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: D6.3 "Report on best practices for simulating tropical Atlantic variability"

Lead beneficiary for this deliverable: 1, University of Bergen

Due date of deliverable: 31.10.2017

Actual submission date: 31.10.2017

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)	
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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 to our best knowledge

Executive Summary:

PREFACE is aimed at enhancing prediction of tropical Atlantic climate and its impacts. Key to this is better understanding the processes determining tropical Atlantic climate and its variability, and to assess how errors in their representation in climate models affects the simulation and prediction of climate in this region. Here we provide a synthesis of the findings from PREFACE WP5, WP6, WP7, WP8, and WP9 on best practices for simulating tropical Atlantic variability, and include recommendations for improving ocean and coupled ocean-atmosphere modelling of the region.

We first summarise the mechanisms for tropical Atlantic variability focusing on the Atlantic Niño (Section 1). Ocean dynamics underlie the Atlantic Niño, with Equatorial Deep Jets driving part of the surface variability. Atlantic and Pacific Niño variability become coupled during certain decades that tend to coincide with the negative phase of the Atlantic Multi-decadal Variability (AMV).

Next we summarise three oceanic processes key for accurate simulation of tropical Atlantic sea-surface temperature (SST): Near inertial frequency upper ocean mixing, upwelling and poleward transports of heat in relation to surface wind patterns, and absorption of solar radiation by chlorophyll (Section 2). The SST climatology in the Benguela eastern boundary upwelling system can be well simulated with oceanic horizontal resolution of 1/10°, and accurate surface wind stress. These results are based on extensive regional ocean model experiments and analysis of *in situ* observations

Section 3 considers the coupled ocean-atmosphere interaction in the simulation of tropical Atlantic climatology, focusing on the ubiquitous warm biases at the equator and in the south eastern Atlantic. The equatorial bias appears largely related to atmospheric model errors that are amplified by coupled dynamics. Biases in the south eastern Atlantic are due to radiation errors, as well as errors in the simulation of coastal winds, and vertical ocean mixing. Increasing oceanic and atmospheric resolution can improve the simulation of climate, but results are model dependent.

Section 4 summarises how the poor representation of the mean state and ocean-atmosphere interaction impacts the variability simulated by climate models (Section 4). Encouragingly, despite large climatological errors, most climate models simulate the two main modes of tropical Atlantic variability: the Atlantic Niño and the Atlantic Meridional Mode (AMM). However, models overestimate the importance of thermodynamic driven SST variability, and this appears linked to mean state errors. While reduction of mean state errors improves the simulation of both modes of variability, results are model dependent and statistical correction approaches did not lead to universal improvements.

Last, the link between model errors in other regions on the simulation of Atlantic Niño and its link to the Pacific El Niño were summarised (Section 5). Reducing mean errors in the southern hemisphere and tropical Pacific leads to an improved simulation of the tropical Atlantic. The connection between the Atlantic and Pacific Niños depends on the mean state, and is active when the intertropical convergence zone is located close to the equator. Thus, tropical biases strongly influence the ability of models to simulate the equatorial Atlantic and Pacific interaction, as well as its multidecadal modulation.

The synthesis here forms a basis for understanding predictability of tropical Atlantic variability and how it is influenced by mean state errors. This contributes to WP11 and the deliverables D11.1 and D11.2.

1. Mechanism for tropical Atlantic variability

Elsa Mohino (UCM)

This executive summary is based on the main outputs obtained in WP9 regarding tropical Atlantic variability with a special focus on the equatorial Atlantic.

Processes involved in the Atlantic El Niño development and model performance

Variance in summer sea surface temperature (SST) in the eastern equatorial Atlantic is dynamically controlled (the component of SST dynamical variance is 4 to 7 times greater than the stochastic driven thermodynamic one), suggesting dynamical processes contribute strongly to the Atlantic El Niño. However, most current state-of-the-art atmosphere-ocean coupled models are not able to reproduce properly such a result. The variability of the South Atlantic Anticyclone can explain up to 50% of the equatorial Atlantic SST variance. The warm anomalies associated with the positive phase of the Atlantic El Niño in the center of the basin are produced by a downwelling Kelvin wave, which triggers stratification anomalies and mixed-layer depth anomalies. The decay of the mode in July is associated with a cooling due to negative horizontal advection anomalies.

Processes acting in the development of the Atlantic El Niño can be different in observation and in models (for instance, models can simulate opposite propagation of SST anomalies, from the western equator to the African coast). This could be related to a poor reproduction of the mixed layer depth seasonality.

Changes in the Atlantic El Niño and its connection with Pacific El Niño

The characteristics of the Atlantic El Niño change depending on the background state: during negative Atlantic Multi-decadal Variability (AMV) periods, the eastern equatorial Atlantic SST variability is enhanced, associated with a shallower mean thermocline. The Atlantic Niño then presents larger amplitude and a westward extension and is preceded by the simultaneous weakening of both north and south subtropical anticyclones during previous winter-spring. Conversely, during positive AMV periods, the Atlantic El Niño is related to a stronger north subtropical anticyclone and a weaker south subtropical anticyclone.

The changes in the characteristics of the Atlantic El Niño lead to changes in the impact on the Pacific atmosphere in the next winter: changes in the Walker Atlantic–Pacific cell produced by the Atlantic El Niño are stronger after the 1970s (negative AMV phase), and are reinforced by the change in the impact of the Atlantic El Niño over the Indian Ocean and the Maritime Continent.

The connection between Atlantic and Pacific Niños is a leading mode of interbasin covariability during certain decades. The positive phase of the mode can be described as warm anomalies over the equatorial Atlantic in summer related to ascending motions locally and descending ones over the Pacific. There, they generate an upwelling Kelvin wave that propagates eastward and favours the development of a Pacific La Niña in winter. The decades in which the mode appears tend to coincide with negative phases of the AMV.

Equatorial Deep Jets

Equatorial SST variability and surface zonal velocity within the North Equatorial Counter Current is influenced by Equatorial Deep Jets (stacked zonal jets along the equator which steadily propagate downwards over time with a time scale of about 4.5 years). Equatorial Deep Jets are driven by deep intraseasonal variability and are associated with upward energy flux.

Decadal and multi-decadal TAV

The summer equatorial Atlantic El Niño index shows a peak of variance at decadal time scales related to the southern subtropics. A possible explanation involves oscillations in the strength of the St. Helena subtropical anti-cyclone inducing equatorial SST variability via the wind-evaporation-SST feedback mechanism.

Variability generated internal to the climate system has an important influence on the observed multi-decadal trends in the tropical Atlantic. The amplitude of the observed trend is much bigger than the robust (multi-model) estimate of the forced response.

2. Oceanic processes

Alban Lazar (UPMC)

This summary of recommendations for a strategy to reduce the warm mean SST biases in forced ocean models is based on ocean model tests on parameterisations, spatial and temporal resolution, and accuracy of surface forcing. Main results are summarized according to the three categories of experiments:

Improving representation of specific misrepresented ocean processes

Three specific processes frequently misrepresented in forced basin scale ocean general circulation models (OGCM) and coupled general circulation models (CGCM) were investigated:

1. *Near inertial (NI) frequency upper ocean mixing from high frequency wind events*. The additional mixing provided to the mixed layer by NI caused its general deepening, and a lowering of mean SST, which compensates to a large extent the model warm bias in the upwelling areas. Both, a sophisticated mixed layer scheme and having high frequency wind forcing (a few hours frequency) is crucial to the inclusion of NI processes.
2. *Upwelling and poleward heat transports in relation to wind stress patterns*. Poleward undercurrents and wind driven upwelling as major elements of the oceanic heat transport are related to local wind stress patterns. Unrealistic winds may lead to a strong model SST bias from a displaced Angola-Benguela Front. However, part of the undercurrent is remotely forced through coastally trapped waves from equatorward coastal regions and the equatorial currents itself. This connection was analysed in detail using PREFACE mooring data.
3. *Absorption of solar radiation by chlorophyll.* The effect of chlorophyll on absorption of shortwave radiation tends to cool by a few tens of degrees (up to 1°C locally) the Canary and Benguela upwelling SST. It also increases a cold bias below the mixed layer in the Benguela system. These results show 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.

Improving spatial resolution

Increasing resolution is costly and produces modest consequences for the SST bias. Our most striking result was obtained with the ocean model NEMO, for which we could cancel the bias in a very narrow coastal band all along the Benguela eastern boundary upwelling system (EBUS), by using a 1/10°

resolution and forcing the model by winds from QuikSCAT. Higher vertical resolution and horizontal resolution up to the local Rossby radius did not improve the realism.

Increasing the realism of air-sea forcings

A key to the improvement of the model performance is the representation of the atmospheric circulation. Using realistic wind fields reduce the SST bias in the EBUS substantially, and coastal winds and wind stress curl need particular attention. However, changes in the air-sea fluxes cannot fully eliminate the warm bias, except in some cases like in the Benguela EBUS along a coastal band.

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 lessen SST biases:

- To force the OGCM with a wind stress product having a climatological seasonal mean distribution as close as possible as that of scaterometer derived winds.
- To validate the shortwave radiative forcing against in-situ observations.
- To use a horizontal resolution in first 500km offshore as close as possible to the Rossby Radius, although 1/10° appear to provide satisfying results.
- To include the effect of primary production on turbidity of the waters, via a realistic chlorophyll distribution in the equation of penetrating solar radiation.
- To consider the importance of transmitting high frequency wind energy into the ocean.

3. Coupled processes in simulating the tropical Atlantic climatology

Aurore Voldoire (CNRM, METEO-France)

The analysis of coupled model mean biases lead to the following conclusions. The SST warm bias in the tropical Atlantic can be regarded as the addition of two different sub-regional biases:

- *The equatorial warm SST bias*, which is a seasonal bias strongly tied to the annual cycle. The spring cooling is largely underestimated in coupled models, leading to strong summer SST biases. There are some indications that errors in the mean state (like a too deep mixed layer in the eastern equatorial Atlantic in early spring) do not favour the cold tongue cooling processes. Improving the surface wind representation in atmospheric models helps in improving the mean state and favours the cold tongue development. The atmospheric wind biases are present in atmospheric models forced by observed SST. This indicates that deficiencies in atmospheric models are the root cause of the warm equatorial Atlantic SST bias, but coupled processes amplify these errors. The surface wind biases are linked to surface pressure gradients errors and in turn to deficiencies in representing the convection. The wind stress biases are thus related to ITCZ errors.

- *The south-eastern warm SST bias*, which develops more progressively and independently of the seasonal cycle. In this strato-cumulus region, the radiative biases play an important role in explaining large scale SST biases, but other elements also play a role: coastal atmospheric wind jets, vertical ocean mixing, and coastal currents representation. All these processes tend to be better represented when increasing resolution both in atmosphere and in ocean models even if the improvement is model dependent.

4. Impact of poor representation of mean state and processes on simulated tropical Atlantic variability

Emilia Sanchez-Gomez (CERFACS)

Impact of model mean biases in simulating the TAV and associated feedback processes

This executive summary is based on deliverables D7.1 and D7.2 which gathers results from the analysis of i) existing simulations (Coupled Model Intercomparison Project 5 (CMIP5) mainly) and ii) model modifications aimed at improving the model climatology.

Representation of tropical Atlantic modes of variability in state-of-the-art models

The analysis of CMIP5 multi-model ensemble (both pre-industrial and historical experiments) reveals that despite of severe biases in the mean state, most of the model represent the two main modes of tropical Atlantic variability: the Atlantic Niño and the Atlantic Meridional Mode (AMM). Nevertheless some deficiencies have been reported. In particular, even if the equatorial variability is present in most of the models, its seasonality is not well represented. Results show that contrarily to observations, the simulated Atlantic Niño peaks in autumn-winter rather than in boreal summer. The northern centre of the AMM is well simulated in most of the models, even if the percentage of variance explained by modelled AMM is lower with respect to observations. This means that the strength of the inter-hemispheric gradient is underestimated in coupled models.

Representation of feedback processes related to tropical Atlantic variability

The Bjerknes (BF) and Wind-Evaporation-SST (WES) feedbacks are key for the Atlantic Niño and AMM. A multi-model analysis based on the CMIP5 database was conducted to investigate how well these feedbacks are represented in models. The main elements of BF are reasonably well simulated, notwithstanding mean model biases in the tropical Atlantic. Nevertheless, coupled models do not reproduce the links between surface and subsurface ocean temperatures, revealing some deficiencies in processes related to ocean subsurface dynamics. WES feedback analysis shows that the SST response to atmospheric forcing is too strong in coupled models compared to observational analysis. This suggest that in coupled models, a greater portion of SST tendency is controlled by atmospheric heat fluxes than that in the observations; this may suggest that ocean processes and being underestimated in coupled models.

In line with this, analysis of slab-ocean versus fully coupled models reveals that thermodynamic ocean processes can explain the greatest portion of equatorial SST variability in the tropical Atlantic. We conclude that the role of ocean processes in coupled models contributing to SST variability in the tropical Atlantic is still uncertain and needs to be further investigated.

Impact of improved model climatology on the simulated tropical Atlantic variability

Several model configurations have been applied in order to improve the mean state (climatology) in the tropical Atlantic. The impact of these improvements in the simulated tropical Atlantic variability has been analysed. These new model configurations include: new ocean and atmospheric parameterizations, increasing model resolution, flux correction and anomaly coupling techniques. In most of the cases, experiments with improved climatology lead to a better representation of tropical Atlantic modes of variability and mechanisms, though these benefits are not universal. In particular, increasing model resolution leading to a better representation of tropical Atlantic variability is quite model dependent, though it seems that the atmospheric horizontal and vertical resolution plays the main role. Other techniques such as flux correction and anomaly coupling, which achieve more realistic SST and surface winds over the tropical Atlantic, do not lead systematically to an improvement of the simulated tropical Atlantic variability for all the models. This suggests that improving the SST and winds mean state is not the only factor to control the tropical Atlantic variability. Other processes, such ocean dynamics, can contribute and their role need to be more investigated in both free coupled models runs and anomaly coupled of flux corrected simulations.

5. Simulation of interannual teleconnections between the Atlantic and Pacific

Belén Rodríguez-Fonseca (UCM)

The analysis of the remote bias on tropical Atlantic climate, variability, and interbasin teleconnections has revealed the following conclusions:

1. Errors on the tropical Pacific seem to remotely affect those in the tropical Atlantic impacting the location of the convection and surface winds. In turn, errors in the tropical Atlantic remotely affect those in the tropical Pacific.
2. A reduction of the incoming solar radiation over the southern ocean improves, in turn, the errors in the Southern Ocean SST and in the tropics. This reduction can result in an improvement of the simulation of tropical Atlantic variability at interannual timescales
3. Analysis of CMIP5 models confirms this finding. Models with a colder extratropical southern ocean better simulate the leading mode of tropical Atlantic interannual variability (i.e., the Atlantic Niño). The fraction of variance explained by the Atlantic Niño is larger in these models than in models with a warmer extratropical southern ocean.
4. Reduction of mean state biases improves the representation of the inter-basin tropical teleconnection between Atlantic and Pacific Niños, and leads to a realistic representation of its multi-decadal variability.
5. Tropical inter-basin teleconnections between Atlantic and Pacific Niños, take place in periods in during which the Intertropical Convergence Zone (ITCZ) is located closer to the equator. This happens under differently depending on model bias. In particular, models with cold (warm) SST bias in the equatorial Pacific tend to shift the ITCZ to the north (south) of the equator. Thus, these models are able to produce the interbasin connection when increasing (decreasing) rainfall south of the equator that occurs when warming (cooling) the Pacific SST.

Recommendation. A better simulation of the ITCZ together with its shifts at interannual to decadal timescales is crucial for the correct assessment of tropical Atlantic variability and tropical inter-basin teleconnections. These shifts are related to changes in AMOC, extratropical clouds in the southern hemisphere, equatorial Pacific SSTs and inter-hemispheric SST gradients.

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