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|---|---|---|
| **Dissemination Level** | | |
| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the Commission Services) | |
| **RE** | Restricted to a group specified by the Consortium (including the Commission Services) | |
| **CO** | Confidential, only for members of the Consortium (including the Commission Services) | |

**Contribution to project objectives** – with this deliverable, the project has contributed to the achievement of the following objectives (from Annex I / DOW, Section B1.1.):

| N.º | Objective | Yes | No |
|---|---|---|---|
| 1 | Reduce uncertainties in our knowledge of the functioning of Tropical Atlantic (TA) climate, particularly climate-related ocean processes (including stratification) and dynamics, coupled ocean, atmosphere, and land interactions; and internal and externally forced climate variability. | X | |
| 2 | Better understand the impact of model systematic error and its reduction on seasonal-to-decadal climate predictions and on climate change projections. | X | |
| 3 | Improve the simulation and prediction TA climate on seasonal and longer time scales, and contribute to better quantification of climate change impacts in the region. | X | |
| 4 | Improve understanding of the cumulative effects of the multiple stressors of climate variability, greenhouse-gas induced climate change (including warming and deoxygenation), and fisheries on marine ecosystems, functional diversity, and ecosystem services (e.g., fisheries) in the TA. | | X |
| 5 | Assess the socio-economic vulnerabilities and evaluate the resilience of the welfare of West African fishing communities to climate-driven ecosystem shifts and global markets. | | X |

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**Deviation from planned efforts for this deliverable:** None

**EXECUTIVE SUMMARY:**

This report summarizes the studies about whether a bias reduction leads to an improved representation of tropical Atlantic variability on seasonal to decadal timescales. The metric used to document this variability is the difference between observed and modelled monthly-averaged standard deviation of the sea surface temperature (SST) in the eastern Equatorial Atlantic (3°S-3°N, 20°W-0°E). Results are first documented for the three following models: CNRM-CM6 in section 1, EC-Earth3.1 in section 2, and GEOMAR in section 3. Anomaly coupling – a statistical correction applied in a climate model to correct its climatology – is applied in three models (NorESM, UCLA and CNRM-CM5); section 4 summarises the results from anomaly coupling experiments.

The new model configurations used in PREFACE can lead to improved simulation of the tropical Atlantic, but improvements are not universal. CNRM used a new version of their model (including new physics, a better sea-ice model and increased vertical resolutions), which significantly improved the representation of the seasonal mean of SST and surface winds. As a result, the variability is also improved. BSC investigated the effect of including a wave model in order to improve the air-sea momentum fluxes and the surface ocean mixing representation, but the results did not show any significant improvement in the SST bias or variability. GEOMAR increased the resolutions of their coupled model and showed that increasing the atmospheric vertical resolution in particular seems to be a key for the bias reduction, and the SST variability was much better represented accordingly.

The anomaly coupling experiments involving UiB, UCM, CERFACS and CNRM were designed to test if the variability is better represented in three different climate models when their mean air-sea

fluxes are constrained to be as observed – i.e. only anomalies around this mean state were freely coupled. The improvement in the mean state does not automatically lead to an improved representation of the equatorial and meridional modes. While in some cases there are improvements, in other cases anomaly coupling appears to degrade substantially the simulated variability. A more detailed analysis indicates that the improved mean state does generally lead to improvements in the representation of the Bjerknes Feedback, which is associated to the equatorial mode. Further investigation is thus required to better understand the different roles of dynamics and thermodynamics in the link between the tropical Atlantic mean state and its variability in climate models.

## 1. CNRM-CM6: assessment of the simulated mean state and variability in the Tropical Atlantic by new coupled model configurations

*Voldoire A. (MF-CNRM), Brient F. (MF-CNRM), Sanchez-Gomez E. (CERFACS)*

The simulated mean state and interannual variability in the Tropical Atlantic are analysed from a numerical experiment performed with the new coupled model CNRM-CM6. CNRM-CM6 has been developed by the CNRM/CERFACS modelling group (Toulouse, France) and is the most updated version of the family of CNRM-CM models. CNRM-CM6 will participate in the CMIP6 (Coupled Model Inter-comparison Phase 6) exercise through several MIPs.

In the following list we describe the model modifications performed to build CNRM-CM6 respect the preceding model version (CNRM-CM5, Voldoire et al. 2013).

- New version of the atmospheric component, the ARPEGE model (from version 5 to version 6 in CNRM-CM6). The greatest change from v5 to v6 is the new model physics, which contains improvements in the deep convection PCMT, the prognostic equation for the convective updraft, and a more detailed microphysics.
- New version of the ocean component, NEMO, from v3.2 in CNRM-CM5 to the most updated NEMO version 3.6.
- New version of the sea-ice model GELATO: from v5 to v6. The new version includes improved thermodynamics and sea-ice dynamics.
- New version of the surface module SURFEX (from v7 to v8), with improved continental hydrology and now running with a new lakes scheme (FLAKE).
- New version of surface flux paramétrisation (ECUME).
- Increasing vertical resolution: from 31 atmospheric levels in CNRM-CM5 to 91 vertical levels in CNRM-CM6.
- Increasing ocean vertical resolution: from 42 levels to 75 levels.
- Increasing coupling frequency: from 24h used in CNRM-CM5 to 1h in CNRM-CM6.
- New I/O server XIOS implemented at IPSL that handles the model outputs for all the components

### a) Mean state in the Tropical Atlantic simulated by CNRM-CM6

In order to evaluate the mean state and the variability in the tropical Atlantic as simulated by CNRM-CM6, an experiment has been conducted. As the model version at this date is not completely set, the experiment will be named CNRM-PRE-CMIP6 hereinafter.

Figure 1 shows the surface temperature and surface wind biases for CNRM-CM5 and CNRM-PRE-CMIP6. For surface temperature ERAI reanalysis (Dee et al. 2011) is used as reference over the continents and ERSST over the ocean. ERAI is also used as reference for surface winds.

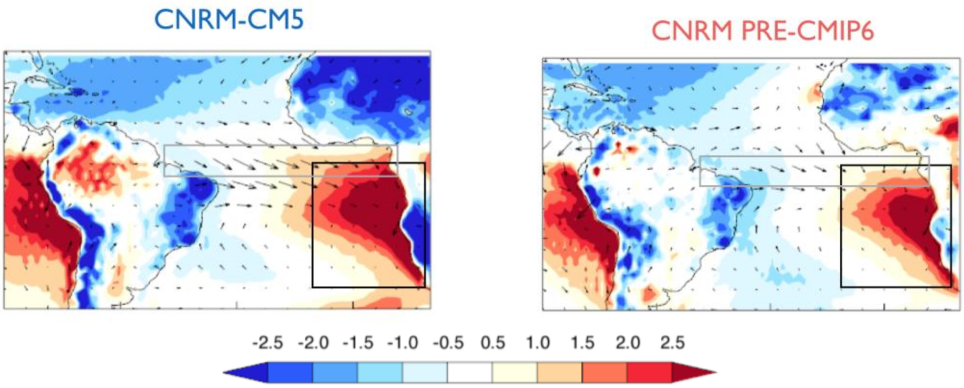


**Figure 1:** Annual surface temperature and surface wind biases of both CNRM-CM5 and CNRM-PRE-CMIP6. For surface temperature ERAI is used as reference over the continents and ERSST over the ocean. For surface wind the reference is ERAI. Units in degrees Celsius.

The new version of the CNRM model shows a reduction of the surface temperature biases over the continents, in particular the cold bias over the Sahara, and also a reduction of the SST bias in the southeast tropical Atlantic, in particular in the summer (not shown). An important fact is the weakening of the equatorial westerly biases, which was particularly strong in CNRM-CM5 (Voldoire et al. 2014).

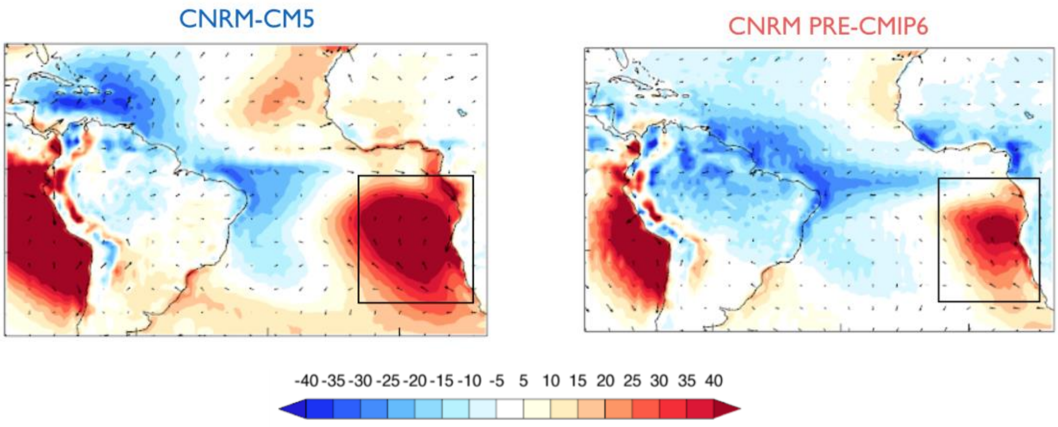


**Figure 2:** Annual surface bias of the short-wave cloud radiative effect for both CNRM-CM5 and CNRM-PRE-CMIP6 for simulations with fixed sea surface temperature (AMIP). The reference dataset is CERES-EBAF (Loeb et al. 2009). Units in $W/m^2$.

The reduction of the warm SST bias can be explained by the weakening of the westerly bias (Fig. 1) and also by a large improvement of the short-wave cloud radiative effect over subsiding regions as seen when comparing the atmospheric versions of the climate model (Fig. 2).

The precipitation bias in April, respect to GPCP is depicted in Figure 3. Even if the double ITCZ problem remains, the new model version exhibits a more meridional precipitation bias with an improved ITCZ structure. A significant reduction of the precipitation bias over equatorial Africa is also observed.

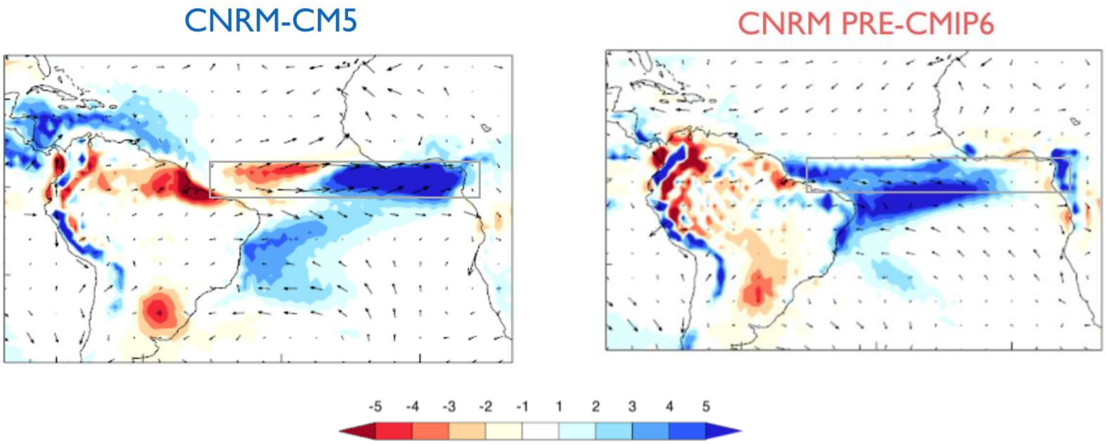


**Figure 3:** Precipitation bias in April for both atmospheric versions (AMIP) of CNRM-CM5 and CNRM-PRE-CMIP6. The reference dataset is GPCP. Units in mm/day.

### b) Tropical Atlantic modes of variability simulated by CNRM-CM6

To analyse how the CNRM-CM6 model simulate the tropical Atlantic interannual variability, the Equatorial Mode (EM, Carton and Huang 1994; Carton et al. 1996; Keenlyside and Latif 2007) and the Atlantic Meridional Mode (AMM, Nobre and Shukla 1996) are computed. Here ERAI reanalysis is used as the reference dataset. To obtain the EM, an Empirical Orthogonal Function (EOFs) analysis of the monthly SST anomalies is performed. As EM peaks in summer, we focus on JAS (July-August-September) months. Trends are removed before computing EOFs. The EM spatial structure is shown for CNRM-CM5 (historical simulation), CNRM-PRE-CMIP6 and ERAI in Figure 4. To compute the AMM we have followed the methodology described in Chiang and Vimont, 2004, which is based on a Maximum Covariance Analysis (MCA) between the SSTs and 10 m winds (two components) fields. The analysis is performed for the spring season (March-April-May) and the temporal trend is removed for all the fields before MCA. Figure 5 shows the SST and 10 wind anomalous patterns associated to the AMM for CNRM-CM5, CNRM-PRE-CMIP6 and ERAI.

Figure 4 shows that the simulation of the equatorial SST variability is improved in the new model version. A cold SST bias is still present and even intensified in the CNRM-CM6 model. The variance explained by the EM is underestimated in both versions of the CNRM-CM model respect to ERAI, for the period considered. The improvement of the simulated EM in CNRM-CM6 can be due to a better representation of the climatological surface winds (reduction of the westerly biases, Fig.1). The next step is to investigate how CNRM-CM6 simulated the Bjerknes feedback (BF) (Ruiz-Barradas et al. 2000, Keenlyside and Latif 2007), which is the physical mechanism explaining the occurrence of the EM. As previously investigated by Deppenmeier et al. 2016, state-of-the-art coupled models present deficiencies in simulating the BF, in particular the link between the ocean heat content and the underlying SSTs in the eastern part of the basin.

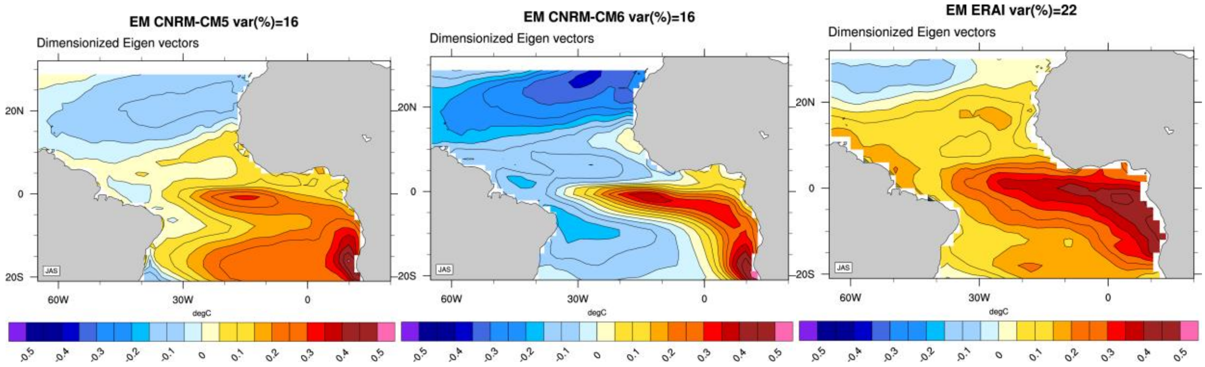


**Figure 4:** SST anomalies associated to the Equatorial Mode (EM, units in degrees Celsius) in JAS for CNRM-CM5, CNRM-CM6 (PRE-CMIP6) and ERAI reanalysis. EM is obtained by EOF analysis. For ERAI the first mode is retained, for CNRM-CM5 and 6 the second mode is retained.

As shown in the previous WP7 deliverable (D7.1), CMIP5 models underestimate the inter-hemispheric SST gradient associated with the AMM. This is also the case for the CNRM-CM5 model, and the new version does not improve the representation of the AMM pattern. Though the latitudinal position of the cross-equatorial winds are better simulated in CNRM-CM6 (in CNRM-CM5 they are located far too south). Further investigation is needed to assess how the Wind-Evaporation-SST feedback (WES, Xie and Philander 1994, Xie and Carton 2004, Chang et al. 1997) is simulated in the new model version. Previous studies (D7.1 and Amaya et al. 2016) show that WES feedback is poorly represented in CMIP5 models, essentially due to i) SST overreacting to heat atmospheric fluxes and ii) a lack of coupling between SST and winds over the southern Tropical Atlantic.

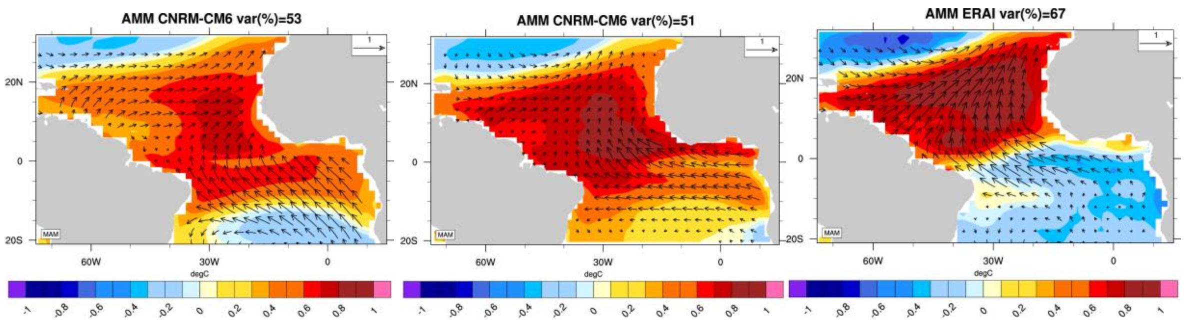


**Figure 5:** SST (colors) and 10m wind (arrows) anomalies associated to the Atlantic Meridional Mode (AMM, units in degrees Celsius for SST and m/s for wind) in MAM for CNRM-CM5, CNRM-CM6 (PRE-CMIP6) and ERAI reanalysis. AMM is obtained by MCA analysis (the first mode is retained).

## 2. EC-Earth3.1 : Impact of a boundary layer parameterization on the Tropical Atlantic variability

*Deppenmeier, A. L. (WU); Bilbao, R., Exarchou, A. (BSC); de Vries, H. (KNMI)*

Tropical Atlantic biases found in the EC-Earth3.1 (IFS-NEMO) climate model are very similar to the ones seen in most CMIP5 models, and are not dramatically improved with increased model resolution. The main bias characteristics consists of a warm bias in the South-Eastern Atlantic coast (along the coast of Namibia and Angola), and a cold bias in the western equatorial region. The cold equatorial bias has been associated with deficiencies in the wind field and ocean mixing, whereas the warm coastal bias has been linked to surface heat fluxes biases (Exarchou et al., 2016).

BSC investigated the effect of including a WAve Model (WAM) in EC-Earth3.1 (IFS(159)-NEMO(ORCA1)) on the Tropical Atlantic bias and variability in a set of sensitivity experiments:

- a control simulation with constant 2000 forcing conditions during 54 years (Cont),

- a simulation with constant 2000 forcing conditions coupling WAM to the atmospheric model only (ocean therefore responds to the changed wind-stress field) during 54 years (Exp_AtmWAM),

- a simulation with constant 2000 forcing conditions coupling WAM to the atmospheric and ocean model (ocean therefore responds to the changed wind-stress field and changed ocean mixing) during 40 years (Exp_AtmOcWAM).

The WAM represents the wave-atmosphere and wave-ocean interactions that affect air-sea momentum fluxes. The ocean responds to the wind-stress field, which is changed by different drag-coefficients and breaking waves (through the Charnock parameter), and which also influences the vertical oceanic mixing (Janssen, 2004).

BSC assessed whether including a more complex physical representation of the air-sea interaction results in improvements in the tropical Atlantic biases. Exarchou et al. (2016) showed that the west equatorial Atlantic bias originates in the NEMO model, due to the stronger subtropical overturning cell north of the equator and a weaker surface westward current. Therefore it is expected that an improvement in ocean mixing may reduce the cold bias in the western equatorial Atlantic.

The SST biases were estimated by subtracting the time mean of the simulations and the time mean for the period 1990-2010 in observations (HadISST). The period 1990-2010 is chosen since idealized simulations are based on constant 2000 forcing: equal number of years before and after the year 2000 are expected to approximately average the effect of increasing anthropogenic forcing.

Figure 6a shows bias in the control simulation, which are similar to those described in Exarchou et al. (2016) and comparable in magnitude, where the warm bias maximum is located along the coast of Namibia and Angola. However in these simulations the warm bias extends further west and there is no equatorial cold bias. Figure 7a-d shows the bias for each season; the bias is largest in summer and is the only season which shows a weak cold bias (statistically significant) along the western equatorial Atlantic (c.f. Exarchou et al., 2016). Note, the estimated model bias is somewhat imprecise, as the simulations use constant 2000 forcing

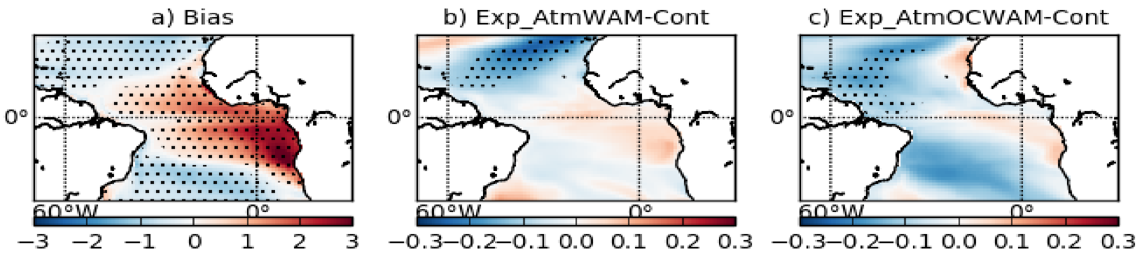


**Figure 6:** a) SST (K) Tropical Atlantic bias in the control simulation with respect to HadISST. b) Difference in SST (K) between the control and exp1. c) Difference in SST (K) between the control and exp2. The dotted areas indicate regions that are statistically significant at the 95% level (using a t-test). Note the difference between the scale between figure a) and the rest.

Figures 6b and 7e-h show that in EC-Earth3.1, including IFS-WAM interactions only (modified wind-stress) has a negligible effect on the tropical Atlantic warm SST bias. These results support the previous work done by WU for WP6, which shows that running EC-Earth with a realistic wind-stress (from ERAI) does not reduce the SST bias in the tropical Atlantic. Interestingly, including NEMO-WAM interactions, which modifies ocean vertical mixing, as well as the wind-stress, does not have a significant effect either (Fig. 6c and 7i-l).

Future work could focus on investigating the effect of cloud cover along the Eastern coast of Africa, as this has not been considered with these simulations and is considered a source of bias. Exarchou et al. (2016) found that in EC-Earth the warm SST bias in the eastern Atlantic coast originates in the atmosphere due to the excessive solar fluxes, caused by the reduced cloud cover in the model that warms the ocean surface and creates a positive feedback by stabilizing the water column, and inhibiting the proper upwelling of cold oceanic waters to the surface, thus further amplifying the SST bias.

BSC then assessed the impact of coupling the WAM model to EC-Earth3.1 on the tropical Atlantic SST variability. In the EC-Earth3.1 simulations, SST has a positive trend (not shown) because the model is not in a quasi-equilibrium state due to insufficient spin-up. This drift was removed in the control simulation by subtracting a linear fit (estimated by ordinary least squares), and the resulting section used to initialize the experiments Exp_AtmWAM and Exp_AtmOcWAM. Therefore the tropical SST variability was analysed around the trend, assuming that coupling the WAM model has negligible effect in changing the trend, as indicated by the small differences in the trends in the individual experiments consistent with sampling differences. For comparison, we use HadISST for the period 1970-2014, and also subtract the linear fit.

Figure 8 shows that EC-Earth3.1 simulates the location of the tropical Atlantic SST anomalies (with respect to the seasonal climatology) fairly realistically, however the magnitude of the variability is overestimated. Coupling the WAM model in EC-Earth3.1 marginally reduces the amplitude of the variability (by approximately 15% with respect to the control) when it is coupled to both the atmosphere and ocean (figure 8d).

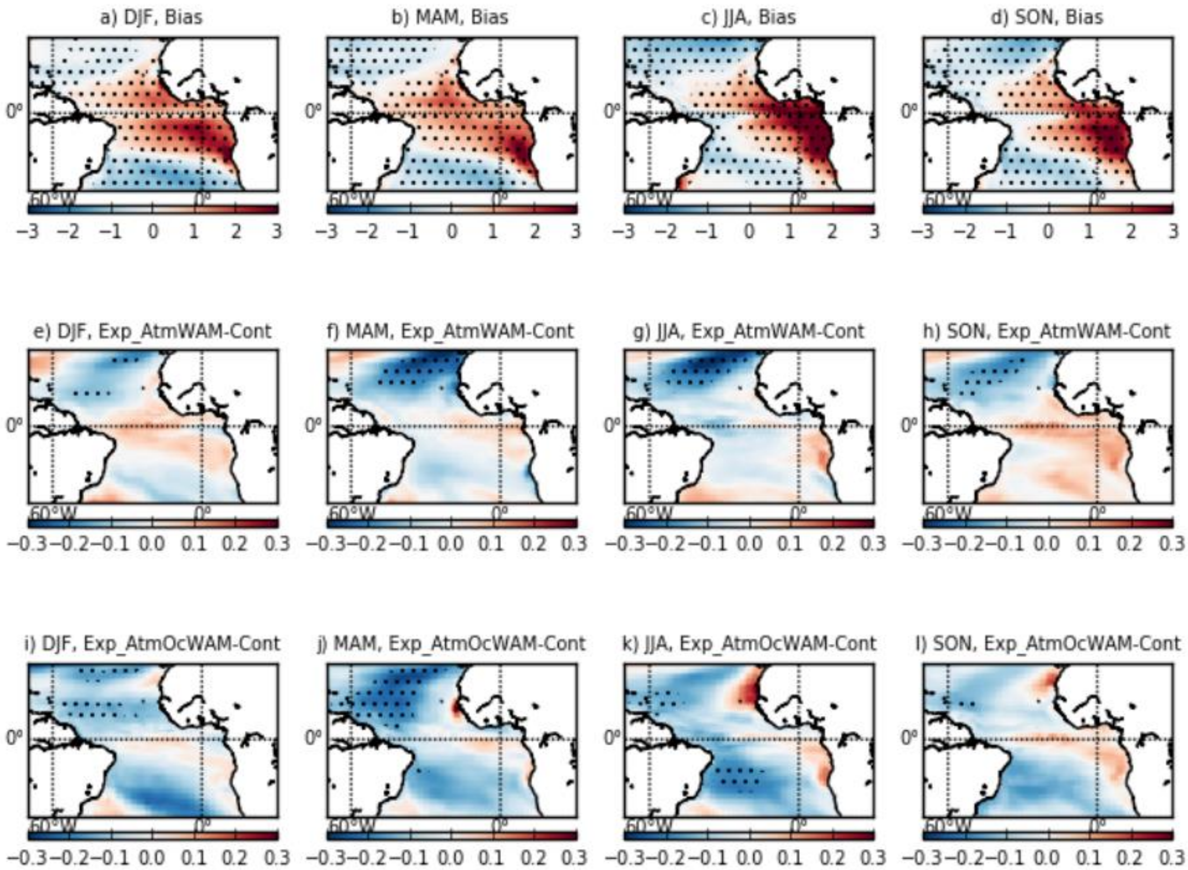


**Figure 7:** First row is the (a-d) SST (K) Tropical Atlantic bias in the control simulation with respect to HadISST for each season (DJF, MAM, JJA and SON). Second row (e-h) is the difference in SST (K) between the control and Exp_AtmWAm for each seasons. Third row (i-l) is the difference in SST (K) between the control and Exp_AtmOcWAm for each seasons. The dotted areas indicate regions that are statistically significant at the 95% level (using a T-test).

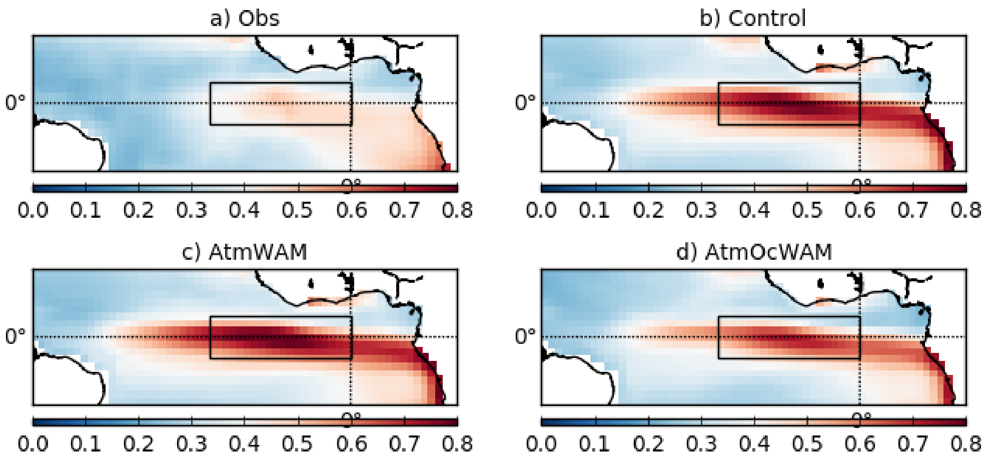


**Figure 8:** Tropical Atlantic SST variability (standard deviation) for observations and EC-Earth3.1 simulations. The monthly SST anomalies were calculated with respect to the seasonal climatology. The box indicates the ATL3 region (20ºW-0, 3ºN-3ºS).

Figure 9a shows the climatological seasonal cycle of the ATL3 index. EC-Earth3.1 reproduces the amplitude and the timing of the ATL3 seasonal cycle fairly realistically. Coupling the WAM model does not seem to have a substantial effect. The largest ATL3 SST variability occurs in the summer months due to the development of the summer cold tongue (figure 7b). As shown in the figure 7b, EC-Earth3.1 overestimates the magnitude of the SST ATL3 variability in the summer months and peaks one month later (July) in comparison to the observations. Coupling the WAM model shows a marginal reduction in the model error.

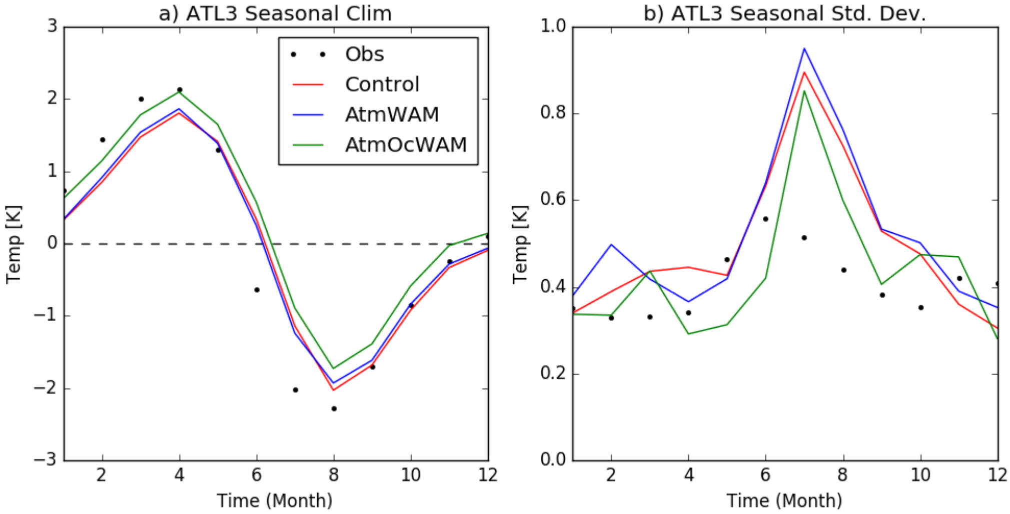


**Figure 9:** a) ATL3 (20ºW-0, 3ºN-3ºS) seasonal climatology and b) standard deviation in HadISST and the EC-Earth3.1 simulations. Months 1-12 correspond to January-December.

Further work is required to determine the physical processes that lead to the overestimation of the tropical Atlantic SST variability in EC-Earth3.1.

## 3. KCM: Impact of horizontal and vertical resolutions on the Tropical Atlantic variability

Harlass, J. and M. Latif (GEOMAR)

GEOMAR investigated the quality of simulating tropical Atlantic (TA) sector climatology and interannual variability in integrations of the Kiel Climate Model (KCM) with varying atmosphere model resolution. The ocean model resolution was kept fixed. Results show that a reasonable simulation of TA sector annual-mean climate, seasonal cycle and interannual variability (including seasonal phase locking) can only be achieved at sufficiently high horizontal and vertical atmospheric resolution (Fig. 10).

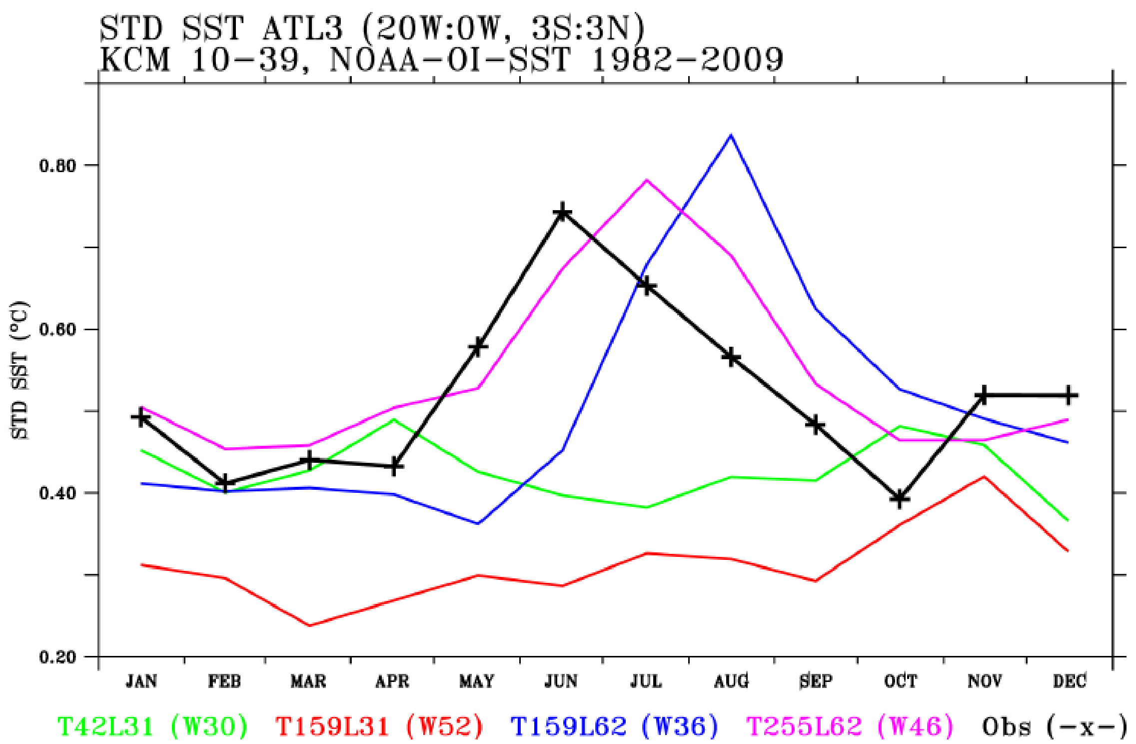


**Figure 10:** Monthly standard deviation of SST anomalies (°C) in the ATL3 region (20°W-0°W, 3°S-3°N). Black cross denotes NOAA-OISST (1982-2009), green: T42 L31, red: T159 L31, blue: T159 L62, purple: T255 L62.

Two major reasons for the improvements can be identified. First, the western equatorial Atlantic westerly surface wind bias in spring can be largely eliminated, which is explained by a better representation of meridional and especially vertical zonal momentum transport. The enhanced atmospheric circulation along the equator in turn greatly improves the thermal structure of the upper equatorial Atlantic with much reduced warm SST biases. Second, the coastline in the southeastern TA and steep orography associated with the Andes are better resolved at high atmospheric resolution, and this leads to stronger alongshore winds and in turn much reduced warm SST biases in the Benguela upwelling region.

The strongly diminished wind and SST biases allows for a more realistic latitudinal position of the Intertropical Convergence Zone (ITCZ). The resulting stronger cross-equatorial winds, in conjunction with a shallower thermocline, enable a rapid cold tongue development in the eastern TA in boreal spring. This enables simulation of realistic interannual SST variability and its seasonal phase locking (Fig. 10) in the KCM, which is primarily the result of a stronger thermocline feedback. Our findings suggest that enhanced atmospheric resolution, both vertical and horizontal, could be a key to achieving more realistic simulation of TA climatology and interannual variability in climate models.

In conclusion, the much better represented ocean state and interannual variability when using high atmosphere model resolution is primarily the result of the improvement in the atmosphere model. In contrast, a coupled model with high oceanic resolution but low atmospheric resolution would not necessarily result in a similar improvement in the KCM system. This is because of intrinsic errors in the atmosphere model at coarse resolution that can be demonstrated by companion experiments with the atmosphere model integrated in uncoupled mode and forced by observed SSTs (not shown).

## 4. Anomaly coupling experiment

(alph. order) Keenlyside, N. (UiB), Koseki, S. (UiB), Losada Doval, T. (UCM), Sanchez-Gomez, E. (CERFACS), Toniazzo, T.(UniRes), Voldoire, A. (MF-CNRM)

In this section anomaly coupling (AC) experiments performed with 3 different coupled models (NorESM, UCLA and CNRM-CM5) are presented. The main goal in WP7 is to investigate if improved model climatologies (SST and wind-stress) lead to benefits in simulated tropical Atlantic variability at interannual timescales. The anomaly coupling protocol consists of replacing the climatological part of the fields exchanged in the model components by those of observations, while leaving free the anomalous parts without modifications (Kirtman 1997). The AC experiment was designed in Xiao and Mechoso (2009) in order to study the link between the seasonal cycle and the interannual variability in the tropical Pacific. The coupling information is modified every coupling timestep. At each coupling time, the OGCM SST (Fig. 11, dashed red box) is modified by subtracting the OGCM SST climatology ((SST)OGCM control) and adding the observed climatology ((SST)obs), the resultant SST (blue box) is passed to the AGCM. In the same way, the surface fluxes (wind-stress in our case) passed from the AGCM (dashed blue box) to the OGCM (red box) are modified by subtracting the AGCM mean fluxes ((surface fluxes)AGCM control) and adding back the observed climatology of fluxes ((surface fluxes)obs).

Koseki and Toniazzo (2017, in revision) have developed an alternative way of AC in which the model climatology is updated as the simulation proceeds. A running time-average provides an estimate of the bias of the actual, corrected coupled model climatology with respect to observations, and the coupling fields are modified accordingly. A fundamental aspect of this technique is that the correction is refined iteratively and thereby converges to the desired climatology. Results show a significant improvement of climatological mean-state over the tropics and subtropics and El Niño/Southern Oscillation (ENSO) variability over the tropical Pacific Ocean in Norwegian Earth System Model (NorESM). In this study, AC is applied to the other two coupled models (UCLA and CNRM-CM5) and we assess the impact of AC on inter-annual variability over the tropical Atlantic Ocean among different three models.

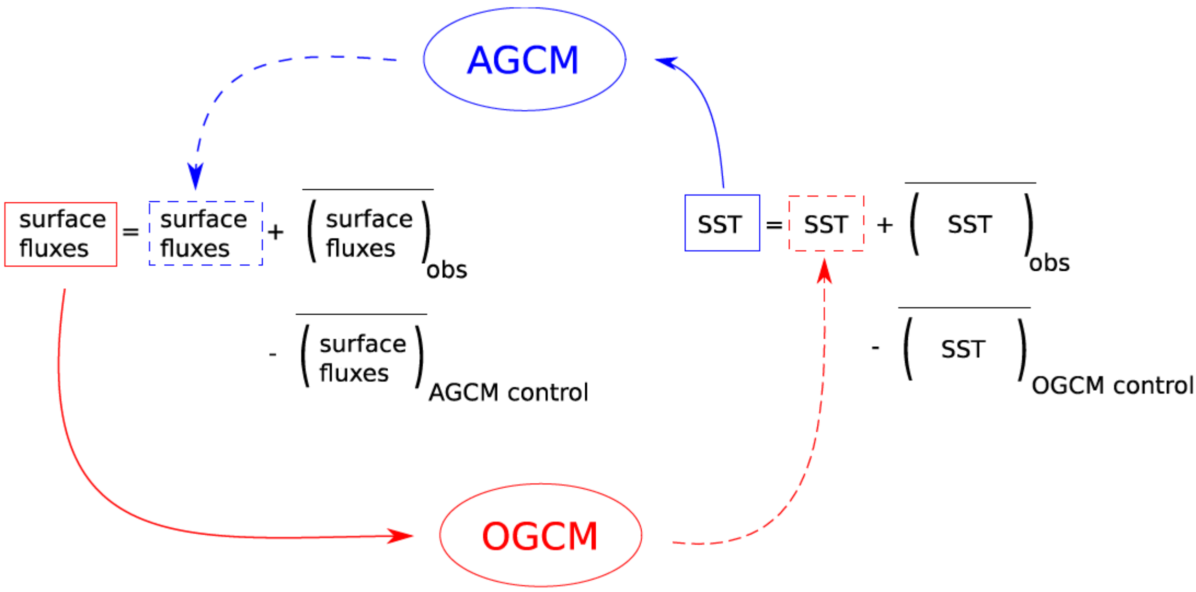


**Figure 11:** schematic illustration of the anomaly-coupling strategy (see text for details) implemented in PREFACE.

The partners involved in this work are UiB/UniRes (lead), UCM and CERFACS/MF-CNRM. A coordinated baseline experiments has been defined amongst the partners: a common observed climatology has been defined for SST and for wind stress for the period 1981-2000. HadISST and ERAI datasets have been selected to compute the respective SST and wind-stress climatologies. Unfortunately the implementation of the anomaly coupling technique is not exactly the same for all the models, since each model has its particularities in the coupling set-up. Hence, some differences exist (described below) in the anomaly coupling experimental design. A control experiment (free model run) has been also performed in order to assess the impact of the anomaly coupling on the model mean state and variability. All the experiments has been run for at least 100 years (except for those with UCLA model that have not been completed yet) to take into account the model adjustment. In the following sub-section a detailed description (4.1) of the anomaly coupling experiment with some basics results are given for each model separately. Section 4.2 shows the representation of variability modes in the Tropical Atlantic: Equatorial Mode (EM) and Atlantic Meridional mode (AMM) for the improved models climatology. Section 4.3 focused on how the mechanism of equatorial variability (Bjerknes feedback) is simulated in anomaly coupling runs, and finally section 4.4 summarizes the main conclusions.

### 4.1 Anomaly Coupling description and basics results

#### a) Anomaly Coupling with NorESM model

*NorESM* is initialized at 1980-01-01 from NorESM historical run and integrated for 100 years with fixed external forcing of CO2 and aerosol of 1990 value. For anomaly coupling, observed monthly climatology (1981-2000) of SST (HadISST) and wind stress (ERAI) are replaced with model climatology. The initial model climatology is obtained from historical run of NorESM for 1981-2000. AC is applied in the global ocean. During the integration, the model climatology is iteratively updated by the model state every time step. A control simulation (CTL) with no correction is also performed.

#### b) Anomaly Coupling with UCLA model

Two different approaches were tested with the UCLA model:

- *Experiment ACI (Iterative anomaly coupling)*: Following Koseki and Toniazzo (2017), the model climatologies were updated at each timestep during the simulation. It includes a λ correction term for the heat fluxes that is calculated on-line in the 44 year-long simulation (including 20 years of spin-up). The SST bias is very much reduced and the seasonal cycle better represented, but the variability in the tropical Atlantic is dramatically reduced with this method.

- *Experiment ACI-bis*: Following the original approach, with model climatologies extracted from uncoupled runs. The UCLA model needs to apply a flux correction term ( λ) in order to avoid spurious feedbacks in the heat fluxes that lead to wrong performance of the OGCM component of the model. The rest of the simulation is similar to the experiment ACI, i.e. 44-year long including 20 years of spin-up. The SST bias is even more reduced with a better seasonal cycle, and the variability is much closer to the observations.

Additionally a control experiment (CTL hereinafter), in which no correction is applied, has been performed.

### c) Anomaly Coupling with CNRM-CM5 model

*CNRM* is initialized at 1970-01-01 from CNRM historical run and integrated for 100 years with fixed external forcing of CO2 and aerosol of 1990 value. For anomaly coupling, observed monthly climatology (1981-2000) of SST and wind stress are replaced with model climatology. The initial model climatology is obtained from historical run of CNRM for 1981-2000. AC is applied only between 30S-30N. Only wind-stress and SST climatologies modified in each coupling time-step, and no additional heat flux correction is applied. Additionally a control experiment (CTL hereinafter), in which no correction is applied, has been performed.

### d) Preliminary analysis on mean state and variability

Model data have been uploaded at the Norstore server for the CTL and AC simulations for each model. A common analysis is presented here. In the following, the experiments without (with) AC are referred to CTL (AC). The analysis has been performed for the later 50 years of NorESM and CNRM, and 22years of UCLA. For the latter only the AC-bis experiment is shown.

As mentioned previously, AC improves the climatological annual-cycle of SST in the equatorial Atlantic Ocean, indicating that the Atlantic cold tongue is developed realistically in three models (Fig. 12). Especially, UCLA model reduces 4 degree of warm bias in a whole year in AC. Corresponding to a better SST annual cycle, sea surface height (SSH, a proxy of thermocline depth) is also improved in terms of annual cycle in AC simulations (Fig. 13). Although the SSH shows a clear annual cycle of SSH in each CTL, the timing of shoaling in JJA in observations is shifted forward by about 2-3 months in the models (Figs. 14 a-c). On the other hand, the annual cycle of SSH in AC run is almost consistent with the observed one in terms of both timing and amplitude.

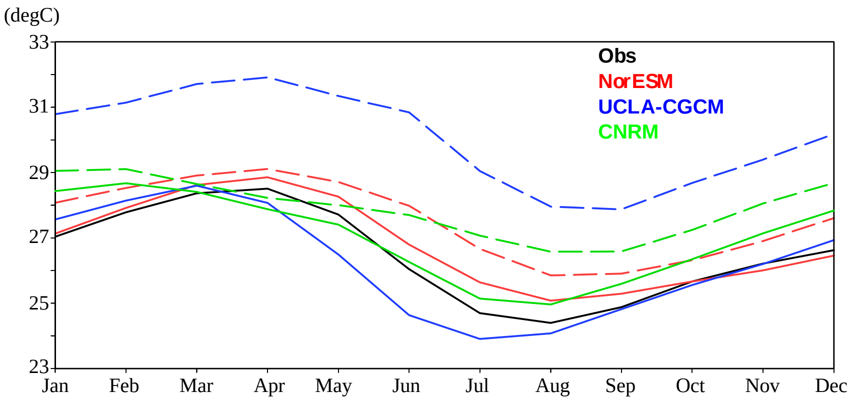


**Figure 12:** Atlantic 3 indices (SST averaged 3S-3N and 20W-0) for (black) OISST, (red) NorESM, (blue) UCLA-CGCM, and (green) CNRM. For models, solid (dashed) line denotes AC (CTL) run for each model. The observation is obtained from OISST from 1982-2010.

Figure 14 illustrates the annual-cycle of SST standard deviation in the equatorial Atlantic. For the CTL simulation, NorESM and UCLA have much larger peak in July than the observation and its timing is late by one month compared to the observation. On the other hand, CNRM has a peak in March in the eastern equatorial Atlantic. AC protocol modifies the annual cycle of SST variability: in NorESM and UCLA models, equatorial variability is substantially reduced throughout year, as shown in next section 4.2. The peak shifts to April and June in NorESM and is still in July in UCLA. In contrast, in

CNRM the variability increases and the peak shifts to July and August. Thus, only in CNRM does AC lead to partial improvement in simulated equatorial variability (see also section 4.2).

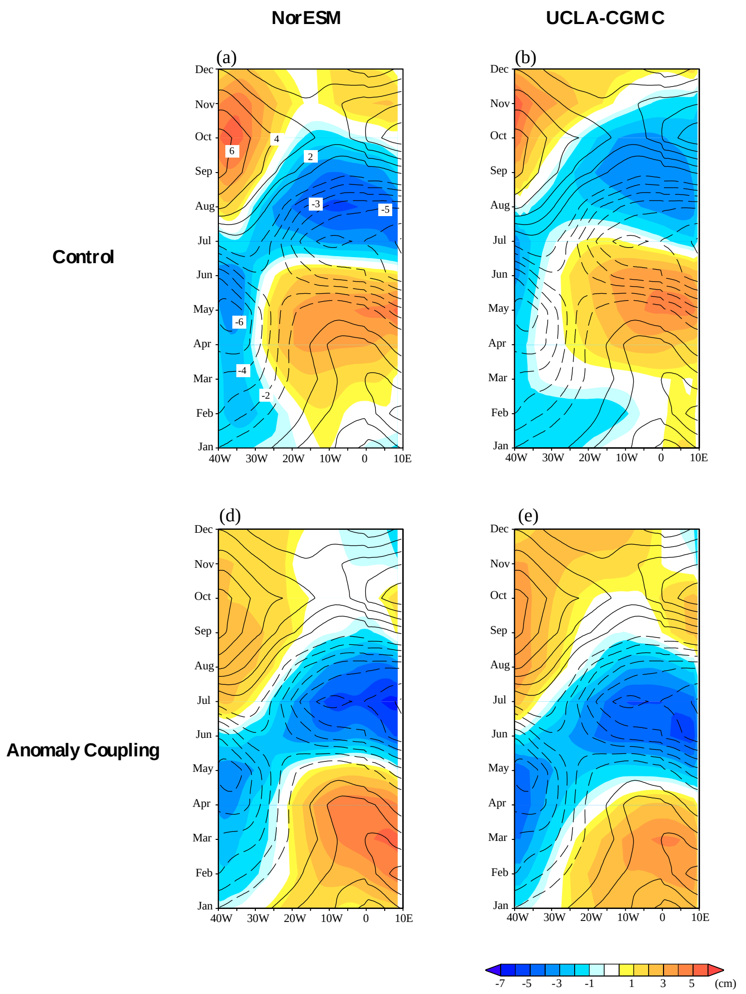


**Figure 13:** Annual cycle of SSH anomaly from annual-mean for (contour) AVISO and (color) each model at the equator. Solid (dashed) line is positive (negative) value of SSH anomaly in the observation. The top (bottom) panel is for CTL (AC) run. The observation if obtained from AVISO from 1993 to 2008.

Figure 15 presents the annual-cycle of one standard deviation of zonal wind stress in the equatorial Atlantic Ocean. In general, the observed zonal wind stress largely varies in the western side of the equatorial Atlantic from April to July (Fig. 15a). In the CTL runs, the high variability tends to be located in the central to eastern equatorial Atlantic. In terms of timing, NorESM is relatively the best performing model. On the other hand, CNRM has an earlier peak of the variability, corresponding to the high SST variability in March-to-April (Fig. 14d). AC simulations lead to some improvements: in NorESM, the central high variability vanishes and variability in the western side is somewhat amplified although the peak timing is still later than in the observation (Fig.15e). The variability is also reduced in the UCLA model in the centre as well. While the variability is still large in March in the CNRM model, the variability in the western side is slightly amplified from March to July (Fig.15f).

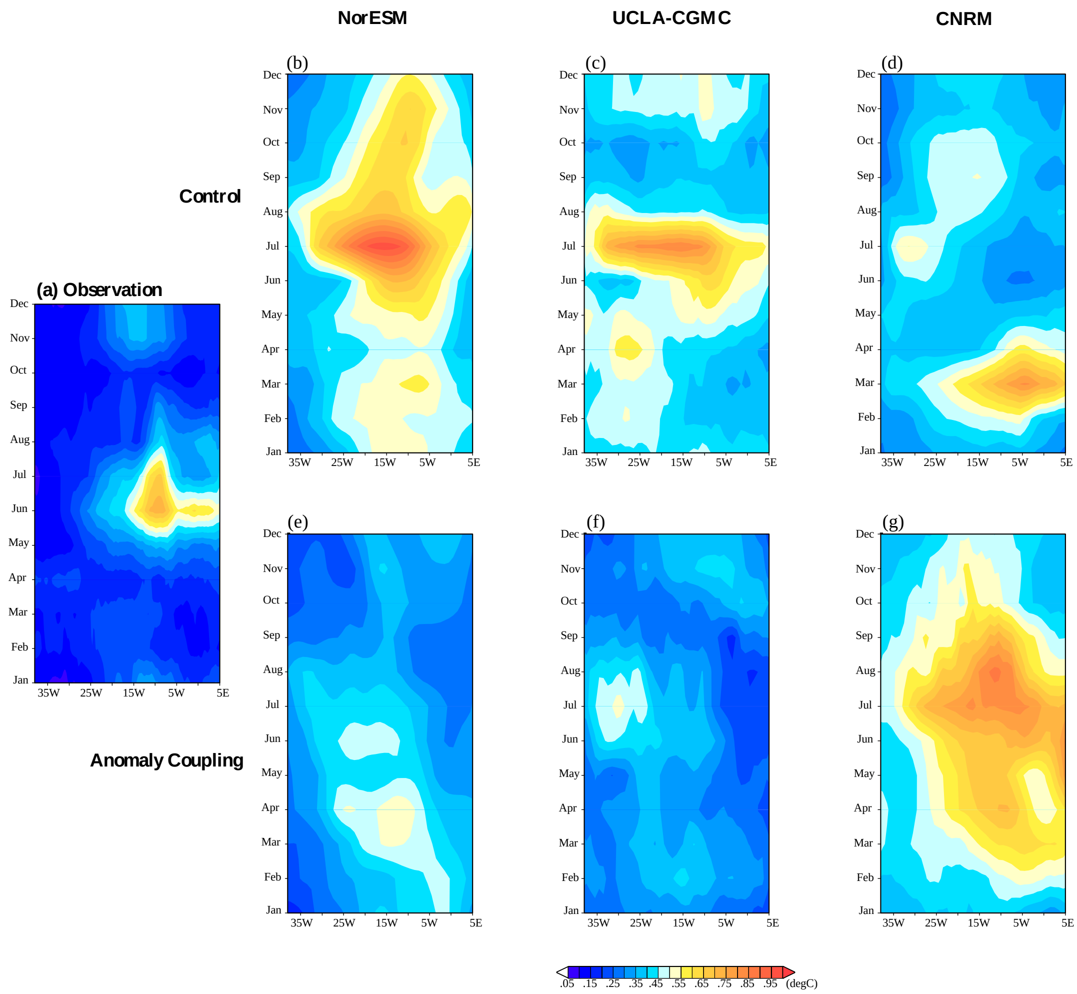


**Figure 14:** Annual cycle of SST standard deviation between 3S and 3N for (a) OISST and (b)-(g) models. The observation is obtained from OISST from 1982-2010.

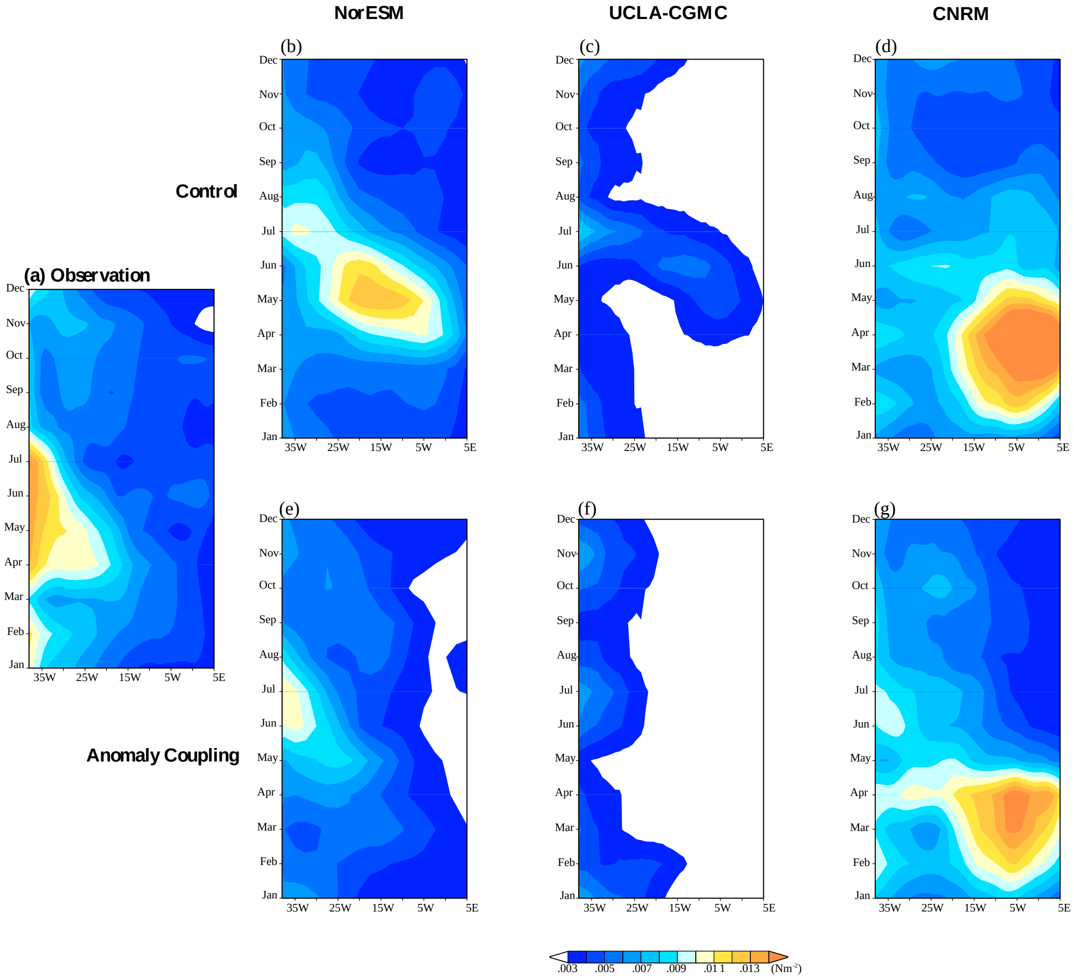


**Figure 15:** Same as Figure 14, but for zonal wind stress standard deviation. The observation is obtained from ERAI from 1982-2010.

## 4.2 Tropical Atlantic variability modes

In this section the impact of the anomaly coupling protocol on the representation of the main modes of variability at interannual timescale is investigated. As for the previous section, to perform the calculations, only the last 50 years of simulations are considered for NorESM and CNRM simulations, and the last 22 years for UCLA model. Following Richter et al. 2012, the Equatorial Mode (EM) is obtained from an EOF analysis on summer (JAS) SST. AMM is computed here from a similar EOF analysis applied on spring SSTs (AMJ) but for a wider domain.

### a) The Equatorial Mode

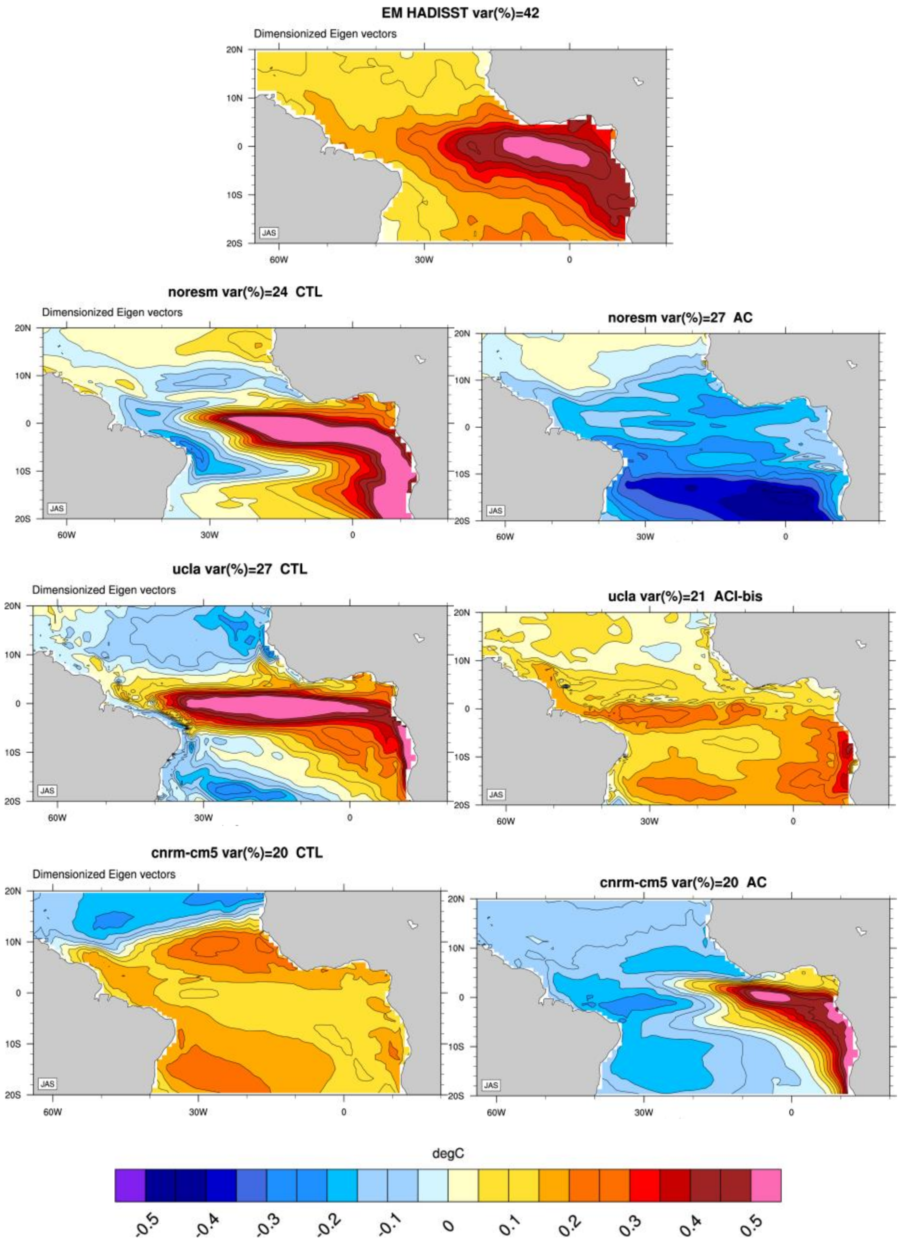


**Figure 16:** EM for the different AC experiments performed with the different models: NorESM (Top), UCLA (middle) and CNRM-CM5 (bottom). The experiments are described in section 4.1 for each particular model. The EM is obtained by EOF analysis of the summer (JAS) SST anomalies. The first plot (top, left) corresponds to the observations (HadISST data as reference).

Figure 16 shows that the equatorial variability exists in the CTL experiments for NorESM and UCLA, even if some bias can be found in the spatial structure of the EM and the explained variance is underestimated comparing to observations. From Fig. 16, the mean state is improved in NorESM and UCLA experiments; the AC leads to a degradation of the simulated EM. In the NorESM AC experiment the equatorial variability in summer is drastically reduced (coherent with Fig. 14). In the case of UCLA model, the simulated EM also worsens and the equatorial variability is largely reduced (Fig. 14). However, for CNRM-CM5, whose simulated equatorial variability is not correct in the CTL run, AC achieves a much better representation of the spatial pattern of the EM in the AC experiment (though the variance is underestimated).

These results suggest that anomaly coupling technique is successful in improving the model mean state in the Tropical Atlantic, though the extent of the improvement highly depend on the protocol and the model. However, the improvement of the mean state does not necessarily lead to an improvement of the simulated EM. Those models showing a correct simulation of the EM in the CTL run (NorESM and UCLA), exhibit a degradation of the EM when the anomaly coupling is applied. In contrast, CNRM-CM5 whose EM in the CTL run is not correct in summer, shows a clear improvement of the EM representation. More insight on these results will be given in the Bjerknes feedback analysis in section 4.3.

**b) The Atlantic Meridional Mode**

In general the AMM is not correctly simulated in CMIP5 models (see D7.1 and Amaya et al. 2016). Most of the models underestimate the SST inter-hemispheric gradient, which can be connected to failure of the representation of the WES (Wind-Evaporation-SST) feedback (Amaya et al. 2016) and a wrong representation of the ITCZ (located too southward). Figure 17 shows that the inter-hemispheric SST gradient is to some extent present in the CTL experiment for NorESM and CNRM models, but it is clearly underestimated in UCLA. AC experiments do not systematically lead an improvement of AMM.

In particular, AC experiments worsen the representation of the AMM for UCLA and CNRM-CM5 models (Fig. 17). Again and as for the EM, when the free model run correctly simulates a mode of variability, even if the mean state is biased, the anomaly coupling can act to improve the mean state but lead to a degradation of the simulated modes.

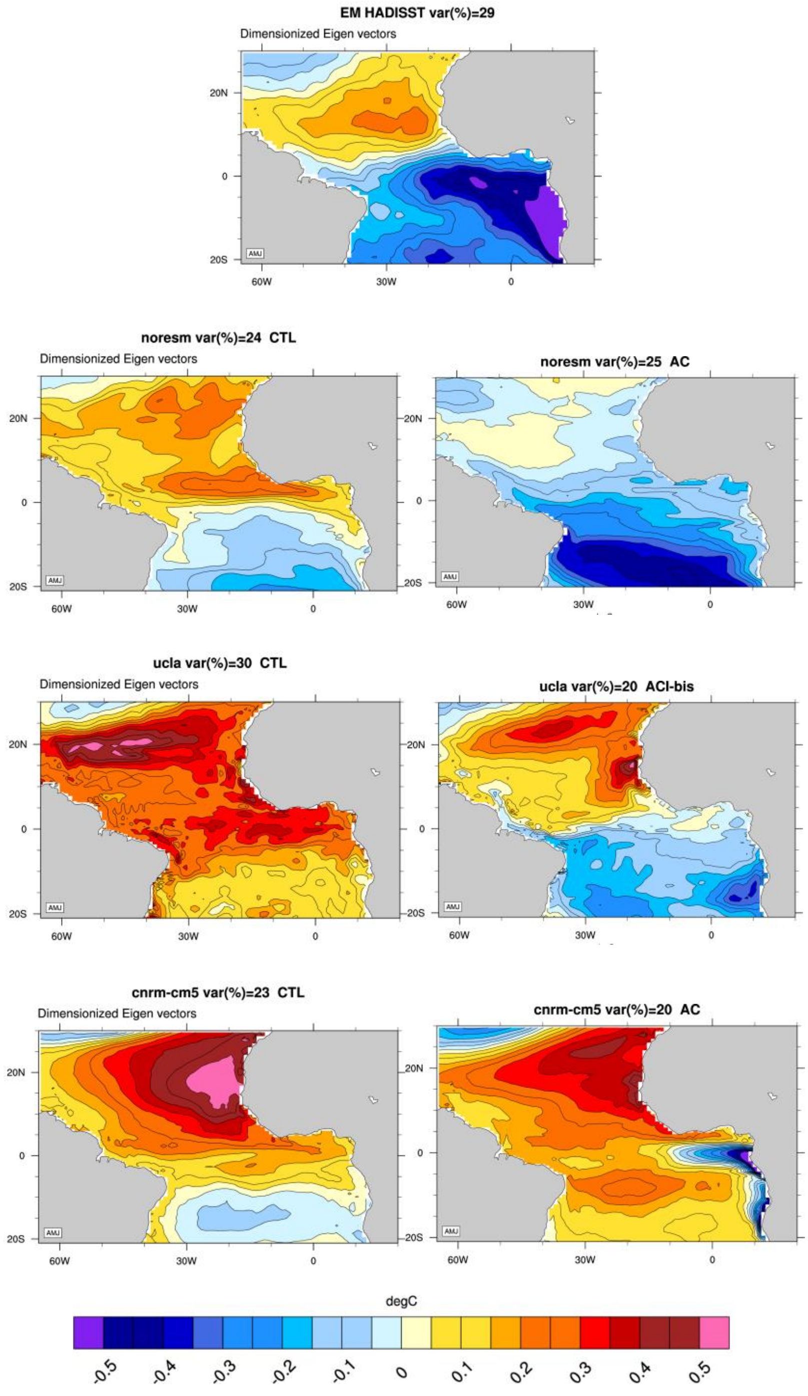


**Figure 17:** AMM for the different anomaly coupling experiments performed with the different models: NorESM (Top), UCLA (middle) and CNRM-CM5 (bottom). The experiments are described in section 4.1 for each particular model. The EM is obtained by EOF analysis of the spring (AMJ) SST anomalies. The first plot (top,left) corresponds to the observations (HadISST data as reference).

### 4.3 Bjerknes feedback in Anomaly Coupling Runs

Because the equatorial tropical Atlantic variability associated to the Equatorial Mode (EM) or Atlantic Niño/Niña is linked to the tropical Bjerknes feedback (e.g., Keenlyside and Latif, 2007), further analysis focusing on the Bjerknes feedback is performed here to understand the impact of the AC technique on the equatorial variability. Basically, the methodology for the analysis follows Ding et al. (2015).

The first element of the Bjerknes feedback, represented by the relationship between surface winds and the western part of the basin and equatorial SST variability is analysed. Figure 18 shows the regression and correlation map between zonal wind stress and Atlantic 3 SST index for the observation and each model in the two different runs. The observations show that the surface wind in the western equatorial Atlantic is highly related to the Atlantic 3 SST index (consistent with the existence of the EM, Fig. 16). This indicates that the warm Atlantic 3 induces the weakening the easterly trade wind in the western and central equatorial Atlantic. This link is to some extent represented in CTL (NorESM and UCLA-CGCM) runs already (Figs. 18b-d), but the regressions coefficients are weaker than in observations. However, CNRM presents negative regression coefficients and correlations between zonal wind stress and Atlantic 3, suggesting a non correct simulation of winds-Atlantic 3 link. On the other hand, AC runs improve significantly this link for all the models. In NorESM, the positive relation in the western side is strengthened and negative relation in the eastern side is reduced. While in UCLA the improvement is weaker, the negative relation in the southern subtropical Atlantic is diminished. For CNRM model, the relationship becomes more realistic.

The second element of the Bjerknes feedback is analysed as the relation between surface winds and thermocline. As mentioned previously, SSH is used here as a thermocline depth proxy. Figure 19 shows the regression and correlation between SSH and zonal wind stress in the western equatorial Atlantic for the observations and each model in the two different runs. The observed pattern indicates that the SSH responds to the surface zonal wind: the westerly anomaly of trade winds induces the higher SSH and consequently, deepening of the ocean thermocline (Ding et al. 2015) via the ocean Kelvin Wave dynamics. Basically, CTL runs show this element of the Bjerknes feedback, but they have higher values of regression coefficients (Figs.19b-d). In AC runs, the regression values become weaker and more realistic.

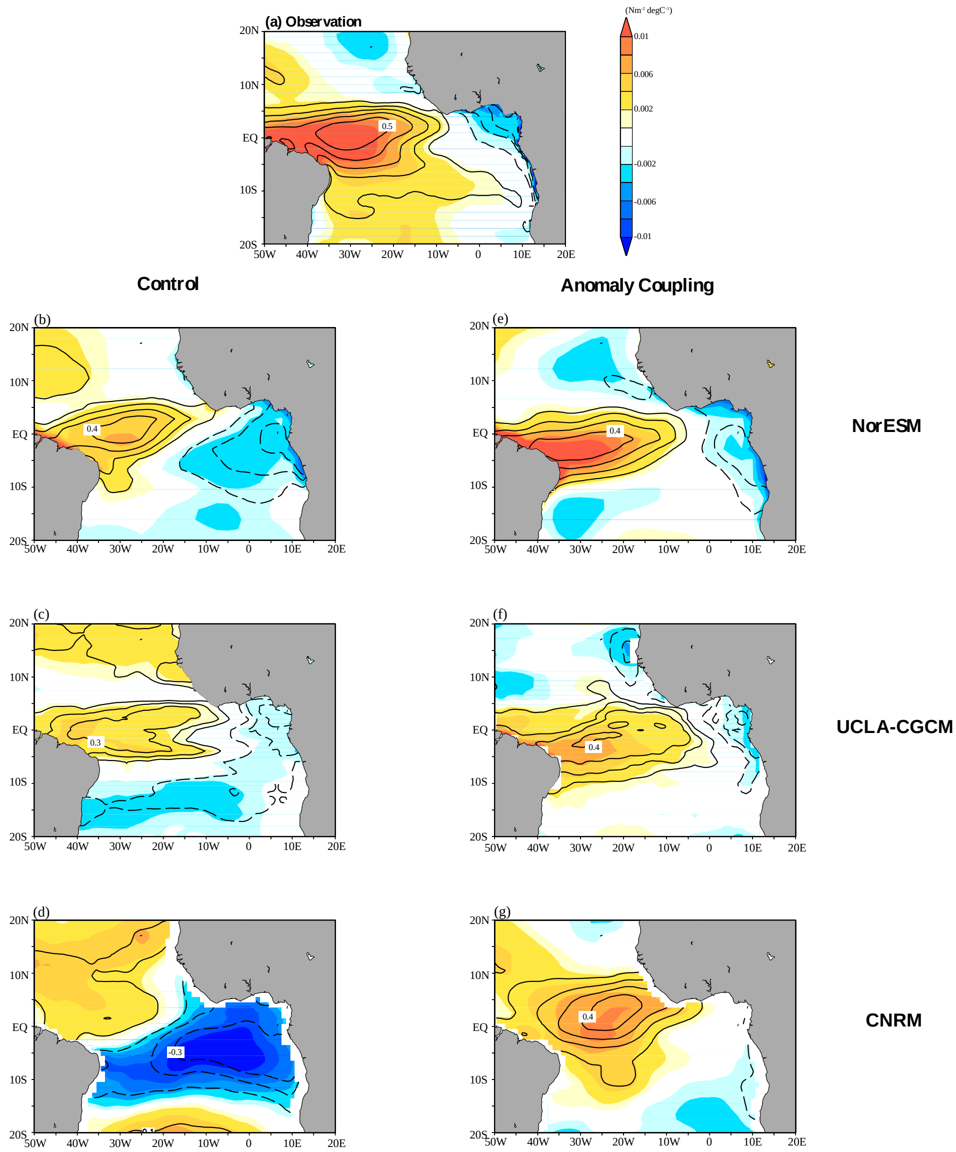


**Figure 18:** (Color) regression of zonal wind stress on to Atlantic 3 and (contour) correlation between zonal wind stress and Atlantic 3 for all 12 months in (a) observation and (b)-(g) each model. Left (right) column is for CTL (AC) run. The observation is ERAI and OISST from 1982-2010.

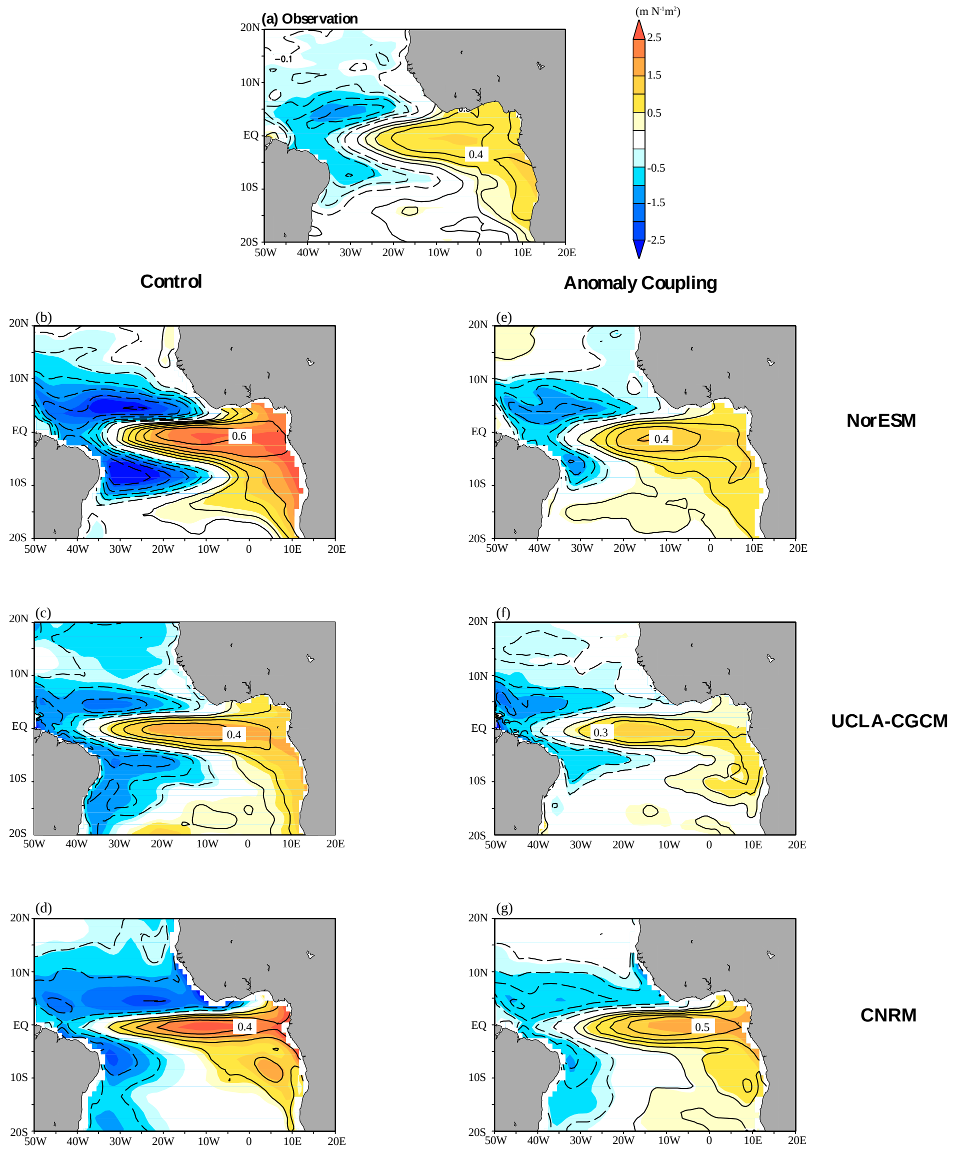


**Figure 19:** Same as Figure18, but for (color) regression of SSH onto zonal wind stress over western equatorial Atlantic (3S-3N and 35W-20W) and correlation between SSH and (contour) zonal wind stress over western equatorial Atlantic. The observation is ERAI and AVISO from 1993-2008.

The last piece of the Bjerknes feedback, regression and correlation of SST and SSH, is showed in Fig.20. This regression map indicates that SST in the central equatorial Atlantic and subtropical upwelling regions is warmed when the SSH (thermocline) is higher (deeper). Although this coupling is well represented in the in NorESM and UCLA models in the central equatorial Atlantic in CTL runs, it is clearly overestimated in the western equatorial Atlantic around Southern America (Figs. 20b-d). The link is not correctly simulated in the CTL simulation of CNRM model. The horizontal distribution of AC simulation of NorESM slightly improved over the western equatorial Atlantic, however the values of the correlation clearly weaken over the central and eastern equatorial Atlantic (0.8 ->0.5), and become unrealistic in the south Atlantic. There is also some improvement for the UCLA model. In CNRM, the regression pattern and correlation values are much more realistic in AC simulation.

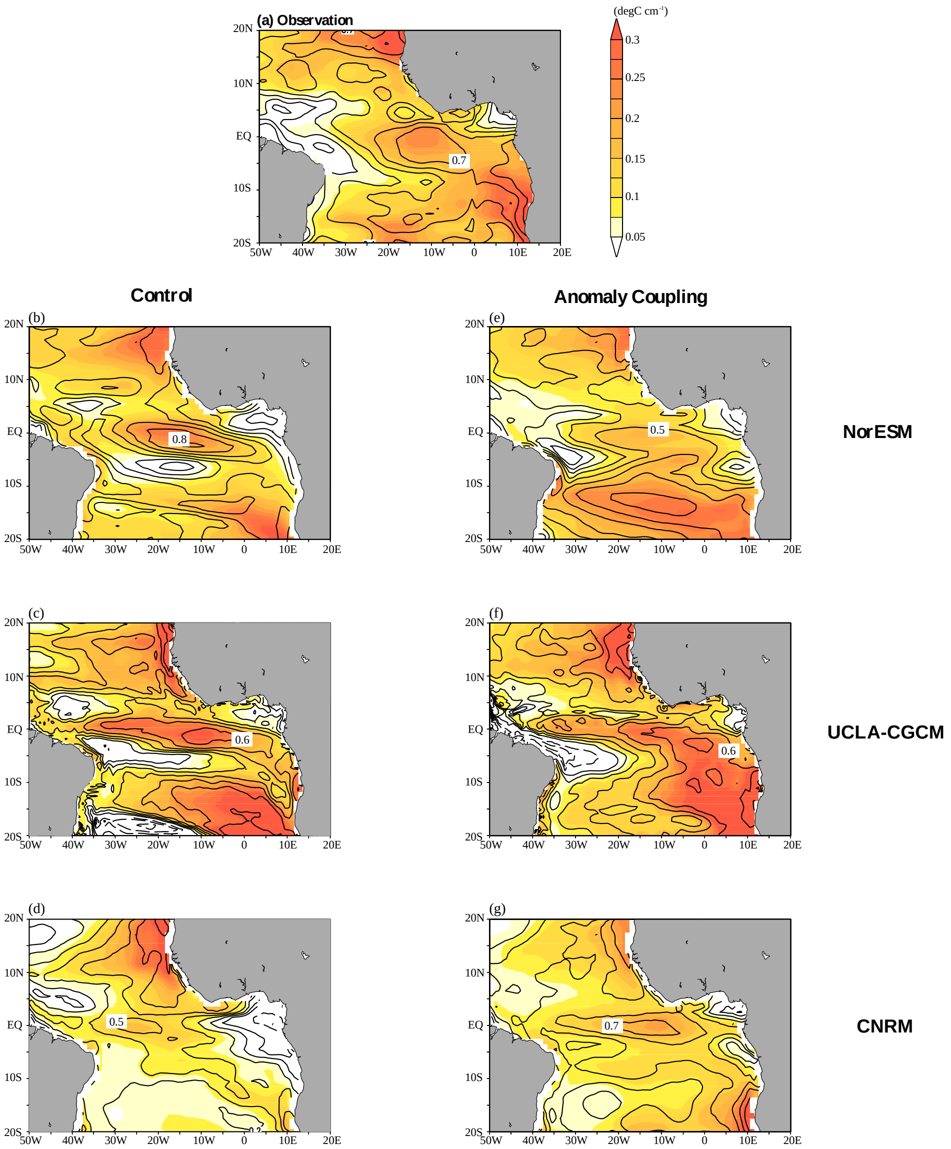


**Figure 20:** Same as Figure 18, but for (color) regression of grid-wise SST onto SSH and (contour) correlation between SST and SSH. The observation is AVISO and OISST from 1993-2008.

Figure 21 illustrates the annual-cycle of the first and third parts of the Bjerknes feedback. In the observations, the coupling between Atlantic 3 SST index and equatorial zonal wind stress is strongest during spring to early summer (March to June, Fig.21a) over the western part of the equator. The linkage between SST and SSH is also strong in May to July at the eastern part. The CTL runs of the three models fail in the representation of the high positive correlation between zonal wind and Atlantic 3 SST in spring (rather, negative correlation is found in May), and strongest correlation is found from June to August (delayed compared to observations). The maximum correlation between the SST and SSH occurs in July to August over the western part of the equator, and it is also delayed with respect to observations. This period of strongest SST/SSH coupling is consistent with the largest SST variability (see Figs.14b-d). In CNRM, the largest variability of SST in March to May seems to be related to the negative correlation between zonal wind and Atlantic 3 in March to May (Fig.14d).

The AC runs clearly improve the annual cycle of the links (Figs.21e-g), in particular the wind-stress/Atlantic 3. In NorESM, the largest positive correlation between zonal wind stress and Atlantic 3 is maximized in May (good agreement with the observation) and associated SSH-SST correlation is also enhanced in May to June, though correlation values are underestimated at the eastern part of the basin, over the cold tongue region. This modification can be associated with the April-to-June peak of SST variability In NorESM (Fig.14c). For UCLA, the negative wind-stress/Atlantic 3 correlations in May disappear and positive correlation can be found in April to although its value is relatively small (Fig.21f). On the other hand, the positive correlation between SST and SSH remains almost unchanged respect to CTL (Figs.21c and f). This may reflect that the SST variability does not change its timing of the peak in UCLA in CTL and AC (Figs.14c and f). For CNRM the simulation of the feedback is generally improved. Although its timing is slightly late (maximized in June), the large positive correlation between zonal wind stress and Atlantic 3 is enhanced in April to July and associated SST-SSH correlation is strengthened in June to August. This can be connected to the improvement of the SST variability in June to July (Fig.14f) and the representation of the EM (Fig. 16).

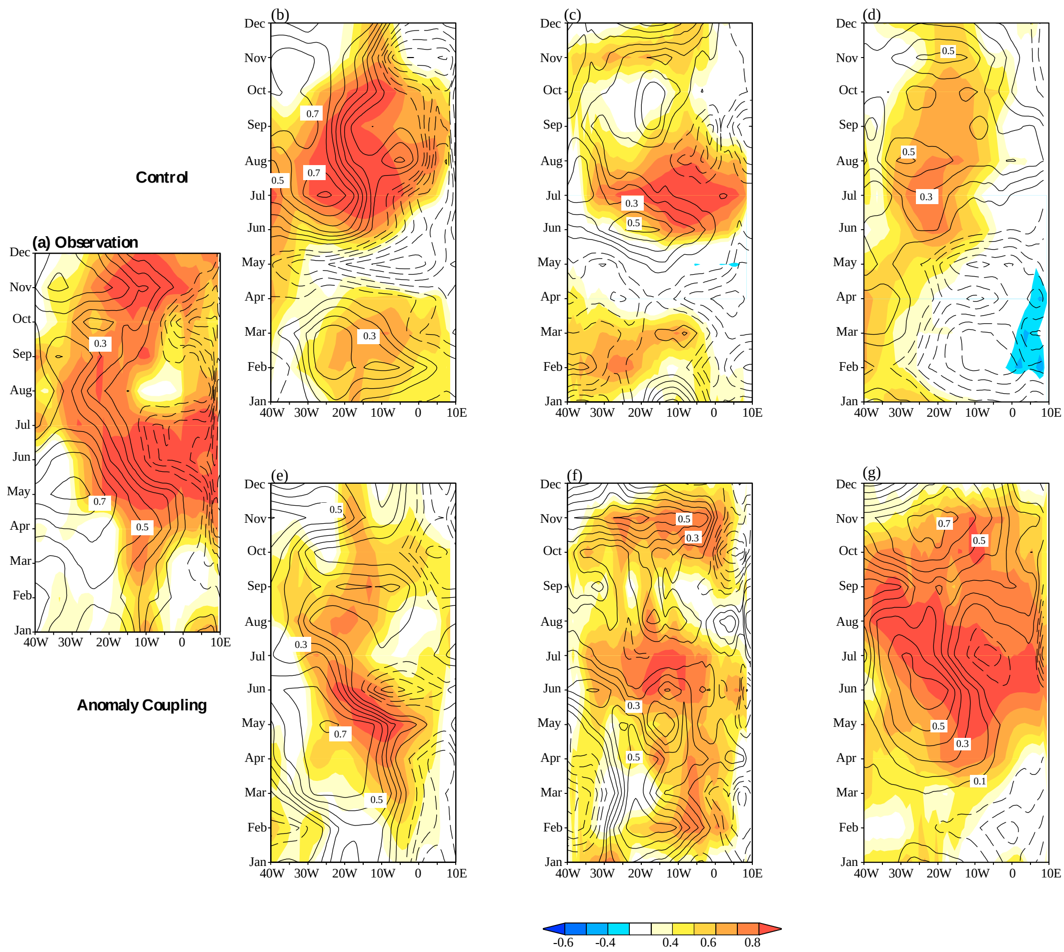


**Figure 21:** Annual-cycle of monthly correlation (contour) between equatorial zonal wind stress and Atlantic 3 SST and (color) between equatorial SST and SSH for (a) observations and (b)-(g) models. The top (bottom) panel is for CTL (AC) run. (b,e) NorESM, (c,f) UCLA, and (d,g) CNRM.

### 4.4 Conclusions

This section introduces the anomaly coupling (AC) protocol developed by Koseki and Toniazzo (2017). This protocol has been applied to 3 different coupled models. Though the AC implementation is different amongst the 3 models, results are comparable to study the modifications of improved mean state in the tropical Atlantic on the simulated variability.

Results show that climatological mean state is improved in the coupled models (SST, wind stress), though the amplitude of the improvement differs from model to model. The analysis also shows that AC modifies substantially the simulated inter-annual variability in the tropical Atlantic. For 2 models (NorESM and UCLA), AC tends to reduce the amplitude of the SST variability in the tropical Atlantic, and to degrade the representation of the modes of variability (EM and AMM). For the CNRM model, the AC significantly improves the simulation of the equatorial variability (EM).

In order to get more insight in the mechanisms of variability, the representation of the Bjerknes feedback in CTL and AC runs has been investigated. Our results show that most of the aspects of the Bjerknes feedback are improved in the AC simulations: relationship between wind stress and SST, and between SSH (thermocline depth) and wind stress. However, the link SST/SSH, which represent the dynamical part of the Bjerknes feedback, is not improved in AC experiments (except for the CNRM), and is already present in the CTL runs. The failure in representing the ocean surface/subsurface relationship by state-of-the-art coupled models has been previously reported by Deppenmeier et al. 2016 by using the CMIP5 database (see also D7.1).

Recent works suggest that the respective importance of the dynamical versus the thermodynamical processes in generating SST variability (in particular equatorial variability) in coupled models is still under debate (Nnamchi et al. 2015, Ding et al. 2015). In a submitted paper, Jouanno et al. (submitted) show that dynamical (wind) largely contributes to the interannual SST variations in the tropical Atlantic. They also show that mean and seasonal upper ocean temperature biases, commonly found in fully coupled models, strongly favour an unrealistic thermodynamic control of the equatorial Atlantic interannual variability.

According to this, the next step is to investigate the relative contributions of the thermodynamical versus the dynamical processes for generating SST variability in CTL and AC experiments. We will investigate the role of air-sea heat and momentum fluxes and how they are modified through the AC protocol.

**REFERENCES:**

*In bold the PREFACE (D7.2) references*

Amaya, D. J., M. J. DeFlorio, A. J. Miller, and S.-P. Xie, 2016: WES feedback and the Atlantic Meridional Mode: observations and CMIP5 comparisons. *Clim. Dyn***,** 1-15.

Carr M. E., Friedrichs M. A. M., Schmeltz M., Aita M. N., Antoine D., Arrigo K. R., Asanuma I., Aumont O., Barber R., Behrenfeld M., Bidigare R., Buitenhuis E. T., Campbell J., Ciotti A., Dierssen H., Dowell M., Dunne J., Esaias W., Gentili B., Gregg W., Groom S., Hoepffner N., Ishizaka J., Kameda T., Le Quere C., Lohrenz S., Marra J., Melin F., Moore K., Morel A., Reddy T. E., Ryan J., Scardi M., Smyth T., Turpie K., Tilstone G., Waters K., Yamanaka Y, 2006 : A comparison of global estimates of marine primary production from ocean color. Deep Sea Research Part II Topical Studies in Oceanography, 53 (5-7), p. 741-770.

Chang, P., Ji, L., Li, H., 1997: A decadal climate variation in the tropical atlantic ocean from thermodynamic air-sea interactions, Nature, 385(6616), 516–518

Chiang J. C. and D.J. Vimont, 2004: Analogous Pacific and Atlantic Meridional Modes of Tropical Atmosphere–Ocean Variability, J. Climate, 17, 4143-4158.

Dee D.P. and coauthors, (2011): The ERA-Interim reanalysis, configuration and performance of the data assimilation system, Quart. J. Roy. Met. Soc., 137, 553-597

De Boyer-Montégut C. G. Madec, A.S. Fisher, A. Lazar, D. Ludicone, 2004, Mixed Layer depth over the global ocean: an examination of profile data and a profile-based climatology. J. Geophys. Res., 109: C12003.

**Deppenmeier, AL., Haarsma, R.J. and Hazeleger, W., The Bjerknes Feedback in the Tropical Atlantic in CMIP5 models, Clim Dyn (2016) 47: 2691. doi:10.1007/s00382-016-2992-z**

**Deppenmeier, Haarsma, and Hazeleger : Ocean mixing - SST - cloud cover - shortwave radiation coupling in the Tropical Atlantic", submitted to Journal of Climate.**

Ding H, Keenlyside N, Latif M, Park W, Wahl S., 2015: The impact of mean state errors on equatorial Atlantic interannual variability in a climate model. J Geophys Res Oceans, 120, 1133-1151.

**Exarchou, E., C. Prodhomme, V. Guemas and F. Doblas-Reyes, 2016. Sources of EC-Earth bias in the Tropical Atlantic. Climate Dynamics (in review).**

**Harlass, J., M. Latif, and W. Park, 2017 : Alleviating Tropical Atlantic Sector Biases in the Kiel Climate Model by Enhancing Horizontal and Vertical Atmosphere Model Resolution: Climatology and Interannual Variability, submitted to Climate Dynamics.**

Hummels, R., M. Dengler, P. Brandt, M. Schlundt, 2014, Diapycnal heat flux and mixedlayer heat budget within the Atlantic cold tongue, Clim. Dyn., 43(11): 3179-3199.

Janssen, P.A.E.M., 2004. The interaction of ocean waves and wind, Cambridge University Press.

**Jouanno J., Hernandez O., Sanchez-Gomez E. and B. Deremble, Equatorial Atlantic interannual variability and its relation to dynamic and thermodynamic processes, submitted to GRL.**

Keenlyside, N. S., and M. Latif, 2007: Understanding Equatorial Atlantic Interannual Variability. *J. Climate*, **20,** 131-142.

Kirtman, B. P., J. Shukla, B. H. Huang, Z. X. Zhu, and E. K. Schneider, 1997, Multiseasonal predictions with a coupled tropical ocean-global atmosphere system, Monthly Weather Review, 125, 789-808.

**Koseki, S and T. Toniazzo, 2017. A methodology of anomaly coupling for climate simulation. In revision (for resubmission to Journal of Advances in Modeling Earth Systems)**

Nnamchi, H. C., J. Li, F. Kucharski, I.-S. Kang, N. S. Keenlyside, P. Chang, and R. Farneti (2015). Thermodynamic controls of the Atlantic Niño. Nat. Commun., 6, 8895, doi:10.1038/ncomms9895.

Nobre, P., and J. Shukla, 1996: Variations in sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate*, **9,** 2464-2479

Lengaigne, M., C. Menkes, O. Aumont, T. Gorgues, L. Bopp, J.M. André, 2007, Influence of the oceanic biology on the tropical Pacific climate in a coupled general circulation model, Clim. Dyn. 28 (5), 503-516.

Loeb, N.G., B.A. Wielicki, D.R. Doelling, G.L. Smith, D.F. Keyes, S. Kato, N.M. Smith, and T. Wong, 2009: Towards optimal closure of the earth's top of atmosphere radiation budget. J. Climate, 22, 748-766.

**Losada-Doval, T., 2017 :**

Ludicone, D., G. Madec, T.J. MacDougall, 2008, Water-mass transformations in a neutral density framework and the key role of light penetration, J. of Phys. Ocean., 38(7): 1357-1376.

Richter, I. and S. P. Xie, 2008. On the origin of equatorial Atlantic biases in coupled general circulation models. Climate Dynamics, 31 (5), 587598, doi:10.1007/s00382-008-0364-z.

Richter I., Xie S.P., Behera S.K., Doi T. and Y. Masumoto, 2014: Equatorial Atlantic variability and its relation to mean state biases in CMIP5, Clim. Dyn., DOI: 10.1007/s00382-012-1624-s.

Richter, I., 2015. Climate model biases in the eastern tropical oceans: causes, impacts and ways forward. WIREs Clim Change 2015. doi: 10.1002/wcc.338

Ruiz-Barradas, A., Carton, J.A., Nigam, S., 2000 : Structure of interannual-to-decadal climate variability in the tropical atlantic sector. Am. Met. Soc. 13

Toniazzo, T. and S. Woolnough, 2013. Development of warm SST errors in the southern tropical Atlantic in CMIP5 decadal hindcasts. Climate Dynamics, doi:10.1007/s00382-0.

Voldoire A., E. Sanchez-Gomez , Salas y Melia D., Decharme B., Cassou C., Senesi S., Valcke S., Beau I., Alias A., Chevallier M., Deque M., Deshayes J., Douville H., Fernandez E., MadecG., Maisonnave E., Moine M.-P., Planton S., Saint-Martin D., Szopa S., Tyteca S. Alkama R., Belamari S., Braun A., Coquart L., Chauvin F., 2013, The CNRM-CM5.1 global climate model : Description and basic evaluation. Clim. Dyn. Special Issue, doi :10.1007/s00382-011-1259-y.

Voldoire, A., M. Claudon, G. Caniaux, H. Giordani, and R. Roehrig, 2014: Are atmospheric biases responsible for tropical Atlantic SST biases in the CNRM-CM5 model? Climate Dyn., 43, 2963–2984, doi:10.1007/s00382-013-2036-x.

Xiao H. And C. R. Mechoso, 2009 : Seasonal cycle – El Nino relationship : validation of hypotheses. J. Atm. Sciences, 66, 1633-1653.

Xie S-P and Philander SGH, 1994 : A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific Tellus 46A 340-350

Xie, S-P., and J. A. Carton, 2004: Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth Climate: The Ocean-Atmosphere Interaction, Geophys. Monogr.,* No. 147, Amer. Geophys. Union, 121–142.

Zebiak, S. E., 1993. Air-sea interaction in the equatorial Atlantic region, J. Clim. , 6, 1567–1586.