Cloud Process Coupling and Time Integration in the E3SM Atmosphere Model

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Key Points:

- Changing time step has as large an effect on E3SMv1's climate as doubling horizontal resolution.
- Only some of the whole model's time step sensitivity can be attributed to individual processes.
- Coupling between processes is the most important source of model time step sensitivity.

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Abstract

In this study, we find significant sensitivity to the choice of time step for the Energy Exascale Earth System Model's atmospheric component, leading to large decreases in the magnitude of cloud forcing when the time step is reduced to 10 seconds. Reducing the time step size for the microphysics increases precipitation, leading to a drying of the atmosphere and an increase in surface evaporation. This effect is amplified when the microphysics is substepped together with other cloud physics processes. Coupling the model's dynamics and physics more frequently reduces cloud fraction at lower altitudes, while producing more cloud liquid at higher altitudes. Reducing the deep convection time step also reduces low cloud mass and cloud fraction. Together, these results suggest that cloud physics in a global circulation model can depend strongly on time step, and in particular on the frequency with which cloud-related processes are coupled with each other and with the model dynamics.

Plain Language Summary

Computer simulations of the Earth's atmosphere take the state of the atmosphere at one point in time, then predict the state of the atmosphere a short interval of time into the future. The length of this time interval is known as the "time step". By doing this repeatedly, models can produce a simulated history of the atmosphere for years or even centuries. A smaller time step size requires more computer time, but should ideally lead to more accurate results. In this study we reduce the time step for the atmosphere in the Energy Exascale Earth System Model from half an hour to ten seconds. The simulation with a smaller time step has more rain, which removes water from the atmosphere and reduces the fraction of the Earth's surface that is covered by clouds. We also experiment with changing the time step for only some parts of the model and not others. We find that the effects of the time step size on the model are related mostly to the frequency of coupling between processes rather than the time step used for any individual processes.

1 Introduction

Time integration strategies for general circulation models (GCMs) have grown more complex, both due to an increase in the number of separate processes within a model (allowing individual parameterizations to adopt different time integration strategies from the "host" model), and due to changes in process coupling, such as modifications that allow different processes to be run concurrently (Balaji et al., 2016; Donahue & Caldwell, 2020). This increase in complexity means that there is often no single time step for the model, but rather a set of interrelated time steps controlling the rate at which various calculations are performed and allowed to interact. This increased complexity can be daunting, but it also provides the opportunity to conduct more detailed experiments regarding the effect of temporal resolution on GCMs. Past research has established that certain cloud processes can be disproportionately responsible for time integration error in GCMs (Wan et al., 2015). When the time steps used for particular processes can easily be adjusted independently from one another, it becomes possible to study the time step sensitivity of these processes with minimal changes to the model code.

Prior research using the Community Atmosphere Model, versions 3 and 4, (CAM3/4), as well as its predecessor, the Community Climate Model, version 3, suggests that time step size for a GCM has significant effects on precipitation in an aquaplanet simulation, particularly in the intertropical convergence zone (ITCZ) (Williamson & Olson, 2003; Williamson, 2008; Mishra et al., 2008). Decreasing the time step increases total precipitation in the ITCZ and the frequency of extreme precipitation events. The partition of precipitation between the large-scale and convective parameterizations is also affected, with an increase in the large-scale precipitation being responsible for the aforementioned effects. For CAM3, the increase in total precipitation was found to be dependent on an increase in evaporation at the surface, which in turn was due to an increase in wind speed and a decrease in specific humidity near the surface (Mishra et al., 2008). Further research using CAM3 for real-planet simulations confirmed these results, and showed that the increased evaporation, in addition to producing increased precipitable water (and precipitation), also produced a larger cloud fraction at low altitude and an increased magnitude of radiative cloud forcing (Mishra & Shanay, 2011). Williamson (2013), using CAM4, found that the time step of the convective schemes, and in particular their rate of coupling with other processes, controlled the repartitioning of precipitation between large-scale and convective processes.

Yu and Pritchard (2015) experimented with changes in the global model time step for a superparameterized version of CAM3 (SPCAM3), without changing its cloud resolving model's time step. Decreasing the CAM time step increased overall precipitation in SPCAM3, as well as the frequency of heavy precipitation events, which also happened for CAM3. However, reducing the time step size in SPCAM3 *decreased* precipitable water, decreased both liquid and ice water path, and ultimately decreased the magnitude of radiative cloud forcings. This was hypothesized to be due to changes in convective organization, producing an increase in precipitation efficiency and effectively drying out the atmosphere.

Although both CAM3 and SPCAM3 experience similar increases in surface evaporation and precipitation (which must match in the long run, to balance the water budget), the proposed mechanisms driving these changes are different. In effect, the increased evaporation in CAM3 "pushes" more precipitable water into the atmosphere, eventually forcing an increase in condensation and precipitation to remove this water, while the increased precipitation efficiency in SPCAM3 "pulls" water out of the atmosphere, drying it out and encouraging evaporation to replace the lost water.

This paper analyzes time step sensitivity in the Energy Earth System Model (E3SM), which shares very little of its physics with CAM3, and almost none with SPCAM3. Nevertheless, E3SM is descended from CAM3 and uses the same general strategies for coupling the physics parameterizations, dynamics, and surface components. We have recently examined the effect of time step size on a specific parameterization used by E3SM, the Morrison-Gettelman microphysics version 2 (MG2). We found that the total precipitation was not sensitive to changes to the MG2 time step alone, though we did see a mild increase in the ratio of stratiform to convective precipitation (Santos et al., 2020). While the details of the precipitation physics and the vertical distribution of rain mass changed significantly at small time steps, the effect on total precipitation reaching the surface was mild.

2 Model Description

E3SM version 1 (E3SMv1) is an earth system model developed by the U.S. Department of Energy, focusing on three main research topics: (1) the water cycle, (2) the cryosphere, and (3) biogeochemistry (Golaz et al., 2019). This study focuses on E3SMv1's atmosphere model, EAMv1 (Rasch et al., 2019; Xie et al., 2018). For a run at $\sim$100 km atmospheric resolution (1°), the standard time step for coupling between the physics parameterizations, dynamical core, and surface parameterizations is 30 minutes (1800 seconds), with the various processes and dynamical core typically coupled using a "sequential split" method. This means that for each time step, each parameterization accepts a state that has already been updated by applying the effects of previous parameterizations, and so at large time steps, the model physics depends on the order in which these updates are applied (Donahue & Caldwell, 2018). (This should be irrelevant for sufficiently small time steps, assuming that the model converges in this limit to the true solution of its spatially discretized motivating equations.)

Component Name	Component Function(s)	Time Step Size(s)
Spectral element dynamics (HOMME)	Dynamics Tracer Advection	Vertical remapping: 900s Dynamics/Advection: 300s Hyperviscosity subcycle: 100s
Cloud Layers Unified By Binormals (CLUBB)	Turbulence Shallow Convection Stratiform Clouds	300s (looped with MG2)
Zhang-McFarlane scheme (ZM)	Deep Convection	1800s
Four-mode Modal Aerosol Module (MAM4)	Aerosols	1800s
Morrison-Gettelman scheme version 2 (MG2)	Stratiform Microphysics	300s (looped with CLUBB)
Linearized ozone chemistry (LINOZ2)	Ozone chemistry	1800s
Rapid Radiative Transfer Model for GCMs (RRTMG)	Radiative transfer	1800s/3600s (tendencies are only recalculated once per hour, but applied every time step)
Gravity wave scheme	Gravity wave propagation and breaking	1800s

Table 1. EAMv1 parameterizations and corresponding time steps for a Δx $\approx$100 km run using default settings

Table 1 shows a summary of the main parameterizations of EAMv1, as well as the relevant time steps for these schemes when default options are used. This is by necessity a broad overview, since each of these parameterizations is a complex piece of software in its own right. Note also that the CLUBB and MG2 parameterizations are substepped within a single loop, so each "sees" the updates from the other during each of their smaller 300 second time steps.

The climate of EAMv1 using default settings is extensively documented, for instance in Golaz et al. (2019), Rasch et al. (2019), and Xie et al. (2018). This work will focus on the climatological differences between various modified runs using shorter time steps and a control EAMv1 run at default settings.

This approach allows us to broadly discuss the magnitude and nature of time integration error in E3SM. However, we note that the model was developed and tuned for much longer time steps than we use here, and therefore the tuning parameters are likely set so as to partially cancel this time integration error. Thus, while the ALL10 run described below should have a dramatically lower *time integration* error, we do not assert that it is "better" than the default configuration as a production model, and in fact it would require significant retuning (at a minimum) to be usable at all.

3 Methodology

We ran E3SM at a ∼100 km atmospheric resolution (ne30_ne30 grid) with standard E3SMv1 tuning and prescribed sea surface temperature. These runs were performed using a maintenance version of E3SM 1.1 (hash 25c94366) with pre-industrial forcings (compset F1850C5AV1C-04P2) unless otherwise specified, and all had prescribed sea surface temperature (SST) and sea ice extent.

The control run (CTRL) is an out-of-the-box run using default settings. We compare this to a new run (ALL10) that changed the atmosphere's dynamics-physics-surface coupling time step, known as "dtime" in the model settings, to 10 s. This time step is chosen to be as small as we could reasonably afford, within the constraints of the computing power we had available for this study. CTRL and ALL10 simulations are both 3 years in length. Results based on years 1-2 were unchanged after adding year 3, which gives us confidence that 3 years is long enough to draw robust conclusions.

The dtime setting is often thought of as specifying the entire atmosphere's time step, but there are three ways in which this is not quite true. First, the radiation parameterization uses a fixed time step of once per hour, regardless of dtime. While the ALL10 run does not modify the radiation time step, our tests with shorter runs show that the model is not especially sensitive to this time step. Second, the dynamics and cloud physics contain some substepping by default, though none run at a time step as small as 10 s. In the ALL10 run, we disable these forms of substepping, so that all major dynamics and physics processes aside from radiation run at the same small time step. Third, because the dtime setting also governs the rate at which EAMv1 exchanges information with the surface components, changing it forces a change in the land and sea ice components, which must run at a 10 s time step as well.

To investigate which processes within EAMv1 were most responsible for its overall time step sensitivity, we configured a series of runs using built-in options to substep individual parameterizations at a 10 s time step. These runs include DYN10, which substepped EAMv1's spectral element dynamical core, CLUBB10, which substepped the CLUBB cloud physics parameterization, and MICRO10, which substepped the MG2 stratiform microphysics. Typically CLUBB and MG2 are substepped together within a single loop, so we also produced a CLUBBMICRO10 run that used this capability to run both schemes at 10 s. Because this run showed clear differences from the control, we produced a CLUBBMICRO60 run where CLUBB and MG2 were substepped together at 60 s. Separately, we also produced a CLUBB10MICRO10 run, where the individual time steps for CLUBB and MG2 were reduced, but the two schemes were only coupled at the default rate of once per 300 s. To verify our prior belief that the model is less sensitive to the radiation time step size than to other physics time steps, we produced the ALLRAD10 run, which is identical to the ALL10 run except that the radiation is also run at a 10 second time step. Finally, we produced the ALL300 and ALL60 runs, which change dtime to 300 s and 60 s, respectively. ALL300 is useful as an additional control, because it decreases the dynamics-physics coupling time step, but does not decrease the CLUBB or MG2 time steps, nor does it decrease the dynamics time steps (except the remapping for the vertically Lagrangian advection scheme, which normally runs every 900 seconds). A summary of all these runs can be found in Table 2.

In EAMv1, the most important parameterization that does *not* have this built-in substepping capability is the ZM deep convection, which always runs at the time step given by dtime. Substepping this parameterization individually is challenging and is described further in section 4.3.

Name	Substepped processes	Substep size	Run length
CTRL	None	N/A	38 mo
ALL10	Dynamics-physics coupling	10 s	38 mo
ALL60		60 s	30 d
ALL300		300 s	30 d
DYN10	Dynamics and tracer advection	10 s	30 d
MICRO10	MG2 microphysics	10 s	30 d
CLUBB10	CLUBB unified cloud parameterization	10 s	30 d
CLUBB10MICRO10	CLUBB and MG2	10 s	30 d
CLUBBMICRO10	CLUBB+MG2 combined loop	10 s	30 d
CLUBBMICRO60		60 s	
ALLRAD10	Dynamics-physics coupling and radiation	10 s	30 d

Table 2. Runs performed using the default aerosol scheme.

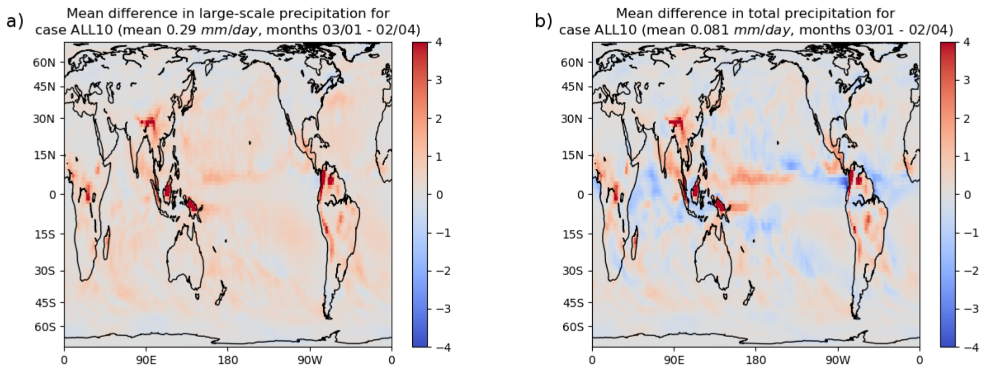

Figure 1. Differences in a) large-scale precipitation and b) total precipitation between CTRL and ALL10 runs.

4 Results

4.1 Effects of Decreasing the Physics Time Step

Consistent with the literature on CAM, we find a 0.08 mm/d increase in global-mean total precipitation with 10 s time steps, mostly stemming from low latitudes. While convective precipitation decreases, large-scale precipitation increases by ∼60% in the tropics (defined here as latitudes from 30S to 30N), especially over land (Figure 1a). The overall effect is an increase in tropical precipitation over the Pacific warm pool, and a near-doubling of precipitation in parts of Borneo, New Guinea, and Colombia (Figure 1b).

Evaporation must increase to fuel the precipitation increases. Over the oceans, this is due to slightly higher wind speed and lower near-surface relative humidity. The average 10 m wind speed in the tropics increases from 5.56 m/s to 5.70 m/s, and occurs mainly

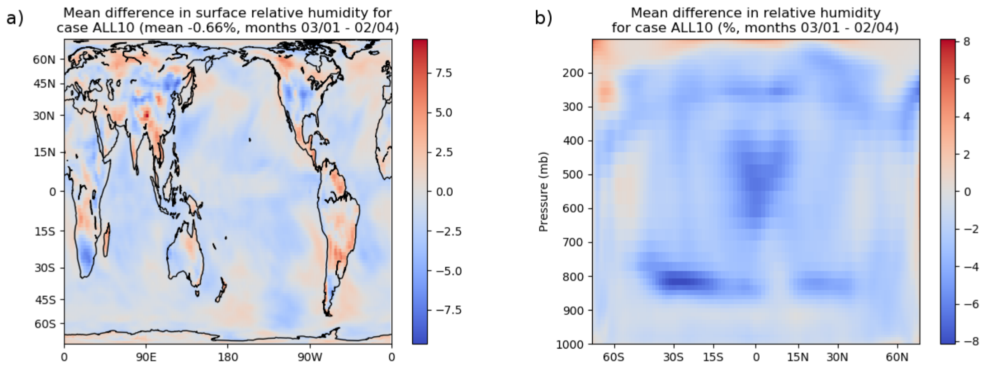

Figure 2. Differences in a) relative humidity and b) zonal mean relative humidity between CTRL and ALL10 runs.

in the northern Indian ocean and central Pacific, while latent heat flux increases in the same areas, by about $4\,\mathrm{W/m^2}$ (not shown). This is consistent with the CAM3 literature, suggesting that an increase in wind speed contributes an increase in evaporation for short time steps.

Unlike in CAM3, the relative humidity decreases throughout the troposphere in the ALL10 run, as shown in Figure 2. The decreases in the 800-850 hPa layer correspond to a significant reduction in low cloud mass (Figure 3). This suggests that the increase in precipitation is caused primarily by increased precipitation efficiency. At the same time, we see an increase in cloud liquid above the boundary layer, particularly at high latitudes. In the ALL10 run, the cloud fraction not only decreases at lower levels, where less liquid cloud is present, but also at higher levels, where the average cloud mass mixing ratios are similar to or greater than their values in CTRL (Figure 4).

Consistent with the decrease in overall cloud mass and fraction, the ALL10 run shows substantially reduced radiative cloud forcing compared with CTRL, as can be seen in Figure 5. The effect on shortwave cloud forcing is especially large, the global mean being reduced from -43.0 $\mathrm{W/m^2}$ to -37.5 $\mathrm{W/m^2}$.

Spatial-pattern differences between CTRL and ALL10 are summarized by a Taylor diagram shown in Figure 6. We find that the effect of reducing the model time step to 10 seconds (black symbols) is comparable to the effect of doubling the model's horizontal grid spacing (red symbols), a natural standard for comparison. Historically, spatial resolution changes have been perceived as a major model change while accompanying time step changes have been taken for granted; Figure 6 illustrates that this viewpoint has shortcomings. The variables most affected by the time step are related to precipitation, with the large-scale precipitation showing the most difference.

4.2 Effects of Changing the Physics Substepping

We did not have the computational resources to run all of our substepped configurations for multiple years, but many of the effects of substepping are quite large and can easily be distinguished with only a few days of data. Since all runs started with the same initial conditions, they followed a similar trajectory for the first 15 days before beginning to diverge, so we focused on comparing the runs during this time period. (In Figure 12, we have included data from 30 days, which shows an example of how, in these different runs, the global means of cloud-related variables become significantly less correlated towards the end of the month.)

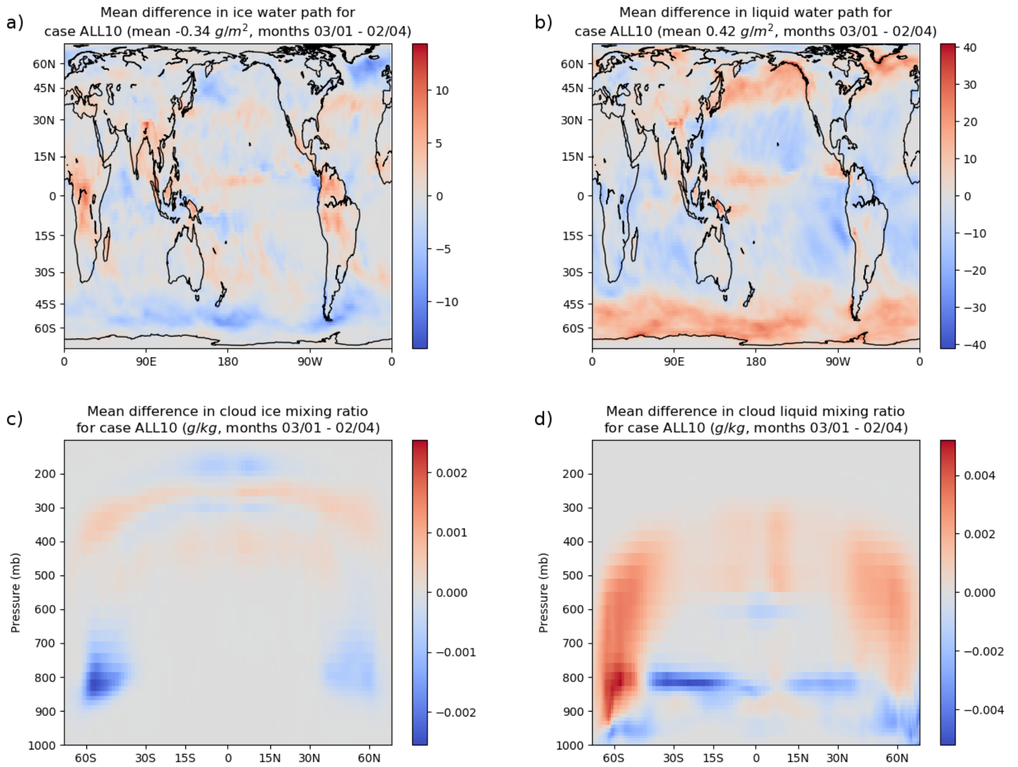

Figure 3. Differences in mass of cloud ice and liquid water between CTRL and ALL10 runs, measured by a) ice water path, b) liquid water path, c) zonal mean cloud ice mixing ratio, and d) zonal mean cloud liquid mixing ratio.

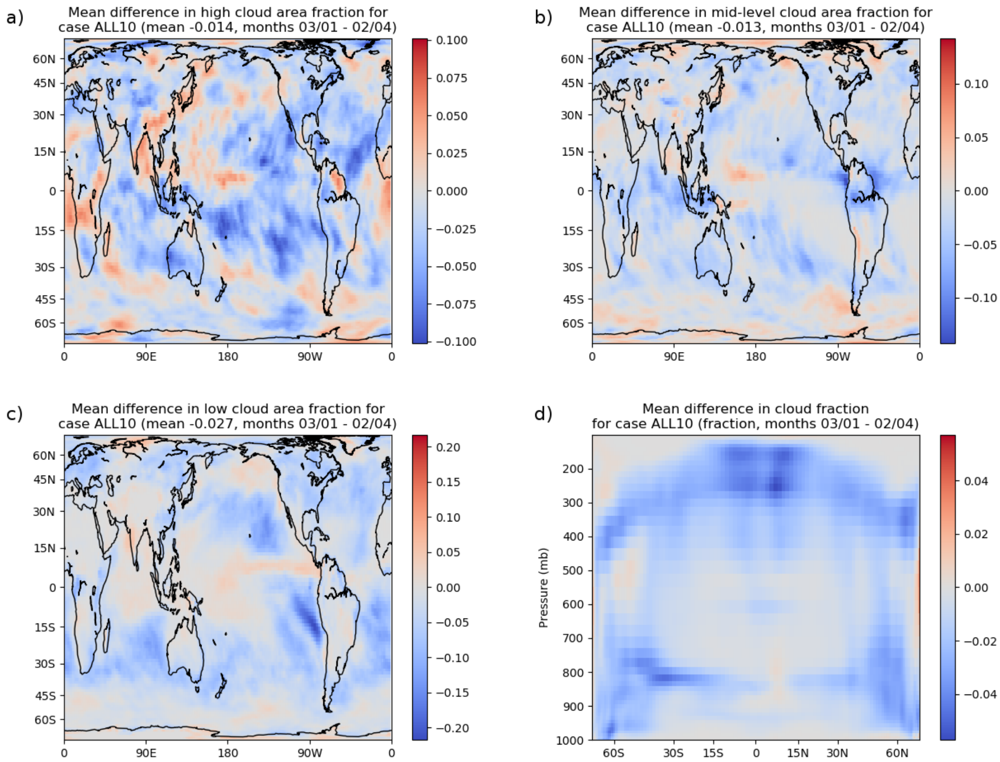

Figure 4. Differences in cloud fraction between CTRL and ALL10 runs: a) high cloud fraction (defined as the vertical integral above 400 mb), b) mid-level cloud fraction (vertical integral over the range 400-700 mb), c) low cloud fraction (vertical integral below 700 mb), and d) zonal mean cloud fraction at each level.

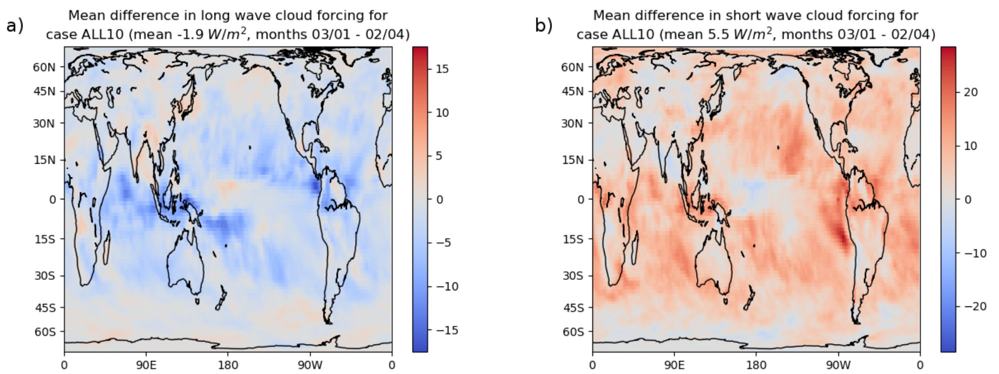

Figure 5. Differences in a) longwave cloud forcing and b) shortwave cloud forcing between CTRL and ALL10 runs.

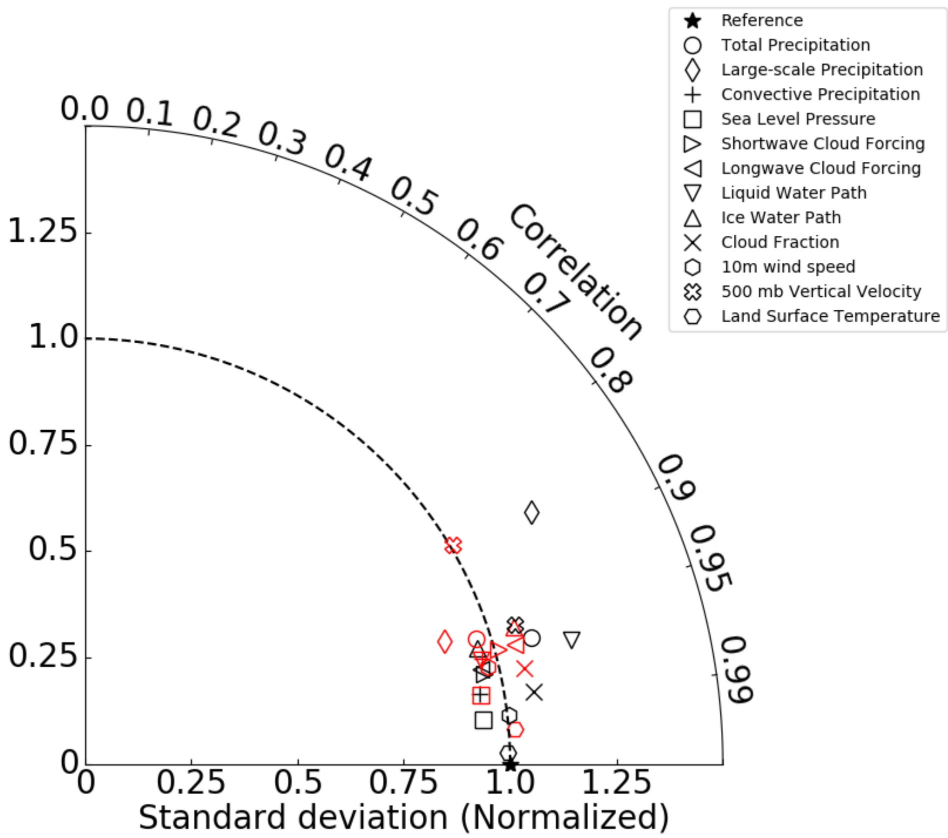

Figure 6. Taylor diagram comparing results from the CTRL and ALL10 runs (black), and comparing results from CTRL to a run with default settings using the ne16 grid (red), which has a grid spacing of ∼1.9°. This diagram uses values averaged over a three year time period starting March of the first simulated year for each run; only spatial variability is accounted for.

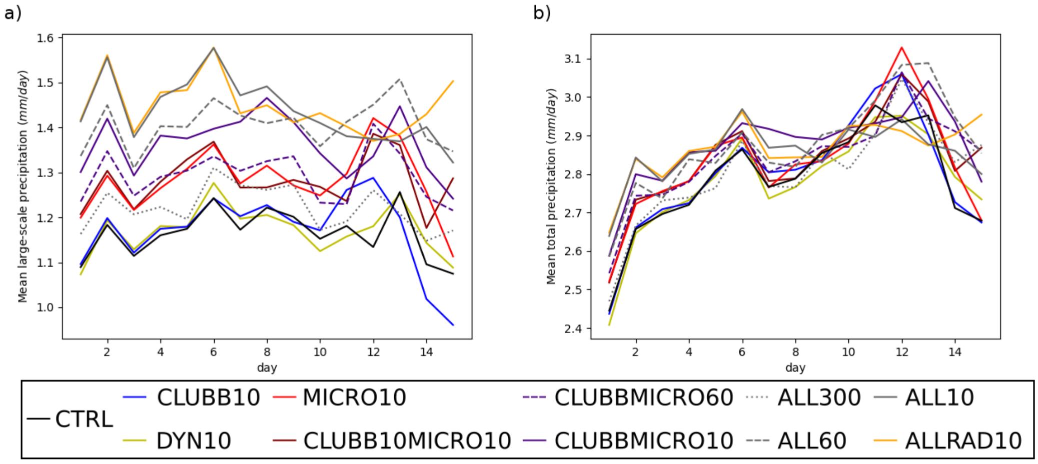

Figure 7. Daily global means of a) large-scale precipitation only and b) total precipitation for substepped runs.

We first examine the changes in precipitation across these runs, shown in Figure 7. We can categorize our runs into five main categories based on large-scale precipitation:

1. The lowest average large-scale precipitation rates are found in CTRL, CLUBB10, and DYN10, suggesting that the cloud physics is not sensitive to the CLUBB or dynamics time steps.
2. A slightly higher large-scale precipitation rate is found in the ALL300 run, which has a reduced time step for the ZM deep convection and an increased dynamics-physics coupling frequency, but does not change the CLUBB or MG2 time steps. This run shows a mild repartitioning of precipitation from the convective to large-scale category, perhaps consistent with the mechanisms described in Williamson (2013).
3. The MICRO10 and CLUBB10MICRO10 runs show signs of increased precipitation efficiency overall, increasing both large-scale *and* total precipitation.
4. One of the largest large-scale precipitation rates comes from CLUBBMICRO10, which couples CLUBB to MG2 every 10 seconds, suggesting that an increase in CLUBB-MG2 coupling frequency has an additional effect beyond that from simply substepping MG2 more frequently. CLUBBMICRO60 may see a similar effect, though it is not as clearly distinguished from the MICRO10 run.
5. The ALL10 and ALLRAD10 runs decrease both the dynamics-physics coupling time step and the time step used for all physics parameterizations, and these show the largest changes in precipitation.

While the increase in large-scale precipitation seen in the MICRO10 run is substantial, the spatial pattern is quite different from the ALL10 case, as seen in Figure 8. In particular, the patterns observed in the ALL10 case, such as the increase in large-scale precipitation over land, only appear when both CLUBB and MG2 are substepped together, as in the CLUBBMICRO10 case. We have also plotted the CLUBB10MICRO10 case, to show that this difference is not due simply to the reduction in the CLUBB time step alone.

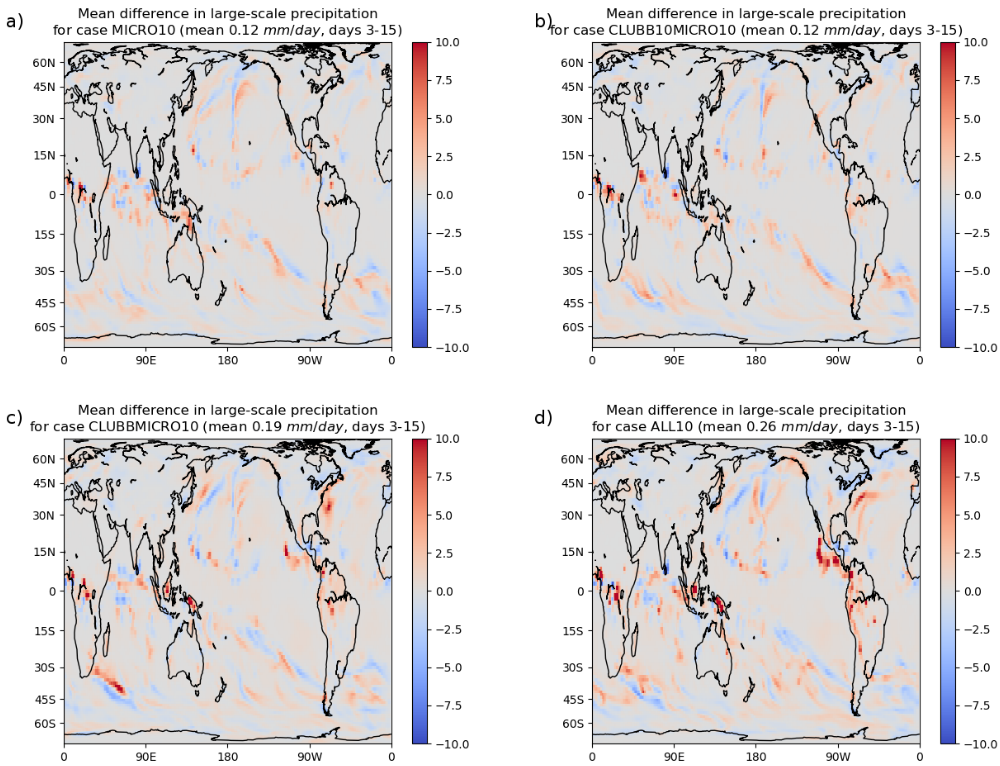

Figure 8. Differences in large-scale precipitation versus CTRL for a) MICRO10, b) CLUBB10MICRO10, c) CLUBBMICRO10, and d) ALL10.

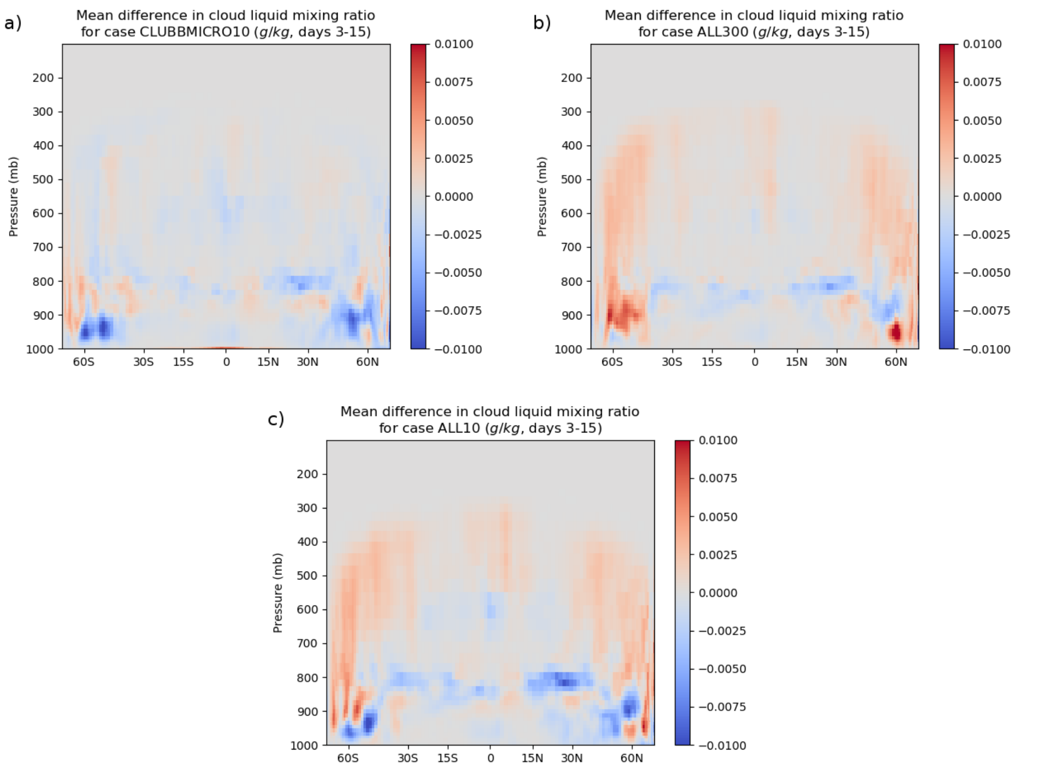

Figure 9. Differences in zonal mean cloud liquid mixing ratio versus CTRL for a) ALL300, b) CLUBBMICRO10, and c) ALL10.

Together, these results suggest that the main time steps affecting the precipitation are the MG2 microphysics time step and the coupling time step between the CLUBB and MG2 schemes. The change in the CLUBB and MG2 combined time step therefore explains most of the precipitation change noted earlier between the CTRL and ALL10 runs. Either the dynamics-physics coupling time step or the ZM deep convection time step could also be affecting the precipitation between the convective and large-scale processes, since both these time steps are changed in the ALL10 and ALL300 runs. We will investigate this further in Section 4.3. The changes in total precipitation are mostly apparent for the first week of the run, after which the runs with default MG2 time step see a significant increase in convective precipitation (not shown), leading to no systematic difference between simulations after this point.

The particular pattern of decreased relative humidity found in the ALL10 run also appears in the CLUBBMICRO10 run, but not the MICRO10 run (not shown). However, as shown in Figure 9, the cloud liquid in the CLUBBMICRO10 run only matches the ALL10 run at low altitudes, while the ALL300 run is much more effective at matching ALL10 at higher altitudes, suggesting that the dynamics-physics coupling time step is responsible for these increases in cloud liquid. The CLUBBMICRO10 also consistently produces clouds in the lowest level of the atmosphere over land, particularly in South America and Southeast Asia, which are not seen in any other run. This may be an artifact resulting from CLUBB and MG2 running at a time step much smaller than the atmosphere-land coupling interval.

The overall differences in ice and liquid water path are shown in Figure 10. We see that, in the tropics, the runs with reduced MG2 time step reduce the liquid water path

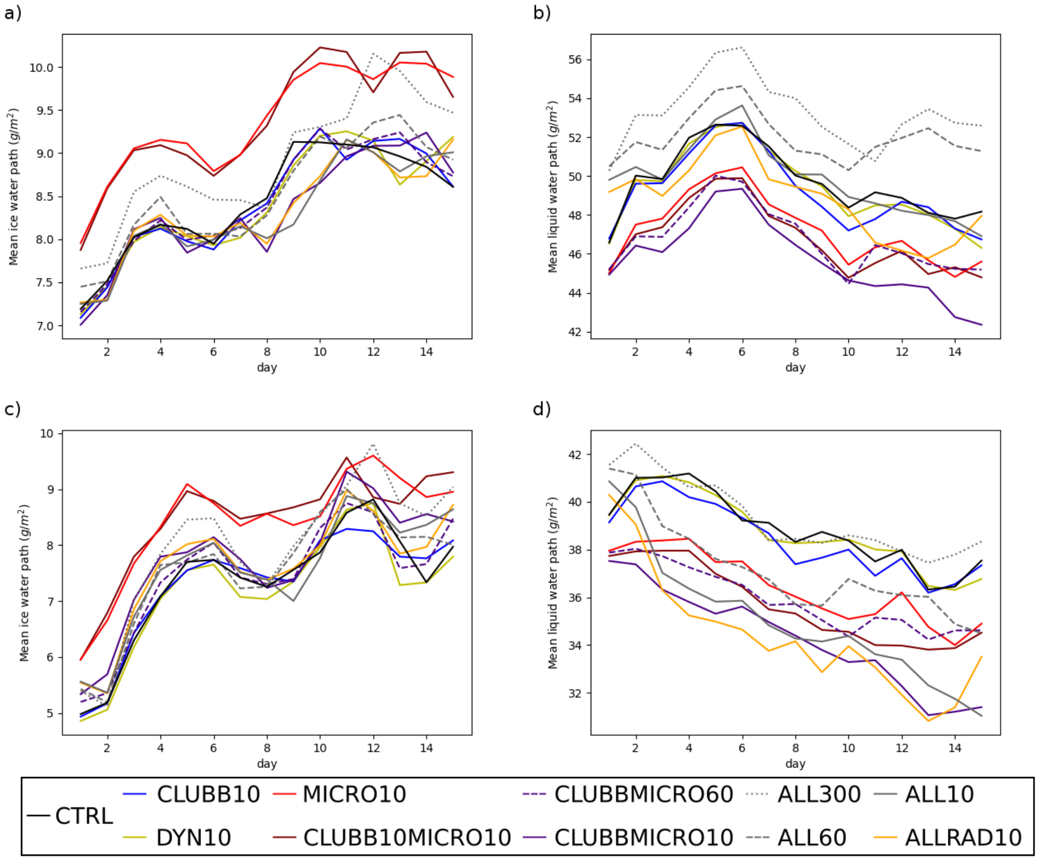

Figure 10. Daily means for a,c) ice water path and b,d) liquid water path for substepped runs. Plots a-b) show global means, while c-d) show means over low latitude grid points (30S–30N).

in a way that is similar to the ALL10 run, while the ALL300 run increases the ice and liquid water path everywhere. We also note that if MG2 is substepped independently from CLUBB, the ice water path increases significantly, but this does not occur when MG2 and CLUBB are substepped together.

We noted earlier that the ALL10 run caused a reduction in cloud fraction throughout most of the atmosphere, especially in the low cloud fraction. As shown in Figure 11, this effect seems to have different causes, depending on which level of the atmosphere is examined. Reductions in low cloud are primarily due to the reduction in the dynamics-physics coupling substep, but the CLUBB and MG2 combined time step has a greater effect on the cloud fraction above 700 mb.

Finally, we turn to the changes in radiative cloud forcing between runs. The magnitudes of both shortwave and longwave cloud forcing are reduced in the ALL10, ALLRAD10, CLUBBMICRO10, and CLUBBMICRO60 runs, likely due to the significant decreases in cloud fraction and liquid water path found in the tropics. The MICRO10 and CLUBB10MICRO10 runs, on the other hand, have a much larger ice water path, leading to an increase in longwave cloud forcing. The ALL300 run has both a reduced low cloud fraction and an increase in liquid and ice water path, leading to a decrease in shortwave cloud forcing and no net change in longwave cloud forcing.

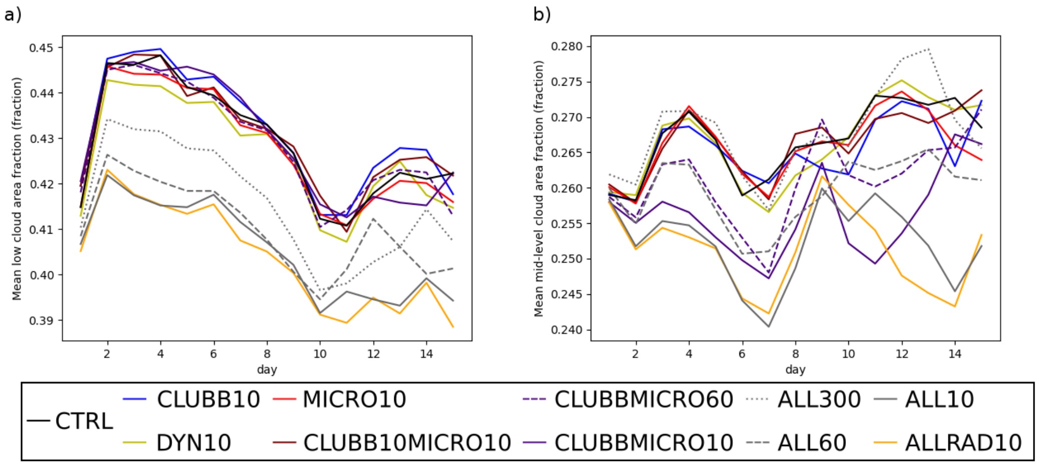

Figure 11. Daily global means of a) low cloud fraction (> 700 mb), and b) mid-level cloud fraction (400-700 mb) for substepped runs.

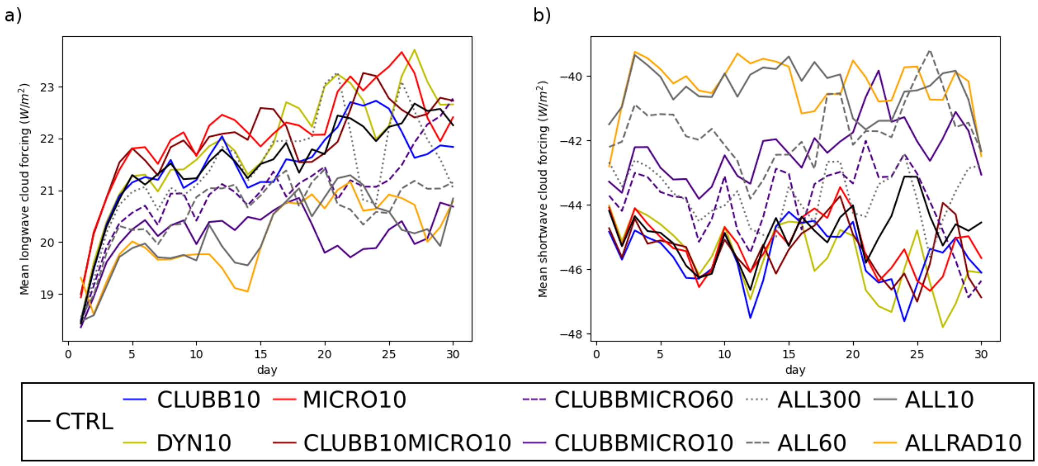

Figure 12. Daily global means of a) longwave cloud forcing and b) shortwave cloud forcing for substepped runs.

We notice that most variables take a few days for the differences between runs to fully develop, but the effect of a change in the MG2 time step strongly affects large-scale precipitation and ice water path within the first day. We suspect that most effects of a decreased time step require a certain degree of "spin up" in order for runs starting with the same initial condition to become more distinct. We hypothesize that the more instantaneous changes are primarily due to the direct effects of a decreased time step on microphysical process rates, which can respond directly and dramatically to changes in time step (Santos et al., 2020).

4.3 Substepping the ZM Deep Convection Scheme

So far, we have been unable to distinguish between the effect of substepping the ZM deep convection scheme and the effect of reducing the dynamics-physics coupling time step. In order to explore the effect of ZM substepping on results, we produced a simple set of code modifications to EAMv1 to allow this scheme to be substepped on its own. Most of these modifications are straightforward, since the main effect of ZM is simply to modify the state of the atmosphere for the next parameterization in the sequentially split physics. Two of ZM's outputs are precipitation process rates that are used by the modal aerosol scheme to calculate the total precipitation produced/evaporated by the deep convection. These rates are averaged over the whole time step in our modifications.

With this modified version of EAMv1, we were able to run the deep convection at a somewhat lower time step size, down to 300 s. However, the model becomes unstable if the ZM deep convection is a smaller time step (60 seconds or less) while the rest of the model runs at a default time step. Specifically, the wet deposition routines in the modal aerosols behave inappropriately, causing an unphysical increase in aerosol mass due to excessive water uptake, which in turn causes the aerosol optical depth to increase exponentially until the model crashes. Even in runs that did not crash, this behavior was present and had a significant impact on model physics. We were therefore unable to investigate the effect of ZM substepping further using the model's default configuration.

Fortunately, we do have an alternative, which is to run the model with prescribed aerosols, an ability commonly used for single column runs (Lebassi-Habtezion & Caldwell, 2015). This required switching to a configuration where prescribed aerosol data was available, so we used a year 2000 compset, FC5AV1C-04P2. As a result, these results cannot be directly compared to our previous runs, though we used the same spatial grid, and the physics of this compset is similar to our previous runs, aside from initial/boundary conditions. We reproduced the CTRL, ALL10, and CLUBBMICRO10 runs using prescribed aerosols, and further produced runs that substep ZM by itself, as well as runs that substep ZM and CLUBB/MG2 separately, and finally a run that substeps all three parameterizations. These simulations are summarized in Table 3.

First, we note that the CLD10PA run, which substeps the ZM deep convection along with CLUBB and MG2 in a single loop, has the same effect on the partitioning of precipitation as seen in the ALL10PA run, being even closer to those results than the CLUBBMICRO10PA run was. This difference can be seen in Figure 13, and suggests that the reduced ZM-CLUBB-MG2 coupling time step was responsible for the increased large-scale precipitation seen in the ALL300 and ALL10 runs in Figure 7. Figure 13 also shows that substepping ZM *by itself* has no effect on precipitation, since the ZM10PA run is similar to CTRLPA and the CLUBBMICRO10ZM10PA run is similar to CLUBBMICRO10PA. Williamson (2013) shows that the ZM scheme is not very active when coupled to other parameterizations at small time step sizes, when using a typical value of the convective relaxation time-scale (on the order of 1 hour, which is also the value in our experiments). We see the same shift from deep convection towards stratiform precipitation at short time steps.

Name	Substepped processes	Substep size	Run length
CTRLPA	None	N/A	30 d
ALL10PA	Dynamics-physics coupling	10 s	30 d
CLUBBMICRO10PA	CLUBB+MG2 combined loop	10 s	30 d
ZM10PA	ZM deep convection	10 s	30 d
CLUBBMICRO10ZM10PA	CLUBB+MG2 combined loop and ZM deep convection	10 s	30 d
CLD10PA	CLUBB+MG2+ZM combined loop	10 s	30 d

Table 3. Runs performed using prescribed aerosols

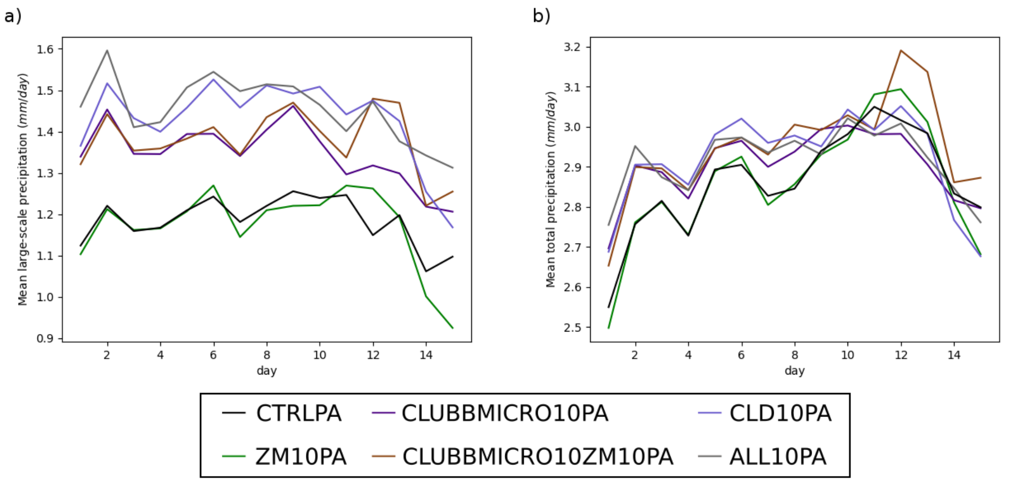

Figure 13. Daily global means of a) large-scale precipitation only and b) total precipitation for prescribed aerosol substepped runs.

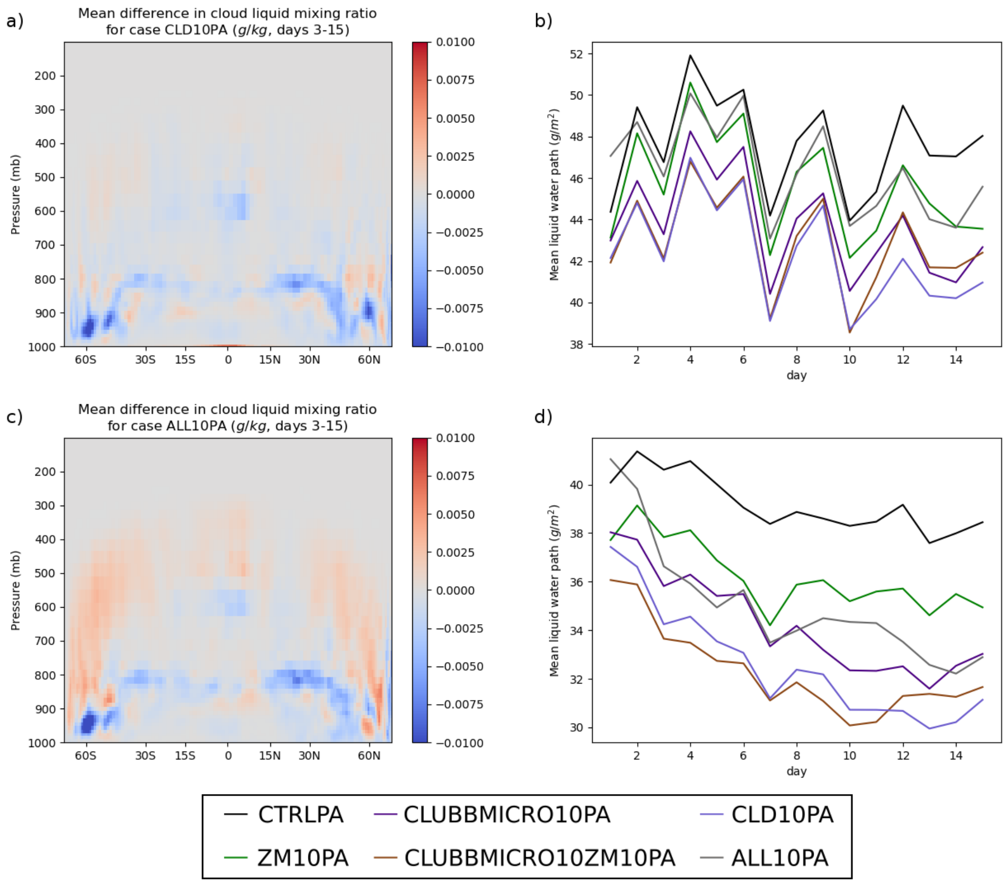

Figure 14. Left: Differences in zonal mean cloud liquid mixing ratio versus CTRLPA for a) CLD10PA and c) ALL10PA. Right: Daily liquid water path for prescribed aerosol substepped runs using b) a global mean, and d) a mean over low latitude grid points (30S–30N).

Second, we note that deep convection substepping, like substepping of the other parameterizations, causes a decrease in low cloud liquid mass, and contributes to the overall pattern seen in the ALL10PA run. This is seen in Figure 14, where the distribution of liquid water below 750 mb agrees quite well between the CLD10PA run and the ALL10PA run. However, the increase in cloud liquid above this level is still absent from the CLD10PA run, implying that that increase requires more frequent dynamics-physics coupling to occur. This means that the CLD10PA "overshoots" the ALL10PA run in the tropics, having an even lower liquid water path. Unlike the effect of ZM substepping on precipitation, the effect on cloud liquid does not rely on coupling with CLUBB and MG2, since the CLUBBMICRO10ZM10PA run (not shown) and the CLD10PA run have fairly similar liquid water path.

Other than this, ZM substepping accounts for very little of the differences between the CTRLPA and ALL10PA runs. There are small decreases in cloud fraction (not shown), but these are much weaker than the effect of increased dynamics-physics coupling frequency below 700 mb, and weaker than the effect of a smaller CLUBB and MG2 time step above 700 mb. The effect on shortwave cloud forcing, as seen in Figure 15, is thus also relatively small compared with the effect of changing the CLUBB and MG2 time step. The effect of ZM substepping on longwave cloud forcing may appear to be more significant, since the CLUBBMICRO10ZM10PA run has almost the same longwave cloud

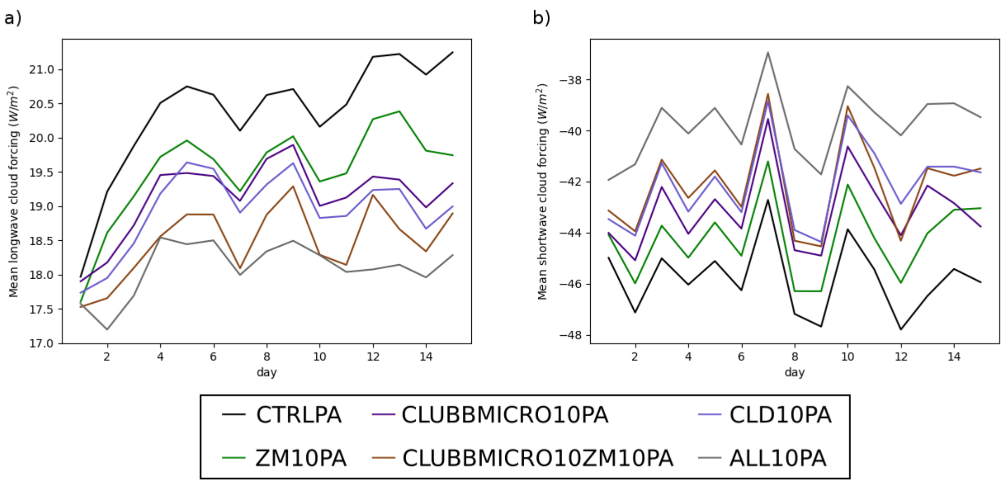

Figure 15. Daily global means of a) longwave cloud forcing and b) shortwave cloud forcing for prescribed aerosol substepped runs.

forcing as the ALL10PA run. However, the mechanism here is completely different; all runs where ZM is substepped, including CLUBBMICRO10ZM10PA, have a dramatically lowered ice water path (not shown). ALL10PA and CLUBBMICRO10PA, on the other hand, have an ice water path similar to the control, and so the decrease in longwave cloud forcing is instead attributable to decreased cloud fraction in these cases.

5 Conclusions

EAMv1 at its default 1800 second time step produces very different results from the same model at a 10 second time step, indicating that the release implementation should not be viewed as calculating the "time-resolved" solution to the system of equations that defines the model physics. The amount and regional distribution of precipitation, and especially the radiatively-important partitioning between large-scale and convective precipitation, shows particularly strong sensitivity to the time step size. The cloud radiative forcings also differ by several watts per square meter, indicating that a reduction in the time step would require, at a minimum, significant retuning of the model to produce reasonable results.

By experimenting with substepping of model components, we have been able to distinguish three main model time steps that account for most of the changes seen between the 1800s and 10s versions of the model. We briefly summarize these findings here.

First, a reduction of the combined CLUBB and MG2 time step causes the following changes:

1. An increase in total precipitation, leading to a reduction in humidity and a reduction in cloud liquid mass below 750 mb.
2. A reduction in the ratio of convective to large-scale precipitation.
3. Regional changes in precipitation, most notably including a massive increase in average precipitation on the maritime continent and in South America.
4. A reduction in cloud fraction above 700 mb, causing a large reduction in the magnitudes of both shortwave and longwave radiative cloud forcing.

The first two of these changes can be produced by changing the time step for MG2 alone, but substepping CLUBB and MG2 together produces a significantly larger effect.

Second, a reduction of the dynamics-physics coupling time step (a.k.a. dtime) causes the following changes:

1. An increase in cloud mass in the upper troposphere, especially in the midlatitudes.
2. A substantial decrease in cloud fraction below 700 mb, causing further large decreases in radiative cloud forcing, especially for shortwave radiation.

Third, a reduction of the ZM time step causes the following changes:

1. A further reduction in cloud liquid mass below 750 mb, though this corresponds to a reduction in net condensation minus evaporation, not an increase in precipitation.
2. A small decrease in cloud fraction everywhere, causing further small decreases in radiative forcings.
3. A further reduction in the ratio of convective to large-scale precipitation. (However, this only occurs when ZM is coupled more frequently with CLUBB and MG2, which in the original code can only be done by reducing dtime.)

These observations indicate that even when individual parameterizations seem to be well resolved in time, a low coupling frequency between parameterizations can still be a significant source of model error. This may be an underappreciated issue, since developers of new parameterizations tend to focus on the time step of their own particular parameterization rather than the frequency with which it is coupled to other parts of a model. For our case, while the MG2 and ZM parameterizations are each mildly sensitive to changes in time step, the majority of the time step sensitivity in E3SM is actually due to sensitivity to the coupling frequencies between different processes.

In EAMv1, most calculations in the dynamics and many physics parameterizations are already running at a five minute time step or less, even for lower resolution runs. Donahue and Caldwell (2020) found that for a 1° simulation, halving the dynamics-physics coupling frequency only increased model cost by 20%. Our ALL300 run had one-sixth the dtime of the CTRL run, but only required 66% more core-hours per simulated year. This raises the question: why not use a shorter time step for the dynamics-physics coupling for all runs? In the short term, this would likely require some significant retuning of existing models. In the long run, however, our results suggest that significant improvements could be attained by reducing the dynamics-physics coupling time step for future model development.

While simply reducing the model time step might be a reasonable way of dealing with E3SM's sensitivity to the dynamics-physics coupling frequency, the sensitivity to CLUBB+MG2 coupling is more difficult to address. CLUBB and MG2 together account for a large share of the model cost, so reducing their time steps by a factor of 30 could be around an order of magnitude slower than the default configuration. Since most modelers will not be able to accept such a large increase in computational cost, we can suggest a few other ways of working around this cost in future model development:

1. Reduce the cost of simulating the most expensive physical processes, e.g. by switching to simpler implementations of these processes. For instance, a model that uses a less accurate approximation for some process, but is able to run at a higher temporal or spatial resolution, may end up being more accurate than a model that uses a more accurate set of equations.
2. Use alternative (e.g. higher-order) time integration schemes to lower the time integration error at moderate time step sizes.

3. Redesign the physics to separate out processes that have a shorter or longer time scale. In the case of E3SM, this would mean refactoring CLUBB and MG2 (or any future set of schemes that cause similar issues), in order to isolate the parts of those parameterizations that are most responsible for the time step sensitivity of the overall model. If this subset of physical processes can be calculated much more cheaply than the total cost of CLUBB and MG2, it could then be handled with a more accurate time integration scheme without incurring an excessive cost.

In practice, errors coming from a coarse temporal resolution are often handled by simply tuning GCMs so that they match observations when run with longer time step sizes, just as models are tuned for a particular horizontal and vertical resolution. While this is an effective approach for many studies to match current climate observations, if a model relies heavily on tuning to cancel large numerical errors, it is unlikely to have the correct sensitivity to forcing changes. This is especially a concern for studies that use a model to simulate conditions very different from those originally used to tune that model (e.g. for paleoclimate).

We recommend that GCM developers continue to study time step sensitivity by running experiments with full model physics. Even when the effect of time step on each individual parameterization is well known, the effect of process coupling can affect model behavior in unpredictable ways. Most users cannot afford to use sub-minute time steps for the entire model, and therefore are likely using a model that is not achieving its own converged small-time-step behavior. Therefore it is important to understand the limitations and biases present in workhorse models that have been tuned for coarse time step sizes.

Acknowledgments
The data used in this paper will be made available using Argonne National Laboratory's Petrel service (data still being uploaded, URL to be added). Until the upload is complete, the data can be found in an xz-compressed tar file at:

`https://drive.google.com/file/d/1yENgyLnaUNBGhEMMx0u6vbivk5lcqDMC/view`

This tar file contains data files from all runs used in this paper, labeled using the following case names:

1. CTRL - timestep_ctrl
2. ALL10 - timestep_all_10s
3. ALL60 - timestep_all_60s
4. ALL300 - timestep_all_300s
5. DYN10 - timestep_dyn_10s
6. MICRO10 - timestep_MG2_10s
7. CLUBB10 - timestep_CLUBB_10s
8. CLUBB10MICRO10 - timestep_CLUBB_10s_MG2_10s
9. CLUBBMICRO10 - timestep_CLUBB_MG2_10s
10. CLUBBMICRO60 - timestep_CLUBB_MG2_60s
11. ALLRAD10 - timestep_all_rad_10s
12. CTRLPA - timestep_presaer_ctrl
13. ALL10PA - timestep_presaer_all_10s
14. CLUBBMICRO10PA - timestep_presaer_CLUBB_MG2_10s
15. ZM10PA - timestep_presaer_ZM_10s
16. CLUBBMICRO10ZM10PA - timestep_presaer_CLUBB_MG2_10s_ZM_10s
17. CLD10PA - timestep_presaer_cld_10s

The ne16 grid data used for Figure 6 is labeled with the case name timestep_ctrl_ne16. Data files are placed into the following directory:

1. timestep_monthly_avgs: Monthly average data sets for the CTRL and ALL10 runs. Data from the ne16 grid run is also in this directory, both on the original grid (h0 files) and regridded to ne30 resolution.
2. timestep_monthly_avgs_lat_lon: Monthly data regridded to a rectangular latitude-longitude grid with 1.4-degree resolution (used for plotting purposes).
3. timestep_daily_avgs: Daily average data sets for all runs (excepting the ne16 grid run) for the first 30 days of simulations.
4. timestep_daily_avgs_lat_lon: Daily data regridded to a rectangular latitude-longitude grid with 1.4-degree resolution (used for plotting purposes).

The code used to process the data in this study is available at:

`https://github.com/quantheory/E3SMTimestepStudy/tree/Santos_JAMES_2020`

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