European Union's Seventh Framework Programme
Grant Agreement Nº: 603521

Project Acronym: **PREFACE**

Project full title: **Enhancing prediction of tropical Atlantic climate and its impacts**

Instrument: Collaborative Project

Theme: ENV.2013.6.1-1 – *Climate-related ocean processes and combined impacts of multiple stressors on the marine environment*

Start date of project: 1 November 2013 Duration: 48 Months

Deliverable Reference Number and Title:

D 5.1

" Processes on seasonal to interannual variability in forced ocean models "

Lead work package1 for this deliverable: WP5

Lead contractor[1] for this deliverable: IRD

Due date of deliverable: 31.10.2015

Actual submission date: 30.10.2015

Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)		
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)	

1 Name of beneficiary (=institute/organisation/university)

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Contribution to project objectives – with this deliverable, the project has contributed to the achievement of the following objectives (see 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

Authors of this deliverable: Gaël ALORY, IRD

Deviation from planned efforts for this deliverable:

(PLEASE ONLY COMMENT IF THERE WERE DEVIATIONS FROM THE ORIGINAL PLAN[2] IN PERSON-MONTHS PER BENEFICIARY[1] AND/OR WORK PACKAGE OR OTHER RESOURCE USE FOR ACHIEVEMENT OF THIS DELIVERABLE)

Report on the deliverable:

(SHORT DESCRIPTION OF WORK PERFORMED; MAIN RESULTS ACHIEVED; CONTRIBUTION TO WP OBJECTIVES and TASKS)

[2] See List of person-months, nature and dissemination level of deliverable

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1- Context

This report D5.1 is produced by PREFACE CT2 WP5 and focuses on the role of various tested processes on seasonal to interannual variability of temperature and salinity in forced ocean models. Indeed, WP5 aims to evaluate to what degree forced medium to very-high-resolution ocean models are able to reproduce observed mean state and variability in the eastern tropical Atlantic Ocean, and in particular to produce control experiments to help interpret observations. This modelling work is strongly linked to the observational WP3 and WP4 that respectively deal with heat and freshwater budgets and air-sea interaction, circulation and wave response. Indeed, some of the ocean properties targeted by model studies described below are heat and freshwater budgets, signal propagation along the equatorial and coastal waveguide. The results reported here rely on WP5 Objective 1 ("Produce and validate an ensemble of reference forced simulations from various models and configurations, from regional to basin scale and global") and Objective 2 ("Carry out model process studies aimed at isolating the effect of specific internal or external forcing, to quantify the role of specific processes on observed variability") that have been filled through tasks 5.1 and 5.2, respectively.

The report is organized geographically, starting with studies that address temperature and salinity variability in the tropical Atlantic, then at regional scale with successive focus on the equatorial upwelling and coastal upwelling regions. Upwelling regions are particularly targeted as they show large temperature variability with important impact on climate and fisheries. More focus is put on scientific results than on model details, which can be found in cited papers or associated MS18 and MS19.

2- Tropical Atlantic

2.1. Salinity variability

A NEMO regional numerical simulation with 1/4° resolution forced by DSF5.2 atmospheric fluxes (ATL025-75, see MS18) was used on the 1993-2009 period to investigate the various processes controlling sea surface salinity (SSS) balance on seasonal and interannual time scales in the Gulf of Guinea (Da-Allada et al., 2014a). Processes were quantified using a mixed-layer salt budget. Model results correctly reproduced the mean, phase, and amplitude of observed seasonal near-surface salinity (fig. 1). The results indicated that on seasonal time scales, the mixed-layer salinity balance differed from one region to another. The surface salinity seasonal cycle was characterized by strong salinization during May for coastal areas north and south of the equator. Model results suggested that vertical mixing controls the mixed-layer salinity increase at the equator during May, while both vertical mixing and vertical advection contribute to the salinity increase in coastal regions (fig. 1). In the same region and period, it was previously shown that vertical mixing also play a strong role on sea surface temperature (SST) cooling (Jouanno et al., 2011). Freshening from horizontal advection and freshwater flux tend to balance the salinization effects of vertical diffusion and vertical advection during the seasonal cycle. Sensitivity experiments were conducted with either interannual wind forcing and climatological precipitation or climatological wind forcing and interannual precipitation. Comparison between the mixed-layer salinity balance in the sensitivity experiments and the reference experiment revealed that for the northern and equatorial Gulf of Guinea changes in near surface salinity were largely due to changes in precipitation and winds. For the southern Gulf of Guinea, only wind changes were determined to be important for explaining near-surface salinity changes.

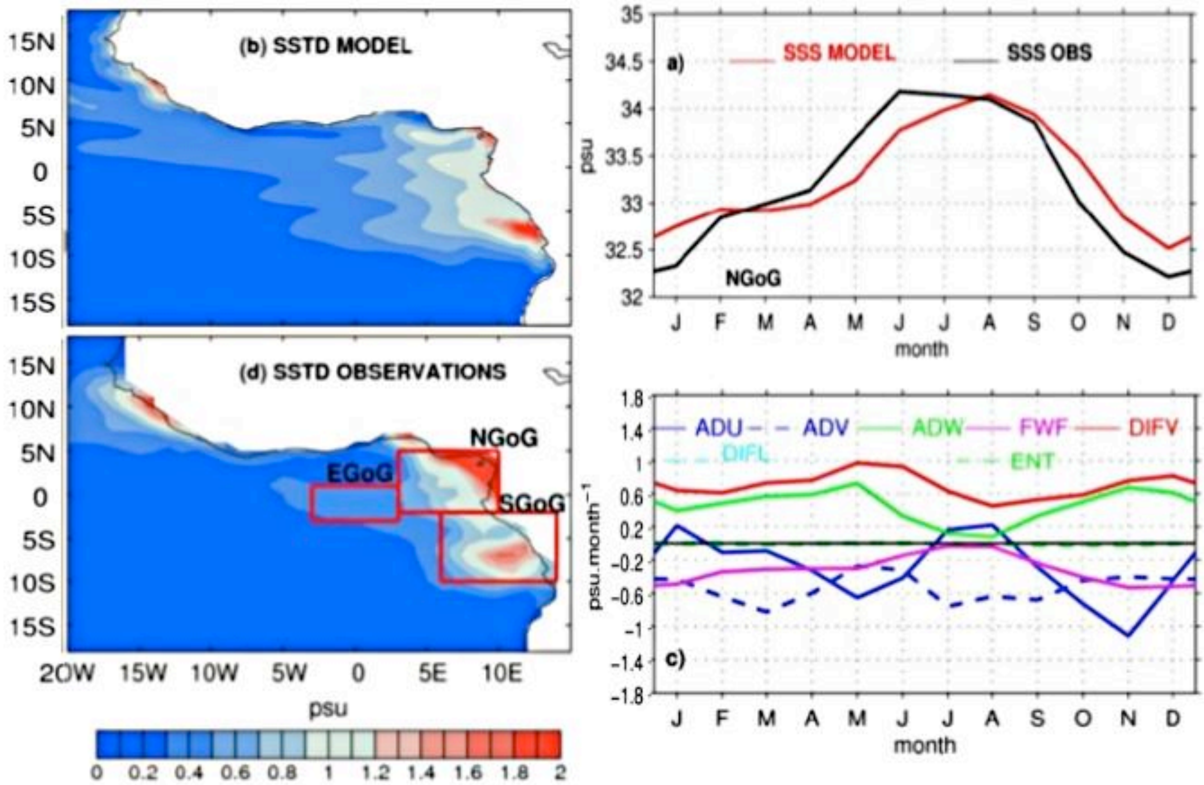

Figure 1. SSS seasonal standard deviation from the model (top left) and in situ observations (bottom left). SSS seasonal cycle in the Northern Gulf of Guinea (top right) and different processes contributing to the SSS tendency in the model (bottom right). ADU, ADV, ADW: advection terms; DIFV, DIFL: vertical and lateral diffusion; ENT: entrainment; FWF: freshwater forcing.

The same model simulation also proved able to reproduce an observed SSS increase >0.5 psu over the period 2002–2009 in the Gulf of Guinea, off the Niger Delta (Da-Allada et al., 2014b). Observed changes in the Niger River runoff were not consistent with this increase in SSS, moreover the model could reproduce it with climatological river runoff. When comparing the period 2002–2009 with the period 1993–2001, significant changes in the salt budget were identified. The increase in SSS in the more recent period appeared to be driven by changes in the atmospheric freshwater flux, mainly attributed to a regional decrease in precipitation. Horizontal advection partly compensated for the effect of freshwater flux through changes in zonal currents and zonal SSS gradients.

A complementary study, using the same model in a slightly different configuration (ATL025-46, see MS18), refined the SSS seasonal budget and extended it to the whole tropical Atlantic Ocean (Camara et al., 2015). The analysis reveals that the SSS cycle is generally weak in comparison of individual physical processes entering in the budget because of strong compensation (fig. 2). In evaporative regions, around the SSS maxima, the ocean acts to freshen the mixed layer against the action of evaporation. Poleward of the southern SSS maxima, the freshening is ensured by geostrophic advection, the vertical salinity diffusion and, during winter, a dominant contribution of the convective entrainment. On the equatorward flanks of the SSS maxima, Ekman transport mainly contributes to supply freshwater from intertropical convergence zone (ITCZ) regions while vertical salinity diffusion adds on the effect of evaporation. All these terms are phase locked through the effect of the wind. Under the seasonal march of the ITCZ and in coastal areas affected by river (7°S-15°N), the upper ocean freshening by precipitation and/or runoff is attenuated by vertical salinity diffusion. In the eastern equatorial regions, seasonal cycle of wind forced surface currents advect freshwaters, which are mixed with subsurface saline water because of the strong vertical turbulent

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diffusion. In all these regions, the vertical diffusion presents an important contribution to the SSS budget by providing, in general, an upwelling flux of salinity. It is generally due to vertical salinity gradient and mixing due to winds. Furthermore, in the equator where the vertical shear, associated to surface horizontal currents, is developed, the diffusion depends also on the sheared flow stability.

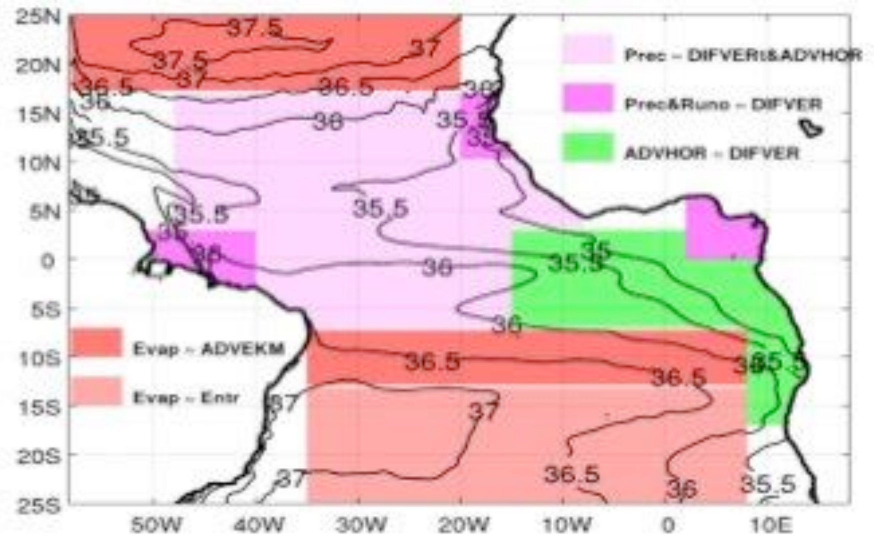

Figure 2. Summary of the main compensating processes influencing the seasonal variability of the mixed layer salinity. Compensation between: evaporation and Ekman advection (red), evaporation and entrainment (light red), precipitation+runoff and vertical diffusion (magenta), precipitation and vertical diffusion (light magenta), horizontal advection and vertical diffusion (green). Contours are annual mean SSS in psu.

2.2. Temperature variability

River runoff affect SSS, particularly in the tropical Atlantic where great river plumes (Amazon, Orinoco, Niger, Congo) are associated with strong freshening. They also enhance vertical stratification of the upper ocean, reducing the mixed layer depth (MLD) and sometimes producing barrier layers (BL) that can isolate the mixed layer from deeper, colder waters (Mignot et al., 2007). As a result, air-sea interaction is enhanced, which can affect SST. To evaluate SST sensitivity to these processes, a NEMO reference experiment with 1/4° horizontal resolution and high vertical resolution (ATL025-75, which has 75 levels, 12 levels in the upper 20 meters and 24 levels in the upper 100 meters, see MS18), including river runoff, has been compared to a test experiment without runoff (Hernandez et al., in preparation). The reference experiment has realistic patterns of MLD and BL, although simulated BL is thicker than observed in the Amazon plume (fig. 3). Comparing experiments with/without runoff shows that despite strong sensitivity of the SSS distribution and associated fields (MLD, BL) in the regions of the great rivers plumes, the impact on the annual mean SST is weak (<0.1°C) and not significant. Specifically, in the region where river induced stratification is maximum (the Amazon-Orinoco plume region), some sensitivity to the response of the ocean to atmospheric storms is observed, albeit weak (~10% cooling reduction in the wake of the most powerful Tropical cyclones). In the Gulf of Guinea, where synoptic winds are much weaker, no first order impact of the fresh river plumes on the response to intraseasonal winds is expected. These results should be further tested in a fully coupled ocean-atmosphere model in collaboration with CT3 (WP6/WP7).

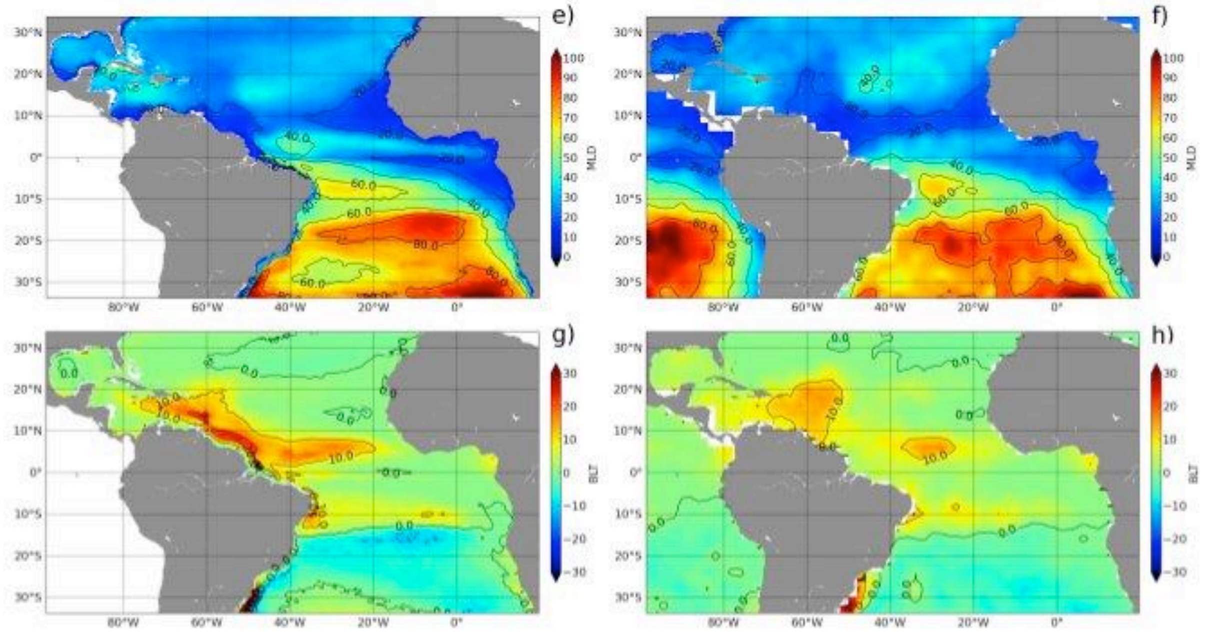

Figure 3. Climatological MLD (top) and BL thickness (bottom), in m, from model (left) and observations (right).

A test experiment with variable shortwave flux penetration, depending on the observed seasonal distribution of chlorophyll concentration in Case-1 waters, has been compared to the same reference experiment for which the shortwave penetration is constant and representative of open ocean waters with weak chlorophyll concentrations (Hernandez et al., in preparation). The comparison (fig. 4) shows that taking into account the distribution of chlorophyll on the shortwave penetration lead to a slight warming (+0.2°C) of the river plumes (Amazon-Orinoco, Niger-Congo) and an important cooling (O~1°C at some locations) of the Tropical Atlantic upwelling systems (Benguela, Senegal, Caribbean and Equatorial with a lesser extent). Overall, including chlorophyll distribution leads to a weakening of the Benguela warm bias. It has been further tested whether interannual and seasonal variability of surface Chl-a could contribute to the seasonal and interannual variability of SST in the Benguela upwelling system. This was achieved through comparison between experiments forced with climatological Chl-a and experiments forced with constant and interannual Chl-a. Despite strong seasonal and interannual variability of the Chl-a in the upwelling system, taking into account constant, seasonal or interannual values of Chl-a has almost no impact on the variability of SST in the upwelling system (fig. 4). The effect of chlorophyll on SST bias and variability should also be tested in coupled models (CT3/WP6 & WP7).

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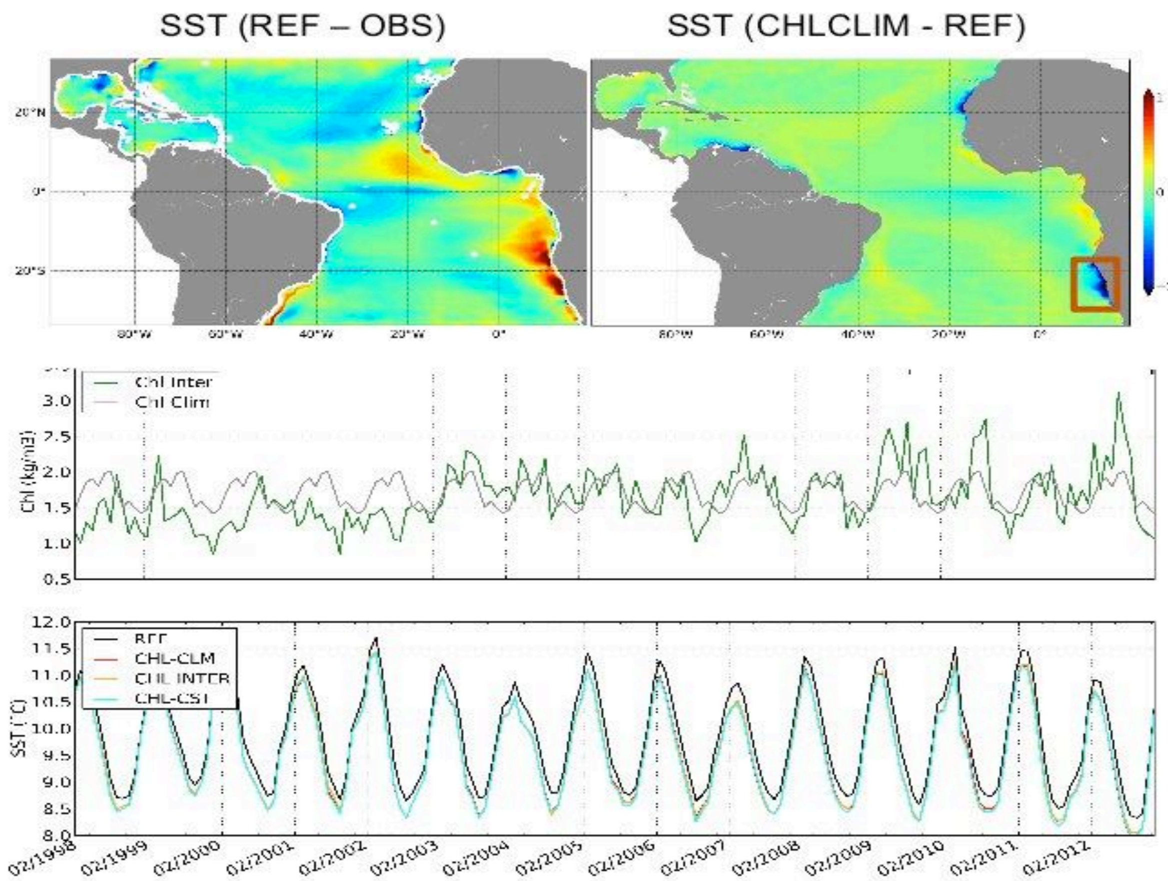

Figure 4. Mean SST difference between REF (no Chl-a) experiment and observations and between CHL-CLM (climatological Chl-a) and REF experiments (top). Interannual variations in the mean Chl-a concentration (middle) and SST (bottom) in the Benguela system for the different experiments : REF (no Chl-a.), CHL-CLM (climatological Chl-a), CHL-INTER (interannual Chl-a), CHL-CST (constant Chl-a).

3- Equatorial upwelling

The Atlantic cold tongue (ACT) is a seasonal cooling that appears from spring to summer around the equator in the Gulf of Guinea, and has a strong influence on the West-African monsoon. Large interannual variability in the characteristics of the ACT has been previously observed (Marin et al., 2009). A NEMO 1° interannual simulation with CORE-II forcing (Danabasoglu et al., 2014) has been used to explore the mechanisms leading to the cold tongue formation during cold and warm ACT events (Planton, 2015). Cold and warm ACT events are classified statistically from several datasets following a criteria previously defined (Richter et al., 2013) and slightly adapted. This classification allows to analyze composites of extreme events. In particular, composites of the mixed layer heat budget have been computed online in the ocean model, to identify the oceanic processes responsible for interannual variability of the ACT. Consistently with earlier studies (Jouanno et al., 2011), the results show that the turbulent mixing at the base of the mixed layer plays a dominant role in controlling the ACT formation. It is also the main driver of the ACT interannual variability (fig. 5). Cold (warm) events are associated with a strong increase (decrease) of the turbulent mixing from March to July. The vertical mixing is shown to be strongly controlled by the wind stress forcing through wind energy flux. Horizontal advection also plays an important role in July and August: during cold events, positive advection anomalies tend to damp the ACT, while during warm events, there is a negative advection anomaly that contributes to cool the region. Consequently, the warm events are characterized by a later than usual cooling.

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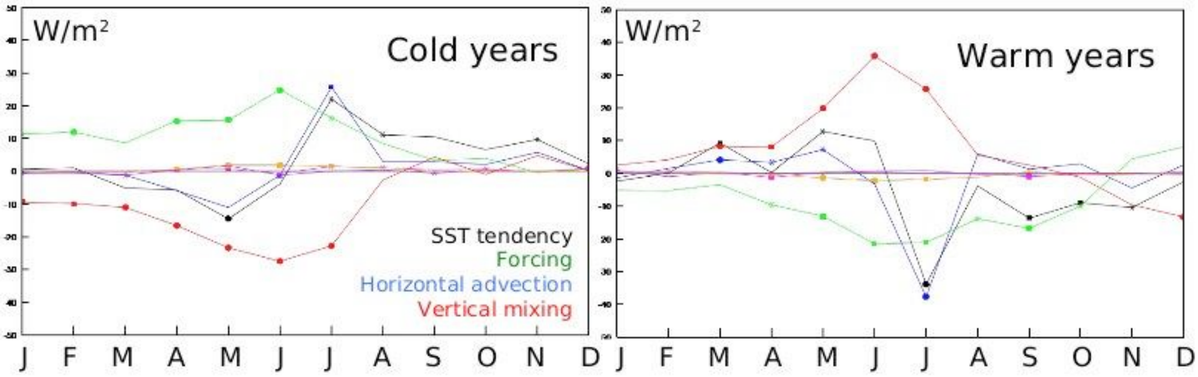

Figure 5. Interannual anomalies of main processes driving the SST tendency in the ACT region (15°W-5°W, 3°S-3°N) during cold (left) and warm years (right).

Contribution of high frequency wind bursts to seasonal and interannual variability of the ACT has been evaluated (Nkwinkwa Njouodo, 2014). For this purpose, simulations of the Tropical Atlantic based on a NEMO reference experiment (ATL025-75, see MS18) have been analyzed for the period 1980-2011. The model reproduces well the seasonal and interannual variability of the ACT, and it has been shown that early ACT are associated with early intensification of trade winds in the western part of the basin. Sensitivity tests to different wind fields and wind stress fields allowed to isolate the dynamical and thermodynamic effects of intraseasonal winds (under a cutoff period of 30 days). In these experiments, the interannual variability of the intraseasonal winds has been found to have very little impact on the interannual variability of the cold tongue intensity and strength (fig. 6). Nevertheless there is a shortcoming in analyzing interannual variability in a model forced with bulk formulae. Indeed, specifying air temperature and humidity exerts a very strong constraints on the air-sea fluxes, damping the interannual sensitivity to the wind bursts. As a follow on of this study, an atmospheric slab layer based on Deremble et al. (2012), with interactive air-sea fluxes, is currently set up in order to further test the sensitivity of the equatorial system to the high-frequency winds.

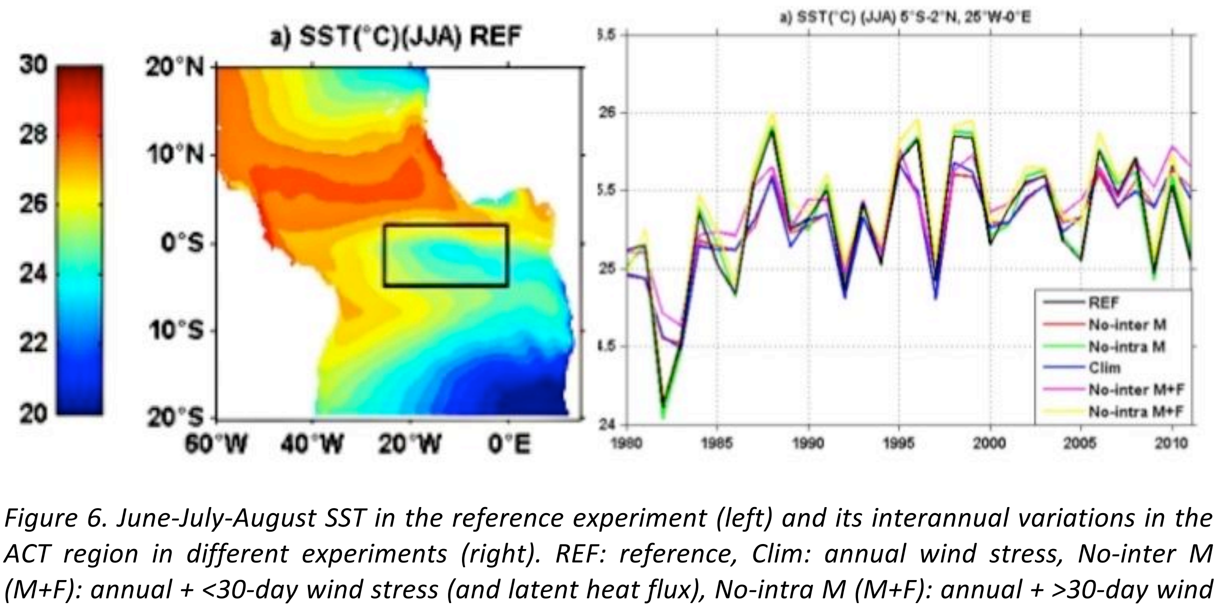

Figure 6. June-July-August SST in the reference experiment (left) and its interannual variations in the ACT region in different experiments (right). REF: reference, Clim: annual wind stress, No-inter M (M+F): annual + <30-day wind stress (and latent heat flux), No-intra M (M+F): annual + >30-day wind stress (and latent heat flux).

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4- Coastal upwelling

The coastal upwelling that takes place in summer off Ivory Coast and Ghana may influence the regional climate through SST and is important for local fisheries. This upwelling is found along a zonal coast and its causes are still not clearly identified: local forcing (wind effect, Guinea Current, cape effect) or remote forcing (Kelvin waves generated at the equator) may all contribute. A modeling approach is used for a better understanding of the processes that lead to this coastal upwelling (Djakouré et al., 2014). A realistic configuration with the ROMS model is built (NGOG5 and NGOG15, see MS18). It is based on two-way nesting over the Tropical Atlantic (1/5°) with a zoom in the Gulf of Guinea (1/15°), and forced by climatological QuikSCAT wind and COADS heat fluxes. Mesoscale cyclonic eddies generated downstream of Cape Palmas (8°W) and Cape Three points (2°W), which have been suggested to contribute to the coastal upwelling, are reproduced by the model and compare well with altimetric data. Mean flow interactions and barotropic instabilities associated with capes are their main generation processes. An idealized experiment where the coast is smoothed and the capes removed is conducted to analyze their effects on coastal upwelling. It reveals that eddies are not the process responsible for this coastal upwelling (fig. 7), while they are the cause of the westward and coastal Guinea Counter Current that is associated with a transfer of energy from eddy kinetic to the mean flow. In another experiment where non-linear terms are removed from the temperature equation, the upwelling disappears east of Cape Palmas (fig. 7). Therefore the upwelling in this region is probably driven by non-linear dynamics, in particular the detachment of the coastal Guinea Current. On the opposite, the upwelling observed east of Cape Three Points seems to be mostly wind driven. The model will also be used to investigate biogeochemical processes of the first trophic level in the Gulf of Guinea ecosystem.

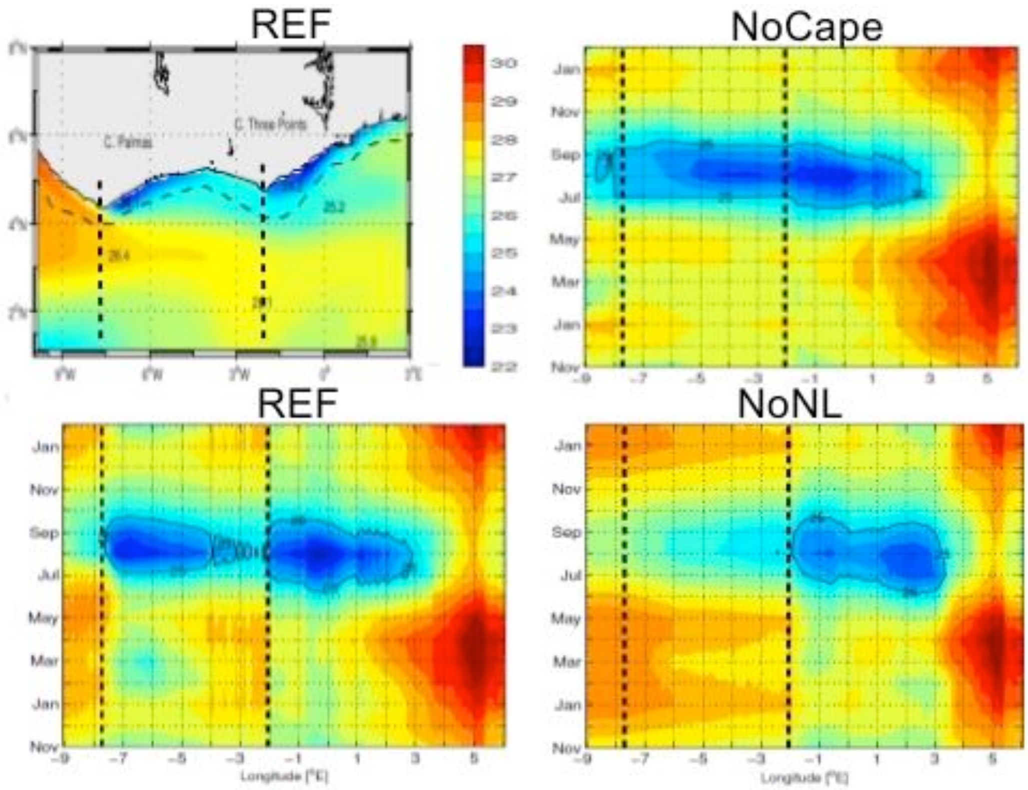

Figure 7. Summer SST off Cape Palmas and Cape Three Points (dashed lines) in the reference experiment (top left). Seasonal SST climatology along the coast in different experiments: REF (reference, bottom left), NoCape (with smoothed coastline, top right), NoNL (without non-linear terms, bottom right).

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The role of intra-seasonal oceanic Kevin waves and their impacts on SST along the West African coast upwelling regions have been investigated with NEMO simulations (Wade et al., in preparation) based on the ATL025-46 (see MS18) reference experiment. A DSF4-forced climatological simulation is first assessed to capture the mean ocean variability. In a second experiment, an idealised westerly wind stress burst is added in the western equatorial Atlantic to generate and characterise a downwelling Kelvin wave. Altimetry datasets, when properly filtered, can capture the propagation of equatorially and coastally trapped intra-seasonal Kelvin waves. They reveal an impressive continuous propagation of sea surface height (SSH) anomalies of about -2 to + 2cm from the equator up to the large upwelling systems of Senegal-Mauritania and Angola-Benguela, with speed estimates of 1.5 to 2.1 m/s. These characteristics are however subject to a certain level of suspicion, due to the near-coast breakdown of measurement quality, as well as tide-model uncertainties. The model runs proved to reproduce with good accuracy most of these characteristics, opening therefore the way to thorough analyses of these signals and their impacts on SST. The idealized experiments support the altimetry results, particularly the observed amplitude and velocity changes, and help to attribute their possible causes. SST impacts of up to 0.5°C/cm, suggested in observations by regression of SSH on SST along coastlines, are also supported by the model runs (fig. 8). The latest allow for a partition of advection and mixing processes at play, and uncover the competing or constructive mechanisms of upwelling and downwelling wave's effects on the thermal stratification and the SST field. Finally, it is shown that Kelvin waves appear to be most effectively amplified during periods when the mean temperature gradient above the thermocline along wave track is strong.

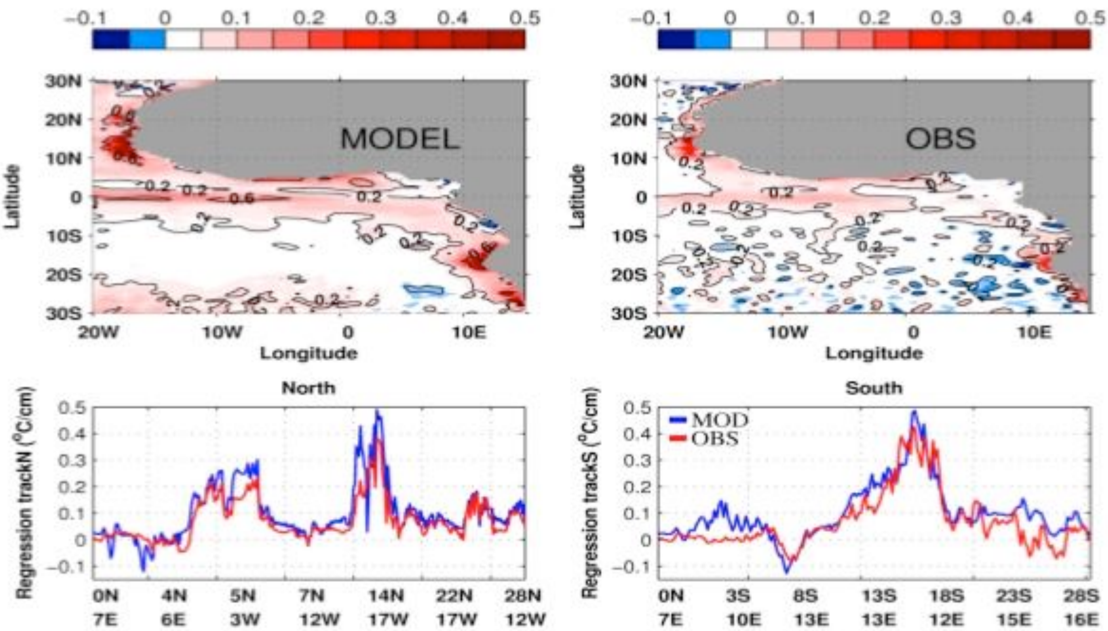

Figure 8. January-February-March regression maps of SST onto SSH over the period 2000-2007 for the Model (top left) and observation (top right). Same regression along the northern (bottom left) and southern (bottom right) wave tracks.

The climatological seasonal cycle of SST in the north-eastern tropical Atlantic (7–25°N, 26–12°W) has been studied using a regional mixed layer heat budget (Faye et al., 2015). Results are based on a NEMO 1/4° reference experiment (ATL025-46, see MS18). The region, which experiences one of the larger SST cycle in the tropics, forms the main part of the Guinea Gyre. It is characterized by a seasonally varying open ocean and coastal upwelling system, driven by the movements of the ITCZ. The model annual mean heat budget has two regimes schematically. South of roughly 12°N, advection of equatorial waters, mostly warm, and warming by vertical mixing, is balanced by net air-sea flux. In the rest of the domain, a cooling by vertical mixing, reinforced by advection at the coast, is balanced by the air-sea fluxes. Regarding the seasonal cycle, within a narrow continental band, in zonal mean, the SST early decrease (from September, depending on latitude, until December) is driven by upwelling dynamics off Senegal and Mauritania (15–20°N), and instead by air-sea fluxes north and south of these latitudes. Paradoxically, the later peaks of upwelling intensity (from March to July, with increasing latitude) essentially damp the warming phase, driven by air-sea fluxes. The open ocean cycle to the west, is entirely driven by the seasonal net air-sea fluxes. The oceanic processes significantly oppose it, but for winter north of 18°N. Vertical mixing in summer-autumn tends to cool (warm) the surface north (south) of the ITCZ, and advective cooling or warming by the geostrophic Guinea Gyre currents and the Ekman drift. This analysis supports previous findings on the importance of air-sea fluxes offshore. It mainly offers quantitative elements on the modulation of the SST seasonal cycle by the ocean circulation, and particularly by the upwelling dynamics. This analysis should be extended to the climatological seasonal cycle of SST variance, to assess the relative importance of ocean processes and atmospheric heat fluxes respectively. This question is also relevant to CT3 and should be performed in collaboration to WP6 and WP7, including coupled models.

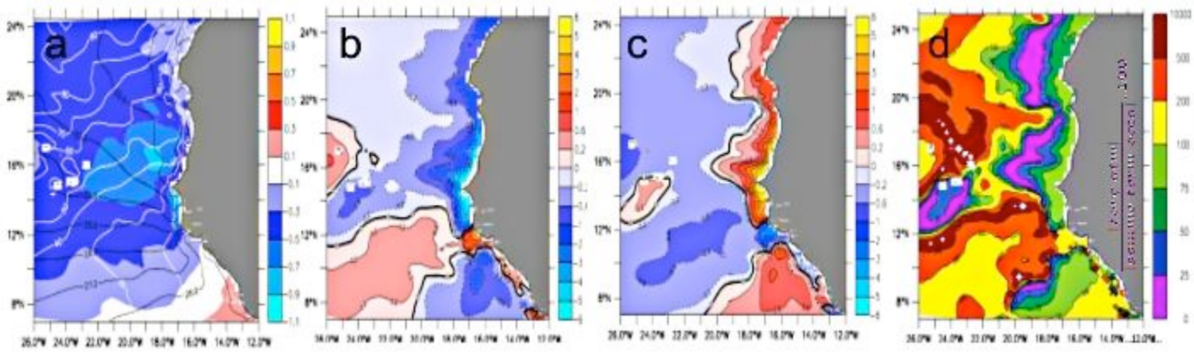

Figure 9. Contribution to the SST tendency (in °C/month) in the November-May cooling season (a) of oceanic processes (b) and air-sea processes (c). Ratio (in %) of air-sea over oceanic contributions (d).

5- Concluding remarks

Although not always detailed, the reference simulations used above have all been preliminarily validated, at least to surface observations. Higher-level observed products generated by WP3 and WP4 (interannual time series of Equatorial Under-Current, seasonal cycle of heat and freshwater budget terms from D3.1) will now be used to strengthen validation.

A warm SST bias is generally found in forced models, which is on average around 0.5°C in the equatorial upwelling, 1°C in the Senegal-Mauritania upwelling, more than 1°C in the Angola-Benguela upwelling. This bias shows some seasonality, however it is smaller than observed SST variability and does not question model results on the main processes that drive seasonal and interannual variability. Resolving the bias problem in forced models is the main focus of WP5 Objective 3 ("Conduct numerical experiments to test the sensitivity to model configurations, and to propose OGCM improvements to better simulate tropical Atlantic variability") that will be addressed later in D5.2. Already, sensitivity experiments to model forcing or resolution suggest technical ways to reduce the bias, and beyond that deepen our understanding on finer processes that affect SST (notably horizontal and vertical gradients within the upper ocean). The bias reduction problem is also a concern of CT3/WP6 for coupled models, and the future work on coupled or forced ocean models should be done in synergy with WP6.

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This report will feed D9.1 and D7.2 that will gather progress made though PREFACE CT2/CT3/CT4 on the mechanisms for seasonal to interannual variability in the Tropical Atlantic and how they are represented by state-of-the-art coupled models, in order to evaluate their impacts and to improve forecasts. Also, some of the model experiments produced in WP5 and described here will be useful for ecosystem and fisheries studies conducted in CT5.

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