Response to Reviewer #2

(Note: referee comments are in italic font, and our replies are in normal font)

The authors investigate the origin of tropical Atlantic SST biases in one particular GCM, the CESM1. To examine the relative contributions from atmospheric and oceanic model components the authors run CESM1 in three different modes: fully coupled, atmosphere-only, and ocean-only. Comparing the simulations with observations and observation-based flux products, the authors conclude that the dominant source of model errors lies in deficient ocean dynamics, particularly in the southeastern and eastern equatorial Atlantic. The authors suggest that other SST biases in the subtropics are more influenced by erroneous surface fluxes originating in the atmospheric component.

The conclusion that misrepresented ocean dynamics play an important role in tropical Atlantic biases is certainly plausible. On the other hand, this notion is certainly not a new one and has been argued in previous studies (Large and Danabasoglu 2006, Grodsky et al. 2012, Xu et al. 2013). Moreover the analysis technique appears to be flawed and not suitable to evaluate the relative contributions from oceanic and atmospheric errors. The analysis of bias evolution in the OGCM provides some evidence for the importance of intrinsic OGCM errors (note that there is a study by Toniazzo and Woolnough (2013) on a similar topic) but it is not clear to what extent such errors might be due to errors in the CORE2 fluxes. I therefore feel that the manuscript is not suitable for Climate Dynamics in its current form. I would like the authors to analyze the ocean interior in order to strengthen their argument about the importance of OGCM errors. Some suggestions follow below (see comment 7). I hope that through additional analysis this work will become a valuable contribution toward solving the tropical Atlantic bias problem.

Reply: We would like to thank the reviewer #2 for the thoughtful comments. In particular, the reviewer correctly pointed out one important weakness of our study on the issue of to what extend intrinsic OGCM errors presented in this study is due to errors in the COREv2 fluxes. The reviewer also suggested that the ocean interior be analyzed in order to strengthen our argument about the importance of OGCM errors. These two points are now addressed in the revised manuscript. We have added two new sections to address these issues (section 5 and 6).

1) <u>To what extend intrinsic OGCM errors presented in this study is due to errors in the CORE2</u>

fluxes?

As the reviewer pointed out, our results are not entirely independent from uncertainty in the observed surface flux product used (i.e., COREv2). For instance, if the net surface heat flux in COREv2 is too large positive downward, it will contribute positively (negatively) to the implicit SST bias in EXP_OCN (EXP_ATM) according to equations (1) and (3). Although considerable effort was invested to minimize errors, COREv2 is still far from error-free. Therefore, in a more strict sense, equation (3) should be considered as the implicit SST bias in EXP_OCN in reference to COREv2. Similarly, equation (1) should be considered as the implicit SST bias in EXP_ATM in reference to COREv2. Nevertheless, it should be noted that the total implicit SST bias in EXP_ATM + EXP_OCN is independent from the observed surface heat flux product used, and is thus not subject to uncertainty in the observed surface heat flux product used at least in a linear sense (see equation 3).

It order to better understand the impact of uncertainty in the COREv2 surface heat flux fields on the implicit SST bias in EXP_ATM and EXP_OCN, two additional stand-alone ocean sea-ice model simulations are performed by using the surface flux fields derived from the European Centre for Medium-Range Weather Forecasts Interim (ERA_INT) reanalysis, and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis.

As shown in Figure 9a, d and g, the implicit SST bias in EXP_ATM referenced to either ERA_INT or MERRA is more negative compared to that referenced to COREv2. On the contrary, the implicit SST bias in EXP_OCN referenced to either ERA_INT or MERRA is more positive compared to that referenced to COREv2. What these suggest is that the net surface heat flux into the tropical Atlantic is larger overall in ERA_INT and MERRA than that in COREv2. Nevertheless, the spatial patterns of the implicit SST bias in EXP_ATM referenced to the three surface flux products (i.e., COREv2, ERA_INT and MERRRA) are quite similar. As shown in Figure 9b, e and h, the same conclusion can be drawn for the implicit SST bias in EXP_OCN.

In sum, the overall magnitude of the implicit SST bias can be attributed more to either the atmosphere-land model or the ocean sea-ice model depending on the reference surface flux product used. However, the spatial pattern of the implicit bias in EXP_ATM (EXP_OCN) is largely determined by inherent deficiency of the atmosphere-land (ocean-sea ice) model component. As such, the total implicit SST bias in EXP_ATM + EXP_OCN is only minimally affected by the reference surface flux product used (Figure 9c, f and i). Therefore, we can conclude that the total implicit bias in EXP_ATM + EXP_OCN is a reliable measure of inherent deficiency in an AOGCM.

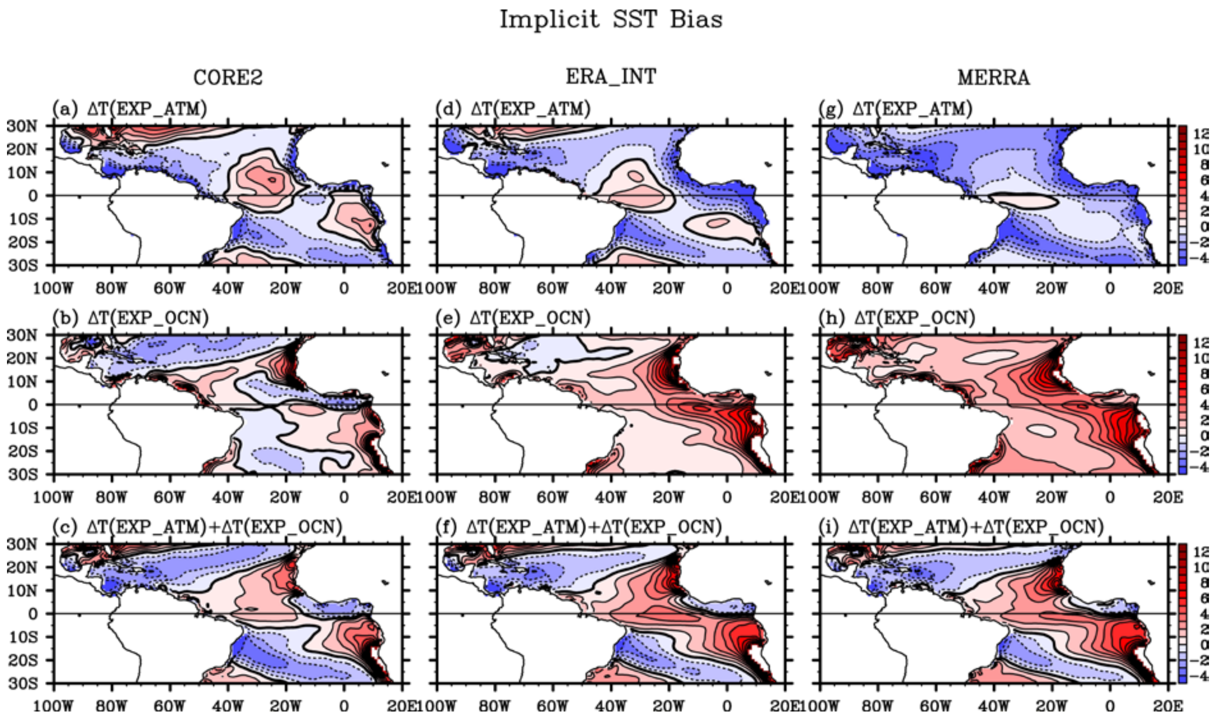

Figure 8. Annually averaged implicit SST bias in (a,d,g) EXP_ATM, (b,e,h) EXP_OCN, and (c,f,i) EXP_ATM + EXP_OCN referenced to (a,b,c) COREv2, (d,e,f) ERA_INT, and (g,h,i) MERRA. The unit is °C.

2) <u>The ocean interior should be analyzed in order to strengthen our argument about the importance of OGCM errors</u>

In response to the reviewer's suggestion, we have added a new figure (Figure 8). The new figure shows the monthly-averaged equatorial temperature bias (averaged for 5S-5N) in EXP_OCN. The green solid (dashed) line shows the corresponding mixed layer obtained from EXP_OCN (observations). This figure clearly shows that the temperature bias near the surface is quite small. However, at the based of the mixed layer, the temperature bias increases up to 6^{o}C. What this suggests is that due to spurious ocean dynamic processes in the ocean model, the upper thermocline water that entrains into the mixed layer during late spring and early summer (e.g., Lee and Csanady, 1999) is too warm. The surface temperature is strongly damped to the observation via the prescribed air temperature and specific humidity in EXP_OCN. However, when the ocean sea-ice model is fully coupled to the atmosphere-land model, the entrainment of the warm upper thermocline layer will produces warm SST bias.

Obviously, this still does not tell us which process or parameterization is responsible for the warm implicit SST bias in EXP_OCN. However, our study in this paper provides a useful tool to investigate those processes or parameterization. For instance, we can perform multiple experiments using the stand-alone ocean sea-ice model by changing the vertical diffusivity. By computing the implicit SST bias using equations 3 and 4, we can estimate the potential impact of ocean vertical diffusivity in the fully coupled model SST bias.

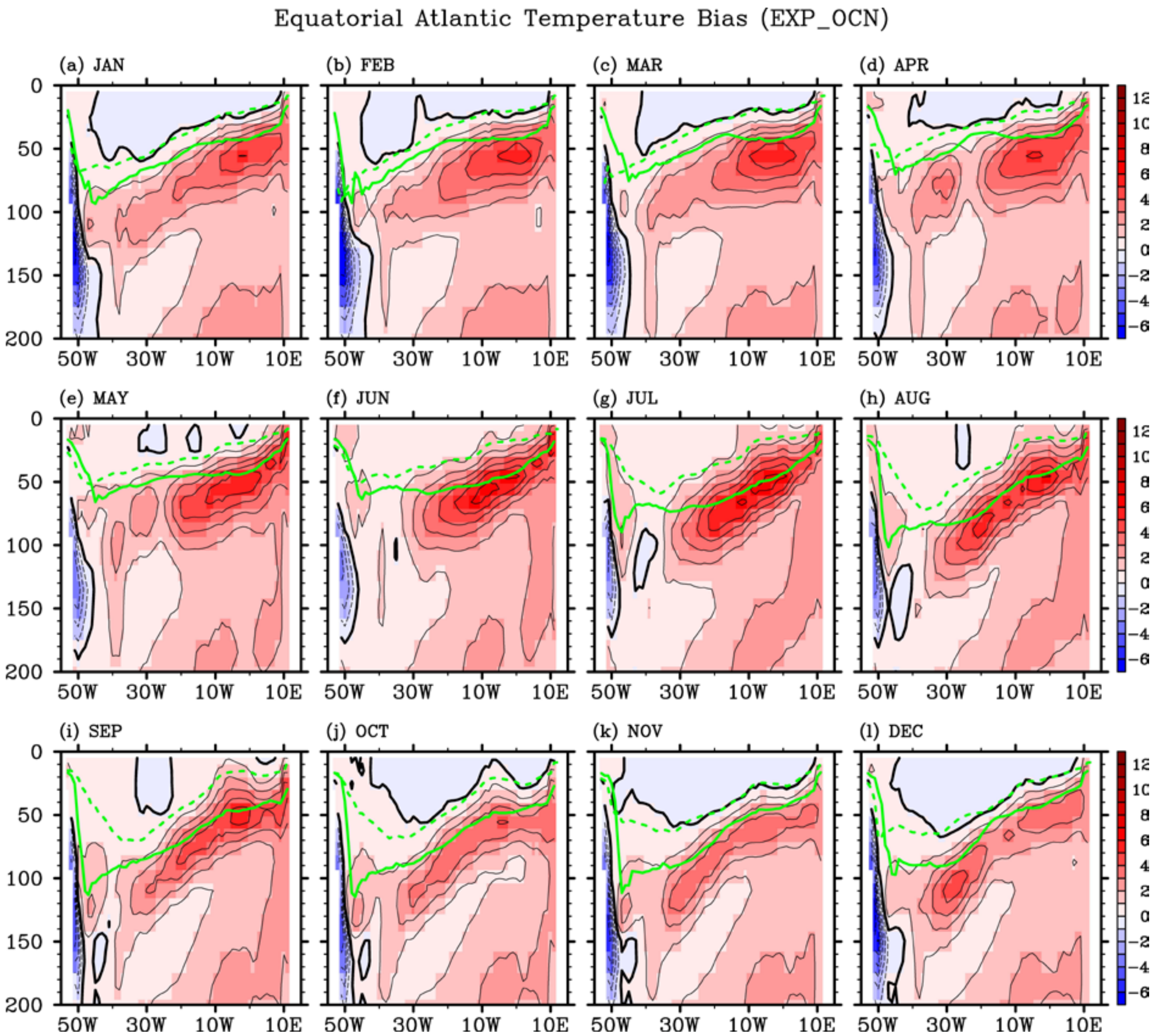

Figure 8. The time-depth evolutions of equatorial temperature bias (shaded) and mixed layer depth (green solid line) averaged for 5S-5N obtained from EXP_OCN. The green dashed line is the mixed layer depth obtained from observations (EN4 from Hadley Center).

The suggested references (Large and Danabasoglu 2006, Grodsky et al. 2012, Xu et al. 2013, and Toniazzo and Woolnough 2013) are now referenced.

1. Equation (1) for the "implicit SST bias" due to AGCM errors is actually an equation for the mixed layer temperature (MLT) bias (though the two are likely very similar). The problem is that when calculating the MLT bias one has to deal with two mixed layer depths (MLDs): the observed MLD (D0) and the one that a "perfect ocean" would produce if forced with the AGCM's surface heat and momentum fluxes (D). Thus equation (1) should be an expression like $d/dt\ (T-T0) = (D0*Q - D*Q0)/(rho*cp*D*D0)$*, where the suffix 0 denotes the observations. The authors assume that D=D0 (which they set to the MLD of the OGCM, presumably to be consistent with equation (3)). This implies that surface fluxes cannot influence MLD, which is physically inconsistent. The approach might be useful where the ocean can be approximated by a motionless slab layer but is problematic where dynamics are important. It is therefore unsurprising that the authors find a relatively small contribution from AGCM errors - they have excluded a vital component of the atmospheric influence by definition.*

2. Likewise equations (2) and (3) assume that the observed and simulated MLD are identical. This is questionable if ocean dynamics are indeed the dominant cause of GCM biases as claimed by the authors. If the two are significantly different, however, equation (2) should be modified analogously to (1).

Reply: This is a very thoughtful comment. The reviewer is correct to point out that D0 should be used to represent the mixed layer heat budget of the real ocean. We find that D is generally larger than D0. Therefore, if we revise equation (1) following the reviewer's suggestion, the model data difference (EXP_ATM – COREv2) of the surface heating term (QSWR) becomes negative, whereas the model data differences of the surface cooling terms (QLWR, QLHF, and QSEN) become positive. As such, the implicit bias of EXP_ATM is now more dictated by the difference between D and D0 than by the surface flux bias. This is also true for the implicit bias of EXP_OCN.

At this point, we are not quite sure how to interpret or correctly represent the impact of mixed layer depth bias on the implicit SST bias in EXP_ATM and EXP_OCN. Therefore, we feel that we are not ready to discuss this issue in the current manuscript. We would like to develop new ideas (or schemes) to properly represent and interpret the impact of mixed layer depth bias in the future work. In the revised manuscript, therefore, we state this limitation in our methodology in section 7: "Although we identify that the inherent errors in the ocean-sea ice model contribute significantly to the tropical SST bias in CESM1, the potential impact of mixed layer depth bias in EXP_OCN is not explored in this study, and thus should be examined in the future work."

3. The equation derived by the authors by assuming equality of the MLDs (3) essentially depends on SST only. The first term on the right-hand side of (3), MLT, should be very close to SST by definition. The surface fluxes (second term) are both calculated from the same observed input parameters, with the exception of SST, and therefore their difference depends on SST only. Thus the ocean dynamic contribution to the SST errors is just a function of the OGCM SST error and equation (3) seems to offer little new insight. Comparing Figs. 3 and 4a suggests that the two are indeed closely related, with the actual OGCM SST bias pattern (Fig. 3) amplified in the implicit bias (Fig. 4a).

Reply: We agree that the implicit SST bias in EXP_OCN is a function of OGCM SST error because the errors in upward longwave radiative flux, latent heat flux and sensible heat flux components all depend on OGCM SST error. However, it is important to note that the link between the SST bias and the implicit SST error is not uniform in space and season. For instance, the 4th power of total SST (i.e., $[\text{observed SST + SST bias}]^4$) will influence the upward longwave radiative flux. Thus, the link between the SST bias and the upward long wave flux bias will also depend on the mean SSTs, which vary in space and season. Additionally, the link between the SST error and the latent and sensible heat flux bias will depend on the mean wind speeds, which are also different in space and season. Therefore, we respectfully disagree with the reviewer's point that equation (3) offers little new insight. We believe that equation (3) is a proper way to represent and quantify intrinsic errors in an OGCM.

4. As a consequence of the issues described in comments 1) and 2) it seems that equation (4) is also problematic. When and where the authors' assumptions hold the method may still provide useful results. Judging from Fig. 4, however, the method does not explain equatorial biases well (with the diagnosed pattern qualitatively different from the actual model bias) and severely overestimates the errors in the subtropical regions. Thus it is not clear how much value the authors' results have and any quantitative attribution of error sources seems questionable.

Reply: We would like to stress that equation (4) is not affected by the issues raised in the reviewer's comment #1 and #2. As shown in equation (4), it should be noted that the total implicit SST bias in EXP_ATM + EXP_OCN is independent from the observed surface heat flux product used, and is thus not subject to the influence of mixed layer depth bias.

The reviewer correctly pointed out that the overall amplitude of the SST bias in CCSM4_20C is smaller than the amplitude of the total implicit SST bias in EXP_ATM + EXP_OCN. This is not unexpected because the total implicit bias in EXP_ATM + EXP_OCN estimates the extent to which the spurious atmosphere-ocean dynamics in the atmosphere-land and ocean sea-ice model components could *potentially* contribute to the SST bias once the air-sea coupling is initiated. For instance, in a region where the total implicit SST bias is positive, once the air-sea coupling is initiated, the model SSTs will increase initially. However, the increased SSTs will in turn enhance the longwave radiative and latent cooling at the surface to reduce the rate of SST warming. Therefore, it is highly unlikely that the SST bias will reach the full extent of the total implicit SST bias. This point is now discussed in section 3.3.

As the reviewer noted, the implicit SST bias in EXP_OCN (Fig. 4b) is slightly negative over the eastern equatorial Atlantic region. This is somewhat inconsistent with the SST bias in CCSM4_20C over the same region (Fig. 1b). Therefore, to better understand the origin of the equatorial Atlantic SST bias in CCSM4_20C, we explore the initial development of the tropical Atlantic SST bias in EXP_CPL. It is shown in section 4 (Figure 6 and 7) that the ocean-sea ice model does contribute significantly in forcing the eastern equatorial Atlantic warm SST bias due to its spurious ocean dynamic processes. However, its influence is limited only in early boreal summer during which massive entrainment of the equatorial cold thermocline water into the surface mixed layer occurs.

5. The fact that the implicit ocean dynamical contribution is mostly just an amplification of the OGCM's SST bias becomes problematic in the presence of significant errors in the forcing fields. While SSTs are known with relative accuracy there is much less confidence in surface fluxes. Small errors in the fluxes could cause SST errors that then get amplified in the calculation of the implicit SST bias. How does the surface wind in CORE2 compare to other observations like QuikSCAT and ICOADS? Are there any systematic differences in the equatorial easterlies?

Reply: COREv2 uses 6hourly QSCAT surface winds for the period of 1999-2004 at 0.5º resolution (Table 1 in Large and Yeager 2000). Thus, there should not be any systematic difference in the equatorial easterlies between COREv2 and QSCAT.

6. The authors suggest in the conclusions that coupled feedbacks play a role in some regions but present little analysis to back this up. The implicit SST biases seem to contradict this claim because their sum is larger than the actual bias and has opposite sign in some regions.

Reply: We have removed or rephrased the related statements.

7. The authors conclude that shortcomings intrinsic to the OGCM's dynamic formulation are the dominant factor in coupled GCM biases in the eastern equatorial and southeastern tropical Atlantic. This may be the case but other than the implicit bias method (which appears to be flawed) there is little analysis to back this up. There is not even a discussion of what the potential error sources might be. Just suggesting that developers increase resolution and experiment with different mixing schemes is not very helpful because this is what the community has been doing for considerable time (with only modest progress to show for it). I believe the authors have an interesting set of simulations that could be used to dig deeper toward the root causes. In particular, there has been relatively little analysis using standalone OGCM simulations. What kind of vertical temperature structure does the OGCM produce? How do thermocline and MLD compare to observations. What are the ocean interior biases of temperature and currents? How sensitive are the OGCM errors to uncertainty in the forcing product? How do the OGCM biases compare with those of the CGCM? I believe the authors could make a valuable contribution toward model improvement by addressing these questions.

Reply: In response to the reviewer’s suggestion, we have added a new figure (Figure 8), which is now discussed in a new section (section 5).