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Geoscientific Model Development Discussions

Interactive comment on "Quantifying and attributing time step sensitivities in present-day climate simulations conducted with EAMv1" *by* Hui Wan et al.

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Referee comment: In this manuscript, the authors investigate the sensitivity to model timestep of the mean climate within the EAMv1 model. They then methodically scrutinize the response to variations of the model sub-component timesteps in a series of experiments that are designed to attribute the root cause of the model sensitivity to the individual components.

Perhaps unsurprisingly to those familiar with model development, the largest deviations can be attributed to the parametrizations of clouds and moist convection. Perhaps less predictable is how and where these deviations are - in part due to the direct change

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to the sub-timestepping of the microphysics scheme and in part arising from timestep sensitivities of their coupling to other components.

The investigations performed are specific to the EAMv1 atmospheric system and in particular to the specific physics parametrizations, dynamical core and transport formulations and split-explicit temporal coupling. That said, the methodology would translate to other modelling systems and formulations, potentially providing a useful framework for identifying physics or dynamics components that are not well resolved or are poorly formulated for a chosen model timestep length. The method can also help in identifying poorly performing components of the system which might otherwise be hidden or explained away with model tuning. For those without an interest in the specific behaviour of EAM, the most valuable take away message is that developing and employing an approach such as this will help to understand deficiencies and biases when developing weather and climate models.

The manuscript is very well laid out, with a clearly constructed story (with an exception noted in comment 5). I would recommend this article for publication subject to consideration of the minor comments below.

Author response: We greatly appreciate the referee's positive assessment of the manuscript, especially their recognition of the general value of our work to the weather and climate modeling community. Our detailed responses to the referee's questions and suggestions are provided below.

Referee comment: General comments
1) On L80, the authors mention the passing of tendencies between different components of the atmospheric model and provide the example of the physics tendencies being passed to the resolved dynamics. It is implied that there are other such instances. Although these aren't the subject of the investigation, it would be useful to know what the other instances are, or if these are too numerous/complex to list, then to clarify if there are cases where different physics components pass their tendencies to

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subsequent physics components. In particular, do those physics components (clouds, microphysics, convection) which are the focus of the sensitivity studies have such a dependency? If they do, are there any consequences to this that should be borne in mind when interpreting the conclusions about timestep choices between the dependent schemes. If they don't, it would be useful to have that made explicit.

Author response: The following clarification and discussion are added to the model description part (Section 2.1) of the revised manuscript:

In terms of the coupling among the coarse-grained components shown in Figure 1a of the original manuscript, the authors are aware of three instances in which tendencies are passed along. These are:

- For the coupling between the parameterized physics and the resolved dynamics, tendencies of temperature and momentum caused by the entire parameterization package are provided to the dynamical core together with the “before-physics" atmospheric state. These are used to update the state variables before each vertical remapping step Δt_{remap}. This method of physics-dynamics coupling is depicted in Figure 2b of Zhang et al. (2018, DOI:10.5194/gmd-11-1971-2018) and also discussed in Lauritzen and Williamson (2019, DOI:10.1029/2018MS001549).
- Sensible heat fluxes and moisture fluxes at the Earth's surface are calculated in the “Misc. processes” box in Figure 1a of the original manuscript. The fluxes are not immediately applied to update the atmospheric state; rather, they are passed into the stratiform cloud macro/microphysics subcycles and used as boundary conditions for CLUBB.
- Deep convection is assumed to detrain a certain amount of cloud liquid, causing a source of stratiform cloud condensate. The detrainment-induced tendency of stratiform cloud liquid mass concentration is not applied within or immediately

> after the deep convection parameterization but passed into the stratiform cloud macro/microphysics subcycles. After CLUBB has operated, detrainment-induced cloud mass tendency is partitioned into liquid and ice phases using the current temperature values; temperature tendency corresponding to the effective phase change is diagnosed; cloud droplet and crystal number tendencies are derived from the partitioned mass tendencies using assumed cloud particle sizes. These tendencies of cloud liquid and ice as well as temperature are used to update the model state variables before the state variables are provided to the aerosol activation and cloud microphysics parameterization.

In this study we did not touch these parts of the model code. All three cases described above involve passing tendencies of some processes (that are discretized with longer step sizes) to subsequent processes that are subcycled (i.e., use shorter step sizes). The spirit of this method resembles the "sequential splitting" advocated in Beljaars et al. (2004) and Beljaars et al. (2018) as well as the "sequential-tendency splitting" defined in Donahue and Caldwell (2018). The method leads to a tighter coupling as the subcycled processes "feel" the influence of the preceding processes and respond at the shorter intervals; this tighter coupling was exactly our motivation for the "v1_Dribble" simulation described in Section 4.3.2. On the other hand, the processes that are sources of the tendencies only respond to the subcycled processes at longer intervals; the temporal truncation error associated with these longer time steps can have a rather direct impact on the subcycled processes through those tendencies and trigger responses in the subcycled processes.

Referee comment: 2) Figure 1: This is a useful schematic to quickly capture the timestepping process. I'm not sure I can see from this where/when the state is updated though. Is it at every point where State is labelled? Could this be made a bit clearer?

Author response: Thanks for asking about this. We have revised all schematics and their captions in the manuscript to explicitly depict where/when the model state is updated.

Referee comment: 3) On first inspection it is quite surprising how little an impact there is in the Δt_{macmic} that can be directly attributed to the reduction of Δt_{macmic}. However, it is noted in the model overview (L74) that the microphysics includes dynamic substepping and so the timestep used within the microphysics itself may already be shorter than 5 minutes - particularly where numerical stability requires it. While this doesn't negate the conclusions, it might be worth re-stating this feature of the microphysics when discussing this lack of sensitivity. Do the authors have any information regarding the minimum timestep that is used or the number of hydrometeor sedimentation substeps that might add to that understanding?

Author response: A clarification is added to the revised manuscript that the dynamic substepping mentioned at L74 of the original manuscript is used only for the sedimentation of hydrometeors; most of the processes in the microphysics parameterization, including for example autoconversion, accretion, and self-collection etc., are calculated using the forward Euler method method with a fixed step size of Δt_{macmic} and parallel splitting. Some further details can be found in Section 2 of Santos et al. (2020, DOI: 10.1029/2019MS001972).

So far we have not done much analysis on the behavior of cloud microphysics in our simulations, and hence unfortunately do not have concrete numbers to help answer the referee's question about minimum step sizes and number of hydrometeor sedimentation substeps. The adaptive sedimentation time steps might be a cause of the lack of sensitivity to Δt_{macmic} in the subtropical low clouds. Another factor to consider is the metrics (physical quantities and their statistics) that are used to assess the time step sensitivity. While the cloud fraction and radiative effects associated with subtropical low clouds generally appear to be much less sensitive to Δt_{macmic} than to step sizes outside the subcycles (Figures 7 and 8 in the original manuscript), the zonal mean specific humidity shown in Figure 6 of the original manuscript does appear to be more sensitive. A somewhat similar example can be found in Section 7 and Figures 13–15 in Santos et al. (2020), where the microphysics time steps were shortened to 1 s; only very minor changes were found in 3-year mean geographical distribution of precipitation, surface temperature, and cloud radiative effects while the differences in the zonal mean vertical distribution of rain mass are substantially larger. (A caveat to mention here is that specific details of the E3SMv1 results from Santos et al. (2020) cannot be directly compared to our results here as our v1_MacMic_Shorter simulation also reduced time steps of CLUBB and its coupling to cloud microphysics.) Some comments are added to the revised manuscript.

Referee comment: 4) Regarding the sensitivity of the tropical upper troposphere to the cloud macro and microphysics, there are a number of ways in which the cloud microphysics can directly and indirectly influence this region. See for example figure 1 of Hardiman, Steven C., et al. "Processes controlling tropical tropopause temperature and stratospheric water vapor in climate models." Journal of Climate 28.16 (2015): 6516-6535.

Author response: Thanks for pointing this out. A brief comment and some references have been added to the revised manuscript.

Referee comment: 5) Section 4.3.3 - Deep convection: This section is at a slight tangent to the rest of the paper and as a result it took me several reads through to be able to absorb the conclusions. Unlike the preceding sections that look to attribute sensitivities, this section attempts to investigate the reason behind the sensitivity of the deep convection to timestep and timescale and then contrasts the findings with the arguments of Williamson (2013). This feels like a half-hearted attempt, with the authors themselves acknowledging more work is needed to fully understand this. I am tempted to suggest removal of this section, however, once I had digested it I did find it interesting and so I would suggest that this goes in an appendix. If the authors do decide to retain the section (in its current location or elsewhere), then please could they clearly signpost at the start of this section that it is a change in direction from the previous stated aims of the paper and is looking beyond attribution?

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Author response: Following the referee's suggestion, we have moved Figure 14 of the original manuscript and the discussions of the figure to an appendix.

Regarding the referee's point that Section 4.3.3 goes beyond the scope of attribution, our original thought was that the discussion on deep convection had an attribution component because for sensitivities in convective activities, there was the question whether they were caused by the step size of the convection parameterization itself or the step size with which deep convection was coupled with other processes. The discussion in Section 4.3.3 was intended to make an attempt to answer that question. But after pondering on the referee's comment and thinking further about our interpretation of the paper by Williamson (2013), we do agree that the referee has a good point. We have revised the section to clean up the wording and logic.

Referee comment:
Typos
L147: 'Working' not 'Wording'
L268: 'Tropical' not 'Topical'

Author response: Thanks. These have been corrected.

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