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“Simulations of idealised 3D atmospheric flows on terrestrial planets using LFRic-Atmosphere” by Sergeev et al.

Reply on RC1

New or modified text is highlighted in **bold**.

Referee #1

This manuscript sets out to describe the new UK Met Office LFRic modelling framework as applied to the general problem of simulating atmospheric circulations that may be well removed from that of present day Earth itself. The detailed formulation is mostly presented fairly thoroughly with plenty of references and the manuscript goes on to present a set of simulations of some well known test cases for planetary atmosphere modelling for comparison with results of other GCMs used recently for exoplanet studies. In general the results seem to be encouraging in demonstrating that LFRic-Atmosphere produces results that are largely consistent with predecessor GCMs (including the current Met Office UM) for most test cases and satisfies some important tests of conservation of key integral quantities such as mass and angular momentum. The results therefore confirm that LFRic-Atmosphere has the potential to be a valuable new tool for planetary and exoplanetary studies, offering the possibility of interfacing it to some quite sophisticated parameterisation schemes for physical and chemical processes. The addition of the Trappist-1 test cases are particularly interesting and would merit further more detailed analysis - though perhaps for another publication that focuses more on scientific results than on the modelling methods.

The manuscript itself seems to be generally well written and organised. It provides much useful detail and background on the model code itself, which has a number of unusual and innovative features. The test cases seem generally well chosen and make for useful and convincing comparisons with the results of similar tests with other GCM codes. The manuscript could be accepted more or less as it is, though I have listed below a few points that the authors can respond to in a revised version.
Thank you very much for your valuable suggestions and encouraging comments.

Major point:

One of the more significant points concerns the choice of the cubed sphere grid. An earlier intercomparison of exoplanetary GCM codes by Polichtchouk et al. (2014) indicated that the cubed sphere version of MITgcm performed least well in some test cases than other discretisation methods, citing issues with conservation properties and other artefacts related to the grid. It may be helpful to include a brief discussion of why LFRic-Atmosphere does not seem to display these kinds of issues compared with MITgcm.
While we are not too familiar with MITgcm, the version used by Politchouk et al. (2014) is based on a finite volume core, which can indeed lead to numerical noise in the form of spurious ripples. On the other hand, LFRic-Atmosphere uses a compatible finite element discretisation, in which vector calculus identities are preserved by the discretisation. It was shown by Cotter and Shipton (2012) that this mimetic structure replicates the favourable properties of the Arakawa C-grid: good wave dispersion and avoidance of spurious computational modes. Conservation is achieved in LFRic-Atmosphere by discretising the conservative form of the transport equation for density, and using finite volume transport schemes, as described in Melvin et al (2018).

While grid imprinting can still be noticeable at coarse resolutions, it does not lead to a significant deterioration of the numerical solution, and the steady-state climate in our simulations is qualitatively and quantitatively close to that in LFRic’s predecessor, the UM. A number of steady-state tests (partly overlapping with those in Politchouk et al., 2014) with a shallow water version of LFRic-Atmosphere have also demonstrated good numerical convergence (Kent et al., 2023). In particular Thuburn & Cotter (2015) show that certain operators, notably the rotation of a vector, which are inconsistent with a finite volume discretisation on a cubed sphere grid, are consistent with a mimetic finite element discretisation. In short, a cubed sphere grid is not in itself a bad choice for a GCM, if one chooses the appropriate numerics correctly.

References:
Cotter, C. J., and Shipton J. (2012). Mixed finite elements for numerical weather prediction. Journal of Computational Physics 231.21. https://doi.org/10.1016/j.jcp.2012.05.020.
Melvin, Thomas, et al. (2019). A mixed finite‐element, finite‐volume, semi‐implicit discretization for atmospheric dynamics: Cartesian geometry. Quarterly Journal of the Royal Meteorological Society 145.724.
Thuburn, J., & Cotter, C. J. (2015). A primal–dual mimetic finite element scheme for the rotating shallow water equations on polygonal spherical meshes. Journal of Computational Physics, 290, 274-297. 10.1016/j.jcp.2015.02.045.
Thuburn, J., Cotter C.J. and Dubos T. (2013). Mimetic, semi-implicit, forward-in-time, finite volume shallow water model: comparison of hexagonal-icosahedral and cubed sphere grids, GMD, (2013) 6867-6925.

Other minor points:

Line 15 - the use of the word “precipice” here may not carry the meaning intended by the authors. Moving beyond a precipice has the sense of falling off a cliff, with the natural (somewhat catastrophic!) consequences! Perhaps “threshold” might be a more auspicious word choice here?
Good point. We replaced it with “**at the dawn of**”.

Line 102 - The neglect of latitudinal variations in geopotential ignores changes in g between equator and pole? This is significant at the 0.5% level for Earth (and is probably bigger on fast-rotating gas giants?).
The spherical geopotential approximation is a common feature of almost all GCMs, even when it comes to exoplanets. You raise a good point though, this approximation could theoretically lead to systematic biases. However, in our study the latitudinal variation of geopotential is equal or smaller than that for Earth because of the slower rotation rate (in the TLE and THAI cases) and smaller radius of the planet (in the THAI cases) — see eq. 18 in White et al. (2008). We leave the exploration of this effect on fast-rotating gas giant atmospheres to a future study.

References:
White, A.A., Staniforth, A. and Wood, N. (2008). Spheroidal coordinate systems for modelling global atmospheres. Q.J.R. Meteorol. Soc., 134: 261-270. https://doi.org/10.1002/qj.208

Line 109 - Perhaps a good place to discuss the choice of cubed sphere in comparison with Polichtchouk et al 2014?
We added this to the text (see our response to your major point above): **“GungHo does not suffer from the same numerical issues as identified in MITgcm's cubed-sphere core (Politchouk et al., 2014), because our model uses a compatible finite element discretisation, in which vector calculus identities are preserved by the discretisation. It was shown by (Cotter & Shipton 2012) that this mimetic structure replicates the favourable properties of the Arakawa C-grid: good wave dispersion and avoidance of spurious computational modes.”**

Eqs (5), (6) and (11) - why split these into 2 lines? Seems unnecessary and leads to potentially confusing disparity in sizes of brackets.
This was done in anticipation of the manuscript being published in a two-column mode, perhaps prematurely. In a revised version we made these equations single-line.

Lines 279-80 - You could use a dimensionless measure of AM such as in Lewis et al. (2021. Characterizing Regimes of Atmospheric Circulation in Terms of Their Global Superrotation, J. Atmos Sci., 78, 1245-58 and references therein)?
Thank you for your suggestion. The main purpose of the metrics in Fig. 2 is, however, to show the conservation of the key properties of the global atmosphere and not necessarily to characterise the

superrotation regime (as done by Lewis et al., 2021). For this reason, and to compare to previous exoplanet GCM benchmarks, we choose to keep the total axial angular momentum in Fig. 2.

Line 347 - Perhaps helpful to emphasise that clouds and microphysics here refer only to water (exoplanets max have clouds of varying composition!).
Good point. We added these sentences **"Here, large-scale cloud and microphysics schemes refer only to water clouds. However, the cloud schemes used in the UM for hot atmospheres of gas giants, which include additional species to just water (Lines et al. 2018, 2019) will be coupled to LFRic soon."**

Lines 352-3 - Perhaps give references for details of GA7.0 and GA9.0 configurations?
Done: "Global Atmosphere 7.0 (GA7.0) configuration **(Walters et al., 2017)**". The GA9.0 configuration is still under development.

Figure 8 and associated text - Zonal mean fields are not necessarily very illuminating for tidally-locked planets. It is perhaps beyond the scope of this paper, but a decomposition following Hammond & Lewis 2021 may be more enlightening?
We agree that zonal mean fields are often not the most appropriate illustration of the atmospheric circulation on TL planets, but the dominant jet is zonally oriented nonetheless. Thus they could still be informative and are widely used in various exoplanet modelling studies. The main reason to include Fig. 8 in our paper is to compare it to the corresponding zonal mean zonal wind plots for the THAI GCMs (Fig. 6 in Turbet et al., 2022; Figs. 10 & 21 in Sergeev et al. 2022). We updated the figure caption: **"Zonal mean eastward wind (contours, m s^{-1}) in steady state of the THAI experiments. Compare to Fig. 6 in Turbet et al., 2022 and Figs. 10 & 21 in Sergeev et al. 2022."**

Line 497 - "While we cannot judge which THAI GCM is more correct due to the absence of observations" - which is the bane of almost all exoplanet circulation studies! But more generally it may be useful to include a statement emphasising what new advantages LFRic-Atmosphere offers to the planetary atmosphere modelling community compared with other codes. Some of this is covered in the Introduction, but may be worth emphasising in the conclusions.
You are right. We added the following to the end of this paragraph: **"While we cannot yet judge which THAI GCM is more correct due to the absence of observations, LFRic-Atmosphere offers a number of key advantages to the planetary atmosphere modelling community: inherently mass-conserving dynamical core, quasi-uniform horizontal resolution, better code portability and parallel scalability (Adams et al. 2019)."**

References - several references display the titles of articles entirely as upper case, which looks strange.
This is how titles appear in the corresponding journals, so we leave this to the copy editor to fix, if required.