. Second, the triangular cells on the sphere are not equilateral. The closer they are located to the pentagon points and the icosahedron edges, the more deformed they are. This leads to additional error in the discrete differential operators and some of the interpolation operators. Strict uniformity of cell area, in contrast, does not seem essential for obtaining good results in the tests we have performed so far.

Heikes and Randall (1995b) developed a grid optimization method that effectively reduces the off-centering of the velocity points, and has been shown to be beneficial in the evaluation of the ICON shallow water model (Ripodas et al., 2009). On the other hand, the smaller off-centering is achieved at the expense of considerably more severe deformation of the triangles than on the unoptimized grids. The spring dynamics optimization of Tomita (2001), originally designed for hexagonal/pentagonal models, offers a good compromise between off-centering and grid deformation, and meanwhile ensures smooth transition of geometric properties throughout the horizontal domain. The optimization method is implemented with linear spring and a tunable spring coefficient beta. Beta = 0.9 is used in our paper based on inspection of the grid properties and results from dynamical core tests. Section 3 (Computational mesh) of the manuscript is revised to include this information.

3) Vector reconstruction

– What shape parameter was used on the inverse multi-quadratic kernel?

The inverse multi-quadratic kernel

$$k(r) = 1/\sqrt{1 + (\epsilon r)^2}$$

is used with the shape parameter $\epsilon = 2$. This is clarified in the revised paper. Test results have shown that the four-point stencil used in our model is very insensitive to the choice of kernel function and shape parameter.

– The RBF vector reconstruction might lead to numerical instabilities on finer grids, due to the ill conditioning of the interpolation matrix. Fortunately, the stencil used is very small and the instabilities will probably not happen on the resolutions of interest. Nevertheless, this is something to be aware of, and could be pointed out in the paper.

– Perot's reconstruction might be an interesting alternative in order to keep some

mimetic properties that RBF do not.

– For some other possible alternatives I suggest the reference [1].

[1] B. Wang, G. Zhao, O.B. Fringer, Reconstruction of vector fields for semi-Lagrangian advection on unstructured, staggered grids, Ocean Modelling, Volume 40, Issue 1, 2011.

We thank the referee for pointing out potential issues with the RBFs and the alternatives for vector reconstruction. According to our knowledge and practical experiences, numerical issues related to the matrix ill conditioning arise in RBF reconstructions for relatively large stencils or in the case of highly irregular node distribution. It is not so much the average node distance that matters, but the ratio of maximum and minimum spacing between neighboring nodes (Bonaventura et al., 2011). For the reconstruction of edge-based tangential velocity discussed in the paper, because of the small stencil and thanks to the quasi-regularity of the icosahedral mesh employed, the ill conditioning problem does not arise. In the revised paper we've added comments on this, and pointed out alternative reconstruction algorithms (including Perot's reconstruction) that are potentially attractive because of their mimetic properties.

4) Horizontal interpolation

– What are the accuracy orders of these operators on the spherical icosahedral grid?

The linear interpolations are first-order accurate if both the interpolation data and the interpolant are understood as pointwise values. The area weighted interpolation from edge to cell is constructed from a finite-volume perspective assuming piecewise constant sub-grid distribution.

– Due to the non regularity of the icosahedral grid, the operator (c2e) will not be necessarily be centred. This may impact on the order of some discrete operators.

This is addressed by the grid optimization algorithm which reduces the off-centering of the velocity point with respect to the dual edge, and ensures that the off-centering decreases when horizontal resolution is increased.

– The formula for the interpolation (e2c,aw) seems strange. If a circumcenter is near a specific edge, the weight of this edge should probably be higher than the other edges of the triangle. But using the area as shown in figure 5a, the edge weight will be the smallest. As it is, the interpolation scheme does not recover the edge value if the interpolation is to be made at the edge.

The (e2c,aw) interpolation is constructed from the finite-volume perspective for conservation purposes. It is assumed that a quantity defined at an edge represents the average value of a kite-like area spanned by the edge in question and its dual. Ac,e in Fig. 5a of the discussion paper is the overlapping area of the triangular cell c and the kite associated with edge e. This is explained in the revised manuscript. Furthermore, the grid optimization algorithm used in this paper helps to reduce the deformation of the triangles, which consequently keeps the circumcenters reasonably away from the edges.

5) Discretization order

–The results shown on the truncation error analysis section are interesting, but are they extendible to the sphere?

The truncation error analysis as presented in the paper is performed on a regular planar grid, in order to reveal the key feature of the triangular C-grid (namely the asymmetric shape and the upward- and downward-pointing directions) that causes the grid-scale noise in the divergence operator. On the sphere, the curvature and irregularity of the grid would introduce additional terms to the truncation error, but these are secondary issues. Our numerical tests carried out with the dynamical core on spherical grids have shown that the magnitude of the numerical diffusion, chosen according to the truncation error analysis, is both necessary and effective in suppressing the grid-scale noise. This indicates that the truncation error analysis provides useful information that

is extendible to the sphere.

A paragraph is added to Section 4.2 (Truncation error analysis) of the revised manuscript in response to the reviewer's comment.

– On the sphere, when using the icosahedral grid, the discretization of the curl (as well as the div) will be only first order accurate on some cells, which is in fact responsible for some grid imprinting (See reference [2] for more details).

[2] P. S. Peixoto, S.R.M. Barros, Analysis of grid imprinting on geodesic spherical icosahedral grids, Journal of Computational Physics, Volume 237, 15 March 2013.

– The gradient discretization will also be only first order, due to the fact that primal and dual edges do not intersect at the midpoint of both.

On the sphere where the cells are no longer equilateral, the deformation indeed introduces first order errors in the divergence, curl and gradient operators, and also affects the accuracy of the higher-order derivatives. We address this issue by using the spring dynamics grid optimization method of Tomita et al. (2001), which prevents strong deformation of the triangular cells hence reduces grid imprinting, and improves the accuracy of the gradient operator by minimizing the off-centering of the velocity points with respect to the corresponding dual edges. This is explained in Section 3 (Computational mesh) of the revised manuscript.

– Are the vector Laplacian discretizations consistent on the spherical grid used? Heikes and Randall 1995 showed that it was necessary to have a special king of grid optimization to achieve this on hexagonal icosahedral grids. I imagine that similar problems could happen on the triangular grid.

The essential effect of the Heikes and Randall (1995b) grid optimization, when used on the triangular C-grid for our discretization, would be to ensure that the off-centering of the velocity points with respect to the corresponding dual edges decrease when horizontal resolution is increased. This could directly help to control the discretization error in the gradient operator. In the paper we use the spring dynamics optimization of Tomita et al. (2001) which has a similar effect but meanwhile does not cause strong deformation of triangular cells and helps reduce grid imprinting at lower resolutions (e.g. R2B4). At medium and high resolutions, the grid imprinting is not clearly visible in the idealized tests we have performed so far, probably due to a general decrease of the absolute error with reduced grid size.

A discussion regarding the Heikes-Randall versus spring dynamics optimization is added to Section 3 (Computational mesh) of the revised manuscript.

– Although many parts of the model are discretized in a second order fashion, considering a regular triangular planar grid, it seems that only first order accuracy is ensured for the icosahedral grid on the sphere. Did the authors observe any drawback regarding this?

As mentioned above, the first order error introduced by grid irregularity is reduced by the spring dynamics grid optimization method which prevents strong deformation of the triangular cells hence reduces grid imprinting, and improves the accuracy of the gradient operator by minimizing the off-centering of the velocity points with respect to the corresponding dual edges.

6) Linear system solver

– The 2D Helmholtz equations are solved with a GMRES solver. I would find interesting to see some motivation for this choice, as it can affect the performance of the model and its parallelism.

In the baseline version of the hydrostatic model, the same semi-implicit time stepping scheme as in ECHAM is used for the sake of a clean evaluation of the spatial discretization. The resulting 2D Helmholtz equations are solved with the GMRES solver. To our understanding, GMRES is one of the standard choices for the solution of large

non-symmetric linear systems, since it is the only iterative method for which convergence can be proven in this case (cf. Saad and Schultz, 1986). The decision of using this solver was based more on the consideration of reliability and stability than that of computational performance. Issues arising in parallel versions of this algorithm have been discussed by, e.g., de Sturler and van der Vorst (1995). These are mentioned in the revised manuscript.

For our hydrostatic model, a series of scaling tests at R2B6 resolution (327 680 triangular cells) have been performed by Leonidas Linadarkis of the Max Planck Institute for Meteorology (MPI-M) on the IBM Power6 system “Blizzard” of the German Climate Computing Center (DKRZ), using the hybrid MPI-OpenMP parallelization and up to about 4000 cores (which is about half of the whole system). The results indicate that up to about 2000 cores (meaning down to the order of approximately 160 cells per core), the semi-implicit time stepping scheme with the GMRES solver scales equally well as the explicit, 4th order 5-stage strong stability preserving Runge-Kutta method (SSPRK(5, 4)), but provides higher throughput. This is partly due to the relatively low number of GMRES iterations (around 15) required in these simulations. For larger setups, and in cases the physics parameterizations take a smaller portion of the total computing time (due to the use of lower temporal and/or spatial resolution), the global communications needed by the linear solver will indeed pose more constraints on the performance and scalability. Explicit schemes are then an option to consider. Results from tests of the computational performance are not included in the paper but only mentioned very briefly near the end of the revised manuscript, because of reasons stated below. Furthermore, for the purpose of achieving tracer-and-air-mass consistency, we have also implemented various two-time-level integration schemes, but these are considered beyond the scope of the baseline model.

7) Computational performance

– The locality properties of the scheme allow a great deal of parallelism, essential for the model to be efficiently used in high resolution, long term climate

scenarios. Was the model parallelized?

– Comparing the model with the spectral one, shown in table 2, respecting resolution and error criteria, what is the relative performance gain/loss?

As mentioned above, the hydrostatic model has been parallelized using both MPI and OpenMP, and has gone through a series of scaling tests on the IBM Power6 system at DKRZ. It is found that the R2B6 simulations using the semi-implicit time stepping scheme achieve linear scaling up to about 2000 cores (i.e., till the number of cells per core decreases to about 160), while the explicit SSPRK(5,4) time stepping scheme achieves linear scaling up to the largest number of cores utilized (3840 cores, i.e., 85 cells per core). On the other hand, because the hydrostatic model is considered only as an intermediate step of the ICON project, the focus of the development has already been/ is being shifted to a nonhydrostatic version at the German Weather Service (DWD) and at MPI-M, respectively. No efforts have been dedicated to the performance optimization of the hydrostatic code. In contrast, the ECHAM model, as the workhorse for climate research at the Max Planck Institute, has been optimized in all possible ways, especially for the computer systems on which it is most often used. We think it would not be very informative to compare the computational performance of the unoptimized ICOHDC with the fully optimized spectral core of ECHAM. Hence the present paper focuses only on assessing the numerical properties of the new hydrostatic model. Pre-operational development and testing led by Günther Zängl at DWD has shown that for a given number of mass points, the nonhydrostatic version of the ICON triangular model performs about a factor of 3 - 4 faster than the operational hydrostatic model GME, and in the meantime delivers significantly better skill scores.

References:

Bonaventura, L., Iske, A., and Miglio, E.: Kernel-based vector field reconstruction in computational fluid dynamic models, Int. J. Numer. Meth. Fl., 66, 714–729, 2011.

de Sturler, E, and van der Vorst, H. A.: Reducing the effect of global communication

in GMRES(m) and CG on parallel distributed memory computers. Applied Numerical Mathematics, Vol. 18, 441-459, 1995.

Heikes, R. and Randall, D. A.: Numerical integration of the shallow-water equations on a twisted icosahedral grid. Part II: A detailed description of the grid and an analysis of numerical accuracy. Mon. Wea. Rev., 123, 1881–1887, 1995b.

Rípodas, P., Gassmann, A., Foerstner, J., Majewski, D., Giorgetta, M., Korn, P., Kornblueh, L., Wan, H., Zängl, G., Bonaventura, L., and Heinze, T.: Icosahedral Shallow Water Model (ICOSWM): results of shallow water test cases and sensitivity to model parameters, Geosci. Model Dev., 2, 231–251, 2009

Saad, Y. and Schultz, M. H.: GMRES: a generalized minimal resid- ual algorithm for solving nonsymmetric linear systems, SIAM J. Sci. Stat. Comp., 7, 856–859, 1986.

Spiteri, R. and Ruuth, S.: A new class of optimal high-order strong-stability-preserving time discretization methods, SIAM Journal on Numerical Analysis, 40, 469–491, 2002

Tomita, H., Tsugawa, M., Satoh, M., and Goto, K.: Shallow water model on a modified icosahedral grid by using spring dynamics, J. Comp. Phys., 174, 579–613, 2001

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