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Abstract: In order to identify and quantify intrinsic errors in the atmosphere-land and ocean-sea ice model components of the Community Earth System Model version 1 (CESM1) and their contributions to the tropical Atlantic sea surface temperature (SST) bias in CESM1, we propose a new method of diagnosis and apply it to a set of CESM1 simulations. Our analyses of the model simulations indicate that both the atmosphere-land and ocean-sea ice model components of CESM1 contain large errors in the tropical Atlantic. When the two model components are fully coupled, the intrinsic errors in the two components emerge quickly within a year with strong seasonality in their growth rates. In particular, the ocean-sea ice model contributes significantly in forcing the eastern equatorial Atlantic warm SST bias in early boreal summer. Further analysis shows that the upper thermocline water underneath the eastern equatorial Atlantic surface mixed layer is too warm in a stand-alone ocean-sea ice simulation of CESM1 forced with observed surface flux fields, suggesting that the mixed layer cooling associated with the entrainment of upper thermocline water is too weak in early boreal summer. Therefore, although we acknowledge the potential importance of the westerly wind bias in the western equatorial Atlantic and the low-level stratus cloud bias in the southeastern tropical Atlantic, both of which originate from the atmosphere-land model, we emphasize here that solving those problems in the atmosphere-land model alone does not resolve the equatorial Atlantic warm bias in CESM1.

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Dear Dr. Anne Marie Treguier,

We would like to sincerely thank you and the two reviewers for evaluating our manuscript and providing thoughtful comments and suggestions. The manuscript is now revised following the suggestions from the two reviewers.

We believe that this study provides a powerful tool to global climate model developers and users to identify and quantify intrinsic errors in the atmosphere-land and ocean-sea ice model components and their contributions to the tropical Atlantic sea surface temperature (SST) bias in fully coupled global climate models.

Sincerely yours,

A handwritten signature in black ink, appearing to read 'Sang-Ki Lee', with a long horizontal flourish extending to the right.

Zhanya Song, Sang-Ki Lee, Chunzai Wang, Ben Kirtman and Fengli Qiao

## Response to Reviewer #1

We would like to thank the reviewer #1 for thoughtful comments and suggestions. The manuscript is now revised following the reviewer's suggestions. Here, we briefly explain how we address each of the comment. The reviewer's comments are in italic font, and our replies are in normal font.

*A well written concise analysis of the TA biases in one particular GCM. The results are not too surprising or novel, but they combine various results of others into one framework, and are therefore worth publishing.*

*I have only a couple of minor comments:*

*it should be called ocean model rather than ocean-seaice, the latter doesn't enter the study and it is confusing*

Reply: We understand this point. However, the sea ice model was coupled to the ocean model in all experiments except in the atmosphere-land model experiment. So, to be consistent, we still would like to call "ocean-sea ice coupled model" rather than "ocean model".

*They authors discuss that their conclusions are dependent on the chosen forcing product for the OGCM; I think they should also add a paragraph on the effects of interpolation and resolution of the observations. Especially off Angola and Namibia the observations may not resolve the wind, and even if, the interpolation across land/ocn boundaries in CESM will deteriorate the quality in this context, I think, Small et al. 2014, JAMES, deserves a citation. They look at the upwelling biases with an ultra-high resolution version of CESM.*

Reply: Thank you for this very thoughtful suggestion and introducing Small et al. (2014), which is important and very relevant to our paper. In the revised manuscript, the last sentence in the summary and discussion section is now revised to address this point. Small et al. (2014) is now discussed and referenced.

L493-497: "Therefore, we recommend sensitivity studies on model resolutions (in both the

horizontal and vertical directions), representation of surface flux fields especially off Angola and Namibia, vertical mixing schemes and isopycnal mixing schemes, using the ocean-sea ice model component of CESM1 and the diagnosis method proposed in this study.”

L103-107: “Large and Danabasoglu (2006) suggested that the warm SST bias in the southeastern tropical Atlantic could be reduced by improving the simulation of coastal upwelling off the coasts of southwest Africa. Recently, Small et al. (2014) used a high-resolution AOGCM (0.1° resolution for the ocean model and 0.25° resolution for the atmosphere model) to demonstrate this hypothesis.”

*At various places the authors state that the mixed layer is too deep. This may well be, but this requires a more careful study. Furthermore, the spatial structure of the MLD biases may matter a lot. In this context Jochum et al 2013 JCLim should be mentioned, they show that improving mixing processes in the ML can lead to shift in the ITCZ and a reduction of biases.*

Reply: Jochum et al (2013) is now discussed and referenced:

L99-101: “Jochum et al. (2013) showed that improving the upper ocean mixing in an ocean model could lead a reduction of the tropical Atlantic SST and rainfall biases.”

*Maybe adding a section with a detailed MLD biases description would make this a much stronger paper. To my knowledge this has not been done before for the TA, and it may give a hint which mixing processes are lacking.*

Reply: We greatly appreciate this suggestion. In the revised manuscript, we further discuss about the equatorial Atlantic MLD bias and its link to the upper thermocline temperature bias in the ocean-sea ice model experiment. We also present a hypothesis on the cause of the MLD and upper thermocline temperature biases:

L395-406: “Fig. 8 also shows that the mixed layer depth is too deep in EXP\_OCN. This suggests that the vertical turbulent mixing may be too intense in EXP\_OCN. It is likely that the warmer-than-observed upper thermocline layer weakens the vertical stratification over the upper thermocline and thus increases turbulent mixing at the mixed layer base. This means that

the mixed layer depth bias may be directly linked to the upper thermocline temperature bias. One hypothesis is that the spurious vertical diffusion in the thermocline layer due to vertical discretization in the ocean model brings too much heat into the upper thermocline layer from the mixed layer, which in turn weakens the vertical stratification and thus further increases the vertical mixing across the mixed layer base, a positive feedback mechanism. To further investigate what processes or parameterizations are responsible for the warmer-than-observed upper thermocline and deeper-than-observed mixed layer depth, it is necessary to perform sensitivity experiments by using the stand-alone ocean sea-ice model and the diagnostic methodology proposed in this study.”

## Response to Reviewer #2

We would like to thank the reviewer #2 for thoughtful comments and suggestions. The manuscript is now revised following the reviewer's suggestions. Here, we briefly explain how we address each of the comment. The reviewer's comments are in italic font, and our replies are in normal font.

*This study explores intrinsic errors in the atmosphere and ocean components of the CESM1 model for the sea surface temperature (SST) bias observed in most coupled models in the tropical Atlantic.*

*The paper will be of great interest for the coupled modeling community in 2 important aspects:*

- 1. The use of an original methodology to quantify the respective contributions of the ocean and atmosphere components of a coupled simulation for the generation of SST biases. This methodology is based on the computation of explicit SST errors in the stand-alone ocean and atmosphere components of CESM1 forced respectively by observed surface fluxes and SSTs, and on the analysis of their growth and fate when the two components are fully coupled.*
- 2. The demonstration that the development of SST biases is strongly related to the growth of SST errors in the forced stand-alone ocean and atmosphere components, and that the ocean component of CESM1 is an important contributor to SST bias in the tropical Atlantic, in contrast with the general idea that SST biases in this region are mainly governed by errors in the atmosphere model (such as westerly wind biases in the western tropical Atlantic or low-level stratus cloud bias in the southeastern tropical Atlantic). The SST errors in the ocean component are shown to be related to a too warm upper thermocline in the eastern tropical Atlantic, that the authors attribute a too weak mixed-layer cooling associated with the entrainment of upper thermocline.*

*The paper is concise, well organized and well written, and the illustrations are of good quality (despite a bad referencing to subfigures in many places throughout the paper). My*

*main criticism concerns the methodology, which to my opinion is an important novelty of the paper and whose limitations should be carefully addressed and discussed in a revised version of the paper.*

*Major comment*

*The used methodology strongly lies on the precise quantification and interpretation of SST errors in stand-alone forced ocean (EXP\_OCN) and atmosphere (EXP\_ATM) models.*

*In the atmosphere, the net surface fluxes anomalies with respect to observed surface fluxes from COREv2 are used to compute an implicit SST error evolution by using the mixed-layer depth, and are then integrated in time to estimate an implicit SST error (Eqn(1) in the paper).*

*In the ocean, the total SST error can be computed directly by comparison with observed SSTs, and processes responsible for this error can be assessed from the time integral of the SST evolution equation in the ocean model (Eqn(2) in the paper).*

*1. However, the estimate of SST error in EXP\_ATM (and of the flux-related part of the implicit SST error in EXP\_OCN) strongly depends upon the choice of the mixed-layer depth (MLD), which is arbitrarily chosen to be the one from the EXP\_OCN experiment. Is the MLD realistic in EXP\_OCN? Is it possible to compute implicit SST errors due to MLD? Moderate errors in the MLD should have large impacts on the results presented in the paper, especially in the eastern tropical Atlantic where the MLD is shallow.*

Reply: We very much appreciate this thoughtful comment. The reviewer correctly pointed out that the choice of MLD will affect the implicit bias in EXP\_ATM. We can use either the observed MLD or the one from EXP\_OCN. As shown in Fig 8. The MLD from EXP\_OCN is deeper than the observed MLD along the equatorial Atlantic. Therefore, the implicit SST bias in EXP\_ATM will be greater if the observed MLD is used instead of the MLD from the EXP\_OCN. This is indeed one limitation in our estimate of the implicit SST bias in EXP\_ATM. This limitation is now discussed in the revised manuscript:

L482-485: “It should be also pointed out that the choice of the mixed layer depth used to

determine the implicit SST bias in EXP\_ATM (see Eq. (1)) is somewhat arbitrary, which is one of the limitations of the proposed method to diagnose the implicit SST bias in EXP\_ATM.

2. *I guess from the paper that the SST errors in EXP\_ATM and EXP\_OCN are computed from the time average of the surface fluxes and MLD. Is this right (lines 202-203 should be clarified for instance)? If it is indeed the case, is this assumption valid, knowing the time variability of surface fluxes and MLD in the region?*

Reply: The non-seasonal time variability of surface fluxes and MLD is very weak in the stand-alone atmosphere-land and ocean sea-ice experiments since EXP\_ATM and EXP\_OCN are forced by climatological SSTs and surface flux fields, respectively. Nevertheless, we averaged the surface fluxes and MLD for the last 10 years of the model simulations to minimize uncertainties in our estimations of the implicit SST biases. We revised the following sentence to clarify this point:

L205-207: “This is computed by integrating the long-term averaged (i.e., averaging the last ten years of the model simulation) net heat flux bias in EXP\_ATM from January 1 to December 31, then dividing it by 12 months.”

3. *The authors claim that the implicit SST bias in EXP\_ATM+EXP\_OCN is independent from the observed surface heat flux product (lines 281-284). It is indeed true. However these fluxes are precisely the forcing of EXP\_OCN and the reference for the computation of EXP\_ATM SST errors, so the choice of the observed surface heat flux product will potentially impact the estimate of SST in EXP\_ATM and EXP\_OCN, and thus the conclusion about the role of the ocean model for SST biases in the CESM1. This should be acknowledged more clearly in the paper.*

Reply: We completely agree with the reviewer that this limitation of the proposed method should be clearly stated. Although we already discuss this point in section 6 and 7, we add the following two sentences in the revised manuscript to further stress this limitation:

L437-438: “In other words, the choice of the reference surface heat flux product will impact the estimates of implicit SST biases in EXP\_ATM and EXP\_OCN.”



L487-489: “In particular, 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.”

*(4) A common color scale in the figures would greatly facilitate the comparison. Is it possible?*

Reply: Note that we mainly use two color scales (-12 ~ 12 and -6 ~ -6), which are necessary to effectively illustrate the spatio-temporal structure of the implicit and explicit SST biases. As such, we think that using a common color scale throughout the figures is not very effective.

## *2. Minor comments*

*(1) Line 61: “almost all...”. Does it mean that some models are able to reproduce the climatology of tropical Atlantic SSTs?*

Reply: Some regional CGCMs use an ad hoc parameterization to tune the model to minimize the Atlantic SST bias. But, those models fail in other regions. Some CGCMs simply use flux adjustments to minimize the Atlantic SST bias.

*(2) Line 124: “rarely”: 3 references using this quantitative analysis are given in Line 161.*

Reply: The three previous studies performed experiments to explore the development of SST biases in a fully coupled model run initialized with the data from uncoupled surface-forced atmosphere and ocean simulations. We do use a similar strategy. However, our proposed methodology allows quantifications of the contributions of the atmosphere-land and ocean-sea ice model components to the tropical Atlantic SST bias in an AOGCM.

*(3) Line 152: change “Figure 1b” to “Figure 1c”.*

Reply: Done.

*(4) Line 161: the correct year for “Toniazzo and Woolnough” is 2014.*

Reply: Done.

(5) Line 202-203: *I do not understand the sentence (see major comment above).*

Reply: The non-seasonal time variability of surface fluxes and MLD is very weak in the stand-alone atmosphere-land and ocean sea-ice experiments since EXP\_ATM and EXP\_OCN are forced by climatological SSTs and surface fluxes, respectively. Nevertheless, we averaged the surface fluxes and MLD for the last 10 years of the model simulations to minimize uncertainties in our estimations of the implicit SST biases. We revised the following sentence to clarify this point:

L205-207: “This is computed by integrating the long-term averaged (i.e., averaging the last ten years of the model simulation) net heat flux bias in EXP ATM from January 1 to December 31, then dividing it by 12 months.”

(6) Line 214: *change “Fig. 2(c)” to “Fig. 2(b)”.*

Reply: Done.

(7) Line 216: *change “Fig. 2(b)” to “Fig. 2(c)”.*

Reply: Done.

(8) Line 235: *change “bulkuations” to “bulk formulae”.*

Reply: Done.

(9) Eqn (2): *the vertical diffusion at the base of the mixed layer is known to be an important contributor to SST evolution in the tropics. This term should be included in the equation.*

Reply: We would like to point out that the vertical diffusion is implicitly expressed by the entrainment term in our bulk mixed layer heat budget equation (Eqns. 2 and 3) as shown in

Moison and Niiller (1998) and Lee et al. (2007). It is true that turbulent mixing is represented by vertical diffusion in z-coordinate. However, in a bulk mixed layer heat budget equation, in which the mixed layer depth is a function of time and space, the turbulent mixing is expressed in terms of entrainment term ( $w_e \times (T_m - T_e)$ ) where the entrainment rate ( $w_e$ ) is typically parameterized based on Richardson number.

Moisan J. R. and P. P. Niiller, 1998: The Seasonal Heat Budget of the North Pacific: Net Heat Flux and Heat Storage Rates (1950–1990). *J. Phys. Oceanogr.*, 28, 401–421.

Lee, S.-K., D. B. Enfield and C. Wang, 2007: What drives seasonal onset and decay of the Western Hemisphere warm pool? *J. Climate*, 20, 2133-2146.

(10) Line 286: change “Fig. 1(b)” to “Fig. 1(c)”.

Reply: Done.

(11) Line 303: change “Fig. 4(b)” to “Fig. 4(a)”.

Reply: Done.

(12) Line 305: change “Fig. 1(b)” to “Fig. 1(c)”.

Reply: Done.

(13) Lines 310-311 and 385-387: *the vertical diffusion term at the base of the mixed layer dominates over the vertical entrainment in the eastern equatorial Atlantic (e.g. Jouanno et al. 2012).*

Reply: As we stated in our reply to reviewer’s comment (9), we would like to point out that the vertical diffusion is implicitly expressed by the entrainment term in our bulk mixed layer heat budget equation (Eqns. 2 and 3) as shown in Moison and Niiller (1998) and Lee et al. (2007).

Jouanno et al. (2011) defined entrainment rate ( $w_e$ ) using the following formula:

$$\frac{\partial h}{\partial t} = w_e,$$

where  $h$  is bulk mixed layer depth. However, entrainment rate should be defined using the following formula:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = w_e.$$

Please also refer to A16 in Moison and Niiller (1998) for the correct definition of the entrainment rate, which is different from that in Jouanno et al. (2011). Again, it is true that turbulent mixing is represented by vertical diffusion in  $z$ -coordinate. However, in a bulk mixed layer heat budget equation as in Eqn 2 in our paper, in which the mixed layer depth is a function of time and space, the turbulent mixing is expressed in terms of entrainment term ( $w_e \times (T_m - T_e)$ ).

Jouanno, J., Marin, F., du Penhoat, Y., Sheinbaum, J., Molines, J.-M., 2011. Seasonal heat balance in the upper 100 m of the equatorial Atlantic Ocean. *J. Geophys. Res.*, 116, C09003, doi:10.1029/2010JC006912.

(14) Line 316 and 317: change “Fig. 1(b)” to “Fig. 1(c)”.

Reply: Done.

(15) Line 339: “... is caused ...”. *The assertion is probably too strong here.*

Reply: We change this to “.... is mainly caused by ....”

(16) Line 525: change “Saravana” to “Saravanan”.

Reply: Done.

(17) Line 575: *the right year is 2009.*

Reply: Done.

*(18) Line 619: the link is no longer valid.*

Reply: The reference is corrected.

1 **Contributions of the atmosphere-land and ocean-sea ice model components to**  
2 **the tropical Atlantic SST bias in CESM1**

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## Abstract

24  
25 In order to identify and quantify intrinsic errors in the atmosphere-land and ocean-sea ice model  
26 components of the Community Earth System Model version 1 (CESM1) and their contributions  
27 to the tropical Atlantic sea surface temperature (SST) bias in CESM1, we propose a new method  
28 of diagnosis and apply it to a set of CESM1 simulations. Our ~~analysis~~analyses of the model  
29 simulations ~~indicates~~indicate that both the atmosphere-land and ocean-sea ice model components  
30 of CESM1 contain large errors in the tropical Atlantic. When the two model components are  
31 fully coupled, the intrinsic errors in the two components emerge quickly within a year with  
32 strong seasonality in their growth rates. In particular, the ocean-sea ice model contributes  
33 significantly in forcing the eastern equatorial Atlantic warm SST bias in early boreal summer.  
34 Further analysis shows that the upper thermocline water underneath the eastern equatorial  
35 Atlantic surface mixed layer is too warm in a stand-alone ocean-sea ice simulation of CESM1  
36 forced with observed surface flux fields, suggesting that the mixed layer cooling associated with  
37 the entrainment of upper thermocline water is too weak in early boreal summer. Therefore,  
38 ~~while~~although we acknowledge the potential importance of the westerly wind bias in the western  
39 equatorial Atlantic and the low-level stratus cloud bias in the southeastern tropical Atlantic, both  
40 of which originate from the atmosphere-land model, we emphasize here that solving those  
41 problems in the atmosphere-land model alone does not resolve the equatorial Atlantic warm bias  
42 in CESM1.

43  
44 Key Words: tropical Atlantic SST bias; implicit SST bias; CESM, atmosphere-land model  
45 experiment; ocean-ice model experiment

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47

48 **1. Introduction**

49 Since the pioneering work of Manabe and Bryan (1969), coupled atmosphere-ocean general  
50 circulation models (AOGCMs) have been significantly improved. AOGCMs are now able to  
51 reproduce the basic features of the global climate system (Covey et al. 2003; Meehl et al. 2005),  
52 and thus become an important tool for seasonal forecasts, climate projections and other climate  
53 research in general. However, the tropical Atlantic biases typically characterized by warmer sea  
54 surface temperatures (SSTs) in the eastern equatorial ocean, a reversed zonal SST gradient along  
55 the equator, colder SSTs in the northwest and southwest tropical Atlantic, and warmer SSTs in  
56 the northeast and southeast tropical Atlantic, are common problems with most AOGCMs (e.g.,  
57 Davey et al. 2002).

58 Model biases have been somewhat reduced in most recent models used in the Coupled Model  
59 Intercomparison Project Phase 5 (CMIP5) compared to those used in CMIP3 (e.g., Liu et al.  
60 2013). Recent studies have also shown that improving the spatial resolution could potentially  
61 reduce such biases (Gent et al. 2010; Patricola et al. ~~2011~~2012; Kirtman et al. 2012; Small et al.  
62 2014). Nevertheless, almost all of the state-of-the-art AOGCMs still cannot reproduce the  
63 climatology of tropical Atlantic SSTs (Mehoso et al. 1995; Davey et al. 2002; Covey et al.  
64 2003; Huang et al. 2007; Richter and Xie 2008; Richter et al. 2012).

65 These systematic tropical Atlantic biases in AOGCMs will affect the models' ability to  
66 simulate and predict climate variability (Xie and Carton 2004). Studies have shown that the  
67 tropical Atlantic affects and modulates climate variability of the Western Hemisphere, such as  
68 the West African summer monsoon (Vizy and Cook 2001; Giannini et al. 2003; Gu and Adler  
69 2004), moisture transport and rainfall over the American continents (Enfield et al. 2001; Wang et



70 al. 2006) and Atlantic hurricane development and intensification (e.g., Goldenberg et al. 2001;  
71 Webster et al. 2005; Wang and Lee 2007). Therefore, in order to increase the seasonal-to-decadal  
72 climate predictability in the Western Hemisphere, it is important to accurately simulate the  
73 tropical Atlantic Ocean in AOGCMs. It is also worthwhile to point out that the tropical Atlantic  
74 problem in AOGCMs is one of the most critical obstacles for achieving confidence in our model-  
75 based future projection of the global SST warming patterns (e.g., Xie et al. 2010; Lee et al. 2011;  
76 DiNezio et al. 2012).

77 Many studies have diagnosed the large systematic errors in the tropical Atlantic, and  
78 attributed the errors to various atmospheric and/or ocean processes. Recent studies argued that  
79 the westerly wind bias over the western tropical Atlantic in boreal spring is the main cause of the  
80 tropical Atlantic biases (Richter and Xie 2008; Richter et al. 2012), and showed that the westerly  
81 wind bias also exists in the atmosphere general circulation models (AGCMs) forced by observed  
82 SSTs (DeWitt 2005; Chang et al. 2007; Richter and Xie 2008; Richter et al. 2012). These studies  
83 argued that the westerly wind bias in boreal spring deepens the thermocline in the eastern  
84 equatorial Atlantic and prevents the development of the cold tongue in boreal summer; then  
85 warm SST bias develops in the cold tongue and further amplifies due to the Bjerknes feedback.

86 Other studies have suggested that a likely source of the tropical Atlantic biases is the  
87 deficiency of AOGCMs in reproducing the low-level stratus cloud deck over the southeastern  
88 tropical Atlantic Ocean (Yu and Mechoso 1999; Large and Danabasoglu 2006; Saha et al. 2006;  
89 Huang et al. 2007; Hu et al. 2008; 2011; Richter and Xie 2008). These studies argue that the  
90 warm SST bias over the southeastern tropical Atlantic is mainly caused by the model's inability  
91 to reproduce the observed amount of low-level cloud in the region, which in turn causes an  
92 excessive local shortwave radiative flux into the ocean. Wahl et al. (2011) explored this

93 hypothesis by performing some sensitivity experiments using the Kiel Climate model. Wahl et  
94 al. (2011) concluded that the westerly wind bias over the western tropical Atlantic in spring and  
95 early summer is the key mechanism for the equatorial Atlantic SST bias, while the low-level  
96 cloud cover and associated excessive surface shortwave radiation contribute to the SST bias in  
97 the southeast tropical Atlantic Ocean.

98 There are also some studies suggesting that ocean processes could contribute to the tropical  
99 Atlantic biases. Hazeleger and Haarsma (2005), for example, suggested that the tropical Atlantic  
100 bias is strongly related to the upper ocean mixing. [Jochum et al. \(2013\) showed that improving](#)  
101 [the upper ocean mixing in an ocean model could lead a reduction of the tropical Atlantic SST](#)  
102 [and rainfall biases.](#) Seo et al. (2006) argued that properly representing equatorial Atlantic  
103 instability waves in climate models could enhance the equatorial upwelling and thus potentially  
104 reduce the equatorial Atlantic warm SST bias. Large and Danabasoglu (2006) suggested that the  
105 warm SST bias in the southeastern tropical Atlantic could be reduced by improving the  
106 simulation of coastal upwelling off the coasts of southwest Africa. [Recently, Small et al. \(2014\)](#)  
107 [used a high-resolution AOGCM \(0.1° resolution for the ocean model and 0.25° resolution for the](#)  
108 [atmosphere model\) to demonstrate this hypothesis.](#) Xu et al. (2014) stressed that the inability of  
109 AOGCMs in simulating the Angola–Benguela front is one the leading causes of the tropical  
110 Atlantic SST biases. Breugem et al. (2008) attributed the warm SST bias in the eastern and  
111 southeastern tropical Atlantic to the spurious barrier layer (BL), which forms due to the  
112 excessive regional rainfall and amplifies via coupled SST-precipitation-BL feedback and thus  
113 prevents surface cooling [via](#) strong salinity stratification. However, Richter et al. (2012)  
114 showed that the BL feedback described by Breugem et al. (2008) is not significant at least in the  
115 Geophysical Fluid Dynamics Laboratory (GFDL) coupled model. There are also other interesting

116 hypotheses on the origin of the tropical Atlantic SST bias in the coupled models, such as the  
117 remote influence from higher latitudes (Lee and Wang 2008; Chang et al. 2007), the West  
118 African monsoon (Deser et al. 2006), rainfall over the Amazon and Africa (Davey et al. 2002;  
119 Chang et al. 2008; Okumura and Xie 2004), and air-sea turbulent flux (Ban et al. 2010).

120 Previous studies such as those briefly reviewed above have suggested a variety of potential  
121 causes of the tropical Atlantic SST biases in AOGCMs. However, these hypotheses (or  
122 conclusions) are derived mostly based on fully spun up AOGCM runs. Since the SST bias in an  
123 AOGCM could cause errors in the atmospheric circulation, which in turn also could feedback  
124 onto the tropical Atlantic SSTs via air-sea interaction, it is almost impossible to identify the exact  
125 processes responsible for the tropical Atlantic SST bias from fully spun up AOGCM runs. It is  
126 also worthwhile to note that a quantitative analysis on the contributions of the atmosphere-land  
127 model and ocean-sea ice model components to the tropical Atlantic SST bias in an AOGCM has  
128 rarely been done. Therefore, in an effort to better understand what causes the tropical Atlantic  
129 SST biases, here we propose a new methodology to analyze the SST bias focusing on the initial  
130 development of the SST bias by using the National Center for Atmospheric Research (NCAR)  
131 Community Earth System Model version 1 (CESM1), which suffers the same systematic tropical  
132 Atlantic SST bias as in other AOGCMs.

133 This paper is organized as follows. The model and numerical experiments design are  
134 described in section 2. The experiment results and analysis are presented in section 3 ~ 6, in  
135 which the SST bias and its development mechanism in CESM1 are analyzed by comparing  
136 results from three model experiments (to be described in section 2). Section 7 provides  
137 conclusions and discussion.

138

139 **2. Model and model experiments**

140 CESM1 is a state-of-the-art global earth system model that can provide simulations of the  
141 Earth's past, present, and future climate. It is the successor to the Community Climate System  
142 Model (CCSM), which was extended and renamed to CESM in June 2010. CESM1, which was  
143 released in November 2012, is a superset of CCSM4 in that its default configuration is the same  
144 science scenarios as CCSM4, although CESM1 also contains options for a terrestrial carbon  
145 cycle and dynamics, and ocean ecosystems and biogeochemical coupling, all necessary for an  
146 earth system model. In this paper, CESM1 is configured as a purely physical model, and is thus  
147 identical to CCSM4, since our focus here is on the physical processes.

148 Many improvements have been made in CESM1/CCSM4 simulations compared with the  
149 previous version of CCSM3, such as the frequency of the Madden-Julian Oscillation (MJO)  
150 and ENSO variability, the annual cycle of SSTs in the eastern equatorial Pacific, and the Arctic  
151 sea-ice concentration (Gent et al. 2011). However, it still displays significant tropical Atlantic  
152 SST biases (Grodky et al. 2012) as shown in Figure 1c. The observed SSTs in the equatorial  
153 Atlantic are warmer in the west and cooler in the east (Figure 1a1c). However, the SSTs in the  
154 CCSM4 control simulation with twentieth century forcing (CCSM4\_20C hereafter), which is  
155 available from the CMIP5 archive, are warmer in the east and cooler in the west with the SST  
156 bias exceeding 3.0°C in the southeast tropical Atlantic along the east coast of Africa (Figure  
157 1b1c). It is clear that CCSM4\_20C fails to reproduce the equatorial Atlantic cold tongue and the  
158 zonal SST gradient along the equator, which are common deficiencies in AOGCMs.

159 The main objective of this study is to identify the processes responsible for the development  
160 of the tropical Atlantic SST biases in CESM1. Our approach to achieve this goal is to diagnose  
161 the development of biases in a fully coupled CESM1 run initialized with data from uncoupled

162 surface-forced atmosphere and ocean only simulations. This approach is analogous to the  
163 methodology proposed in the Transpose-Atmospheric Model Intercomparison Project Phase II  
164 (T-AMIP2) as discussed in Williams et al. (2013). Similar methods were also used in previous  
165 studies (e.g., Huang et al. 2007; Toniazzo and Woolnough ~~2013~~2014; Voltaire et al. 2014).

166 Three numerical experiments are designed and performed using CESM1. These experiments  
167 are (1) dynamic atmosphere-land run forced by observed SSTs (EXP\_ATM hereafter); (2)  
168 dynamic ocean-sea ice run forced by observed surface atmospheric fluxes (EXP\_OCN  
169 hereafter); and (3) fully coupled atmosphere-land-ocean-sea ice run initialized with data from  
170 EXP\_ATM and EXP\_OCN (EXP\_CPL hereafter).

171 The atmosphere model component is Community Atmosphere Model version 4 (CAM4;  
172 Neale et al. 2010) and the land model is Community Land Model version 4 (CLM4; Lawrence et  
173 al. 2011). Both CAM4 and CLM4 have horizontal resolution of  $1.9^\circ \times 2.5^\circ$ , and are forced by  
174 observed climatological monthly SSTs (Hurrell et al. 2008). ~~This experiment (EXP\_ATM)~~ is  
175 integrated for 30 years and the last ten years are used for analysis. The ocean model is Parallel  
176 Ocean Program version 2 (POP2; Danabasoglu et al. 2012) and the sea-ice model is Community  
177 Ice Model version 4 (CICE4; Hunke and Lipscomb 2008). Both POP2 and CICE4 have a  
178 nominal  $1^\circ$  horizontal resolution, and are forced by Coordinated Ocean Reference Experiment  
179 phase 2 (COREv2) normal-year surface fluxes (Large and Yeager 2004; 2009). ~~This experiment~~  
180 ~~(EXP\_OCN)~~ is integrated for 210 years and the last ten years are used for analysis.

181 For the fully coupled experiment (EXP\_CPL), 10-member ensemble experiments are  
182 performed to achieve statistically significant model results. The atmosphere and surface land  
183 models are initialized by using EXP\_ATM, while the ocean and sea-ice models are initialized by  
184 using EXP\_OCN. The 10-member ensemble experiments are initialized by using the

185 combination of the EXP\_ATM and EXP\_OCN obtained from the last 10 years of the model  
 186 integrations, and integrated for five years. In the following sections, the ensemble-mean of  
 187 EXP\_CPL along with the results from EXP\_ATM and EXP\_OCN are analyzed to identify the  
 188 processes that cause the development of the tropical Atlantic SST biases in CESM1.

189

### 190 3. Implicit SST bias in EXP\_ATM and EXP\_OCN

#### 191 3.1 EXP\_ATM

192 In order to understand and quantify the roles of the atmospheric-land model (EXP\_ATM) in  
 193 the generation of the tropical Atlantic SST bias, the net surface heat flux bias in EXP\_ATM is  
 194 integrated in time:

$$195 \quad \Delta T_{\text{EXP\_ATM}}(t) = \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{OBS}]}{\rho_w C_{pw} D} dt$$

$$196 \quad \Delta T_{\text{EXP\_ATM}}(t) = \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{OBS}]}{\rho_w C_{pw} D} dt, \quad (1)$$

Field Code Changed

197 where  $\rho_w$  is sea water density,  $C_{pw}$  is the specific heat of sea water,  $D$  is the mixed layer depth  
 198 from EXP\_OCN,  $Q_{\text{NET}}[\text{EXP\_ATM}]$  and  $Q_{\text{NET}}[\text{OBS}]$  are the net surface heat fluxes from  
 199 EXP\_ATM and COREv2, respectively. Note that  $\Delta T_{\text{EXP\_ATM}}$  represents SST bias, which could  
 200 be potentially caused by the net surface heat flux bias for the duration of  $t$ , with assumptions that  
 201 the atmosphere-land model is coupled with a perfect ocean (i.e., all oceanic heat flux terms are  
 202 error-free) and there is no air-sea feedback to amplify or damp out the net surface heat flux bias.  
 203 Obviously, the net heat flux bias in this case (EXP\_ATM) does not change the model SSTs  
 204 because the model SSTs are fixed. Therefore, it is referred to as *implicit SST bias* in EXP\_ATM,  
 205 hereafter.

206 Fig. 2(a) shows the annually averaged implicit SST bias in EXP\_ATM due to the net surface  
207 heat flux bias. This is computed by integrating the long-term averaged (i.e., averaged the last ten  
208 years of the model simulation) net heat flux bias in EXP\_ATM from January 1 to December 31,  
209 then dividing it by 12 months. Using a similar method, the annually averaged implicit SST bias  
210 in EXP\_ATM due to the latent heat flux, shortwave radiative heat flux, and longwave radiative  
211 heat flux, are computed and shown in Figs. 2(b), (c), and (d), respectively. As shown in Fig. 2(a),  
212 the north-central equatorial Atlantic and ~~also~~ the southeastern tropical Atlantic between 20°S and  
213 the equator are characterized by warm (implicit) SST bias; while in other regions, especially in  
214 the south and north tropical Atlantic, there are two bands of cold (implicit) SST bias across the  
215 Atlantic basin. These results suggest that if the atmosphere-land model is coupled with a perfect  
216 ocean and the SST bias does not feedback onto the atmosphere-land model, warm SST bias is  
217 expected in the north-central equatorial Atlantic and the southeastern tropical Atlantic, whereas  
218 cold SST bias is expected in the north and south tropical Atlantic.

219 Fig. 2(~~eb~~) shows that the warm/cold implicit SST biases in EXP\_ATM are mainly caused by  
220 weaker/stronger surface wind ~~stress~~-bias and associated positive (i.e., into the ocean)/negative  
221 (i.e., out of the ocean) latent heat flux bias. As shown in Fig. 2(~~bc~~), the shortwave radiative flux  
222 is larger than observations over the stratus cloud deck region of the south-central and  
223 southeastern tropical Atlantic Ocean, south of around 10°S (Large and Danabasoglu 2006;  
224 Huang et al. 2007; Grodsky et al. 2012). ~~Although not shown here,~~Note that CCSM4\_20C also  
225 contains the positive shortwave radiative flux bias in the southeastern tropical Atlantic with  
226 about the same amplitude of that in EXP\_ATM; ~~(not shown here)~~, suggesting that the low-level  
227 cloud and shortwave radiation errors in CCSM4\_20C are inherent to its atmospheric-land  
228 component.

229

### 230 3.2 EXP\_OCN

231 Fig. 3 shows the SST bias in the surface-forced ocean-sea ice model experiment  
232 (EXP\_OCN). Overall, the tropical Atlantic SSTs are reasonably well simulated with relatively  
233 low amplitude of SST bias. Nevertheless, the amplitude of warm SST bias in the southeastern  
234 tropical Atlantic especially near the west coast of Africa is quite large (up to 2°C). This suggests  
235 that inherent errors in the ocean-sea ice model can significantly contribute to the warm SST bias  
236 in CCSM4\_20C, in agreement with earlier studies (Large and Danabasoglu 2006; Grodsky et al.  
237 2012).

238 It is important to note that in EXP\_OCN the ocean-sea ice model is forced with prescribed  
239 atmospheric conditions. Flux forms of atmospheric forcing, namely short and longwave radiative  
240 heat fluxes, precipitation rate and wind stress are directly used to force the ocean-sea ice model.  
241 For latent and sensible heat fluxes, however, ~~bulk equations~~ bulk formulae are used to compute them  
242 interactively using wind speed, air humidity and air temperature at 10 m along with the model  
243 SSTs. Such a treatment of the turbulent heat fluxes ultimately relaxes the model SSTs toward the  
244 prescribed surface air temperature as discussed in earlier studies (e.g., Lee et al. 2007; Liu et al.  
245 2012). Therefore, the SST bias in EXP\_OCN shown in Fig. 3 is not a good measure of inherent  
246 errors in the ocean-sea ice model.

247 To better quantify the inherent errors in EXP\_OCN, we attempt to compute implicit SST bias  
248 in EXP\_OCN associated with spurious ocean dynamic processes. The equation for the surface  
249 mixed layer temperature bias in EXP\_OCN can be written as



250 
$$\frac{\partial \Delta T_m}{\partial t} = -\Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) + \frac{Q_{NET}[\text{EXP\_OCN}] - Q_{NET}[\text{OBS}]}{\rho_w C_{pw} D}$$

251 
$$\frac{\partial \Delta T_m}{\partial t} = -\Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) + \frac{Q_{NET}[\text{EXP\_OCN}] - Q_{NET}[\text{OBS}]}{\rho_w C_{pw} D}, \quad (2)$$

Field Code Changed

252 where  $\Delta T_m$  is the difference in ocean mixed layer temperature between EXP\_OCN and the  
 253 observation,  $u_m$  and  $v_m$  are the ocean mixed layer currents in the  $x$ - and  $y$ -directions,  $w_e$  is the  
 254 entrainment rate at the mixed layer base,  $T_e$  is the ocean temperature immediately below the  
 255 mixed layer, and  $Q_{NET}[\text{EXP\_OCN}]$  is the net surface heat flux in EXP\_OCN (see Lee et al.  
 256 2007 for the derivation of the bulk mixed layer temperature equation). The first three terms on  
 257 the right side of Eq. (2) can be regarded as the errors in ocean dynamic **and mixing** processes.  
 258 Integrating Eq. (2) in time, after a minor manipulation, we get

259 
$$\Delta T_{\text{EXP\_OCN}} \equiv -\int_0^t \Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) dt$$

$$= \Delta T_m - \int_0^t \frac{Q_{NET}[\text{EXP\_OCN}] - Q_{NET}[\text{OBS}]}{\rho_w C_{pw} D} dt.$$

260 
$$\Delta T_{\text{EXP\_OCN}} \equiv -\int_0^t \Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) dt$$

$$= \Delta T_m - \int_0^t \frac{Q_{NET}[\text{EXP\_OCN}] - Q_{NET}[\text{OBS}]}{\rho_w C_{pw} D} dt. \quad (3)$$

Field Code Changed

261  $\Delta T_{\text{EXP\_OCN}}$  represents the implicit SST bias in EXP\_OCN due to the inherent errors in the ocean  
 262 dynamic **and mixing** processes, including advection and turbulent mixing, for the duration of  $t$   
 263 with assumptions that there is no air-sea feedback to amplify or damp out the net surface heat  
 264 flux bias.

265 Fig. 4(a) shows the annually averaged implicit SST bias in EXP\_OCN linked to spurious  
 266 ocean dynamic **and mixing** processes. Its amplitude is of the same order of magnitude as that in  
 267 EXP\_ATM (Fig. 2(a)). Comparing Fig. 4(a) with Fig. 2(a), in the southeastern and northeastern

268 tropical Atlantic, especially near the west coast of Africa, the implicit SST bias due to spurious  
 269 ocean dynamic and mixing processes is much larger than that due to net heat flux bias in  
 270 EXP\_ATM. This strongly suggests that the warm SST biases in CCSM4\_20C over these regions  
 271 (see Fig. 1(b)) are mainly associated with spurious ocean dynamic and mixing processes.

272 It is interesting to note that ocean dynamic cooling in EXP\_OCN is too strong in the eastern  
 273 equatorial Atlantic, but too weak in the central equatorial Atlantic. Given that vertical  
 274 entrainment of cold thermocline water due to turbulent mixing is what maintains the cold tongue  
 275 in the central equatorial Atlantic (e.g., Lee and Csanady 1999a; 1999b; Goes and Wainer 2003),  
 276 it is possible that the parameterization of vertical mixing, and/or the mean state variables that  
 277 affect the vertical mixing, namely vertical shear and stratification at the mixed layer base, are the  
 278 source of the SST bias. It is also possible that failings failure to resolve equatorial Atlantic  
 279 instability waves reduces the equatorial upwelling and is thus responsible for the warm implicit  
 280 SST bias in the central equatorial Atlantic (Seo et al. 2006).

281

### 282 3.3 EXP\_ATM + EXP\_OCN

283 The linear combination of the implicit SST bias in EXP\_ATM due to net surface heat flux  
 284 bias (Eq. (1)) and the implicit SST bias in EXP\_OCN due to spurious ocean dynamic and mixing  
 285 processes (Eq. (3)) can be written as

$$\begin{aligned}
 & \cancel{\Delta T_{\text{EXP\_ATM}} + \Delta T_{\text{EXP\_OCN}} - \Delta T_m + \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{EXP\_OCN}]}{\rho_w C_{pw} D} dt.} \\
 \Delta T_{\text{EXP\_ATM}} + \Delta T_{\text{EXP\_OCN}} &= \Delta T_m + \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{EXP\_OCN}]}{\rho_w C_{pw} D} dt. \quad (4)
 \end{aligned}$$

288 This total implicit SST bias is directly linked to the net surface heat flux mismatch between  
 289 EXP\_ATM and EXP\_OCN, and is what is expected when the atmosphere-land model is joined

Field Code Changed

290 together with the ocean-sea ice model but without any air-sea feedback. It is important to note  
291 that the implicit SST bias in EXP\_ATM + EXP\_OCN is independent from the observed surface  
292 heat flux product used in the analysis, and is thus not subject to uncertainty in the observed (or  
293 referenced) surface heat flux product used at least in a linear sense.

294 Fig. 4(b) shows the total implicit SST bias in EXP\_ATM + EXP\_OCN. Comparing this with  
295 the SST bias in CCSM4\_20C (Fig. 1(bc)), their spatial patterns are surprisingly similar. In  
296 particular, in both CCSM4\_20C and EXP\_ATM + EXP\_OCN, the southwestern and  
297 northwestern tropical Atlantic are characterized by cold SST bias, while the southeastern and  
298 northeastern tropical Atlantic are characterized by warm SST bias. This result mainly suggests  
299 that the cold/warm SST biases over these off-equatorial regions in CCSM4\_20C originate from  
300 the intrinsic biases in the atmosphere-land and ocean-sea ice model components, and are further  
301 weakened/amplified by atmosphere-ocean coupling.

302 It is noted that the overall amplitude of the SST bias in CCSM4\_20C is smaller than the  
303 amplitude of the total implicit SST bias in EXP\_ATM + EXP\_OCN. This is not unexpected  
304 because the total implicit bias in EXP\_ATM + EXP\_OCN estimates the extent to which the  
305 spurious atmosphere-ocean dynamics in the atmosphere-land and ocean sea-ice model  
306 components could *potentially* contribute to the SST bias once the air-sea coupling is initiated.  
307 For instance, in a region where the total implicit SST bias is positive, once the air-sea coupling is  
308 initiated, the model SSTs will increase initially. However, the increased SSTs will in turn  
309 enhance the longwave radiative and latent cooling at the surface to reduce the rate of SST  
310 warming. Therefore, it is highly unlikely that the SST bias will reach the full extent of the total  
311 implicit SST bias.

312 | It is interesting to note that the implicit SST bias in EXP\_OCN (Fig. 4(ba)) is slightly  
313 | negative over the eastern equatorial Atlantic region. This is somewhat inconsistent with the SST  
314 | bias in CCSM4\_20C over the same region (Fig. 1(bc)). Therefore, to better understand the origin  
315 | of the equatorial Atlantic SST bias in CCSM4\_20C, in the next section we explore the initial  
316 | development of the tropical Atlantic SST bias in EXP\_CPL. It is shown in the next section that  
317 | the ocean-sea ice model does contribute significantly in forcing the eastern equatorial Atlantic  
318 | warm SST bias due to its spurious ocean dynamic and mixing processes. However, its influence  
319 | is limited only in early boreal summer during which massive entrainment of the equatorial cold  
320 | thermocline water into the surface mixed layer occurs (e.g., Lee and Csanady 1999a; 1999b).

321

#### 322 **4. Initial development of the SST bias in EXP\_CPL**

323 | Fig. 4(c) shows the SST bias in EXP\_CPL averaged over the first year. Overall, both the  
324 | amplitude and spatial pattern of the SST bias in EXP\_CPL developed over the first year are very  
325 | similar to those of the annually averaged SST bias in CCSM4\_20C (Fig. 1(bc)), suggesting that  
326 | the tropical Atlantic SST bias develops very quickly (note the different scales used in Fig. 1(bc)  
327 | and Fig. 4(c)).

328 | Fig. 5 shows the bi-monthly SST bias development in the fully coupled model experiment  
329 | (EXP\_CPL) during the first and second years of the model integration. An interesting point is  
330 | that the cold SST bias in the eastern equatorial Atlantic, which apparently originates from the  
331 | ocean-sea ice model (Fig. 4(a)), persists only during the first four months of the coupled model  
332 | integration. It disappears afterward and is completely masked by the warm SST bias in June of  
333 | the first year. Among other features, perhaps the most striking is the fast development of the

334 warm SST bias in the southeastern tropical Atlantic - the SST bias along the coast of Angola  
335 exceeds 6°C by June of the first year.

336 Although the tropical Atlantic SST bias in EXP\_CPL develops very quickly within a year,  
337 largely due to the combined effect of intrinsic biases in EXP\_ATM and EXP\_OCN, in some  
338 regions the SST bias in the first year is further weakened or amplified, probably due to the active  
339 atmosphere-ocean coupling. For instance, the cold SST bias over the southwestern tropical  
340 Atlantic in the first year is much reduced in the second year due to the eastward expansion of the  
341 warm SST anomalies in the southeastern tropical Atlantic. It is also clear that the warm SST bias  
342 in the eastern equatorial Atlantic during the first year strengthens and expands westward in the  
343 second year.

344 In order to better describe the tropical Atlantic SST biases in EXP\_CPL and how they are  
345 forced by EXP\_ATM, EXP\_OCN and the atmosphere-ocean coupling, the bi-monthly tropical  
346 Atlantic SST bias tendencies ( $^{\circ}\text{C month}^{-1}$ ) in EXP\_CPL, EXP\_ATM + EXP\_OCN, EXP\_ATM  
347 and EXP\_OCN during the first year are shown in Fig. 6. It is clearly shown that the southeastern  
348 tropical Atlantic warm SST bias in EXP\_CPL, which is largely forced in boreal spring, is mainly  
349 caused by EXP\_OCN due to spurious ocean dynamic and mixing processes, with an assumption  
350 that the surface fluxes prescribed in EXP\_OCN is error-free. It is also clear that the initial  
351 development of the eastern equatorial warm SST bias, which is mainly forced in early boreal  
352 summer, is also caused by EXP\_OCN due to spurious ocean dynamic and mixing processes. By  
353 comparing the SST bias tendency in EXP\_CPL and the implicit SST bias tendency in  
354 EXP\_OCN, it is clear that the atmosphere-ocean coupling tends to weaken the implicit SST bias  
355 tendency in these regions. This clearly suggests that the atmosphere-ocean coupling is not the  
356 cause of the eastern equatorial warm SST bias at least in the first year of the coupling. These

357 features in the equatorial Atlantic are much more clearly illustrated in Fig. 7, which shows the  
358 time evolutions of the SST bias tendencies (implicit SST bias tendencies) along the equatorial  
359 Atlantic and the contributions by the surface heat flux errors and by errors involving ocean  
360 dynamic and mixing processes in EXP\_CPL (EXP\_ATM and EXP\_OCN). Therefore, we may  
361 conclude that the eastern equatorial and southeastern tropical Atlantic warm SST biases in  
362 EXP\_CPL are mainly forced by EXP\_OCN due to its spurious ocean dynamic and mixing  
363 processes during boreal spring and summer.

364 Richter and Xie (2008) analyzed CMIP3 models and argued that the westerly wind bias in  
365 boreal spring over the western equatorial Atlantic deepens the thermocline in the eastern  
366 equatorial Atlantic preventing the development of the cold tongue in boreal summer, and thus is  
367 the root cause of the equatorial Atlantic warm SST bias in CMIP3 models. Our analysis of the  
368 three CESM1 experiments, however, suggests that the ocean-sea ice model due to its spurious  
369 ocean dynamic and mixing processes may contribute more significantly than the atmosphere-  
370 land model to the eastern equatorial Atlantic warm SST bias in CCSM4/CESM1. Therefore,  
371 while although we acknowledge the potential importance of the westerly wind bias in boreal  
372 spring over the western equatorial Atlantic, which originates from the atmosphere-land model  
373 (see Fig. 2(b)), here we stress that solving this problem in the atmosphere-land model alone does  
374 not resolve the equatorial Atlantic warm bias in CCSM4/CESM1.

375 Grodsky et al. (2012) showed that mean sea level pressure in CCSM4 is erroneously high by  
376 a few millibars in the subtropical highs and erroneously low in the polar lows similar to CCSM3,  
377 and thus the trade winds are  $1 \sim 2 \text{ m s}^{-1}$  too strong. Since the cold SST biases in the southwestern  
378 and northwestern tropical Atlantic are closely linked to the strength of the trade winds in

379 EXP\_ATM, it is likely that their root cause is linked to the subtropical highs in the atmosphere-  
380 land model.

381

## 382 **5. Equatorial Atlantic subsurface temperature bias in EXP\_OCN**

383 The methodology used in this study only provides a mean to estimate the integrated effects of  
384 the spurious ocean dynamic and mixing processes in EXP\_OCN via “implicit SST bias”. To  
385 further understand what causes the spurious ocean dynamic and mixing processes, the equatorial  
386 Atlantic subsurface temperature bias in EXP\_OCN is explored here. Figure 8 shows the  
387 monthly-averaged equatorial Atlantic temperature bias (averaged for 5°S - 5°N) in EXP\_OCN for  
388 the upper 200 m. In order to compute the temperature bias, we use EN4, which is a global quality  
389 controlled ocean temperature data set provided by the Met Office Hadley Centre (Good et al.  
390 2013). The green lines show the corresponding mixed layer depths obtained from EXP\_OCN  
391 (solid line) and EN4 (dashed line).

392 This figure clearly shows that the temperature bias near the surface is quite small because the  
393 model-simulated surface temperature is strongly damped to the prescribed air temperature and  
394 specific humidity. However, at the basedbase of the model-simulated mixed layer, the  
395 temperature bias increases up to 6°C. This suggests that due to spurious ocean dynamic and  
396 mixing processes in the ocean-sea ice model, the upper thermocline water entrained into the  
397 mixed layer during early summer (e.g., Lee and Csanady 1999a; 1999b) is too warm. Therefore,  
398 once the ocean sea-ice model is fully coupled to the atmosphere-land model, the extra heat in the  
399 mixed layer caused by the entrainment of the warmer-than-observed upper thermocline layer will  
400 produces warm SST bias in the equatorial Atlantic upwelling region.

401 Fig. 8 also shows that the mixed layer depth is too deep in EXP\_OCN. This suggests that the  
402 vertical turbulent mixing may be too intense in EXP\_OCN. It is likely that the warmer-than-  
403 observed upper thermocline layer weakens the vertical stratification over the upper thermocline  
404 and thus ~~contributes to increase turbulent mixing at the mixed layer base~~increases turbulent  
405 mixing at the mixed layer base. This means that the mixed layer depth bias may be directly  
406 linked to the upper thermocline temperature bias. One hypothesis is that the spurious vertical  
407 diffusion in the thermocline layer due to vertical discretization brings too much heat into the  
408 upper thermocline layer from the mixed layer, which in turn weakens the vertical stratification  
409 and thus further increases the vertical mixing across the mixed layer base, a positive feedback.  
410 To further investigate what processes or parameterizations are responsible for the warmer-than-  
411 observed upper thermocline and deeper-than-observed mixed layer depth, it is necessary to  
412 perform sensitivity experiments by using the stand-alone ocean sea-ice model and the diagnostic  
413 methodology proposed in this study.

414

## 415 **6. Impact of uncertainty in the reference surface flux fields**

416 It should be pointed out that our results are not entirely independent from uncertainty in the  
417 reference surface flux product used (i.e., COREv2). For instance, if the net surface heat flux in  
418 COREv2 is too large, it will contribute positively (negatively) to the implicit SST bias in  
419 EXP\_OCN (EXP\_ATM) according to Eqs. (1) and (3). Although considerable effort was  
420 invested to minimize errors (see Large and Yeager [20082009](#) for more details), COREv2 is still  
421 far from error-free. Therefore, in a more strict sense, Eq. (3) should be considered as the implicit  
422 SST bias in EXP\_OCN referenced to COREv2. Similarly, Eq. (1) should be considered as the  
423 implicit SST bias in EXP\_ATM referenced to COREv2. Nevertheless, it should be noted that the



424 total implicit SST bias in EXP\_ATM + EXP\_OCN is independent from the reference surface  
425 flux product used, and is thus not subject to uncertainty in the reference surface flux product at  
426 least in a linear sense (see Eq. (3)).

427 To better understand if and how the uncertainty in the reference surface flux product  
428 influences the implicit SST bias in EXP\_ATM and EXP\_OCN, two additional experiments are  
429 performed by forcing the stand-alone ocean sea-ice model for 120 years with the surface flux  
430 fields derived from the European Centre for Medium-Range Weather Forecasts Interim  
431 (ERA\_INT) reanalysis (Dee et al. 2011), and the Modern-Era Retrospective Analysis for  
432 Research and Applications (MERRA) reanalysis (Rienecker et al. 2011)

433 As shown in Figs. 9(a), (d) and (g), the implicit SST bias in EXP\_ATM referenced to  
434 ~~COREv2 is generally more positive compared to that referenced to~~ either ERA\_INT or MERRA  
435 ~~is more negative compared to that referenced to COREv2.~~ On the contrary, the implicit SST  
436 bias in EXP\_OCN referenced to ~~COREv2 is generally more negative compared to that~~  
437 ~~referenced to~~ either ERA\_INT or MERRA ~~is more positive compared to that referenced to~~  
438 ~~COREv2.~~ What these mean is that the net surface heat flux into the tropical Atlantic is larger  
439 overall in ERA\_INT and MERRA than that in COREv2. Nevertheless, the spatial patterns of the  
440 implicit SST bias in EXP\_ATM referenced to the three surface flux products (i.e., COREv2,  
441 ERA\_INT and MERRA) are quite similar. As shown in Figs. 9(b), (e) and (h), the same  
442 conclusion can be drawn for the implicit SST bias in EXP\_OCN.

443 In sum, the overall magnitude of the implicit SST bias can be attributed more to either the  
444 atmosphere-land model or the ocean sea-ice model depending on the reference surface flux  
445 product used. In other words, the choice of the reference surface heat flux product will impact  
446 the estimates of implicit SST biases in EXP ATM and EXP OCN. However, the spatial

447 | ~~pattern~~patterns of the implicit bias in EXP\_ATM ~~(and EXP\_OCN)~~ ~~is~~ ~~are~~ largely determined by  
448 | inherent ~~deficiency~~deficiencies of the atmosphere-land ~~(, and ocean-sea ice)~~ model  
449 | ~~component~~components, respectively. As such, the total implicit SST bias in EXP\_ATM +  
450 | EXP\_OCN is only minimally affected by the reference surface flux product used (see Figs. 9(c),  
451 | (f) and (i)). Therefore, we can conclude that the total implicit bias in EXP\_ATM + EXP\_OCN is  
452 | a reliable measure of inherent deficiency in CESM1.

453

## 454 | **7. Summary and Discussions**

455 | In order to better understand the initial development of the tropical Atlantic SST bias in  
456 | AOGCMs, we ~~have~~ performed a series of model experiments using CESM1. These experiments  
457 | are a forced atmosphere-land model experiment (EXP\_ATM), a forced ocean-ice model  
458 | experiment (EXP\_OCN) and a fully coupled model experiment with its atmosphere-land model  
459 | initialized using EXP\_ATM and the ocean-ice model using EXP\_OCN (EXP\_CPL).

460 | We propose and use a new method of diagnosis to identify and quantify intrinsic errors in the  
461 | atmosphere-land and ocean-sea ice model components of CESM1. It is shown here that both the  
462 | atmosphere-land and ocean-sea ice model components contain significant errors in the tropical  
463 | Atlantic. In boreal summer, the ocean-sea ice model could cause large amplitudes of warm SST  
464 | bias in the eastern equatorial and southeastern tropical Atlantic due to its spurious ocean dynamic  
465 | ~~and mixing~~ processes even if it is coupled to a perfect atmosphere-land model and the SST bias  
466 | does not feedback onto the ocean-sea ice model. In the atmosphere-land model, the trade winds  
467 | and associated surface latent cooling are too strong in the northwestern and southwestern tropical  
468 | Atlantic, while they are too weak in the northeastern and southeastern tropical Atlantic.  
469 | Therefore, even if the atmosphere-land model is coupled to a perfect ocean-sea ice model and the

470 SST bias does not feedback onto the atmosphere-land model, warm (cold) SST bias could be  
471 generated in the northeastern (northwestern) and southeastern (southwestern) tropical Atlantic.

472 In the fully coupled model simulation with its atmosphere-land model initialized using  
473 EXP\_ATM and the ocean-sea ice model using EXP\_OCN, the tropical Atlantic SST bias  
474 develops very quickly within a year, and its seasonality and spatial pattern are largely determined  
475 by the linear combination of the implicit SST bias in EXP\_ATM and EXP\_OCN. In particular, it  
476 is shown ~~here~~ that the eastern equatorial and southeastern tropical Atlantic warm SST bias in the  
477 fully coupled simulation are forced in early boreal summer by the ocean-sea ice model due to its  
478 spurious ocean dynamic and mixing processes. Further analysis shows that the upper thermocline  
479 water underneath the eastern equatorial Atlantic surface mixed layer is too warm in EXP\_OCN.  
480 This suggests that the mixed layer cooling in boreal summer associated with the equatorial  
481 entrainment of upper thermocline water is too weak.

482 The main emphasis in this paper is to explore how the tropical Atlantic SST bias in CESM1  
483 is initiated and evolves. Here, we identify that the intrinsic errors in the ocean-sea ice model  
484 contribute significantly to the tropical SST bias in CESM1. However, this does not mean that the  
485 atmosphere-land model contributes less to the tropical SST bias. In addition to the intrinsic errors  
486 in the atmosphere-land model explored in this study, the equatorial Atlantic surface wind bias in  
487 EXP\_ATM could affect the upper ocean dynamics in EXP\_CPL, which may feedback ~~on~~ onto  
488 the equatorial Atlantic SST in EXP\_CPL (Richter and Xie 2008). Therefore, we acknowledge  
489 the importance of improving critical problems in the atmosphere-land model. We only stress here  
490 that solving those problems in the atmosphere-land model alone does not resolve the equatorial  
491 Atlantic warm bias in CESM1. It should be also pointed out that the choice of the mixed layer  
492 depth used to determine the implicit SST bias in EXP\_ATM (see Eq. (1)) is somewhat arbitrary.

493 which is one of the limitations of the proposed method to diagnose the implicit SST bias in  
494 EXP\_ATM.

495 ~~It should be pointed~~Additionally, we would like to point out that our results are not entirely  
496 independent from uncertainty in the reference surface flux product used. In particular, the overall  
497 magnitude of the implicit SST bias can be attributed more to either the atmosphere-land model or  
498 the ocean sea-ice model depending on the reference surface flux product used. Nevertheless, the  
499 total implicit SST bias in EXP\_ATM + EXP\_OCN is only minimally affected by  
500 ~~uncertainty~~uncertainties in the reference surface flux product used, and thus is a reliable measure  
501 of inherent deficiency in CESM1. Further studies are also needed to trace the parameterizations  
502 and/or configurations in the ocean-sea ice model that are directly linked to the errors. Therefore,  
503 we recommend sensitivity studies on model resolutions (in both the horizontal and vertical  
504 directions), representation of surface flux fields especially off Angola and Namibia, vertical  
505 mixing schemes and isopycnal mixing schemes, using the ocean-sea ice model component of  
506 CESM1 and the diagnosis method proposed in this study.

507  
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516

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706

#### 707 **Figure captions**

708 **Fig. 1.** Annually averaged climatological SSTs in the tropical Atlantic from (a) EN4, a global  
709 quality controlled ocean temperature data set provided by the Met Office Hadley Centre (Good et  
710 al. 2013), for 1949-2005, and (b) CCSM4 historical simulation for 1949-2005. The SST bias in  
711 CCSM4 is shown in (c). The unit is °C. The SST bias values higher than 6°C are masked.

712

713 **Fig. 2.** Annually averaged implicit SST bias in EXP\_ATM due to (a) the net surface heat flux  
714 bias, which is computed by integrating the net heat flux bias in EXP\_ATM for one year from  
715 January 1 to December 31, then dividing it by 12 months. Contributions by (b) shortwave  
716 radiative heat flux bias, (c) latent heat flux bias and (d) longwave radiative heat flux bias. The  
717 vectors in (c) show the annually averaged surface wind stress bias. The unit for the implicit SST  
718 bias is °C.

719

720 **Fig. 3.** Annually averaged SST bias in EXP\_OCN. The unit is °C.

721

722 **Fig. 4.** Annually averaged implicit SST bias in (a) EXP\_OCN and (b) EXP\_ATM + EXP\_OCN,  
723 (c) Annually averaged SST bias in EXP\_CPL during the first year. The unit is °C. The implicit  
724 SST bias values higher than 12°C are masked.

725

726 **Fig. 5.** Time evolution of the SST bias in EXP\_CPL during the first and second year. The unit is  
727 °C.

728

729 **Fig. 6.** (1st column) Time evolution of the SST bias tendency in EXP\_CPL during the first year.  
730 Time evolution of the implicit SST bias tendency in (2nd column) EXP\_ATM + EXP\_OCN,  
731 (3rd column) EXP\_ATM, and (4th column) EXP\_OCN. The unit is °C month<sup>-1</sup>.

732

733 **Fig. 7.** Time-longitude evolutions of (a) the SST bias tendencies along the equatorial Atlantic,  
734 and the contributions by (b) the surface heat flux errors and (c) errors involving ocean dynamic  
735 processes in EXP\_CPL during the first year. Time-longitude evolutions of implicit SST bias  
736 tendencies in (d) EXP\_ATM + EXP\_OCN, (e) EXP\_ATM and (f) EXP\_OCN. The unit is °C  
737 month<sup>-1</sup>.

738

739 **Fig. 8.** Time-depth evolutions of the equatorial Atlantic temperature bias (shaded) and mixed  
740 layer depth (green solid line) averaged for 5°S-5°N obtained from EXP\_OCN. The green dashed  
741 line is the mixed layer depth obtained from EN4.

742

743 **Fig. 9.** Annually averaged implicit SST bias in (a,d,g) EXP\_ATM, (b,e,h) EXP\_OCN, and (c,f,i)  
744 EXP\_ATM + EXP\_OCN referenced to (a,b,c) COREv2, (d,e,f) ERA\_INT, and (g,h,i) MERRA.  
745 The unit is °C. The SST bias values higher than 12°C are masked.

Highlights: (85 character limit):

- This study explores intrinsic errors in the atmosphere & ocean components of CESM1.
- Both components contain large errors in the tropical Atlantic with strong seasonality.
- The ocean component mainly forces the eastern Atlantic SST bias in early summer.
- The equatorial Atlantic thermocline is too warm in a stand-alone ocean simulation.
- The ocean model must be improved to reduce the tropical Atlantic SST bias in CESM1.



1 **Contributions of the atmosphere-land and ocean-sea ice model components to**  
2 **the tropical Atlantic SST bias in CESM1**

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## Abstract

In order to identify and quantify intrinsic errors in the atmosphere-land and ocean-sea ice model components of the Community Earth System Model version 1 (CESM1) and their contributions to the tropical Atlantic sea surface temperature (SST) bias in CESM1, we propose a new method of diagnosis and apply it to a set of CESM1 simulations. Our analyses of the model simulations indicate that both the atmosphere-land and ocean-sea ice model components of CESM1 contain large errors in the tropical Atlantic. When the two model components are fully coupled, the intrinsic errors in the two components emerge quickly within a year with strong seasonality in their growth rates. In particular, the ocean-sea ice model contributes significantly in forcing the eastern equatorial Atlantic warm SST bias in early boreal summer. Further analysis shows that the upper thermocline water underneath the eastern equatorial Atlantic surface mixed layer is too warm in a stand-alone ocean-sea ice simulation of CESM1 forced with observed surface flux fields, suggesting that the mixed layer cooling associated with the entrainment of upper thermocline water is too weak in early boreal summer. Therefore, although we acknowledge the potential importance of the westerly wind bias in the western equatorial Atlantic and the low-level stratus cloud bias in the southeastern tropical Atlantic, both of which originate from the atmosphere-land model, we emphasize here that solving those problems in the atmosphere-land model alone does not resolve the equatorial Atlantic warm bias in CESM1.

Key Words: tropical Atlantic SST bias; implicit SST bias; CESM, atmosphere-land model experiment; ocean-ice model experiment

47 **1. Introduction**

48 Since the pioneering work of Manabe and Bryan (1969), coupled atmosphere-ocean general  
49 circulation models (AOGCMs) have been significantly improved. AOGCMs are now able to  
50 reproduce the basic features of the global climate system (Covey et al. 2003; Meehl et al. 2005),  
51 and thus become an important tool for seasonal forecasts, climate projections and other climate  
52 research in general. However, the tropical Atlantic biases typically characterized by warmer sea  
53 surface temperatures (SSTs) in the eastern equatorial ocean, a reversed zonal SST gradient along  
54 the equator, colder SSTs in the northwest and southwest tropical Atlantic, and warmer SSTs in  
55 the northeast and southeast tropical Atlantic, are common problems with most AOGCMs (e.g.,  
56 Davey et al. 2002).

57 Model biases have been somewhat reduced in most recent models used in the Coupled Model  
58 Intercomparison Project Phase 5 (CMIP5) compared to those used in CMIP3 (e.g., Liu et al.  
59 2013). Recent studies have also shown that improving the spatial resolution could potentially  
60 reduce such biases (Gent et al. 2010; Patricola et al. 2012; Kirtman et al. 2012; Small et al.  
61 2014). Nevertheless, almost all of the state-of-the-art AOGCMs still cannot reproduce the  
62 climatology of tropical Atlantic SSTs (Mechoso et al. 1995; Davey et al. 2002; Covey et al.  
63 2003; Huang et al. 2007; Richter and Xie 2008; Richter et al. 2012).

64 These systematic tropical Atlantic biases in AOGCMs will affect the models' ability to  
65 simulate and predict climate variability (Xie and Carton 2004). Studies have shown that the  
66 tropical Atlantic affects and modulates climate variability of the Western Hemisphere, such as  
67 the West African summer monsoon (Vizy and Cook 2001; Giannini et al. 2003; Gu and Adler  
68 2004), moisture transport and rainfall over the American continents (Enfield et al. 2001; Wang et  
69 al. 2006) and Atlantic hurricane development and intensification (e.g., Goldenberg et al. 2001;

70 Webster et al. 2005; Wang and Lee 2007). Therefore, in order to increase the seasonal-to-decadal  
71 climate predictability in the Western Hemisphere, it is important to accurately simulate the  
72 tropical Atlantic Ocean in AOGCMs. It is also worthwhile to point out that the tropical Atlantic  
73 problem in AOGCMs is one of the most critical obstacles for achieving confidence in our model-  
74 based future projection of the global SST warming patterns (e.g., Xie et al. 2010; Lee et al. 2011;  
75 DiNezio et al. 2012).

76 Many studies have diagnosed the large systematic errors in the tropical Atlantic, and  
77 attributed the errors to various atmospheric and/or ocean processes. Recent studies argued that  
78 the westerly wind bias over the western tropical Atlantic in boreal spring is the main cause of the  
79 tropical Atlantic biases (Richter and Xie 2008; Richter et al. 2012), and showed that the westerly  
80 wind bias also exists in the atmosphere general circulation models (AGCMs) forced by observed  
81 SSTs (DeWitt 2005; Chang et al. 2007; Richter and Xie 2008; Richter et al. 2012). These studies  
82 argued that the westerly wind bias in boreal spring deepens the thermocline in the eastern  
83 equatorial Atlantic and prevents the development of the cold tongue in boreal summer; then  
84 warm SST bias develops in the cold tongue and further amplifies due to the Bjerknes feedback.

85 Other studies have suggested that a likely source of the tropical Atlantic biases is the  
86 deficiency of AOGCMs in reproducing the low-level stratus cloud deck over the southeastern  
87 tropical Atlantic Ocean (Yu and Mechoso 1999; Large and Danabasoglu 2006; Saha et al. 2006;  
88 Huang et al. 2007; Hu et al. 2008; 2011; Richter and Xie 2008). These studies argue that the  
89 warm SST bias over the southeastern tropical Atlantic is mainly caused by the model's inability  
90 to reproduce the observed amount of low-level cloud in the region, which in turn causes an  
91 excessive local shortwave radiative flux into the ocean. Wahl et al. (2011) explored this  
92 hypothesis by performing some sensitivity experiments using the Kiel Climate model. Wahl et

93 al. (2011) concluded that the westerly wind bias over the western tropical Atlantic in spring and  
94 early summer is the key mechanism for the equatorial Atlantic SST bias, while the low-level  
95 cloud cover and associated excessive surface shortwave radiation contribute to the SST bias in  
96 the southeast tropical Atlantic Ocean.

97 There are also some studies suggesting that ocean processes could contribute to the tropical  
98 Atlantic biases. Hazeleger and Haarsma (2005), for example, suggested that the tropical Atlantic  
99 bias is strongly related to the upper ocean mixing. Jochum et al. (2013) showed that improving  
100 the upper ocean mixing in an ocean model could lead a reduction of the tropical Atlantic SST  
101 and rainfall biases. Seo et al. (2006) argued that properly representing equatorial Atlantic  
102 instability waves in climate models could enhance the equatorial upwelling and thus potentially  
103 reduce the equatorial Atlantic warm SST bias. Large and Danabasoglu (2006) suggested that the  
104 warm SST bias in the southeastern tropical Atlantic could be reduced by improving the  
105 simulation of coastal upwelling off the coasts of southwest Africa. Recently, Small et al. (2014)  
106 used a high-resolution AOGCM (0.1° resolution for the ocean model and 0.25° resolution for the  
107 atmosphere model) to demonstrate this hypothesis. Xu et al. (2014) stressed that the inability of  
108 AOGCMs in simulating the Angola–Benguela front is one the leading causes of the tropical  
109 Atlantic SST biases. Breugem et al. (2008) attributed the warm SST bias in the eastern and  
110 southeastern tropical Atlantic to the spurious barrier layer (BL), which forms due to the  
111 excessive regional rainfall and amplifies via coupled SST-precipitation-BL feedback and thus  
112 prevents surface cooling through strong salinity stratification. However, Richter et al. (2012)  
113 showed that the BL feedback described by Breugem et al. (2008) is not significant at least in the  
114 Geophysical Fluid Dynamics Laboratory (GFDL) coupled model. There are also other interesting  
115 hypotheses on the origin of the tropical Atlantic SST bias in the coupled models, such as the

116 remote influence from higher latitudes (Lee and Wang 2008; Chang et al. 2007), the West  
117 African monsoon (Deser et al. 2006), rainfall over the Amazon and Africa (Davey et al. 2002;  
118 Chang et al. 2008; Okumura and Xie 2004), and air-sea turbulent flux (Ban et al. 2010).

119 Previous studies such as those briefly reviewed above have suggested a variety of potential  
120 causes of the tropical Atlantic SST biases in AOGCMs. However, these hypotheses (or  
121 conclusions) are derived mostly based on fully spun up AOGCM runs. Since the SST bias in an  
122 AOGCM could cause errors in the atmospheric circulation, which in turn also could feedback  
123 onto the tropical Atlantic SSTs via air-sea interaction, it is almost impossible to identify the exact  
124 processes responsible for the tropical Atlantic SST bias from fully spun up AOGCM runs. It is  
125 also worthwhile to note that a quantitative analysis on the contributions of the atmosphere-land  
126 model and ocean-sea ice model components to the tropical Atlantic SST bias in an AOGCM has  
127 rarely been done. Therefore, in an effort to better understand what causes the tropical Atlantic  
128 SST biases, here we propose a new methodology to analyze the SST bias focusing on the initial  
129 development of the SST bias by using the National Center for Atmospheric Research (NCAR)  
130 Community Earth System Model version 1 (CESM1), which suffers the same systematic tropical  
131 Atlantic SST bias as in other AOGCMs.

132 This paper is organized as follows. The model and numerical experiments design are  
133 described in section 2. The experiment results and analysis are presented in section 3 ~ 6, in  
134 which the SST bias and its development mechanism in CESM1 are analyzed by comparing  
135 results from three model experiments (to be described in section 2). Section 7 provides  
136 conclusions and discussion.

137

## 138 **2. Model and model experiments**

139 CESM1 is a state-of-the-art global earth system model that can provide simulations of the  
140 Earth's past, present, and future climate. It is the successor to the Community Climate System  
141 Model (CCSM), which was extended and renamed to CESM in June 2010. CESM1, which was  
142 released in November 2012, is a superset of CCSM4 in that its default configuration is the same  
143 science scenarios as CCSM4, although CESM1 also contains options for a terrestrial carbon  
144 cycle and dynamics, and ocean ecosystems and biogeochemical coupling, all necessary for an  
145 earth system model. In this paper, CESM1 is configured as a purely physical model, and is thus  
146 identical to CCSM4, since our focus here is on the physical processes.

147 Many improvements have been made in CESM1/CCSM4 simulations compared with the  
148 previous version of CCSM3, such as the frequency of the Madden-Julian Oscillation (MJO) and  
149 ENSO variability, the annual cycle of SSTs in the eastern equatorial Pacific, and the Arctic sea-  
150 ice concentration (Gent et al. 2011). However, it still displays significant tropical Atlantic SST  
151 biases (Grodky et al. 2012) as shown in Figure 1c. The observed SSTs in the equatorial Atlantic  
152 are warmer in the west and cooler in the east (Figure 1c). However, the SSTs in the CCSM4  
153 control simulation with twentieth century forcing (CCSM4\_20C hereafter), which is available  
154 from the CMIP5 archive, are warmer in the east and cooler in the west with the SST bias  
155 exceeding 3.0°C in the southeast tropical Atlantic along the east coast of Africa (Figure 1c). It is  
156 clear that CCSM4\_20C fails to reproduce the equatorial Atlantic cold tongue and the zonal SST  
157 gradient along the equator, which are common deficiencies in AOGCMs.

158 The main objective of this study is to identify the processes responsible for the development  
159 of the tropical Atlantic SST biases in CESM1. Our approach to achieve this goal is to diagnose  
160 the development of biases in a fully coupled CESM1 run initialized with data from uncoupled  
161 surface-forced atmosphere and ocean only simulations. This approach is analogous to the

162 methodology proposed in the Transpose-Atmospheric Model Intercomparison Project Phase II  
163 (T-AMIP2) as discussed in Williams et al. (2013). Similar methods were also used in previous  
164 studies (e.g., Huang et al. 2007; Toniazzo and Woolnough 2014; Voltaire et al. 2014).

165 Three numerical experiments are designed and performed using CESM1. These experiments  
166 are (1) dynamic atmosphere-land run forced by observed SSTs (EXP\_ATM hereafter); (2)  
167 dynamic ocean-sea ice run forced by observed surface atmospheric fluxes (EXP\_OCN  
168 hereafter); and (3) fully coupled atmosphere-land-ocean-sea ice run initialized with data from  
169 EXP\_ATM and EXP\_OCN (EXP\_CPL hereafter).

170 The atmosphere model component is Community Atmosphere Model version 4 (CAM4;  
171 Neale et al. 2010) and the land model is Community Land Model version 4 (CLM4; Lawrence et  
172 al. 2011). Both CAM4 and CLM4 have horizontal resolution of  $1.9^\circ \times 2.5^\circ$ , and are forced by  
173 observed climatological monthly SSTs (Hurrell et al. 2008). EXP\_ATM is integrated for 30  
174 years and the last ten years are used for analysis. The ocean model is Parallel Ocean Program  
175 version 2 (POP2; Danabasoglu et al. 2012) and the sea-ice model is Community Ice Model  
176 version 4 (CICE4; Hunke and Lipscomb 2008). Both POP2 and CICE4 have a nominal  $1^\circ$   
177 horizontal resolution, and are forced by Coordinated Ocean Reference Experiment phase 2  
178 (COREv2) normal-year surface fluxes (Large and Yeager 2004; 2009). EXP\_OCN is integrated  
179 for 210 years and the last ten years are used for analysis.

180 For the fully coupled experiment (EXP\_CPL), 10-member ensemble experiments are  
181 performed to achieve statistically significant model results. The atmosphere and surface land  
182 models are initialized by using EXP\_ATM, while the ocean and sea-ice models are initialized by  
183 using EXP\_OCN. The 10-member ensemble experiments are initialized by using the  
184 combination of the EXP\_ATM and EXP\_OCN obtained from the last 10 years of the model



185 integrations, and integrated for five years. In the following sections, the ensemble-mean of  
186 EXP\_CPL along with the results from EXP\_ATM and EXP\_OCN are analyzed to identify the  
187 processes that cause the development of the tropical Atlantic SST biases in CESM1.

188

### 189 **3. Implicit SST bias in EXP\_ATM and EXP\_OCN**

#### 190 3.1 EXP\_ATM

191 In order to understand and quantify the roles of the atmospheric-land model (EXP\_ATM) in  
192 the generation of the tropical Atlantic SST bias, the net surface heat flux bias in EXP\_ATM is  
193 integrated in time:

$$194 \quad \Delta T_{\text{EXP\_ATM}}(t) = \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{OBS}]}{\rho_w C_{pw} D} dt, \quad (1)$$

195 where  $\rho_w$  is sea water density,  $C_{pw}$  is the specific heat of sea water,  $D$  is the mixed layer depth  
196 from EXP\_OCN,  $Q_{\text{NET}}[\text{EXP\_ATM}]$  and  $Q_{\text{NET}}[\text{OBS}]$  are the net surface heat fluxes from  
197 EXP\_ATM and COREv2, respectively. Note that  $\Delta T_{\text{EXP\_ATM}}$  represents SST bias, which could be  
198 potentially caused by the net surface heat flux bias for the duration of  $t$ , with assumptions that the  
199 atmosphere-land model is coupled with a perfect ocean (i.e., all oceanic heat flux terms are error-  
200 free) and there is no air-sea feedback to amplify or damp out the net surface heat flux bias.  
201 Obviously, the net heat flux bias in this case (EXP\_ATM) does not change the model SSTs  
202 because the model SSTs are fixed. Therefore, it is referred to as *implicit SST bias* in EXP\_ATM,  
203 hereafter.

204 Fig. 2(a) shows the annually averaged implicit SST bias in EXP\_ATM due to the net surface  
205 heat flux bias. This is computed by integrating the long-term averaged (i.e., averaged the last ten  
206 years of the model simulation) net heat flux bias in EXP\_ATM from January 1 to December 31,  
207 then dividing it by 12 months. Using a similar method, the annually averaged implicit SST bias

208 in EXP\_ATM due to the latent heat flux, shortwave radiative heat flux, and longwave radiative  
209 heat flux, are computed and shown in Figs. 2(b), (c), and (d), respectively. As shown in Fig. 2(a),  
210 the north-central equatorial Atlantic and the southeastern tropical Atlantic between 20°S and the  
211 equator are characterized by warm (implicit) SST bias; while in other regions, especially in the  
212 south and north tropical Atlantic, there are two bands of cold (implicit) SST bias across the  
213 Atlantic basin. These results suggest that if the atmosphere-land model is coupled with a perfect  
214 ocean and the SST bias does not feedback onto the atmosphere-land model, warm SST bias is  
215 expected in the north-central equatorial Atlantic and the southeastern tropical Atlantic, whereas  
216 cold SST bias is expected in the north and south tropical Atlantic.

217 Fig. 2(b) shows that the warm/cold implicit SST biases in EXP\_ATM are mainly caused by  
218 weaker/stronger surface wind bias and associated positive (i.e., into the ocean)/negative (i.e., out  
219 of the ocean) latent heat flux bias. As shown in Fig. 2(c), the shortwave radiative flux is larger  
220 than observations over the stratus cloud deck region of the south-central and southeastern  
221 tropical Atlantic Ocean, south of around 10°S (Large and Danabasoglu 2006; Huang et al. 2007;  
222 Grodsky et al. 2012). Note that CCSM4\_20C also contains the positive shortwave radiative flux  
223 bias in the southeastern tropical Atlantic with about the same amplitude of that in EXP\_ATM  
224 (not shown here), suggesting that the low-level cloud and shortwave radiation errors in  
225 CCSM4\_20C are inherent to its atmospheric-land component.

226

### 227 3.2 EXP\_OCN

228 Fig. 3 shows the SST bias in the surface-forced ocean-sea ice model experiment  
229 (EXP\_OCN). Overall, the tropical Atlantic SSTs are reasonably well simulated with relatively  
230 low amplitude of SST bias. Nevertheless, the amplitude of warm SST bias in the southeastern

231 tropical Atlantic especially near the west coast of Africa is quite large (up to 2°C). This suggests  
 232 that inherent errors in the ocean-sea ice model can significantly contribute to the warm SST bias  
 233 in CCSM4\_20C, in agreement with earlier studies (Large and Danabasoglu 2006; Grodsky et al.  
 234 2012).

235 It is important to note that in EXP\_OCN the ocean-sea ice model is forced with prescribed  
 236 atmospheric conditions. Flux forms of atmospheric forcing, namely short and longwave radiative  
 237 heat fluxes, precipitation rate and wind stress are directly used to force the ocean-sea ice model.  
 238 For latent and sensible heat fluxes, however, bulk formulae are used to compute them  
 239 interactively using wind speed, air humidity and air temperature at 10 m along with the model  
 240 SSTs. Such a treatment of the turbulent heat fluxes ultimately relaxes the model SSTs toward the  
 241 prescribed surface air temperature as discussed in earlier studies (e.g., Lee et al. 2007; Liu et al.  
 242 2012). Therefore, the SST bias in EXP\_OCN shown in Fig. 3 is not a good measure of inherent  
 243 errors in the ocean-sea ice model.

244 To better quantify the inherent errors in EXP\_OCN, we attempt to compute implicit SST bias  
 245 in EXP\_OCN associated with spurious ocean dynamic processes. The equation for the surface  
 246 mixed layer temperature bias in EXP\_OCN can be written as

$$247 \quad \frac{\partial \Delta T_m}{\partial t} = -\Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) + \frac{Q_{NET}[\text{EXP\_OCN}] - Q_{NET}[\text{OBS}]}{\rho_w C_{pw} D}, \quad (2)$$

248 where  $\Delta T_m$  is the difference in ocean mixed layer temperature between EXP\_OCN and the  
 249 observation,  $u_m$  and  $v_m$  are the ocean mixed layer currents in the  $x$ - and  $y$ -directions,  $w_e$  is the  
 250 entrainment rate at the mixed layer base,  $T_e$  is the ocean temperature immediately below the  
 251 mixed layer, and  $Q_{NET}[\text{EXP\_OCN}]$  is the net surface heat flux in EXP\_OCN (see Lee et al. 2007  
 252 for the derivation of the bulk mixed layer temperature equation). The first three terms on the

253 right side of Eq. (2) can be regarded as the errors in ocean dynamic and mixing processes.  
 254 Integrating Eq. (2) in time, after a minor manipulation, we get

$$\begin{aligned}
 \Delta T_{\text{EXP\_OCN}} &\equiv -\int_0^t \Delta \left( u_m \frac{\partial T_m}{\partial x} + v_m \frac{\partial T_m}{\partial y} + w_e (T_m - T_e) \right) dt \\
 &= \Delta T_m - \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_OCN}] - Q_{\text{NET}}[\text{OBS}]}{\rho_w C_{pw} D} dt.
 \end{aligned}
 \tag{3}$$

256  $\Delta T_{\text{EXP\_OCN}}$  represents the implicit SST bias in EXP\_OCN due to the inherent errors in the ocean  
 257 dynamic and mixing processes, including advection and turbulent mixing, for the duration of  $t$   
 258 with assumptions that there is no air-sea feedback to amplify or damp out the net surface heat  
 259 flux bias.

260 Fig. 4(a) shows the annually averaged implicit SST bias in EXP\_OCN linked to spurious  
 261 ocean dynamic and mixing processes. Its amplitude is of the same order of magnitude as that in  
 262 EXP\_ATM (Fig. 2(a)). Comparing Fig. 4(a) with Fig. 2(a), in the southeastern and northeastern  
 263 tropical Atlantic, especially near the west coast of Africa, the implicit SST bias due to spurious  
 264 ocean dynamic and mixing processes is much larger than that due to net heat flux bias in  
 265 EXP\_ATM. This strongly suggests that the warm SST biases in CCSM4\_20C over these regions  
 266 (see Fig. 1(b)) are mainly associated with spurious ocean dynamic and mixing processes.

267 It is interesting to note that ocean dynamic cooling in EXP\_OCN is too strong in the eastern  
 268 equatorial Atlantic, but too weak in the central equatorial Atlantic. Given that vertical  
 269 entrainment of cold thermocline water due to turbulent mixing is what maintains the cold tongue  
 270 in the central equatorial Atlantic (e.g., Lee and Csanady 1999a; 1999b; Goes and Wainer 2003),  
 271 it is possible that the parameterization of vertical mixing, and/or the mean state variables that  
 272 affect the vertical mixing, namely vertical shear and stratification at the mixed layer base, are the  
 273 source of the SST bias. It is also possible that a failure to resolve equatorial Atlantic instability

274 waves reduces the equatorial upwelling and is thus responsible for the warm implicit SST bias in  
275 the central equatorial Atlantic (Seo et al. 2006).

276

### 277 3.3 EXP\_ATM + EXP\_OCN

278 The linear combination of the implicit SST bias in EXP\_ATM due to net surface heat flux  
279 bias (Eq. (1)) and the implicit SST bias in EXP\_OCN due to spurious ocean dynamic and mixing  
280 processes (Eq. (3)) can be written as

$$281 \quad \Delta T_{\text{EXP\_ATM}} + \Delta T_{\text{EXP\_OCN}} = \Delta T_m + \int_0^t \frac{Q_{\text{NET}}[\text{EXP\_ATM}] - Q_{\text{NET}}[\text{EXP\_OCN}]}{\rho_w C_{pw} D} dt. \quad (4)$$

282 This total implicit SST bias is directly linked to the net surface heat flux mismatch between  
283 EXP\_ATM and EXP\_OCN, and is what is expected when the atmosphere-land model is joined  
284 together with the ocean-sea ice model but without any air-sea feedback. It is important to note  
285 that the implicit SST bias in EXP\_ATM + EXP\_OCN is independent from the observed surface  
286 heat flux product used in the analysis, and is thus not subject to uncertainty in the observed (or  
287 referenced) surface heat flux product used at least in a linear sense.

288 Fig. 4(b) shows the total implicit SST bias in EXP\_ATM + EXP\_OCN. Comparing this with  
289 the SST bias in CCSM4\_20C (Fig. 1(c)), their spatial patterns are surprisingly similar. In  
290 particular, in both CCSM4\_20C and EXP\_ATM + EXP\_OCN, the southwestern and  
291 northwestern tropical Atlantic are characterized by cold SST bias, while the southeastern and  
292 northeastern tropical Atlantic are characterized by warm SST bias. This result mainly suggests  
293 that the cold/warm SST biases over these off-equatorial regions in CCSM4\_20C originate from  
294 the intrinsic biases in the atmosphere-land and ocean-sea ice model components, and are further  
295 weakened/amplified by atmosphere-ocean coupling.

296 It is noted that the overall amplitude of the SST bias in CCSM4\_20C is smaller than the  
297 amplitude of the total implicit SST bias in EXP\_ATM + EXP\_OCN. This is not unexpected  
298 because the total implicit bias in EXP\_ATM + EXP\_OCN estimates the extent to which the  
299 spurious atmosphere-ocean dynamics in the atmosphere-land and ocean sea-ice model  
300 components could *potentially* contribute to the SST bias once the air-sea coupling is initiated.  
301 For instance, in a region where the total implicit SST bias is positive, once the air-sea coupling is  
302 initiated, the model SSTs will increase initially. However, the increased SSTs will in turn  
303 enhance the longwave radiative and latent cooling at the surface to reduce the rate of SST  
304 warming. Therefore, it is highly unlikely that the SST bias will reach the full extent of the total  
305 implicit SST bias.

306 It is interesting to note that the implicit SST bias in EXP\_OCN (Fig. 4(a)) is slightly negative  
307 over the eastern equatorial Atlantic region. This is somewhat inconsistent with the SST bias in  
308 CCSM4\_20C over the same region (Fig. 1(c)). Therefore, to better understand the origin of the  
309 equatorial Atlantic SST bias in CCSM4\_20C, in the next section we explore the initial  
310 development of the tropical Atlantic SST bias in EXP\_CPL. It is shown in the next section that  
311 the ocean-sea ice model does contribute significantly in forcing the eastern equatorial Atlantic  
312 warm SST bias due to its spurious ocean dynamic and mixing processes. However, its influence  
313 is limited only in early boreal summer during which massive entrainment of the equatorial cold  
314 thermocline water into the surface mixed layer occurs (e.g., Lee and Csanady 1999a; 1999b).

315

#### 316 **4. Initial development of the SST bias in EXP\_CPL**

317 Fig. 4(c) shows the SST bias in EXP\_CPL averaged over the first year. Overall, both the  
318 amplitude and spatial pattern of the SST bias in EXP\_CPL developed over the first year are very

319 similar to those of the annually averaged SST bias in CCSM4\_20C (Fig. 1(c)), suggesting that  
320 the tropical Atlantic SST bias develops very quickly (note the different scales used in Fig. 1(c)  
321 and Fig. 4(c)).

322 Fig. 5 shows the bi-monthly SST bias development in the fully coupled model experiment  
323 (EXP\_CPL) during the first and second years of the model integration. An interesting point is  
324 that the cold SST bias in the eastern equatorial Atlantic, which apparently originates from the  
325 ocean-sea ice model (Fig. 4(a)), persists only during the first four months of the coupled model  
326 integration. It disappears afterward and is completely masked by the warm SST bias in June of  
327 the first year. Among other features, perhaps the most striking is the fast development of the  
328 warm SST bias in the southeastern tropical Atlantic - the SST bias along the coast of Angola  
329 exceeds 6°C by June of the first year.

330 Although the tropical Atlantic SST bias in EXP\_CPL develops very quickly within a year,  
331 largely due to the combined effect of intrinsic biases in EXP\_ATM and EXP\_OCN, in some  
332 regions the SST bias in the first year is further weakened or amplified, probably due to the active  
333 atmosphere-ocean coupling. For instance, the cold SST bias over the southwestern tropical  
334 Atlantic in the first year is much reduced in the second year due to the eastward expansion of the  
335 warm SST anomalies in the southeastern tropical Atlantic. It is also clear that the warm SST bias  
336 in the eastern equatorial Atlantic during the first year strengthens and expands westward in the  
337 second year.

338 In order to better describe the tropical Atlantic SST biases in EXP\_CPL and how they are  
339 forced by EXP\_ATM, EXP\_OCN and the atmosphere-ocean coupling, the bi-monthly tropical  
340 Atlantic SST bias tendencies ( $^{\circ}\text{C month}^{-1}$ ) in EXP\_CPL, EXP\_ATM + EXP\_OCN, EXP\_ATM  
341 and EXP\_OCN during the first year are shown in Fig. 6. It is clearly shown that the southeastern

342 tropical Atlantic warm SST bias in EXP\_CPL, which is largely forced in boreal spring, is mainly  
343 caused by EXP\_OCN due to spurious ocean dynamic and mixing processes, with an assumption  
344 that the surface fluxes prescribed in EXP\_OCN is error-free. It is also clear that the initial  
345 development of the eastern equatorial warm SST bias, which is mainly forced in early boreal  
346 summer, is also caused by EXP\_OCN due to spurious ocean dynamic and mixing processes. By  
347 comparing the SST bias tendency in EXP\_CPL and the implicit SST bias tendency in  
348 EXP\_OCN, it is clear that the atmosphere-ocean coupling tends to weaken the implicit SST bias  
349 tendency in these regions. This clearly suggests that the atmosphere-ocean coupling is not the  
350 cause of the eastern equatorial warm SST bias at least in the first year of the coupling. These  
351 features in the equatorial Atlantic are much more clearly illustrated in Fig. 7, which shows the  
352 time evolutions of the SST bias tendencies (implicit SST bias tendencies) along the equatorial  
353 Atlantic and the contributions by the surface heat flux errors and by errors involving ocean  
354 dynamic and mixing processes in EXP\_CPL (EXP\_ATM and EXP\_OCN). Therefore, we may  
355 conclude that the eastern equatorial and southeastern tropical Atlantic warm SST biases in  
356 EXP\_CPL are mainly forced by EXP\_OCN due to its spurious ocean dynamic and mixing  
357 processes during boreal spring and summer.

358 Richter and Xie (2008) analyzed CMIP3 models and argued that the westerly wind bias in  
359 boreal spring over the western equatorial Atlantic deepens the thermocline in the eastern  
360 equatorial Atlantic preventing the development of the cold tongue in boreal summer, and thus is  
361 the root cause of the equatorial Atlantic warm SST bias in CMIP3 models. Our analysis of the  
362 three CESM1 experiments, however, suggests that the ocean-sea ice model due to its spurious  
363 ocean dynamic and mixing processes may contribute more significantly than the atmosphere-  
364 land model to the eastern equatorial Atlantic warm SST bias in CCSM4/CESM1. Therefore,



365 although we acknowledge the potential importance of the westerly wind bias in boreal spring  
366 over the western equatorial Atlantic, which originates from the atmosphere-land model (see Fig.  
367 2(b)), here we stress that solving this problem in the atmosphere-land model alone does not  
368 resolve the equatorial Atlantic warm bias in CCSM4/CESM1.

369 Grodsky et al. (2012) showed that mean sea level pressure in CCSM4 is erroneously high by  
370 a few millibars in the subtropical highs and erroneously low in the polar lows similar to CCSM3,  
371 and thus the trade winds are  $1 \sim 2 \text{ m s}^{-1}$  too strong. Since the cold SST biases in the southwestern  
372 and northwestern tropical Atlantic are closely linked to the strength of the trade winds in  
373 EXP\_ATM, it is likely that their root cause is linked to the subtropical highs in the atmosphere-  
374 land model.

375

## 376 **5. Equatorial Atlantic subsurface temperature bias in EXP\_OCN**

377 The methodology used in this study only provides a mean to estimate the integrated effects of  
378 the spurious ocean dynamic and mixing processes in EXP\_OCN via “implicit SST bias”. To  
379 further understand what causes the spurious ocean dynamic and mixing processes, the equatorial  
380 Atlantic subsurface temperature bias in EXP\_OCN is explored here. Figure 8 shows the  
381 monthly-averaged equatorial Atlantic temperature bias (averaged for  $5^{\circ}\text{S} - 5^{\circ}\text{N}$ ) in EXP\_OCN for  
382 the upper 200 m. In order to compute the temperature bias, we use EN4, which is a global quality  
383 controlled ocean temperature data set provided by the Met Office Hadley Centre (Good et al.  
384 2013). The green lines show the corresponding mixed layer depths obtained from EXP\_OCN  
385 (solid line) and EN4 (dashed line).

386 This figure clearly shows that the temperature bias near the surface is quite small because the  
387 model-simulated surface temperature is strongly damped to the prescribed air temperature and

388 specific humidity. However, at the base of the model-simulated mixed layer, the temperature bias  
389 increases up to 6°C. This suggests that due to spurious ocean dynamic and mixing processes in  
390 the ocean-sea ice model, the upper thermocline water entrained into the mixed layer during early  
391 summer (e.g., Lee and Csanady 1999a; 1999b) is too warm. Therefore, once the ocean sea-ice  
392 model is fully coupled to the atmosphere-land model, the extra heat in the mixed layer caused by  
393 the entrainment of the warmer-than-observed upper thermocline layer will produces warm SST  
394 bias in the equatorial Atlantic upwelling region.

395 Fig. 8 also shows that the mixed layer depth is too deep in EXP\_OCN. This suggests that the  
396 vertical turbulent mixing may be too intense in EXP\_OCN. It is likely that the warmer-than-  
397 observed upper thermocline layer weakens the vertical stratification over the upper thermocline  
398 and thus increases turbulent mixing at the mixed layer base. This means that the mixed layer  
399 depth bias may be directly linked to the upper thermocline temperature bias. One hypothesis is  
400 that the spurious vertical diffusion in the thermocline layer due to vertical discretization brings  
401 too much heat into the upper thermocline layer from the mixed layer, which in turn weakens the  
402 vertical stratification and thus further increases the vertical mixing across the mixed layer base, a  
403 positive feedback. To further investigate what processes or parameterizations are responsible for  
404 the warmer-than-observed upper thermocline and deeper-than-observed mixed layer depth, it is  
405 necessary to perform sensitivity experiments by using the stand-alone ocean sea-ice model and  
406 the diagnostic methodology proposed in this study.

407

## 408 **6. Impact of uncertainty in the reference surface flux fields**

409 It should be pointed out that our results are not entirely independent from uncertainty in the  
410 reference surface flux product used (i.e., COREv2). For instance, if the net surface heat flux in

411 COREv2 is too large, it will contribute positively (negatively) to the implicit SST bias in  
412 EXP\_OCN (EXP\_ATM) according to Eqs. (1) and (3). Although considerable effort was  
413 invested to minimize errors (see Large and Yeager 2009 for more details), COREv2 is still far  
414 from error-free. Therefore, in a more strict sense, Eq. (3) should be considered as the implicit  
415 SST bias in EXP\_OCN referenced to COREv2. Similarly, Eq. (1) should be considered as the  
416 implicit SST bias in EXP\_ATM referenced to COREv2. Nevertheless, it should be noted that the  
417 total implicit SST bias in EXP\_ATM + EXP\_OCN is independent from the reference surface  
418 flux product used, and is thus not subject to uncertainty in the reference surface flux product at  
419 least in a linear sense (see Eq. (3)).

420 To better understand if and how the uncertainty in the reference surface flux product  
421 influences the implicit SST bias in EXP\_ATM and EXP\_OCN, two additional experiments are  
422 performed by forcing the stand-alone ocean sea-ice model for 120 years with the surface flux  
423 fields derived from the European Centre for Medium-Range Weather Forecasts Interim  
424 (ERA\_INT) reanalysis (Dee et al. 2011), and the Modern-Era Retrospective Analysis for  
425 Research and Applications (MERRA) reanalysis (Rienecker et al. 2011)

426 As shown in Figs. 9(a), (d) and (g), the implicit SST bias in EXP\_ATM referenced to  
427 COREv2 is generally more positive compared to that referenced to either ERA\_INT or MERRA.  
428 On the contrary, the implicit SST bias in EXP\_OCN referenced to COREv2 is generally more  
429 negative compared to that referenced to either ERA\_INT or MERRA. What these mean is that  
430 the net surface heat flux into the tropical Atlantic is larger overall in ERA\_INT and MERRA  
431 than that in COREv2. Nevertheless, the spatial patterns of the implicit SST bias in EXP\_ATM  
432 referenced to the three surface flux products (i.e., COREv2, ERA\_INT and MERRRA) are quite

433 similar. As shown in Figs. 9(b), (e) and (h), the same conclusion can be drawn for the implicit  
434 SST bias in EXP\_OCN.

435 In sum, the overall magnitude of the implicit SST bias can be attributed more to either the  
436 atmosphere-land model or the ocean sea-ice model depending on the reference surface flux  
437 product used. In other words, the choice of the reference surface heat flux product will impact  
438 the estimates of implicit SST biases in EXP\_ATM and EXP\_OCN. However, the spatial patterns  
439 of the implicit bias in EXP\_ATM and EXP\_OCN are largely determined by inherent deficiencies  
440 of the atmosphere-land, and ocean-sea ice model components, respectively. As such, the total  
441 implicit SST bias in EXP\_ATM + EXP\_OCN is only minimally affected by the reference surface  
442 flux product used (see Figs. 9(c), (f) and (i)). Therefore, we can conclude that the total implicit  
443 bias in EXP\_ATM + EXP\_OCN is a reliable measure of inherent deficiency in CESM1.

444

## 445 **7. Summary and Discussions**

446 In order to better understand the initial development of the tropical Atlantic SST bias in  
447 AOGCMs, we performed a series of model experiments using CESM1. These experiments are a  
448 forced atmosphere-land model experiment (EXP\_ATM), a forced ocean-ice model experiment  
449 (EXP\_OCN) and a fully coupled model experiment with its atmosphere-land model initialized  
450 using EXP\_ATM and the ocean-ice model using EXP\_OCN (EXP\_CPL).

451 We propose and use a new method of diagnosis to identify and quantify intrinsic errors in the  
452 atmosphere-land and ocean-sea ice model components of CESM1. It is shown here that both the  
453 atmosphere-land and ocean-sea ice model components contain significant errors in the tropical  
454 Atlantic. In boreal summer, the ocean-sea ice model could cause large amplitudes of warm SST  
455 bias in the eastern equatorial and southeastern tropical Atlantic due to its spurious ocean dynamic

456 and mixing processes even if it is coupled to a perfect atmosphere-land model and the SST bias  
457 does not feedback onto the ocean-sea ice model. In the atmosphere-land model, the trade winds  
458 and associated surface latent cooling are too strong in the northwestern and southwestern tropical  
459 Atlantic, while they are too weak in the northeastern and southeastern tropical Atlantic.  
460 Therefore, even if the atmosphere-land model is coupled to a perfect ocean-sea ice model and the  
461 SST bias does not feedback onto the atmosphere-land model, warm (cold) SST bias could be  
462 generated in the northeastern (northwestern) and southeastern (southwestern) tropical Atlantic.

463 In the fully coupled model simulation with its atmosphere-land model initialized using  
464 EXP\_ATM and the ocean-sea ice model using EXP\_OCN, the tropical Atlantic SST bias  
465 develops very quickly within a year, and its seasonality and spatial pattern are largely determined  
466 by the linear combination of the implicit SST bias in EXP\_ATM and EXP\_OCN. In particular, it  
467 is shown that the eastern equatorial and southeastern tropical Atlantic warm SST bias in the fully  
468 coupled simulation are forced in early boreal summer by the ocean-sea ice model due to its  
469 spurious ocean dynamic and mixing processes. Further analysis shows that the upper thermocline  
470 water underneath the eastern equatorial Atlantic surface mixed layer is too warm in EXP\_OCN.  
471 This suggests that the mixed layer cooling in boreal summer associated with the equatorial  
472 entrainment of upper thermocline water is too weak.

473 The main emphasis in this paper is to explore how the tropical Atlantic SST bias in CESM1  
474 is initiated and evolves. Here, we identify that the intrinsic errors in the ocean-sea ice model  
475 contribute significantly to the tropical SST bias in CESM1. However, this does not mean that the  
476 atmosphere-land model contributes less to the tropical SST bias. In addition to the intrinsic errors  
477 in the atmosphere-land model explored in this study, the equatorial Atlantic surface wind bias in  
478 EXP\_ATM could affect the upper ocean dynamics in EXP\_CPL, which may feedback onto the

479 equatorial Atlantic SST in EXP\_CPL (Richter and Xie 2008). Therefore, we acknowledge the  
480 importance of improving critical problems in the atmosphere-land model. We only stress here  
481 that solving those problems in the atmosphere-land model alone does not resolve the equatorial  
482 Atlantic warm bias in CESM1. It should be also pointed out that the choice of the mixed layer  
483 depth used to determine the implicit SST bias in EXP\_ATM (see Eq. (1)) is somewhat arbitrary,  
484 which is one of the limitations of the proposed method to diagnose the implicit SST bias in  
485 EXP\_ATM.

486       Additionally, we would like to point out that our results are not entirely independent from  
487 uncertainty in the reference surface flux product used. In particular, the overall magnitude of the  
488 implicit SST bias can be attributed more to either the atmosphere-land model or the ocean sea-  
489 ice model depending on the reference surface flux product used. Nevertheless, the total implicit  
490 SST bias in EXP\_ATM + EXP\_OCN is only minimally affected by uncertainties in the reference  
491 surface flux product used, and thus is a reliable measure of inherent deficiency in CESM1.  
492 Further studies are also needed to trace the parameterizations and/or configurations in the ocean-  
493 sea ice model that are directly linked to the errors. Therefore, we recommend sensitivity studies  
494 on model resolutions (in both the horizontal and vertical directions), representation of surface  
495 flux fields especially off Angola and Namibia, vertical mixing schemes and isopycnal mixing  
496 schemes, using the ocean-sea ice model component of CESM1 and the diagnosis method  
497 proposed in this study.

498

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507

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694

## 695 **Figure captions**

696 **Fig. 1.** Annually averaged climatological SSTs in the tropical Atlantic from (a) EN4, a global  
697 quality controlled ocean temperature data set provided by the Met Office Hadley Centre (Good et  
698 al. 2013), for 1949-2005, and (b) CCSM4 historical simulation for 1949-2005. The SST bias in  
699 CCSM4 is shown in (c). The unit is °C. The SST bias values higher than 6°C are masked.

700

701 **Fig. 2.** Annually averaged implicit SST bias in EXP\_ATM due to (a) the net surface heat flux  
702 bias, which is computed by integrating the net heat flux bias in EXP\_ATM for one year from

703 January 1 to December 31, then dividing it by 12 months. Contributions by (b) shortwave  
704 radiative heat flux bias, (c) latent heat flux bias and (d) longwave radiative heat flux bias. The  
705 vectors in (c) show the annually averaged surface wind stress bias. The unit for the implicit SST  
706 bias is °C.

707

708 **Fig. 3.** Annually averaged SST bias in EXP\_OCN. The unit is °C.

709

710 **Fig. 4.** Annually averaged implicit SST bias in (a) EXP\_OCN and (b) EXP\_ATM + EXP\_OCN.  
711 (c) Annually averaged SST bias in EXP\_CPL during the first year. The unit is °C. The implicit  
712 SST bias values higher than 12°C are masked.

713

714 **Fig. 5.** Time evolution of the SST bias in EXP\_CPL during the first and second year. The unit is  
715 °C.

716

717 **Fig. 6.** (1st column) Time evolution of the SST bias tendency in EXP\_CPL during the first year.  
718 Time evolution of the implicit SST bias tendency in (2nd column) EXP\_ATM + EXP\_OCN,  
719 (3rd column) EXP\_ATM, and (4th column) EXP\_OCN. The unit is °C month<sup>-1</sup>.

720

721 **Fig. 7.** Time-longitude evolutions of (a) the SST bias tendencies along the equatorial Atlantic,  
722 and the contributions by (b) the surface heat flux errors and (c) errors involving ocean dynamic  
723 processes in EXP\_CPL during the first year. Time-longitude evolutions of implicit SST bias  
724 tendencies in (d) EXP\_ATM + EXP\_OCN, (e) EXP\_ATM and (f) EXP\_OCN. The unit is °C  
725 month<sup>-1</sup>.



726

727 **Fig. 8.** Time-depth evolutions of the equatorial Atlantic temperature bias (shaded) and mixed  
728 layer depth (green solid line) averaged for 5°S-5°N obtained from EXP\_OCN. The green dashed  
729 line is the mixed layer depth obtained from EN4.

730

731 **Fig. 9.** Annually averaged implicit SST bias in (a,d,g) EXP\_ATM, (b,e,h) EXP\_OCN, and (c,f,i)  
732 EXP\_ATM + EXP\_OCN referenced to (a,b,c) COREv2, (d,e,f) ERA\_INT, and (g,h,i) MERRA.  
733 The unit is °C. The SST bias values higher than 12°C are masked.

Figure-1 Tropical Atlantic SST and SST Bias  
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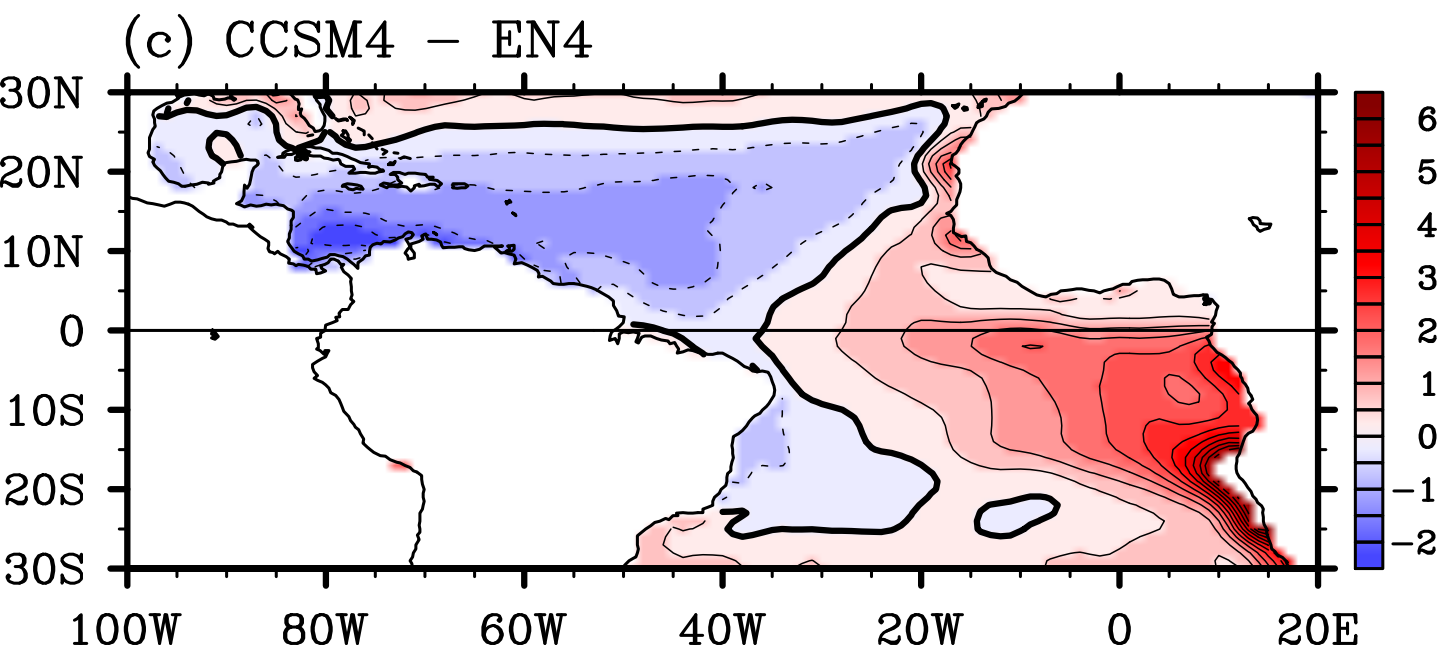
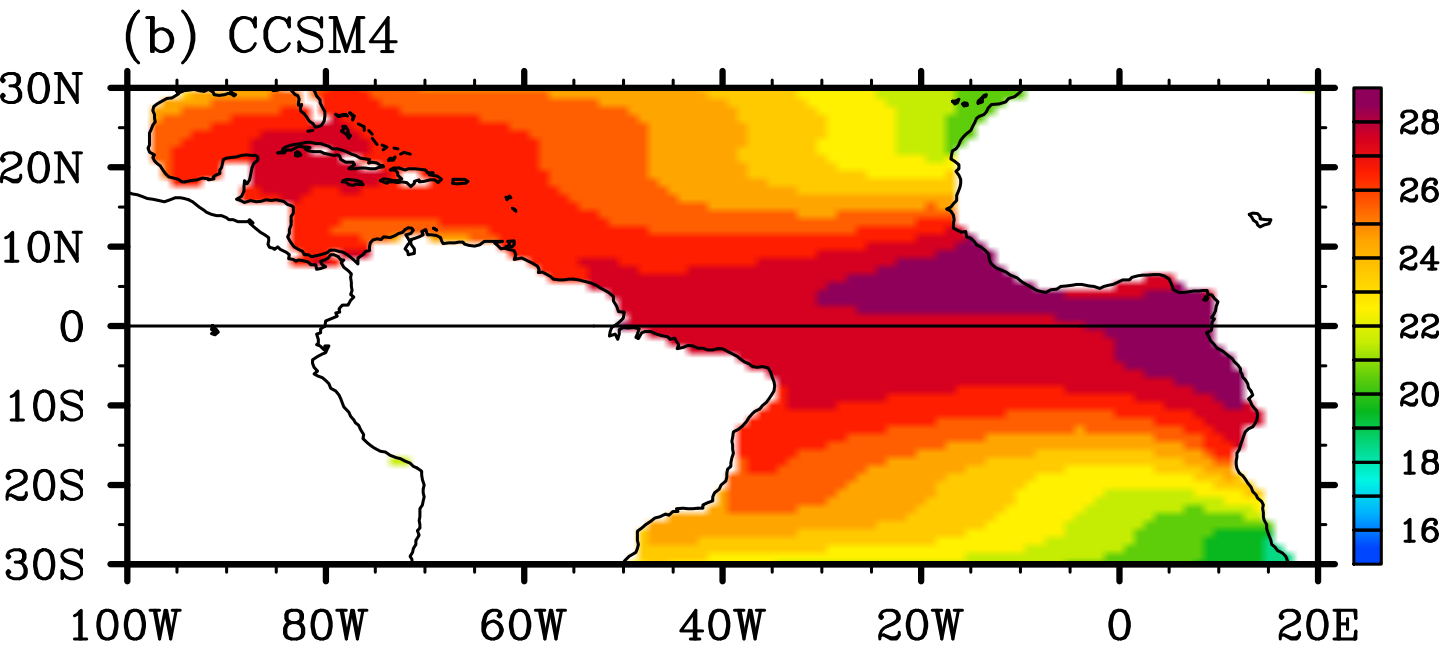
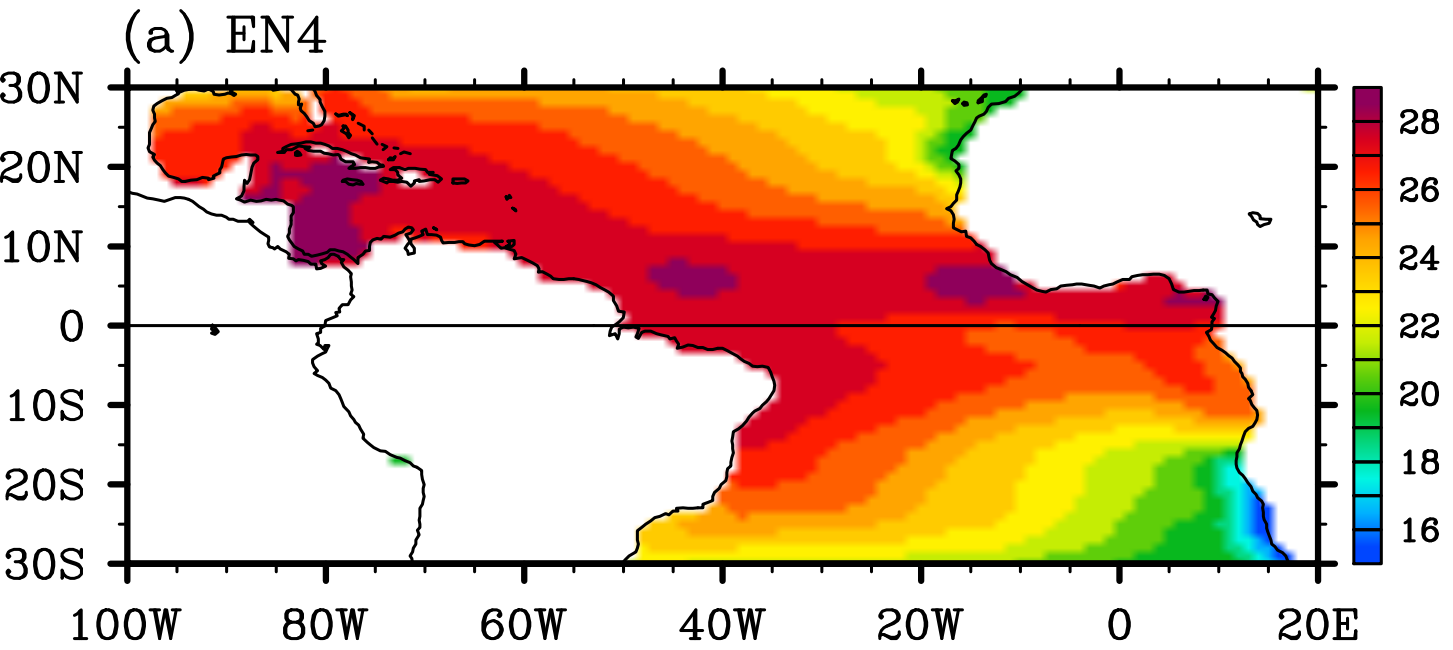
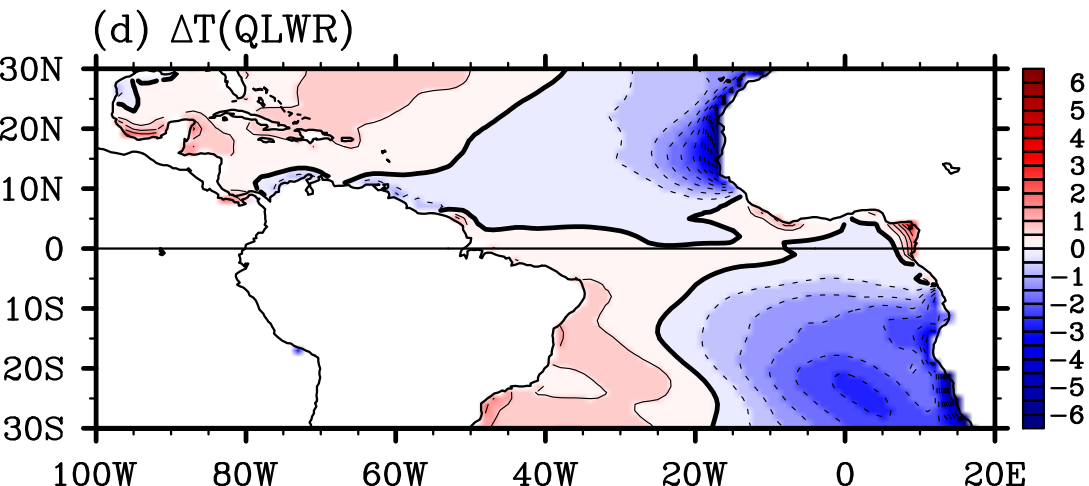
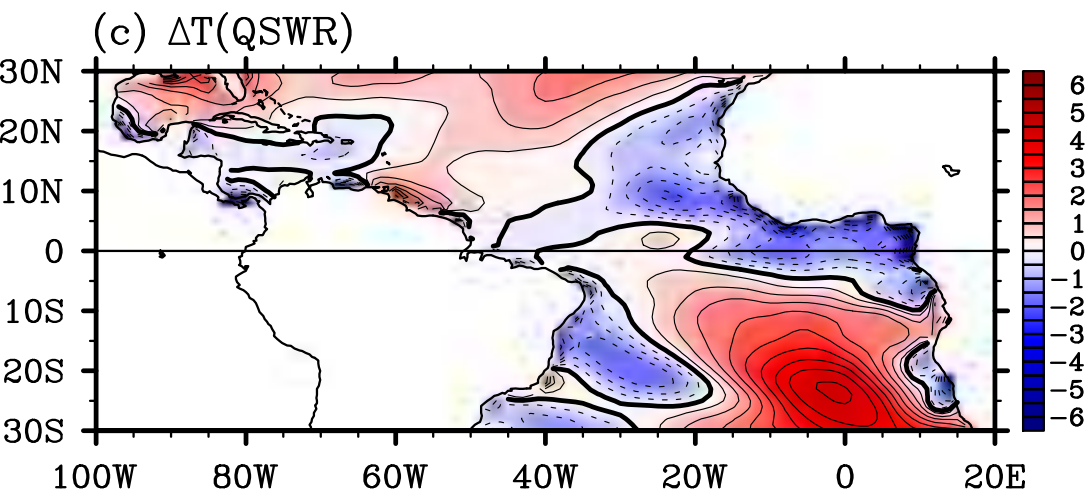
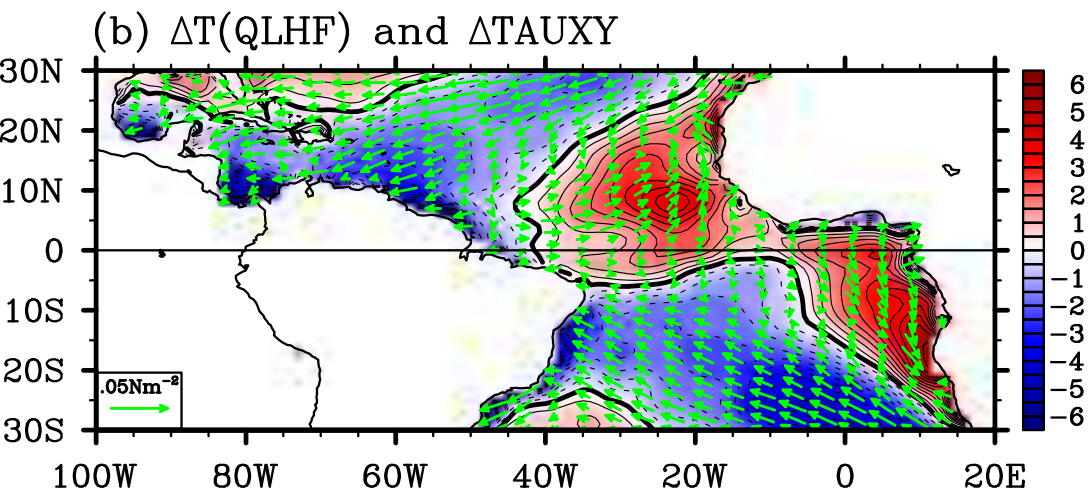
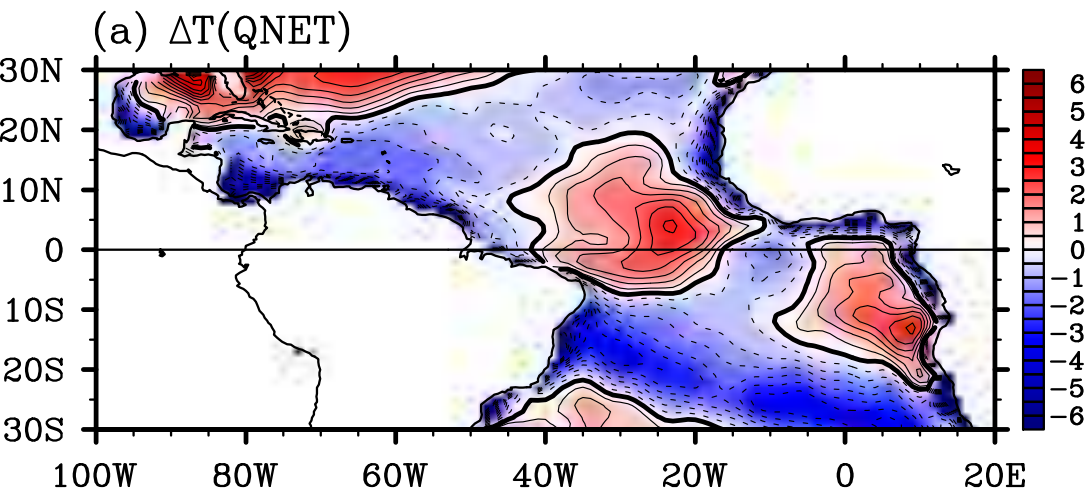
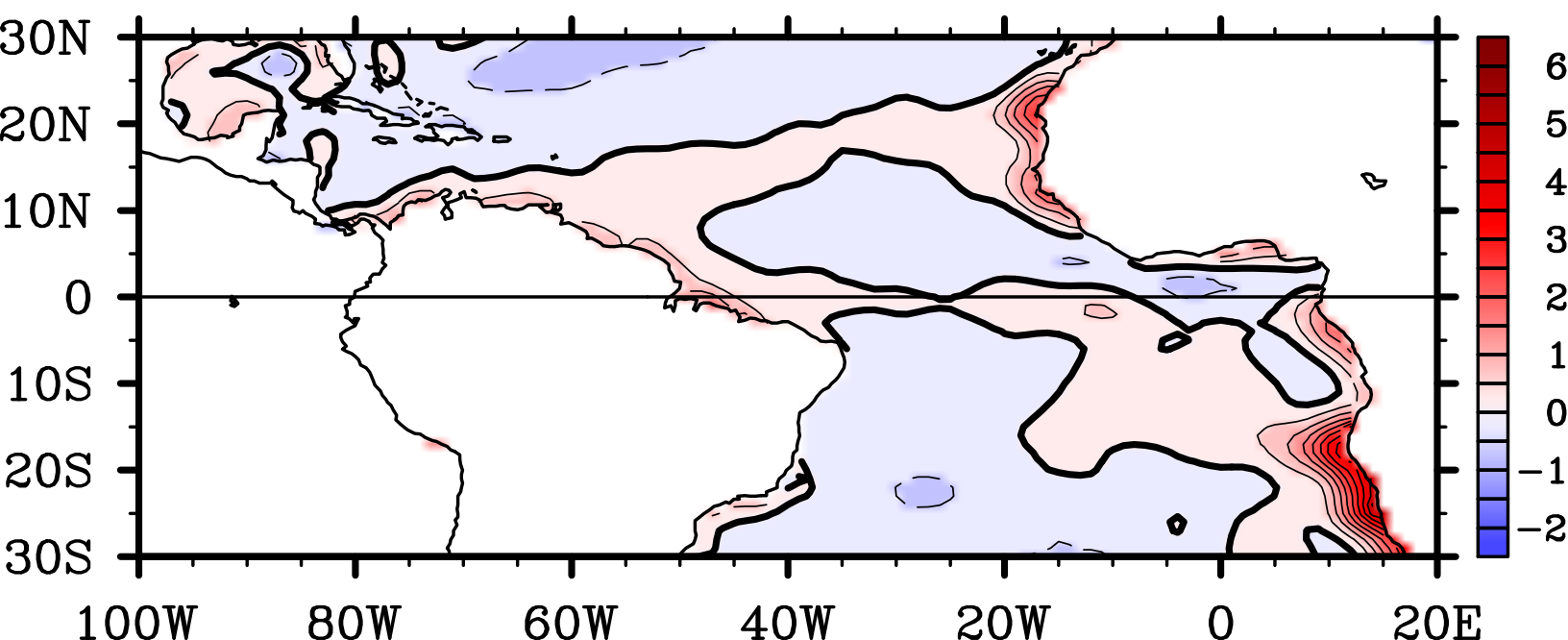


Figure-2 Implicit SST bias (EXP\_ATM)  
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### SST Bias (EXP\_OCN)



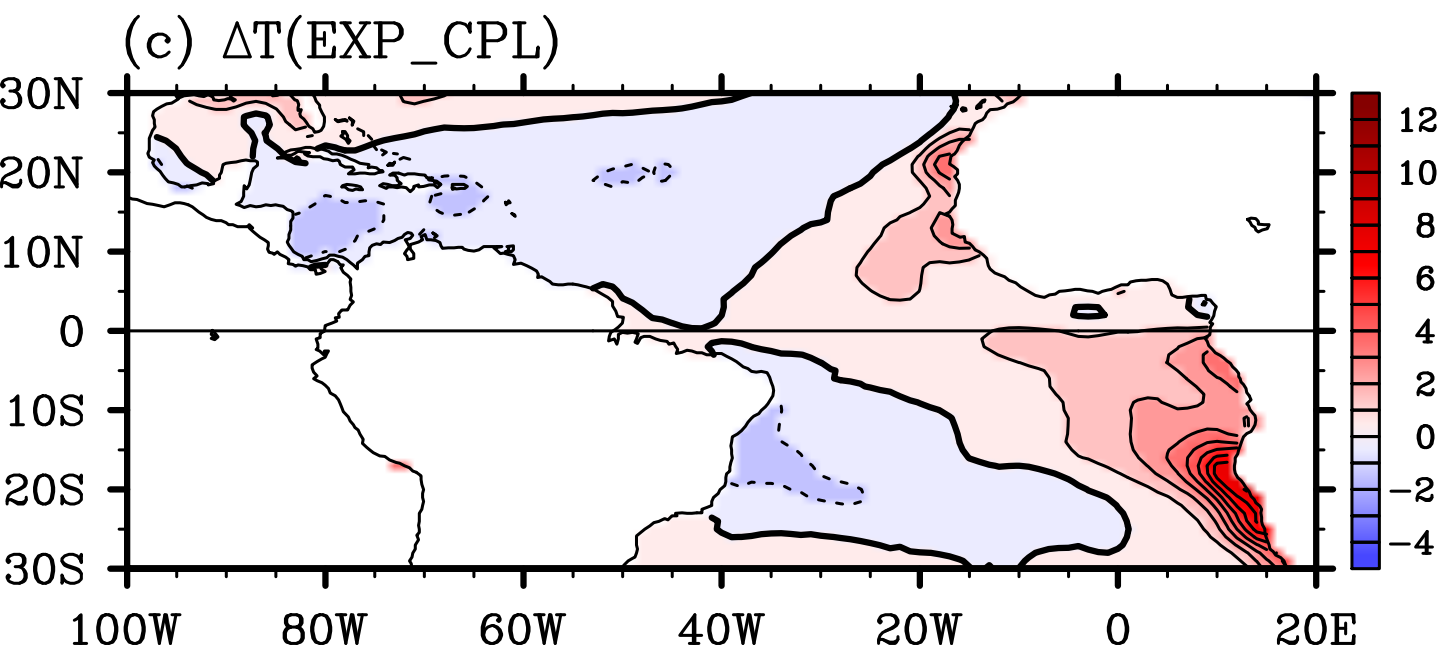
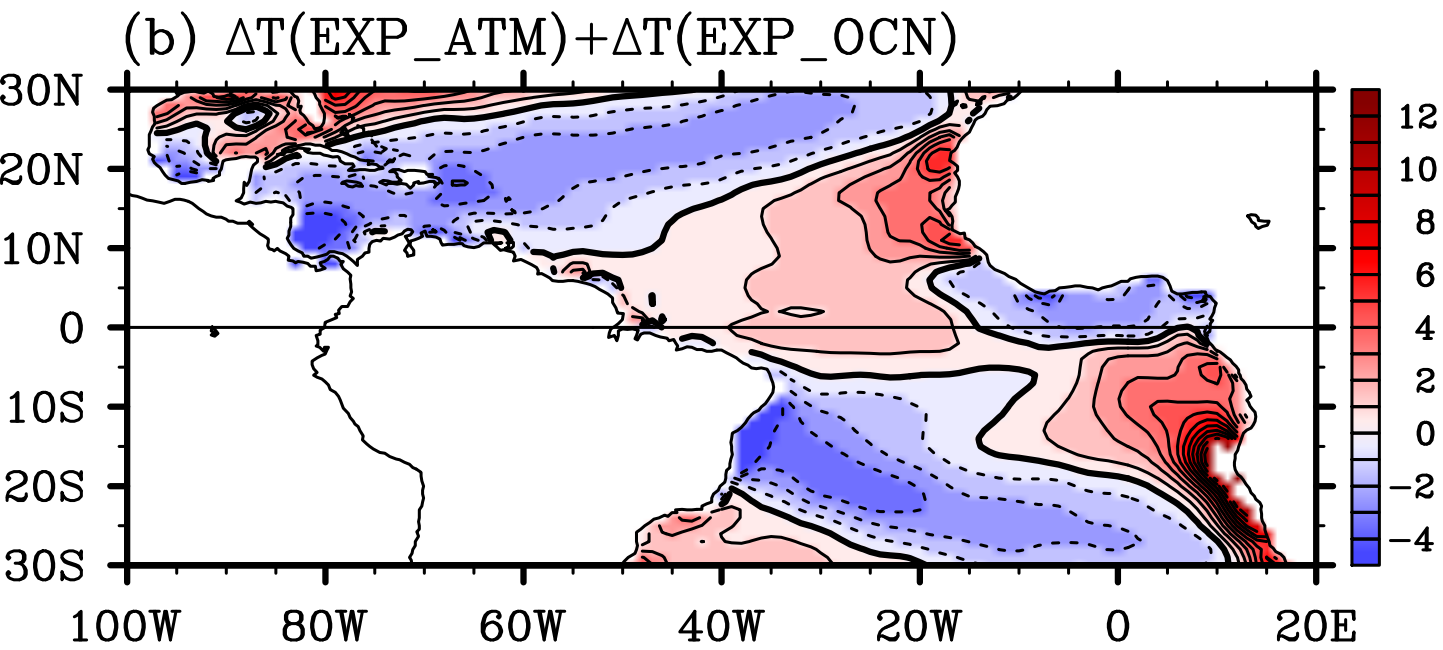
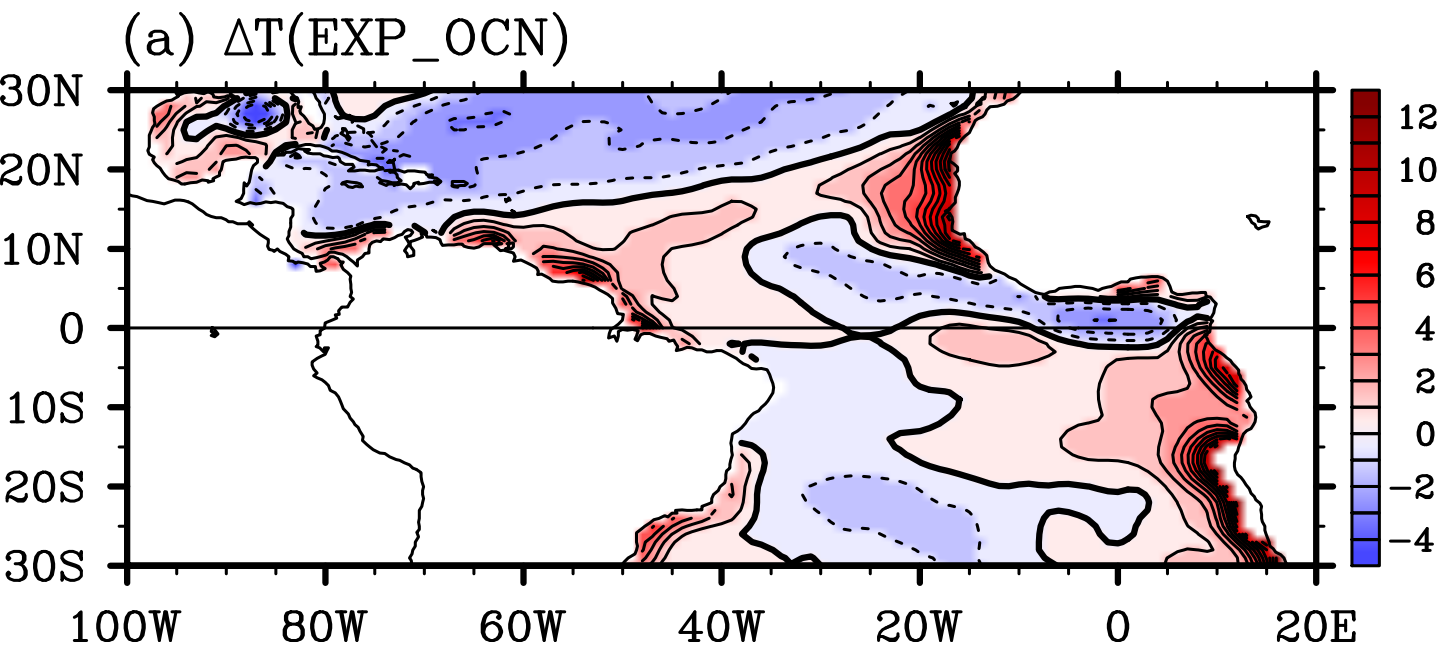
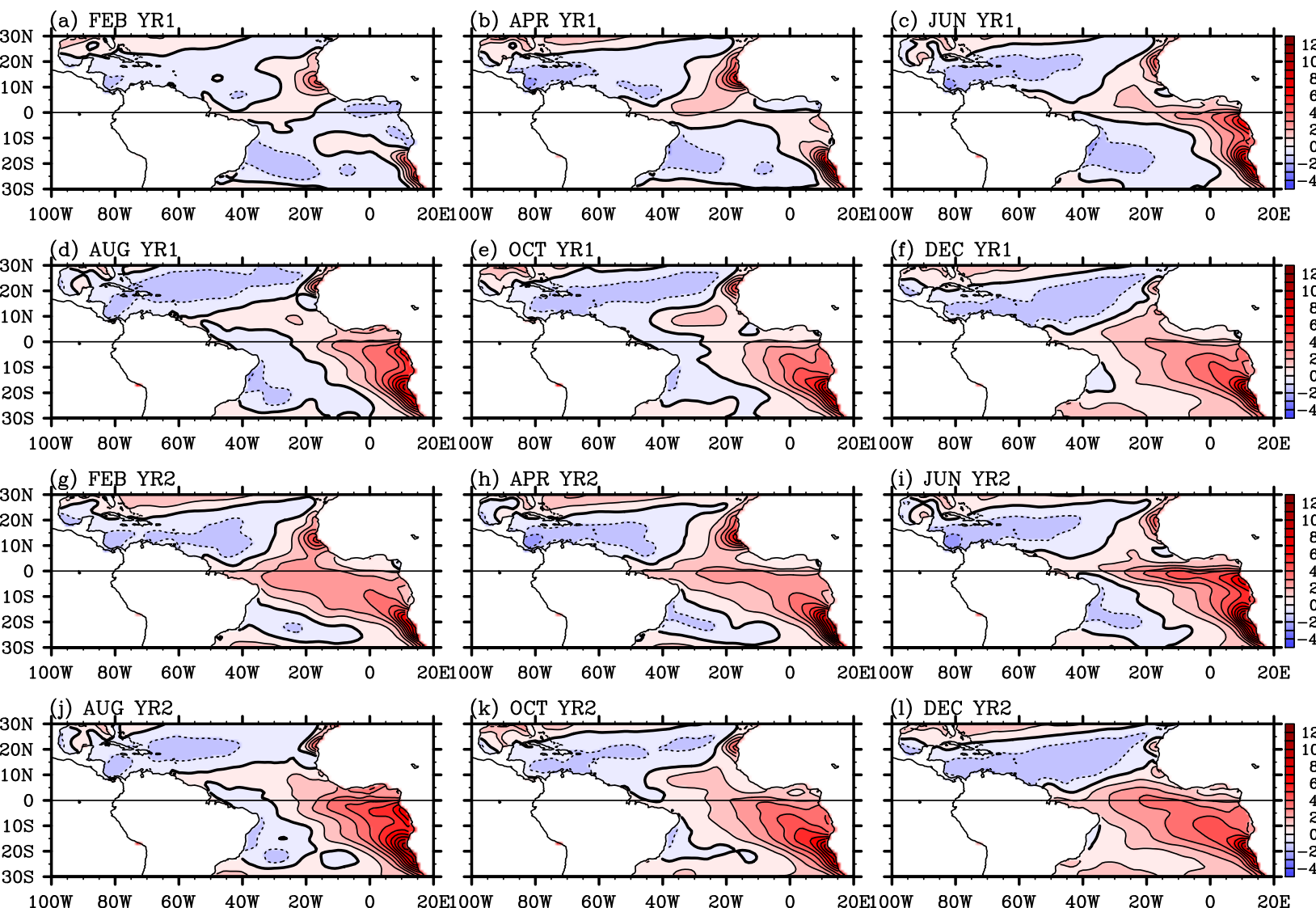


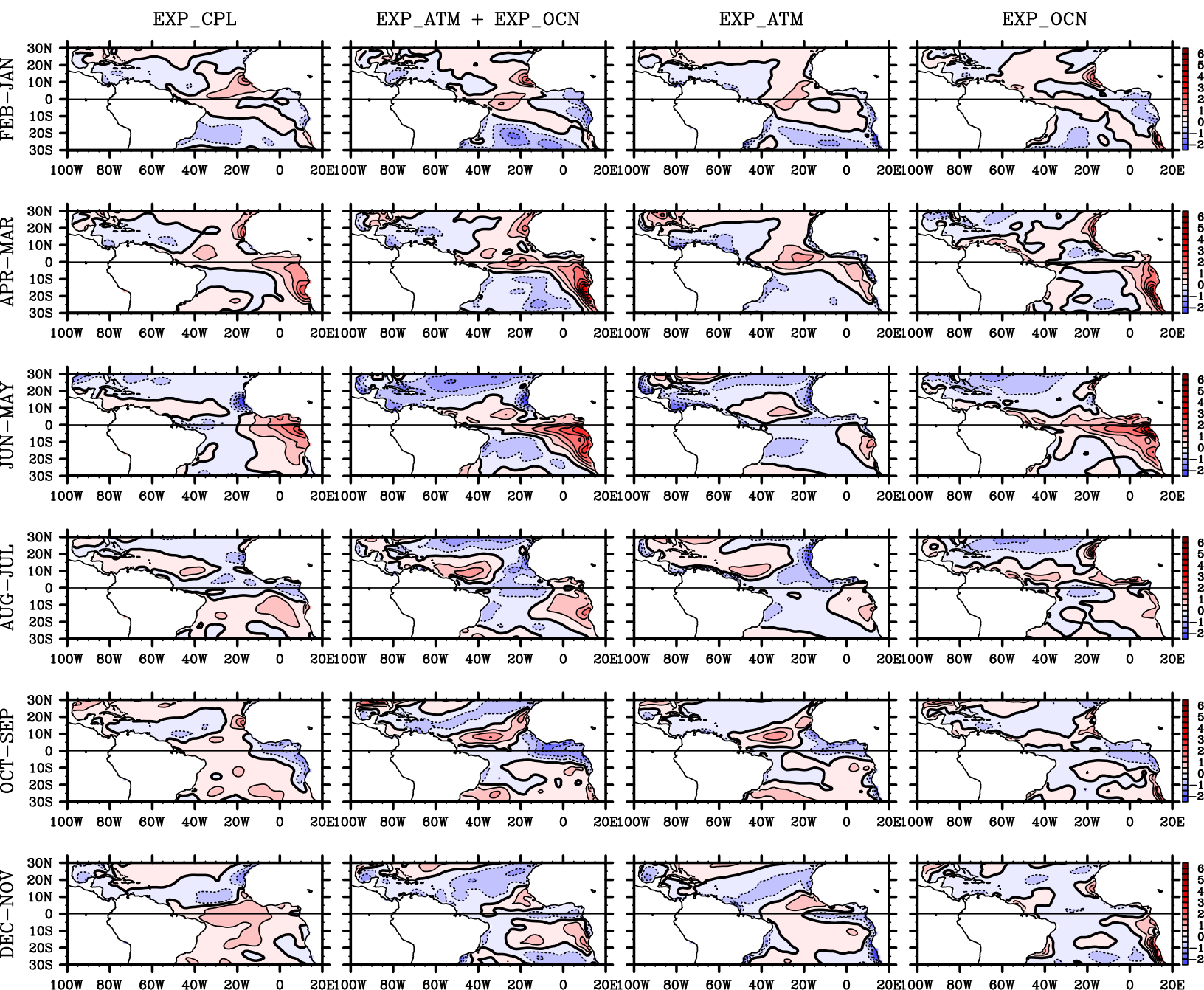
Figure-5

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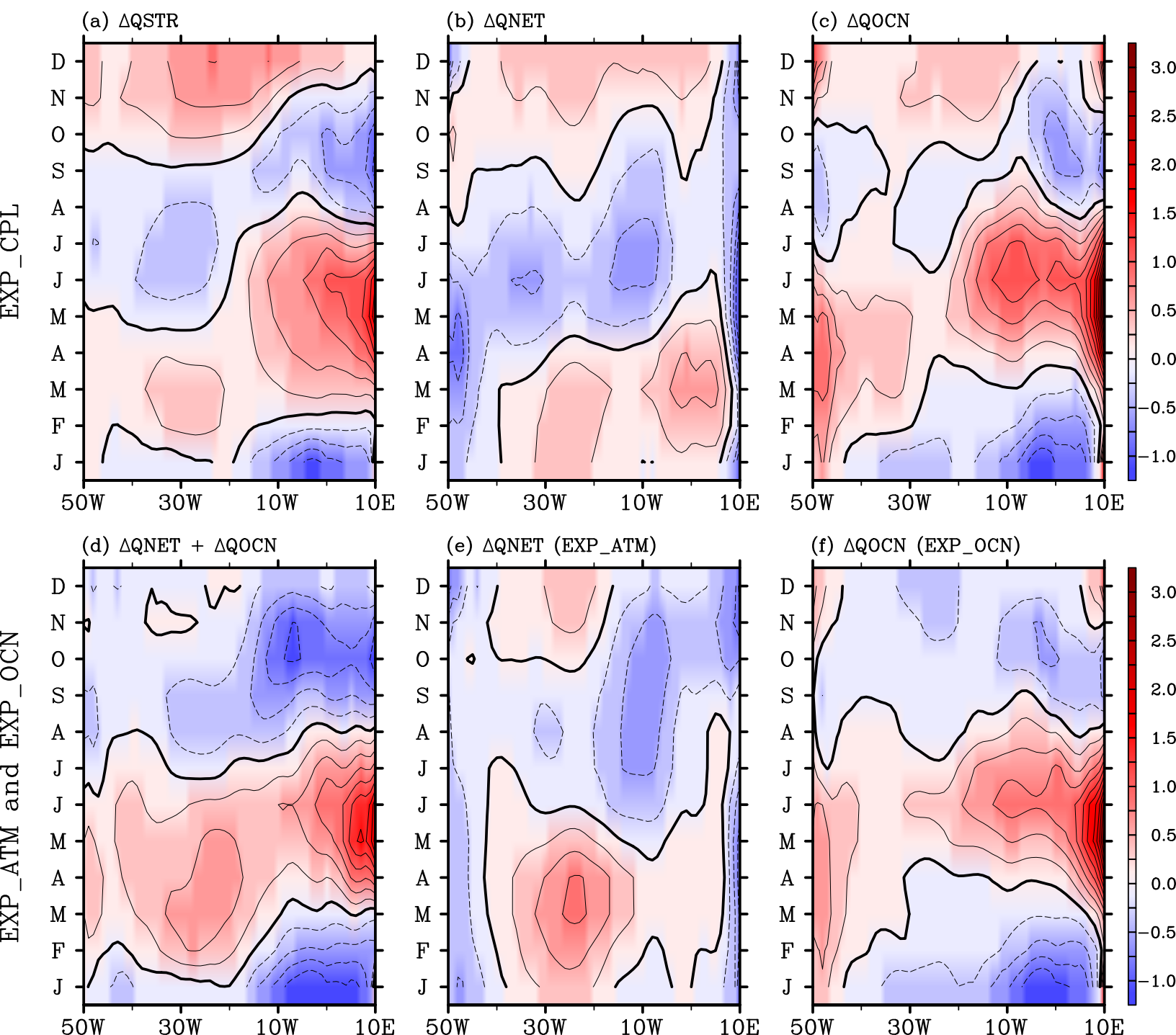
SST Bias in the 1st and 2nd Years (EXP\_CPL)



### SST Bias Tendency and Implicit SST Bias Tendency



### SST Bias Tendency and Implicit SST Bias Tendency





**Figure-8**  
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Equatorial Atlantic Temperature Bias (EXP\_OCN)

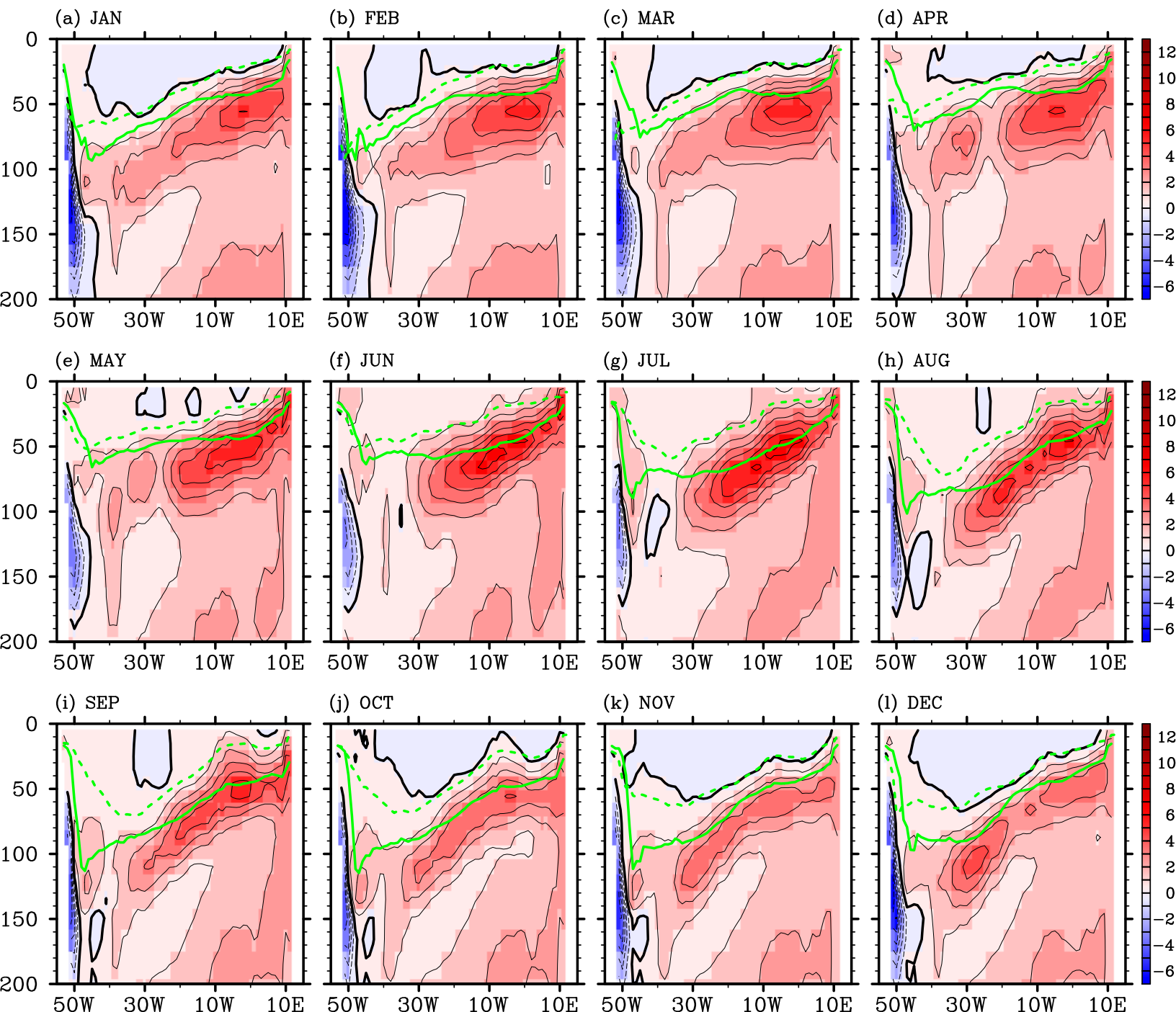


Figure-9

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### Implicit SST Bias

