We thank referee #1 for your helpful comments and suggestions, especially those on our idealized advection experiments. Our reply is given below.

1. **In the title and abstract the paper claims to introduce an orthogonal terrain following coordinate which reduces the error of the pressure gradient force (PGF) and also reduces the error of advection for numerical schemes in grids generated by the vertical coordinate of atmospheric models. Given the large errors often associated with the vertical coordinate, it is very interesting to investigate a potential reduction of errors by introducing orthogonal coordinates. In reality the authors address a much smaller problem. The orthogonal coordinate is already introduced in an earlier paper and there also the PGF is investigated. In the present paper the authors investigate only the accuracy of advection using the very simple test problem of homogeneous (in x-z) horizontal advection in two dimensions.**

Response:

First of all, the coordinate proposed in this paper is totally different from that proposed by Li et al. 2012. We will revise the associated sentences in our manuscript which may lead to this confusion.

The method proposed by Li et al. 2012 is an alternative one that "uses the classic non-orthogonal σ coordinate" (the box with blue border and arrow in Fig. R1). However, in this paper, we create a new coordinate system, which is the orthogonal terrain-following coordinate (green-border boxes with green arrows in Fig. R1).

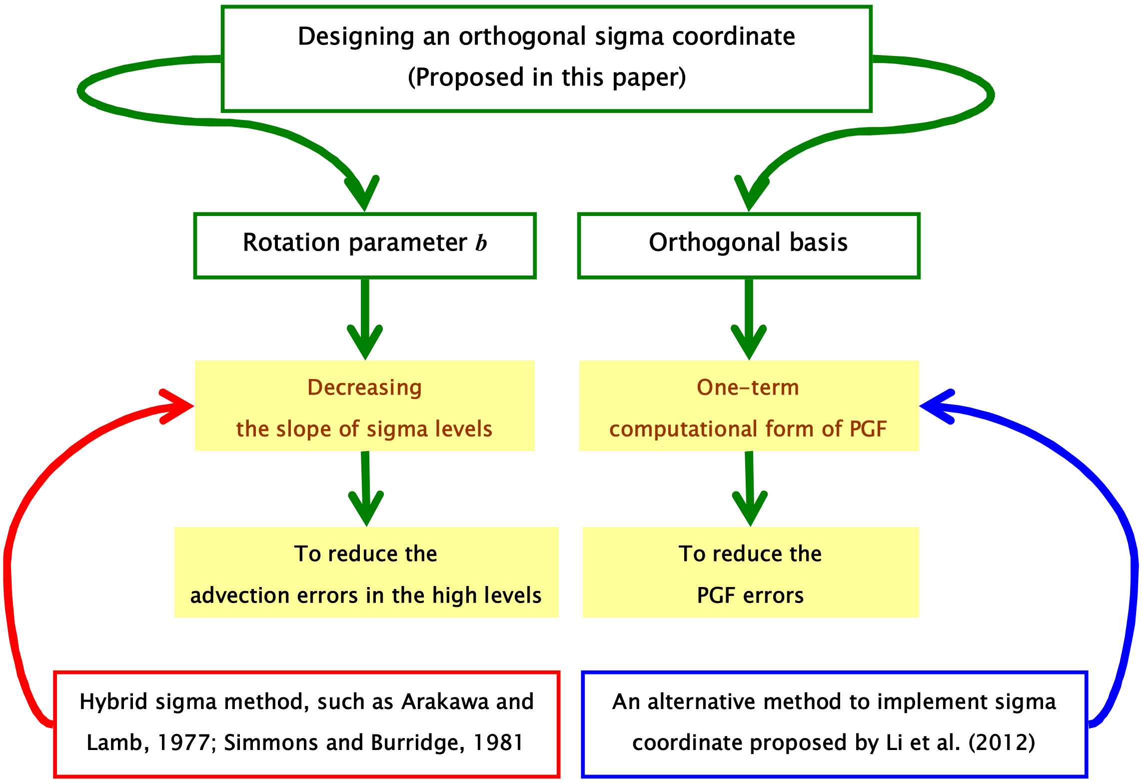

Figure R1: The schematic of the differences between the coordinates proposed in this paper and by Li et al. (2012), respectively. The green-border boxes with green arrows give the method proposed in this paper, the blue-border box with blue arrow represent the method proposed by Li et al. (2012), and the red-border box with red arrow shows the related previous work to design the hybrid σ coordinate to reduce the advection errors. PGF represents the pressure gradient force.

Second, the specific differences between the orthogonal sigma coordinate (OS coordinate) proposed in this paper and the one proposed in Li et al. (2012) are listed in Table R1.

Third, although we create the one-term PGF in each momentum equation in the OS coordinate, we haven't implement an experiment to investigate the PGF errors in the OS coordinate. We thank the referee for pointing out this. In the revised manuscript, we will only emphasize the reduction of the advection errors, and change the description about 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".

Table R1: The main characteristics of the OS coordinate designed in this paper and the method proposed by Li et al. (2012).

Characteristics		**OS coordinate proposed in this paper**	**An alternative method proposed by Li et al. (2012)**
Differences	**Different coordinate system**	Creating an orthogonal σ coordinate system	Proposing an alternative method based on the classic non-orthogonal σ coordinate
	Different basis	Basis are orthogonal.	Basis are non-orthogonal.
	Different scalar equations	Scalar equations are as simple as those in the z-coordinate.	The horizontal momentum equations have curvilinear terms due to the non-orthogonal characteristics of the classic σ coordinate.
	Different capability of adjusting the slopes of σ levels	The rotation parameter b can smooth the σ levels above steep terrain.	The slope of σ levels can not be changed. (Unless the hybrid σ coordinate is used)
Common characteristics		The computational form of pressure gradient force (PGF) in each momentum equation is one-term.	

Finally, we would like to clarify that this paper is mainly to propose a new coordinate system (the OS coordinate) which is terrain following as well as orthogonal. Because the advection errors in the high levels above the steep terrain due to the non-horizontal σ levels are one of the most concerned errors of the classic σ coordinate, in the old manuscript, as a baby step, we only implemented a simple 2-D advection experiment to show the ability of the OS coordinate, which can smooth the slope of σ levels as the hybrid σ coordinate, and therefore reduce the advection errors in the high levels above the steep terrain. We appreciate the referee's good suggestion and will add four experiments based on the existed advection experiments. The details will be included in our last response.

2. **The paper is very difficult to read, as the authors give much information which is of no concern for the simple 2-d test problem they investigate, such as technical details for the computation of the coordinate in 3-d, when their test problem is 2-d. They derive several continuous forms of the Euler equations in 3-d, even though their test is linear advection. Only one equation is about the discretized equations, even though the numerical schemes used are very important for accuracy. All other equations of the rather long paper concern the continuous equations for problems which are actually not solved. The derivation of coordinates and equations is too extensive and goes very much into technical details. This is appropriate for a technical report or a manual, not for a journal paper.**

Response:

We will simplify the descriptions of the design of the OS coordinate to make the paper more concise. Since the orthogonal and terrain-following basis of the OS coordinate is first solved, we have introduced the details for someone who is interested in solving this kind of basis and can follow the steps to solve it by themselves. And the same reason for we solve the 3-D full equations of the OS coordinate. However, to keep concision of the paper, we will remove the details of the design so that the description is as short as possible. We may put the details into the supplementary material in the revised manuscript.

3. **The presentation uses terms whose definition is not introduced and gives the impression to be addressed to members of the same institute, not the outside world. For example right in the first sentence when explaining the coordinate, the term "the basis vectors" is used. On this all later explanations hinge. Basis vectors are not unique and the authors should use a name to indicate their special choice, such as natural Basis. This term should then be defined before it is used.**

Response:

Thanks for referee's comments. We will replace "basis vector" by "basis" in the revised paper. We used "basis vectors" in the old manuscript because it was ever used in literature, such as Zdunkowsi and Bott (2003); Ballani and Grasedyck (2013), and Martinoli et al. (2013). In addition, the word "basis" has two meanings: "basis vectors" and "basis functions". We used "basis vectors" just to avoid the confusion and to emphasize "vector". Anyway, we will revise the paper according to this referee's suggestion.

Ballani, J., and Grasedyck, L.: A projection method to solve linear systems in tensor format, 2013. [Available at: http://onlinelibrary.wiley.com/doi/10.1002/nla.1818/full]

Martinoli, A., Mondada, F., Correll, N, Mermoud, G., Egerstedt, M, Hsieh, M. A., Parker, L. E., and StØy, K.: Distributed autonomous robotic systems, Springer Berlin Heidelberg, 2013. [Available at: http://link.springer.com/chapter/10.1007/978-3-642-32723-0_39]

Zdunkowski, W., and Bott, A.: Dynamics of the atmosphere a course in theoretical meteorology, Cambridge University press, 2003.

4. **After some consideration I now believe that I understand what the authors want. For the following I will use the following understanding of the paper: 1) The natural basis consists of unit vectors in the directions of the coordinate lines. The coordinate is orthogonal when the natural basis is orthogonal. 2) Starting point can be any terrain following coordinate, being called the sigma system. 3) The basis ix,iz of the x-z system is for each point in space rotated such that the image of iz becomes orthogonal to the sigma line. The orthogonal coordinate lines are those which have this rotated field as natural basis. The ordinary differential equation defining the coordinates is obvious. 4) The rotations of 3 define a rotation angle theta which is used to define different versions of orthogonal coordinates. 5) Using theta and a function b of the coordinates, modified versions of the orthogonal natural bases can be defined, which again lead to new orthogonal coordinates. They also lead to new standard terrain following schemes, which are not used in the paper. 6) By giving 3 definitions for functions b 3 additional versions of are derived. 7) As numerical schemes only centered differences in space and time are used. Arakawa A grid is used and no fancy stuff, such as Asselin filters is considered. 8) The advection tests use homogeneous horizontal velocities above a threshold z-value.**

Response:

We appreciate the referee's comprehensive understanding of this paper. However, the No. 4 and 5 are not very exactly. We use two angles which are "the theta and lambda" in the 3-D rotation and a function b to define a version of orthogonal coordinate (Table 3, on P40 of the original manuscript). The two angles are fixed (related to different shapes of terrain), only the function of b can be modified, and lead to different versions of the orthogonal coordinate.

5. **Most orthogonal schemes are less curved above the threshold than the sigma scheme used for comparison. The fourth scheme is not curved at all in this area. It is identical to regular x-z grid in this area. In its current version the paper does not substantiate the claim that an improved accuracy is caused by the orthogonal coordinate. From figs 10 and 11 it follows that a strong reduction of the error is obtained with one of the grids, which has also the property to be identical to the x-z grid where the velocity is different from 0. The tests presented investigate the combined effect of orthogonal coordinates and the regularity of grids. This is not too surprising. It is well known that centered**

differences have good accuracy only for fairly regular grids. So the increased accuracy of some schemes can well be explained by the fact that the more accurate schemes have grids being more regular and more similar to the x-z grid in the relevant areas.

Response:

Since all the four experiments Cs, OsBr1, OsBr2, and OsBr3 use regular grids (Fig. 10 on P53 of original manuscript), we don't think the improved accuracy is contributed by the regular grids. The differences among these experiments are at their slopes of vertical levels and orthogonality of vertical coordinate, and thus the reduction of the errors by the OS coordinate is mainly due to the combined effect of the smoothed vertical levels and the orthogonal grids, where the first one has the main impact in the current experiments. Furthermore, we will add an experiment using the irregular grids to investigate the results obtain by both the CS coordinate and the OS coordinate.

We can also see the contribution of the orthogonality to the improved accuracy from the difference between the RMSEs of the experiments Cs and OsBr1 (see Table R2), because their slopes of vertical levels are almost the same (see black and red lines in Fig. 8 on P51 of the original manuscript). The main difference between these two experiments are non-orthogonal and orthogonal, respectively. The reduction of RMSE in OsBr1 comparing with Cs is due to its orthogonality (Fig. 12 on P55 of original manuscript), although it is not very significant (see Table R2).

Table R2: Average of RMSE of Cs and OsBr1 in the experiments of different horizontal resolutions

	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%

6. **The authors define different versions of terrain following coordinates. Current evidence indicates that it is the terrain following coordinate defined by the vectors and not the orthogonality being responsible for the accuracy. Even though much less results are obtained than expected from title and abstract, some of the results are valuable and make the paper interesting: Investigations of vertical accuracy concentrate often on PGF. Therefore the investigation of advection is useful Until now there are not many investigations investigating orthogonal coordinates for the vertical The construction of terrain following coordinates by defining natural bases may be useful when investigating orthogonal coordinates. These results appear to be important enough to merit publication after a very substantial revision.**

Response:

As Table R2 shows, the error reduction is not mainly due to the orthogonality but the improvement of the advection through the function b. Thank the reviewer for this positive comment.

7. **As the paper presents rather simple tests, the revision should be more concise and much shorter (see below). The revision should also present some more results in order to be consistent with the claim to investigate the Impact of grids generated by orthogonal coordinates: A Fig. 8 suggests that for the coordinates generated by the different choices of b ordinary terrain following schemes can be defined. The accuracy of these schemes should be compared to the OS schemes. I would propose publication also when the impact of OS should turn out to be not very high.**

Response:

Firs, we would like to make clear a definition: is “the ordinary terrain following schemes” the classic sigma scheme we called in the paper? If yes, we can not define “the ordinary terrain following schemes” by choosing b, because the classic sigma coordinate is non-orthogonal and does not include a function b, unless a hybrid coordinate is used. Second, the results obtained using the OS coordinates with 3 different b were compared with those of the “ordinary terrain following schemes”. Finally, similar to the response to Comment No.5, the reduction of RMSE is mainly due to the increased accuracy of advection calculation with smoothed σ levels in the OS coordinate, and “the effects of the orthogonal grids” are not very high in the current experiments (Table R2).

8. B The mountain is rather smooth. The impact of steep mountains up to those supported by one point only should be investigated, also the impact of steepness on stability.

Response:

We will increase the terrain slope and add a table including the time steps of the experiments according to the increasing terrain slope in the revised manuscript.

9. C One of the coordinates concentrates the curvature to a small area near the mountain, which in current tests has no velocity different from 0. The impact of this area should be investigated by using velocities different from 0 right to the top of the mountain.

Response:

First, we want to clarify that this kind of wind profile is commonly used in idealized advection experiments of investigating the advection errors of the classic *σ*-coordinate on the high levels above steep terrain, such as in Schär et al. (2002), Zängl (2003), and also in Good et al. (2013). And the reason of using this profile was described by Zängl (2003) on Page 2878: “Between the surface and z = 3km (p = 700 hPa), zero wind is assumed to inhibit the generation of orographic gravity waves. Then, the wind speed smoothly increase up to 10 m s^{-1} at z $\approx$6.3 km (p = 450 hPa) and remains constant farther above.”

Anyway, according to your suggestion, we will add an experiment using the non-zero u field and q field closer to the top of the mountain, as the experiment implemented by Good et al. (2013), to investigate the impact of the orthogonal grids created by the OS coordinate near the surface in the revised manuscript, although the OS coordinate is now designed to reduce the advection errors in the high levels above the steep terrain, which is one of the most concerned errors in the classic σ coordinate.

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.

Schar, C., Leuenberger, D., Fuhrer, O., Lüthi, D., and Girard, C.: A new terrain-following vertical coordinate formulation for atmospheric prediction models, Mon. Weather Rev., 130, 2459-2480, 2002.

Zängl, G.: A generalized sigma-coordinate system for the MM5, Mon. Weather Rev., 131, 2875-2884, 2003.

10. As already indicated, the Paper is much too long and not concise. In the following detailed comments are given with the aim to make it more suitable for publication: The current title suggests that the orthogonal coordinates are presented in this paper. However, they where introduced in Li (2012). A new title should reflect the fact that advection tests are done using a coordinate already introduced earlier. The abstract and conclusion read like they belong to Li (2012).

Response:

The difference between this paper and Li et al. (2012) is illustrated in Fig. R1 and Table R1. We will revise the title, the abstract and the conclusion to get rid of this confusion.

The title may be changed into "An orthogonal curvilinear terrain-following coordinate and its preliminary tests using 2-D idealized advection experiments"

11. In the current paper no work on PGF is done. So this does not need to be mentioned. It should be mentioned what kind of advection tests and grids are used and that centered difference schemes are used and a sentence on results. Nearly all current content should be deleted as it is not relevant to the investigation.

Response:

We will properly revise the paper according to this comment. Because the OS coordinate introduced in this paper is quite different from the one proposed by Li et al (2012), we will have to keep a short descriptions of the OS coordinate design in the revised paper, and put the details into the supplementary materials.

12. Most of the introduction is nicely written and gives an account of current vertical schemes and current attempts to avoid vertical errors. A paragraph should be added at the end indicating the advection tests to be done. The paper "Performance of the

cut-cell method of representing orography in idealized simulations" by Beth Good et al uses rather similar advection tests and you may want to refer to it. It is in print "ATL Atmospheric Science Letters 2013.

Response:

We appreciate your suggested paper and the related papers such as Lock et al. (2012), Regayre et al. (2013). We will refer to them in the introduction or in the section related to the experiment design.

13. **Most of the material in sections2,3, including Appendix A,B,C and the tables and Fig 1,2,3 are not relevant to the advection tests and concerning the description of the coordinate it is too technical and detailed for a Journal publication. A very short presentation of the coordinate and scheme should be given involving Eqs 34,35,36, 60,61,62,63 and not much more. The description of the tests in 4 should remain. Fig. 4 gives a nice illustration of the new coordinate. It is redundant with Fig. 5,6,7. Fig 8,9,10 illustrate the experiments done, but Fig 9 is redundant with Fig 10. I suggest to keep the latter. The red grid may be taken out, as everybody can imagine the regular x-z grid. In the legend of Fig. 10 the names of the grids should be mentioned under a, b, c, d with reference to the text of the paper. It would help understanding, if the graphic presentation of the figs would be as in Fig. 10.**

Response:

Many thanks for your constructive suggestions. We will make proper revisions on the manuscript according to your suggestions.

Because of the difference between the OS coordinate in this paper and the coordinate in Li et al (2012), some contents related to the design of the OS coordinate will be kept, such as Figs. 5, 8, 9, others will be added to the supplementary materials of the revised manuscript.

14. **When introducing the discretized equations the authors should shortly discuss other possibilities. Centered differences on the Arakawa A- grid are not considered the most suitable approach to numerical modeling.**

Response:

We will add descriptions to introduce other possible discretization methods.

15. **The advection experiments are sufficiently described, that a reader can reproduce them. Presentation quality: I found no mayor language problems. The logic of the presentation could, however, be improved. Definitions were missing, when introducing a subject. This problem could become better, if the authors follow the suggestion of presenting less of the technical detail.**

Response:

Yes, we will give a detail description of the advection experiments, but simplify the introduction of OS coordinate. We will also give definitions whenever introducing a subject. Thank you.

16. X and z should be scaled to correspond to resolutions currently used in models. Mesh lengths of 8 m and smaller are not often used for atmospheric models. It will not be necessary to create new results, just to rename the axes.

Response:

How about the "km" to replace "m" in the figures?

17. Also, the paper should be made more easily readable. For example in the figure captions under each letter a-e the schemes corresponding to the results should be named.

Response:

Yes, I will do this.

18. The grid fig 10e is Cartesian for a large part of the area and for this area the coordinate is z. The curved coordinate lines occur only near the surface. The advection velocities and advection fields are different from 0 for the Cartesian part of the grid in Fig 10e only. In comparison to the other cases this shows only that centered differences perform better on regular Cartesian grids than in irregular grids. This result is well known and by itself does not merit publication. In order to be sufficiently interesting the advection tests should be done for an area reaching down to the top of the mountain.

Response:

Yes, we will do this (also see the responses in No. 5 and 9).

19. The functions b define different sets of terrain following coordinates. Only one of the 3 choices offered are investigated using orthogonal and standard grids/coordinates for comparison. For the other choices the differences in accuracy can be due to orthogonality or the change to orthogonal coordinates. Only the grid reported in fig. 10e shows a good increase of accuracy. This is due to the standard grid, not to the orthogonal coordinates. For the tested part of the grid Fig 10e the standard terrain following grid is already orthogonal.

Response:

We appreciate the referee for pointing out this, and in the revised manuscript, we will compare the OS coordinate with 3 different b to the corresponding hybrid σ coordinate to investigate the impact of the orthogonal grids created by the OS coordinate. Although, as our response in No. 1, at the first step, we want to show the ability of the OS coordinate to reduce the advection errors through the smoothed vertical levels as a hybrid σ coordinate.

The increase of the accuracy in the advection experiments is due to both the smoothed σ levels and the orthogonal grids; however, the first one plays a key role in the current experiments. In addition, the classic terrain following grid is always non-orthogonal on a mountain, unless a very strong edition of a hybrid σ coordinate is used. And the grids in Fig. 10e are the grids created by the OS coordinate with exponential function of b not by the CS coordinate.

20. To do justice to the title of the paper it will be necessary for each of the 3 coordinates to create results for standard and orthogonal grids/coordinates and compare these.

Response:

Yes, we will do this. (also see the response in No. 19)

21. As described above, the theoretical part of the paper should be made to correspond to the results obtained. In its present form the paper just finds better accuracy for a regular Cartesian grid than for an irregular grid. This is not enough to merit publication. The authors have found an interesting subject, as for the grids generated by terrain following coordinates little work has been done concerning advection testing and the same is true for orthogonal coordinates. Therefore with the suggested further work the paper would merit publication, whether or not a certain of the schemes a-e is very accurate.

Response:

In conclusion, the main modifications in the revised manuscript are given below.

(1) The title, abstract and conclusion will be revised to get rid of the confusion of the OS coordinate and the method proposed by Li et al. (2012).

(2) The title may be changed into "An orthogonal curvilinear terrain-following coordinate and its preliminary tests using 2-D idealized advection experiments".

(3) The abstract and the introduction will be revised to only emphasize the reduction of advection errors of the OS coordinate, and to mention that the PGF errors of the OS coordinate *might be* reduced due to its one-term computational form in the OS coordinate. A careful evaluation of the contribution of OS to the reduction of PGF errors will call other study. And a paragraph will be added to the end of introduction to introduce more details about the advection experiments.

(4) The descriptions of the design of the OS coordinate (Sections 2 and 3) will be simplified as short as possible, and put some details into the supplementary materials in the revised manuscript.

(5) The “basis vectors” will be replaced by “basis” in the revised manuscript.

(6) More descriptions of the discretization method on the advection equations will be added.

(7) The red grids in Fig. 10a will be removed.

(8) The name of each method in Fig. 10 will be emphasized.

(9) The unit of axes dX and dZ in Figs. 14 and 15 will be changed to “km”.

(10) Four new experiments based on the existed advection experiments will be implemented as follows:

- **a)** Using irregular grids to investigate the difference between the CS coordinate and the OS coordinate;
- **b)** Using non-zero “advection velocities and advection fields” (*u* and *q*) just on the top of terrain, to investigate the impact of the orthogonal grids created by the OS coordinate near the surface;
- **c)** Comparing the OS coordinate with 3 different b to the corresponding hybrid σ

coordinate, to investigate the impact of the orthogonal grids of the OS coordinate;

d) Increasing the terrain slope to investigate the accuracy and stability of the OS coordinate.

And after the above modification is done, the logic of the revised manuscript can be as Fig. R2 shows.

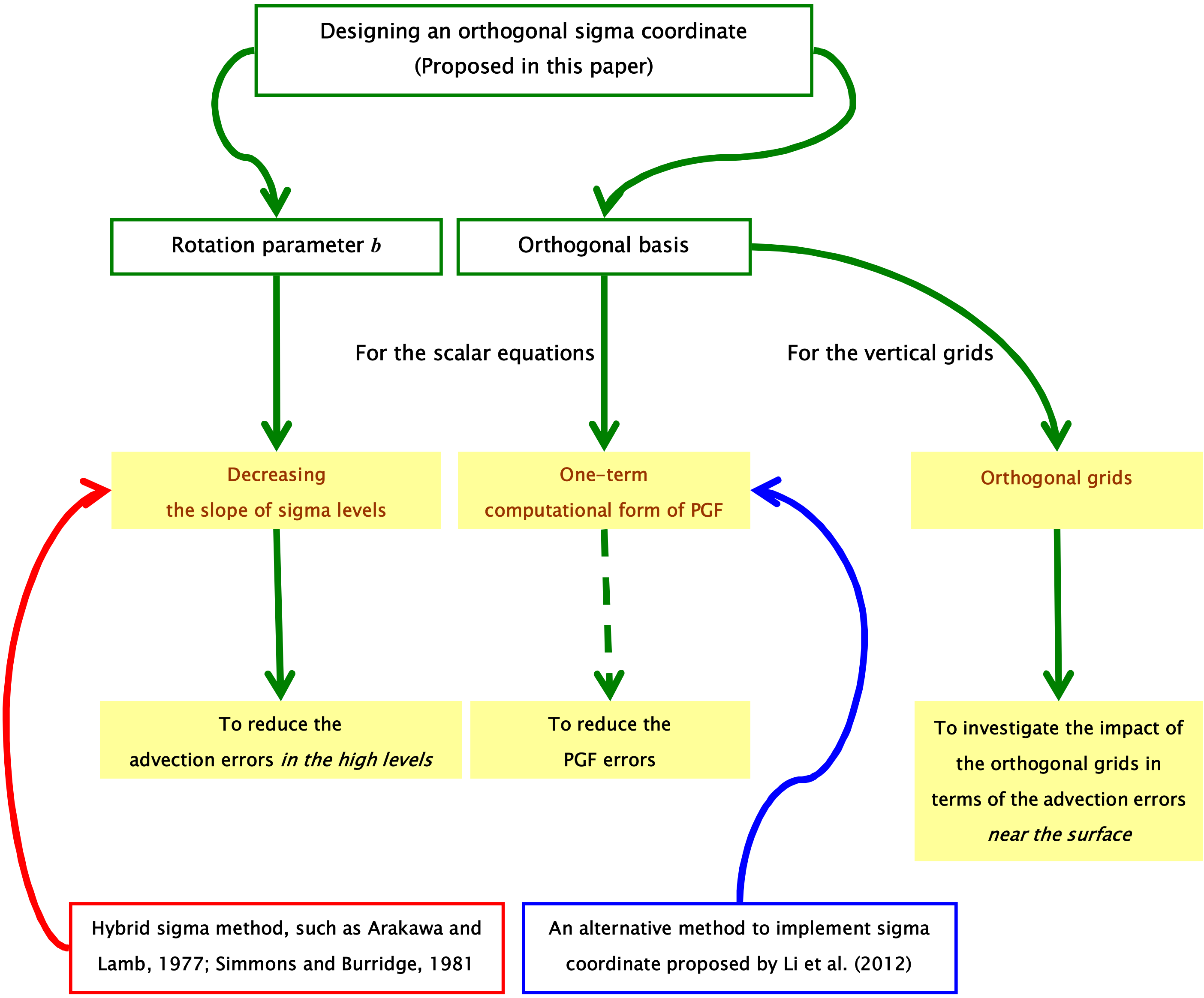

Figure R2: Same as Fig. R1, except two new yellow boxes are added on the right, and the solid arrow associated with the PGF errors changed into a dashed arrow.

Thank you for your comments and suggestions.