Geosci. Model Dev. Discuss., 6, C2395–C2403, 2014
www.geosci-model-dev-discuss.net/6/C2395/2014/

Geoscientific Model Development Discussions Open Access

Interactive comment on "An orthogonal curvilinear terrain-following coordinate for atmospheric models" *by* Y. Li et al.

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Received and published: 21 January 2014

We thank the referee #2 for your helpful comments and suggestions, especially those on the design of the OS coordinate in 3-D. Our reply is given below.

1. The authors present a formulation for an orthogonal curvilinear terrain-following coordinate that may have some attractive features for use in atmospheric models. They derive the orthogonal coordinate transformation using a "rotation parameter b" in the basis vectors that controls that rate at which the terrain influence is removed from the coordinate surfaces, and demonstrates results for Schar's (2002) advection test case. However, their presentation is superficial and somewhat misleading, and the authors are apparently unaware of previous published work relevant to this research. Therefore, I believe this paper is not suitable for publication in the reviewed literature in

its current form.

Response:

Thanks for the referee's comments. We will refer to the papers you suggested and the associated works on numerical grid generation of orthogonal grid in the revised manuscript.

2. The authors state that with their orthogonal sigma (OS) coordinate, pressure gradient force (PGF) errors are reduced because "the computational form of PGF in each momentum equation has only one term." However, this statement is misleading; since the velocity components are aligned with the OS coordinate directions (i.e. no longer horizontal and vertical), each momentum equation has an additional gravitational acceleration term that is proportional to the slope of the coordinate surface. This term is essentially the same as the second term that arises in the classic sigma (CS) coordinate (the vertical pressure gradient times the coordinate slope). Thus, PGF errors still arise due to computational imbalances in removing the hydrostatically balanced portion of the PGF to recover the (often small) residual that actually induces accelerations along the coordinate surface. The authors present no evidence, either theoretical or numerical, to support their claim of reduced PGF errors.

Response:

We thank the referee for pointing out this. In the revised manuscript, we will change the descriptions of reducing the PGF errors into "Since the computational form of PGF has only one term in each momentum equation of the OS coordinate, the PGF errors might be reduced in the OS coordinate, which will be tested carefully in the other study", because we haven't implement an experiment on this.

3. The only idealized test case considered by the authors is a simple Schar-type advection test with the pressure-gradient and buoyancy terms removed from the equations. A disturbance is advected over a mountain with a wind that is constant at the level of the

disturbance and that decreases to zero at a height above the mountain-top level. Thus, the correct numerical solution should be the same as that obtained with no mountain present. The authors present results for three different rotation parameters (Br1, linear b: Br2, squared b; and Br3, exponential b), and in comparison with the CS coordinate, they conclude that the OC coordinate results are superior, particularly those obtained with the increased "smoothing" in the Br2 and Br3 simulations. The suggestion that these results indicate any inherent benefits of the OC coordinate is highly misleading. The results actually just confirm that a hybrid coordinate formulation (terrain influences removed from the coordinate surfaces faster than linearly with height) is superior to the classic approach (terrain influences removed linearly with height) for this test case.

Response:

First, the Schär-type advection test is simple but common as a preliminary test for a new method aimed to tackle the terrain, and it had been implemented by many researchers, such as Zängl (2003) and Good et al. (2013).

Second, at present, one of the philosophies of designing the OS coordinate is to obtain the smoothed vertical levels above the steep terrain similar to the hybrid σ coordinate. However, the important difference between them is that the OS coordinate is orthogonal but the hybrid σ coordinate is non-orthogonal. Moreover, this orthogonality can create two benefits: (1) one-term PGF; (2) orthogonal and terrain-following grids in the vertical. Additionally, as our response in No. 2, in the revised manuscript, we will only clarify the reduction of the advection errors by the smoothed vertical levels and the orthogonal grids of the OS coordinate, and not emphasize its reduction of the PGF errors.

Third, we will implement new experiments to analyze the distinct effect of the smoothed vertical levels and the orthogonal grids of the OS coordinate. (see the response in No. 5)

Good, B., Gadian, A., Lock, S-J., and Ross, A.: Performance of the cut-cell

method of representing orography in idealized simulations, Atmos. Sci. Let., DOI:10.1002/ASL2.465, 2013. Zängl, G.: A generalized sigma-coordinate system for the MM5, Mon. Weather Rev., 131, 2875-2884, 2003.

4. In the authors' OS formulation, the rotation parameter b is not a smoothing parameter in the sense that the influences of small-scale terrain features are selectively removed more rapidly with height than larger scale terrain features. Rather, this parameter regulates how rapidly the overall terrain influences on the coordinate surfaces decrease with height. In this regard, the variable b just adds flexibility to the OS coordinate that allows it to behave similarly to the hybrid variation of the CS coordinate. For this case it's obvious that the more rapidly the coordinate surfaces approach constant height surfaces, the more accurate the results (i.e. the better they agree with the no mountain results). For the Br1 (linear b) simulation, the results are virtually the same as those for the CS coordinate (linear decrease of terrain influence with height).

Response:

Thanks for the referee's comments, as our response in No. 3, the rotation parameter b is now a parameter which can regulate how rapidly the overall terrain influences on the vertical coordinate surfaces decrease with height. However, we gave three the requirements of b on Page 5808 of the original manuscript, and people can design their own b according to those requirements. Actually, for the second step of the OS coordinate, we are going to design some formulations of b to regulate the scale-selected terrain influences on the vertical layers as the SLEVE (Schär et al. 2002) or STF (Klemp, 2011), and this will be proposed in other studies.

In addition, the Br1 simulation is similar to the results obtained by the CS coordinate; however they do have small differences due to the orthogonal grids created by the OS coordinate (Fig. 1). And in the revised manuscript, we will add an experiment to further investigate the distinct effect of the orthogonal grid by using non-zero velocity and the tracer right down to the top of the mountain, where the difference between the grids created by the OS coordinate and the CS coordinate are much more significant than those above the top of terrain.

5. For a fair comparison of the Br2 and Br3 OS simulations, they should be compared with the corresponding hybrid version of the traditional sigma coordinate. To be specific, by defining sigma = z - b(z) * h(x) for the hybrid version of the CS coordinate, setting b(z) = Br1, Br2, or Br3 will produce appropriate comparisons with the OS simulations, and I expect will produce very similar results.

Response:

According to your suggestion, we will add new experiments to compare the result obtained by the OS coordinate to that of the corresponding hybrid version of the traditional sigma coordinate.

6. It's also important to note that this test case, by itself, is of limited value in assessing the coordinate design; while a strong hybrid character is beneficial for this case, in any realistic flow, rapid removal of the terrain influences with height can cause increased problems with accuracy and stability near the surface, where coordinate surfaces may be highly compressed. These effects are not included in this test case.

Response:

Any hybrid edition of a terrain-following coordinate will face the coordinate surface compressed near the surface of terrain, including the OS coordinate. We will add an experiment of advection just over the top of terrain to investigate this in the revised manuscript.

Furthermore, coordinate surfaces in the OS coordinate are adjustable via the rotation parameter b (Fig. 10c-e in the original manuscript). So in the OS coordinate, people can design special formulations of b to obtain the proper distance of neighbouring vertical levels above the terrain.

7. The authors make no reference to similar previous work in developing and testing

nonhydrostatic models in orthogonal curvilinear coordinates. While there may be other related studies, two come to mind that are particularly relevant: Sharman, R. D., T. L. Keller, and M. G. Wurtele, 1988: Incompressible and anelastic flow simulations on numerically generated grids. Mon. Wea. Rev., 116, 1124-1136. In this study, Sharman et al. derive the equations in orthogonal curvilinear coordinates for the 2-D incompressible and an elastic systems and present credible mountain wave solutions for a variety of terrain profiles. In these systems acoustic modes are filtered and numerical integration requires solving an implicit Poisson equation at each time step. Their motivation in considering orthogonal coordinates was that it led to a much simpler form of the Poisson equation since cross terms were eliminated. Satomura, T.,1989: Compressible flow simulations on numerically generated grids. J. Meteor. Soc. Japan, 67, 473-482. Satomura developed an orthogonal coordinate formulation for the 2-D compressible equations and demonstrated good agreement with linear theory for hydrostatic and nonhydrostatic mountain-wave simulations. He also obtained better results with the orthogonal coordinate than with the CS coordinate for a case with steep terrain having discontinuities in slope (to be expected, since the orthogonal coordinate removes the singularity in coordinate slope above the surface).

Response:

We appreciate your suggested papers very much, and we will refer to these papers and the related ones on the numerical grid generation in the introduction of the revised manuscript.

Additionally, we didn't find the “Compressible flow simulations on numerically generated grids”. Could you please tell us how to get this paper if possible?

8. Both of these papers focus on 2-D systems, and emphasize that in three dimensions it is not possible to generate orthogonal coordinates that follow an arbitrary terrain shape. If the authors of the current paper believe their techniques will be suitable for real world applications, this will be an important issue for them to address.

Response:

Many thanks for the referee's comments. We will give a brief description of the way to solve each coordinate surface of the OS coordinate in 3-D, and also draw out the numerical solutions of the 3-D coordinate surfaces of the OS coordinate in the revised manuscript.

The main three steps of solving each coordinate surface of the OS coordinate are shown in Fig.2. Now, we are trying to solve those linear algebraic equations of the coordinate surfaces using the least squares, and we need more time to program. However, we will give out the numerical solution of each coordinate surface of the OS coordinate in the revised manuscript.

Interactive comment on Geosci. Model Dev. Discuss., 6, 5801, 2013.

	Average of RMSE in the whole integration (time step from 1 to 400)				
	Dx = 0.5m	**Dx = 1.0m**	**Dx = 2.0m**	**Dx = 4.0m**	**Dx = 8.0m**
Cs	0.02521474	0.02533834	0.03218225	0.03929803	0.03929803
OsBr1	0.02455592	0.02467973	0.03041426	0.03811315	0.03811315
Reduction ratio of RMSE by the OS coordinate	2.6%	2.6%	5.5%	3.0%	3.0%

Fig. 1. Average of RMSE of Cs and OsBr1 in the experiments of different horizontal resolutions

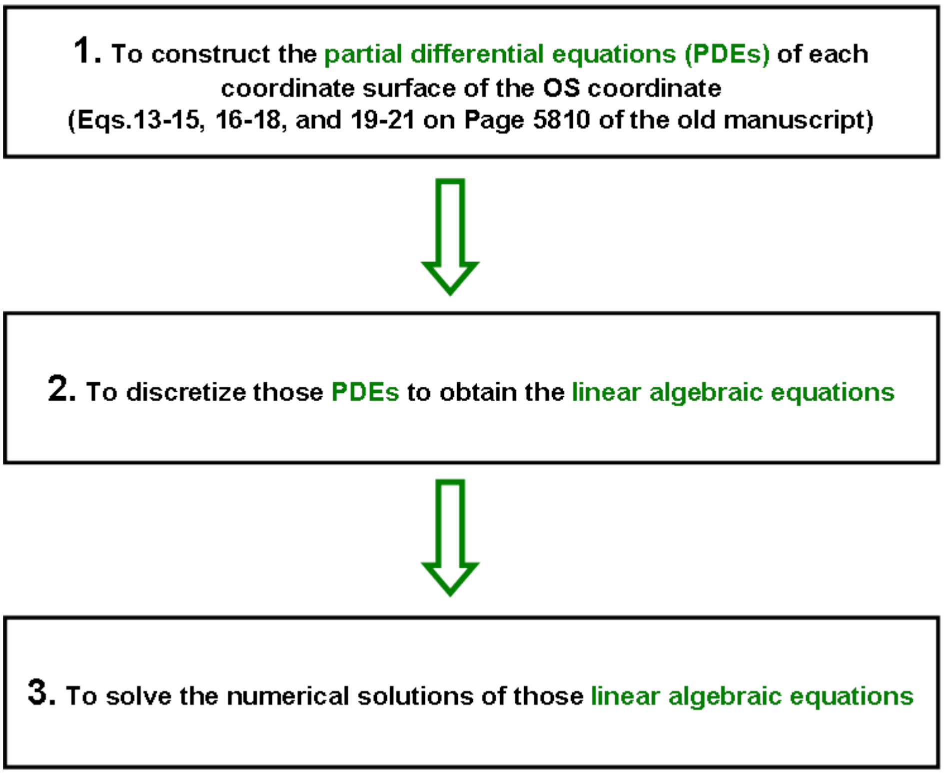

Fig. 2. Three steps of solving each coordinate surface of the OS coordinate.