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Key Points:

- Global climate models exhibit severe SST biases in tropical Atlantic
- High vertical atmosphere model resolution substantially improves SST simulation
- There is potential to improve climate predictions in the tropical Atlantic

Supporting Information:

- Table S1 and Figures S1 to S4

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Improving climate model simulation of tropical Atlantic sea surface temperature: The importance of enhanced vertical atmosphere model resolution

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Abstract A long-standing problem in climate modeling is the inaccurate simulation of tropical Atlantic (TA) sea surface temperature (SST), known as the TA SST bias. It has far-reaching consequences for climate prediction in that area as it goes along, among others, with erroneous precipitation patterns. We show that the TA SST bias can be largely reduced by increasing both the atmospheric horizontal and vertical resolutions in a climate model. At high horizontal resolution, enhanced vertical resolution is indispensable to substantially improve the simulation of TA SST by enhancing surface wind stress. This also reduces biases in the upper ocean thermal structure and precipitation patterns. Although, enhanced horizontal resolution alone leads to some improvement in the mean climate, typical bias patterns characterized by a reversed zonal SST gradient at the equator and too warm SST in the Benguela upwelling region are mostly unchanged at a coarser vertical resolution.

1. Introduction

State of the art coupled climate models still exhibit severe biases in the tropical Atlantic (TA) mean climate [*Xu et al.,* 2014], while they simulate basic structures of equatorial climate in the Pacific and Indian Ocean sectors sufficiently well [*Flato et al.,* 2013]. The current generation of climate models (Coupled Model Intercomparison Project Phase 5 (CMIP5)) did not succeed in making large progress solving these problems, compared to the previous CMIP3 [*Richter et al.,* 2012]. In fact the TA bias problem was already reported more than a decade ago [*Davey et al.,* 2002]. The errors appear to originate from a number of different sources that depend on the specific region considered. For example, the relatively small zonal extent of the TA and the existence of persistent easterly zonal surface winds, giving rise to a warm pool-cold tongue structure in equatorial Atlantic sea surface temperature (SST), are factors that make large-scale interactions between the atmosphere, ocean, and land in the equatorial region more sensitive to initial errors than in the equatorial Pacific.

Pronounced biases in the TA are too warm SSTs in the eastern tropical Atlantic (ETA, 10°E–20°E) around 20°S, a reversed zonal SST gradient along the equator, an underestimated warm pool in the western equatorial Atlantic and too shallow (deep) thermocline in the western (eastern) basin [*Flato et al.,* 2013]. Furthermore, most models do not capture the seasonal cold tongue development which is linked to the onset of the West African monsoon and the associated cross equatorial winds [e.g., *Caniaux et al.,* 2011] generating upwelling south of the equator. *Richter and Xie* [2008] as well as *Richter et al.* [2011] showed that precipitation biases over the surrounding continents have an influence on sea level pressure (SLP) and hence surface winds. These in turn affect thermocline depth and remotely, via equatorial and coastal Kelvin waves, the SST warm bias in the ETA. The incorrect simulation of the mean state and annual cycles degrades simulation of interannual SST variability in the TA, which in turn may lead to reduced predictability of SST and related impacts in and outside the TA region in climate models [*Keenlyside et al.,* 2013; *Stockdale et al.,* 2006].

It is still under debate how to effectively reduce these biases in coupled models. Several studies investigated the impact of the marine low-level stratus cloud deck which is generally underestimated in climate models [*Huang and Hu*, 2007]. By artificially reducing incoming shortwave radiation, *Wahl et al.* [2011] alleviated the warm SST bias in the eastern TA by 2.5°C. The bias was also reduced in a study by *Hu et al.* [2010], where they highlighted the importance of the cloud liquid water path and absorption of shortwave radiation. More realistic representation of land convection in the deep tropics has been shown to improve simulations of the tropical Atlantic mean climate, without artificially changing the wind stress, by *Richter et al.* [2011] and *Wahl et al.* [2011]. Attempts to reduce the warm bias have also been made by changing the ocean component of climate models, e.g., by enhancing mixing at the base of the ocean mixed layer [*Hazeleger and Haarsma*, 2005] or by increasing resolution [*Seo et al.,* 2006; *Doi et al.,* 2012.]. However, multiple mechanisms are likely to contribute to biases in the TA. In this paper, we investigate the impact of an increased atmosphere model resolution on the TA warm bias, while leaving the ocean resolution unchanged. Special emphasis is given to the impact of enhanced atmospheric vertical resolution.

2. Data and Methods

The Kiel Climate Model (KCM) [*Park et al.,* 2009], a coupled atmosphere-ocean-sea ice general circulation model, is used to conduct a series of climate simulations with different atmosphere model resolutions. The ocean component Nucleus for European Modelling of the Ocean (NEMO) [*Madec*, 2008] is kept unchanged at a horizontal resolution of 2°, with a latitudinal refinement of 0.5° in the equatorial region, and 31 levels. Four different versions of the atmospheric general circulation model (ECHAM5) [*Roeckner et al.,* 2003] are employed in the KCM. First, a low-resolution (T42, ~2.8°; hereafter "LR") and a high-resolution (T159, ~0.75°; hereafter "HR") versions are used, both with 31 levels (L31). Second, both horizontal resolutions are run with 62 vertical levels (L62). The latter two integrations are referred to as "LR_V" and "HR_V," respectively. The additional levels are placed in between the original levels, with six levels below 850 hPa in L31 and 14 levels in L62. The top levels remain at a similar height of 10 hPa (LR, HR) and 5 hPa (LR_V, HR_V), respectively. No fine tuning has been applied to the model setups.

Each experiment is run for 20 years, which is long enough to allow for the development of the TA SST bias, as the time of the gravest baroclinic waves to cross the equatorial Atlantic and propagate along the African coast is rather short, amounting to less than a year. Further, a comparison of the first and last 30 years of a 1299 years long control run with the standard KCM configuration [*Park et al.,* 2009; *Wahl et al.,* 2011] did not depict any significant differences regarding the mean state in the upper TA. This does also apply to the extended LR simulation of 100 years length, from which the last 50 years have been analyzed. In this study the last 14 years on the basis of monthly data are used. Results are only shown for boreal summer from July to September (JAS), when the TA bias is largest. For verification, the observational data sets Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) [*Rayner et al.,* 2003], Levitus [*Levitus et al.,* 1998], and the Global Precipitation Climatology Project (GPCPv2) [*Adler et al.,* 2003] are used, as well as reanalysis data products from ERA-Interim [*Dee et al.,* 2011].

3. Results

We first analyze the model biases in SST. The LR configuration of the KCM exhibits a large warm SST bias in the ETA, which is typical for many climate models, with errors even exceeding +7°C in small regions along the Benguela upwelling region during JAS (Figure 1a). In the standard version of the KCM (T31, L19), the SST in the Benguela Current region is even 3°C warmer [*Wahl et al.,* 2011], indicating large sensitivity to atmosphere model resolution. The HR configuration with increased horizontal resolution yields a significant decrease in bias magnitude, whereas the spatial structure of the bias pattern remains mostly unchanged (Figure 1b). Yet the bias in the zonal SST gradient along the equator is somewhat alleviated, with reductions in both the cold bias in the west and the warm bias in the east.

We now turn to the influence of the vertical atmosphere model resolution. A cooling of the SST with a magnitude of less than 1°C in the cold tongue region and a warming exceeding 1°C in the western equatorial Atlantic is achieved in LR_V (Figure 1c). The major result of this study is that magnitude and spatial structure of the TA SST bias change drastically in HR_V (Figure 1d), i.e., when both horizontal and vertical atmosphere model resolutions are enhanced. The SST bias in this configuration is reduced to less than 2°C in most regions of the TA, and the major warm bias area in the southeast moves westward away from the African coast. Most obvious are the improvements in JAS (other seasons are not shown) when the seasonal equatorial cold tongue is fully developed and almost no SST bias is seen anymore. The mean absolute SST error (over 40°S–20°N, 60°W–20°E) in JAS is halved in HR_V compared to LR (Table S1 in the supporting information).

Like SST, the simulation of total (convective plus large-scale) precipitation in LR also exhibits large biases in the TA, with a dipole pattern characterized by too wet conditions in the east and too dry conditions in the west (Figure 2a), partly reflecting the structure of the SST bias. The latitudinal position of the marine intertropical convergence zone (ITCZ) is located too far south in the tropics and maximum rainfall is simulated

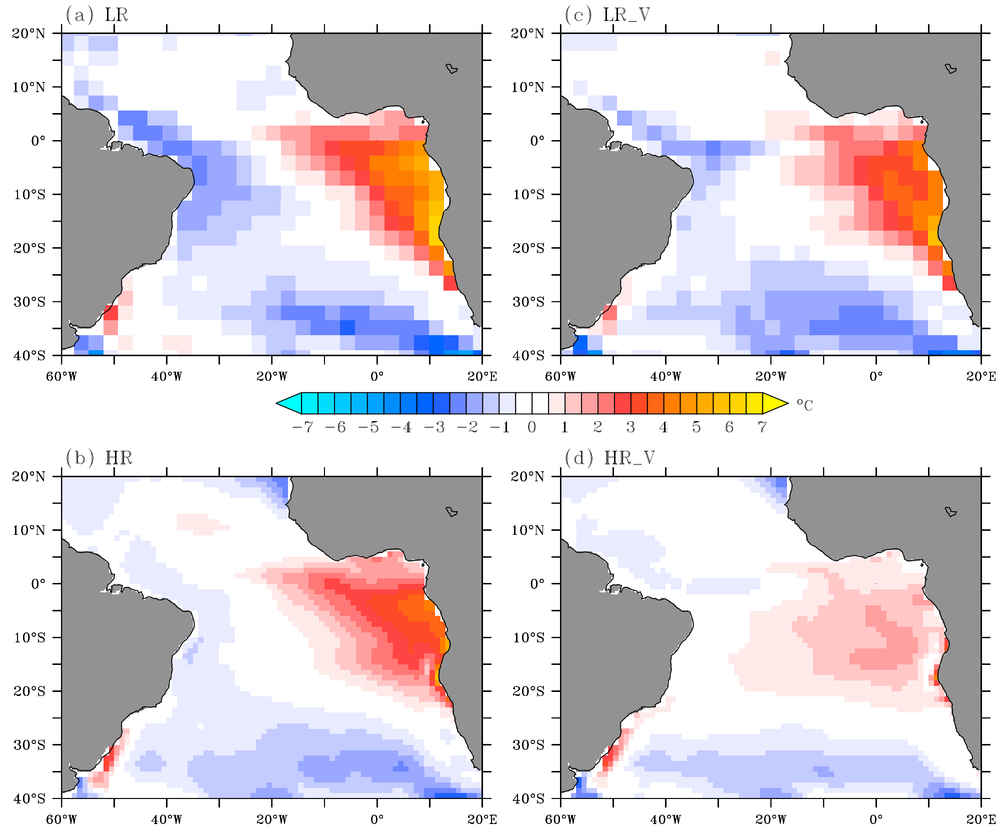

Figure 1. Sea surface temperature (SST) bias with respect to HadISST (°C) in JAS. (a) LR (T42, L31); (b) HR (T159, L31); (c) LR_V (T42, L62); and (d) HR_V (T159, L62).

in the area of too warm SSTs. The choice of higher horizontal resolution in HR leads to a northwestward shift of the wet bias and decreased (increased) precipitation over the Sahel region (northern South America) (Figure 2b). There is a noticeable effect in LR_V (Figure 2c), where the bias magnitude over equatorial West Africa and the eastern equatorial Atlantic is somewhat smaller than in HR. It is only the HR_V configuration (Figure 2d) that is capable of pushing rainfall sufficiently far north of the equator to significantly improve the West Africa monsoon system. The mean absolute error (MAE) over the TA (Table S1) shows that precipitation biases are larger over the ocean than over land. Enhanced vertical resolution at coarse horizontal resolution *(*LR_V*)* reduces precipitation biases over the ocean but not over land. The smallest MAE over land is in HR_V. We note, however, that the rainfall biases are still on the order of the climatological values. This suggests that an attempt should be made to adjust the physical parameterizations to the higher resolution, which have been left unchanged here.

Further insights into the dynamical processes responsible for the SST bias reduction at the equator can be gained from analyzing zonal sections (3°S–3°N) of selected quantities. All CMIP3 and CMIP5 models, which are integrated without flux correction, simulate a reversed zonal SST gradient along the equator [*Richter et al.,* 2012] with lower than observed SST in the west and higher SST in the east. This is also evident in LR, whereas LR_V and HR depict some improvements relative to LR (Figure 3a). Only the HR_V configuration reasonably well reproduces the observed zonal SST gradient, with biases less than 1°C. Interestingly, the equatorial SST bias in LR_V is not only substantially reduced compared to LR but also less than that in HR in the center of the cold tongue, which again demonstrates the importance of the vertical atmospheric resolution. However, LR and LR_V do not differ significantly in the very east close to the coast.

Looking at the ocean interior, we find that the depth of the 20°C isotherm in the western part of the basin deepens with higher vertical resolution (Figure 3b), which gives rise to higher SSTs (Figure 3a). Again, the importance of the vertical resolution is obvious, as LR_V simulates a thermocline depth in the west that is larger and thus closer to observations than in HR. There is much reduced resolution sensitivity of thermocline

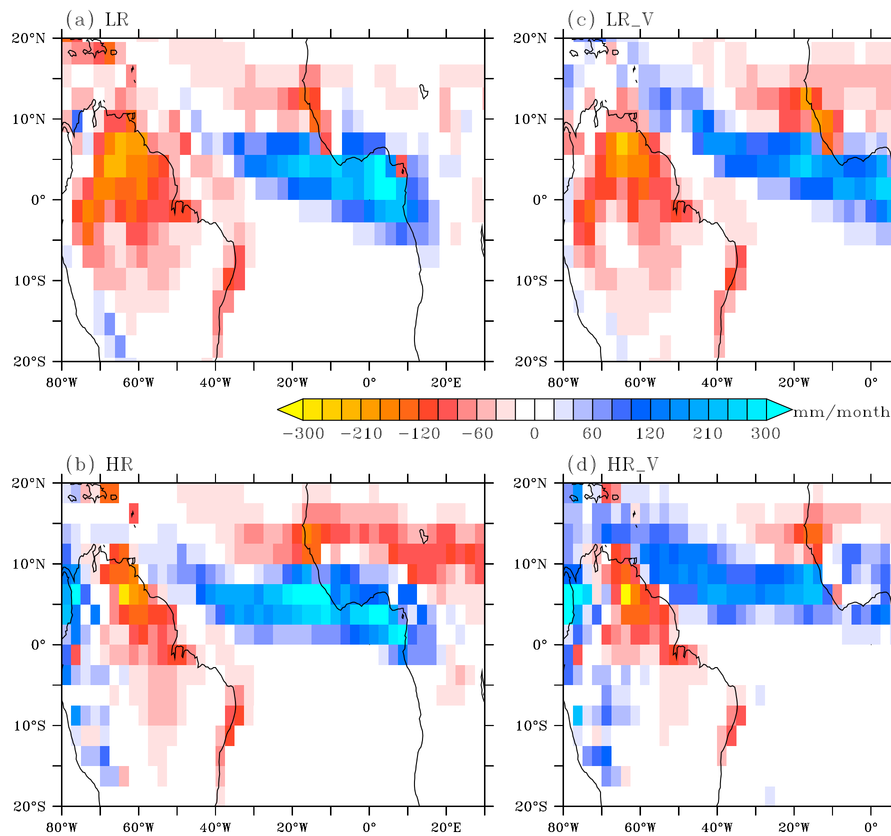

Figure 2. Total precipitation bias with respect to GPCP (mm per month) in JAS. (a) LR (T42, L31); (b) HR (T159, L31); (c) LR_V (T42, L62); and (d) HR_V (T159, L62).

depth in the eastern part of the basin, where all configurations do not well capture the thermocline shoaling important to establish colder SSTs.

The vertical thermal structure of the equatorial Atlantic depends in part on the zonal wind stress. There is a clear separation of model runs with and without high vertical resolution, where the higher vertical resolution configurations of the KCM simulate equatorial zonal wind stress much closer to observations (Figure 3c). The improved wind stress results in a more realistic representation of temperatures along the equator in the upper 250 m that are shown here only for the two high horizontal resolution configurations (Figures 4a and 4b). The better representation of zonal wind stress along the equator in HR_V relative to HR goes along with much reduced subsurface temperature biases, especially in the depth range 50–150 m. Since the zonal wind stress is also much closer to observations in LR_V compared to LR, a similar decrease of subsurface temperature biases along the equator is achieved in LR_V (Figure S1).

We now turn to the vertical thermal structure in the ETA off the southwestern African coast. The HR configuration exhibits, in addition to the pronounced SST bias in the upwelling region around 20°S (Figure 1c), severe subsurface temperature biases in the same area, with too warm temperatures at and north of the upwelling region and too cold temperatures further south (Figure 4c). In contrast, HR_V shows not only a strongly reduced SST bias in the ETA (Figure 1d), but also somewhat reduced subsurface temperature biases, especially north of the upwelling region (Figure 4d). However, the improvement in subsurface temperature is modest and relatively large deviations from observations remain. Only slight improvements occur from LR to LR_V, with subsurface biases in LR_V being larger than in HR (Figure S1).

The seasonal cycle of equatorial SST does improve with enhanced vertical resolution. We depict the seasonal cycle of SST along the equator (3°S–3°N) as a function of calendar month for the low and high horizontal resolution configurations (Figure S2). The seasonal cold tongue is fully developed in August and located at around 10°W. Regardless of the horizontal resolution, enhanced vertical resolution increases the amplitude to

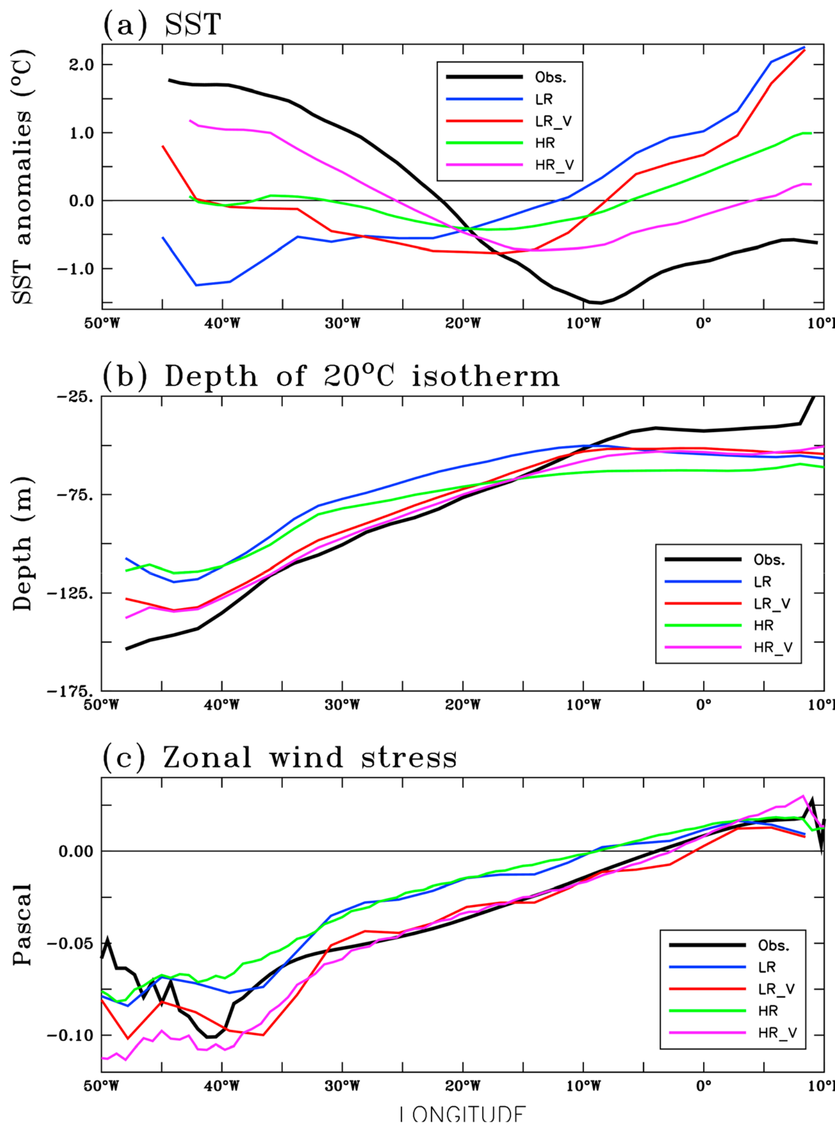

Figure 3. Seasonal mean JAS zonal sections along the equator (3°S–3°N) for (a) SST anomalies (°C) with respect to their zonal mean, (b) depth of 20°C isotherm (m), and (c) Zonal wind stress (Pa). Black line denotes the following observations: (Figure 3a) HadISST, (Figure 3b) Levitus, and (Figure 3c) ERA-Interim. Blue: LR (T42, L31); red: LR_V (T42, L62); green: HR (T159, L31); and purple: HR_V (T159, L62).

asimilar level as observed, but a westward shift by roughly 10° and a time delay by around 1 month still exist. HR and HR_V reproduce the spatiotemporal pattern of the seasonal cycle better, than their LR counterparts.

Finally, we consider the TA SST interannual variability which involves subtle interactions with the seasonal cycle [e.g., *Lübbecke et al.,* 2010]. The simulation of the interannual SST variability in the equatorial region is much improved when the vertical atmosphere model resolution is enhanced. We note, however, that the runs are relatively short so that there is some uncertainty in the estimation of the interannual variability. The standard deviations of the SST anomalies in the ATL3 region (3°S–3°N, 20°W–0°) are depicted as a function of calendar month (Figure S3). In contrast to the observations, which exhibit a strong seasonality peaking in June, LR and HR depict no seasonal cycle in the variability. Increasing the number of levels in the atmosphere model leads to a more realistic simulation of the overall level of interannual SST variability and its seasonal phase locking. This also demonstrates the importance of enhanced vertical resolution for improving equatorial TA interannual variability. However, there is a phase lag in the peak variability of 2 (HR_V) and 3 (LR_V) months compared to the observations. We further regress the boreal summer TA SSTs on the

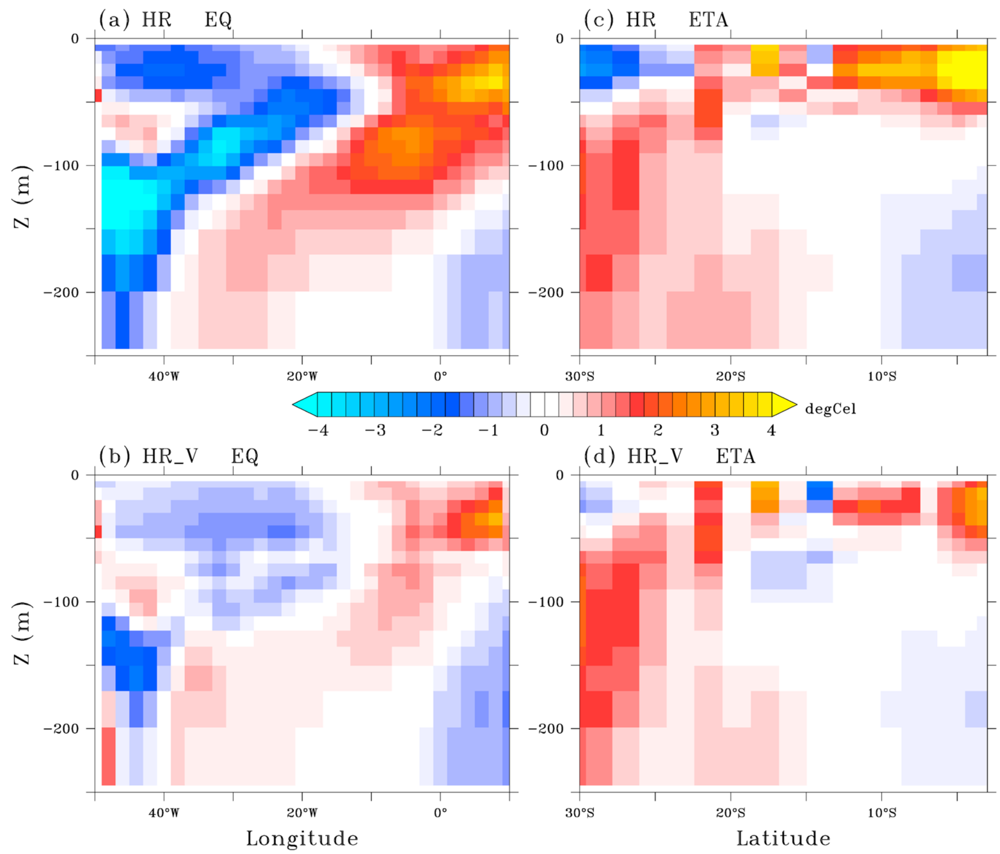

Figure 4. Subsurface temperature bias (°C) in the upper 250 m with respect to Levitus 1998 in JAS for (a, b) the equatorial region (EQ, 3°S–3°N) and (c, d) the eastern tropical Atlantic (ETA, 10°E–20°E). (Figures 4a and 4c) HR (T159, L31) and (Figures 4b and 4d) HR_V (T159, L62).

ATL3 index, which reveals a northward shift of maximum regression coefficients in LR_V and HR_V and is closer to observations (Figure S4). The better agreement with observations is especially seen in the Benguela upwelling region and south of it. In terms of amplitude and pattern correlation, HR_V performs best.

4. Conclusions

A series of fully coupled climate model integrations revealed that the quality of tropical Atlantic (TA) SST and rainfall simulations can be substantially improved by enhancing horizontal and vertical atmospheric resolutions. By increasing only the horizontal resolution, biases in the TA SST are reduced mostly with regard to the area-mean SST, while the spatial bias pattern remains unchanged. The simulation of precipitation is not significantly improved either. Features such as a reversed zonal SST gradient at the equator, large warm SST and subsurface temperature bias in the ETA as well as a too southerly position of the ITCZ still exist. Only when using high resolution in both the horizontal and vertical, these biases are strongly reduced. The marine ITCZ is now sufficiently far north of the equator and the West African monsoon system is much improved. Furthermore, this configuration has a much better representation of the upper ocean thermal structure, especially at the equator.

The question arises why only higher resolution in both the horizontal and the vertical has such a strong impact on the mean climate in the TA. As proposed by *Richter and Xie* [2008], a major cause of the equatorial TA SST bias is precipitation over the adjacent land areas: too dry (wet) conditions over South America (Africa) lead to a local increase (decrease) of surface pressure, which alters the zonal SLP distribution and finally impacts surface winds and surface wind stress along the equator. There is an overall improvement of total precipitation over the continents, especially over South America in both HR and HR_V. One factor contributing to the reduced dry bias is an increase in large-scale precipitation along orographic features, as they are much better resolved. This is also reflected in the zonal SLP distribution along the equator. Too high (low) SLP in the west (east) is simulated in LR, LR_V, and HR, compared to a realistic SLP gradient in HR_V (not shown).

The representation of the marine low stratus cloud deck in the eastern TA is underestimated in the KCM, as it is in most models, and does not improve in the four configurations described in this study. In fact, net surface shortwave radiation increases in the cases of higher vertical resolution over the Benguela upwelling region, but this goes along with an increase in net surface longwave radiation. Orography might also impact the Benguela upwelling region where high elevations next to the coast is challenging for spectral models, as they tend to place land points too far in the ocean and exaggerate elevation peaks. Further, a larger number of vertical levels might impact transport of heat and momentum in the lower atmosphere. It is hard to find one root cause for the substantial improvements in HR_V, since many processes act together and influence each other, given the coupled nature of the problem.

Substantial improvements are seen already when high vertical resolution is used in conjunction with coarse horizontal resolution, which stresses the importance of sufficient vertical resolution. Further, the model results suggest that horizontal and vertical resolutions ought to be chosen consistently and thus lend support to scaling arguments deduced from quasi-geostrophic theory by *Lindzen and Fox-Rabinovitz* [1989]. In the Kiel Climate Model (KCM), which was used here, an atmospheric horizontal resolution of T159 with 62 levels yields a reasonable representation of the TA mean climate and its interannual variability. As our results are based on a single model, other coupled models may exhibit different sensitivities to model resolution. The computational costs for LR_V are similar to those of LR, but from our point of view LR_V is not consistent in terms of the horizontal and vertical resolution. Nevertheless, it underlines the value and necessity of an increased vertical resolution. As the time step reduces when horizontal resolution increases, the vertical resolution should also increase. High horizontal resolution will resolve processes on a finer scale that if they are not adequately resolved in the vertical, will add noise too the system and reduce the overall performance of the model [*Lindzen and Fox-Rabinovitz*, 1989]. Recent publications with very high horizontal resolutions in the atmosphere (and the ocean), but only relatively coarse vertical resolutions, also show large improvements in the simulation of Eastern TA SST [e.g., *Small et al.,* 2014; *Doi et al.,* 2012]. This suggests that better physical parameterizations and/or enhanced ocean resolution is an alternative to enhancing vertical atmospheric resolution. *Tozuka et al.* [2011] support this conjecture by exploring the effect of different cumulus convection schemes. They report a large sensitivity. In their climate model, one scheme almost completely eliminated the equatorial TA SST bias.

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