The Role of Process Coupling in the Time Step Sensitivity of E3SM's Microphysics

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Abstract

A common goal of next-generation Global Circulation Models (GCMs) is that they should be "scale-aware", which typically implies that such models should not be excessively sensitive to grid spacings, and that they should in some sense converge monotonically towards a result as grid spacings decrease. While both horizontal and vertical resolution have been treated in this manner, time resolution is typically viewed differently. Specifically, a decrease in time step size is often viewed as a "necessary evil", being decreased only in cases where spatial resolution is also decreased, requiring a change to the time resolution to satisfy a CFL condition. Our experiments with the E3SM Atmosphere Model suggest that cloud physics and precipitation in GCMs is in fact quite sensitive to process coupling time step size, and that the biases affected by time integration error are independent from (and of comparable size to) biases due to other common sources of error, such as grid spacing and choice of sub-grid-scale physics parameterizations. This suggests that process coupling frequency is a key feature that should be adjusted for future models.

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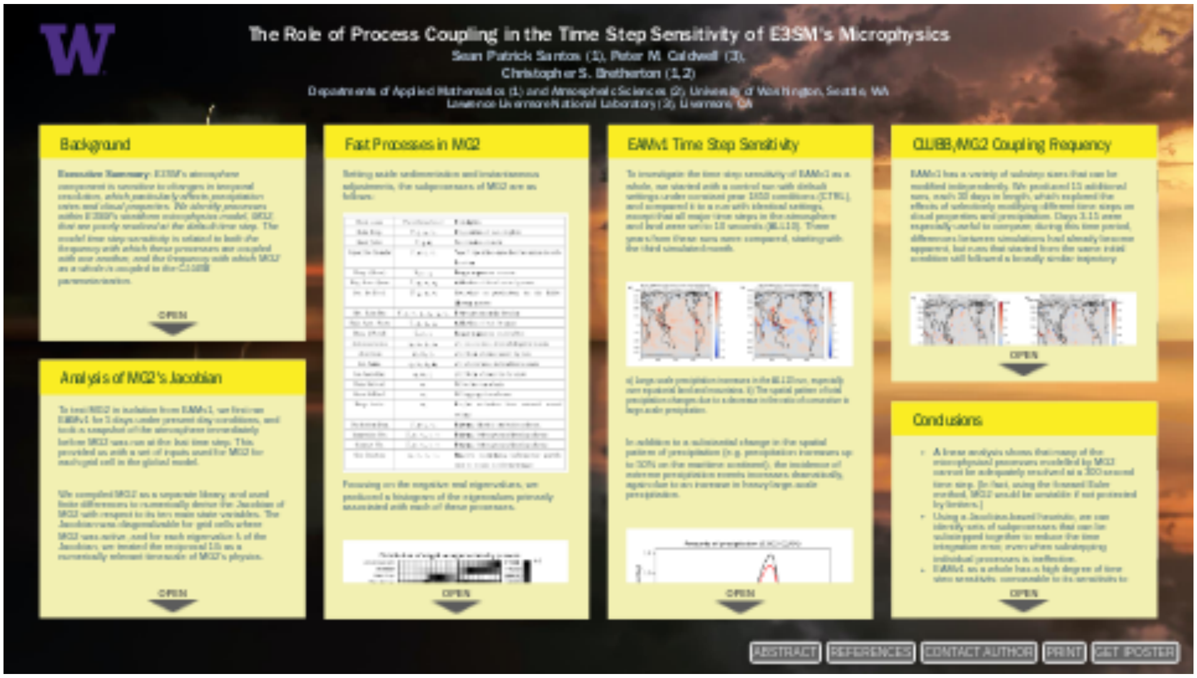

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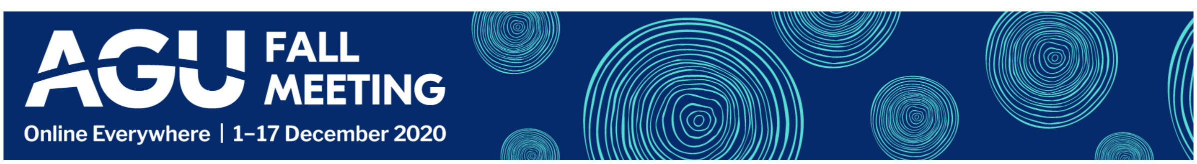


BACKGROUND

Executive Summary: *E3SM's atmosphere component is sensitive to changes in temporal resolution, which particularly affects precipitation rates and cloud properties. We identify processes within E3SM's stratiform microphysics model, MG2, that are poorly resolved at the default time step. The model time step sensitivity is related to both the frequency with which these processes are coupled with one another, and the frequency with which MG2 as a whole is coupled to the CLUBB parameterization.*

The Energy Exascale Earth System Model version 1 (E3SMv1) uses the Morrison-Gettelman microphysics version 2 (MG2) as its stratiform microphysics parameterization. This study discusses the role that sub-process coupling within MG2 affects the time step sensitivity of the microphysics particularly [1], and the way in which coupling between MG2 and other E3SM parameterizations affects the time step sensitivity of the model as a whole [2].

In the E3SM atmosphere model version 1 (EAMv1), a 30 minute time step is used to couple the dynamics and physics to each other and to the surface components of E3SMv1. Much of the physics also uses this 30 minute time step. However, MG2 is an exception to this, as is the Cloud Layers Unified By Binormals parameterization (CLUBB), which is responsible for macrophysics, shallow convection, and turbulence. CLUBB and MG2 are substepped together at a 5 minute (or 300 second) time step. The dynamics is also substepped, with most dynamics calculations also performed using a 5 minute time step.

MG2 is a 2-moment bulk microphysics model containing four types of hydrometeor: cloud liquid, cloud ice, rain, and snow. For each of these hydrometeors, mass mixing ratio (q_c, q_i, q_r, and q_s, respectively) and number concentration (n_c, n_i, n_r, and n_s, respectively) determine the size distribution. These hydrometeor variables, along with temperature (T) and water vapor mass mixing ratio (q), are the main state variables affected by MG2.

Most of MG2's microphysical processes are integrated using a parallel split, after which limiters are applied to enforce conservation of mass and enforce restrictions on maximum/minimum particle size. Sedimentation is applied sequentially after these limiters using an upwind method with an adaptive time step. To focus on the processes that are run at the overall 300 second time step, we disable sedimentation for the MG2-specific part of this study.

ANALYSIS OF MG2'S JACOBIAN

To test MG2 in isolation from EAMv1, we first ran EAMv1 for 5 days under present day conditions, and took a snapshot of the atmosphere immediately before MG2 was run at the last time step. This provided us with a set of inputs used for MG2 for each grid cell in the global model.

We compiled MG2 as a separate library, and used finite differences to numerically derive the Jacobian of MG2 with respect to its ten main state variables. The Jacobian was diagonalizable for grid cells where MG2 was active, and for each eigenvalue λ of the Jacobian, we treated the reciprocal 1/λ as a numerically relevant timescale of MG2's physics.

If the time step sensitivity of MG2 is related to its short timescale physics, we are interested in associating these short timescales with particular subprocesses or sets of subprocesses within MG2. We begin by calculating the matrices of eigenvalues (Λ) and eigenvectors (V) of the Jacobian of MG2. For each subprocess, we calculate the Jacobian of that particular process as well (J_p). We note that:

$$\Lambda = \sum_p (V^{-1} J_p V)$$

We can associate an eigenvalue to a particular set of processes by noting the processes for which the corresponding diagonal element of the matrix on the right-hand side is large.

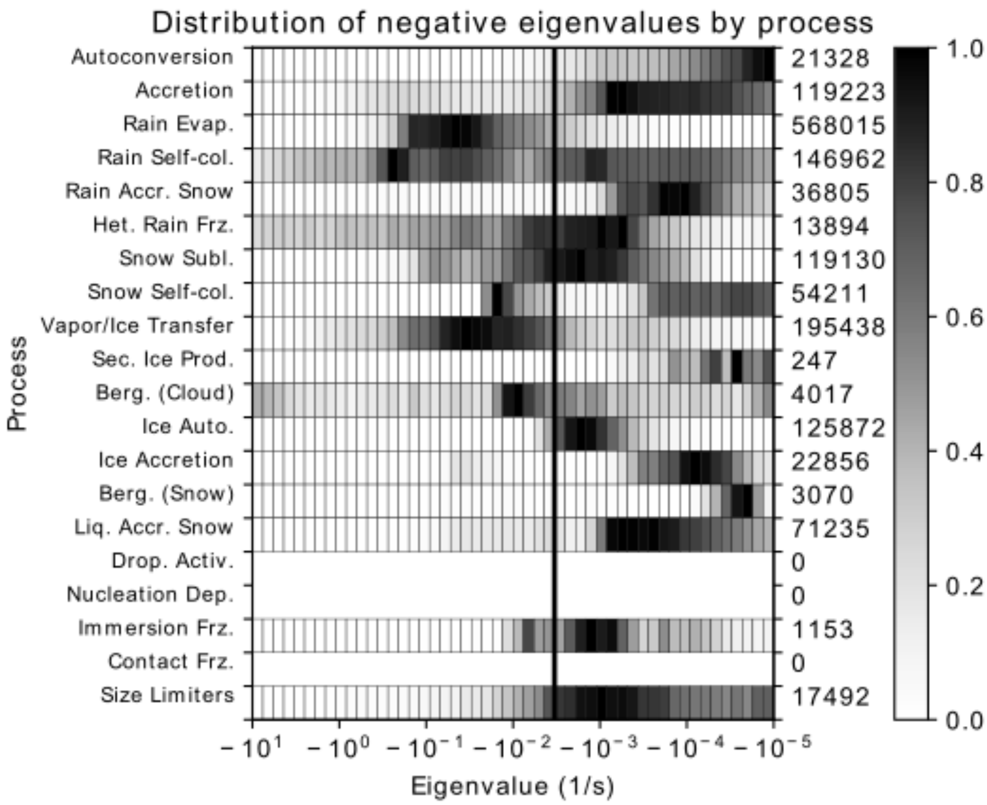
This gives us a target for improvement: if we can find a fast subset of MG2's physics in this way, we can target that subset when choosing an improved time integration method and/or shorter time step size.

FAST PROCESSES IN MG2

Setting aside sedimentation and instantaneous adjustments, the subprocesses of MG2 are as follows:

Short name	Variables affected	Description
Rain Evap.	T, q, q_r, n_r	Evaporation of rain droplets
Snow Subl.	T, q, q_s	Sublimation of snow
Vapor/Ice Transfer	T, q, q_i, n_i	Vapor deposition onto cloud ice minus ice sublimation
Berg. (Snow)	T, q_c, q_s	Bergeron process on snow
Liq. Accr. Snow	T, q_c, n_c, q_s	Collection of cloud water by snow
Sec. Ice Prod.	T, q_c, q_i, n_i	Secondary ice production via the Hallet-Mossop process
Het. Rain Frz.	T, q_i, n_i, q_r, n_r, q_s, n_s	Heterogeneous rain freezing
Rain Accr. Snow	T, q_r, n_r, q_s	Collection of rain by snow
Berg. (Cloud)	T, q_c, q_i	Bergeron process on cloud ice
Autoconversion	q_c, n_c, q_r, n_r	Autoconversion of cloud droplets to rain
Accretion	q_c, n_c, q_r	Accretion of cloud water by rain
Ice Auto.	q_i, n_i, q_s, n_s	Autoconversion of cloud ice to snow
Ice Accretion	q_i, n_i, q_s	Accretion of cloud ice by snow
Rain Self-col.	n_r	Self-collection of rain
Snow Self-col.	n_s	Self-aggregation of snow
Drop. Activ.	n_c	Droplet activation from external aerosol scheme
Nucleation Dep.	T, q, q_i, n_i	External classical nucleation scheme.
Immersion Frz.	T, q_c, n_c, q_i, n_i	External heterogeneous freezing scheme.
Contact Frz.	T, q_c, n_c, q_i, n_i	External heterogeneous freezing scheme.
Size Limiters	n_c, n_i, n_r, n_s	Limiters constraining hydrometeor particle sizes to remain in relevant ranges

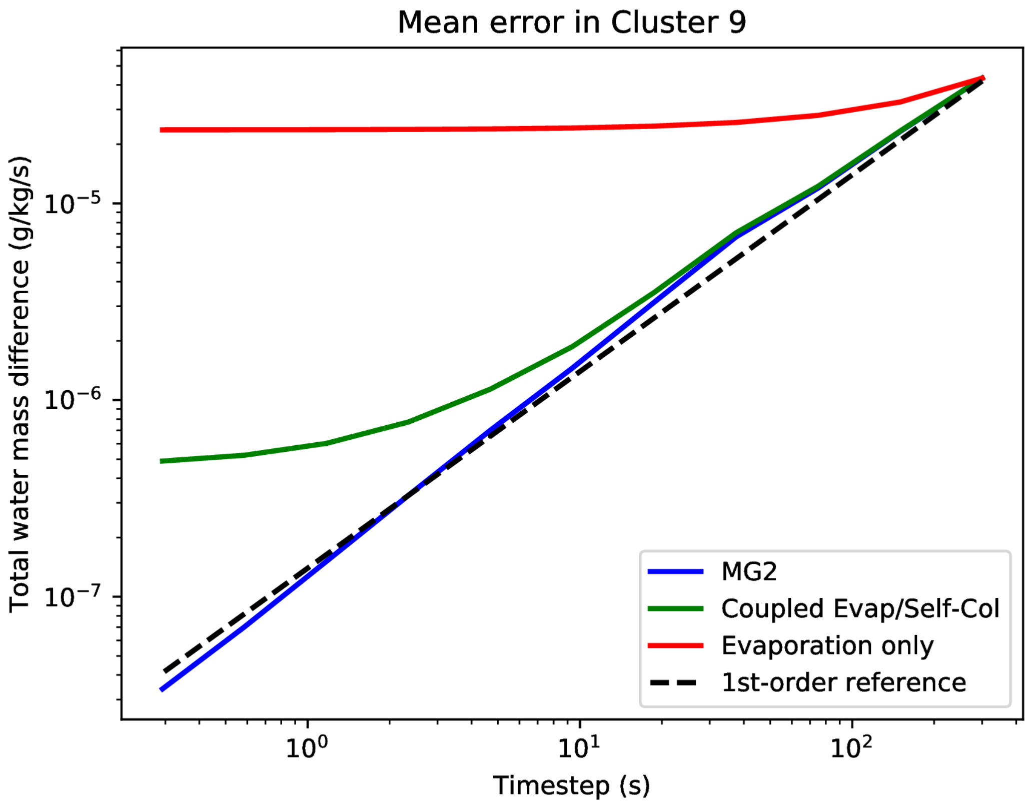
Focusing on the negative real eigenvalues, we produced a histogram of the eigenvalues primarily associated with each of these processes.



Distribution of negative eigenvalues for each subprocess of MG2. Each row is normalized so that the maximum value is 1, and the count of negative eigenvalues plotted for each process is provided on the right axis. The black line shows 1/(300 seconds).

Some processes, such as autoconversion, are only associated with smaller eigenvalues, so we expect them to be well resolved at MG2's 300 second time step. However, most processes are associated with larger magnitude eigenvalues, and some, such as rain evaporation, are probably never well-resolved at coarse time steps.

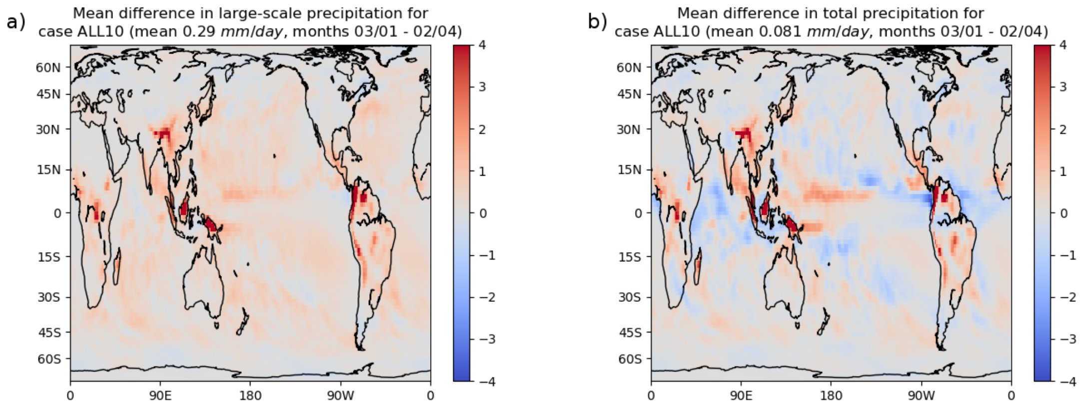
Often, multiple processes are associated with the same timescales. For instance, the large eigenvalues associated with rain evaporation are typically also associated with rain self-collection. This indicates that coupling between these processes is critical for adequately representing them.



Log-log plot of time step versus a measure of average error in rain evaporation rate for a number of grid cells where rain evaporation is the dominant process. Reducing the time step for MG2 as a whole (blue) produces first-order convergence. For time step sizes above 10 seconds, we get similar results by substepping only the rain evaporation and self-collection (green), running all other processes at a time step of 300 seconds. However, substepping the rain evaporation alone (red) is ineffective, reducing the error by at most a factor of 2.

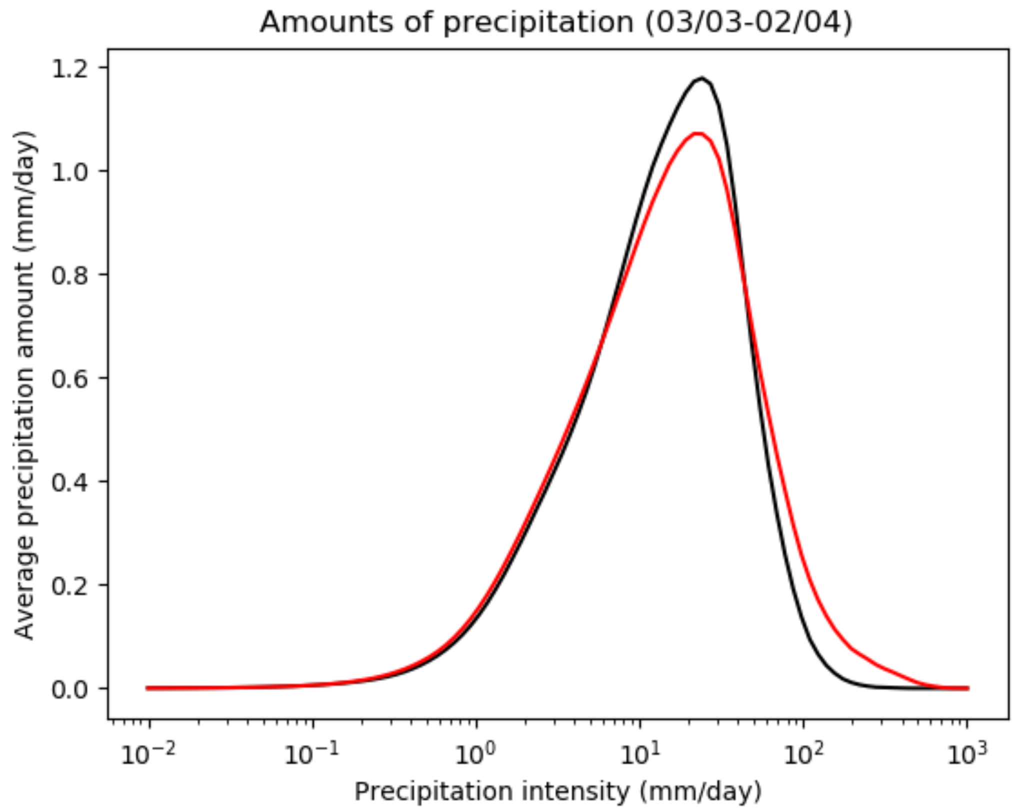
EAMV1 TIME STEP SENSITIVITY

To investigate the time step sensitivity of EAMv1 as a whole, we started with a control run with default settings under constant year 1850 conditions (CTRL), and compared it to a run with identical settings, except that all major time steps in the atmosphere and land were set to 10 seconds (ALL10). Three years from these runs were compared, starting with the third simulated month.



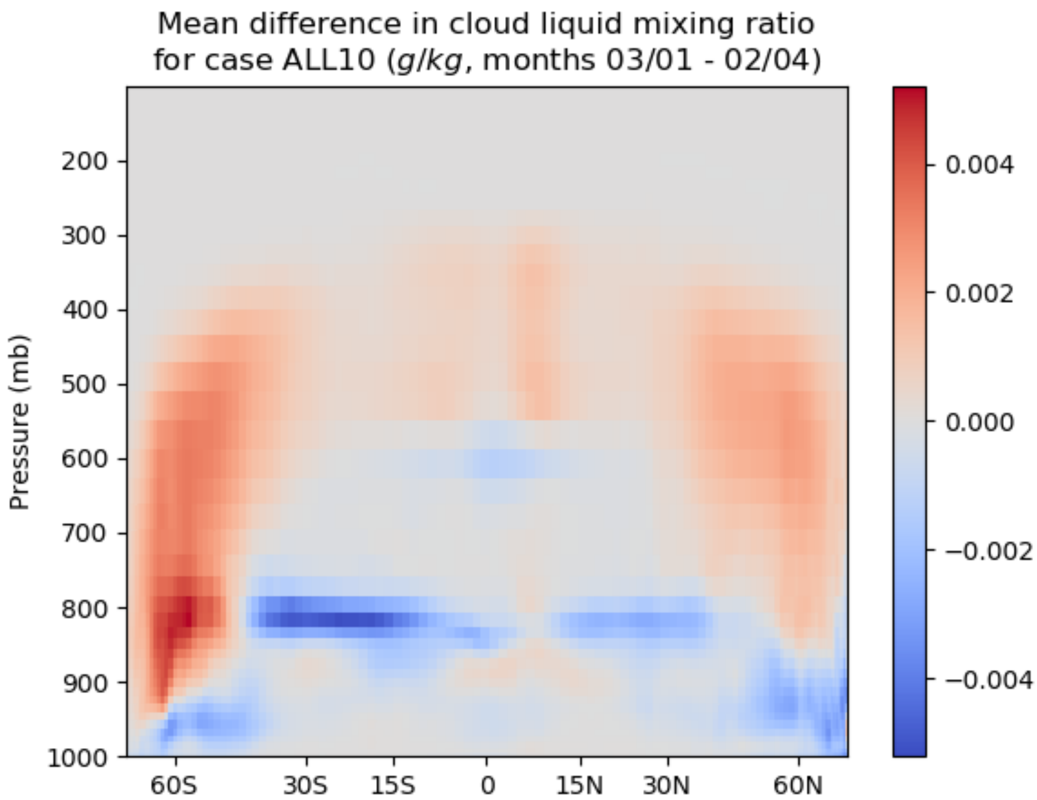
a) Large-scale precipitation increases in the ALL10 run, especially over equatorial land and mountains. b) The spatial pattern of total precipitation changes due to a decrease in the ratio of convective to large-scale precipitation.

In addition to a substantial change in the spatial pattern of precipitation (e.g. precipitation increases up to 50% on the maritime continent), the incidence of extreme precipitation events increases dramatically, again due to an increase in heavy large-scale precipitation.



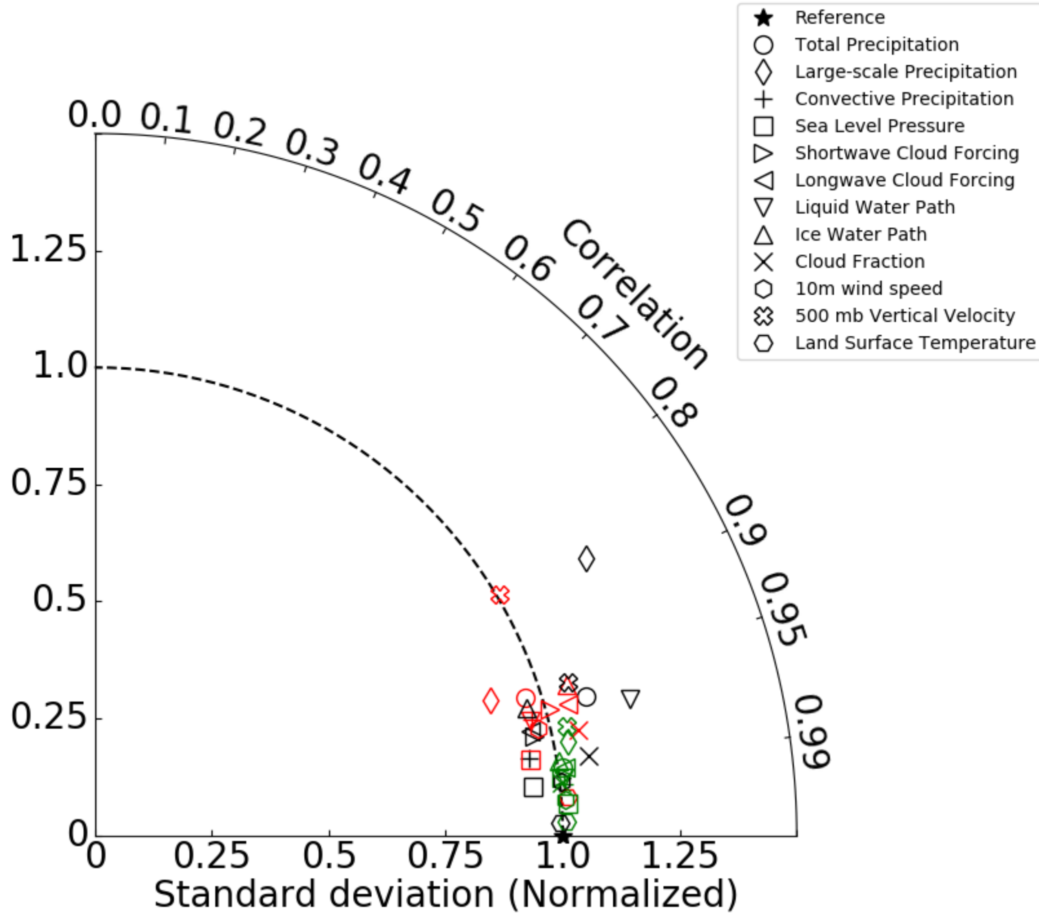
The amount of rain falling in heavy or extreme precipitation events is increased in the ALL10 run (red) compared with CTRL (black). Plot is derived from hourly data from the third simulated year, and normalized to yield average global precipitation for the year when integrated with respect to the natural logarithm of precipitation intensity.

The amount of cloud liquid also changes substantially in the ALL10 run, with a reduction of up to 10% in low cloud mass at lower latitudes, while increasing at higher latitudes and above 650 mb in the tropics.



Differences between CTRL and ALL10 of zonally-averaged cloud liquid mass mixing ratio.

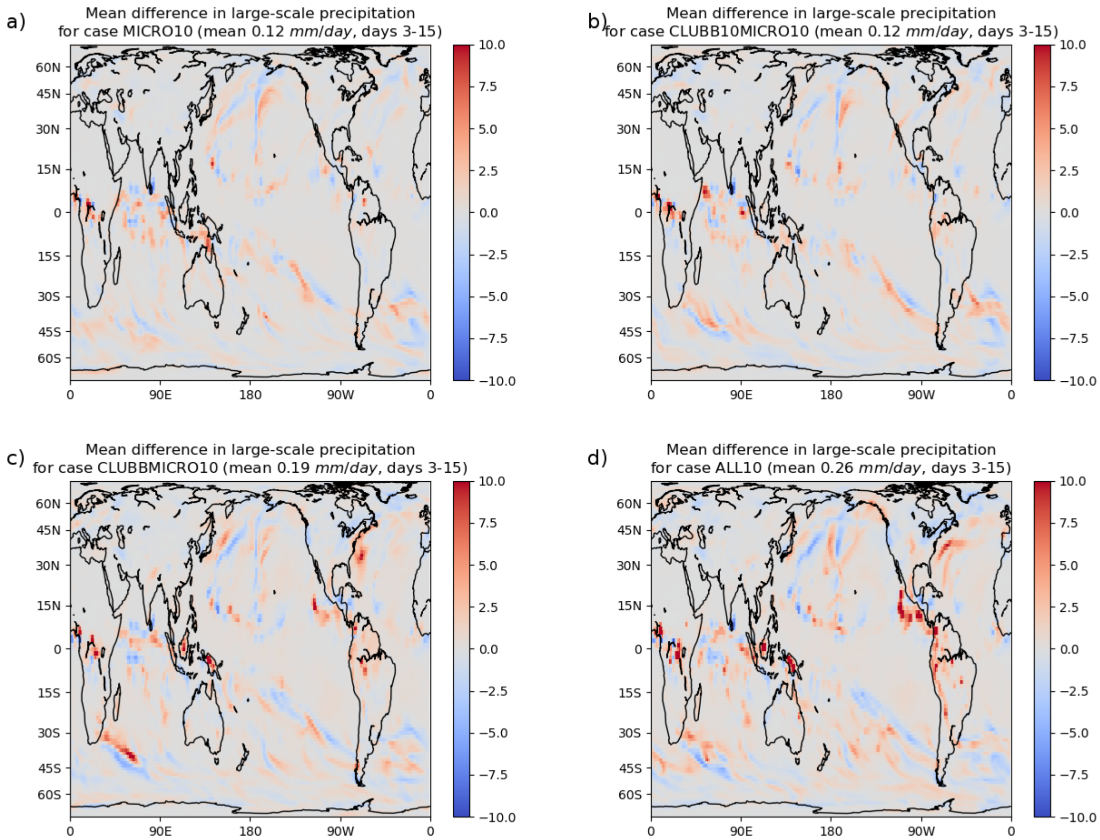
The differences in mean climate between CTRL and ALL10 were similar in magnitude to the effect of doubling the model grid spacing, showing that EAMv1 has a similar degree of sensitivity to changes in temporal and horizontal resolution.



Taylor diagram comparing the spatial variability of different variables between ALL10 (black) and CTRL (reference). The effect of decreasing the time step is similar to the effect of doubling the horizontal resolution (red). We also run CTRL for an additional three years, and compare these to the first three years of CTRL (green), showing that the effects of changing model resolution are discernibly greater than those produced by simply modifying the initial condition for a three year run.

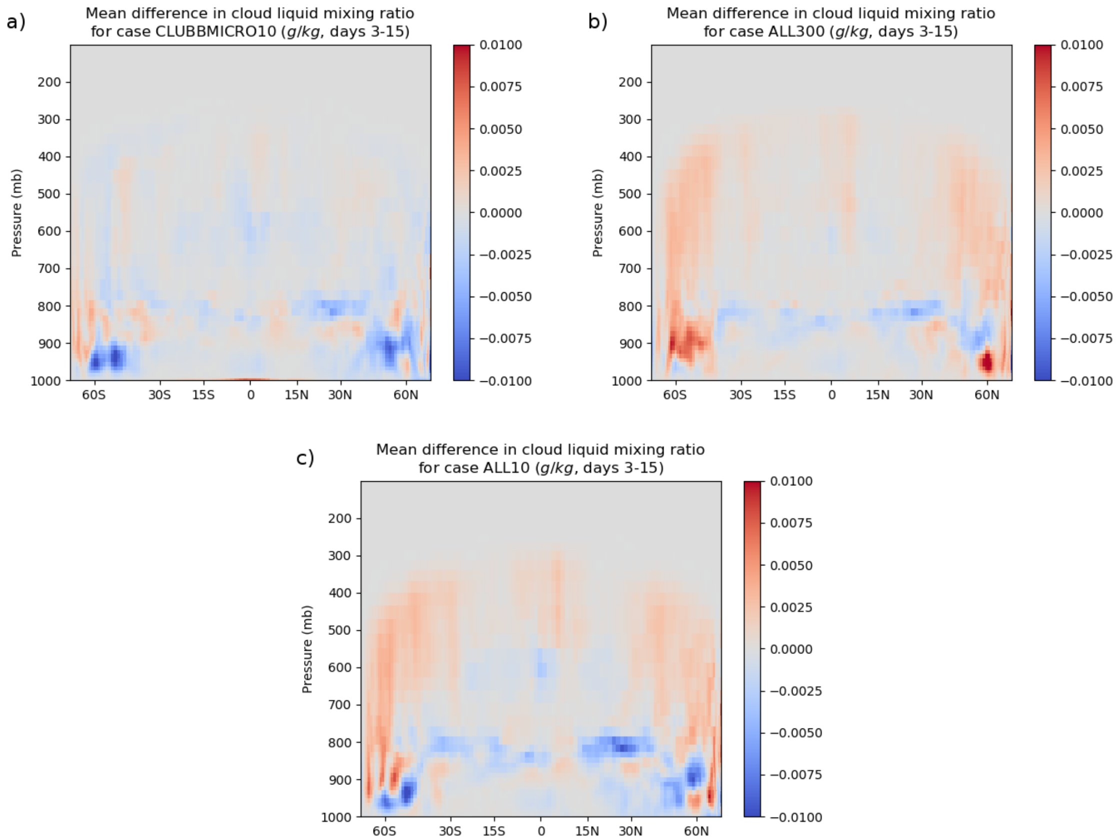
CLUBB/MG2 COUPLING FREQUENCY

EAMv1 has a variety of substep sizes that can be modified independently. We produced 15 additional runs, each 30 days in length, which explored the effects of selectively modifying different time steps on cloud properties and precipitation. Days 3-15 were especially useful to compare; during this time period, differences between simulations had already become apparent, but runs that started from the same initial condition still followed a broadly similar trajectory.



Differences in large-scale precipitation averaged over days 3-15 compared to CTRL, for four substepped runs. a) Only MG2 substepped at 10 seconds. b) CLUBB and MG2 substepped at 10 seconds, coupled at 300 seconds. c) CLUBB and MG2 substepped and coupled at 10 seconds. d) Whole model time step reduced to 10 seconds.

Substepping MG2 alone produced a decrease in the ratio of convective to large-scale precipitation, but the overall pattern of precipitation seen in ALL10 could only be reproduced when CLUBB and MG2 were substepped together at shorter time steps. Reducing the combined CLUBB/MG2 time step can reproduce the large increases in precipitation over land, and the increase in heavy precipitation events.



Differences in zonally-averaged cloud liquid mixing ratio for days 3-15 compared with CTRL, for three substepped runs. a) CLUBB and MG2 substepped and coupled at 300 seconds. b) Whole model time step reduced to 300 seconds. c) Whole model time step reduced to 10 seconds.

The combined CLUBB/MG2 time step also plays a role in reducing low cloud liquid mass. However, the dynamics-physics coupling interval is responsible for the *increases* in cloud liquid mass at higher latitudes and higher altitudes. This can be seen by lowering the overall model time step to 300 seconds. Doing so does not change the CLUBB/MG2 time step, nor the dynamics time step, but does increase the frequency of coupling between the two.

CONCLUSIONS

- A linear analysis shows that many of the microphysical processes modelled by MG2 cannot be adequately resolved at a 300 second time step. (In fact, using the forward Euler method, MG2 would be unstable if not protected by limiters.)
- Using a Jacobian-based heuristic, we can identify sets of subprocesses that can be substepped together to reduce the time integration error, even when substepping individual processes is ineffective.
- EAMv1 as a whole has a high degree of time step sensitivity, comparable to its sensitivity to horizontal resolution.
- EAMv1's time step sensitivity is dominated by its sensitivity to the coupling frequency between different processes, rather than by the sub step used for individual processes.
- The CLUBB/MG2 coupling frequency and dynamics/physics coupling frequency are particularly important for precipitation and cloud properties.

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ABSTRACT

A common goal of next-generation Global Circulation Models (GCMs) is that they should be "scale-aware", which typically implies that such models should not be excessively sensitive to grid spacings, and that they should in some sense converge monotonically towards a result as grid spacings decrease. While both horizontal and vertical resolution have been treated in this manner, time resolution is typically viewed differently. Specifically, a decrease in time step size is often viewed as a "necessary evil", being decreased only in cases where spatial resolution is also decreased, requiring a change to the time resolution to satisfy a CFL condition.

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REFERENCES

[1] Santos, S. P., Caldwell, P. M., & Bretherton, C. S. (2020). Numerically relevant timescales in the MG2 microphysics model. Journal of Advances in Modeling Earth Systems, 12(4), e2019MS001972. https://doi.org/10.1029/2019MS001972 (https://doi.org/10.1029/2019MS001972)

[2] Santos, S. P., Caldwell, P. M., & Bretherton, C. S. (2020). Cloud process coupling and time integration in the E3SM atmosphere model. [Submitted to JAMES, currently in review.] Earth and Space Science Open Archive, 23. https://doi.org/10.1002/essoar.10504538.1 (https://doi.org/10.1002/essoar.10504538.1)

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