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Key Points:

- High atmospheric horizontal resolution eliminates the coastal SST bias in the southeastern tropical Atlantic
- The coastal SST bias is caused by a misrepresentation of the surface wind stress at low atmospheric horizontal resolution
- The orography at low atmospheric resolution causes approximately half of the coastal SST bias via its influence on the surface wind stress

Supporting Information:

- Supporting Information S1

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High atmospheric horizontal resolution eliminates the wind-driven coastal warm bias in the southeastern tropical Atlantic

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Abstract We investigate the strong warm bias in sea surface temperatures (SST) of the southeastern tropical Atlantic that occurs in most of the current global climate models. We analyze this bias in the Max Planck Institute Earth System Model at different horizontal resolutions ranging from 0.1° to 0.4° in the ocean and 0.5° to 1.8° in the atmosphere. High atmospheric horizontal resolution eliminates the SST bias close to the African coast, due to an improved representation of surface wind stress near the coast. This improvement affects coastal upwelling and horizontal ocean circulation, as confirmed with dedicated sensitivity experiments. The wind stress improvements are partly caused by the better represented orography at higher horizontal resolution in the spectral atmospheric model. The reductions of the coastal SST bias obtained through higher horizontal resolution do not, however, translate to a reduction of the large-scale bias extending westward from the African coast into the southeastern tropical Atlantic.

1. Introduction

The SST biases in the tropical Atlantic are a long-standing problem common to most climate models [*Richter et al.*, 2014]. *Ding et al.* [2015] find that the mean state biases affect the representation of interannual variability in the tropical Atlantic, which might not be true for other models [*Richter et al.*, 2014]. The warm bias is largest along the eastern boundary of the southeast tropical Atlantic (SETA) and, while covering large parts of the tropical south Atlantic, decreases toward the west.

In this study, we focus on the coastal SST bias that we define as the localized, strong rise of simulated SST close to the African coast in the SETA region. We show that increased horizontal resolution in the atmosphere eliminates the coastal SST bias due to a better representation of the surface wind stress which can be partly explained by better resolved orography.

Multiple causes for the development of the coastal warm bias in the SETA region have been suggested [*Richter*, 2015]. A local underrepresentation of low-level clouds was found to create excessive heating of the ocean by shortwave radiation [*Wahl et al.*, 2011], but also, a remote contribution from the surface wind stress on the equator via Kelvin waves traveling southward along the coast has been suggested [*Richter et al.*, 2011]. Locally, strong winds close to the coast drive coastal upwelling, bringing cold water masses to the surface [*Nicholson*, 2010]. These surface winds are too weak in many models, leading to an underestimation of the coastal upwelling [*Vanniere et al.*, 2014; *Gent et al.*, 2010; *Large and Danabasoglu*, 2006; *Richter et al.*, 2011] and misrepresentation of horizontal ocean circulation [*Small et al.*, 2015]. At higher atmospheric horizontal resolution, these winds were found to increase, coincident with a reduction of the coastal SST bias [*Doi et al.*, 2012; *Small et al.*, 2014]. These studies indicated that increasing horizontal resolution in the atmosphere can alleviate the persistent SST biases in the models. However, the attribution of the too weak winds close to the coast to a certain atmospheric model component remains elusive [*Griffies et al.*, 2011; *Small et al.*, 2015].

A possible cause for the wind bias might be the misrepresentation of the coastal orography [*Large and Danabasoglu*, 2006; *Harlaß et al.*, 2015]. Low-resolution spectral atmospheric models fail to represent the gradients and the height of the orography in the vicinity of strong orographic gradients, such as on the African coastline in the SETA region. This misrepresentation is due to the Gibbs phenomenon that arises from the truncation of higher-order terms during the transformation of the observed orography to the spectral domain. Close to strong gradients in the observed orography, the truncation of the higher-order terms leads to a more gradual slope as well as overshooting and undershooting of the observed height [*Washington and Parkinson*, 2005]. These deficiencies can be reduced by including more higher-order terms in the spectral domain, that is, increasing the horizontal resolution of the spectral atmospheric model. In the Pacific, the coastal low-level jet off the coast of California was found to depend on an adequate representation of coastal orography, land-sea contrast, and the shape of the coastline [*Ranjha et al.*, 2016]. Although it seems plausible that the orography contributes to the wind bias and thus to the SST bias, it has not been shown that the misrepresentation of the orography in spectral models is the cause of the wind bias and how much it contributes to the SST bias.

Here we systematically investigate the influence of the orographic resolution on the surface winds by replacing the orography in a high-resolution simulation with a low-resolution orography. This isolates the effect of the low-resolution orography on the surface winds and subsequently on the SST bias while maintaining the high resolution for all other model components. Furthermore, we examine the effect of the improved surface winds on upwelling and advection in the ocean model by using dedicated sensitivity experiments.

2. Model, Data, and Methods

The Max Planck Institute Earth System Model (MPI-ESM) [*Giorgetta et al.*, 2013] is used for this study. It consists of the MPI Ocean Model [*Jungclaus et al.*, 2013] version 1.5 and the spectral European Center-Hamburg (ECHAM6) [*Stevens et al.*, 2013] atmospheric model version 6.1. Both the ocean and atmosphere models are used at high and low horizontal resolution in different combinations. The high-resolution ocean model is running on an eddy-resolving 0.1° tripolar grid with 40 vertical levels [*von Storch et al.*, 2012], whereas the low-resolution model version is using a tripolar grid with 0.4° horizontal resolution but the same vertical resolution. The high-resolution atmospheric model is running at T255, denoting a triangular truncation of the spherical harmonics to 255 wave numbers, providing a horizontal resolution of approximately 40 km. The low-resolution model has a resolution of T63 (˜200 km); both have 95 vertical layers. We use a set of four experiments that cover all possible combinations of high and low horizontal resolution in the atmosphere and ocean (*HR*: T255 atm/0.1°oc.; *LR*: T63 atm/0.4°oc.; HRatm: T255 atm/0.4°oc.; HRoc: T63 atm/0.1°oc.; note that LR here is the same as *MR* in *Giorgetta et al.* [2013]). All simulations are initialized from a spun-up state of an LR control run for the ocean and use the same preindustrial forcing. The ocean and the atmosphere are coupled every hour. We use a 26 year mean from each experiment to analyze the SST differences. The experiments have different integration lengths, ranging from 38 to 90 years. We analyzed periods from the beginning and end of each simulation and found no evidence for SST drift in the tropical Atlantic.

As a reference SST we use the period 1980–2005 (26 years) from the HadISST1 data set [*Rayner et al.*, 2003] on a 1°grid. The time mean SST bias is calculated relative to HadISST by subtracting the spatially averaged SST for the tropics (30°S–30°N, all longitudes) from all experiments and the observations to account for the different mean states. All data sets are interpolated to a regular horizontal 0.25°grid.

A flux adjusted experiment with a modified surface wind stress is carried out with the LR model version. We derive the flux correction terms for the wind stress from the climatological difference between LR and HR wind stress. This correction term is added to the momentum flux computed by the atmospheric model before it is applied to the ocean. The experiment is run for 20 years; the last 10 years are used for the analysis. The model adjusts to the different wind stress within the first 2 years and does not show any drift thereafter.

A sensitivity experiment with modified mean orography, HRatmMOD, is constructed based on the HRatm setup. We implement the mean orography from the T63 model version into the HRatm setup to quantify the effect of the resolution of the orography on the surface wind stress and SST bias. To construct this orographic field, the T255 surface geopotential is truncated to T63 by setting all higher wave numbers to zero. The subgrid-scale fields, which affect parameterizations, have not been changed. This experiment is integrated for 10 years, preceded by a 2 year spin-up.

3. Results

We differentiate between the coastal and the large-scale bias and focus mostly on the coastal bias. The large-scale bias is defined as the warm bias covering most of the south-equatorial Atlantic with an

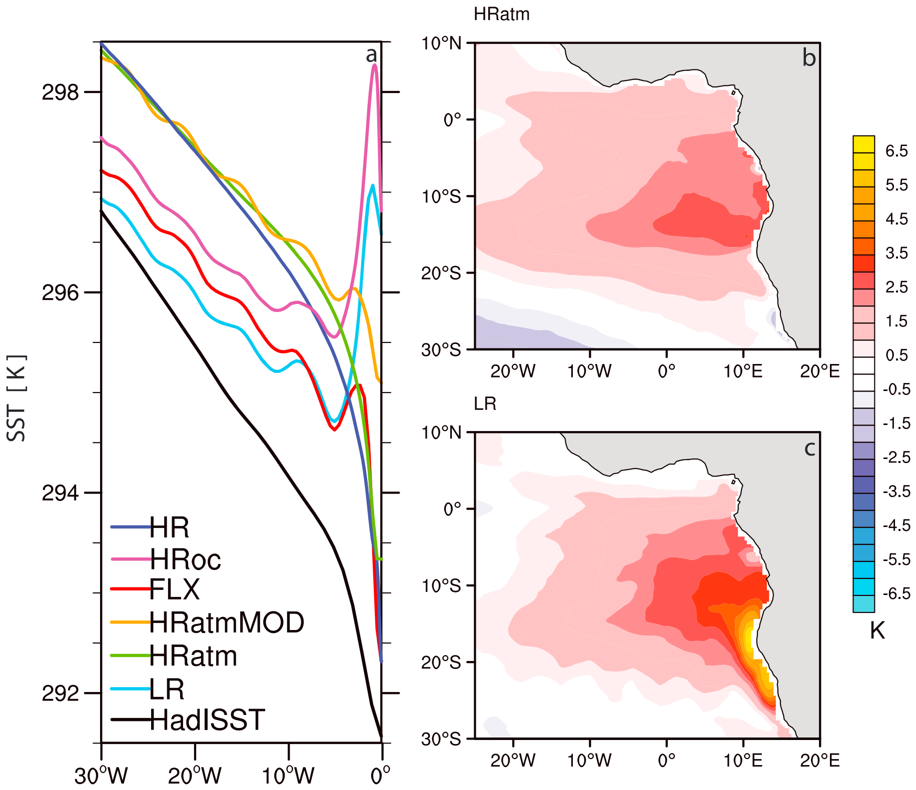

Figure 1. High atmospheric horizontal resolution eliminates coastal SST bias in the SETA region: (a) coast-following meridional mean of SST on model grid, averaged 15°S to 25°S; (b) time mean SST bias for HRatm (0.5° horizontal resolution); and (c) time mean SST bias for LR (1.8° horizontal resolution).

approximately linear increase toward the coastline in the east. The coastal bias is defined as the localized, strong warm anomaly close to the coast that is superimposed on the linear eastward increase of the large-scale bias.

Increased atmospheric horizontal resolution eliminates the coastal SST bias in the SETA region, while it does not significantly affect the large-scale SST bias in the MPI-ESM. In a suite of experiments with different combinations of high and low horizontal resolution in the atmosphere and ocean, the coastal SST bias is eliminated in those experiments with high horizontal resolution in the atmosphere (HR, HRatm), whereas the experiments with low atmospheric horizontal resolution (LR, HRoc) exhibit a strong coastal SST bias (Figure 1a). The observed SST is monotonically decreasing toward the eastern coast of the south Atlantic. A zonal slope similar to the observations can be seen in those experiments with a high horizontal resolution in the atmosphere albeit with a positive offset in the global average SST. The experiments with low resolution in the atmosphere (LR, HRoc) exhibit a sharp rise in SST close to the African coast. This coastal bias is even stronger in HRoc where only the ocean horizontal resolution is increased, whereas the ocean resolution has no substantial effect on the coastal bias at high atmospheric resolution. The large-scale SST bias, which is the difference in the zonal slope of the SST between observations and the model further off the coast in Figure 1a, is not significantly affected by changes in atmospheric or oceanic horizontal resolution. This is also evident from the two-dimensional distribution of the bias in Figures 1b and 1c: the coastal bias is reduced at high atmospheric horizontal resolution, while the large-scale bias is not affected.

We have established that the origin of the coastal SST bias lies within the atmospheric model component. Thus, the surface fluxes that are provided by the atmosphere cause the coastal SST bias. Because the local dynamical forcing of the ocean is mainly determined by the surface wind stress, we test the influence of the surface wind stress on the SST bias in a sensitivity experiment.

In Figure 2a, the difference in meridional wind stress between the reference experiment with low and the experiment with high atmospheric horizontal resolution is shown. In a region extending 1–2° off the coast, the southerly meridional wind stress is stronger at higher atmospheric resolution. The difference between

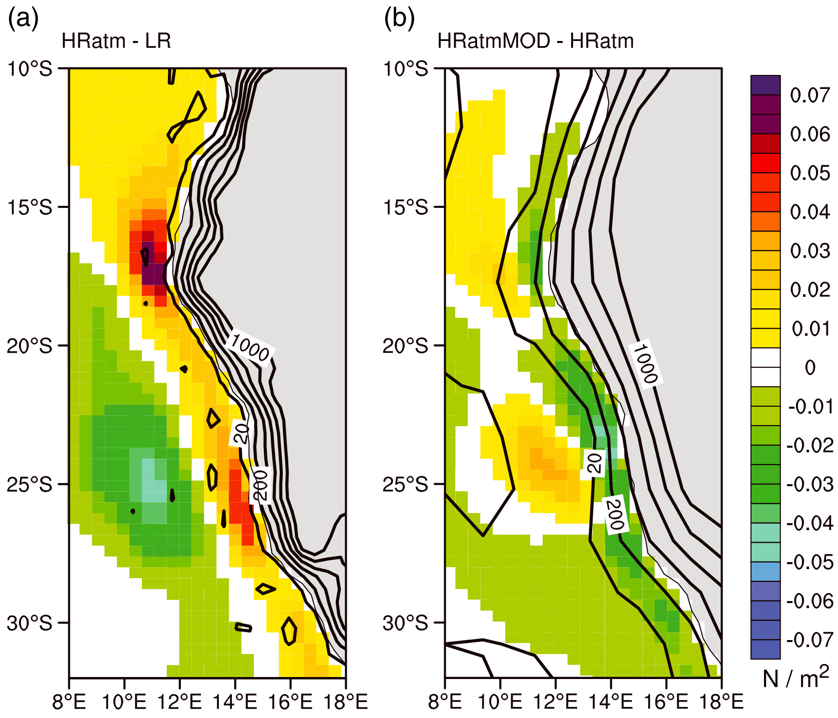

Figure 2. Meridional surface wind stress difference: (a) meridional wind stress difference between high and low horizontal resolution in the atmosphere; there are stronger southerly winds close to the coast at high resolution; (b) effect of the low-resolution orography on the surface wind stress. The plot shows the difference between HRatm and HRatmMOD (high-resolution atmosphere, but low-resolution orography). The contour lines show the height of the orography at high resolution (Figure 2a) and low resolution (Figure 2b).

the HR and LR wind stress is applied to a low-resolution experiment as a flux adjustment. The SST close to the coast in this flux-adjusted experiment (Figure 1a, FLX, red curve) closely follows the SST in the high-resolution simulation (HR, dark blue curve), showing that the coastal SST bias is indeed caused by the surface wind stress.

The coastal orography has in the past been suggested to contribute to the coastal SST bias and the accompanying too weak southerly winds. The coincidence of the too weak winds in LR with the positive elevation of the orography over the ocean close to the coast (Figure 2b, orography contours) suggests that the orography at low resolution might cause the surface wind stress bias and thus the coastal SST bias. We test this hypothesis by replacing the orography in the HRatm setup with the low-resolution orography. Thus, we can isolate the effect of the orography on the surface wind stress and SST in a model setup, which has hardly any coastal SST bias in its nonmodified form. The meridional surface wind stress in the modified orography experiment is reduced close to the coast (Figure 2b). Consequently, the SST bias increases in HRatmMOD compared to HRatm (Figure 1). However, the coastal SST bias in HRatmMOD is not as large as in the experiments with low atmospheric horizontal resolution (LR, HRoc). This means that the low-resolution orography accounts for half of the SST bias difference between HRatm

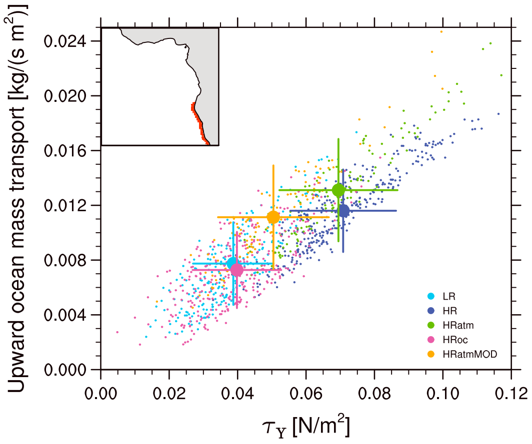

Figure 3. Larger wind stress at high atmospheric horizontal resolution causes increased upwelling: Monthly mean meridional wind stress and upward ocean mass transport into the uppermost layer. Spatially averaged from the coastline to 1° off the coast from 15°S to 30°S (region marked in map). The large dots indicate the mean values for each experiments; the lines mark one standard deviation in each direction.

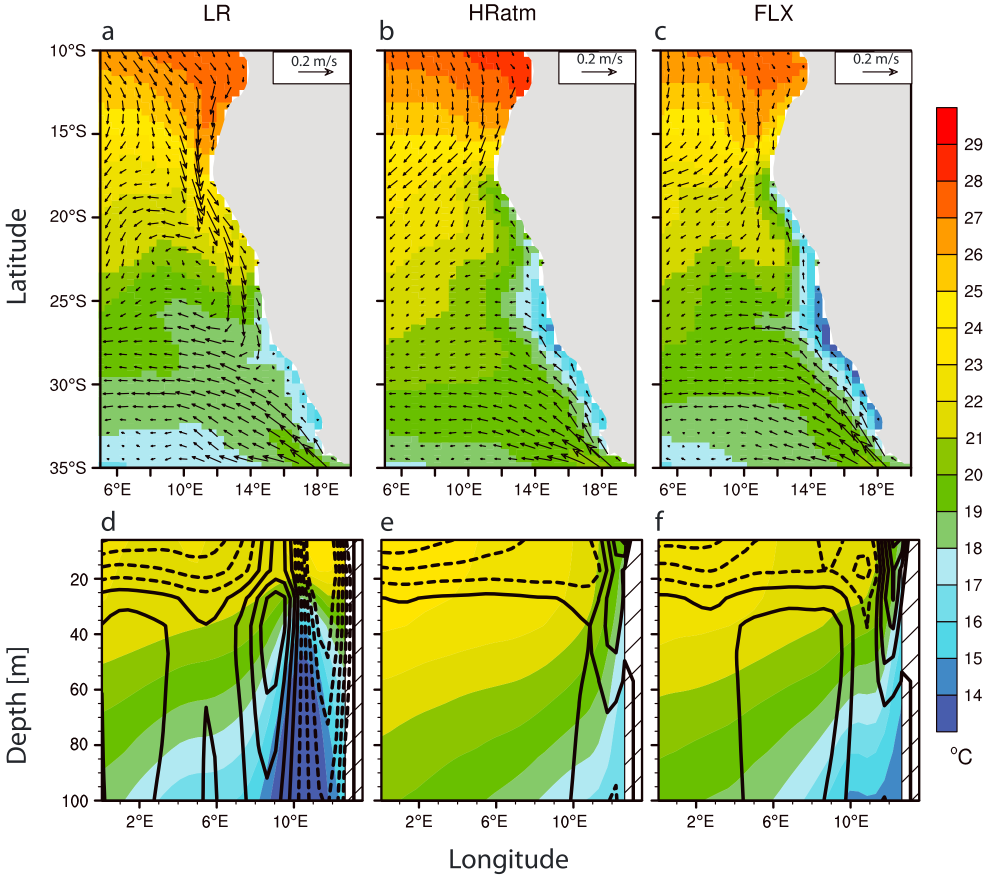

Figure 4. The representation of horizontal ocean circulation mostly depends on the surface wind stress: (a–c) maps of average velocity and temperature at 17 m; (d–f) sections (depth/longitude) of meridional velocity and temperature at 20°S covering the realistic location of the northward Benguela Current. Velocity contours are from −0.1 m/s to 0.1 m/s with 0.02 m/s interval. Southward velocities are dashed lines; northward velocities are solid lines.

and LR. The remaining difference in the wind stress and SST is therefore caused by other better resolved features at high atmospheric horizontal resolution.

The surface wind stress, which is responsible for the coastal SST bias, can affect the SST in two different ways: first, it affects the coastal upwelling and thus the cooling of the surface from below and second, it affects the horizontal oceanic circulation and thus advection in the current system of the southward Angola and northward Benguela Current.

The coastal upwelling is mainly driven by alongshore winds causing offshore Ekman transport leading to upwelling close to the coast. The meridional surface wind stress in the model, which contributes most to the coast-parallel component of the surface wind stress, is well correlated with the upward ocean mass transport into the surface layer in all experiments (Figure 3). Those experiments with low atmospheric horizontal resolution (LR, HRoc) have a weaker surface wind stress than those experiments with high resolution in the atmosphere (HR, HRatm). The oceanic upwelling adjusts to the applied surface wind stress, irrespective of the ocean resolution. Thus, the 0.4° ocean resolution is sufficient to represent the upwelling, provided that the correct surface wind stress is applied. The modified orography reduces the surface wind stress and thus the upwelling, but not as much as in the low-resolution atmosphere experiments.

The horizontal ocean circulation is also affected by the surface wind stress, and it contributes to the wind-driven coastal SST bias. In the region where the coastal bias is most pronounced, the southward, warm Angola Current and the northward, cold Benguela Current meet to form a zonally oriented front [*Shannon et al.*, 1987]. Any shift in this current system leads to a bias in the SST due to the large horizontal temperature gradients at the oceanic front. In the low-resolution model (Figure 4a), an unrealistically strong Angola Current is following the coast southward to 30°S. In the subsurface at 20°S, the core of the Angola Current is located close to the coast and associated with a core of warm water in the upper 30 m (Figure 4d). There is no evidence for a Benguela Current at 20°S at low resolution. In contrast, at high atmospheric resolution (Figure 4b), the Angola Current is substantially weaker and deflected to the ocean interior before reaching 20°S. Close to the coast in the south, the northward Benguela Current is colocated with colder water masses. In the subsurface near 20°S, the upward slope of the isotherms toward the coast indicates coastal upwelling (Figure 4e). The Angola Current reaching too far south in LR is replaced by the Benguela Current in HRatm and FLX, associated with colder temperatures. In the low-resolution experiment with the adjusted surface wind stress (FLX), both the horizontal structure of the currents (Figure 4c) and the vertical structure (Figure 4f) are very similar to the experiment with high atmospheric resolution (Figures 4b and 4e). The Benguela Current is slightly stronger in FLX than in HRatm, but still very similar to HRatm. The flux-adjusted experiment shows that improved surface wind stress is sufficient to explain the improvements in the coastal SST bias via changes in coastal upwelling and horizontal ocean circulation.

4. Discussion and Conclusions

The coastal SST bias in the southeastern Atlantic in the MPI-ESM can be explained by the model's deficiency in simulating surface wind stress. At high atmospheric horizontal resolution (0.5°), the wind bias is reduced, which in turn eliminates the coastal SST bias. By adjusting the surface wind stress in a low-resolution coupled ocean-atmosphere model, we have shown that the coastal SST bias is purely wind driven. The origin of the wind bias can be partly attributed to the representation of orography in the atmospheric model. The misrepresentation of the orography at low horizontal resolution causes half of the coastal SST bias, as shown in a coupled experiment with modified orography.

However, we cannot quantify the contributions of the particular deficiencies of the orography in the model, which are the too weak slope at the coast, the positive elevation over the ocean, and the overshooting in the vertical in both directions. Spectral filtering can reduce the overshooting at the cost of creating even weaker slopes that would cause positive elevation over the ocean farther off the coast [*Navarra et al.*, 1994]. Because the largest wind bias can be found at the coast where the slope of the orography is much weaker than observed and the elevation is still positive over the ocean, we assume these deficiencies to be the major problem, rather than the overshooting. Therefore, we conclude that spectral filtering is unlikely to reduce the bias. A steeper slope can only be included by increasing the atmospheric horizontal resolution, which might not be feasible for all studies due to the increased computational cost. Furthermore, the orography accounts for approximately half of the coastal SST bias; thus, we infer that the remaining coastal bias is caused by the misrepresentation of features other than the orography at low horizontal resolution.

The strength of the coastal wind jet depends not only on the steep orography but also on the shape of the coastline and the land-sea contrast close to the coast [*Ranjha et al.*, 2016]. The representation of these features is closely linked to the horizontal resolution of the atmosphere. This again suggests that the only pertinent way to reduce the coastal SST bias is to increase the atmospheric horizontal resolution, which has to be done globally for spectral atmospheric models.

Grid-point models, on the other hand, do not suffer from the same constraints on the resolution of the orography. When both types of models are run at a similar coarse horizontal resolution, grid-point models can represent a steep slope of the orography between adjacent grid cells, while spectral models suffer from deficiencies such as the weaker slope and positive elevation extending over the ocean. Furthermore, grid-point models allow for a regionally increased resolution without the additional computational cost of increasing horizontal resolution globally, thus allowing a better resolution in the coastal upwelling regions in the vicinity of prominent orographic features. Despite their potential to address the typical problems of the spectral models, grid-point models suffer from similar biases in the SETA region [*Grodsky et al.*, 2012; *Patricola et al.*, 2012]. One possible reason might be that the surface properties of ocean grid points close to the shore are affected by adjacent land grid points during the interpolation from the atmospheric to the oceanic grid. This impairs the representation of strong horizontal gradients in surface properties as pointed out for CCSM4 by *Small et al.* [2015]. There might be further differences between spectral models like ECHAM6 (used in this study) and grid-point atmosphere models like CAM4. At 0.5° horizontal resolution, CAM4 still places the coastal wind jet too far off the coast, and some of the coastal SST bias remains, while ECHAM6 places the jet closer to the coast at a similar horizontal resolution.

The large-scale SST bias is almost identical in all our simulations, neglecting the uniform offset between the untuned experiments due to slightly different global mean surface temperatures. Thus, we conclude that the large-scale bias is independent of oceanic and atmospheric horizontal resolution in the examined range. Moreover, the large-scale bias does not change when the coastal bias is reduced or eliminated (HR, HRatm, FLX, and HRatmMOD). From this we conclude that the coastal warm bias cannot be the root cause of the large-scale bias. If the large-scale bias was caused by the coastal bias either via ocean advection or by enhanced convection over anomalous warm SST that suppresses the formation of low level stratocumulus clouds over the SETA region, we would expect the large-scale bias to change when the coastal bias is reduced. However, it is still possible that parameterizations affecting cloud formation are not sensitive enough to the underlying SST and thus do not adjust to the colder SST at the coast. Further work concentrating on the representation of low-level clouds and their sensitivity to SST might contribute to the understanding of the large-scale SST bias. In this context, it might be necessary to increase the vertical resolution of the atmosphere as suggested by *Harlaß et al.* [2015].

Here we presented evidence for local mechanisms causing the coastal SST bias. The coastal SST bias can be eliminated by adjusting the surface wind stress applied to the ocean model. However, changes in either the coastal upwelling or the horizontal circulation cannot be unambiguously attributed to a certain feature in the surface wind stress based on the available experiments. This is evident from the upwelling in HRatmMOD in Figure 3. While the meridional wind stress is smaller than in HR and HRatm, the upwelling is stronger than one might expect from the relationship between meridional wind stress and upwelling in the other experiments. This deviation is most likely caused by a wind stress curl-driven contribution to the upwelling. Considering the warmer SST close to the coast in HRatmMOD compared to HRatm/HR (Figure 1a) despite the similar upwelling, we can conclude that the difference in SST between HRatmMOD and HRatm/HR is mainly caused by differences in the horizontal circulation. This highlights two limitations of our study: (1) we cannot attribute changes in upwelling and horizontal circulation to a certain feature in the wind stress distribution and (2) the relative contributions of upwelling and horizontal circulation to the heat budget of the coastal region cannot be derived from the experiments. The bias in the coastal region is sensitive to small changes in the frontal position of the Angola-Benguela front (ABF) that is characterised by a strong meridional SST gradient. The location of the frontal position has been found to be related to the wind stress curl [*Xu et al.*, 2014]. Furthermore, *Toniazzo and Woolnough* [2014] noted that small-scale features near the ABF can have a significant contribution to the heat advection, further complicating an exact quantification of the changes in heat advection due to changes in wind stress. In addition, the heat advection is not only determined by the strength and position of the currents in the SETA region but can also change due to differences in the properties of the advected water masses.

Previous studies suggested that remote effects from the equatorial Atlantic also contribute to the SST biases in the SETA region. Zonal wind anomalies on the equator excite downwelling Kelvin waves that suppress the coastal upwelling in the SETA region [*Richter*, 2015; *Toniazzo and Woolnough*, 2014; *Richter et al.*, 2011]. This mechanism might contribute to the remaining large-scale SST bias in our model since the MPI-ESM suffers from similar zonal wind and SST biases on the equator as other coupled models.

Here we show that increased horizontal atmospheric resolution can eliminate the coastal SST bias, which is purely wind driven. The large-scale warm bias remains although the coastal bias is reduced, which implies that the patterns of the coastal and large-scale bias are superimposed and caused by different mechanisms. Because the large-scale bias is insensitive to the horizontal resolution, its cause is most likely to be found in an erroneous parameterization. Half of the coastal SST bias can be attributed to the representation of the coastal orography at low horizontal resolution. The possibilities to modify the spectral orography are limited and not likely to reduce the problem. Half of the coastal SST bias is not caused by the orography but by other better resolved features at high horizontal resolution. Therefore, the only pertinent way to eliminate the coastal SST bias in spectral atmospheric models at this time is to increase the horizontal resolution.

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