Will Increasing Climate Model Resolution Be Beneficial for ENSO Simulation?

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Abstract  Increasing climate model resolution offers multifaceted benefits, such as improving modeled tropical cyclones. However, the extent to which it benefits El Niño-Southern Oscillation (ENSO) simulation remains unknown. Here, comprehensive information on the sensitivity of ENSO performance to various resolutions is provided, based on a multi-model and multi-resolution ensemble of global coupled models. Overall, the reduced model biases of the equatorial sea surface temperature (SST) and precipitation mean state in higher-resolution models may be attributed to increased oceanic resolution, and thus, better resolved eddy-driven heat transport. ENSO spatial patterns were reproduced clearer in the eddy-present models, likely due to the improved mean state and associated surface thermodynamic feedback. However, increasing atmospheric resolution alone deteriorates ENSO asymmetry, which may be due to the degradation of nonlinear atmospheric feedback. It remains challenging to alleviate the SST–shortwave-flux feedback bias, which is a major source of too-weak net heat flux feedback, irrespective of model resolution.

Plain Language Summary  The impact of model resolution on simulated weather and climate phenomena has received much attention in recent studies. In this study, we used seven global coupled models, at horizontal grid spacings ranging from 250 to 10 km, to assess El Niño-Southern Oscillation (ENSO) performance in historical simulations from 1950 to 2014. Several metrics regarding the tropical Pacific mean states, ENSO characteristics, feedback processes, and teleconnections were evaluated. We found that in higher resolution models, the model biases of sea surface temperature and precipitation climatology in the equatorial Pacific had reduced, which may be because of the increased resolution of oceanic components. Such improvements would appear to be beneficial for a better representation of the ENSO spatial structure. However, solely refining the atmospheric resolution of climate models substantially degrades the reproduction of ENSO asymmetry and could conflict with the improvements made by the high-resolution oceanic component. A comprehensive assessment of impacts from various resolutions offers a useful perspective for future model development.

1. Introduction

El Niño-Southern Oscillation (ENSO) is the most dominant climate variability on interannual timescales and has substantial impacts on global climate via far-reaching teleconnections (Cai et al., 2021; Dai & Wigley, 2000; Horel & Wallace, 1981; McPhaden et al., 2006; C. Wang et al., 2017). Although numerical experiments enrich our understanding of ENSO dynamics, there are deviations and uncertainties in simulating its key characteristics, such as amplitude, phase locking, diversity, and asymmetry between El Niño and La Niña events in contemporary climate models (Bellenger et al., 2014; Vijayeta & Dommengen, 2018). In particular, many climate models suffer from the long-standing problem of equatorial cold tongue bias, which is considered to be a source of bias in the simulation of the Intertropical Convergence Zone (ITCZ) and ENSO atmospheric feedbacks (Bayr et al., 2018; Kim et al., 2014; Xiang et al., 2012; Zhou et al., 2020).

High-resolution modeling presents evidence that heat transport induced by oceanic eddies in the equatorial Pacific is an important heat source, comparable to the heat supply from the atmosphere (Jochum & Murtugudde, 2006; Menkes et al., 2006). Eddy heating decreases during El Niño but increases during La Niña, constraining ENSO.
amplitude and contributing to ENSO asymmetry (An, 2008; Graham, 2014). However, the eddy-induced heat source is not explicitly resolved in the majority of coupled model intercomparison project climate models at coarse horizontal resolution, which could be partly responsible for the equatorial cold tongue bias. High-resolution climate models outperform their coarse-resolution counterparts. They generate more realistic representations of many aspects of the Earth's system, including the spatial distribution and frequency of tropical cyclones, finescale air-sea fluxes, heat transports of boundary currents, the Atlantic meridional overturning circulation, as well as weather extremes at regional scales (Bellucci et al., 2021; Docquier et al., 2019; Hewitt et al., 2020; Koenigk et al., 2021; Kreussler et al., 2021; M. J. Roberts et al., 2018, 2020; Small et al., 2019; Wengel et al., 2021). However, the impact of climate model resolution on ENSO simulations is yet to be fully understood.

Previous studies based on one individual climate model suggest that the high spatial resolution of the atmospheric component produces improvements in the main features of the simulated ENSO variability (Guilyardi et al., 2004; Hua et al., 2018; Navarra et al., 2008) and ENSO-related seasonal prediction (Jia et al., 2015). In contrast, some studies have reported that simply increasing atmospheric resolution does not necessarily lead to major improvements in ENSO prediction (Zhu et al., 2015) and seasonal forecasts (Scaife et al., 2019). Solely taking the oceanic component to a higher resolution shows either small improvements (M. J. Roberts et al., 2004; Schneider et al., 2003) or higher skill in simulating mean climate, ENSO amplitude, and seasonal prediction (Dawson et al., 2013; Kirtman et al., 2012; Prodhomme et al., 2016). Increasing both oceanic and atmospheric resolutions has improved some ENSO-related characteristics and teleconnections (e.g., Delworth et al., 2012; Prodhomme et al., 2016; Sakamoto et al., 2012; Shaffrey et al., 2009; Small et al., 2014). However, MacLachlan et al. (2015) concluded that increasing the resolution had little impact on ENSO forecasts. Most of the aforementioned findings are model-dependent, with insufficiently high-resolution regimes. Inter-model comparisons at different resolutions are also not well documented. Therefore, we considered whether increasing the climate model resolution is a promising way of improving the representation of ENSO. In the present study, we aimed to answer this question by comprehensively assessing ENSO performance in a multi-model and multi-resolution ensemble from the High-Resolution Model Intercomparison Project (HighResMIP, R. J. Haarsma et al., 2016).

2. Data and Methods

2.1. Observations and Models

For the ENSO metrics calculation, the monthly mean sea surface temperature (SST) and zonal wind stress (Taux) from the Tropflux data set (Kumar et al., 2012), surface air temperature (SAT) and sea level pressure (SLP) from ERA-Interim (Dee et al., 2011), precipitation data from the Global Precipitation Climatology Project version 2.3 (GPCPv2.3; Adler et al., 2003) for the period 1979–2018, and the satellite altimeter product (Ducet et al., 2000) for 1993–2018 were used as observational references for comparison with the model simulation. The monthly mean net heat flux (NHF) data were also obtained from Tropflux, including turbulent (sensible plus latent) surface heat fluxes and radiative (longwave plus shortwave) fluxes.

Seven global coupled climate models participating in HighResMIP were evaluated using the “hist-1950” experiment over the period 1950–2014. The experiment was conducted at different horizontal resolutions varying from standard CMIP6 resolutions (~250 km atmosphere and 100 km ocean) to higher resolutions (25 km atmosphere and 10–25 km ocean), with the same parameterizations, except for the necessary change to scale-dependent ones. There are three regimes of oceanic components (Hewitt et al., 2020): eddy-free (50–100 km), eddy-present (25 km), and eddy-rich (~10 km). The model information is provided in Text S1 and Table S1 in Supporting Information S1, and the detailed configurations are referred to as CESM1-3 (Chang et al., 2020), CMCC-CM2 (Cherchi et al., 2019), CNRM-CM6-1 (Voldoire et al., 2019), EC-Earth3P (R. Haarsma et al., 2020), ECMWF-IFS (C. D. Roberts et al., 2018), HadGEM3-GC31 (M. J. Roberts et al., 2019), and MPI-ESM1-2 (Gutjahr et al., 2019). In the present study, models were grouped into two sub-ensembles: increasing both oceanic and atmospheric resolution, and increasing atmospheric resolution solely, named HR and Atm-HR, respectively. Comparing HR with Atm-HR may highlight the impact of increasing the oceanic resolution on model simulations. It is worth noting that a hierarchical configuration set of ECMWF-IFS was used and consists of an increased oceanic resolution from 100 to 25 km with the same 50 km atmosphere (ECMWF-IFS-LR vs. -MR) and further increased atmospheric resolution to 25 km with 25 km ocean unchanged (ECMWF-IFS-MR vs. -HR). HR-PRIMAVERA (PRocess-based climate sIMulation: Advances in high resolution modeling and European
climate Risk Assessment, www.primavera-h2020.eu) was named for excluding CESM1-3 in HR since only CESM is not included in PRIMAVERA-HighResMIP and has eddy-rich regime.

2.2. ENSO Metrics Package

We used the recently developed CLIVAR ENSO metrics package (Planton et al., 2021) with several modifications to highlight the improvements and shortcomings of ENSO performance in a set of high- and low-resolution configurations. The metrics were composed of four different groups: background climatology, ENSO characteristics, physical processes, and teleconnections. The background climatology group assessed biases in the time-mean and seasonal cycle amplitude of the equatorial Pacific SST, precipitation, Taux, and ITCZ. Some basic ENSO properties (e.g., amplitude, spatial pattern, and seasonality) were evaluated in the ENSO characteristic group. The physical process group collected Bjerkenes feedback along with the thermodynamic damping effect from the NHF and shortwave flux (SWF) feedback, establishing a strong connection among SST, trade winds, thermocline tilt, and heat flux adjustment. The teleconnections group characterizes the global pattern of precipitation, SAT, and SLP associated with ENSO, during boreal winter (December–February (DJF)) and summer (June–August (JJA)). See Text S2 and Table S2 in Supporting Information S1 for detailed explanations and definitions of the metrics. The methods for evaluating the statistical significance of increasing the model resolution for metrics and their relationships are described in Text S3 in Supporting Information S1.

3. Results

3.1. Tropical Pacific Mean States

We first evaluated the root-mean-square error (RMSE) of eight properties between the model and observation and compared model sub-ensembles in the background climatology group (Figure 1). As an illustration, the metric $eq_{-SST\_bias}$ (shown in Figure 1a1) elucidates the well-known cold tongue SST biases of climate models. As for CESM1-3, the RMSE value 0.46 and 1.05 of HR and LR, is plotted as a red and gray circle with mark “H” and “L,” respectively. Whereby the closer the circle is to the dashed orange observational line, the more realistic the cold tongue SST the model represents. The “56%” in red and blue at the bottom of the subpanel measures the extent of improvement and degradation of the CESM1-3-HR and CMCC-CM2-VHR4, respectively, compared to its lower-resolution counterpart by calculating relative difference described in Text S2 in Supporting Information S1. The other subpanels document information in a similar manner. A comparison of the eight properties among all models in the equatorial Pacific is shown in Figure S1 in Supporting Information S1.

Remarkably, the cold tongue SST bias is alleviated as the model resolution is increased in HR (Figure 1a1). However, this prominent improvement disappears when solely the atmospheric component is at a higher resolution in Atm-HR. The reduction in SST cold bias has been speculated to result from the presence of oceanic eddies, such as tropical instability waves (TIWs) in the eddy-present model, which advect heat toward the equator (Jochum et al., 2008). The spatial patterns of SST bias in the ECMWF-IFS models (Figure S2 in Supporting Information S1) provide macroscopic evidence of increasing oceanic resolution: the equatorial SST cold bias in eddy-free ECMWF-IFS-LR is considerably reduced in eddy-present ECMWF-IFS-MR, while further increasing atmospheric resolution in ECMWF-IFS-HR inversely exacerbates the cold bias to an extent. Higher atmospheric resolution in both sets of CMCC-CM2 and MPI-ESM1-2 exacerbated the equatorial SST bias by causing a warm bias extending from the Ecuador coast (Figure S2 in Supporting Information S1), which could be due to weak coastal upwelling under weak easterly winds in the equatorial eastern Pacific (Figure S4 in Supporting Information S1). An unrealistic lack of stratocumulus cloud feedback and weak convective feedback may also contribute to the warm biases, as suggested by previous studies (Caldwell et al., 2019; Small et al., 2014). However, the warm biases in both the Peru-Chile and California upwelling region are alleviated in CMCC-CM2-VHR4 and MPI-ESM1-2-XR with higher atmospheric resolution. This may be due to better representation of surface wind stress with better-resolved coastal topography in finer atmospheric resolution (Gent et al., 2010).

Another significantly improved simulation in HR is equatorial precipitation (Figure 1a2), such that a dry equatorial lower-resolution models is alleviated in higher resolution models, except CESM1-3. This may be partly explained by the reduced SST cold bias through a positive SST-convection relationship. However, compared to GPCPv2.3, all models still have the double-ITCZ problem (Figure 1a3), with a spurious southern ITCZ band extending from the central to eastern basin (Figure S3 in Supporting Information S1). There is conspicuously
excessive northern ITCZ precipitation in CESM1-3-HR, which is inherent to its atmospheric component and may be due to the strong low-level convergence resulting from excessive low-level moist heating associated with precipitation (Bacmeister et al., 2014). In Atm-HR, CMCC-CM2-VHR4 and MPI-ESM1-2-XR represent more equatorial precipitation and larger precipitation seasonal cycles than their lower-resolution counterparts and observations (Figures 1a2 and 1a6).

The equatorial Taux was not evidently improved (Figures 1a4 and 1b) and was weak in the Niño4 region in all models (Figure S4 in Supporting Information S1), among which CMCC-CM2-VHR4 was the weakest. The weakened equatorial zonal SST gradient due to the cold tongue warm bias in CMCC-CM2-VHR4 may be a reason for this. The diversity in the seasonal cycle of equatorial Taux is larger than its mean state (Figure 1a4 and 1a8), and this also holds for other metrics. Increasing the oceanic resolution of ECMWF-IFS in HR presents improvements in all metrics except the equatorial Taux seasonal cycle, while increasing atmospheric resolution tends to deteriorate all metrics except the equatorial Taux bias and the double-ITCZ seasonal cycle.

### 3.2. ENSO Characteristics

We evaluated seven key ENSO properties in the ENSO characteristic group (Figure 2). The ENSO pattern is significantly improved in the eddy-present models in HR-PRIMAVERA (Figures 2a1 and 2c), manifesting as a reduction in ENSO variability bias near the date line and the far eastern region (Figures S5 and S6 in Supporting Information S1). Although the eddy-resolving/rich CESM1-3-HR represents stronger eastern Pacific SST variability than its lower-resolution counterpart, as observed, it spuriously enlarges the variability in the warm-pool region and contradicts such an improvement. CESM1-3-HR also suffers from an ENSO lifecycle with very slow growth and decay (Figure 2a2), and thus, an extremely long ENSO duration (~30 months, Figure 2a3). Whereas
the HR-PRIMAVERA models reproduced the observed ENSO duration (13 months) better but showed insensitivity to model resolution (Figures 2b and 2c).

HighResMIP models exhibit irregular effects on ENSO amplitude compared to observational Niño3.4 SST standard deviation of 0.9°C when refining model resolution (Figure 2a4): some have a weaker amplitude (e.g., CNRM-CM6-1-HR has the weakest), while others have a stronger amplitude (e.g., CMCC-CM2-VHR4 has the strongest). It seems that the uncertainty of modeled ENSO amplitude tends to be heightened in high-resolution models because the inter-model spread becomes larger in high-resolution models compared to low-resolution models (0.19°C vs. 0.12°C per standard deviation), which is more evident in Atm-HR.

ENSO amplitude is asymmetric between El Niño and La Niña with a Niño3.4 SST skewness of 0.4°C (yellow line in Figure 2a5). It is strongest in winter (November–January) but weakest in spring (March–May); this is referred to as ENSO asymmetry and seasonality (i.e., phase locking). Most of the models underestimated ENSO asymmetry and presented extremely weak seasonality (Figures 2a5 and 2a6). ENSO asymmetry shows a tendency to reduce bias in higher resolution models (Figure 2b). However, increasing the resolution of atmospheric components alone notably degrades the representation of ENSO asymmetry (Atm-HR in Figure 2b) and reverses the SST skewness sign. In particular, the ENSO asymmetry of HadGEM3-GC31 models is highly sensitive to model resolution, such as the SST skewness changing from negative to positive in HR and then to negative in Atm-HR (Figure 2a5). El Niño diversity in the central location at either the central or eastern tropical Pacific is not significantly improved in HR but seems to become worse with increased atmospheric resolution (Atm-HR in Figure 2a7).

**3.3. ENSO Feedbacks**

Bjerknes feedback is key to the growth of ENSO instability and consists of three elements: zonal wind stress response to SST anomalies (SST-Taux feedback), SST response to thermocline change (SSH-SST feedback), and thermocline response to zonal wind stress change (Taux-SSH feedback; Figure 3). The SST-Taux feedback is greatly underestimated by 27%–71% in all models except MPI-ESM1-2-HR, while SSH-SST feedback is overestimated by 6%–146% and Taux-SSH feedback is generally close to observations (Figures 3a1–3a3). Too-weak SST-Taux feedback in CNRM-CM6-1/-HR and MPI-ESM1-2-XR may be related to the weak mean zonal wind
stress state in the equatorial Pacific (Figure S1 in Supporting Information S1). MPI-ESM1-2-XR led to a significant deterioration in Atm-HR (Figure 3b). The overly reduced SST-Taux feedback and SSH-SST feedback in the MPI-ESM1-2-XR may be responsible for the weakened ENSO amplitude. ENSO instability is dampened by negative SST-NHF feedback, in which SWF and latent heat flux are dominant contributors (Figure S7a in Supporting Information S1). The SST-NHF feedback is also greatly underestimated by 33%–59% in all models except CMCC-CM2-VHR4 (Figure 3a4). There may be error compensation between the too-weak positive zonal wind feedback and weak negative heat flux feedback, which leads to a simulated ENSO amplitude comparable to that observed (Bayr et al., 2019). Higher resolution models in HR, except CESM1-3-HR, seemed to improve SST-NHF feedback as a result of reduced SST-SWF feedback bias (Figures 3a4 and 3a5). The weaker NHF feedback in higher resolution CESM1-3 is due to the substantial weakening of the SWF feedback. With the exception of CNRM-CM6-1/-HR, too-weak SWF feedback was the main source of weak NHF feedback (Figure S7b in Supporting Information S1). CNRM-CM6-1/-HR has negative shortwave feedback for both warm and cold SST anomalies; however, this contrasts sharply with the observation that shortwave feedback is negative in the convection regime for warm SST anomalies and positive in the subsidence regime for cold SST anomalies (Figure S8 in Supporting Information S1; Bellenger et al., 2014; Lloyd et al., 2012). The shortwave feedbacks in MPI-ESM1-2 and ECMWF-IFS-LR are in the subsidence regime.

Increasing the oceanic resolution of the ECMWF-IFS in HR yielded reduced biases of the positive SST-Taux feedback, positive Taux-SSH feedback, and negative SST-NHF/shortwave feedback. These improved feedback processes may be linked to improved ENSO patterns and amplitudes, which require a detailed investigation of the dynamics.

3.4. ENSO Teleconnections

We evaluated global terrestrial precipitation during DJF and JJA, northern hemisphere (NH)/southern hemisphere SAT, and El Niño composite minus La Niña composite of the global SLP during DJF. All metrics were measured...
using the spatial RMSE. We noted a tendency for degradation of global terrestrial precipitation during DJF in the Atm-HR (Figure 4a1). The model resolution also had a significant impact on global terrestrial precipitation during JJA: all except the ECMWF-IFS models exhibit degradation as model resolution is increased (Figure 4a2). Such a degradation mainly comes from disparities in the American continent (Figure 4c), to which increasing atmospheric resolution solely in Atm-HR seems to be more relevant. In particular, all models underestimated the terrestrial precipitation around the Caribbean Sea and Amazon area during El Niño (Figure S9 in Supporting Information S1), indicating an underestimation of the Walker circulation response.

The impact of increasing resolution on hemispheric SAT teleconnections is not statistically significant, but the eddy-present PRIMAVERA models in HR show better simulation of winter SAT teleconnection over NH land (Figure 4a3). The sensitivity of SLP teleconnection in DJF to model resolution is also ambiguous (Figures 4a5 and 4b). CNRM-CM6-1-HR erroneously represents a teleconnection akin to the Pacific-South American pattern (Figure S10 in Supporting Information S1). It should be noted that ENSO teleconnections have considerable uncertainties arising mainly from atmospheric internal variability (Deser et al., 2017, 2018), thus a single-member-based evaluation may not be conclusive.
4. Discussion

We analyzed the inter-metric correlation to show the potential links between metrics in background climatology, ENSO characteristics, and physical process groups. ENSO lifecycle, duration, pattern, and seasonality biases are exacerbated in CESM1-3-HR, which are inter-correlated, and all of them are associated with the double-ITCZ bias, given that the significant correlations shown in HR disappear in HR-PRIMAVERA (Figures 5a vs. 5b). Although the investigation of their physical connections is beyond the scope of this study, as per Xie et al. (2018), there may be an indication that the seasonal evolution of the double-ITCZ is accompanied by southeasterly cross-equatorial wind anomalies in February-March. This could cause moderate ENSO to dissipate rapidly due to intensified ocean upwelling, while extreme ENSO is difficult to resist. The double-ITCZ bias is inherent to the atmospheric component of CESM1-3-HR, which can be traced back to the deficiency in the Zhang-McFarlane convection scheme (Song & Zhang, 2018). Albeit with the same convection scheme as in CESM1-3-LR/-HR, atmospheric high-resolution may incur spurious low-level convergence to promote excessive convection (Bacmeister et al., 2014).

The significantly improved performance of the ENSO pattern in the eddy-present models in HR-PRIMAVERA is likely due to the reduced biases of the cold tongue SST and precipitation mean state and associated surface thermodynamic feedback. This is inferred from the close relationships between the ENSO pattern bias and the SST-NHF feedback bias, which are further associated with the time-mean equatorial SST and precipitation (Figure 5b). The ENSO asymmetry bias also appears to be related to the cold tongue SST bias (Figures 5b and 5c). As noted earlier, increasing the atmospheric resolution alone significantly degrades the ENSO asymmetry performance. One reason may be the degradation of the cold tongue SST, which is closely related to the increase in equatorial precipitation bias (Figure 5c). The degradation of the nonlinear atmospheric Bjerknes feedback may also contribute to this. Geng et al. (2019) suggested that nonlinear atmospheric feedback, by which the zonal wind response increases with positive SSTA anomalies, plays a dominant role in controlling ENSO asymmetry. We preliminarily examined the inter-model relationship between ENSO asymmetry and nonlinear atmospheric feedback. The results showed that most models with smaller SST-Taux feedback nonlinearity tended to have weaker ENSO asymmetry (Figure S11 in Supporting Information S1). However, this relationship does not seem to operate in CESM1-3-HR/-LR and HadGEM3-GC31-HM, regarding which in-depth analysis is required.

Cold tongue SST bias was significantly reduced in the eddy-present HR-PRIMAVERA models and eddy-rich CESM1-3-HR. We conjecture that a reasonable representation of heat transport by oceanic eddies with an increased oceanic resolution may be an important contributor. As can be clearly seen from the standard deviation of the 70-day highpass-filtered SST in CESM1-3-LR/-HR, the eddy-rich resolution configuration shows vigorous TIW activity between the equator and 5°N, stronger than that observed, while the lower-resolution counterpart shows much weaker TIW activity (Figure S12 in Supporting Information S1). The large sub-70-day SST variability in CESM1-3-HR may be due to the additional heat supply from sub-mesoscale eddies (S. Wang et al., 2022).

Figure 5. Linear correlation between metrics in background climatology, El Niño-Southern Oscillation characteristics and physical process in (a) HR, (b) HR-PRIMAVERA, and (c) Atm-HR sub-ensembles. Only correlations significant above the 95% confidence level are shaded. Hatching plots indicate the correlations that are significant above the 95% confidence level using the Wald test but insignificant as per Student’s t-test.
Notably, the TIWs also contribute to modulate negative ENSO feedbacks in eddy-present/rich models especially in a warming climate (Wengel et al., 2021).

5. Concluding Remarks

The current study elucidated comprehensive information on the impacts of various model resolutions on tropical Pacific mean states and ENSO performance (summarized in Figure S13 in Supporting Information S1), which may help the community to continue increasing confidence in simulating ENSO and its global impacts with high-resolution Earth system models. In general, eddy-present/rich climate models reproduce more realistic equatorial time-mean SST and precipitation than their low-resolution counterparts, suggesting that oceanic eddies play an important role in promoting heat transport to alleviate cold tongue bias. The benefits of increasing resolution become evident when looking at the ENSO pattern, which is well reproduced by the eddy-present oceanic resolution. It is further inferred that the improved ENSO pattern could be partly ascribed to the eddy-present oceanic SST and equatorial precipitation associated with the NHF feedback. One of the more significant findings is that increasing atmospheric resolution alone would deteriorate the representation of ENSO asymmetry, likely resulting from the degradation of the SST mean state and nonlinear atmospheric feedback (SST-Taux feedback nonlinearity). In addition, the thermodynamic effect from the NHF feedback is indispensable to ENSO dynamics; however, it remains substantially underestimated. The biased shortwave feedback predominantly contributes to the underestimated of the NHF feedback and is insensitive to the increase in the model resolution. This calls into question the model representation of cloud properties, leaving plenty of room for improving the cloud parameterization. The mechanisms underlying the impact of model resolution require detailed investigation, which should be the focus of future work.

Data Availability Statement

Detailed information on the El Niño-Southern Oscillation (ENSO) metrics can be found at https://github.com/CLIVAR-PRP/ENSO_metrics/wiki/. Observational datasets can be downloaded as follows: GPCPv2.3 https://www.esrl.noaa.gov/psd/. TropFlux https://incois.gov.in/tropflux/tf_products.jsp. ERA-Interim https://esgf-node.llnl.gov/search/create-ip/. AVISO https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global.html.

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