Geosci. Model Dev. Discuss.,
doi:10.5194/gmd-2016-296-AC3, 2017

Geoscientific Model Development Discussions
Open Access

Interactive comment on “Locally-orthogonal unstructured grid-generation for general circulation modelling on the sphere*” *by* Darren Engwirda

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Received and published: 19 February 2017

Dear reviewer,

Thank you for your comments and recommendations regarding the draft manuscript. I propose to incorporate the majority of your suggested changes ‘as-is’ in the revised submission. In all cases I have tried to respond in detail to your comments, including one or two instances where I have attempted to clarify the intent of the current draft.

I have found all of your suggestions to be helpful, and look forward to amending the manuscript in response to your review.

Overall, I agree with your suggestion that additional algorithmic detail should be provided, and will include such material in the revised submission. I intend to include additional details on the Frontal-Delaunay algorithm, in addition to brief pseudo-code descriptions of the full grid-generation process.

To better emphasise the novelty of the proposed approach, I additionally suggest a slight reorganisation of the paper. I suggest to move the discussion currently contained in Sections 2.6 (Figure 3 — staggered unstructured C-grid formulations) and pages 16–17 (benefits of 'well-centred' staggered orthogonal grids) to the beginning of Section 2. Such a change will better motivate the remaining discussions — explaining that such numerical schemes (i.e. the MPAS framework) require grids that are locally-orthogonal, centroidal and well-centred — a set of constraints that are, in the general case, difficult to satisfy and are not reliably achieved by conventional grid-generation techniques.

Reviewer comments are presented in italics, my responses are included in plain-text.

There is a sufficiently detailed description of the techniques used to improve the mesh quality, but the frontal-Delaunay technique is just mentioned. It would be helpful if it is described in some detail, for the intention of this paper is to help the potential user to learn about the technical details of the algorithm, and it is still a bit difficult to do. It would be very helpful to present a schematic of the algorithm at the very beginning, followed by the description of separate steps. This is partly done for the iterative mesh quality improvement, but I think that the entire algorithm has to be included. Also I would advice to be more clear with what is new in the algorithm.

Fig 1. The coloring used is non-informative. I was struggling to see some familiar topographic features but I could not. I would recommend to omit the topographic height, it does not have any sense here, only distracts you reader. Same concerns other mesh figures.

Agreed. I suggest to adopt a simple flat yellow colour-scheme for the ocean grid-cells, with the existing white-fill adopted for the land-cells. This combination appears to offer good visual contrast.

Page 2, line 6 'A majority of ...' âĂŤ I do not think this statement is correct. Many of practically used ocean circulation models use so-called tripolar meshes with Mercator-type stretching. Cubed sphere is used less frequently (the internal Rossby radius of deformation in the ocean is decreasing toward high latitudes, and meshes refined in high latitudes are more natural)

I agree that both cubed-sphere and tri-polar type grids are currently in wide use. I will update this sentence accordingly.

Line 10 'leading to significant...' If lon-lat mesh is used for ocean modeling, it is of course rotated, so that poles are on the land and there is no singularity. What is discussed has relevance to the atmosphere, but not to the ocean. Since your mesh examples are related to the ocean, the discussion creates misunderstanding.

I agree that this is true for Earth-centric ocean-modelling based on current continental configurations. Our requirements are somewhat more expansive than this though, also seeking to encompass Paleo-Earth studies, aqua-planets, exo-planets, and etc. In such cases, the polar singularities of lat-lon grids lead to numerical issues as per the current discussion.

I will amend this paragraph to better explain context and requirements here.

Page 3, line 5 The discussion here misses the point that FESOM, FVCOM, SLIM, Fluidity may work on general triangular meshes. SUNTANS (and its numerous predecessors) need orthogonal (well-centered) meshes (with the circumcenters inside respective triangles).

I agree. I will update the text accordingly to note that such models offer more flexibility in terms of grid requirements.

Line 29 I think the main point of Lambrecht et al. is that a care is taken of the shape of coastlines, resolution of passages etc. This question is not reflected in the manuscript (except for conclusions), although it presents the main challenge. It is quality of trian-

gles close to coastlines that is problematic in many practical cases.

I would also recommend to mention Admesh (DOI 10.1007/s10236-012-0574-0) which relies on the Persson's approach.

Agreed. I will add a reference and brief description of Admesh and amend that of Lambretch et al.

The focus of the current work though is on multi-resolution global simulations, in which coastal constraints are typically neglected. The main challenge here is the generation of locally-orthogonal, centroidal and well-centred grids appropriate for unstructured C-grid schemes such as MPAS.

I look forward to incorporating coastal constraints in a future version of the algorithm.

Page 4. Section 2. I would start here with brief description of the entire algorithm. Your reader keeps wondering what is the algorithm before the end of section 3. Present details of the Frontal -Delaunay algorithm and explain that in reality it is a 3D procedure with the central point of the sphere used to form the tetrahedra, and the restriction is just surface triangulation. Otherwise your preliminaries and Fig.2 are a bit embarrassing for a general reader (who would keep asking about v_e *and its relation to the surface).*

Page 5 Line 13 Restricted Delaunay tessellation âĂŤ try to explain this better, by using illustrations. I do not see your Fig. 2 to be of much help.

Page 6. It is not clear how mesh spacing functions are used in the mesh construction. Are they taken in account in the frontal procedure? It is not mentioned. Help you reader to clearly see the steps of the algorithm.

I agree. I suggest updating Figure 2 — adding additional detail illustrating the underlying tetrahedral grid emanating from the sphere centre. I will also update the description of the 'restricted' Delaunay structure accordingly.

I will expand the description of the Frontal-Delaunay algorithm as suggested, explicitly describing the ‘off-centre’ point-placement scheme and the way in which the mesh-spacing function is utilised. This material is already available in Engwirda and Ivers (2016), but I will include a summary of the algorithmic detail here.

A full and general description of the Frontal-Delaunay algorithm and it’s underlying theory is provided in Engwirda and Ivers (2016), and I am conscious not to dwell on excessive detail here, but to instead focus on a practical application of the techniques to general-circulation modelling. I fully agree though that the reader may benefit from a little more detail, and I will update the manuscript accordingly.

Page 7. Line 10 .. fully inverted elements? Please define what do you mean.

In some cases, unconstrained updates to vertex coordinates and/or grid topology could ‘invert’ triangles, reversing their orientation. Such cases would represent a local ‘tangling’ of the grid, which is obviously invalid. I will include the explanation "reversing its orientation".

Fig. 3. Is not it generally known?

Various unstructured general circulation models stagger variables according to a variety of different strategies. The staggered unstructured C-grid scheme described here has proven to be particularly successful (as per the MPAS framework) and I feel it’s description is useful to the reader. This particular arrangement of variables also helps explain the necessity of the constraints on the grids themselves — that grids are required to be locally-orthogonal, centroidal and well-centred.

As per my initial remarks, I propose to move this discussion to the beginning of Section 2, better contextualising and motivating the subsequent description of the grid-generation algorithm.

Page 8 Line 16 Fluid velocity and vorticity are commonly at different locations.

Agreed. I will change this line to: "...and the fluid velocity field and vorticity distribution represented at other spatially distinct grid-points."

Page 9, Line 4 ... Mention that you mean C-grid type techniques. There are other possibilities.

Agreed. I will change this line to: "In this study, the development of locally-orthogonal grids appropriate for staggered unstructured C-grid schemes..."

Page9, line 7 'described previously'? It was not really described here.

I agree. As per the responses above, I will included additional description of the Frontal-Delaunay algorithm.

Beginning from line 9, there is discussion that is either well known or irrelevant to the mesh generation.Why do you need it?

I believe a basic description of the generation and usefulness of Voronoi grids — especially the well-centred, centroidal variety — is of use to the general reader. There is currently not consensus as to the optimal staggering of variables for unstructured general circulation models — MPAS uses the locally-orthogonal C-grid scheme described here, FESOM2 uses a type of B-grid finite-volume approach defined using a (non-orthogonal) barycentric dual-cell. A variety of other approaches also exist, including finite-element type formulations.

Additionally, while the use and construction of locally-orthogonal staggered unstructured grids (i.e. Voronoi diagrams) is a well-known concept in computational geometry, it may be less so to general readers in the atmospheric/ocean-modelling communities.

As per my initial remarks, I propose to move this discussion to the beginning of Section 2, better contextualising and motivating the subsequent description of the grid-generation algorithm.

Page 11. Please define all quantities in (7) and better explain how computations are implemented.

I do not fully understand this comment. All quantities in equation 7 appear to be defined, and the subsequent paragraphs describe the way that the local 'gradient-ascent' type optimisation step is implemented. Please let me know which variables/steps need clarification.

Page 13, line 14 What is the grid-quality vector?

The 'grid-quality vector' is an array of element quality 'scores', one for each triangle in the grid. An 'area-length' quality metric is used in this study. The paragraph at the beginning of Section 3 (page 9, line 30) contains a description of the grid-quality vector.

Page 13, line 26 What is the lexicographical comparison?

A lexicographical comparison is a 'worst-first' comparison of grid-quality scores. This term is defined on page 10, line 32, where it is first introduced in the manuscript. Use of this terminology is consistent with it use in Klinger and Shewchuk (2008).

Page 20, Section 5. Please clearly define the novelty. What is describe is the selection of known steps.

Page 22 , line 14 (ii)–? I think it is secondary and technical issue. Well-centeredness and coastlines are real algorithmic questions.

Unstructured general circulation frameworks, such as MPAS, require grids that are locally-orthogonal, centroidal and well-centred. It is not my experience that conventional grid-generation algorithms are successful in satisfying this set of constraints in the general case.

The JIGSAW-GEO algorithm introduced here has been shown to effectively produce such grids, allowing the multi-resolution capabilities of a framework such as MPAS to be better utilised. The use of complex grids with highly non-uniform spacing constraints, such as those shown in Figures 9–10, can now be investigated. Fully solution-adaptive simulations, as mentioned at page 22, line 17, can now also be explored as a result. I look forward to reporting on these studies in the future.

As per my initial comments, I suggest slightly rearranging the order of the paper — moving the discussion of 'local-orhogonality', 'centroidalness' and 'well-centredness' to the beginning of Section 2 and better emphasising the importance and difficulty of satisfying these characteristics in the general case. This change is intended to better contextualise the grid-generation techniques described here — showcasing their novelty and usefulness.

Please let me know if you have further suggestions or comments regarding the submission or my responses to your review.

Kind regards,

Darren Engwirda

Interactive comment on Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-296, 2016.