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Key Points:

- Concurrent increases in the horizontal and vertical resolution are essential for major bias reduction in subtropical marine stratocumulus
- Coastal stratocumulus benefit more from high horizontal resolution, whereas high vertical resolution is more critical for offshore one
- A novel framework for running selected physics parameterizations on a higher vertical resolution grid reduces computational cost

Supporting Information:

Supporting Information may be found in the online version of this article.

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Resolving Away Stratocumulus Biases in Modern Global Climate Models

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Abstract Increased horizontal and vertical resolution in global atmospheric models can reduce a significant amount of the biases associated with subtropical marine stratocumulus. The sensitivity of offshore and coastal marine stratocumulus to different horizontal and vertical resolutions has been investigated by using Energy Exascale Earth System Model (E3SM) coupled with the novel Framework for Improvement by Vertical Enhancement which has been demonstrated as a viable tool to improve the representation of marine stratocumulus while saving computational cost. Our study shows that high vertical resolution is the key to improve marine stratocumulus simulations in E3SM. Concurrent horizontal and vertical resolution increases are needed for substantial overall reduction of stubborn marine stratocumulus biases over the coastal region but not necessarily in the offshore area.

Plain Language Summary Most global climate models (GCMs) underestimate low-level clouds. Increasing vertical or horizontal resolution in GCMs could eliminate potential causes contributing to the problem. In this study, we use a new computational method, known as the Framework for Improvement by Vertical Enhancement, coupled with the Energy Exascale Earth System Model to investigate the sensitivity of offshore and coastal marine stratocumulus to different horizontal and vertical resolutions. Our results show that vertical resolution is more important than the horizontal resolution in simulating realistic marine stratocumulus; however, concurrent horizontal and vertical resolution increases are needed for substantial overall reduction of stubborn marine stratocumulus biases over the coastal region, especially along the coastal region of Peru.

1. Introduction

Stratocumulus clouds cover approximately 20% of Earth's surface in the annual mean (Warren et al., 1986; Wood, 2012). They have strong shortwave cloud radiative effects through reflecting incoming solar radiation and a small effect on outgoing longwave radiation (Chen et al., 2000; Hartmann et al., 1992; Stephens & Greenwald, 1991; Wood, 2012). Both shortwave and longwave radiative effects associated with stratocumulus result in a strong negative net radiative effect that significantly affects Earth's radiative balance. Thus, a small change in the coverage and thickness of stratocumulus clouds can strongly alter the local radiative effects and then impact the Earth's radiative balance. In spite of its significant role to climate, quantitatively understanding stratocumulus clouds and accurately simulating them in global climate models (GCMs) remain critical challenges.

Low stratiform clouds are primarily formed over oceans and classified into three types: stratiform clouds on the east side of the oceanic subtropical highs, stratocumulus clouds over the warm western boundary currents in winter, and Arctic stratus (Klein & Hartmann, 1993). Most GCMs severely underestimate the first type of stratocumulus clouds, especially in Southeastern Pacific Ocean (Lin et al., 2014; Xie et al., 2018). Since the biases of stratocumulus clouds in GCMs are a common issue, improving cloud parameterization or increasing vertical resolution are two options to potentially diminish these biases, with the latter option being relatively more straightforward compared to the former. Bogenschutz et al. (2012) show that single column model simulations with the Cloud Layers Unified By-Binormals (CLUBB) (Larson & Golaz, 2005) parameterization performs best in the stratocumulus and transitional regimes when high vertical resolution is used in the lower troposphere. More recently, Bogenschutz et al. (2021) show that coarse vertical resolution in the Energy Exascale Earth System Model (E3SM) (Golaz et al., 2019) is a significant cause of low-level cloud bias because CLUBB cannot realize the sharp temperature and moisture gradients often found at the top of subtropical stratocumulus layers. Bogenschutz et al. (2021) demonstrated that increasing vertical resolution in E3SM, toward those approaching vertical resolutions often used in large eddy simulation (LES), is a key ingredient toward improving the representation of marine stratocumulus. However, increasing the vertical resolution comes with excessive computational cost and is not a panacea as stratocumulus biases still remain particularly near the coast.

In our previous study (Lee et al., 2021), we implemented the novel Framework for Improvement by Vertical Enhancement (FIVE) (Yamaguchi et al., 2017) into E3SM and showed that it is a viable option to improve the representation of low-level clouds while saving computational cost. FIVE predicts prognostic variables by computing selected one-dimensional processes on the locally high vertical resolution grid (e.g., microphysics, radiation, turbulence, and vertical advection) and other processes (e.g., horizontal advection) on the host model vertical grid. Using FIVE in E3SM with standard ne30 configuration (1° horizontal mesh and with 72 vertical layers) but with these selected processes computed on a LES-like vertical grid in the lower troposphere greatly improves the simulation of subtropical marine stratocumulus and saves computational cost, compared to high resolution benchmarks, by more than a factor of six. However, these simulations still suffer from significant biases along the coastal regions of California, Peru, and Namibia. In this study, we seek to determine if increasing the horizontal resolution with concurrent increases in the vertical resolution can "resolve away" these persistently stubborn stratocumulus biases. We demonstrate that concurrent horizontal and vertical resolution increases are required for substantial overall reduction of stubborn marine stratocumulus biases when compared to observations. We also discuss the impact of our results on the future versions of GCMs and global cloud resolving models.

2. Model Overview and Numerical Experiment Designs

For this study, we use version 1 of E3SM, a fully coupled Earth system model developed by the Department of Energy (Golaz et al., 2019). The atmosphere component of E3SMv1, E3SM Atmosphere Model (EAM) (Rasch et al., 2019), uses a spectral element dynamical core with standard ne30 configuration (1° horizontal mesh) on a cubed sphere geometry and a traditional hybridized sigma pressure vertical coordinate. There are 72 vertical levels in EAM with a top at approximately 60 km in altitude.

We also utilize the novel FIVE (Yamaguchi et al., 2017), which has been implemented into E3SM to improve marine stratocumulus clouds while saving computational cost (Lee et al., 2021). In the current E3SM-FIVE, three physics schemes are interfaced for vertically enhanced physics (VEP), which are run at a higher vertical resolution, compared to E3SM's default vertical resolution, to better represent low clouds: CLUBB turbulence parameterization (Golaz et al., 2002, 2007; Larson & Golaz, 2005), Morrison and Gettelman microphysics scheme version 2 (Gettelman et al., 2015; Morrison & Gettelman, 2008), and Rapid Radiative Transfer Model for GCMs longwave and shortwave radiation schemes (Iacono et al., 2008; Mlawer et al., 1997). In addition to the aforementioned physics schemes, large-scale vertical advection in the dynamical core is computed on the high-resolution grid, which is necessary to accurately balance entrainment via the turbulence scheme. The tendencies calculated in VEP with higher vertical resolution are averaged and applied to the host model (i.e., E3SM) for prediction. The VEP calculation does not interfere with the order of the computation of processes in the host model, so the calculation of processes is not repeated between the host model and VEP. The Supporting Information S1 provides the extended model description of E3SM and FIVE.

The purpose of this study is to investigate whether the marine stratocumulus biases in E3SM can be "resolved away" by using E3SM-FIVE when the horizontal resolution increases (from 1° to 0.25° resolution) or/and vertical resolution in VEP increases (from 72-layer grid to 212-layer grid). The configuration of the control run (ne30_CNTL) is based on the configuration of E3SMv1 using 1° horizontal resolution (ne30) and 72 vertical layers. The first experiment is designed to octuple (ne30_FIVE) the vertical resolution of VEP between 995 and 700 hPa with the same 1° horizontal resolution (Table S1 in Supporting Information S1). The vertical grid spacings for high vertical resolution simulations (Figure S1 in Supporting Information S1) are representative of those typically used for LES studies of marine stratocumulus (∼10 m) (Stevens et al., 2005; van der Dussen et al., 2013). Two additional experiments, ne120_CNTL and ne120_FIVE, follow the same vertical resolution designs as ne30_CNTL and ne30_FIVE, respectively, but with ne120 (0.25° horizontal resolution) configuration.

We note that all simulations presented in this paper use the exact same set of tunable parameters. While the E3SM ne30 and ne120 models use a slightly different set of tunable parameters in CLUBB and the Zhang-McFarlane (ZM) deep convection scheme (Zhang & McFarlane, 1995) to achieve radiation balance for coupled simulations

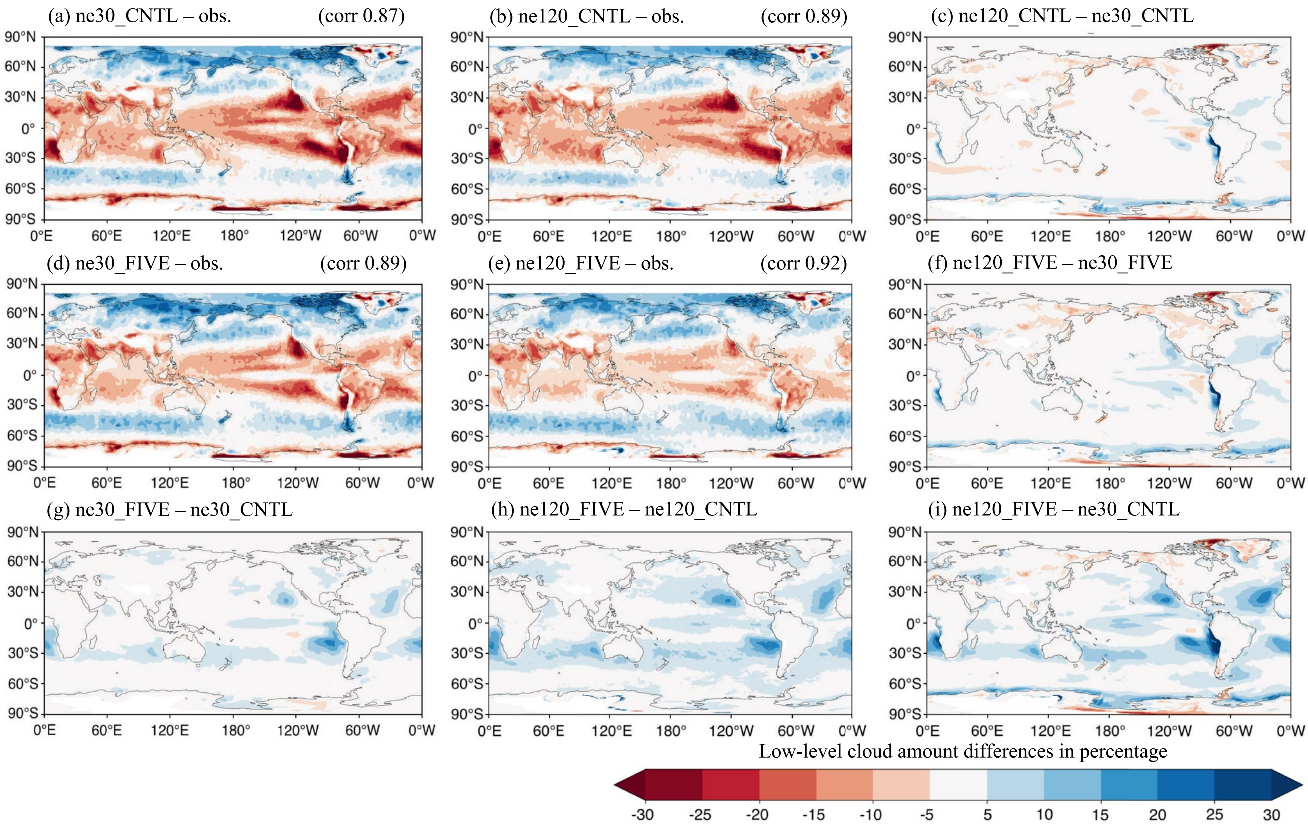

Figure 1. (a) The differences of low-level cloud amount between ne30_CNTL and observation (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation lidar data from January 2007 to January 2010). (b, d, and e) are the same as (a) but for ne120_CNTL, ne30_FIVE, and ne120_FIVE, respectively. (c, f, and g–i) are the differences of low-level cloud amount between two models described on the title of each figure. Units are percentage. The duration of all experiments is 5 years. Corr in (a, b, d, and e) indicates the correction coefficient between the model and observations.

(Caldwell et al., 2019), we chose to run all of our simulations with ne30 tunable parameters. This is because it can be difficult to disentangle whether improvements in our region of interest are due to resolution or tuning, and is a similar approach Caldwell et al. (2019) took when comparing low resolution and high resolution E3SMv1 simulations.

3. Results

3.1. Low-Level Cloud Climatology

Compared to the climatologically averaged low-level cloud amount from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) lidar data from January 2007 to January 2010, ne30_CNTL captures the general pattern of low-level cloud amount with a relatively high correlation coefficient of ~0.87 (Figure 1a). Despite this high correlation, ne30_CNTL suffers from an underestimated low-level cloud amount, primarily in the subtropical regions, with regional deficits of more than 30% (Figure 1a) that also results in poor shortwave cloud radiative effects in these regions (Bogenschutz et al., 2021). This low-level cloud bias is typical of most GCMs and not specific to E3SM. To conduct an apples-to-apples comparison, our E3SM simulations use the Cloud Feedback Model Intercomparing Project Observation Simulator Package (Bodas-Salcedo et al., 2011) when evaluating simulated low cloud climatology with the observations.

In our previous study (Lee et al., 2021), we demonstrated that when VEP vertical resolution approaches that of LES, the climatological low cloud amount increases by 30% in the southeastern Pacific Ocean, but is mainly focused on offshore stratocumulus (Figures 1a, 1d, and 1g), with lingering coastal biases. Table 1 displays the global biases and root mean squared errors (RMSE) for various climatologically important variables for the different resolution configurations and shows the positive impact on low-level cloud skill metrics for the simulations

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Table 1

The Mean Biases of Low-Level Cloud Amount (%), Mid-Level Cloud Amount (%), High-Level Cloud Amount (%), Shortwave Cloud Radiative Effect (W/m²), Longwave Cloud Radiative Effect (W/m²), and Precipitation (mm/day) for Each Experiment Against the Observations

	ne30		ne120	
	CNTL	FIVE	CNTL	FIVE
Low-level cloud amount (%)	−5.54 (12.75)	−2.66 (11.36)	−5.95 (11.90)	−1.47 (9.69)
Mid-level cloud amount (%)	−4.21 (7.32)	−3.79 (7.28)	−4.67 (7.23)	−4.46 (7.04)
High-level cloud amount (%)	−4.97 (7.87)	−4.70 (7.84)	−6.10 (9.30)	−5.82 (9.27)
Shortwave cloud radiative effect (W/m²)	1.03 (9.54)	−1.03 (9.35)	3.71 (10.28)	0.43 (9.40)
Longwave cloud radiative effect (W/m²)	−5.18 (8.43)	−4.37 (8.05)	−4.64 (10.77)	−6.55 (10.13)
Precipitation (mm/day)	0.42 (1.06)	0.51 (1.14)	0.51 (1.19)	0.62 (1.28)

Note. Parentheses show RMSE biases. RMSE, root mean squared errors.

using high vertical resolution compared to the lower vertical resolution configurations. Regionally, we show that the simulation with ne120 configuration (0.25° horizontal resolution) and increased vertical resolution (i.e., ne120_FIVE) substantially improves low cloud amount not only in the offshore regions but also in the coastal areas compared to the observation (Figure 1e).

Approaching higher horizontal resolution is of growing interest for most GCMs to improve process representation in physics and dynamics, such as tropical cyclones (Haarsma et al., 2016). In this study, we find that the increase of horizontal resolution for the simulations with standard 72 vertical layers (ne120_CNTL vs. ne30_CNTL) primarily improves subtropical stratocumulus that reside directly along the coast, especially for the Peruvian and Namibian regions (Figure 1c), with little effect for other cloud regimes including the subtropical stratocumulus that reside offshore. Therefore, in the standard E3SM model (ne30 configuration and 72 vertical layers; ne30_CNTL), increasing horizontal resolution is not sufficient to elucidate the bias of marine stratocumulus cloud. Only when we increase horizontal and vertical resolutions, both the offshore and coastal regions experience significant increases in low level cloud with substantial bias reduction (Figures 1e and 1i). While not shown, this also leads to associated improvements in regard to shortwave radiative cloud effect in the stratocumulus regions.

3.2. Stratocumulus Regions

To quantitatively discuss the responses of low-level cloud amount by increasing horizontal or/and vertical resolution, in this section we focus on three areas: the Peruvian region, the Californian region, and the Namibian region. Each region has a defined coastal and offshore 10° by 10° domain (Figure 2a).

We find that offshore stratocumulus cloud is not sensitive to the increase of horizontal resolution in most of the regions, regardless if high or low vertical resolution is used (Figure 2b). The exception being the offshore Californian stratocumulus, which exhibits a modest improvement in the bias score when the higher horizontal resolution is used. On the other hand, the coastal low-level clouds show improvements to the increase of horizontal resolution, even if low vertical resolution is used (Figure 2c). In the low vertical resolution simulations, a significant improvement of the coastal low-level cloud bias occurs over the Peruvian region by about 8%. However, we note that the biggest improvements for the coastal stratocumulus are seen when both the horizontal and vertical resolutions are increased, as demonstrated by the skill scores for the ne120_FIVE simulation. This highlights the importance of concurrent increases to the horizontal and vertical resolution in GCMs to tackle this stubborn bias.

Unlike the offshore stratocumulus clouds, the coastal stratocumulus clouds are more sensitive to the increase of horizontal resolution, especially in the high vertical resolution simulations (Figures 2c and 2e). It is especially striking that the magnitude of the bias improvement is more than double in the coastal region of Peru compared to the other two regions (Figure 2c). One potential reason as to why the improvement of the coastal stratocumulus cloud biases over the Peruvian region is particularly responsive to the increase of horizontal resolution might be due to an improved representation of the sharp terrain gradient over the coast of Peru.

Xu et al. (2004) have demonstrated the effects of the narrow and steep Andes on eastern Pacific climate. In their study, they found the Andes helps maintain the divergence and temperature inversion and, hence, the

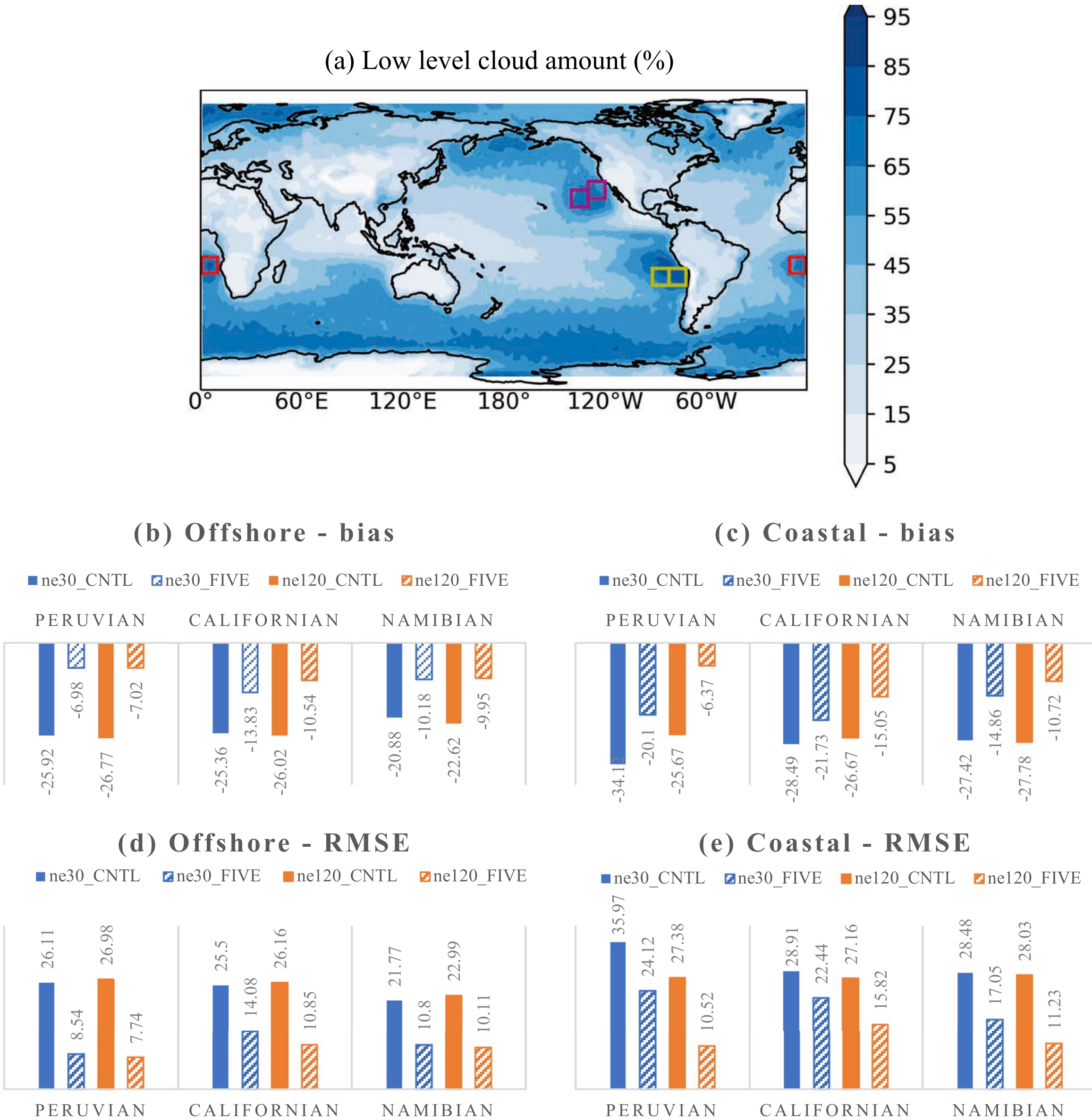

Figure 2. (a) Low level cloud amount from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) lidar data from January 2007 to 2010. Magenta boxes show the coastal and offshore analysis domain for the Californian region. Yellow boxes and red boxes indicate the analysis domain for the Peruvian region and the Namibian region, respectively. (b and c) Bias and (d and e) root mean squared errors (RMSE) computed relative to CALIPSO observations for the low cloud amounts in the offshore and coastal analysis domain for the Californian, Peruvian, and Namibian region (Figure 1) for each experiment against the observations.

stratocumulus cloud over the Peruvian region. Once the Andean mountains are removed in their simulations, the warm advection from the South American continent lowers the inversion height and reduces the low-level divergence offshore, and then leads to a significant reduction in cloud amount. This conclusion is also supported by Richter and Mechoso (2006) who show that removing the Andean mountains decreases the lower tropospheric stability and allows for more frequent stratocumulus destruction through the model's cloud-top entrainment instability mechanism. Richter and Mechoso (2006) also compared their results to their previous study in the Namibian region (Richter & Mechoso, 2004) to conclude that the orography of South America is high enough to cause substantial blocking of the lower tropospheric flow, while the orographic heights in the southern Africa are not sufficient to cause blocking of the flow from the Indian Ocean. Thus, we hypothesize that the improvements of the coastal stratocumulus cloud biases due to the increase of horizontal resolution over the Californian and Namibian coasts are not quite as dramatic since the terrain gradient over these regions are relatively flat compared to the Peruvian coast.

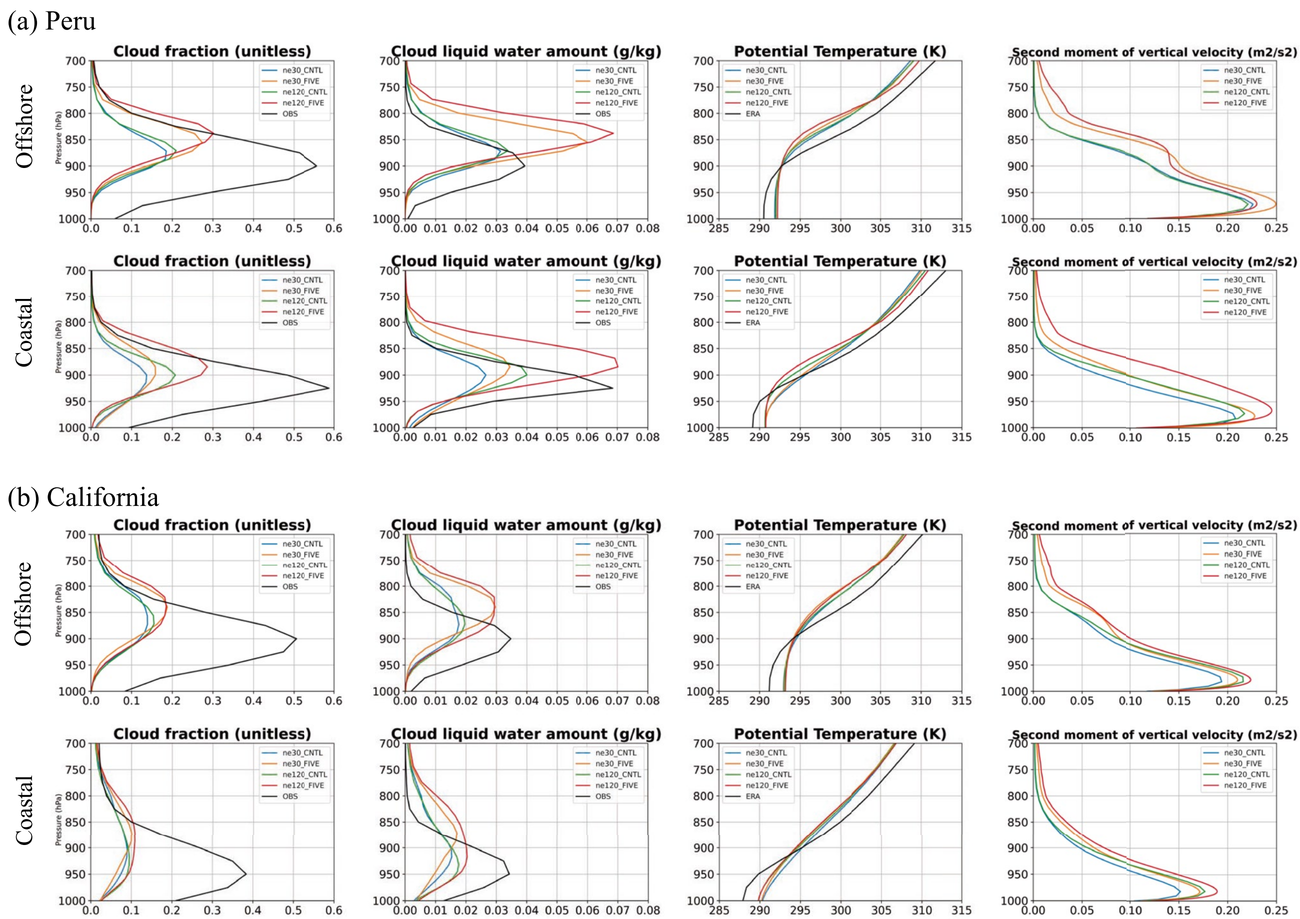

Figure 3. (a) Spatial-and temporal-averaged profiles of cloud fraction (unitless), cloud liquid water amount (g/kg), potential temperature (k), and second moment of vertical velocity ($\overline{w'^2}$; m^2/s^2) in the offshore and coastal area of the Peruvian region from the simulations of Energy Exascale Earth System Model-Framework for Improvement by Vertical Enhancement (FIVE). (b) is the same as (a) but in the Californian region. The observational data (OBS) is provided by C3M. ERA indicates ERA-Interim, which is a global atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ERA-Interim Project, 2009).

3.3. Cloud and Turbulence Vertical Structure

Figure 3 displays profiles for the cloud fraction, cloud liquid water amount, potential temperature, and vertical velocity variance for our four experiments and segregated by the coastal and offshore stratocumulus for the California and Peruvian regions. For the analysis of cloud fraction and cloud liquid water, we compare to observational data provided by CALIPSO, CloudSat, and Moderate Resolution Imaging Spectroradiometer in a merged product called C3M (Kato et al., 2010). We choose to present the Peruvian and Californian regions since the former has the most significant response to resolution, while the latter region has the least significant response.

Examining the simulated cloud fraction and cloud liquid profiles for both regions, clearly all experiments underestimate the cloud fraction amount; with the higher vertical resolution simulations providing a modest boost that is most substantial for Peruvian stratocumulus. The four simulations can only capture about half of the observed cloud fraction amount in the Peruvian region, but ne120_FIVE can reasonably match with the observed cloud liquid water amount over the coast of Peru (Figure 3a). This is consistent with the well-known "too bright too few" problem (Nam et al., 2012) often associated with GCMs, where clouds are simulated to be too few in amount but compensated by an overabundance of liquid water. Thus, while higher horizontal and vertical resolution can indeed help to simulate more clouds, it is clear that the "too bright too few" problem remains entrenched in parameterization deficiencies.

Among the four simulations, the potential temperature profiles in the high vertical resolution simulations (ne30_FIVE and ne120_FIVE) have higher PBL inversion top and stronger inversion strength over the offshore region of Peru (Figure 3a), resulting in a higher cloud top and thicker cloud deck compared to their low vertical resolution simulation counterparts. The sharper temperature inversion represented by the high vertical resolution simulations agrees with Bogenschutz et al. (2021) who found that high vertical resolution is needed to resolve the cloud top cooling that occurs over a thin layer in the marine stratocumulus regime, which is a crucial ingredient for the maintenance of these clouds. Although this process is better represented in the high vertical resolution simulations, we note a systematic bias for the cloud top to be too high for these experiments when compared to the C3M observations. Although the high vertical resolution simulations capture higher inversion height compared to the reanalysis data (i.e., ERA-Interim), increasing vertical resolution can help the model to get stronger inversion strength, especially over the offshore regions, which is a preferred environment to simulate more marine stratocumulus clouds. Over the coast of Peru, high horizonal resolution still plays more important role in inversion strength, while over California, the differences between simulations seem negligible.

The second moment of vertical velocity ($\overline{w'^2}$) predicted by the CLUBB parameterization can be interpreted as a measure of the turbulence intensity. The offshore $\overline{w'^2}$ profiles for all simulations tend to demonstrate two defined peaks, indicative of a more decoupled stratocumulus layer (Figure 3). On the other hand, the coastal $\overline{w'^2}$ profiles have a decidedly more single peaked structure which is a behavior often associated with a well-mixed coupled stratocumulus regime (Stevens et al., 2005).

A common theme in most of the regions is that simulations with higher vertical resolution (ne30_FIVE, but especially ne120_FIVE) often have higher magnitudes of $\overline{w'^2}$ compared to their lower vertical resolution simulation counterparts. This is in agreement with Bogenschutz et al. (2021) and Lee et al. (2021) who found that higher vertical resolution is needed to better resolve the longwave cooling processes that reside at cloud top which is the primary mechanism for turbulence generation for the stratocumulus regime. The increased turbulence acts to feedback to help in the maintenance of the stratocumulus layer. The most striking behavior can be found with the high vertical and horizontal resolution experiment in the coastal Peruvian stratocumulus region, which produces an abundance of turbulence compared to the rest of the experiments. While this result is not especially surprising, in light of the results that show this configuration produces more cloud compared to the rest, it continues to highlight the importance of concurrent increased of horizontal and vertical resolution to adequately represent stratocumulus processes.

Compared to the coastal Peruvian region, the increase of horizontal resolution does not show the same magnitude of improvement in the coastal Californian region. It could be because this region does not have a sharp orographic terrain to maintain local general circulation like the Peruvian region. Besides orographic factors, some untuned parameters used in CLUBB and the ZM deep convection scheme could affect physical processes at higher resolution as well.

4. Conclusion and Discussion

This work shows the significant role that spatial resolution, both in the horizontal and vertical direction, plays toward reducing the biases associated with subtropical marine stratocumulus in modern conventional GCMs. We use E3SMv1 coupled with a novel computational method known as FIVE, which allows selected processes to be computed on a higher vertical resolution grid rather than default vertical resolution used in the model. This allows us to perform a series of experiments with various combinations of increased horizontal and vertical resolution at a reasonable computational cost. We show that increasing the vertical resolution helps to primarily improve the representation of more "offshore" stratocumulus, while increasing the horizontal resolution helps to reduce the bias of stratocumulus along the coasts. However, it is not until one concurrently increases the horizontal and vertical resolution where significant bias reduction occurs, as is evident in our ne120_FIVE simulation. We note that all of our simulations use the exact same set of tunable parameters, so that sensitivity comes primarily from resolution changes.

What are the minimum resolution requirements to achieve credible simulations of marine stratocumulus? Based on the results of this work we advocate that a horizontal resolution with 25 km mesh size, to resolve details of terrain and coastlines, is warranted while vertical resolution with ~10–20 m grid spacing is required within the lower troposphere to properly resolve the sharp inversions that often reside at stratocumulus cloud top. While our results are based on simulations from one model, specifically E3SMv1, we believe these guidelines are applicable to any GCMs.

While we demonstrate that increased horizontal and vertical resolution can "resolve away" a significant amount of the biases associated with subtropical marine stratocumulus, it clearly is not a panacea. The CLUBB parameterization used in E3SM has advanced the representation of low clouds, but it is not a perfect parameterization. This begs the question of whether the remaining bias is due to the need for higher resolution in our simulations, even beyond those presented in this paper, or the need for improved parameterizations. We argue that while both needs are likely still playing a role, the former is probably the more likely culprit than the latter; as we point out in this study, without the necessary horizontal and vertical resolution, marine stratocumulus would still not be represented properly.

We recognize that the minimum resolution requirements established in this paper are computationally expensive and something that most modeling centers cannot achieve for even short-term climate simulations. However, tools are available which allow for specific regions or processes to be refined. For example, this work takes advantage of FIVE and allows us to run selected physical parameterizations (i.e., those that are most crucial for representing stratocumulus clouds) at a much higher vertical resolution than the host model (i.e., dynamical core, deep convection, etc.). While the ne120-FIVE simulation was certainly expensive, with a throughput of 0.06 SYPD/2048 (simulation years per day) cores, the cost would have been prohibitively expensive had FIVE not been used. Without FIVE, a ne120 simulation with 212 vertical layers would have a cost approximately an order of magnitude higher. Even with the reduced expense that FIVE offers, it is still possible to further optimize its application within GCMs. For instance, marine stratocumulus covers a relatively small portion of the globe, therefore it makes sense to apply FIVE only in columns where stratocumulus is prevalent. This could be implemented in a geographically prescribed manner or with the FIVE columns adaptive to the large-scale environment.

In terms of horizontal resolution, the application of what is known as the regionally refined model (RRM) is also very relevant to this problem. RRM is designed to simulate a fraction of the globe at high resolution, and it has been adopted by EAMv1 to serve as a testbed for high resolution exploration and model development (Ringler et al., 2008; Tang et al., 2019; Zarzycki & Jablonowski, 2014). Thus, it would be possible to generate RRM over stratocumulus regions, with FIVE running within that region, to gain the benefits of high horizontal and vertical resolution presented in this work and at a fraction of the computational expense.

As GCMs naturally increase their horizontal resolution as computational power increases, the minimum horizontal resolution required to successfully simulate stratocumulus could be met relatively soon. However, meeting the minimum vertical requirement will likely take longer. Even as global cloud resolving models (Caldwell et al., 2021) are being developed with 3–5 km horizontal grid spacing, they typically have only ∼100 vertical levels. Bogenschutz et al. (2021) and Lee et al. (2021) demonstrate that this type of vertical grid is much too coarse to adequately represent marine stratocumulus. Thus, this highlights the importance of tools, such as FIVE, to help represent important cloud regimes even in the next generation of GCMs.

Data Availability Statement

The model code used in this study is located at https://doi.org/10.5281/zenodo.3893210. The output from the E3SM-FIVE simulations can be found at https://doi.org/10.5281/zenodo.6366246. All simulations use the FC5AV1C-L compset for EAMv1.

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