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 full title: D5.2: “Final report on best practices and results of model/observations comparison, and proposed strategies to improve forced models”

Lead beneficiary for this deliverable: 6 (UPMC)

Due date of deliverable: 31.10.2016

Actual submission date: 02.11.2016

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)	

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

Author(s) of this deliverable: A. Lazar, M. Martín del Rey, M. Krebs, H. R. Pillar, S. Ndoye, J. Jouanno, X. Capet, B. Sow, M. Schmidt, M. Jochum

Deviation from planned efforts for this deliverable: none to our knowledge

REPORT

Executive Summary: PREFACE work package 5 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, to identify causes of failure and ways of improvement and to produce control experiments to help interpret observations. Main ocean properties targeted are heat and freshwater budgets, velocity or transport time series, signal propagation along the equatorial and coastal waveguide and horizontal and vertical gradients within the upper ocean. Its three specific objectives are:

a) To produce and validate an ensemble of reference forced simulations from various models and configurations, from regional set up to basin scale and global ones.

b) To 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.

c) To conduct numerical experiments testing the sensitivity to model configurations, to propose OGCM improvements to better simulate tropical Atlantic variability.

The present deliverable synthesises results of sensitivity studies of OGCM configurations aimed at reducing warm biases in the two eastern boundary upwelling systems (EBUS) of the tropical Atlantic: the Benguela and the Canary ones. Literature on the eastern tropical Atlantic bias tends to suggest that resolution increase in the ocean model is only a part of the solution, and its role remains to be quantified (*e.g.* Patricola et al. 2012). Modification of the air-sea forcing, radiative or dynamical, has

also long been considered in experiments for reducing the eastern tropical warm biases in forced OGCM (Brodeau et al. 2010). Last but not least, improvement of ocean processes via better parameterisations is possibly crucial, especially those affecting most strongly SSTs in the regions. Vertical mixing in the upper ocean, by high frequency wind-induced near inertial turbulence (Zhai et al. 2009, Jochum et al. 2013), as well as chlorophyll control of turbidity, especially in EBUS (Oschlies, 2004; Duteil et al. 2009), are known to be particularly important for upwelling system SST. They are most frequently misrepresented in climate ocean and coupled models Hence they are two natural candidates for helping to simulate more realistic hydrological structures in EBUS.

This report specifically presents outcomes of three types of model sensitivity experiments validated against observations: increasing horizontal and vertical resolution, improving air-sea forcing, and embedding improved parameterisations of turbidity effect on penetration of solar radiation and near inertial surface mixing.

The conclusion proposes recommendations on strategies to improve forced models, which should help in reducing the warm biases in coupled climate models. Main results from our work can be summarised according to the three categories of experiments:

1. **Improving spatial resolution:**

The conclusion we can draw from our results is that increasing resolution seem to produce relatively modest consequences, relative to its cost. Typical improvement of a few tens of a degrees can at least be expected compared to coarse ocean models. Our most striking result was obtained for one configuration of NEMO forced with realistic QuikSCAT winds, for which we could cancel the bias in a very narrow coastal band all along the Benguela EBUS meridional extension, by using a 1/10° resolution. Increasing vertical resolution from 46 to 75 did not improve the realism. Surprisingly, increasing further the horizontal resolution up to the resolution of the local Rossby Radius did not improve significantly the realism of the Benguela EBUS SST.

2. **Increasing the realism of air-sea forcings:**

Substantial reduction of the SST bias in the EBUS can be achieved by using realistic wind fields. Coastal winds and wind stress curl need particular attention. Hence, a key to the improvement of the model performance is the improvement of the representation of the atmospheric circulation. However, changes in the air-sea fluxes cannot generally eliminate the warm bias, except in some cases like in the Benguela EBUS along a narrow coastal band. Therefore we underline the importance of other causes, still to be explored. For example it is very likely that part of the warm biases is remotely forced, through coastally trapped waves and currents, by equatorward coastal regions and the equator itself.

3. **Improving representation of specific misrepresented ocean processes**

We tested the impact of including two parameterised processes, that are frequently misrepresented in forced basin scale OGCM and moreover in coupled general circulation model (CGCM): (i) near inertial (NI) frequency upper ocean mixing forced by high frequency wind events, and (ii) differential upper ocean absorption of solar radiations in relation to the turbidity caused by realistic three dimensional distribution of chlorophyll.

(i) The addition of NI mixing processes was tested only in a single PREFACE coupled model (NorESM), but produced results that we consider important to consider for forced OGCM as well as all coupled models. The additional mixing provided to the mixed layer caused its general deepening, and a non-uniform mean cooling of sea surface temperature (SST) that is not limited to warm tropical bias regions. However the cooling in eastern tropical Atlantic upwellings specifically is particularly intense and compensates to a large extent the model warm bias there.

Despite an expected quantitative limitation in the confidence level of the amplitude of the modifications, due to a lack of knowledge of NI mixing at global scale, we think that this process should be better represented in ocean models. The maximum intensity of its cooling effect in the eastern tropical Atlantic upwellings, advocates for developing a strategy of optimisation of high frequency upper ocean mixing in OGCM and CGCM. The mixed layer scheme (a bulk one in NorESM) is hence important to consider, but it is as important to have high frequency wind forcing (a few hours frequency) to properly represent the occurrence of NI processes.

(ii) The addition of the effect of chlorophyll on absorption of shortwave radiations strikingly modifies specifically tropical eastern boundary upwellings SST, as expected from high primary production level there. It tend to cool by a few tens of degrees (up to 1°C locally) the Canary and Benguela upwelling SSTs, more specifically their poleward parts, corresponding to the well-developed upwelling poleward of the Angola-Benguela and Senegal-Mauritania Fronts. We note however that it also increases a subsurface cold bias below the mixed layer there in the Benguela system. These results point out to the importance that should be granted to a correct representation of the vertical penetration of the radiative forcing in the ocean, and its potential for improving realism of SSTs in the eastern Atlantic basin.

General recommendations:

Based on our perception of the functioning of two Atlantic EBUS, we tend to believe that the following practices should help significantly to obtain more realistic simulations of ocean processes, and in particular reduce SST biases:

- To force the OGCM with a wind stress product having a climatological seasonal mean distribution as close as possible as that of scatterometer derived winds.
- To validate the shortwave radiative forcing against in-situ observations.
- To increase up to about 1/10° the OGCM horizontal resolution, if possible over the first 1000km or 500km offshore of the EBUS, and along the equatorial and coastally trapped waves guide (this latter recommendation, based on our general knowledge of EBUS remote forcing, was not tested though). The improvement observed when resolutions is increased from 1 or 1/2 ° to 1/12° or 1/10° in our models is at least 0.1 to 0.2°C. Within the large open ocean area, starting about 500 km off the EBUS coasts and extending to about 1000 km to the west, it represents 50-100% of the typical 0.5°C large-scale moderate bias observed there. Within the 500km band closer to the coast however, where the bias is much larger, our results are quite contrasted and we were not able to exhibit a strong coherency in the level of improvement. It may reach only 5-10% for NEMO in global

configuration, but for another configuration (the regional NEMO nested configuration for the Benguela EBUS), it increases towards the coast up to 1°C and 50% of the bias. Strikingly, and only for this model, the bias is even entirely corrected in a narrow coastal band of a few grid-points width.

- To include the effect of primary production on turbidity of the waters, via a simple and costless addition of realistic chlorophyll distribution in the equation of penetrating solar radiation.
- To consider the importance of transmitting high frequency wind energy into the ocean.

1. Improving spatial resolution

Low resolution forced OGCM suffer from large scale warm biases in the Senegal-Mauritania EBUS and in the Benguela EBUS, reaching in annual mean up a few degrees next to the coast, depending especially a lot on the chosen air-sea forcings. Increasing spatial resolution is of course generally welcome, since it allows for the model to better represent processes occurring at scales close to the grid cell size. However, for a given air-sea forcing set or a given atmosphere model, it is most necessary for the climate community to quantify how much more realism, in the SST distribution or the mixed layer depth, is permitted by a costly increase in spatial resolution. Understanding this bias robustness in function of resolution increase is crucial because it will affect downscaling approaches where a regional refinement on eastern boundary systems is implemented in GCMs [Small et al, 2015]. In this part of the report, we provide a perspective on this sensitivity of forced OGCMs, using 3 different models (NEMO, ROMS and MOM) for four different configurations.

For the sake of convenience, we can describe these EBUS warm biases as zonally constituted of 1) a large scale and weak (<1°C) component extending west over about approximately 1000km, and a more intense signal (>1°C) next to the coast and ranging over about 500km. It can be sometimes also convenient to consider a third part, much narrower, the in-shore band of a few coastal grid points.

(i) NEMO in the MERCATOR configuration forced by ERA-INTERIM derived datasets.

The bias in the seasonal cycle and variability of the simulated SST in the tropical Atlantic basin has been analysed using two global MERCATOR oceanic simulations (carried out by R. Bourdallé-Badie) with the version 3.5 of the global ocean NEMO model (Madec et al. 2008). Two different horizontal resolutions were used for configuration ORCA1 (1°x1°) and ORCA12 (1/12°x1/12°). The atmospheric forcings is common to the two configurations and derived from ERA-INTERIM data set (Dee et al. 2011), and 75 vertical levels were used. The period of study goes from 2000 to 2008 and the SST observations we used are those of Reynolds et al. (2007). The two simulations present the well-known coastal warm bias within the two Atlantic EBUS (Fig. 1.1). Positive SST bias is maximal in the ORCA1 1° resolution model (left column). It peaks in the Senegal-Mauritania (SM) region [see SM area 10°N-20°N,25°W-15°W] where it reaches locally up to +2°C, and in the Benguela system [see "AB" area 5°W-15°W,10°S-30°S], with values up to one degree larger. Increasing the horizontal resolution by a factor 12x12 reduces slightly the amplitude and zonal extension of the bias, but some of its maximum local values (seen near topographic changes) are unchanged or even slightly enhanced (Fig. 1.1, right column).

Plotting the difference over the two EBUS better shows the ubiquitous decrease over the large zonal band of about 1000km, and up to about 500km from the coast, by about 0.1-0.3°C, which represents a significant improvement of about 50% to 100% (Fig. 1.2, left column). Nearshore within about 500km from the coast, the changes are more contrasted with some cooling and warming at 1/12° resolution, relative to 1° resolution. Spatial averages within this 500km in-shore zonal band quantify the overall spatial mean effect in function of time there (Fig. 1.2, right column). The time-mean improvement is in both EBUS of about 0.1°C, representing an improvement of about 5% to 10% only, and with large variations in function of seasons. It appears also that the year to year variability for a given month, computed as a standard deviation, increases with horizontal resolution, as expected from the improvement of the resolution of eddy activity.

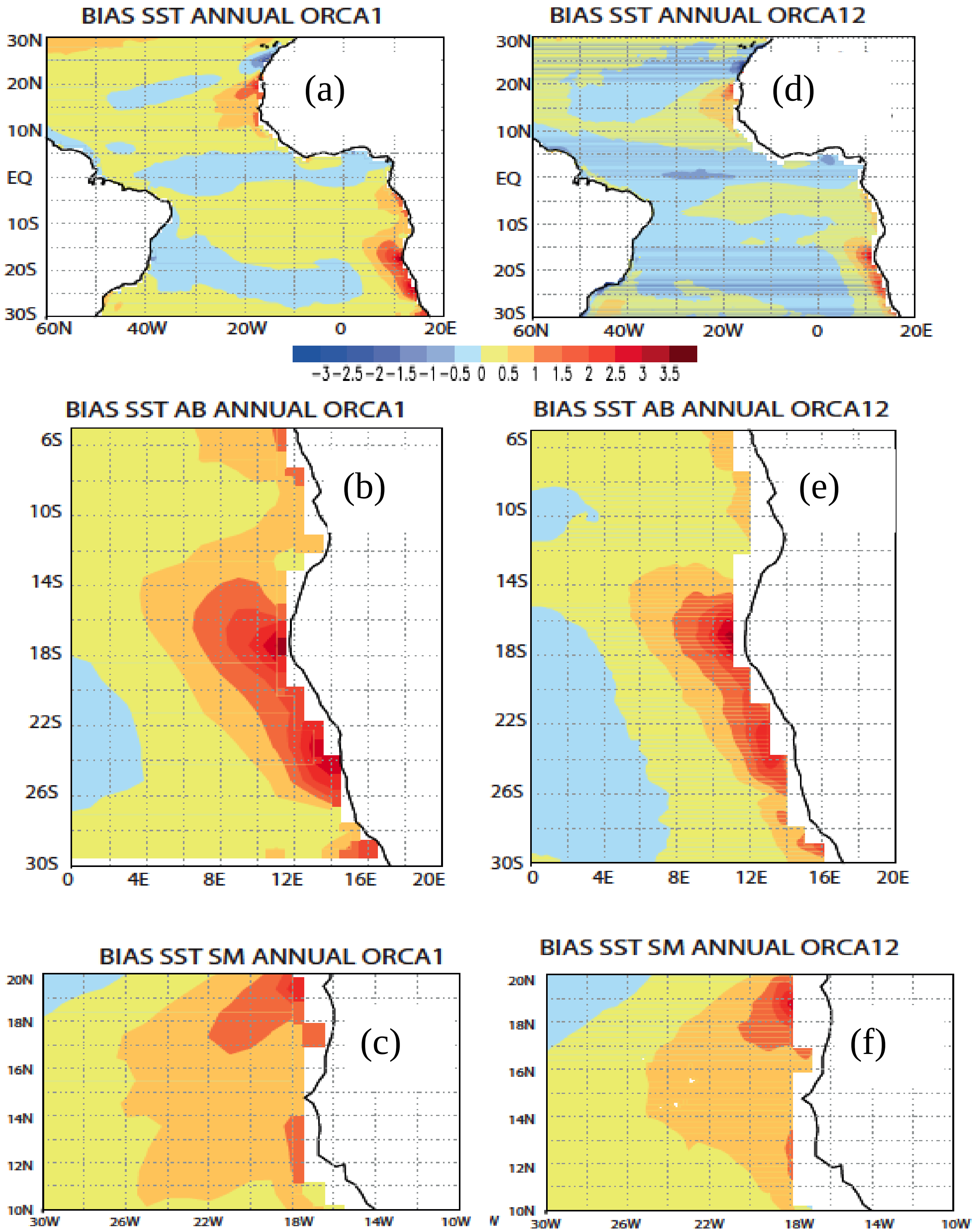

Figure 1.1: Time-mean SST bias (°C) with NEMO-MERCATOR global OGCM in function of two horizontal resolution of 1° (left column, a, b ,c), and 1/12° (right column, d, e, f). The period goes from 2000 to 2008.

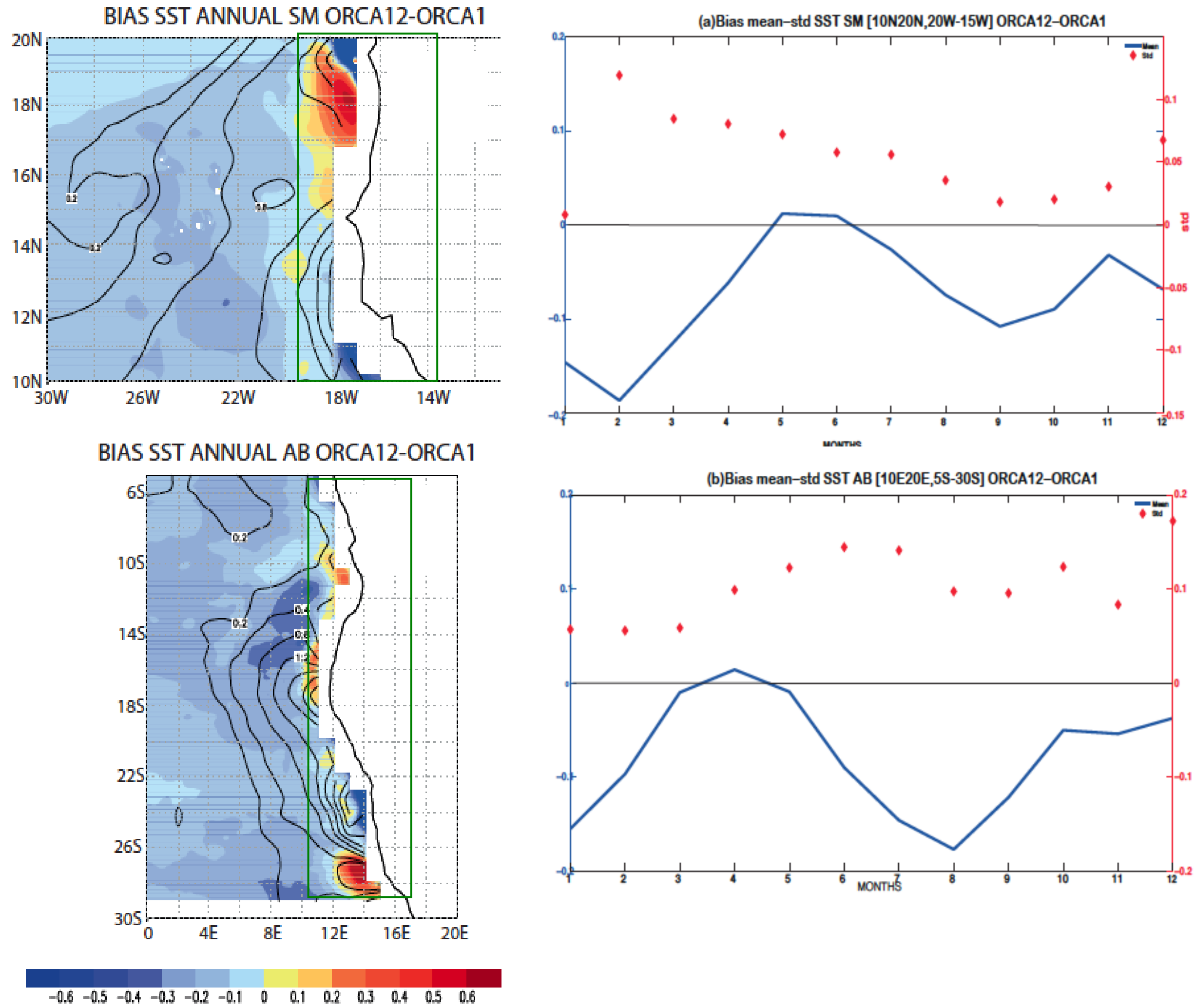

Figure 1.2: SST differences between ORCA12 and ORCA1 for Senegal-Mauritania (a, b) and Benguela (c, d) EBUS regions. Left panels: Time mean difference. Black contours represents the SST bias at 1° resolution (isoline every 0.2°C). Right panels: Monthly climatological mean of the difference (blue line). Red dots represent the difference in the interannual standard-deviation by month.

(ii) NEMO, in the INALT01 South-Atlantic configuration, forced by CORE2b and several satellite winds.

Our second configuration of NEMO is based on a global configuration with different embedded nests at 1/10° and 1/30° resolutions. The model is based on NEMO 3.1.1 (Madec et al., 2008), with the bottom cell allowed to be partially filled. All configurations share ORCA05, a global model ocean circulation model (Biastoch et al., 2008) at 1/2° nominal resolution and a tripolar grid. Within ORCA05, regional nests enhance the resolution: INALT01 (Durgadoo et al., 2013) has a 1/10° nest around Africa and cover the whole Southern Atlantic and part of the Indian Ocean. To resolve the coastal upwelling, we added a secondary nest with 1/30° horizontal resolution, which only covers the Benguela region. We used CORE2b (Large et al., 2009) for surface forcings except for the wind. For the wind we tested three products: 1) CORE; 2) CCMP (Cross-Calibrated Multi-Platform Ocean Surface Wind Vector v1, Atlas et al., 2011); 3) “Blended” wind forcing: QuikSCAT mean plus CCMP variability.

The relatively coarse 1/2° ORCA05 configuration has a relatively high coastal SST bias (~2,5°C), similar to the MERCATOR ORCA1 configuration, since both cannot resolve correctly the coastal upwelling processes, in particular those with a length scale (Rossby Radius) of only about 10 km south of this EBUS. INALT01 with 1/10° displays a slightly lower bias at large scale, but a much significantly reduced bias over the narrow band of coastal grid point (Fig. 1.3 a, b). Figure 1.4 shows that the large scale improvement ranges from 0.25 to 0.5°C far from the coast, in a band approximately within 1000km to 500km from the coast, and represents about 50 to 100% of the typical 0.5°C SST bias there. Closer to the coast, the correction increases up to 0.75 to 1°C, still forming a 50% improvement. It reaches more than 1°C over the last grid points next to the coast, where the bias is then basically reduced to zero. This very narrow near-shore striking improvement contrasts with the modest result of 0.1°C with MERCATOR NEMO configuration. We think that the deceptive performance of MERCATOR NEMO in this region could be due to the lowest realism of the ERA-I wind field used to drive the model. It is to be compared to the more realistic blended product used for INALT01, whose Ekman pumping allows for a very good resolution of the circulation, when ocean model resolution is sufficient. This conclusion is supported also by Figure 2.2, revealing a much stronger poleward transport of warm tropical water if a model is driven with ERA-I or CCMP winds Therefore, comparing MERCATOR ORCA12 and INALT01 we tend to conclude that spectacular improvements are possible when ocean resolution reaches the scale of the Rossby Radius, at least in a narrow coastal band of the EBUS, but only for a very realistic wind field.

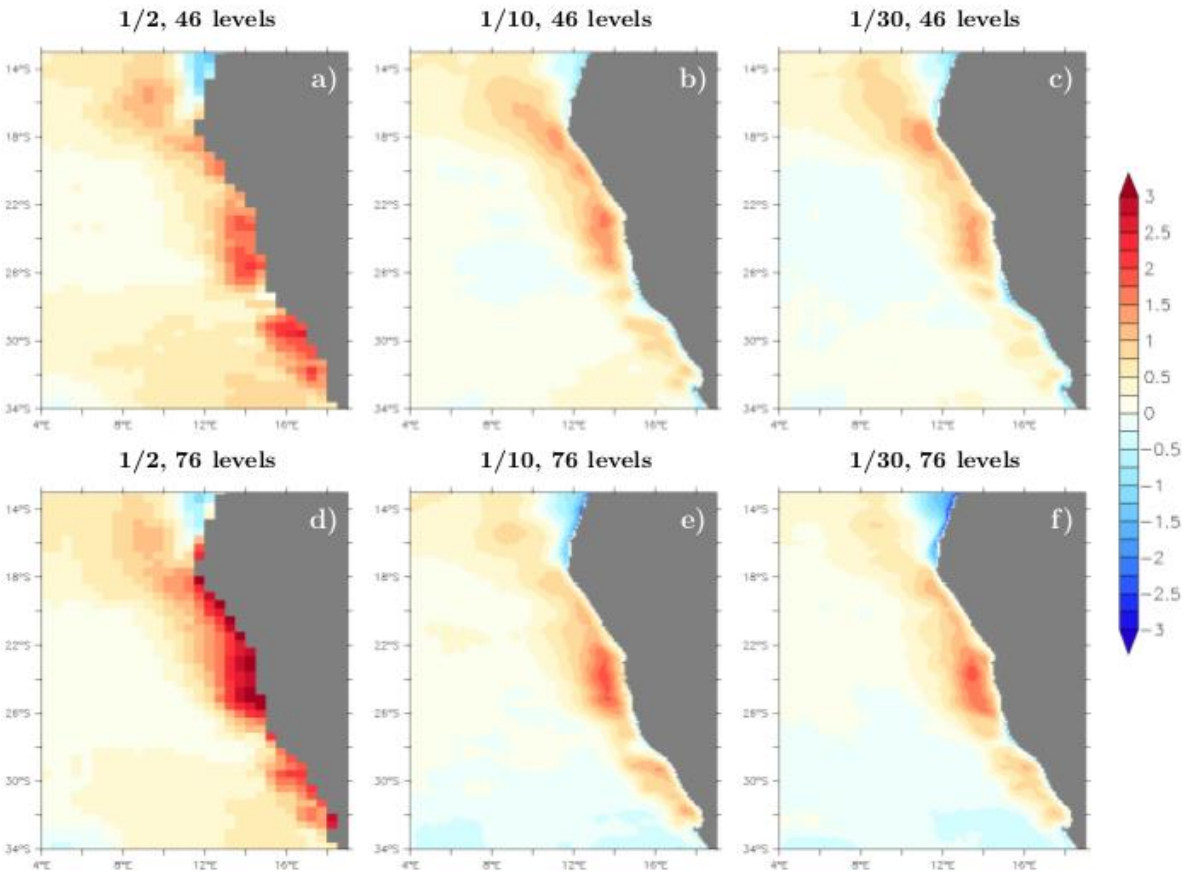

Figure 1.3: Mean SST bias [°C] for different horizontal resolutions (left: ORCA05; middle: INALT01; right: REBUS30 (right) and different number of vertical levels (top: 46 levels, bottom: 76 levels), averaged 2003-2009, all with blended wind forcing

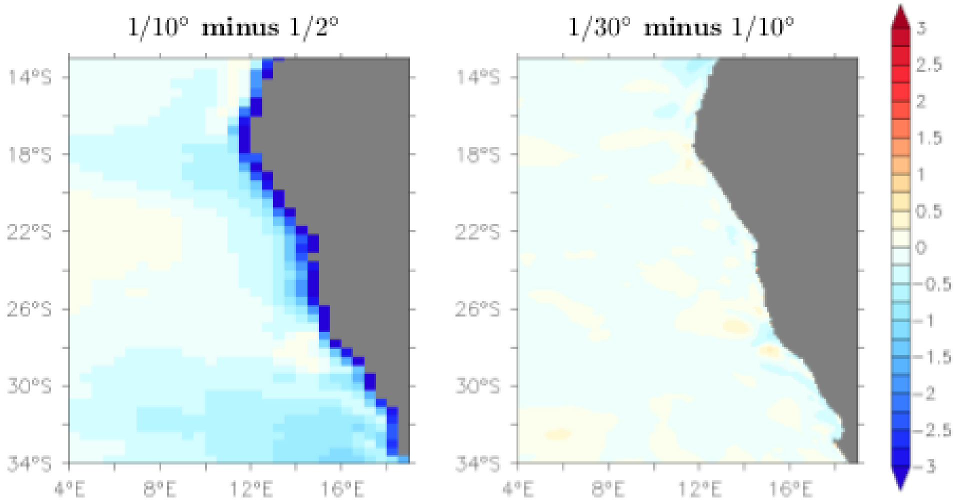

Figure 1.4: Mean SST difference [°C] between INALT01 and ORCA05 (left) and between REBUS30 and INALT01 (right), 76 levels, averaged 2003-2009, blended wind forcing.

In order to assess the possible need for increasing even further horizontal and vertical resolution, we performed additional experiments. It appears that increasing horizontal resolution by a factor 3x3 with the second 1/30° nest of REBUS30 does not have a significant effect on the bias (Fig. 1.3c). Thus here, finer than 1/10° ocean scales are not important for the SST distribution. Surprisingly, increasing the vertical resolution (76 instead of 46 levels, number of levels in the upper 200m more than doubled) also does not decrease the coastal SST bias (Fig. 1.3d, e, f). On the contrary, it even increases the offshore SST bias slightly. Note that this error increase with higher vertical resolution is obtained despite a reduction in the subsurface temperature bias. These opposing behaviours of the SST and the subsurface temperature suggest that a bias in the thermocline is not the main reason for the relatively high SST bias in ORCA05, as proposed by Xu et al. (2013). More details can be found in Krebs et al. (submitted).

(iii) ROMS West-Africa and Senegal upwelling very high resolution configuration, forced by QuickSCAT winds.

We also used a regional model, the ROMS model, configured at very high resolution Δx ~ 2km over the Senegalese coastal ocean [Ndoye et al, 2016]. A baseline simulation using basic climatological forcings for air-sea fluxes and in particular QuikSCAT winds, did exhibit the typical coastal bias (Fig. 1.5) observed in lower resolution models and presented above, and in agreement with the little improvement obtained with our regional NEMO for the Benguela when going from 1/10° to 1/30° of resolution.

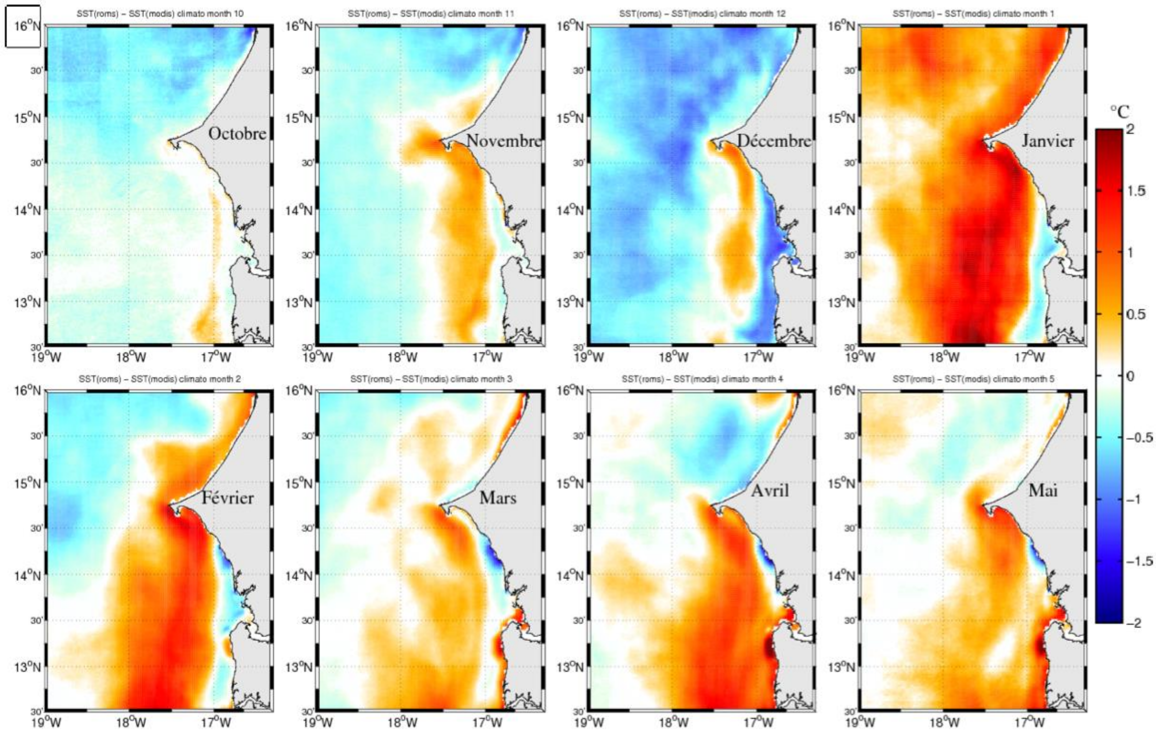

Figure 1.5: Model-satellite data SST difference over the Senegal upwelling region. Biases in excess of 1°C can be found during most of the period of sustained upwelling winds (Dec. May). These biases are robust vis-à-vis all tested numerical and forcing realism improvements. They are spatially confined in our forced-ocean simulations due to heat-flux restoring but represent an ocean-dynamics bias that will need further investigation.

(iv) MOM South-Eastern Atlantic and Benguela upwelling very high-resolution configuration, forced by several wind products.

Our fourth model configuration is MOM with regional nests increasing the resolution in the Benguela EBUS up to 8km close to the coast. The model is configured as "forced" model, feedback from the ocean to the atmosphere is not considered. The non-local kpp mixed layer dynamics is applied. The model, as the ROMS Senegal regional configuration, resolves the first baroclinic Rossby radius and is able to produce the mesoscale current pattern typical for wind driven upwelling systems. The model is driven with atmosphere boundary layer data, namely 10m winds, 2m air temperature and specific humidity, precipitation, incoming solar and infrared radiation. Wind stress, sensible and latent heat flux are calculated from bulk formulas as for the other models of this study.

As shown by Figure 1.6, the warm bias is present with comparable amplitude as for the other high resolution models of this study.

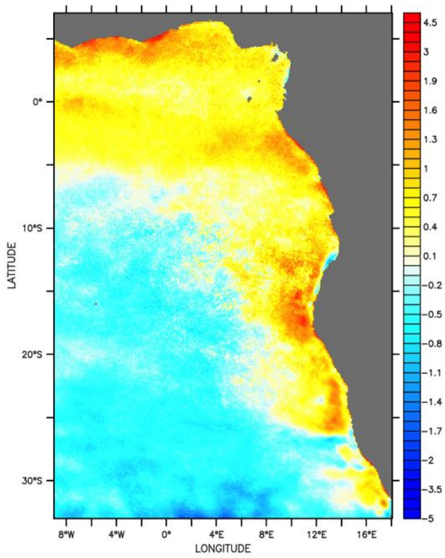

Figure 1.6: MOM Benguela model time-mean SST bias, relative to MODIS SST.

Conclusion on improving spatial resolution:

Our results suggest that an improvement of the realism of the SST can be obtained by increasing up to about 1/10° the OGCM horizontal resolution, if possible over the first 1000km or 500km offshore of the EBUS, and, better, along the equatorial and coastally trapped waves guide (this latter recommendation, based on our general knowledge of EBUS remote forcing, was not tested though). The improvement observed when resolutions is increased from 1 or 1/2 ° to 1/12° or 1/10° in our models is at least 0.1 to 0.2°C. Within the large open ocean area, starting about 500 km off the EBUS coasts and extending to about 1000 km to the west, it represents 50-100% of the typical 0.5°C large-scale moderate bias observed there.

Within the 500km band closer to the coast however, where the bias is much larger, our results are quite contrasted and we were not able to exhibit a strong coherency in the level of improvement. It may reach only 5-10% for NEMO in global configuration, but for another configuration (the regional NEMO nested configuration for the Benguela EBUS), it increases towards the coast up to 1°C and 50% of the bias. Strikingly, and only for this model out of the four, the bias is even entirely corrected in a narrow coastal band of a few grid-points width.

Increasing vertical resolution from 46 to 75 was tested for the Benguela regional NEMO model and did not improve the SST realism. Surprisingly, for this same model, increasing further the horizontal resolution up to 1/30° the resolution of the local Rossby Radius did not improve significantly the realism of the Benguela EBUS SST.

2. Improving air-sea fluxes

First, the wind is the crucial factor for the upwelling structure and its SST, so we tested multiple wind products and compared the SST biases. The alongshore coastal wind, which drives the coastal upwelling, is often compromised in many wind products. CORE has too strong coastal winds, because of extrapolating ocean winds to the coast. CCMP uses ECMWF operational analysis, which mixes the weak land wind into the coastal wind (Fig. 2.1a, b, c). Hence, for all our three regional models, we observe that using the realistic scatterometer derived winds gives the lowest SST bias against observed SST, as illustrated with NEMO Benguela (Fig. 2.1d, e, f).

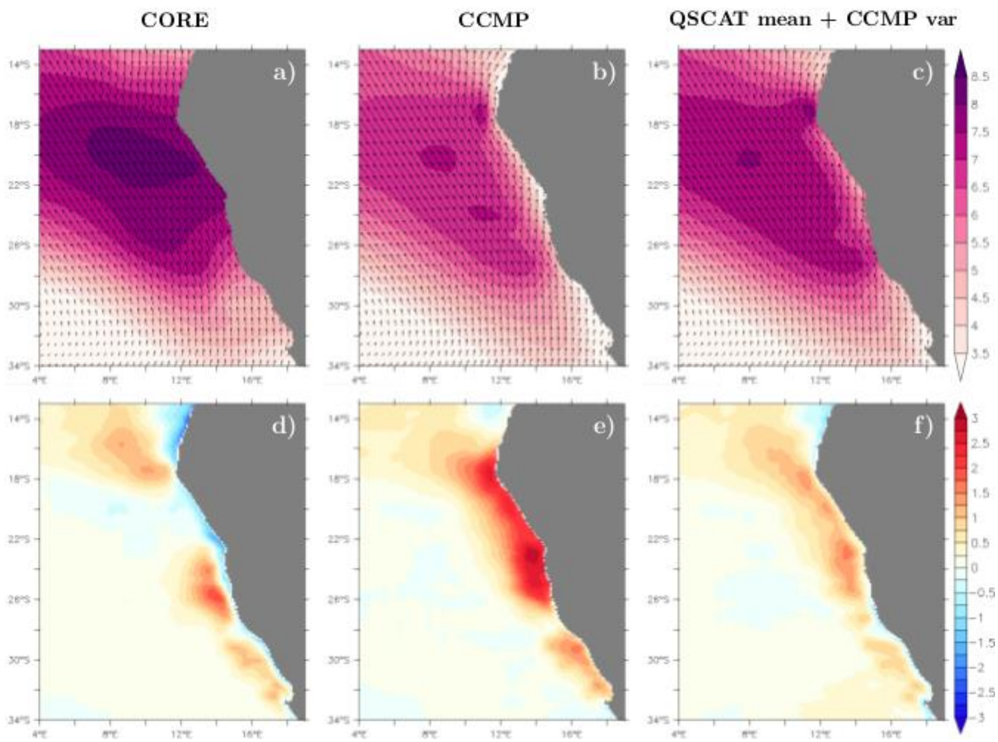

Figure 2.1: Mean wind [m/s] (top) and SST bias [°C] compared to MUR satellite SST, averaged 2003-2009 (bottom) for CORE (left), and CCMP (middle) and blended winds (QuikSCAT mean plus CCMP variability in INALT01) (right).

Compared with QuikScat winds, several wind products, like NCEP and ECMWF, underestimate the coastal wind speed. We observe in the MOM Benguela model that the effects of underestimated meridional coastal winds are, first, a reduced coastal upwelling and a weaker equatorward transport of colder upwelled water with the coastal jet. Results from NCEP and ECMWF reanalysis show only weak coastal jets. Second, this underestimation causes a too strong westward intensification of the meridional wind, which implies a stronger than observed negative wind stress curl. A negative wind stress curl drives upwelling in the open ocean and brings the poleward undercurrent near to the surface. This implies strong poleward subsurface coastal currents, as observed in the MOM Benguela model (Fig. 2.2). In the Benguela EBUS, a water mass analysis in comparison to field data reveals that warm and saline near surface water of tropical origin (north of 16°S) is penetrating far southward.

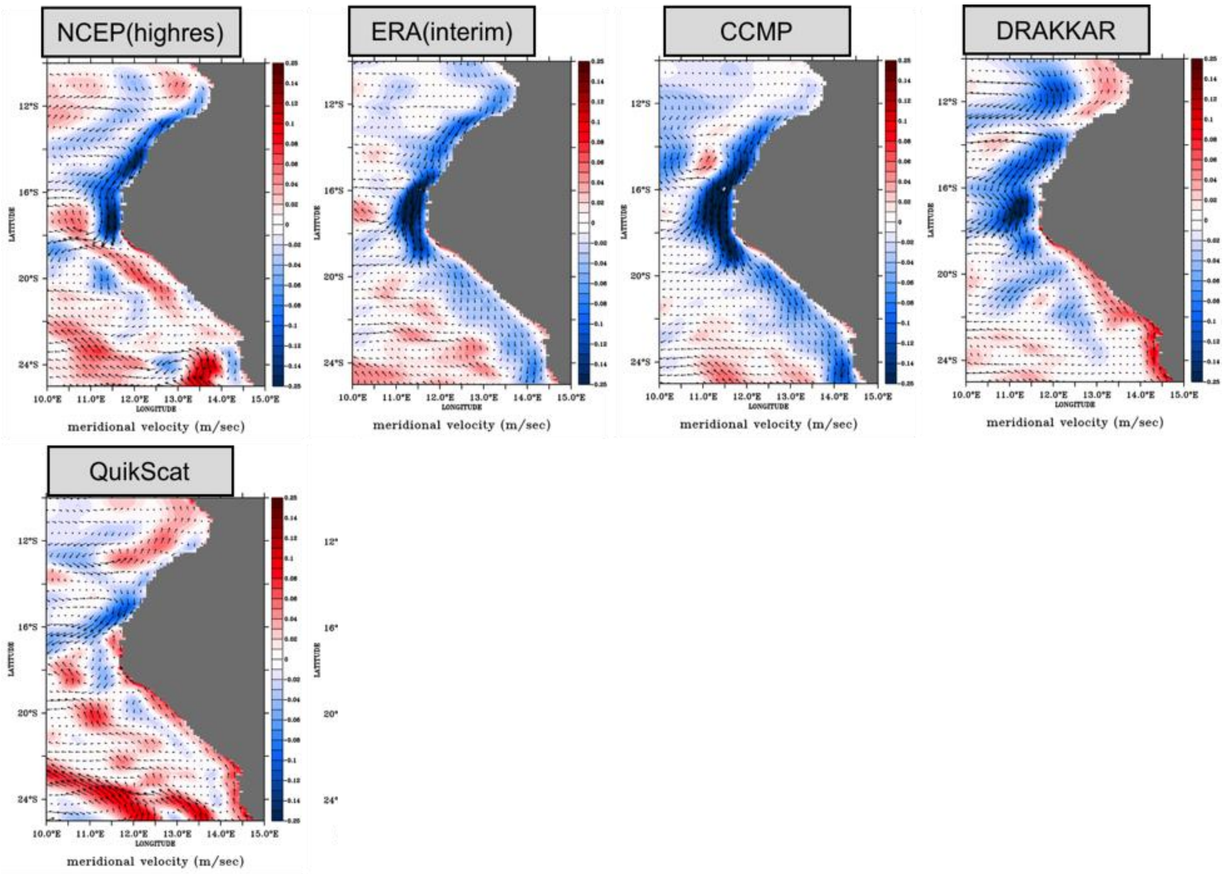

Figure 2.2: Average meridional flow in the first 50m depth in MOM-Benguela climatology.

A second air-sea flux is suspected to be able to cause part of the warm bias; this is the solar radiation, which can be overestimated. This hypothesis was tested with field data to evaluate the radiation products in reanalysis data sets, and we compared underway measurements of research vessels with reanalysis radiation data. Although the results are very scattered, we found indication for overestimation of solar and long wave radiation in ECMWF by 80 to 120 Wm^{-2} (Fig. 2.3). We tested in the MOM Benguela EBUS that reducing radiation by about 50 Wm^{-2} reduces the large scale SST bias by about 2° K.

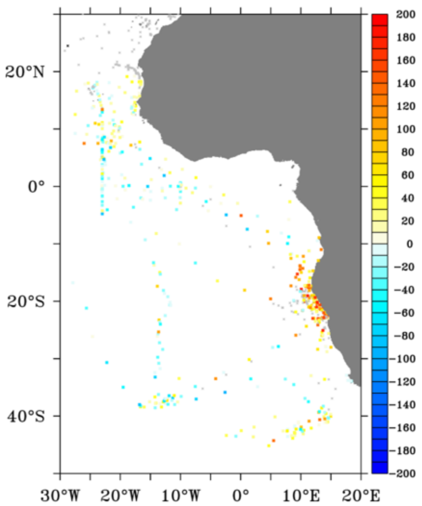

Figure 2.3: Difference between solar radiation in the ECMWF reanalysis data set to ships weather station of RV “Meteor” and “Maria S. Merian”. Especially within the Benguela upwelling system, reanalysis data are systematically larger than measured fluxes. Pyranometer data from RV ” Discovery” in the BUS (Sep. Oct. 2010) reveal a similar positive bias of the ECMWF radiation data of 100 +/- 60 Wm-2 .

Sensitivity tests to the atmospheric forcing realism have also been performed over the Senegalese EBUS for the ROMS configuration. Accounting for synoptic wind fluctuations (using best estimates of daily winds) and fine-scale heat flux forcings only provided marginal improvement in terms of model SST realism, and so did the inclusion of tidal forcings. Tests to quantify the importance of synoptic variability in the oceanic forcings are still underway and again, suggest relatively limited improvements in situations where boundaries are located many hundreds of kilometres from the upwelling study region. These results and recent publications for the California Current System point to an incorrect representation of remote upwellings or other dynamical regimes (taking place hundreds to thousands kilometres away, perhaps also involving equatorial dynamics/upwelling), through poleward propagation of coastal waves, perhaps as a consequence of bottom friction errors. Further numerical investigations are beyond the scope of the PREFACE project but will be incorporated as key recommendations for future research.

Conclusion on improving air-sea fluxes

Substantial reduction of the SST bias in the EBUS can be achieved by using realistic wind fields. Coastal winds and wind stress curl need particular attention. Hence, a key to the improvement of the model performance is the improvement of the representation of the atmospheric circulation. However, changes in the air-sea fluxes cannot eliminate the warm bias, except in some cases like in the Benguela EBUS along a narrow coastal band. Therefore we underline the importance of possible remote forcing of the warm biases, through coastally trapped waves and currents emanating from equatorward locations.

3. Sensitivity to parameterisations of upper ocean processes

(i) Near Inertial mixing

Near-inertial (NI) mixing is unresolved in climate models due to coarse spatial and temporal resolution of atmosphere and missing boundary layer physics. Recent work has suggested this mixing may be important for the global coupled climate system, deepening the mixed layer, increasing oceanic heat uptake and redistributing the majority of this heat to the equatorial thermocline (Jochum et al. 2013). Motivated by this result, we develop a parameterisation for use in the Norwegian Earth System Model (NorESM Bentsen et al. 2013), a key model in PREFACE that employs a bulk representation of the oceanic mixed layer.

Development of the parameterisation for missing mixing by NI oscillations can be split into three steps. The first step is to generate a global surface NI current distribution and kinetic energy levels consistent with observational constraints. The second step is to enable a fraction of this energy to be spent on shear-driven entrainment at the mixed layer base. The remaining energy is assumed to escape the mixed layer and propagate vertically: the third step parameterises the contribution of surface generated NI waves to interior diapycnal mixing. Following Jochum et al. (2013) our focus is on parameterising upper ocean mixing by NI currents generated by local wind forcing. A serious deficiency of the current NorESM release is the diurnal atmosphere-ocean coupling frequency. The ocean component of NorESM receives wind forcing only once per day, which is equal to the inertial frequency at 30 degrees. Poleward of this latitude, wind-driven inertial activity is severely limited and grossly underestimates observational- based constraints (Fig. 3.1).

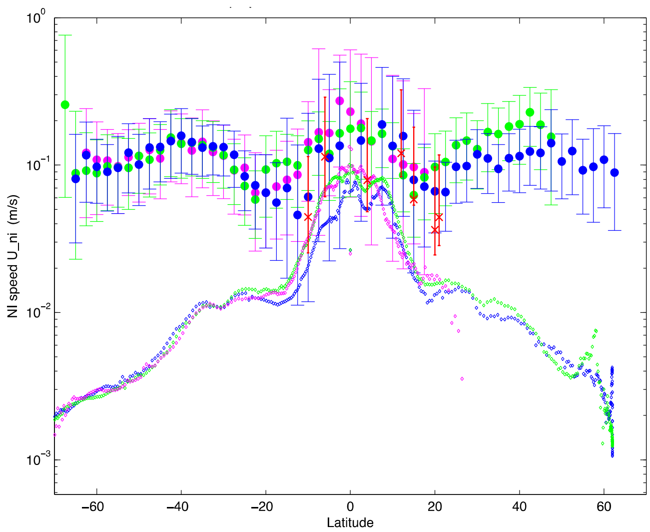

Figure 3.1: Comparison of zonally- averaged NI current speeds in (◇) the CONTROL configuration of NorESM with observational constraints from (o) near-surface drifters shown for the (blue) Atlantic, (green) Pacific and (magenta) Indian basins. Additional observational constraints from (x) PIRATA Atlantic moorings are also shown. The CONTROL version of NorESM is fully coupled and configured with a horizontal resolution of 2° in the atmosphere and 1° in the ocean. The CONTROL profile is averaged over 10 years.

Sub-diurnal air-sea wind forcing cannot be simply incorporated as it would rapidly destroy the seasonal pycnocline in NorESM's bulk ocean mixed layer. Since NorESM's coupler receives wind information every 30 minutes, we enable wind-forced generation of NI currents by incorporating a simple slab model (Pollard and Millard 1970) in the coupler, instead of simulating NI currents directly in NorESM's ocean component, retrieving a current distribution consistent with observational constraints from PIRATA moorings (Pillar et al. 2016) and near-surface drifters (Elipot et al. 2008). Informed by high resolution modelling studies (e.g. Zhai et al. 2009) we then assume 70% of the slab NI kinetic energy is available to contribute to the mixed layer TKE budget. The imposed slab model damping determines the rate at which this NI TKE source is available to drive entrainment. The damping is typically used as a tuning coefficient, but here is based on observational constraints from near-surface drifters (Park et al. 2009) to minimise parametric dependencies.

Inclusion of the parameterisation leads to long-term widespread mixed layer deepening of approximately 30% in the zonal mean at most latitudes. Weak mixed layer shoaling is found along the Equator and in the Nordic Seas due to perturbed air-sea buoyancy exchange. Large scale mixed layer deepening off the Equator leads to widespread SST cooling, exceeding 1°C in regions within the southern hemisphere eastern boundary upwelling regimes (Fig. 3.2, panel a), where large warm model biases exist in the mean state, and a few patches of isolated SST warming, most notable in the central and eastern equatorial Pacific. The latter enhances equatorial deep convective precipitation (Fig. 3.2, panel b), helping to offset the persistent double ITCZ bias in NorESM.

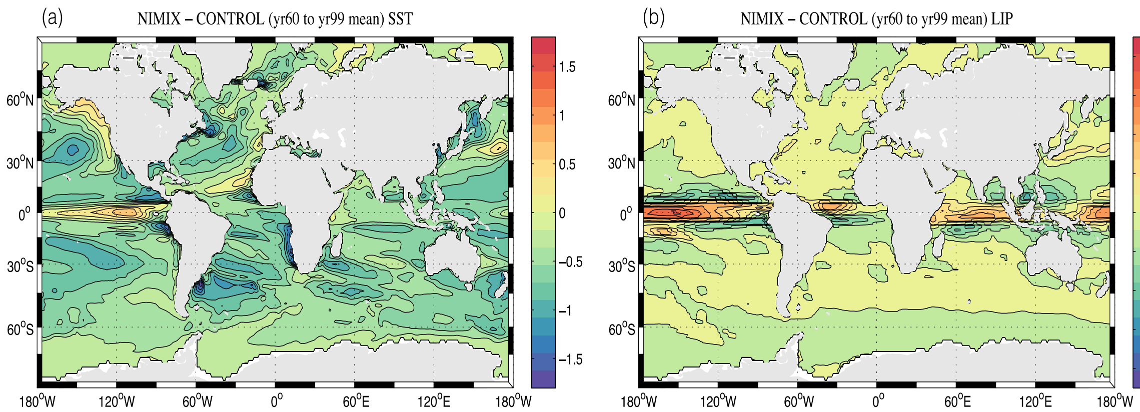

Figure 3.2:

(a) Impacts of near-inertial mixing on NorESM (a) SST (°C) and (b) precipitation (mm/day) computed as NIMIX-CONTROL averaged over model years 60-100. Experiment CONTROL is the fully coupled release configuration of NorESM. Experiment NIMIX is identical to CONTROL except for the inclusion of a parameterisation for upper ocean mixing by wind-driven near-inertial currents.

(ii) Absorption of solar radiations by realistic distribution of chlorophyll

The influence of the chlorophyll on the upper Tropical Atlantic Ocean has been investigated with long term (1998-2012) regional oceanic simulations with 1/4° horizontal resolution based on the NEMO3.6 model. The solar radiation penetration depends on the chlorophyll concentration, and simulations with time and spatially varying concentrations obtained from satellite ocean colour observations were compared with a simulation forced with constant chlorophyll concentration of 0.05 mg m^{-3}, representative of chlorophyll depleted waters. Results suggest that the vertical modulation of the penetration of the solar radiation is a key parameter of the tropical climate. Inclusion of the biological feedback contributes to reduce the strong warm bias observed along the Benguela and Senegal-Mauritania upwellings, and reported in most of the CMIP5 models (Fig. 3.3). Indeed the 1ºC warm bias in the Benguela upwelling in our reference simulation is reduced to 0-0.5ºC in the upwelling area from 20ºS to 27ºS (Hernandez et al., submitted). Thus, taking into account the effect of the chlorophyll improves the representation of the Benguela and Senegal-Mauritania upwelling SST. We note however that it also increases a subsurface cold bias below the mixed layer in the former. The surface temperature cold bias in the equatorial region from 10ºS to 10ºN is also moderately amplified when including the chlorophyll effect in our simulations. Ultimately, these results, combined with previous studies of this effect point out the importance that should be granted to a correct representation of the vertical penetration of the radiative forcing in the ocean.

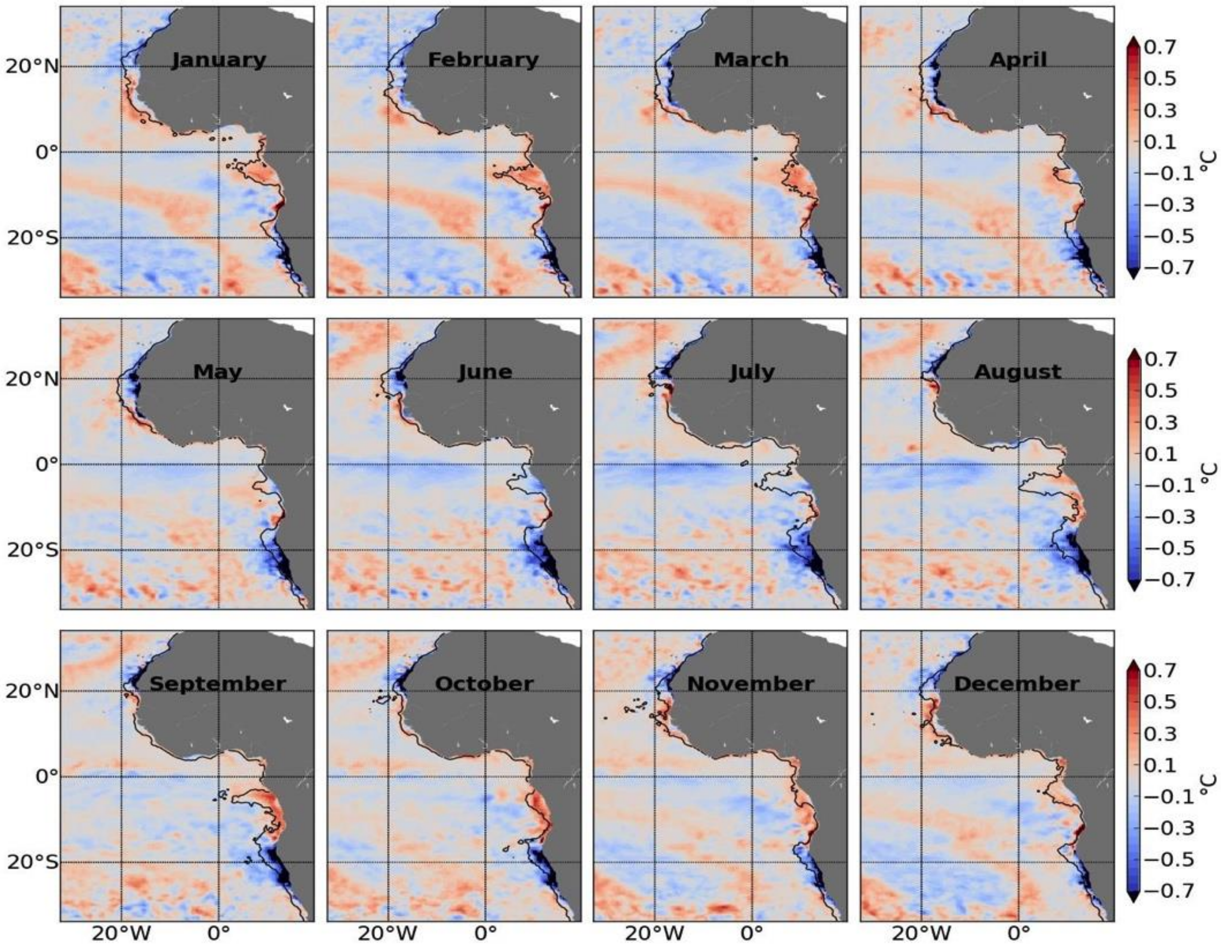

Figure 3.3: Differences of monthly temperature in the mixed layer (in °C) between a simulation with climatological chlorophyll (CHL_{CLIM}) and a reference simulation with low chlorophyll concentrations ($CHL_{0.05}$). Data were averaged from 2005 to 2012. Black lines indicate the 1 mg.m^{-3} monthly mean chlorophyll concentration iso-contour.

Conclusion on the sensitivity to parameterisations of upper ocean processes

We tested the impact of including two parameterised processes, that are frequently misrepresented in forced basin scale OGCM and moreover in coupled general circulation model (CGCM): (i) near inertial (NI) frequency upper ocean mixing forced by high frequency wind events, and (ii) differential upper ocean absorption of solar radiations in relation to the turbidity caused by realistic three dimensional distribution of chlorophyll.

(i) The addition of NI mixing processes was tested only in a single PREFACE coupled model (NorESM), but produced results that we consider important to consider for forced OGCM as well as all coupled models. The additional mixing provided to the mixed layer caused its general deepening, and a non-uniform mean cooling of sea surface temperature (SST) that is not limited to warm tropical bias regions. However the cooling in eastern tropical Atlantic upwellings specifically is particularly intense and compensates to a large extent the model warm bias there.

Despite an expected quantitative limitation in the confidence level of the amplitude of the modifications, due to a lack of knowledge of NI mixing at global scale, we think that this process should be better represented in ocean models. The maximum intensity of its cooling effect in the eastern tropical Atlantic upwellings, advocates for developing a strategy of optimisation of high frequency upper ocean mixing in OGCM and CGCM. The mixed layer scheme (a bulk one in NorESM) is hence important to consider, but it is equally important to represent high frequency wind forcing (a few hours frequency) for the occurrence of NI processes.

(ii) The addition of the effect of chlorophyll on absorption of shortwave radiations strikingly modifies specifically tropical eastern boundary upwellings SST, as expected from high primary production level there. It tend to cool by a few tens of degrees (up to 1°C locally) the Canary and Benguela upwelling SSTs, more specifically their poleward parts, corresponding to the well-developed upwelling poleward of the Angola-Benguela and Senegal-Mauritania Fronts. We note however that it also increases a subsurface cold bias below the mixed layer there in the Benguela system. These results point out the importance of a correct representation of the vertical penetration of the radiative forcing in the ocean, and its potential for improving realism of SSTs in the eastern Atlantic basin.

Acknowledgments

The authors wish to acknowledge use of the Ferret program for analysis and graphics in this paper. Ferret is a product of NOAA's Pacific Marine Environmental Laboratory. Information is available at www.ferret.noaa.gov. QuikSCAT data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. Data are available at www.remss.com.We also acknowledge the MODIS mission scientists and associated NASA personnel for the production of the data used in this research effort. NCEP reanalysis data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. MOM simulations have been carried out at computers of the North-German Supercomputing Alliance (HLRN). Model results are available at phy-50.io-warnemuende.de:8080/thredds.

References

Bentsen, M., et al., 2013: The Norwegian Earth System Model, NORESM part 1: Description and basic evaluation of the physical climate. Geoscientific Model Development, 6 (3), 687–720.

Brodeau, L., B. Barnier, A. Treguier, T. Penduff, and S. Gulev, 2010: An ERA40-based atmospheric forcing for global ocean circulation models. *Ocean Model.*, **31**, 88–104.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol. Soc., 137: 553–597. doi: 10.1002/qj.828

Brodeau, L., B. Barnier, A. Treguier, T. Penduff, and S. Gulev, 2010: An ERA40-based atmospheric forcing for global ocean circulation models. *Ocean Model.*, **31**, 88–104, doi:10.1016/j.ocemod.2009.10.005. http://dx.doi.org/10.1016/j.ocemod.2009.10.005.

Duteil, O., A. Lazar, Y. Dandonneau, I. Wainer, and C. Menkes, 2009: Deep chlorophyll maximum and upper ocean structure interactions: Case of the Guinea Thermal Dome. *J. Mar. Res.*, **67**, 239–271.

Elipot, S., and R. Lumpkin, 2008: Spectral description of oceanic near- surface variability. Geophys. Res. Lett., 35 (L05606).

Hernandez, O, J. Jouanno, V. Echevin, and O. Aumont. Impacts of chlorophyll concentrations on the Tropical Atlantic Ocean. Submitted to JGR.

Jochum, M., B. Briegleb, G. Danabasoglu, W. Large, N. Norton, S. Jayne, M. Alford, and F. Bryan, 2013: The impact of oceanic near-inertial waves on climate. J. Clim., 26, 2833–2844.

Krebs, M., A Biastocha, J. Durgadooa, C. Böning, M. Latif. 2016. Ingredients to the warm bias in the Benguela Upwelling System in an ocean-only model. Submitted to Elsevier

Ndoye, S., X. Capet, P. Estrade, B. Sow, E. Machu, T. Brochier, and P. Brehmer, 2016: Dynamics of a low enrichment-high retention upwelling center over the southern Senegal shelf, Geophys. Res. Lett., to be submitted.

Oschlies, A. 2004. Feedbacks of biotically induced radiative heating on upper-ocean heat budget, circulation, and biological production in a coupled ecosystem-circulation model. J. Geophys. Res., 109, C12031

Park, J. J., K. Kim, and R. Schmitt, 2009: Global distribution of the decay timescale of mixed layer inertial motions observed by satellite- tracked drifters. J. Geophys. Res., 114, C11 010.

Patricola, C. M., M. Li, Z. Xu, P. Chang, R. Saravanan, and J.-S. Hsieh, 2012: An investigation of tropical Atlantic bias in a high-resolution coupled regional climate model. *Clim. Dyn.*, **39**, 2443–2463

Pillar, H., M. Jochum and R. Nuterman, 2016: Characteristics of the air-sea inertial energy flux at the tropical Atlantic PIRATA array. In prep. for submission to J. Geophys. Res.

Pollard, R., and R. Millard, 1970: on the generation by winds of inertial waves in the ocean. Deep-Sea Res., 17, 795– 812.

Polo, I., B. Rodríguez-Fonseca, T. Losada, and J. García-Serrano, 2008: Tropical Atlantic Variability Modes (1979–2002). Part I: Time-Evolving SST Modes Related to West African Rainfall. *J. Clim.*, **21**, 6457–6475, doi:10.1175/2008JCLI2607.1. http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2607.1 (Accessed April 25, 2013).

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature. Journal of Climate, 20(22), 5473-5496.

Small, R. J., Curchitser, E., Hedstrom, K., Kauffman, B., & Large, W. G. (2015). The Benguela Upwelling System: Quantifying the Sensitivity to Resolution and Coastal Wind Representation in a Global Climate Model*. Journal of Climate, 28(23), 9409-9432.

Zhai, X., R. Greatbatch, and C. Eden, 2009: On the loss of wind- induced near-inertial energy to turbulent mixing in the upper ocean. J. Phys. Oceanogr., 39, 3040–3045.