Reply to Reviewer #2

March 27, 2018

We greatly appreciate the referee's careful and insightful review. Our responses are detailed below.

I recommend publication after addressing concerns cited below. The paper is a useful description of water conservation errors in EAM V1.

Suggested word changes. if these suggestions are not correct then there are more serious problems that I do not understand in this paper.

- *1-16: ".. errors in early V1 versions decrease .."*
- *1-17: "Increased vertical resolution in V1 results .."*
- *1-20: ".. beneficial for V1."*
- *2-18: ".. errors in V1α and .."*
- *3-3: " .. 30 everywhere .." I assume this model does not use step-mountain.*
- *3-15: ".. 6 sub-steps of 5 minutes each as .."*
- *5-1: "..chemical processes that operate on a single vertical column."*
- *5-7: "..passed on .."*
- *6-11: ".. which includes advection of air mass, momentum, and heat."*
- *8-20: ".. evaporation and ignoring the heat of sublimation."*
- *8-32: ".. clipped amount of downward moisture .."*
- *9-2: ".. received by the sub-surface components .."*
- *9-3: ".. are unclipped, .."*
- *9-9: "This can be seen .."*

- *9-20: ".. used in this alternative .."*
- *17-5: ".. advection time steps of 5 minutes for each vertical remapping step."*
- *17-6: ".. increase in linear horizontal resolution)," or ".. increase in Dx),*
- *17-8: ".. advection steps stays at 3 per remapping step."*
- *17-14: ".. increased to 2 hours, 4 times that of 1 .."*

The suggested wording changes are applied in the revised manuscript.

Confusing things.

*3-2: 90*90*6 = 48600. Why are there 2 additional columns on the cube sphere grid.*

The physical parameterizations are computed at the vertices (instead of quadrilateral faces) of the cubed sphere grid. 48600 ($90\times90\times6$) is the number of quadrilaterals, while $48600+2=48602$ is the number of vertices. The relationship between these two numbers can be derived using Euler's polyhedron formula. For example, the cube has 6 faces, and $6+2=8$ vertices. This is explained in the revised manuscript.

3-12: How thick are the 14 layers over mountains?

The original sentence in the discussion paper reads "...the vertical resolution is increased to 72 layers for both the dynamics and physics, with about 14 levels between the surface and 850 hPa." We replaced the second half of the sentence by "with a typical layer thickness of 50–120 m in the bottom 1 km of the atmosphere, except for the lowest model layer that is about 20 m thick". These new numbers are valid both over the ocean and over the mountains.

6-Fig2: It should be mentioned that this diagram shows processes of the stadium shaped cells of Figure 1, that (a) relates to se_type = 1, and (b) relates to se_type 0. From what I understand, that are 3 se_rsplit steps for each se_nsplit which makes the diagram misleading. I suggest you discard Figure 2 and explain its contents in the text.

Both Fig. 1 and Fig. 2, as well as the text, are revised to address this comment.

6-11 to 7-3: Clean this up. According to Table 4 there are 2 to 3 r steps for each n step. Make this clear. Mention that humidity advection is grouped with dynamical advection or with tracers depending on model version.

The corresponding paragraph is rewritten to describe the two levels of sub-stepping. We point out during the description of se_ftype =2 that water vapor is grouped with other tracers (e.g., cloud

condensate and aerosols).

7-22 to 7-24: Does this sentence apply to all se-ftypes? If so, move it.

Yes, the sentence describes a feature of the transport scheme and is valid for all se_ftypes. We clarify in the revised manuscript that the condition of positive element-total concentration is fulfilled by se_ftype = 1 and for the first dynamics sub-step of se_ftype = 0, but can be violated for the later dynamics sub-steps when se_ftype = 0 is used, resulting in a situation that is not anticipated by the transport scheme.

8-27: Say more about the time stepping method. Is it explicit? If it is implicit, is it intelligent enough no recognize the availability of water vapor in the boundary layers and not just the lowest layer?

We agree with the referee that how the downward moisture flux affects near-surface humidity depends on how the flux is applied in the subsequent calculations. In the revised manuscript, we point out that QNEG4 assumes (1) the downward flux affects only the bottom layer, (2) no moisture source is provided from the layers aloft, and (3) an Euler forward method is used for time integration. QNEG4 is admittedly a very simplistic and aggressive limiter. Although experience has shown that *some* amount of adjustment in the downward moisture flux is needed, the actual amount applied by QNEG4 is likely an overestimation since the turbulence parameterizations in both E3SM V0 and V1 uses implicit time stepping methods. We also added text in the same subsection to note that the new QQFLX fixer determines the amount of water vapor to borrow based on the same 3 assumptions used by QNEG4, hence QQFLX probably also does more work than necessary. Future work on the coupling between surface fluxes and the turbulence parameterization could help to address this issue.

9-22: Do these errors occur consistently over mountain tops of at ocean cells adjacent to mountains, or are they more sporadic? Same question applies to other sub-sections of Section 3.

In terms of geographical distribution, the PDC errors in V1α systematically occur in cloudy regions with strong horizontal gradient in cloud condensate. The LHFLX errors occur typically in middle and high latitudes due to the lower surface temperature there and the more frequent occurrence of ice sublimation/deposition. The QNEG4 errors mostly occur as isolated and sporadic large values over land, while the QNEG3 and INTERR errors are typically very small and randomly distributed in cloudy regions over the globe. A paragraph is added to Section 5 (”Simulations and results”) to describe the above-mentioned features. We did not see frequent occurrences of those errors over mountain tops or at ocean cells adjacent to mountains.

10-27: It appears that your water mass change is distributed uniformly over the globe. This water mass mainly affects the ocean fraction of the Earth. Should your sea-level changes be computed as ΔH / (1 - OceanFraction). Please comment on this.

The water mass change we report in the paper is indeed uniformly distributed over the globe. In reality, the mass change is likely to end up in the oceans and in reservoirs over land such as lakes, ice caps and glaciers, hence our formula (Eq. 6) is likely to underestimate the resulting change in sea level. To provide an accurate assessment of the impact of the conservation error, one should conduct a pair of coupled model simulations with and without the fixes discussed in our paper, and compare the simulated sea levels. Unfortunately we did not have sufficient resources to conduct such simulations to evaluate the impact of water conservation in isolation. (The coupled simulations presented in the paper were not specifically conducted for the water conservation investigation, and therefore contained various other code changes that had impact on the simulated sea level.) The "equivalent sea level rise" reported in our paper is essentially a measure of water conservation error, not the actual sea level drift in E3SM. This is clarified in the revised manuscript after Eq. (6) is presented.

12-Figure3: Most noticeable in the lower left panel, do these spikes originate from large errors at single grid cells? Although water mass borrowing has eliminated the spikes in model V1γ, the original errors are still there.

Yes, the spikes seen in the QNEG4 error originate from large errors at single grid cells over land. This is mentioned in a new paragraph added to Section 5 (see also our response to the referee's comment on line 9-22 above).

The last sentence of the abstract and the last paragraph in the conclusions section of our paper both point out that the proposed fixers are remedies rather than root cure of the conservation problems. Future improvements in the time integration methods would be beneficial for the V1 model.

17-14 to 17-16: "increased" or "decreased" relative to what. Perhaps this sentence should start: "Comparing V1a model at 2.8° versus that at 1°: the .."

The comparison was made with respect to the 1° simulation. The corresponding sentence is revised in the new manuscript.