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Key Points:

- High vertical resolution in the lower troposphere is a crucial ingredient to improve marine stratocumulus (Sc) in GCMs
- These simulations are expensive and require time step adjustment, which introduces sensitivities
- Vertical resolution alone cannot improve coastal Sc, likely concurrent increases in horizontal resolution are needed

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The Energy Exascale Earth System Model Simulations With High Vertical Resolution in the Lower Troposphere

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Abstract General circulation models (GCMs) are typically run with coarse vertical resolution. For example, the Energy Exascale Earth System Model (E3SM) has a vertical resolution of about 200 m in the boundary layer, which is far too coarse to resolve sharp gradients often found in the thermodynamic fields capping subtropical marine stratocumulus. In this article, we present a series of multiyear atmosphere only simulations of E3SM version 1 where we progressively increase the vertical resolution in the lower troposphere to scales approaching those often used in large eddy simulation (LES). We report marginal impacts in regards to the simulation of boundary layer clouds when vertical resolution is moderately increased, yet find significant positive impacts when the vertical resolution approaches that typically used in LES (∼10 m). In these experiments, there is a marked change in the simulated turbulence and thermodynamics which leads to more abundant marine stratocumulus. However, these simulations are burdened with excessive computational cost. They are also subject to degradations in overall climate metrics due to time step sensitivities and because some processes and parameterizations are sensitive to changes in the vertical resolution.

Plain Language Summary Models that are used to simulate and predict climate often have trouble representing specific cloud types, such as stratocumulus, that are particularly thin in the vertical direction. It has long been speculated that one of the reasons for this deficiency relates to coarse vertical resolution used in these models. In this study, we increase the vertical resolution to scales that previous process oriented studies suggest are needed to represent these cloud types. We find that increasing the vertical resolution is a necessary ingredient toward simulating stratocumulus, though deficiencies remain and the simulations are computationally expensive.

1. Introduction

Advances in computation are allowing General Circulation Models (GCMs) to be run with progressively finer horizontal and vertical resolutions. The first generation of climate models, in the 1980s, typically had less than 10 vertical levels with a model top of around 33 km and 4.4° × 7.5° horizontal resolution for their atmospheric components (Pitcher et al., 1983). Today's "workhorse" GCMs (those that are used to produce centennial long simulations) typically have around 30–100 levels in the vertical and 0.5°–1.0° horizontal resolution (Golaz et al., 2019; Hurrell et al., 2013; Held et al., 2019). In addition, many modeling centers support higher-resolution versions of their models (Caldwell et al., 2019; Gettelman et al., 2018), typically with 0.25° resolution in the horizontal, that are primarily used for shorter duration simulations than the standard workhorse versions. However, these higher resolution GCMs often use the same vertical resolution as their low-resolution counterparts.

While some studies have focused on the impact of vertical resolution sensitivity on various phenomena (Richter et al., 2014; Byrkjedal et al., 2008), ranging from the representation of Arctic inversions or the seasonal cycle of the extratropical temperature, the discussion of horizontal resolution generally receives more attention in the community of numerical models. An improved simulation of clouds and convection is one motivating factor toward increasing the horizontal resolution. Indeed, increasing the horizontal resolution often leads to better simulation in regards to tropical cyclones (Wehner et al., 2014) and improvements in precipitation where topographic effects may be playing a role, such as the summertime Indian monsoon simulation (Bacmeister et al., 2014). However, many studies also note stubborn persistence of certain cloud biases with horizontal resolution increases alone, such as the stratocumulus deficiency in eastern subtropical oceans (Caldwell et al., 2019).

Subtropical stratocumulus clouds strongly influence the global climate due to their radiative effects. These clouds form over oceans with relatively cold sea surface temperatures and are capped by strong inversions of temperature and moisture (Klein & Hartmann, 1993). The poor simulation of marine stratocumulus clouds is a problem that has long plagued GCMs, and remains a crucial problem given their strong relationship with climate sensitivity (Bony & Dufresne, 2005). While each generation of GCMs tends to provide modest improvements in regards to simulated marine stratocumulus due to better parameterizations (Bretherton & Park, 2009; Bogenschutz et al., 2013), the continuing trend is that most models underrepresent these stratocumulus clouds, even with very sophisticated higher-order turbulence parameterizations (Y. Zhang et al., 2019; Medeiros et al., 2012). If our parameterizations are becoming more sophisticated, and arguably more physical, then why does this not translate to more substantial impacts in regards to marine stratocumulus biases?

As already stated, most modern GCMs utilize 30 to 100 vertical layers. For example, the Department of Energy's (DOE's) Energy Exascale Earth System Model version 1 (E3SMv1; Golaz et al. (2019); Caldwell et al. (2019)) has a horizontal resolution of 1° and 72 vertical layers. Of these 72 vertical layers, 21 reside in the lower troposphere (between the surface and 700 hPa). In terms of vertical grid spacing, E3SM uses a stretched grid and has $\Delta z \approx 25$ m at the surface, $\Delta z \approx 125$ m near 850 hPa, and $\Delta z \approx 300$ m near 700 hPa.

The turbulence needed to sustain a subtropical stratocumulus boundary layer is generated at cloud top as a result of an abundance of radiative cooling occurring over a thin layer (Lilly, 1968). A coarse vertical grid has the tendency to entice too much entrainment of dry free tropospheric air into the cloud layer and promote cloud thinning, which reduces the cloud top cooling feedback needed to sustain the cloud (Bretherton & Coauthors, 1999). Considering that most LES studies have determined that to adequately resolve the inversion that caps stratocumulus topped boundary layers requires Δz of 5–25 m (van der Dussen et al., 2013; Stevens et al., 2005) throughout the boundary layer, it is therefore not surprising that even a theoretically perfect parameterization suite would not be able to properly simulate a stratocumulus topped boundary layer with a vertical grid similar to that of E3SM. Parameterization assesses sub-grid scale (SGS) processes with resolved scale quantities. When resolved quantities such as an inversion are biased, then the parameterization is unable to properly represent SGS processes.

E3SM uses higher-order turbulence closure (HOC), specifically the Cloud Layers Unified by Bi-normals (CLUBB, Golaz et al. (2002)) scheme, to serve as the unified moist turbulence, shallow convection, and macrophysics scheme. These HOC models have been shown to improve the representation of low clouds in GCMs, including a more gradual transition from stratocumulus to trade wind cumulus regime (Bogenschutz et al., 2013) compared to more traditionally used boundary layer and shallow convective schemes. However, in idealized single column model (SCM) and cloud resolving modeling (CRM) studies it has been demonstrated that these HOC schemes have a much better representation of marine stratocumulus clouds when the vertical resolution approaches that typically used for LES. For example, while Bogenschutz et al. (2012) found that the Community Atmosphere Model (CAM) coupled with CLUBB produces an improved simulation of stratocumulus and cumulus-under-stratocumulus regimes, compared to the control version of CAM when the standard 30 layer configuration was used, it wasn't until the vertical resolution was increased by a factor of four when cloud and temperature profiles more resembled those of observations and LES. Yamaguchi et al. (2017) found substantial improvements in the simulated stratocumulus layer for CRMs when physics processes (including CLUBB) were run at much higher vertical grid than dynamical processes.

In this study we address the sensitivity of the simulated marine stratocumulus in global simulations when we increase the vertical resolution of E3SM in the lower troposphere similar to that used in LES. We seek to address what improvement we can expect from vertical resolution alone when we do not consider other circumstances such as modifications to the parameterization suites or tuning; thus exposing HOC to vertical resolutions that it was optimized for in development.

This article is organized as follows: Section 2 describes the atmosphere component of E3SM, while Section 3 describes the various vertical resolution configurations as well as supplemental sensitivity experiments. Presentation of results resides in Section 4 with implications of these results discussed in Section 5.

Table 1
Description of the Principle Vertical Resolution Sensitivity Experiments Performed

Run Name	Levels	E3SM time step (s)	Microphysics and CLUBB time step (s)	Simulation Length (yr)
CNTL	72	1800	300	5
DOUB	92	1800	300	5
QUAD	132	1800	300	5
OCT	212	900	150	5

2. Model Description

The Energy Exascale Earth System Model version 1 (E3SMv1: Golaz et al. (2019)) is an Earth system model designed with funding by the Department of Energy (DOE) for research and applications relevant to its mission. The atmosphere model of E3SM (Xie et al., 2018; Rasch et al., 2019) was originally branched off from the National Center for Atmospheric Research's (NCAR's) CAM, but with many changes to its physics package. E3SM includes the CLUBB parameterization (Golaz et al., 2002) which unifies the treatment of planetary boundary layer turbulence, shallow convection, and cloud macrophysics. CLUBB is coupled to version two of the Morrison and Gettelman microphysics scheme (MG2; Morrison and Gettelman (2008); Gettelman and Morrison (2015)), while deep convection is treated using that developed by G. Zhang and McFarlane (1995) (hereafter ZM).

3. Experiment Design

All simulations presented in this article are run with 1° horizontal resolution, with only the vertical resolution in the lower troposphere and certain time step settings being different between experiments. All simulations are run with climatologically prescribed sea surface temperatures (SSTs). We recognize the implications and limitations of neglecting the SST feedback due to changes in clouds that occur in our experiments and provide further discussion in Section 5.

3.1. Principle Experiments

Table 1 summarizes the principle vertical resolution experiments performed in this article. The control experiment (CNTL) is E3SMv1 (Golaz et al., 2019) run out of the box with its default time steps and default configuration of vertical levels, which contains 72 staggered levels in the vertical.

The DOUB experiment (doubled vertical resolution in the lower troposphere relative to CNTL) contains 92 vertical levels, with the additional vertical levels placed solely in the lower troposphere between 995 hPa and 700 hPa, relative to the E3SM CNTL interface reference levels. We note that in the principle experiments we do not refine the lowest model level, the reasoning of which will be discussed in Section 3.2. To construct the DOUB grid we simply take the vertical grid of the CNTL simulation and halve each layer between 995 hPa and 700 hPa. The vertical grid for the QUAD (quadrupled vertical resolution in the lower troposphere, relative to CNTL) experiment halves each layer of the DOUB vertical grid between 995 hPa and 700 hPa, while the OCT (octupled vertical resolution in the lower troposphere, relative to CNTL) experiment halves each layer of the QUAD grid between 995 hPa and 700 hPa. This corresponds to 72, 92, 132, and 212 total vertical levels for CNTL, DOUB, QUAD, and OCT simulations, respectively.

All principle experiments are run for five years. In terms of computational cost, while CNTL, DOUB, and QUAD simulations have reasonable throughputs of 3.9, 1.9, and 1.3 simulated years per day (SYPD) when run on 1024 computational processing units (CPUs), the throughput for OCT is 0.37 SYPD. All simulations were run on the Livermore Computing cluster Syrah. Unlike the rest of the principle experiments, the OCT simulation required reductions in model time steps, which contributes toward the substantial cost. In this article and the companion paper of Lee et al. (2021), we will exploit reasons that required the time step reduction.

E3SM uses a stretched grid in the vertical, so that vertical resolution is finest near the surface, with levels that are defined on the pressure grid. Using hydrostatic assumption, we obtain approximate estimates for the vertical grid spacing (Δz). Figure 1 shows the estimated Δz for the simulations in this study between the surface and 700 hPa. While the maritime stratocumulus inversion top obviously exhibits variability based on location and seasonality, it generally occurs between 900 hPa to 850 hPa. At these layers, the E3SM control simulation has an average Δz of 135 m, whereas the DOUB simulation has an average Δz of about 70 m. The vertical resolution of the DOUB simulation is comparable to the vertical resolution used in the lower

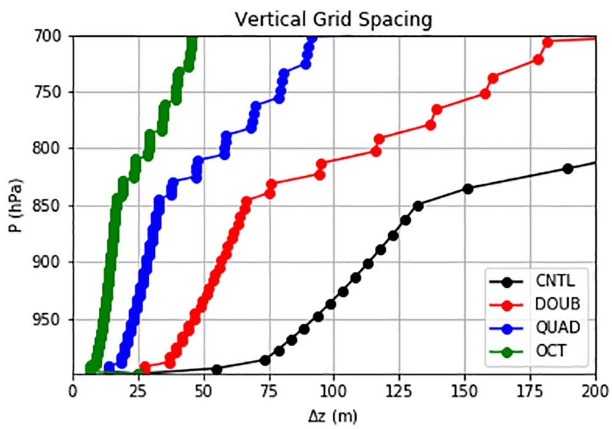

Figure 1. Estimated vertical grid spacing for the control (CNTL) simulation the various principle experiments described in Table 1 in the lower troposphere.

troposphere in many global cloud resolving models (Satoh et al., 2008). The QUAD simulation has an average Δz of about 35 m and is typical of the vertical grid spacing one might find in idealized and limited area cloud resolving models (Khairoutdinov & Randall, 2003). It is not until we get to the vertical grid used in the OCT simulation where we see vertical grid spacings representative of those typically used in LES studies of marine stratocumulus (van der Dussen et al., 2013; Stevens et al., 2005), with an average Δz of 15 m between 900 hPa and 850 hPa.

We note that none of the principle experiments were tuned in any way and that the differences between CNTL, DOUB, QUAD, and OCT are only due to the vertical grid and time step adjustments required to get a stable simulation. This was a conscience decision we made to most clearly elucidate the effects of vertical resolution.

3.2. Sensitivity and Supplemental Experiments

In addition to our principle experiments, we perform several experiments to explore possible sensitivities arising from differences in time steps and our choice of grid configuration. We also perform a higher vertical resolution supplemental experiment.

3.2.1. Sensitivities to Time Step

Table 2 describes our time step sensitivity experiments. As previously stated, our principle OCT experiment required reduction in time step to run stable. Wan et al. (2020) reports sensitivity of marine stratocumulus cloud to changes in E3SM time step. Therefore, to elucidate what effect time step could be playing on this simulation we perform an experiment using the CNTL 72 Layer grid but with the time step settings of the OCT simulation (experiment CNTL-T900). An additional experiment is performed where we run the 72 layer model, but with a 300 s E3SM time step (experiment CNTL-T300).

Finally, we perform simulation OCT-NODEEP, in which the OCT grid configuration is used but we turn off the ZM deep convection scheme. We run this simulation for a year with the default E3SM time steps. The purpose of this simulation is to assess what part of the E3SM model our time step constraint may be arising from.

3.2.2. Sensitivities to Grid Configuration

Table 3 describes the grid configuration sensitivity experiments. The 16XL simulation (16 time increase, or sexdecuple, vertical resolution in the lower troposphere relative to CNTL) is a higher vertical resolution simulation relative to our principle experiments, where each OCT vertical level is sliced in half between 995 hPa and 700 hPa. This results in an averaged vertical grid spacing of ~7.5 m within the lower troposphere and is close to the advised vertical resolution used in some LES studies such as Stevens et al. (2005).

Unfortunately, the 16XL simulation required large reduction of the model time steps. Not only does it make this simulation unwieldy expensive, which allows us to only perform two simulated years, but it also introduces large uncertainties in results due to sensitivities arising from the modified time step settings. Therefore, we only take a cursory look at results in this study. However, the companion paper of Lee et al. (2021) explores a 16XL configuration in E3SM where no time step reduction is needed.

Table 2
Description of Time Step Sensitivity Experiments Performed

Run Name	Levels	E3SM time step (s)	Microphysics and CLUBB time step (s)	Simulation Length (yr)
CNTL	72	1800	300	5
CNTL-T900	72	900	150	3
CNTL-T300	72	300	50	3
OCT-NODEEP	212	1800	300	1

As already discussed, the lowest model layer was not refined in our principle experiments. This is because refining the lowest layer also required large time step reduction for most configurations to achieve a stable solution. This time step constraint is presumably because the surface layer is where the surface fluxes are deposited in the model. We chose not to use these configurations in our principle experiments due to sensitivities of

Table 3
Description of Grid configuration Sensitivity Experiments Performed

Run Name	Levels	E3SM time step (s)	Microphysics and CLUBB time step (s)	Deep convective Timescale (s)	Simulation Length (yr)
CNTL	72	1,800	300	3,600	5
16XL	373	300	50	600	2
DOUB-LL	93	900	300	3,600	3
QUAD-LL	134	300	100	600	3
OCT-LL	216	300	100	600	2
OCT-UL	218	900	150	1,800	2

marine stratocumulus clouds arising from time step changes in E3SM, as documented by Wan et al. (2020). Thus we decided on a vertical resolution configuration that required a minimum time step adjustment so that differences could primarily be attributed to changes in the vertical grid. However, we do present a series of short duration experiments where the lowest model layers are refined to demonstrate that the overall conclusions obtained by our principle experiments are not sensitive to this choice. In Table 3 these simulations are denoted as DOUB-LL, QUAD-LL, and OCT-LL.

We note that in the 16XL, QUAD-LL, and OCT-LL experiments where the E3SM time step was substantially reduced, we chose to reduce the deep convective timescale to keep the deep convection scheme sufficiently active (G. Zhang & McFarlane, 1995; Wan et al., 2020).

Finally, in our principle experiments we only refine reference levels between 995 hPa and 700 hPa, while leaving layers in the mid and upper troposphere untouched. To alleviate concerns that this sharp grid transition may be influencing our results, we perform two years of experiment OCT-UL, which adds additional levels between 700 hPa and 550 hPa to allow for a more gradual transition from the high resolution boundary layer to the relatively low vertical resolution mid-troposphere.

4. Results

Table 4 displays the top of atmosphere radiation budgets for the principle experiments. Since these simulations use present day forcing, we cannot expect a near zero top of atmosphere energy balance. The E3SM CNTL simulation shows an energy balance of about 2.77 Wm^{-2}, with a globally averaged shortwave cloud radiative effect (SWCRE) value of −44.91 Wm^{-2} and longwave cloud radiative effect (LWCRE) of 22.86 Wm^{-2}. We note that the untuned principle experiments fall within 1 Wm^{-2} of the E3SM CNTL for all three budget terms. This indicates that only minor retuning would be necessary should these experimental configurations be integrated in fully coupled climate simulations, which could have some minor impact on the results presented here.

4.1. Low Cloud Climatology

Figures 2a and 2b display the low cloud climatology for the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observation (CALIPSO, Cesana and Chepfer (2013); Chepfer et al. (2010)) and E3SMv1, respectively. We note that our E3SM simulations use the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al. (2011)), which contains several independent satellite simulators and diagnoses model clouds in a similar way that these instruments would view an atmosphere. This allows for an apples-to-apples comparison when evaluating simulated low cloud climatology with observations. Figure 2c displays the low cloud climatology bias for E3SM, computed relative to CALIPSO observations. It is clear that the largest bias occurs in the subtropical stratocumulus regions, over the cool waters on the western side of the continents. This bias is most pronounced off the coast of California, Peru, and Namibia; with less prevalent biases occurring off the coast of Northern Africa and Australia. For all locations these biases are present for both the near coastal and offshore stratocumulus (or "core" regions of stratocumulus as defined in Klein and Hartmann (1993)).

Table 4
Top of Atmosphere Radiation Budgets for Experiments Performed

Run Name	Restom ($W m^{-2}$)	SWCRE ($W m^{-2}$)	LWCRE ($W m^{-2}$)
CNTL	2.7	−44.9	22.8
DOUB	3.2	−45.1	23.0
QUAD	3.2	−45.2	23.2
OCT	3.5	−43.8	22.6

What is the effect of lower tropospheric vertical resolution on the low cloud climatology? To answer this we examine Figures 2c–2f, which display the evolution of the geographical biases, root mean squared errors (RMSE), and correlation coefficients of the DOUB, QUAD, and OCT simulations computed relative to CALIPSO observations. Each simulation demonstrates a successive reduction in the RMSE, primarily due to the reduction of the stratocumulus biases. In addition, correlation coefficients also improve modestly as vertical resolution increases. In terms

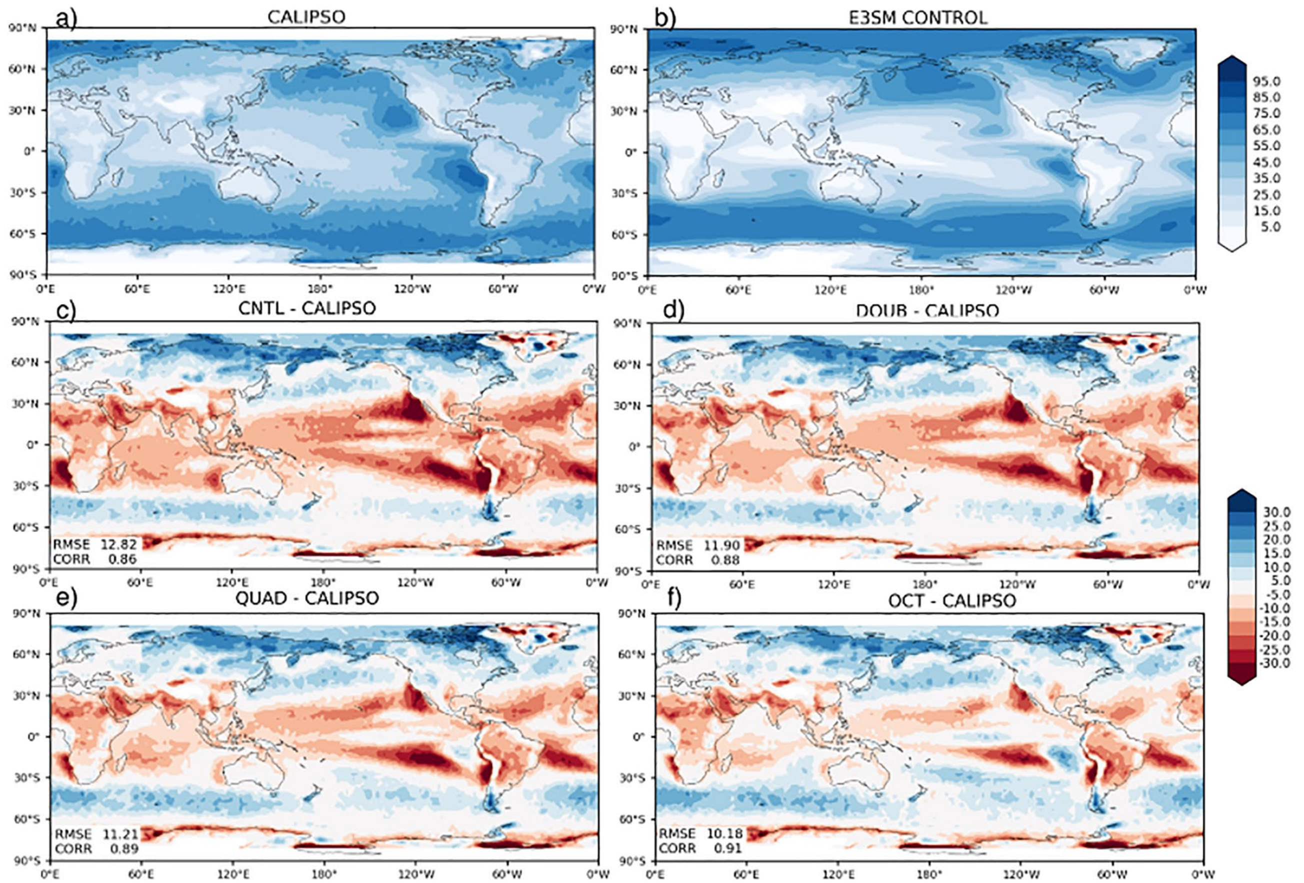

Figure 2. (a) Low cloud amounts from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) from January 2007 to January 2010 and (b) E3SM control simulation. (c)–(f) The biases for CNTL and the principle experiments, with the correlation coefficient and root mean squared error (RMSE) denoted for each simulation.

of geographical bias reduction, we can clearly see that the DOUB simulation has very little impact toward increasing the low cloud amount in these marine stratocumulus areas, whereas the QUAD simulation demonstrates marginal impacts. On the other hand, once we run E3SM with LES-like vertical resolution in the lower troposphere with the OCT simulation, we begin to see large decreases in the low cloud biases.

The evolution of biases in Figure 2 clearly demonstrates that most of the low level cloud amount increases tend to occur for the offshore core stratocumulus, rather than the coastal stratus. With this said, there is a noticeable reduction of the bias for most coastal stratus when LES-like vertical resolution is achieved. The Californian and Namibian coastal Sc exhibit monotonic bias reduction with increased resolution, while the Peruvian coastal region has more nuanced improvements. However, this also suggests that vertical resolution increases alone may not be enough to ameliorate biases in these regions. We speculate that horizontal resolution increases, in addition to vertical resolution increases, are warranted for further coastal Stratocumulus (Sc) bias reduction. This is an area of research that should be explored in the future.

To more clearly see the impact on the simulated low cloud climatology due to vertical resolution, we examine Figure 3, which displays the geographical differences of each experiment simulation relative to CNTL. This depiction more clearly demonstrates that LES-like vertical resolution is needed to achieve significant impacts for the simulation of low level cloud amount relating to marine stratocumulus, while merely doubling the vertical resolution has a negligible impact.

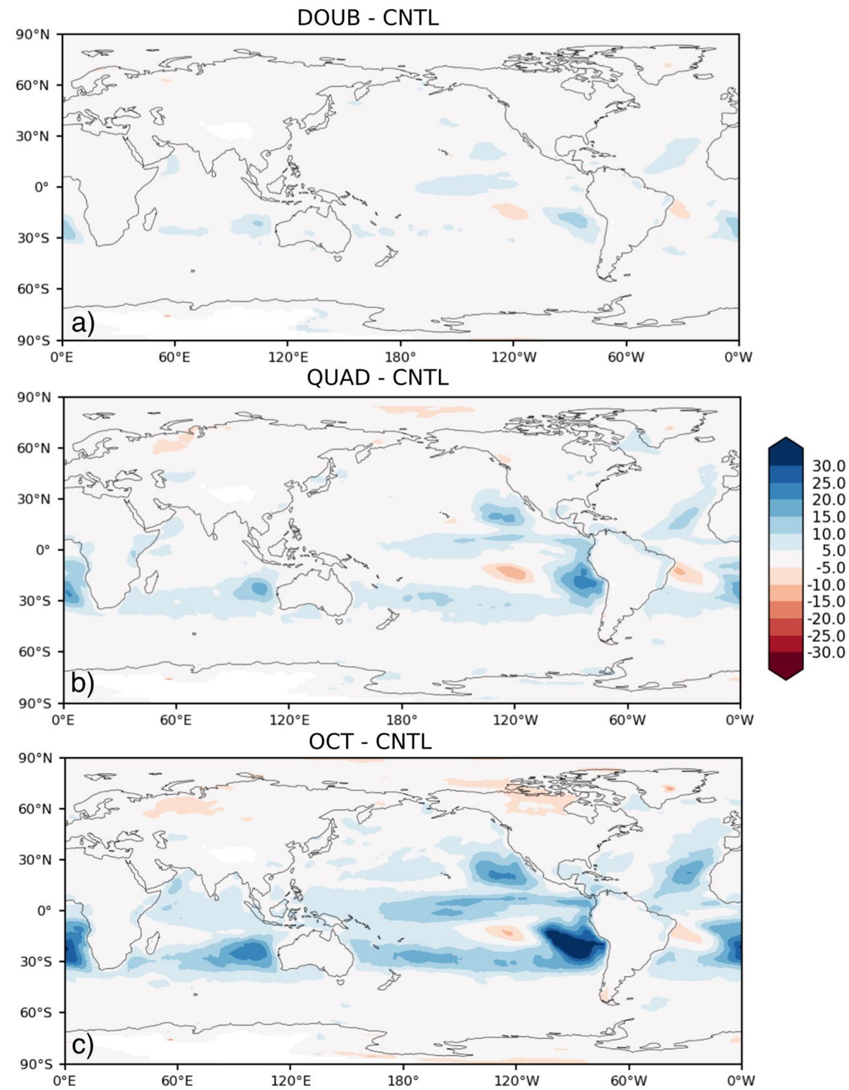

Figure 3. Low cloud amount differences computed relative to CNTL for (a) DOUB, (b) QUAD, and (c) OCT principle experiments.

There are a few interesting behaviors in Figure 3 worth pointing out. While there are some differences seen in the low cloud amount in areas of the tropics, typically characterized by deep convection, the high vertical resolution in the lower troposphere only has large impacts in the areas characterized by maritime stratocumulus. Outside of these areas, the principle experiments show little sensitivity to the vertical grid. This includes the southern ocean and northern hemisphere storm tracks, which are areas typically characterized by high amounts of low cloud cover. Though, these are also areas where E3SM CNTL slightly overestimates the low cloud amount.

Figure 3 also suggests that there is more impact on the low cloud amount due to vertical resolution in the Peruvian and Namibian Sc regions as compared to the Californian Sc region. This is interesting since Figure 2 suggests that the Californian Sc bias is arguably the most severe compared to other regions, yet exhibits the least amount of improvement. Furthermore, we see that although the simulation of offshore "core" stratocumulus is mainly improved in the OCT simulation, there are only modest improvements in the simulation of coastal Sc.

To quantify differences in the stratocumulus regions, Figure 4 displays the RMSE and bias for the Peruvian, Californian, and Namibian regions as defined in Klein and Hartmann (1993) (see caption text for exact

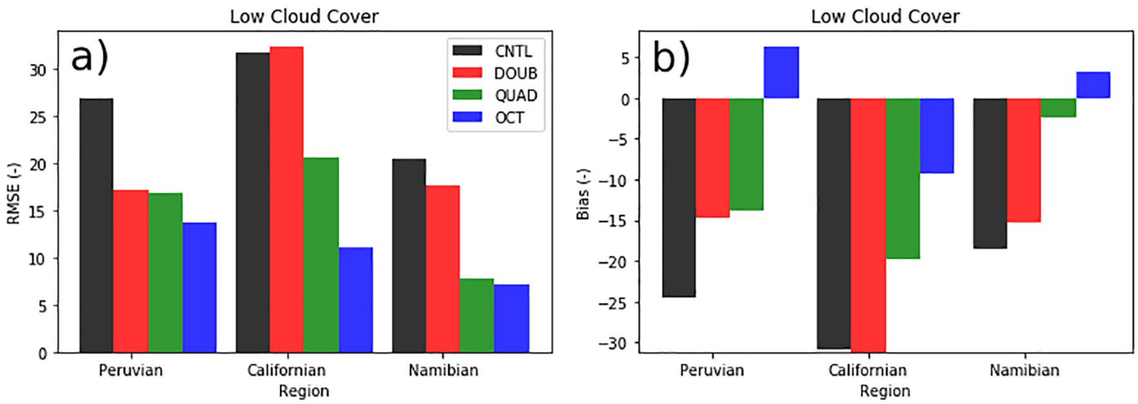

Figure 4. (a) Root mean squared error (RMSE) and (b) bias computed relative to CALIPSO observations for the low cloud amounts for three stratocumulus regions for each principle experiment. The California region is defined as the area bounded by 20°N to 30°N and 230°E to 240°E, the Peruvian region is defined as the area bounded by 20°S to 10°S and 260°E to 270°E, and the Namimbian region is defined as the area bounded by 20°S to 10°S and 0°E to 10°E.

latitude/longitude bounds). In terms of RMSE, the three regions generally show increasing skill for each region as resolution increases, with the OCT simulation performing the best for all regions. For the Peruvian and Namibian regions, the OCT simulation is an outlier in the regards that it is the only configuration to show a net positive bias. The Californian region shows that the OCT simulation has the closest bias to zero but still underestimates the low cloud cover, as seen in Figures 3 and 2.

We are most concerned with the simulation of low clouds because of their impact on shortwave radiation, thus we examine the biases of the SWCRE in the CNTL run in Figure 5, computed relative to the Clouds and Earth's Radiant Energy System (CERES) Energy Balance and Filled (EBAF) product. Similar to the low cloud bias, here we see that E3SM CNTL shows behavior of clouds that are not reflective enough in the marine stratocumulus regions. This is a classic bias that is characteristic of most GCMs. The bias in E3SM tends to be most severe closest to the coast in all subtropical Sc regions and is the most pronounced for the Peruvian region. E3SM CNTL also exhibits substantial SWCRE biases outside of the subtropical stratocumulus regions, such as the Tropical Pacific warm pool, Arctic, and the midlatitude storm tracks.

Figures 5c–5f display the geographical bias, RMSE, and correlation coefficient of SWCRE for each principle experiment computed relative to CERES-EBAF. Here we see fairly large reductions of SWCRE biases in the OCT simulation for most of the subtropical stratocumulus regions. Again, the bias reduction is most prominent (and sometimes overdone) for the offshore "core" stratocumulus and more muted for coastal stratocumulus, though there are noticeable reductions in these areas when comparing the OCT simulation to other experiments. Unlike the analysis for low cloud cover, the RMSE does not decrease for each progressive increase in resolution, where the OCT simulation has a higher RMSE than the QUAD simulation. This is likely because of the increased bias in SWCRE for the Tropical Pacific warm pool that is counteracting improvements seen in the low cloud regions.

Figure 6 displays the geographical differences between each experiment simulation relative to CNTL. While the DOUB simulation shows little radiative impact, the OCT simulation with its LES-like vertical resolution in the lower troposphere starts to show large regional impacts relative to CNTL. Locally, the OCT simulation shows a reduction of 50 Wm^{-2} for Peruvian offshore stratocumulus, indicating the clouds are more reflective compared to the CNTL run. While the Namibian region also shows a large reduction in terms of SWCRE for the OCT simulation, the Californian region is more resistant to change with vertical resolution. Outside of the stratocumulus regimes, we note that the OCT simulation shows a large decrease of SWCRE in the Tropical Pacific warm pool. The reasoning for this sensitivity seems to stem from the deep convection scheme and is further exploited in Section 3.2 and the companion paper of Lee et al. (2021).

The bias and RMSE focused on the specific stratocumulus regions is presented in Figure 7. Despite a RMSE that is worse globally for the OCT simulation versus the QUAD run, here we see that the simulation with LES-like vertical resolution has the lowest error for all three major stratocumulus regions. While the bias of SWCRE is closest to zero for the OCT simulation for Californian and Namibian regions, the OCT simulation

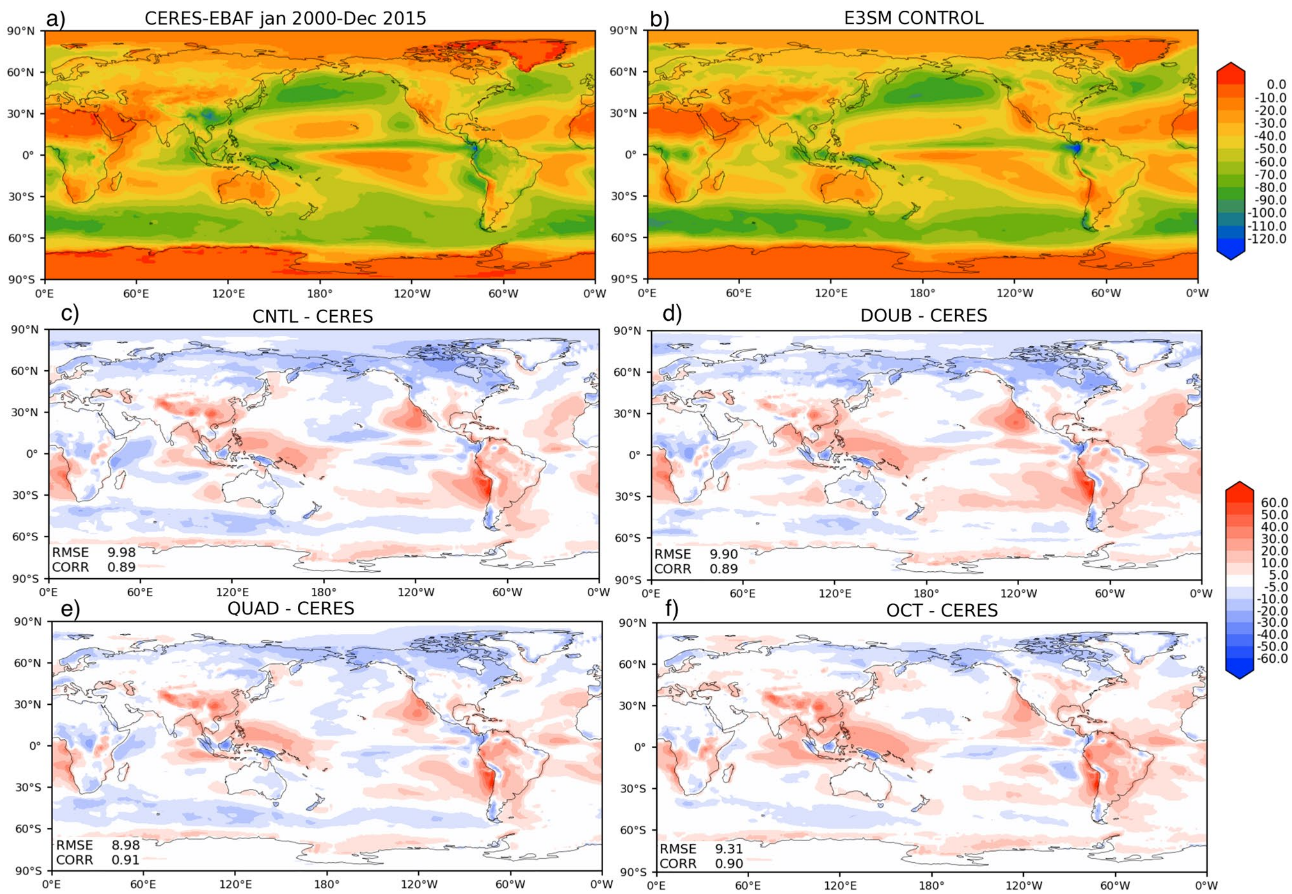

Figure 5. Same as Figure 2 but for shortwave cloud radiative effect (SWCRE). CERES-EBAF serves as the observational reference.

exhibits a negative bias of nearly equal magnitude to the positive bias seen in the DOUB and QUAD simulations for the Peruvian region. This is consistent with Figure 5 that shows the OCT simulation is perhaps too aggressive toward improving the positive SWCRE bias. As previously noted, while improvements are seen for Californian Sc with increasing resolution, the errors and bias are much higher than other regions.

These climatological results agree with the idealized case studies of Bogenschutz et al. (2012) and Cheng et al. (2010) which shows that models and higher order turbulence closure parameterization represent marine stratocumulus best at high vertical resolution. However, since E3SM is a GCM with many complex parameterizations that feedback to the model, one may speculate about the effect very high vertical resolution may be having on these parameterizations and the solution.

Gettelman and Morrison (2015) investigated the sensitivity of the MG2 microphysics parameterization to vertical resolution, in the context of an SCM, and found little sensitivity in the solution going from the CAM standard 30 layer model to a configuration using 25 m. Though at very coarse resolutions, which we do not investigate in this study, a sensitivity is noted. The RRTMG radiation is another scheme, which uses maximum/random assumption for cloud overlap, where a sensitivity to vertical resolution could exist since there could potentially be more frequent occurrence of gaps between cloud decks and thus more randomly overlapped clouds. However, some studies (Räisänen, 1998) demonstrate that maximum/random overlap assumption tends to greatly reduce vertical resolution sensitively compared to other overlap assumptions.

While the large scale vertical advection in the dynamical core does not have stringent time step limitation due to the semi-Lagrangian methods employed, this does not necessarily mean it is immune to time step sensitivity. This raises concerns on the possibility of mass and trace constituents being evacuated from a layer when layer thickness is decreased and time step held constant. To alleviate these concerns, we performed time step sensitivity experiments using the E3SM Single Column Model (Bogenschutz et al., 2020)

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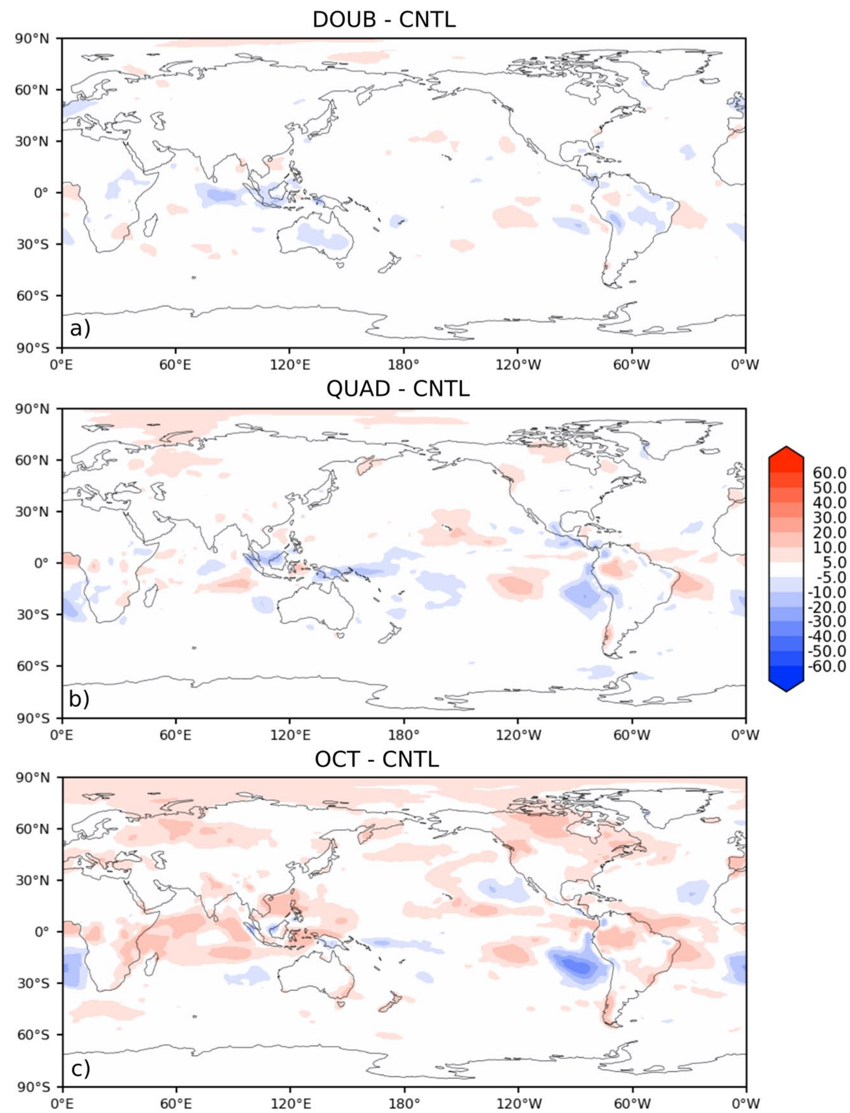

Figure 6. Same as Figure 3 but for SWCRE.

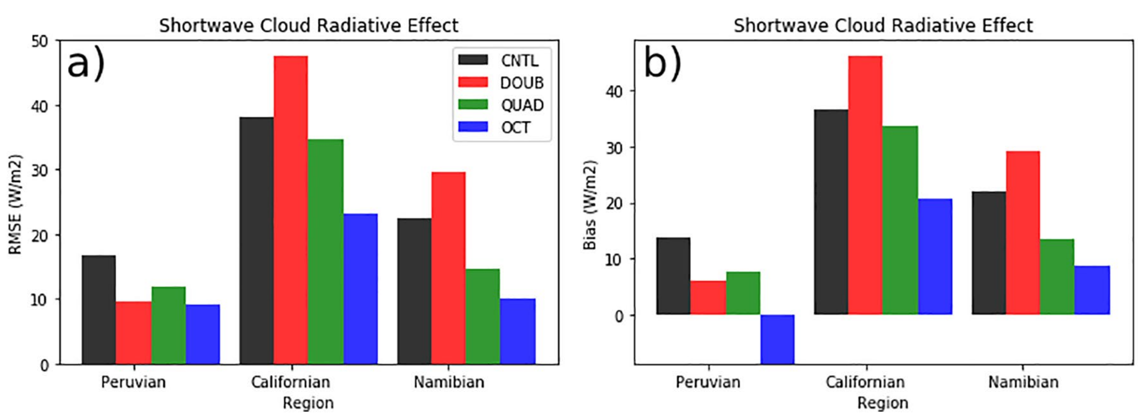

Figure 7. Same as Figure 4, but for SWCRE.

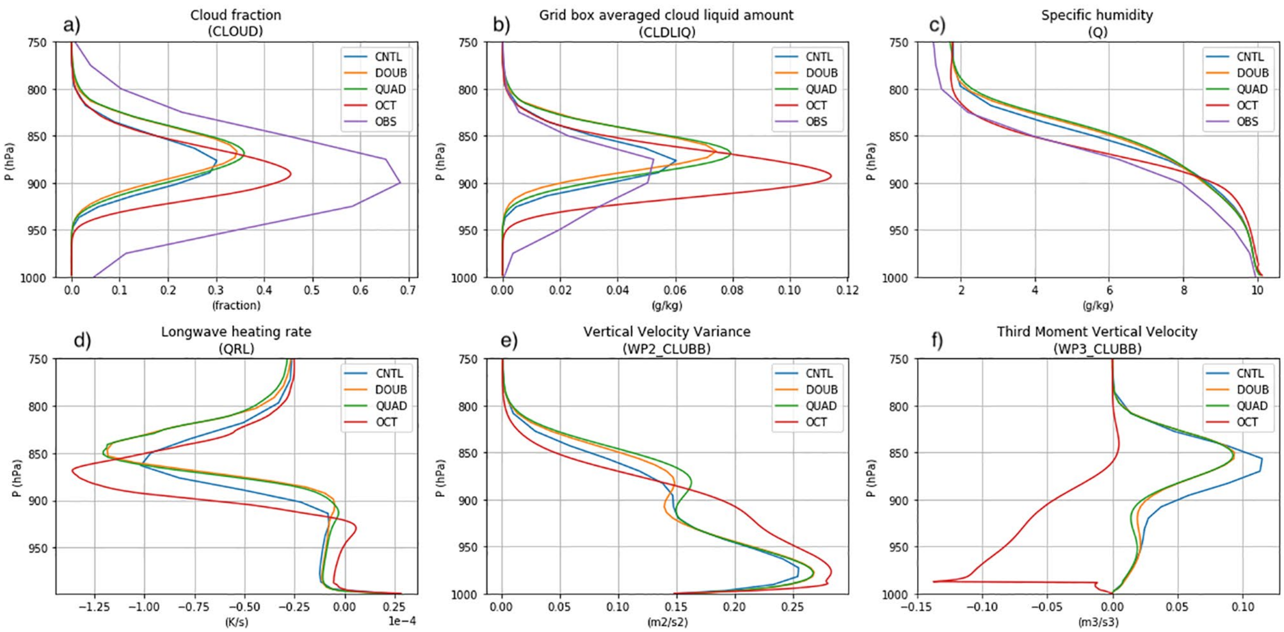

Figure 8. Temporarily averaged profiles from September, October, and November for (a) cloud fraction, (b) cloud mixing ratio, (c) specific humidity, (d) longwave heating rate, (e) second moment of vertical velocity, and (f) third moment of vertical velocity for CNTL and the principle vertical resolution experiments. CALIPSO, CloudSat, and Moderate Resolution Imaging Spectroradiometer (MODIS) (C3M Kato et al. (2010)) observations are used for cloud fraction and cloud liquid water, while Era-Interim is used as the observational guidance for specific humidity. Profiles displayed are from the Peruvian stratocumulus area bounded by 20°S to 10°S and 260°E to 270°E.

and the OCT vertical grid. We found virtually no sensitivity for the stratocumulus regime we investigated whether we used the dynamics and vertical remapping time steps in this article (225 s) or time steps that were a factor of three smaller (75 s).

4.2. Cloud and Turbulence Vertical Structure

Previous sections have demonstrated that LES-like vertical resolution in E3SM can result in more abundant simulation of marine stratocumulus, but how do these clouds and the associated turbulence differ when examining the vertical structure? In this section, we examine the select profiles of various quantities for the Peruvian region, which demonstrates large climatological impacts to vertical resolution, and the Californian region, which demonstrates considerably less improvement as vertical resolution increases.

Figure 8 shows the spatiotemporally averaged profiles of cloud fraction, cloud liquid mixing ratio, specific humidity, long wave heating rate, vertical velocity variance, and the third moment of vertical velocity for the Peruvian region for the September, October, November (SON) time period; when stratocumulus is most numerous for this area. The profiles of cloud fraction and cloud liquid mixing ratio includes observational guidance provided by CALIPSO, CloudSat, and Moderate Resolution Imaging Spectroradiometer (MODIS) in a merged product called C3M (Kato et al., 2010). Overall, CNTL tends to produce too little cloud fraction compared to the C3SM observations, but produces a peak cloud liquid water amount that is fairly comparable to observations. Thus, the radiational biases in the CNTL experiment appear to stem from Sc clouds that are simulated to be too few in amount.

In terms of the cloud structure, the DOUB and QUAD simulations are quantitatively similar to that of CNTL, though the cloud fractions and liquid water amounts are somewhat more plentiful. On the other hand, the OCT simulation exhibits behavior that is quite different from the other simulations, with much larger cloud fractions and liquid mass. In addition, the height of the maximum climatological fraction and mass has been lowered, relative to the other simulations, to more closely match observations. However, it should be noted that the OCT simulation still underpredicts the cloud fraction while severely overpredicting the magnitude of the cloud liquid amount. In addition, while C3M observations shows cloud below 950 hPa, all E3SM simulations maintain a climatologically cloud free mixed layer.

The profiles of specific humidity are accompanied by the European Center for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) for reference. While the CNTL, DOUB, and QUAD simulations produce very similar profiles, only the OCT experiment can simulate an inversion height similar to that of ERA-Interim. However, it is important to note that the OCT simulation produces a much more climatologically well mixed sub-cloud layer as compared to ERA-Interim. This behavior could be a contributing factor as to why the model refuses to simulate near surface cloud, as seen in the C3M observations. Since the OCT experiment produces more abundant cloud fraction and cloud liquid water amounts, it is therefore not surprising that this simulation produces stronger cloud top radiative cooling rates (Figure 8d).

The vertical velocity variance ($\overline{w'^2}$) and the third moment of vertical velocity ($\overline{w'^3}$), both of which are predicted by the CLUBB parameterization, provide information on the differences in turbulence between these simulations. The climatological $\overline{w'^2}$ for CNTL, DOUB, and QUAD simulations looks very similar to each other with two defined peaks, one in the sub-cloud layer and another within the cloud. Counter to this, $\overline{w'^2}$ for the OCT simulation is not only a fair amount stronger than the lower resolution simulations, but contains one peak within the boundary layer. Although observational guidance is not available for this quantity, this suggests that OCT, climatologically, is simulating an inherently different boundary layer regime than the remainder of the configurations. Whereas a double peaked structure in $\overline{w'^2}$ is more characteristic of a decoupled cumulus layer, a single peaked structure is what one would expect from a coupled stratocumulus layer (Stevens et al., 2005).

This point is further highlighted by examining $\overline{w'^3}$, in which the OCT simulation produces negative values in contrast to the lower resolution simulations which produce positive values throughout the boundary layer. Negative values of $\overline{w'^3}$ indicate that the OCT simulation is parameterizing stratocumulus with few but narrow downdrafts within this region. This is consistent with our understanding of stratocumulus where the majority of the turbulence is generated at cloud top due to longwave radiational cooling. The lower resolution simulations, on the other hand, produce positive values of $\overline{w'^3}$, which is indicative of few but narrow updrafts within this region and is more characteristic of a shallow cumulus regime. This indicates a rather profound regime shift in the OCT simulation, relative to the lower vertical resolution counterparts.

Therefore, since the OCT simulation is able to better resolve the cloud top inversion (Figure 8c), this leads to a more accurate representation of the height of maximum cloud amount and liquid (Figures 8a and 8b), which generates more abundant radiational cloud top cooling (Figure 8d). This stronger cloud top cooling encourages the turbulence of the boundary layer to be primarily driven from cloud top. In the absence of ample cloud fraction and liquid, an abundance of solar radiation reaching the surface during the daytime could cause the turbulence generation to be surface driven, leading to the decoupled profiles of $\overline{w'^2}$ and positive values of $\overline{w'^3}$ seen in the lower resolution simulations (Figures 8e and 8f), which are more indicative of a shallow cumulus boundary layer. The negative and neutral values of vertical velocity skewness (defined as: $(\overline{w'^3} \ / \ \overline{w'^2})^{3/2}$) simulated by the OCT experiment can further feedback to encourage more cloud generation because the macrophysics parameterization in CLUBB is a function of the vertical velocity skewness (Golaz et al., 2002). In other words, the near zero values of vertical velocity skewness parameterized by OCT within the cloud will directly result in more cloud fraction and cloud liquid compared to the positive values simulated in the lower resolution counterparts.

While not shown, the profiles displayed in Figure 8 are quantitatively similar to those of the Namibian region, which is a region that also demonstrates much improved low cloud climatology for the OCT simulation (see Section 4.1).

Now we examine the same profiles for the Californian region (for the period of June, July, August), which demonstrated considerably more resistance to change with increases to vertical resolution (Figure 9). It is interesting to note that much of the characteristics observed for the OCT simulation found in the Peruvian region can be applied to the discussion for the Californian region, but to a much lesser extent. In regards to

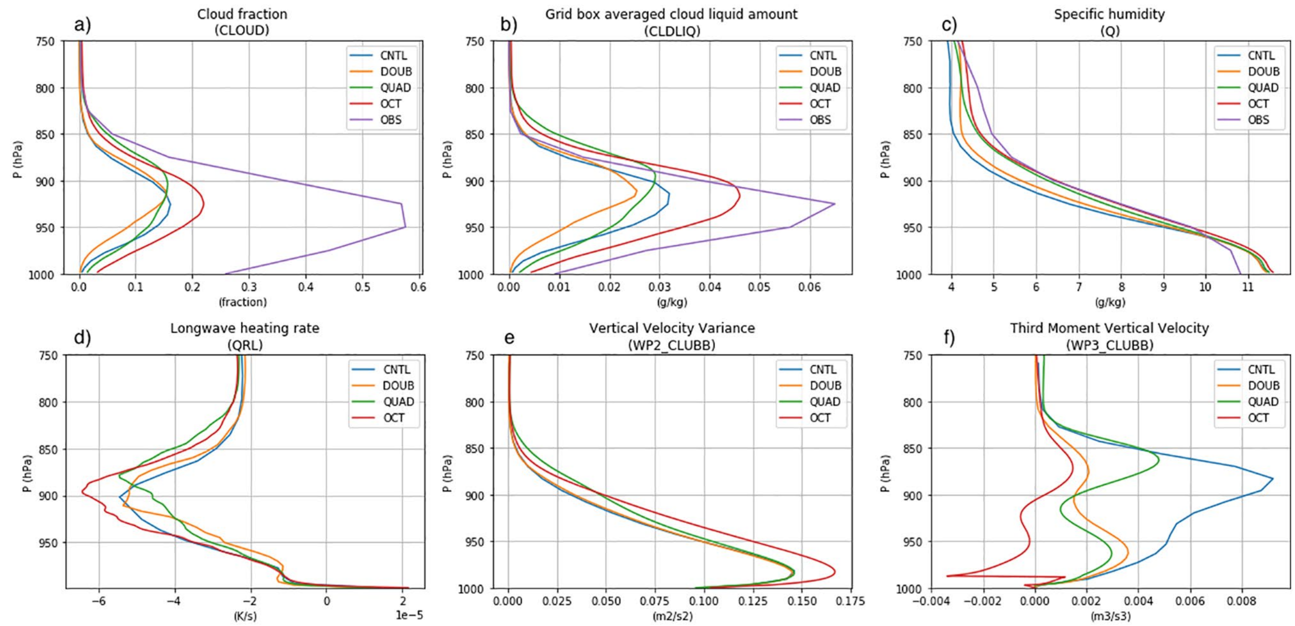

Figure 9. Same as Figure 8 but for June, July, and August and for the Californian stratocumulus area bounded by 20°N to 30°N and 230°E to 240°E.

the simulation of clouds, the OCT simulation certainly produces cloud liquid mixing ratios in better agreement with C3M observations, but severely underpredicts the cloud fraction. However, the climatological vertical structure of the simulated cloud is generally comparable to observations. It is worthwhile to note that CNTL and DOUB simulations do not predict any surface based cloud, as C3M does, but the QUAD and especially OCT do. However, the increase of cloud mixing ratio at the surface for these configurations is accompanied by miniscule increases in the cloud fraction, suggesting an overestimation of the in-cloud condensate amount.

We note that while the differences in the simulated turbulence ($\overline{w'^2}$ and $\overline{w'^3}$) profiles are not quite as dramatic as in the Peruvian region between the experiment simulations, the profile of $\overline{w'^3}$ for the OCT experiment shows the characteristic near zero or negatively skewed values that are typical of marine stratocumulus. One speculates whether the Californian Sc region is a location where even higher vertical resolution is needed for more substantial improvements. This question will be addressed in Section 3.2 and the companion paper of Lee et al. (2021).

We also note that the profound differences seen in this (and previous) analysis for the OCT simulation are not related to the changes in time step settings (see Table 1). We examined the turbulence profiles from various time step setting experiments (see Table 2) and found no evidence that the time steps produce any significant changes in the behavior of the simulated turbulence (not shown).

4.3. General Climatology

Although the focus of this article has been to evaluate how subtropical marine stratocumulus clouds respond with aggressive increases in vertical resolution, it is also important to analyze what effect this has on the mean state climate. We note that we do not intend this section to be exhaustive, yet point out the most significant and interesting differences of the higher vertical resolution simulations compared to CNTL.

Table 5 provides the RMSEs for each configuration and for several climatically important variables, to gauge an assessment on the overall fidelity of the climate simulation. Given that the higher vertical resolutions are not tuned and they are compared to CNTL, which has been extensively tuned, it is therefore expected that RMSEs for most of the experiment configurations will experience some level of degradation. Consistent with results presented in previous sections, we see that variables most directly related to low clouds

Table 5
RMSE for Various Atmospheric Quantities

Variable	Obs. Source	Units	CNTL	DOUB	QUAD	OCT
Low-level cloud amount	CALIPSO	%	12.8	11.9	11.2	10.18
Mid-level cloud amount	CALIPSO	%	7.3	7.3	7.5	7.9
High-level cloud amount	CALIPSO	%	7.9	8.0	8.0	9.0
SWCRE	CERES-EBAF	W m^{-2}	9.6	9.5	8.9	9.3
LWCRE	CERES-EBAF	W m^{-2}	6.7	8.2	8.0	9.0
TOA Albedo	CERES-EBAF	-	0.03	0.03	0.03	0.03
Global Precip Rate	GPCP	mm day^{-1}	1.1	1.1	1.3	1.6
Global Precip Water	MERRA2	mm	2.6	2.3	2.1	2.3
Land 2-m air temperature	CRU-IPCC	K	2.3	2.4	2.4	2.5
850-hPa temperature	ERA-I	K	1.1	1.2	1.2	1.2
200-hPa temperature	ERA-I	K	2.5	2.4	2.3	2.0
Sea level pressure	ERA-I	mb	3.2	2.7	2.9	2.4
Liquid water path (ocean)	SSMI	g m^{-2}	47.2	45.2	42.2	41.7
Surface latent heat flux	WHOI-OAFlux	W m^{-2}	27.3	27.8	26.7	30.9
Surface sensible heat flux	WHOI-OAFlux	W m^{-2}	11.3	11.2	10.9	10.9

(Low-level cloud amount, SWCRE, liquid water path over the ocean) generally see a decrease in RMSE as the vertical resolution increases. However, there are degradations in regards to the longwave cloud radiative effect (LWCRE) and high-level cloud amounts. The most notable increase in RMSE as resolution increases is the global precipitation rate, which is a metric of great interest when assessing GCM performance.

To exploit the differences in the simulated precipitation rates, we present biases with respect to the Global Precipitation Climatology Project (GPCP) observation dataset in Figure 10. By this depiction we see that the degradation in precipitation skill is due to an increase in the precipitation rate in the tropics; namely over topography and the maritime continent. In addition, areas which are too dry in CNTL (e.g., equatorial Atlantic, Amazon, and Tropical Pacific warm pool) become even drier as the vertical resolution increases. This degradation of tropical precipitation is consistent with the degradation of SWCRE seen in the tropics in the previous sections.

Figure 11 presents the zonal averages of the total precipitation rate, as well as the contributions from the convective precipitation and large-scale precipitation rate. It should be noted that E3SM uses a unified turbulence and shallow convective scheme (CLUBB) that is coupled with the MG2 microphysics scheme. Therefore shallow convective precipitation is included in the large-scale precipitation rate and the convective precipitation rate represents precipitation generated solely by the ZM deep convection scheme. While the zonal average of precipitation from all experiments generally exhibits the same behavior, we see profound differences in the partitioning of precipitation.

As vertical resolution increases we see a gradual increase in the large-scale precipitation rate and a decline in the convective precipitation rate, with the OCT simulation producing nearly 2.0 mm day^{-1} more large-scale precipitation in the tropics versus the control simulation. By this analysis, it is not clear if this shift in partitioning and degradation of precipitation skill scores as vertical resolution increases represents a sensitivity arising from the deep convection scheme itself or due to a sensitivity from the CLUBB and/or microphysical parameterizations, or the interactions between the parameterizations. Section 3.2 and the companion paper of Lee et al. (2021) will examine this sensitivity with more conclusive results.

Figure 12 displays the zonal mean averages for SWCRE, LWCRE, liquid water path (LWP), and ice water path (IWP). We present these variables because they represent quantities that exhibit some inherent differences as the vertical resolution increases. Focusing on the SWCRE and LWCRE (Figures 12a and 12b), we compare against the CERES-EBAF observations. Consistent with Figure 5f, we see that the OCT run

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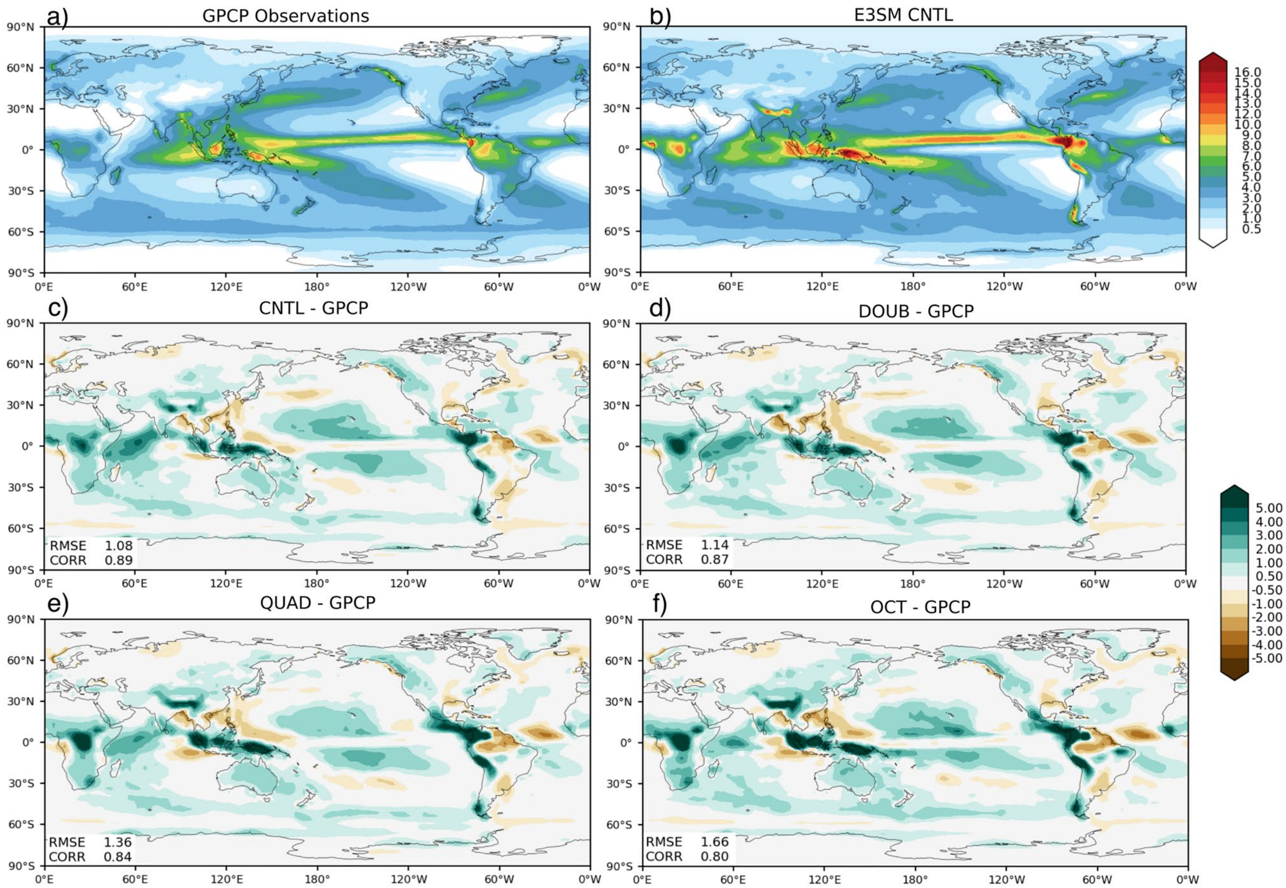

Figure 10. Same as Figure 2 but for surface precipitation rate. The Global Precipitation Climatology Project (GPCP) serves as the observational reference.

generally decreases the magnitude of the SWCRE in the tropics. This is also reflected in the analysis of LWCRE, where the OCT simulation tends to exacerbate the LWCRE bias exhibited by the other models. This is in general agreement with previous analysis that shows that increasing the vertical resolution, without tuning, tends to degrade the climate in the deep convective tropics.

Interesting behavior in the partitioning between liquid and ice is seen when examining the LWP and IWP in Figures 12c and 12d. Here we see the tendency for the higher vertical resolution simulations to produce significantly more/less liquid/ice in the storm tracks relative to CNTL. The opposite is true in the tropics, where increasing the vertical resolution tends to increase IWP. In addition, the Arctic sees a fairly large reduction of LWP, which likely explains the decreased SWCRE seen in the Arctic in Figure 5f for the OCT simulation. These partitioning differences in the mid and high latitudes are interesting and could potentially represent a sensitivity in the microphysics that could be explored in future work.

4.4. Sensitivity Experiments

4.4.1. Time Step Sensitivity

For our principle experiments, we strived to maintain time step settings as close to E3SM CNTL as possible, so we could evaluate differences solely due to vertical resolution without introducing uncertainties of time step sensitivity. Unfortunately, for the OCT simulation this was not possible as E3SM with the OCT vertical grid and default E3SM time steps crashed after 23 steps. Our strategy to decrease the time step was to achieve a stable simulation using as little computational resources as possible. Through trial and error the configuration we converged on was a reduction of the E3SM time step to 900 s and a reduction of the microphysics and CLUBB time steps to 150 s (experiment CNTL-T900). We note that we were also able to achieve

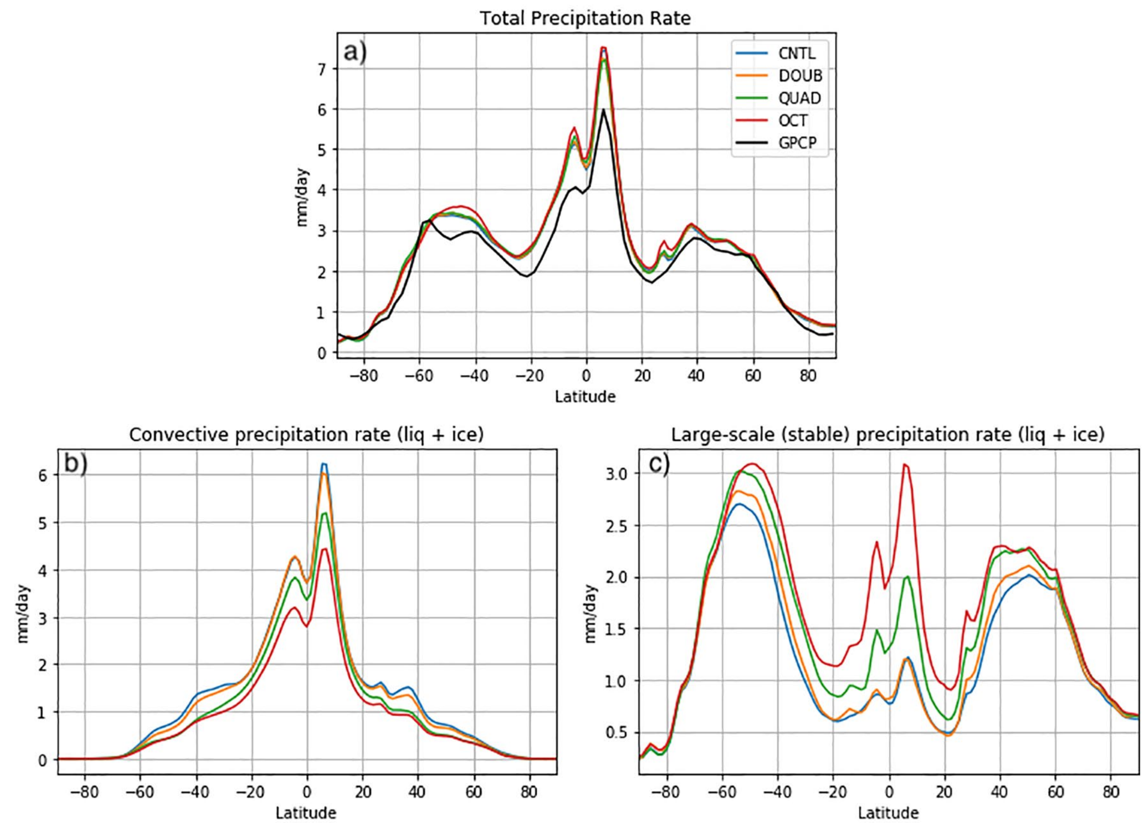

Figure 11. Zonally averaged (a) total surface precipitation rate, (b) contribution from convective precipitation, and (c) contribution from large-scale precipitation for CNTL and the principle vertical resolution experiments.

a stable simulation with the E3SM time step set to 600 s while preserving the microphysics and CLUBB time step at 300 s. However, this simulation was more computational intensive than the former.

We run CNTL-T900 simulation to help elucidate the possible effects of reducing the time step in our OCT simulation. Figure 13a displays the differences in SWCRE for this experiment simulation compared to CNTL. We see that reducing the time step in E3SM leads to a reduction of marine stratocumulus cloud, primarily driven by a reduction in the cloud fraction (not shown). This is consistent with the findings of Wan et al. (2020), who found that the cloud fraction sensitivity stems from process coupling between CLUBB, MG2, and with the host model. Wan et al. (2020) provide methods to reduce this sensitivity, but it is beyond the scope of this work to implement and tune. Nonetheless, Figure 13a suggests that the gains in low cloud we see due to vertical resolution increases in the OCT simulation could be potentially be offset by the time step sensitivity, which acts to reduce marine stratocumulus.

Further sensitivity of SWCRE is seen when the time step is decreased to 300 s (Figure 13b), which is the target time step of our aggressive 16XL experiment. While the time step effects for the CNTL-T900 simulation are fairly modest in nature, the time step effects for CNTL-T300 are quite significant and a chief reason why evaluating the resolution effects of a 16XL simulation is difficult. In addition, we do see large sensitivity of SWCRE in the tropics when the time step is reduced to 300 s. Upon further investigation we find that this sensitivity is due to a weakening of tendencies and mass fluxes from the ZM scheme. Aa reduction of the ZM time scale helps to consume convective available potential energy (CAPE) more efficiently to ameliorate this bias in the tropics (not shown (G. Zhang & McFarlane, 1995),), though the bias in the low cloud regions is very similar.

Of course, the question remains why the time step needs to be reduced for the OCT simulation? In E3SM the CLUBB parameterization, MG2 microphysics, and large scale vertical advection in the dynamical core should not have time step limitation since they employ implicit, semi-Lagrangian, and timesplitted

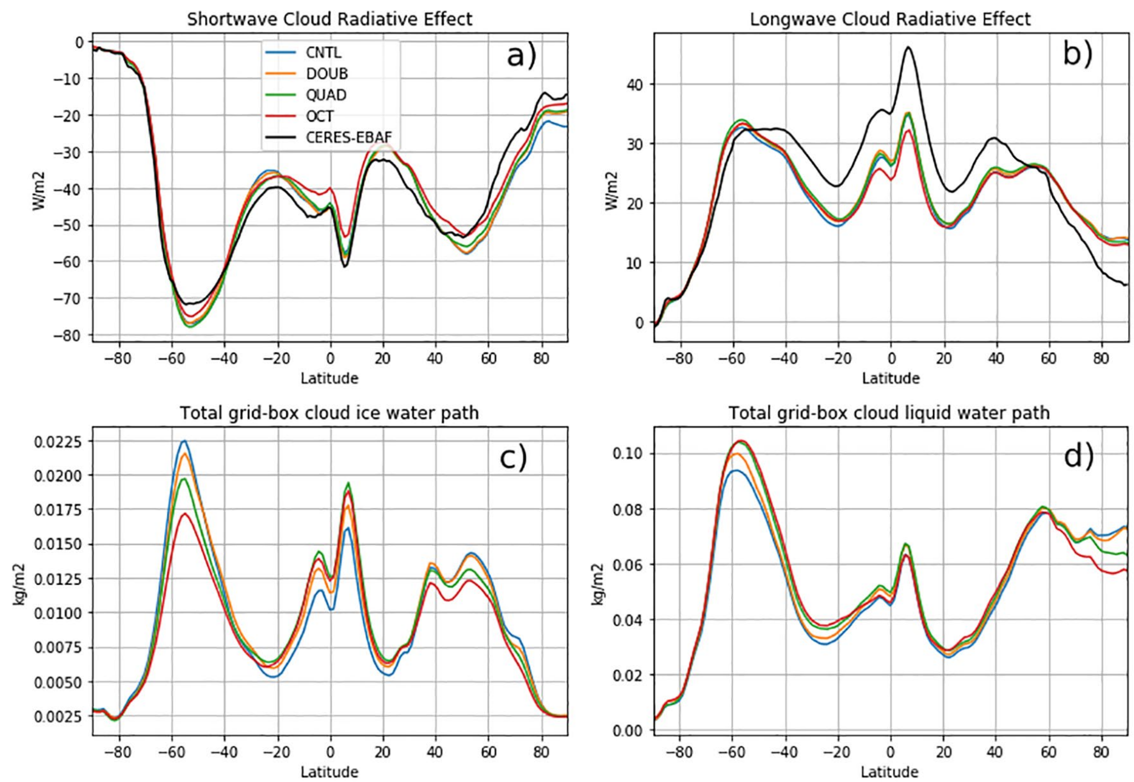

Figure 12. Zonally averaged (a) shortwave cloud radiatve effect (SWCRE), (b) longwave cloud radiative effect (LWCRE), (c) liquid water path, and (d) ice water path (bottom right) for CNTL and the principle vertical resolution experiments.

sedimentation methods, respectively. Though we do note that even if these schemes do not present stringent time step limitations, that does not necessarily mean they are insensitive to time step changes. In addition, our simulations do not increase the horizontal resolution so should not be limited by constrains from horizontal advection.

To help elucidate where the time step limitations arise, we run the OCT simulation with the ZM deep convection scheme shut off (sensitivity simulation OCT-NODEEP). In such a simulation, the CLUBB parameterization is then responsible for removing instabilities in the deep convective regions (Thayer-Calder et al., 2015). While we do not evaluate the climate of the OCT-DEEP simulation, since it is not a scientifically supported parameterization suite, we simply note that this simulation ran stably for one year, whereas a simulation of OCT with default E3SM time steps ran only for 23 steps. This appears to suggest that the time step limitation in our OCT principle experiment arises from the deep convection scheme. This is further suggested in the companion paper of Lee et al. (2021) who present results from a version of E3SM where CLUBB, MG2, radiation, and large-scale vertical advection are run on a high vertical resolution grid independent of E3SM's vertical grid. In their simulations, the aforementioned processes are run on the OCT grid, while the remaining processes (including ZM deep convection) are run on the 72 layer grid. For their simulations to run stable, they did not require a reduction of any time step setting.

The time step limitation in ZM is likely due to the explicit solution of the mass flux equation, which can only remain stable if the local Courant-Friedrichs-Lewy (CFL) condition is satisfied (Mishra & Sahany, 2011). This condition implies a maximum mass flux, such that if the vertical resolution is refined without a reduction of time step, the CFL criterion will be violated.

4.4.2. Grid Configuration Sensitivity

The 16XL experiment further refines the vertical resolution in the lower troposphere compared to OCT. The intention was to include this as a principle experiment to determine whether or not the simulation of stratocumulus converges with this higher vertical resolution or whether further improvements occur. However,

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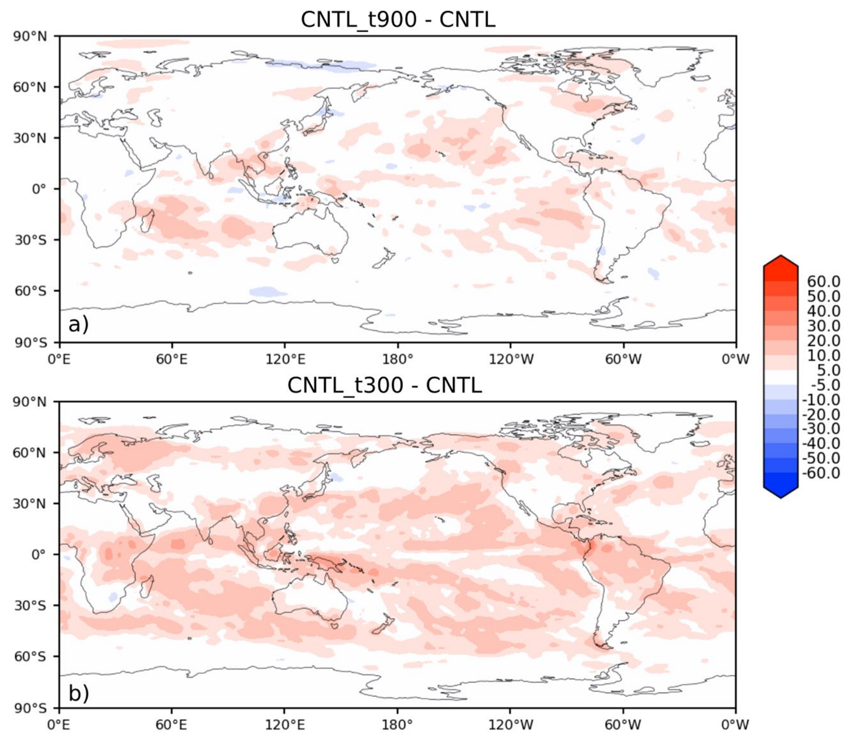

Figure 13. Differences of shortwave cloud radiative effect (SWCRE), relative to CNTL, for sensitivity experiments where the time step E3SM time step is adjusted to (a) 900 s and (b) 300 s. See Table 2 for simulation details.

we quickly realized that due to the extreme time step reduction necessary to achieve a stable simulation with this configuration, that a proper scientific comparison with our principle experiments would not be possible.

Figure 14 displays the difference in the low cloud amount relative to CNTL. This can be compared to the results of the principle experiments in Figure 3. It is apparent that low cloud amount increases with 16XL configuration compared to OCT, and arguably with increases to coastal stratocumulus. However, we caution with the interpretation of these results as the 16XL simulation contains extreme sensitivities in the radiation budgets which do not warrant an apples-to-apples comparison with the principle experiments. Thus, the question of whether further vertical refinement beyond the OCT experiment improves marine stratocumulus simulation remains inconclusive and we refer the reader to the companion paper of Lee et al. (2021). In their work, they are able to address this question with a novel modeling framework.

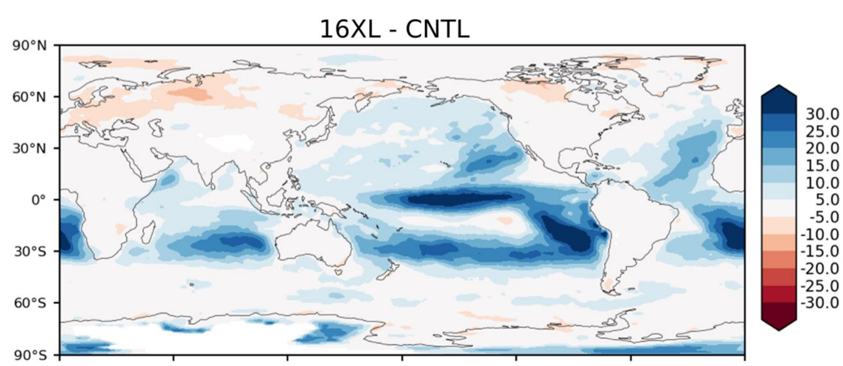

Figure 14. Low cloud amount difference relative to CNTL for the 16XL experiment simulation. See Table 3 for simulation details. Results can be compared against those in Figure 3.

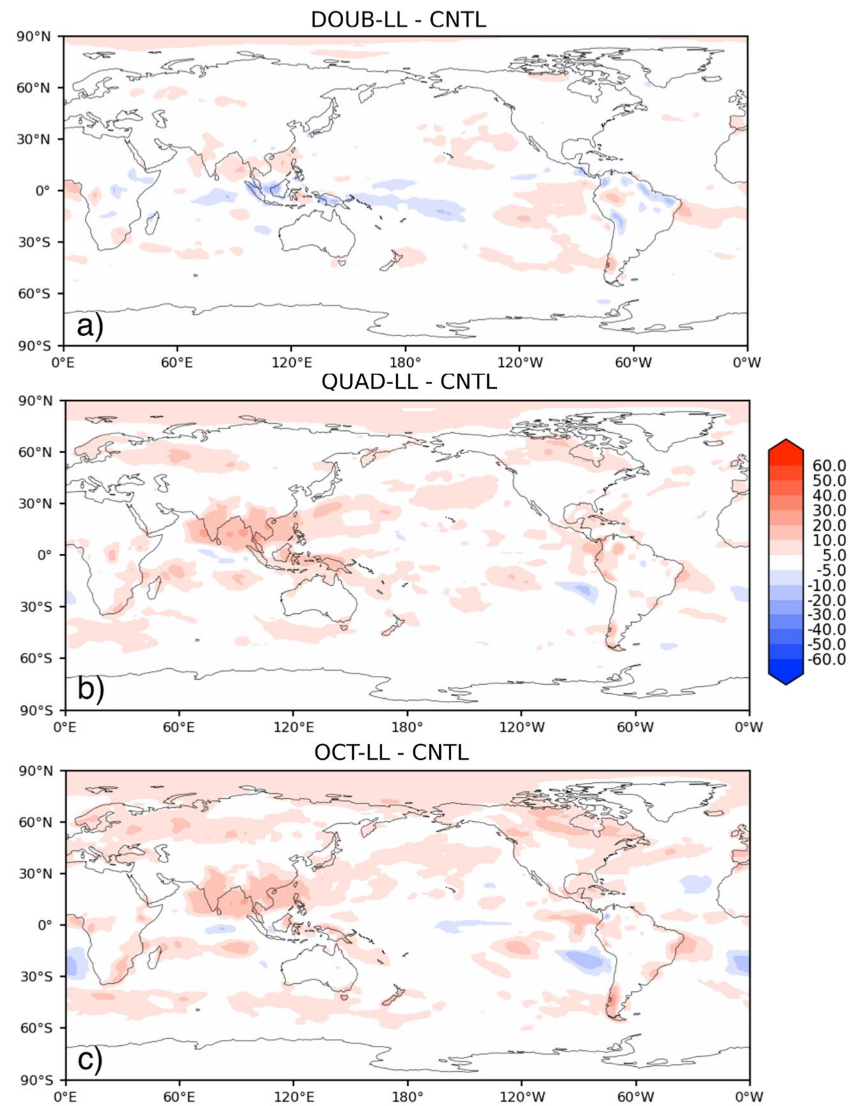

Figure 15. Evolution of the SWCRE biases relative to CNTL for vertical grid experiments where the lowest model level is refined for the (a) DOUB, (b) QUAD, and (c) OCT experiments. Results can be compared against those in Figure 6.

As noted in Section 3.2.2, our principle experiments did not refine the lowest model level. The reason is because doing so required substantial time step decreases to our simulations. The previous section, as well as Wan et al. (2020), demonstrates that E3SM marine stratocumulus are particularly sensitive to E3SM time step and therefore these experiments are not desirable when attempting to tease out vertical resolution effects alone. However, we do perform three year experiments of DOUB, QUAD, and OCT with the lowest level refined to ensure that the overall conclusions of this article are not dramatically effected by this grid configuration choice.

Figure 15 displays the SWCRE differences for the DOUB-LL, QUAD-LL, and OCT-LL sensitivity experiments relative to CNTL. We note that the evolution of the SWCRE in the stratocumulus regions is generally similar to the principle experiments, as seen in Figure 6. However, the magnitudes are indeed muted, relative to CNTL, which is expected from the time step sensitivity results presented in Figure 13. Although not shown, we examined the profiles of various quantities, similar to Figures 8 and 9 and note that the same general conclusions are reached as well; with the OCT-LL simulation showing negative vertical velocity skewness in the stratocumulus layers for the Peruvian stratocumulus.

The OCT-UL simulation, where the grid is progressively coarsened between levels 700 hPa and 500 hPa, shows no clear sensitivity in results when compared to the OCT simulation (not shown).

5. Summary and Discussion

Despite advances made in boundary layer parameterizations over the last generation of GCM development, many still struggle to adequately simulate marine stratocumulus. In a sense, this is not very surprising given that many LES studies suggest that vertical resolution of 10–20 m is needed to resolve the sharp thermodynamic gradients that cap stratocumulus boundary layers, yet many GCMs often have vertical resolutions on the order of 100 m in the lower troposphere. In this article, we explore how simulated marine stratocumulus respond, in a climatological sense, in E3SM when the vertical resolution is increased to scales approaching that used in LES. This is exploited in three principle experiments where the vertical resolution in the lower troposphere is doubled, quadrupled, and octupled (DOUB, QUAD, and OCT, respectively); the later of which has vertical resolution characteristic of that used in LES.

Does increasing vertical resolution in E3SM lead to a better simulation of marine stratocumulus? We conclude that vertical resolution increases, toward LES scales, is a crucial ingredient toward achieving better representation of stratocumulus; but it is not a panacea. The results of our principle experiments suggest that negligible to modest effects are seen in the simulated low cloud when vertical resolution is doubled or quadrupled, yet large and significant impacts are seen when one octuples the vertical resolution in the boundary layer. In the OCT simulation the biases and RMSE of the low level cloud amount and SWCRE are significantly reduced in most stratocumulus regions. In addition, the vertical structure of the marine Sc and associated turbulence in the OCT simulation are inherently different than that of the CNTL, DOUB, and QUAD simulations. Whereas the three former simulations tend to produce climatological turbulence profiles characteristic of a decoupled cumulus region, the OCT simulation produces a stratocumulus boundary layer that is more turbulent, less decoupled, and with a negative vertical velocity skewness.

However, this improvement is largely seen for offshore stratocumulus as coastal stratocumulus appear resistant to change. It is possible that concurrent horizontal and vertical resolution increases are needed to reduce the biases related to coastal stratocumulus. This can be explored via techniques described in the companion paper of Lee et al. (2021). Perhaps further vertical resolution refinement is needed beyond the OCT simulation to capture the coastal and California Sc. Unfortunately, our ultra-high vertical resolution 16XL simulation provides inconclusive results on this matter as that simulation required extreme time step adjustments to run stably, to which we find E3SM is quite sensitive to the time step. Lee et al. (2021) will address whether or not the 16XL grid configuration leads to further improvements with a novel modeling framework. It is also possible that lingering deficiencies in the model parameterizations, which vertical resolution alone cannot solve, are also contributing to the coastal stratocumulus problem. Identifying and and fixing these potential issues, however, is beyond the scope of this current work.

We also note that the results presented in this article represent the sensitivities from one model and with one parameterization suite, therefore it is not clear how other GCMs would respond to aggressive increases in the vertical resolution. For instance, Bogenschutz et al. (2012) reports a substantial degradation in the simulated marine stratocumulus when CAM5's vertical grid is doubled, likely a side effect of interactions between modular PBL and shallow convective schemes in that model. The unified nature of the CLUBB parameterization used in E3SM makes it less susceptible to vertical resolution changes since it does not have to directly interact with other transport schemes which may or may not be scale insensitive in the vertical.

In addition, it would be interesting to examine how the climate sensitivity evolves in such a model with increased vertical resolution and more abundant stratocumulus. E3SM is known to have a climate sensitivty that is considered too high (Golaz et al., 2019) and improved represensation of marine Sc could potential lead to better representation of cloud feedbacks. This should be explored in future work. Furthermore, our prescribed SST configuration also has implications for the precipitation response, which is primarily a "fast response" to changes in the surface energy budget in these simulations.

While going to LES-like vertical resolution appears to be a crucial ingredient for accurate simulation of marine stratocumulus, these simulations are exceedingly expensive. For example, the OCT simulation has a throughput of 0.37 simulated years per day (SYPD) when run on 1024 CPUs, compared to the throughput of 3.9 SYPD produced by the CNTL simulation. Such a high computational cost is a hard sell for modeling centers to get on board with. However, the authors cannot recommend compromising with marginal increases in vertical resolution as we have demonstrated doing so does not buy you much in terms of stratocumulus simulation. So then what is the path forward?

The companion paper of Lee et al. (2021) addresses a potential solution, which involves the implementation of the Framework for Improvement by Vertical Enhancement (FIVE, Yamaguchi et al (2017)) to E3SM. The implementation of FIVE into E3SM will allow select physics processes to be run on a higher vertical resolution grid relative to the rest of model, which could provide a useful framework in obtaining similar results seen in this article but with a computation cost that is more digestible.

Data Availability Statement

The model used in this article can be found at https://doi.org/10.5281/zenodo.3834277 and the data can be accessed at https://dabdceba-6d04-11e5-ba46-22000b92c6ec.e.globus.org/publications/Bogensch_JAMES_2020.tar.gz.

Acknowledgments
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