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: D.3.4. "Report on the interannual variability mixed layer heat and salt balances"

Lead beneficiary for this deliverable: 7, GEOMAR

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)	
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CO	Confidential, only for members of 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.

Report

Executive Summary

This report is Deliverable 3.4 of the PREFACE project, produced by the work package WP3. WP3 focuses on improving the understanding of the physical processes controlling the mixed layer heat and freshwater balances in the Atlantic equatorial cold tongue, the Gulf of Guinea and in the eastern boundary upwelling regions of the tropical Atlantic. Within WP3, observational and model process studies are performed, the Atlantic observing system is extended, and datasets to evaluate regional ocean and atmospheric, and global climate models are provided. The report focuses on advances in the understanding of the variability of the mixed layer heat and salt balances in the WP3 regions with a focus on interannual time scales.

Seasonal heat and salinity budgets in the equatorial cold tongue and the Gulf of Guinea

Interannual variability in the equatorial cold tongue region and in the Gulf of Guinea is phase-locked to the seasonal cycle. Understanding of the seasonal cycle is thus fundamental to understanding interannual variability. Prior to PREFACE, several studies had focussed on the seasonal heat budgets in the equatorial cold tongue and the Gulf of Guinea, but the leading processes fluxing fresh water in the mixed layer had not been identified.

Three studies extended previous knowledge of the seasonal mixed-layer heat budget. In an extensive observational study, Hummels et al. (2014) showed that within the equatorial region, the diapycnal heat flux is essential for the seasonal development of the Atlantic cold tongue. It dominated over all other cooling terms in the central and eastern equatorial cold tongue, while it is of similar size as the zonal advection in the western equatorial cold tongue region. Similarly, Schlundt et al. (2014) found that during May to July 2011, strong mixed layer heat loss in the Atlantic cold tongue region was found to be the result of the balance of warming due to net surface heat flux and a stronger cooling due to zonal heat advection and diapycnal mixing. North of the equatorial cold tongue region, the mixed layer heat balance was dominated by net surface heat flux and zonal advection during the same period. Finally, Lüdke et al. (2017) showed that the heat budget east of 5°W to the Nigerian coast must be dominated by a balance between net heating by surface heat flux and net cooling by diapycnal heat fluxes at the base of the mixed layer.

Several studies focussed on seasonal salinity budgets in the mixed layer. Da-Allada et al. [2014] used an ocean general circulation model to investigate mixed layer salinity variations in the Gulf of Guinea region. The surface salinity seasonal cycle is characterized by strong salinization during May for coastal areas north and south of the equator. The 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. In the equatorial cold tongue, Camara et al. (2015) suggested that diapycnal freshwater fluxes due to mixing are an important contribution to the mixed layer budget by providing, in general, an upwelling flux of salinity. Similarly, Da-Allada et al. (2017) suggested that the vertical processes play a crucial role in the sea surface salinity variability within the cold tongue. Finally, model studies (Camara et al., 2014; Da-Allada et al., 2017) as well as observational studies (Schlundt et al., 2014; Lüdke et al., 2017) agree that the boreal spring sea surface salinity maximum within the cold tongue can be explained by an upward flux of high salinity originating from the core of the Equatorial Undercurrent (EUC) through vertical mixing and advection.

Interannual variability of the equatorial Atlantic cold tongue region

Interannual variability of the mixed-layer heat and salt budget in the equatorial Atlantic were studied using combined observational and modelling approaches. Interannual variability of sea surface temperature in the equatorial Atlantic strongly impacts tropical Atlantic climate variability and in particular rainfall variability over northeast Brazil and the coastal regions surrounding the Gulf of Guinea. Equatorial sea surface temperatures are also well known to influence the onset and strength of the West African Monsoon. Hence, in order to improve climate prediction in those regions, interannual sea surface temperature variability and its causes need to be understood.

A rather unexpected result was put forth by Nnamchi et al. (2015) who investigated the impact of thermodynamic forcing (i.e. surface net heat flux forcing) on interannual variability of the equatorial cold tongue temperatures in the Atlantic and Pacific using a set of different CMIP3 climate models. They showed that in the tropical Atlantic the thermodynamic feedbacks excited by stochastic atmospheric perturbations can generate elevated interannual variability in the Atlantic cold tongue that explains 68 ± 23% of the observed interannual variability. In the Pacific, thermodynamic forcing explained only 32 ± 11% of the interannual variability. Nnamchi et al. (2015) hypothesized that atmospheric fluctuations associated with the interannual Atlantic cold tongue variability can generate the space-time structure of the interannual equatorial Atlantic cold tongue events via the wind-evaporation-SST feedback mechanisms even under motionless ocean conditions. Coupled dynamics can further enhance the characteristic structure and energize the interannual variance of the Atlantic cold tongue, via the Bjerknes feedback and changes in mixed layer depth.

The relative contributions of the dynamic and thermodynamic forcing to the interannual variability of the equatorial Atlantic sea surface temperature were also investigated by Juanno et al. (2017) using a set of interannual regional simulations of the tropical Atlantic Ocean. They found, in agreement with leading theories and in contrary to Nnamchi et al. (2015) that the interannual variations of the dynamical forcing largely contributes to this variability. Moreover, they showed that mean and seasonal upper ocean temperature biases, commonly found in fully coupled climate models, strongly favor an unrealistic thermodynamic control of the equatorial Atlantic interannual variability.

Similarly, Planton et al. (2017) found interannual Atlantic cold tongue variability to be associated with dynamical forcing. They use an ocean general circulation model capable of simulating the interannual variability of the Atlantic cold tongue in agreement with observations to demonstrate that cold interannual anomalies develop rapidly from May to June mainly due to intense cooling by vertical mixing and horizontal heat advection. Anomalously cool cold tongue events are a result of the combined effects of non-local and local processes. Non-local processes are associated with eastward-propagating upwelling Kelvin waves generating shallow mixed layers. The preconditioned mixed layer is subsequently cooled by diapycnal mixing at the base of the mixed layer, which is amplified by a stronger local injection of wind energy from the atmosphere. During anomalously warm Atlantic cold tongue events, Planton et al. (2017) found that processes are reversed. Downwelling Kelvin waves trigger stratification anomalies and mixed layer depth anomalies that are amplified by a weaker injection of energy from the atmosphere in May–June and thus weaker diapycnal mixing.

It should be noted that Juanno et al. (2017) as well as Planton et al. (2017) stress the damping nature of the thermodynamic forcing during anomalous cold tongue events. From observations, it is evident that net surface heat fluxes are increased (i.e. anomalously warm the ocean) during anomalously cool cold tongue events, while they are decreased during anomalously warm cold tongue events, further questioning a dominant role of thermodynamic forcing of interannual Atlantic cold tongue variability.

The interannual variability of mixed layer salinity was studied in the Gulf of Guinea by Da-Allada et al. (2014). They showed that for the northern and equatorial Gulf of Guinea, interannual variability of near-surface salinity was largely due to interannual variability of precipitation and winds. For the southern region of the Gulf of Guinea, only interannual wind variability was important for explaining near-surface salinity variability. Interannual variability of salinity was investigated by Awo et al. (2017) who described meridional and zonal variability modes of salinity.

Studies have also focused on understanding individual anomalous Atlantic cold tongue events. Burmeister et al. (2016) investigated the cause for a cold sea surface temperature event that occurred in the Atlantic cold tongue region in boreal summer 2009. It was preceded by a strong negative Atlantic meridional mode event associated with north-westerly wind anomalies along the equator from March to May. Although classical equatorial wave dynamics suggest that westerly wind anomalies should be followed by a warming in the Atlantic cold tongue region, an abrupt cooling occurred. Two mechanisms - meridional advection of subsurface temperature anomalies and planetary wave reflection - are discussed as potential causes of such an event. Using a set of different observations, Burmeister et al. (2016) showed that meridional advection is less important in anomalously cool Atlantic cold tongue events than in corresponding warm events, and that this process did not cause the 2009 cold event. Instead, Argo float data confirmed previous findings that planetary wave reflection contributed to the onset of the 2009 cold event.

Mixed layer heat and salt budgets in the eastern South Atlantic

Mixed-layer heat budgets from the Angola and Benguela upwelling regions calculated from the PREFCLIM climatology (Rath et al. 2016) by Lüdke et al. (2017) suggest that the most important cooling term is zonal heat advection. Additionally, horizontal heat advection due to eddy steering is a major heat flux term and supplies heat to the Angola and Benguela upwelling regions from offshore. Net surface heat flux is identified as the main driver of seasonal heat content variations due to the large annual cycle of short-wave radiation. Throughout the Angola and Benguela upwelling regions evaporation is larger than precipitation and their combined impact on the mixed layer salinity is balanced by zonal freshwater advection. Model results by Kom et al. (2017) show freshwater flux balances that are comparable to the results by Lüdke et al (2017). In the Benguela region, model and observations roughly agree on freshwater fluxes and seasonal variation of advection. However, off Angola, sea surface salinity variations are uncorrelated between the model and the PREFCLIM analysis.

Interannual variability of the Angola Benguela upwelling region

Interannual variability of sea surface temperature in the Angola-Benguela regions is often explained as being remotely by the impact of upwelling and downwelling coastal trapped waves as well as by local meridional winds along the southwestern coast of Africa. The link between equatorial Atlantic Ocean variability and the coastal region of Angola-Namibia was investigated at interannual time scales from 1998 to 2012 by Imbol Koubgue et al. (2017). Their systematic analysis of all strong interannual equatorial sea surfaced height anomalies showed that they precede interannual sea surface temperature anomalies along the African coast by 1–2 months, confirming the hypothesis that major warm and cold events in the Angola-Benguela current system are remotely forced by ocean atmosphere interactions in the equatorial Atlantic. Equatorial wave dynamics is at the origin of their developments. Wind anomalies in the western equatorial Atlantic force equatorial downwelling and upwelling Kelvin waves that propagate eastward along the equator and then poleward along the African coast triggering extreme warm and cold events, respectively.

A perhaps overlooked mechanism contributing to interannual variability of mixed layer temperatures in the Angola Benguela upwelling region is interannual variability of heat content in the upper thermocline below the mixed layer. Tchipalanga et al. (2017) used hydrographic data from the Dr. Fridtjof Nansen cruises and three RV Meteor cruises carried out within PREFACE along the eastern boundary off Angola and Namibia. The data revealed remarkable variability in subsurface upper ocean heat content on interannual to decadal timescales. Warm water mass anomalies were found further to the south between 1999 and 2001 as well as between 2008 and 2013, while cold water mass anomalies, likely associated with enhanced contributions of Eastern South Atlantic Central Waters were displaced further to the north between 1996 and 1998, from 2002 to 2006 and since 2015. Such anomalies on isopycnals might represent an additional forcing of sea surface temperature variability.

Similar as for the equatorial Atlantic cold tongue, studies also focused on understanding individual interannual warm events in the Angola-Benguela region. Rouault et al. (2017) investigated the processes leading to a particularly strong Angola-Benguela warm event in 2011, where sea surface temperature anomalies in the Angola-Benguela front were larger than 4°C. Consistent with previous Benguela Niños, they found that this event was generated by a relaxation of the trade winds in the western equatorial Atlantic, which triggered a strong equatorial Kelvin wave propagating eastward along the equator and then southward along the southwest African coast. In the equatorial band, the associated ocean sub-surface temperature anomalies were detectable in data from the PIRATA mooring array and the wave propagation was also evident in satellite sea surface height data. In contrast to previous Benguela Niños however, the initial propagation of sub-surface temperature anomalies along the equator started earlier in the year (in October) and the associated warming in the Angolan Benguela Front Zone also followed earlier - in November 2010.

A strong but short-lived warm event in the Angola-Benguela region occurred in January 2016, with sea surface temperature anomalies reaching 3°C. Lübbecke et al. (2017) showed that this warm event, however, was not linked to equatorial Kelvin wave propagation. Instead, their analysis suggested that a shallow layer of warm and fresh surface water was advected poleward by southward surface currents, consistent with a weakening of the southerly winds. This southward flow also carried low salinity surface waters southward that were caused by excess precipitation and enhanced Congo River outflow. The fresh water surface cap led to enhanced stratification below the mixed layer. Additionally, the fresh water anomaly formed barrier layers that inhibited the entrainment of cool subsurface waters into the surface mixed layer, thus supporting the development of a surface warm anomaly.

The individual contributions are summaries below.

Sea Surface Salinity signature of the interannual climatic modes in the Tropical Atlantic

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The impact of the tropical Atlantic meridional and equatorial modes on sea surface salinity (SSS) is investigated using *in situ* data and model simulations. Results indicate the existence of a meridional SSS dipole in the equatorial region during boreal spring. Strong SSS anomalies in north and south west tropical Atlantic and off Congo River are related to the meridional mode (Fig. 1). Moreover, the results also indicate strong SSS anomalies in the equatorial band, north and north-west tropical Atlantic, related to the equatorial mode in boreal summer. Using mixed-layer salt budget calculations from numerical simulations, the oceanic and atmospheric processes responsible for these signatures were investigated. For the meridional mode, changes in fresh water flux explain the observed equatorial dipole while the signature in north and south west regions is explained by horizontal advection (Fig. 1). For instance, during a positive phase of the meridional mode, the northward shift of the ITCZ is related to enhanced precipitation north of the equator where SSS subsequently decreases, and less precipitation occurs south of the equator where SSS increases. Moreover, the strengthening of the North Brazil Current carries relatively fresh waters from the mouth of the Amazon River northward while the Brazil Current also carries relatively fresh waters southward. Off Congo River, the signature is mainly due to meridional advection by the Angola Current south of the Congo outflow located at 6°S and vertical advection north of this latitude. For the equatorial mode in boreal summer (not shown), both fresh water flux and horizontal advection explain the observed signature in the north tropical region. Indeed, during a positive equatorial mode, the presence of a strong mean meridional SSS gradient in this region favors the southward advection of salty waters from the northern subtropical gyre into the region around 10°N. Also, the southward shift of the ITCZ brings more rain into the region around 5°N where SSS then decreases, and less rain in around 10°N where SSS increases. However, in the south equatorial region, the signature is explained by the combined subsurface contribution of vertical advection and diffusion at the base of mixed layer.

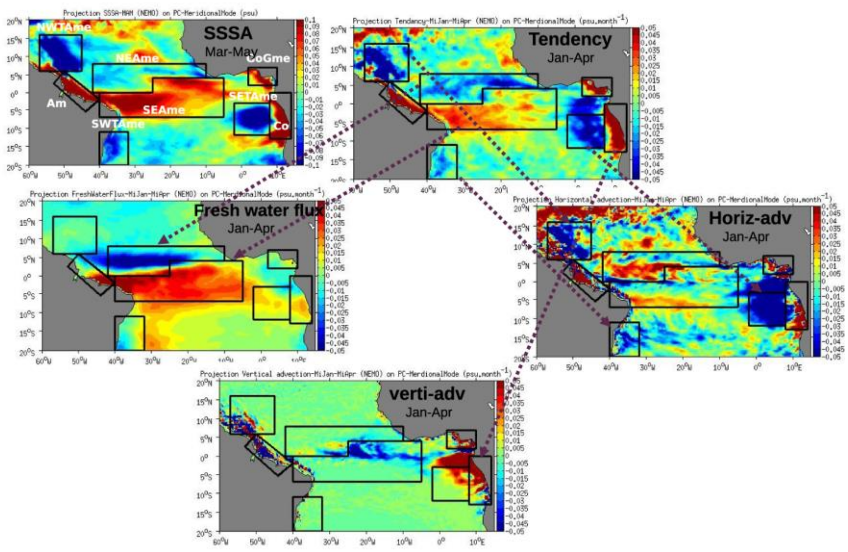

Fig. 1: Modeled salinity anomalies associated with the meridional mode in psu per month (upper left), the salinity tendency of the mixed layer (upper right), salinity anomalies due to atmospheric fluxes (middle left), due to horizontal advection (middle right) and due to vertical advection and mixing (lower panel).

Revisiting the cause of the eastern equatorial Atlantic cold event in 2009

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An extreme cold sea surface temperature event occurred in the Atlantic cold tongue region in boreal summer 2009. It was preceded by a strong negative Atlantic meridional mode event associated with north-westerly wind anomalies along the equator from March to May. Although classical equatorial wave dynamics suggest that westerly wind anomalies should be followed by a warming in the eastern equatorial Atlantic, an abrupt cooling took place. In the literature two mechanisms—meridional advection of subsurface temperature anomalies and planetary wave reflection—are discussed as potential causes of such an event. Here, for the first time we use in situ measurements in addition to satellite and reanalysis products to investigate the contribution of both mechanisms to the 2009 cold event. Our results suggest that meridional advection is less important in cold events than in corresponding warm events, and, in particular, did not cause the 2009 cold event. Argo float data confirm previous findings that planetary wave reflection contributed to the onset of the 2009 cold event (Fig. 2). Additionally, our analysis suggests that higher baroclinic modes were involved.

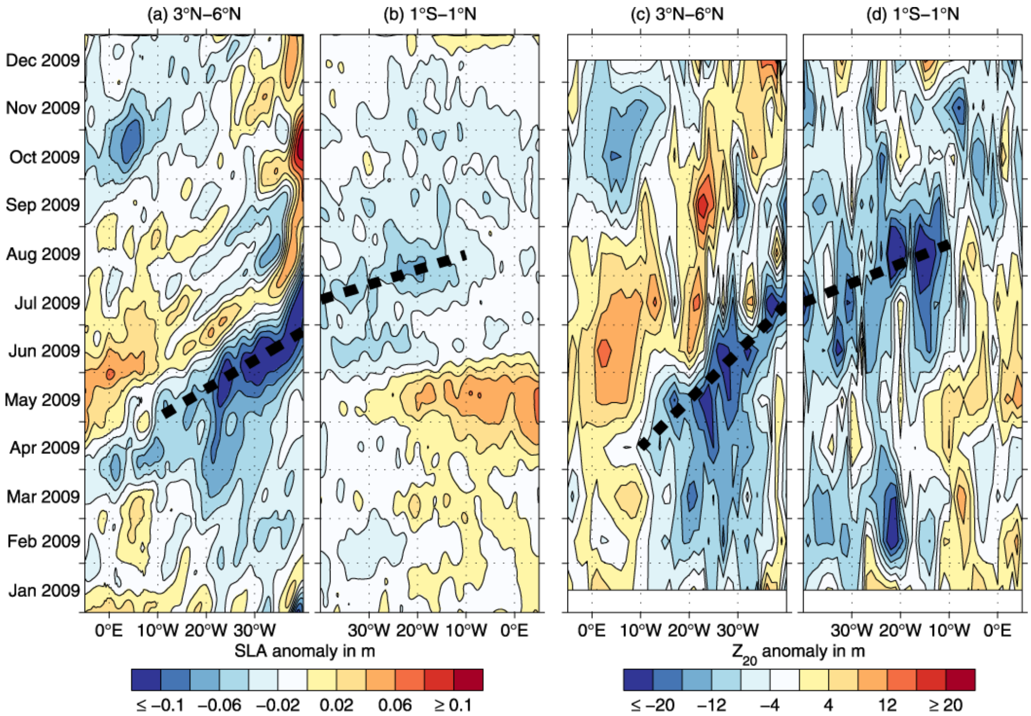

Fig. 2: Anomalies of (a, b) AVISO SLA and (c, d) gridded Argo Z20 for the year 2009 with respect to the climatological mean (2005–2012), averaged in the latitude bands (a, c) 3°N–6°N, and (b, d) 1°S–1°N. The daily SLA data were smoothed by a 20 day running mean filter. Monthly means of Argo Z 20 data were linearly interpolated onto a 1° horizontal resolution grid. The black-dashed lines represent estimated propagation velocities of the negative anomalies of (a) -0.70 m s^{-1}, (b) 1.36 m s^{-1}, (c) -0.43 m s^{-1}, and (d) 1.05 m s^{-1}.

On the seasonal variations of salinity of the tropical Atlantic mixed layer

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The physical processes controlling the mixed layer salinity (MLS) seasonal budget in the tropical Atlantic Ocean are investigated using a regional configuration of an ocean general circulation model. The analysis reveals that the MLS cycle is generally weak in comparison of individual physical processes entering in the budget because of strong compensation. In evaporative regions, around the surface salinity maxima, the ocean acts to freshen the mixed layer against the action of evaporation (Fig. 3). 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 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 to 15°N), the upper ocean freshening by precipitations 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 diffusion. In all these regions, the vertical diffusion presents an important contribution to the MLS 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.

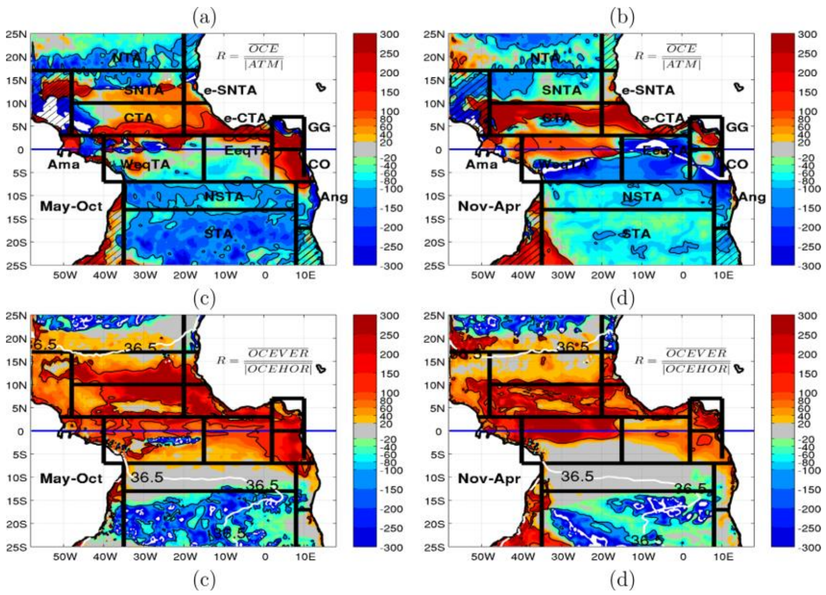

Fig. 3: Ratio (in %) of (a) May to October and (b) November to April averages of the oceanic and the atmospheric contributions to MLS variations in the model. (c, d) Same as (a) and (b) between vertical oceanic and horizontal oceanic processes. Black contours lines are ratios of 100% and 2100%. White contour lines in (c) and (d) represent mixed layer salinity in psu. Hatched areas were not investigated in the study.

Modeled mixed-layer salinity balance in the Gulf of Guinea: seasonal and interannual variability

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A regional numerical simulation and observations were used to investigate the various processes controlling mixed-layer salinity balance on seasonal and interannual time scales in the Gulf of Guinea. 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. 4). 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. We also determined that freshening from horizontal advection and freshwater flux tended to balance the salinization effects of vertical diffusion and vertical advection during the seasonal cycle. On interannual time scales, based on the mixed-layer salinity balance and sensitivity experiments, we determined that for the northern and equatorial Gulf of Guinea (NGoG and EGoG in Fig. 4, respectively), changes in near-surface salinity were largely due to changes in precipitation and winds. For the southern Gulf of Guinea (SGoG in Fig. 4), only wind changes were determined to be important for explaining near-surface salinity changes.

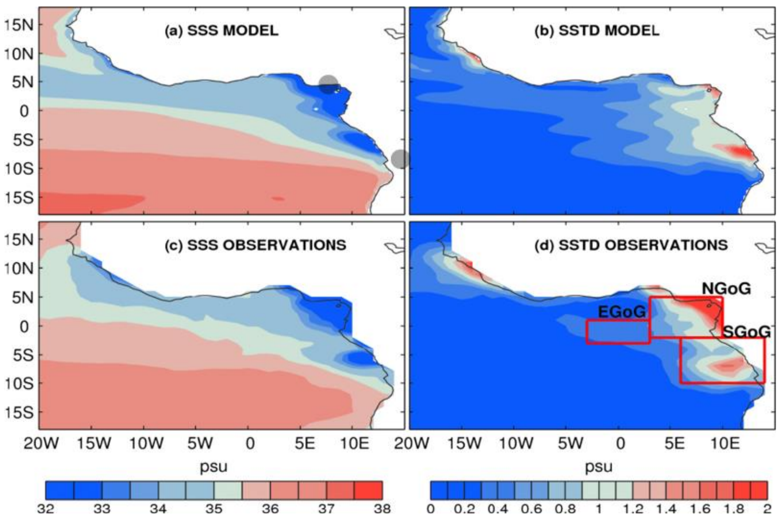

Fig. 4: Annual mean and standard deviation of sea surface salinity (SSS) from the model (a, b) and observations (c, d) calculated from monthly averaged values spanning the 1993–2009 period. The positions of the two major rivers (the Niger and Congo) are indicated in a. Subregions used in the study are marked in d).

Importance of the Equatorial Undercurrent on the sea surface salinity in the eastern equatorial Atlantic in boreal spring.

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The physical processes implied in the sea surface salinity (SSS) increase in the equatorial Atlantic Cold Tongue (ACT) region during boreal spring (Fig. 5) and the lag observed between boreal spring SSS maximum and sea surface temperature (SST) summer minimum (Fig. 5) are examined using mixed-layer salinity budgets computed from observations and model during the period 2010–2012. The boreal spring SSS maximum is mainly explained by an upward flux of high salinity originating from the core of the Equatorial Undercurrent (EUC) through vertical mixing and advection. The vertical mixing contribution to the mixedl ayer salt budget peaks in April–May. It is controlled primarily by (i) an increased zonal shear between the surface South Equatorial Current and the subsurface EUC and (ii) the presence of a strong salinity stratification at the mixed-layer base from December to May. This haline stratification that is due to both high precipitations below the Inter Tropical Convergence Zone and zonal advection of low-salinity water from the Gulf of Guinea explains largely the seasonal cycle of the vertical advection contribution to the mixed-layer salt budget. In the ACT region, the SST reaches its maximum in March/April and minimum in July/August. This SST minimum appears 1 month after the maximum of SSS. The 1 month lag observed between the maximum of SSS in June and the minimum of SST in July is explained by the shallowing of the EUC salinity core in June, then the weakening/erosion of the EUC in June–July which dramatically reduces the lateral subsurface supply of high-saline waters.

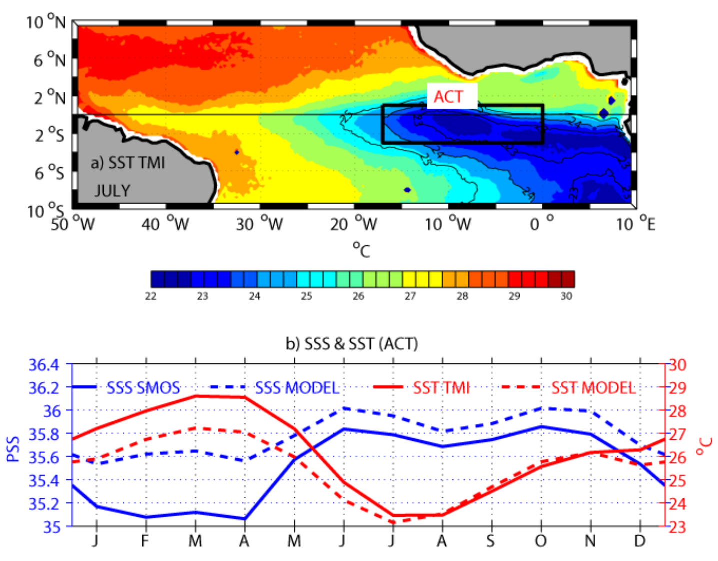

Fig. 5: Satellite-SST distribution during July showing the spatial extend of the equatorial Atlantic Cold tongue (ACT) region (upper panel). Contours represent 23°, 24°, and 25°C isotherms. Lower panel shows the seasonal evolution of the sea surface salinity (SSS, blue lines) and the sea surface temperature (SST, red lines) for the satellite observations (full lines) and the model (dashed lines) in the ACT (box marked in Figure 1a). The seasonal cycle of the SSS and of the SST is computed for the 2010–2012 period.

Diapycnal heat flux and mixed layer heat budget within the Atlantic Cold Tongue

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Sea surface temperatures (SSTs) in the eastern tropical Atlantic are crucial for climate variability within the tropical belt. Despite this importance, state-of-the-art climate models show a large SST warm bias in this region. Knowledge about the seasonal mixed layer (ML) heat budget is a prerequisite for understanding SST mean state and its variability. Within this study all contributions to the seasonal ML heat budget are estimated at four locations within the Atlantic cold tongue (ACT) that are representative for the western (0°N, 23°W), central (0°N, 10°W, Fig. 6) and eastern (0°N, 0°E) equatorial as well as the southern (10°S, 10°W) ACT. To estimate the contribution of the diapycnal heat flux due to turbulence an extensive data set of microstructure observations collected during 10 research cruises between 2005 and 2012 is analyzed. The results for the equatorial ACT indicate that with the inclusion of the diapycnal heat flux the seasonal ML heat budget is balanced (Fig. 6). Within the equatorial region, the diapycnal heat flux is essential for the development of the ACT. It dominates over all other cooling terms in the central and eastern equatorial ACT, while it is of similar size as the zonal advection in the western equatorial ACT. In contrast, the SST evolution in the southern ACT region can be explained entirely by air-sea heat fluxes

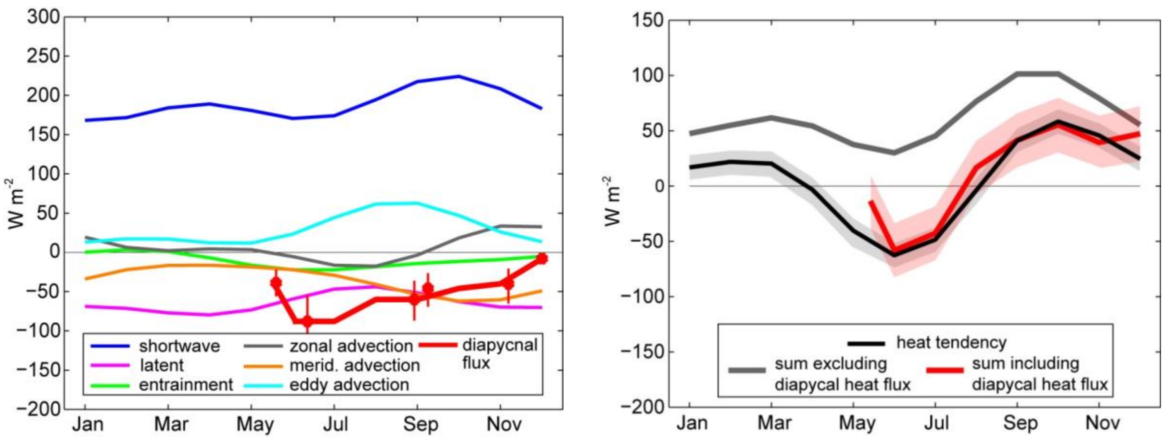

Fig. 6: Individual heat flux contributions (left panel) to the mixed layer heat budget on the equator at 10°W (color code explained in the legend). Vertical red lines denote 95 % confidence limits for the diapycnal heat flux. The right panel shows the sum of the individual flux contributions without (grey) and with (red) the diapycnal mixed layer heat flux; observed heat tendency is indicated by the black line. Light grey shading and light red shading denotes 95 % confidence limits for heat tendency and the sum of all flux terms including the diapycnal ML heat loss.

Role of interannual Kelvin wave propagations in the equatorial Atlantic on the Angola Benguela Current system

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The link between equatorial Atlantic Ocean variability and the coastal region of Angola-Namibia is investigated at interannual time scales from 1998 to 2012. An index of equatorial Kelvin wave activity is defined based on Prediction and Research Moored Array in the Tropical Atlantic (PIRATA). Along the equator, results show a significant correlation between interannual PIRATA monthly dynamic height anomalies, altimetric monthly sea surface height anomalies (SSHA), and SSHA calculated with an Ocean Linear Model. This allows us to interpret PIRATA records in terms of equatorial Kelvin waves. Estimated phase speed of eastward propagations from PIRATA equatorial mooring remains in agreement with the linear theory, emphasizing the dominance of the second baroclinic mode. Systematic analysis of all strong interannual equatorial SSHA shows that they precede by 1–2 months extreme interannual sea surface temperature anomalies along the African coast (Fig. 7), which confirms the hypothesis that major warm and cold events in the Angola-Benguela current system are remotely forced by ocean atmosphere interactions in the equatorial Atlantic. Equatorial wave dynamics is at the origin of their developments. Wind anomalies in the Western Equatorial Atlantic force equatorial downwelling and upwelling Kelvin waves that propagate eastward along the equator and then poleward along the African coast triggering extreme warm and cold events, respectively (Fig. 7). A proxy index based on linear ocean dynamics appears to be significantly more correlated with coastal variability than an index based on wind variability. Results show a seasonal phasing, with significantly higher correlations between our equatorial index and coastal SSTA in October–April season.

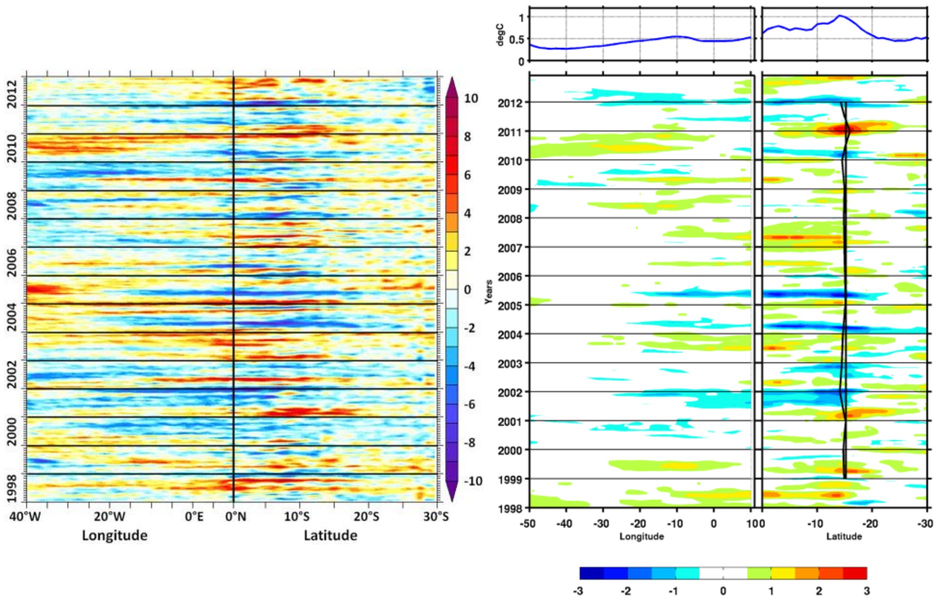

Fig. 7: Longitude-time and latitude-time Hovmøller diagrams of monthly detrended sea surface height anomalies (left panel) and sea surface temperature anomalies (right panel) in cm and °C respectively. Upper right panel shows standard deviation of sea surface temperature. Data used in the figures were averaged between 1°S and 1°N along the equator, and from the coast to 1° offshore at the boundaries.

Equatorial Atlantic interannual variability and its relation to dynamic and thermodynamic processes

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The contributions of the dynamic and thermodynamic forcing to the interannual variability of the equatorial Atlantic sea surface temperature are investigated using a set of interannual regional simulations of the tropical Atlantic Ocean. The ocean model is forced with an interactive atmospheric boundary layer, avoiding damping toward prescribed air-temperature as is usually the case in forced ocean models. The model successfully reproduces a large fraction ($R^2 = 0.55$) of the observed interannual variability in the equatorial Atlantic. In agreement with leading theories, our results confirm that the interannual variations of the dynamical forcing largely contributes to this variability. We show that mean and seasonal upper ocean temperature biases, commonly found in fully coupled models, strongly favor an unrealistic thermodynamic control of the Equatorial Atlantic interannual variability.

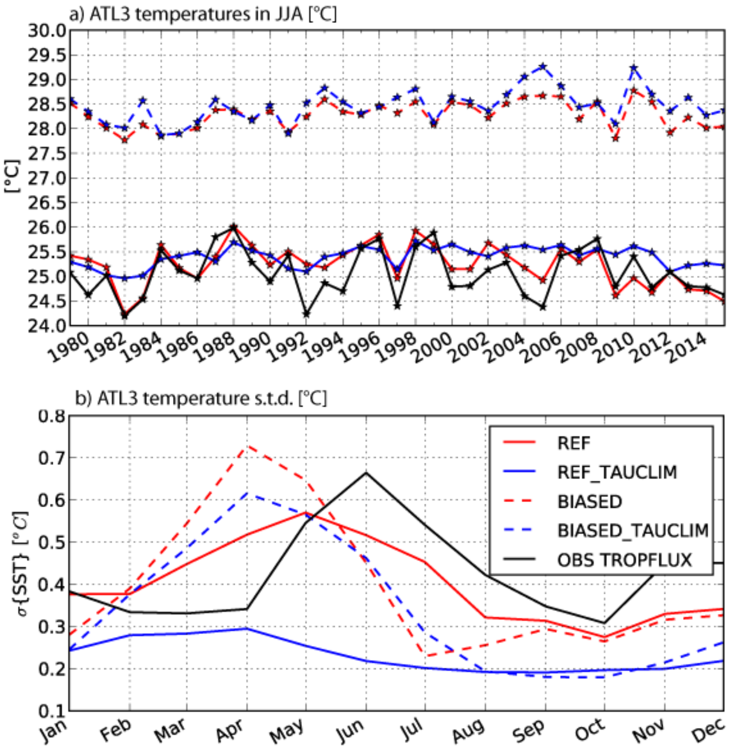

Fig. 8: Time series of Atl3 index (sea surface temperature averaged from June through August between 20°W-0°N and 3°S-3°N) obtained from TropFlux and simulations (upper panel). Lower panel shows monthly standard deviation of Atl3 SST using data from 1979 to 2015 from TropFlux (black) and from different model runs. Units are °C. The model run forced with heat fluxes only (Ref_Tauclim, blue solid line) does not produce interannual variability in the Atl3 region.

Mixed layer heat and salt budget and Equatorial Undercurrent dynamics in the tropical Atlantic from a joint model-observations approach

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Climatological mixed layer heat and salt budget terms derived from a NEMO 1/4° forced model simulation and from a PREFACE observation-based product are compared in the eastern tropical Atlantic. Mean spatial patterns of mixed layer depth, SST and SSS are in good agreement despite some local biases. For the annual mean heat balance, atmospheric fluxes are quite different along the coasts, while horizontal advection mostly differs around the equator, maybe due to the low resolution of the observations (2.5°) that cannot resolve small meridional scales. The seasonal heat balance is compared in boxes off Angola, in the northeast Gulf of Guinea and in the Atlantic cold tongue. Seasonal variations of heat fluxes are correlated except in the last box, while advection is everywhere poorly correlated. For the annual mean salt balance, model and observations show similar freshwater fluxes, with larger spatial contrasts in the model, while advection mostly differs around the ITCZ. In the Benguela region, model and observations roughly agree on freshwater fluxes and advection seasonal variations. Off Angola, SSS variations are uncorrelated. The observation-based product does not explicitly resolve vertical diffusion, an important process for the heat and salt balance in the Gulf of Guinea.

The seasonal characteristics of the simulated EUC transport are compared to observations based on cruises and moorings at 23°W. In the model, the EUC transport is slightly larger than observed on average, while its seasonal cycle is of comparable amplitude and shows a maximum around September and minimum in November, leading the observations by one month. The maximum velocity is also biased high but seasonal cycles are consistent and roughly phased with the transport seasonal cycle. The EUC core in the model is shallower than observed but with a similar seasonal cycle and coinciding maxima in depth and transport. Its latitudinal position is more south of the equator, with a seasonal cycle opposite in phase and larger than observed. A test simulation with interannual wind forcing but climatological fluxes forcing is compared to the reference simulation to identify the respective role of dynamic and thermodynamic forcing on the EUC characteristics, in particular its salinity maximum.

The Angola Current: Flow and hydrographic characteristics as observed at 11°S

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The eastern boundary circulation off the coast of Angola has been described only sparsely to date, although it is a key element in the understanding of the highly productive tropical marine ecosystem off Angola. Here, we report for the first time direct velocity observations of the Angola Current (AC) at 11°S collected between July 2013 and October 2015 in the depth range from 45 to 450 m. The measurements reveal an alongshore flow that is dominated by intraseasonal to seasonal variability with periodically alternating southward and northward velocities in the range of +/- 40 cm s^{-1}. During the observation period, a weak southward mean flow of 5–8 cm s^{-1} at 50 m depth is observed, with the southward current extending down to about 200 m depth. Corresponding mean southward transport of the AC is estimated to be 0.32 +/- 0.05 Sv. An extensive set of hydrographic measurements is used to investigate the thermal structure and seasonality in the hydrography of the eastern boundary circulation (Fig. 9). Within the depth range of the AC, the superposition of annual and semiannual harmonics explains a significant part of the total variability, although salinity in the near surface layer appears to be also impacted by interannual variability and/or short-term freshening events. In the central water layer, temperature and salinity on isopycnals vary only weakly on seasonal to annual time scales. The available data set is further used to evaluate different reanalysis products particularly emphasizing the ocean's role in coupled climate model SST biases in the Eastern Tropical Atlantic.

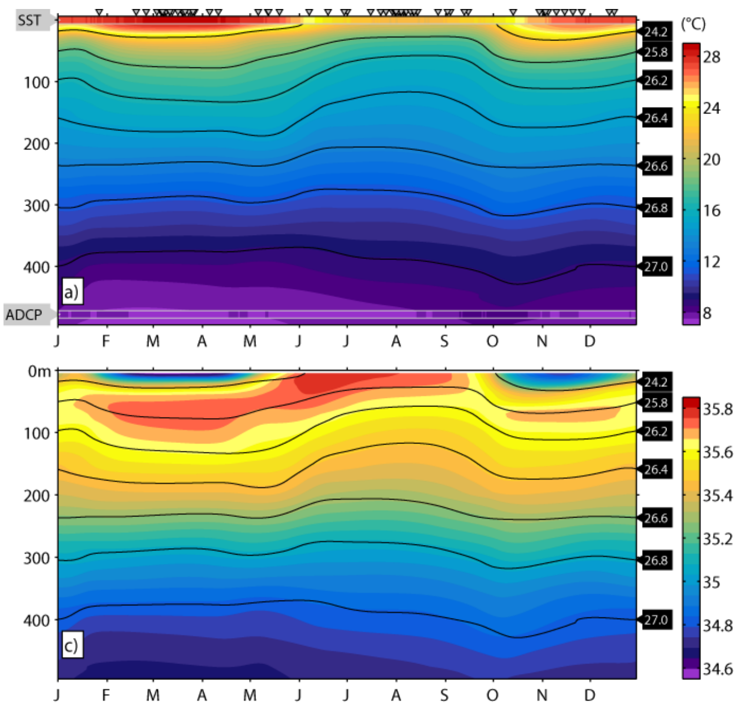

Fig. 9: Seasonal distribution of potential temperature a) and salinity c) derived from available hydrographic measurements at 11°S. Sampling times relative to the calendar year are indicated at the top. Black lines represent isopycnals.

Causes and evolution of the Southeastern Tropical Atlantic warm event in early 2016

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A strong but short-lived warm event occurred in the Southeastern tropical Atlantic Ocean off Angola and Namibia in January 2016 with sea surface temperature anomalies reaching 3°C (Fig. 10). The analysis of direct observations aided by a model simulation suggests that the warming was, in contrast to previous Benguela Niño events, not linked to equatorial Kelvin wave propagation or a significant reduction in upwelling of subsurface waters. Instead, our analysis suggests that a shallow layer of warm and fresh surface water was advected poleward by southward surface currents, consistent with a weakening of the southerly winds. Velocity measurements at 11°S show that at the time of the event subsurface velocities were directed northward while surface velocities were directed southward, indicating enhanced upper ocean stratification. This is supported by satellite sea surface salinity data that show a pronounced negative anomaly in February 2016. The surface freshwater anomaly, caused by excess precipitation and enhanced Congo river outflow, can form a barrier layer that inhibits the entrainment of cool subsurface waters into the surface mixed layer, thus supporting the development of a surface warm anomaly.

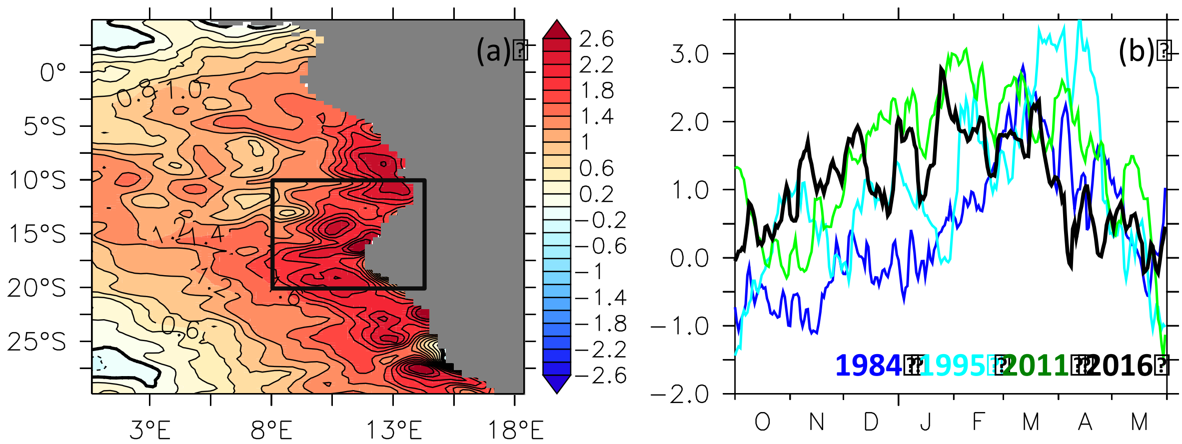

Fig. 10: Sea surface temperature anomaly (in °C, NOAA OI-SST product) averaged over the time period January 15 to February 15, 2016 (left panel). Right panel shows time series of interannual sea surface temperature anomalies averaged over the Angola-Benguela index (20°S to 10°S and from 8°E to the coast) from October 2015 to May 2016 (black solid line); previous Benguela Niño events added for comparison: 1983/84 (blue), 1994/95 (light blue), 2010/11 (green).

Seasonal Mixed Layer Heat and Salinity Budget in the south eastern tropical Atlantic

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An extensive hydrographic dataset, compiled from public as well as previously unavailable archives, is used to quantify the physical processes contributing to the mixed layer heat and salinity budgets in the south eastern tropical Atlantic. This new climatology provides seasonal variations of mixed layer heat content and salinity. The surface heat and freshwater fluxes, horizontal advection from near-surface velocities, horizontal eddy advection, and vertical entrainment contributing to these variations are calculated for several subregions (Fig. 11) of the south eastern tropical Atlantic and the potential impact of diapycnal mixing is assessed. In the off-equatorial areas, the most important cooling term is zonal heat advection during the whole year. Horizontal heat advection due to eddy steering is an additional major heat flux and supplies heat to the Angola and Benguela upwelling regions from offshore. The surface heat flux is identified as the main driver of seasonal heat content variations due to the large annual cycle of short-wave radiation. Throughout the off-equatorial areas, evaporation is larger than precipitation and their combined impact on the mixed layer salinity is balanced by zonal freshwater advection. Particularly in the eastern equatorial Atlantic, other oceanic processes also contribute to the mixed layer salinity budget.

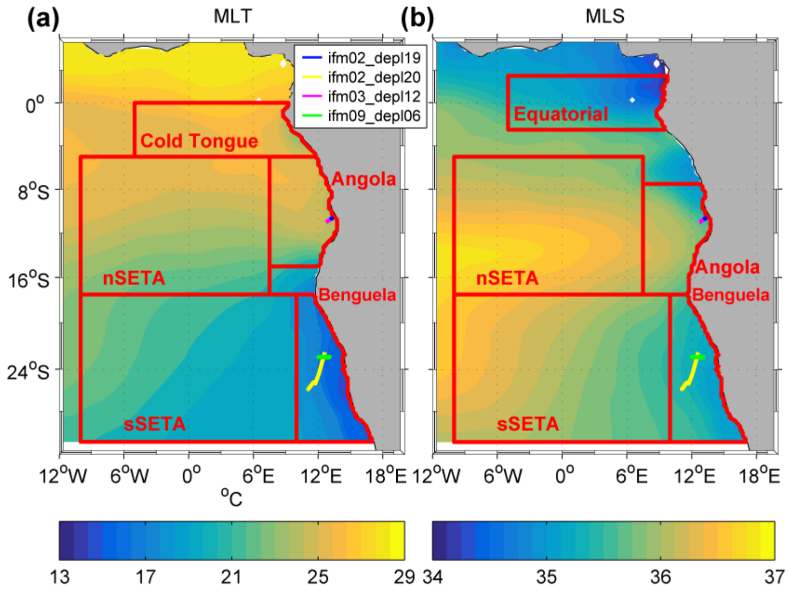

Fig. 11: Annual mean mixed layer temperature (a) and salinity (b) as shaded contours, regions for mixed layer budget calculations (red boxes) and glider tracks.

Is there evidence of changes in Tropical Atlantic Variability modes under AMO phases in the observational record?

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The Atlantic Multidecadal Oscillation (AMO) is the leading mode of Atlantic sea surface temperature (SST) variability at multidecadal time-scales. Previous studies have denoted that AMO could modulate El Niño-Southern Oscillation (ENSO) variance. However, the role played by AMO in the Tropical Atlantic Variability (TAV) is still uncertain. Here, it is demonstrated that during negative AMO phases, associated with a shallower thermocline, the eastern equatorial Atlantic SST variability is enhanced by more than 150% in boreal summer. Consequently, the inter-annual TAV modes are modified. During negative AMO, the Atlantic Niño displays larger amplitude and a westward extension (Fig. 12) and it is preceded by a simultaneous weakening of both Subtropical Highs in winter-spring. In contrast, a meridional seesaw SLP pattern evolving into a zonal gradient, leads the Atlantic Niño during positive AMO. The North Tropical Atlantic mode is related to a Scandinavian blocking pattern during winter-spring in negative AMO, while under positive AMO it is part of the SST-tripole associated with the North Atlantic Oscillation. Interestingly, the emergence of an overlooked variability mode, denoted as Horse-Shoe (HS) pattern, is favored during negative AMO (Fig. 12 e). This anomalous warm (cool) HS surrounding an eastern equatorial cooling (warming) is remotely forced by an ENSO phenomenon. During negative AMO, the tropical extratropical teleconnections are enhanced and the Walker circulation is altered. This, together with the increased equatorial SST variability, could promote the ENSO impacts on TAV. Our results give a step forward in the better understanding of TAV, which is essential to improve its modelling, impacts and predictability.

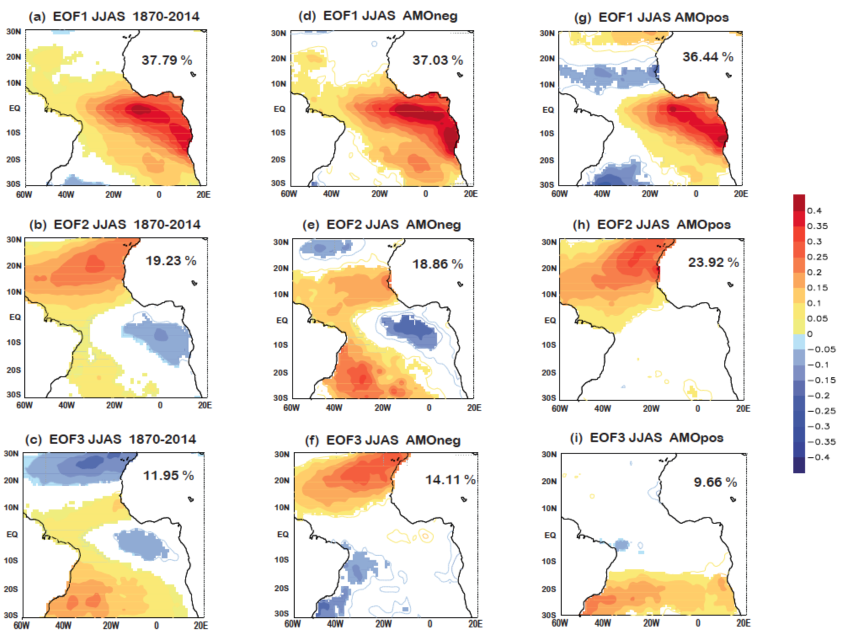

Fig. 12: Modes of inter-annual SST variability in the Tropical Atlantic. Regression maps of the anomalous SSTs for the first three Empirical Orthogonal Functions (EOFs) of inter-annual tropical Atlantic [60°W-20°E, 30°N-30°S] variability in June-July-August-September (JJAS) for the total period 1870-2014 (a-c), negative (d-f) and positive (g-i) AMO phases. Significant values exceeding 95% confidence level according to a Monte Carlo test are shown in shaded, while the total regression field is presented in contours.

Thermodynamic controls of the Atlantic Niño

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Prevailing theories on the equatorial Atlantic Niño are based on the dynamical interaction between atmosphere and ocean. However, dynamical coupled ocean-atmosphere models poorly simulate and predict equatorial Atlantic climate variability. Here we use multi-model numerical experiments to show that thermodynamic feedbacks excited by stochastic atmospheric perturbations can generate Atlantic Niño s.d. of ~ 0.28 ± 0.07 K, explaining ~ 68 ± 23 % of the observed interannual variability. Thus, in state-of-the-art coupled models, Atlantic Niño variability strongly depends on the thermodynamic component ($R^2 = 0.92$). Coupled dynamics acts to improve the characteristic Niño-like spatial structure but not necessarily the variance. Perturbations of the equatorial Atlantic trade winds (~ ± 1.53 m s^{-1}) can drive changes in surface latent heat flux (~ ± 14.35 W m^{-2}) and thus in surface temperature consistent with a first-order autoregressive process. By challenging the dynamical paradigm of equatorial Atlantic variability, our findings suggest that the current theories on its modelling and predictability must be revised.

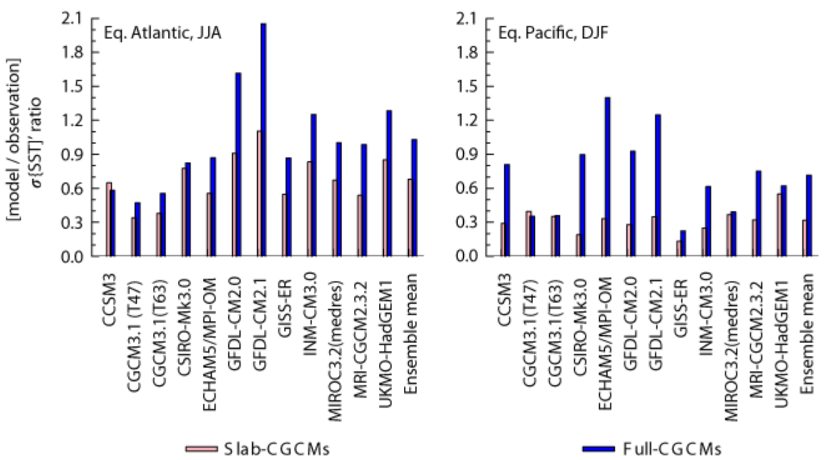

Fig. 13: Atlantic Niño (left) and Pacific Niño-3 (right) model/observation ratio of the σ{SST}'. Blue bars denote the ratios for full-CGCMs, light-pink bar denote model runs using slab-CGCMs. A ratio of >1.0 denotes an overestimation of observed variability of ~0.40 K and ~0.95 K for the Atlantic Niño and Pacific Niño-3, respectively. The calculations are based on the June through August (left panel) and December through February (right panel) seasonal means, respectively.

Main processes of the Atlantic cold tongue interannual variability

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The authors investigate the interannual variability of the Atlantic cold tongue (ACT) by means of a mixed-layer heat budget analysis. A method to classify extreme cold and warm ACT events is proposed and applied to ten various analysis and reanalysis products. This classification allows 5 cold and 5 warm ACT events to be selected over the period 1982–2007. Cold (warm) ACT events are defined by the presence of negative (positive) sea surface temperature (SST) anomalies at the center of the equatorial Atlantic in late boreal spring, preceded by negative (positive) zonal wind stress anomalies in the western equatorial Atlantic. An ocean general circulation model capable of reconstructing the interannual variability of the ACT correctly is used to demonstrate that cold ACT events develop rapidly from May to June mainly due to intense cooling by vertical mixing and horizontal advection (Fig. 14). The simulated cooling at the center of the basin is the result of the combined effects of non-local and local processes. The non-local process is an upwelling associated with an eastward-propagating Kelvin wave, which makes the mixed-layer more shallow and preconditions the upper layers to be cooled by an intense heat loss at the base of the mixed-layer, which is amplified by a stronger local injection of energy from the atmosphere. The early cooling by vertical mixing in March is also shown to be a good predictor of June cooling. In July, horizontal advection starts to warm the mixed-layer abnormally and damps SST anomalies. The advection anomalies, which result from changes in the horizontal temperature gradient, are associated in some cases with the propagation of Rossby waves along the equator. During warm ACT events, processes are reversed, generating positive SST anomalies: a downwelling Kelvin wave triggers stratification anomalies and mixed-layer depth anomalies, amplified by a weaker injection of energy from the atmosphere in May–June. In July, warm ACT events are abnormally cooled due to negative horizontal advection anomalies resulting from processes similar to those that occur during cold ACT events. This additional cooling process extends the period of cooling of the ACT, reducing SST anomalies.

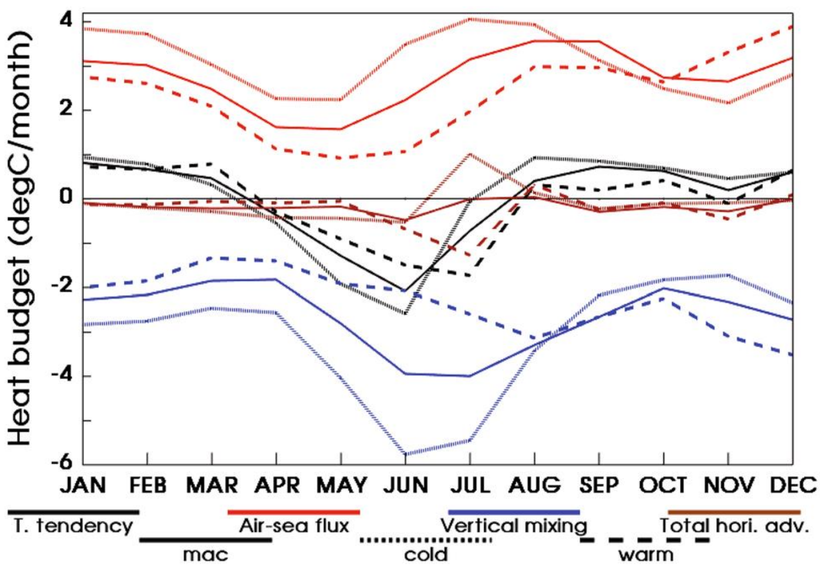

Fig. 14: Mean annual cycle in solid line, and composites of cold and warm ACT events years in dotted line and dashed lines respectively of different terms of the mixed-layer heat budget in (°C/month) averaged from 15°W to 6°W and from 4°S to 1°N. Black lines indicate temperature tendency, red lines indicate net heat flux between ocean and atmosphere, blue lines indicate heat flux due to vertical mixing at the base of the mixed layer and brown lines represent the sum of low and high frequency horizontal advection.

PREFCLIM: A high-resolution mixed-layer climatology of the eastern tropical Atlantic.

Willi Rath[1], Marcus Dengler[1], Jan Lüdke[1], Sunke Schmidtko[1], Peter Brandt[1], Rebecca Hummels[1], Michael Schlundt[1] Karl Bumke[1], Marek Ostrowski[2], Pedro Tchipalanga[3], Anja van der Plas[4], Tim Junker[5], Volker Mohrholz[5], Abdoulaye Sarre[6], Bomba Sangolay[3]

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A new mixed-layer climatology for the eastern tropical Atlantic is presented. The climatology contains a high-resolution (0.25 degrees) monthly-mean mixed layer hydrography (mixed-layer depth, temperature, salinity), and coarse-resolution (2.5 degrees) estimates of the mixed-layer heat and salt balance, as well as of near-surface velocities and of air-sea fluxes. All existing hydrographic products of the region were hampered by the sparse availability of near-shore data owned by the West-African coastal countries, which could, however, be included in the new climatology (Fig. 15).

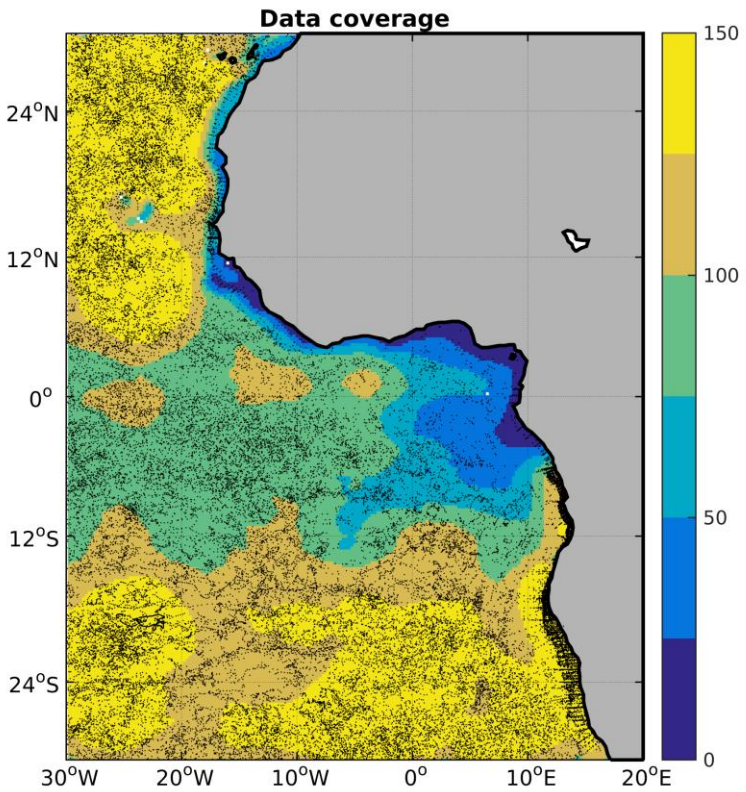

Fig. 15: Distribution of data included in the new PREFACE hydrographic climatology. Colours show the number of data points of each respective ¼°-degree grid box. Black dots show positions of newly included data (CTD profiles, Glider profiles, Argo profiles, see text for details) in reference to an existing climatology.

Origin, development and demise of the 2010-2011 Benguela Niño

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A Benguela Niño developed in November 2010 and lasted for 5 months along the Angolan and Namibian coastlines. Maximum amplitude was reached in January 2011 with an interannual monthly sea surface temperature anomaly larger than 4°C at the Angola-Benguela Front. It was the warmest event since 1995. Consistent with previous Benguela Niños, this event was generated by a relaxation of the trade winds in the western equatorial Atlantic, which triggered a strong equatorial Kelvin wave propagating eastward along the equator and then southward along the southwest African coast. In the equatorial band, the associated ocean sub-surface temperature anomaly clearly shows up in data from the PIRATA mooring array. The dynamical signature is also detected by altimetry derived Sea Surface Height and is well reproduced by an Ocean Linear Model. In contrast to previous Benguela Niños, the initial propagation of sub-surface temperature anomalies along the equator started in October and the associated warming in the Angolan Benguela Front Zone followed on as early as November 2010. The warming was then advected further south in the Northern Benguela upwelling system as far as 25°S by an anomalously strong poleward sub-surface current. Demise of the event was triggered by stronger than normal easterly winds along the equator in April and May 2011 leading to above normal shoaling of the thermocline along the equator and the south-west African coastline off Angola and an associated abnormal equatorward current at the Angola Benguela Front in April and May 2011.

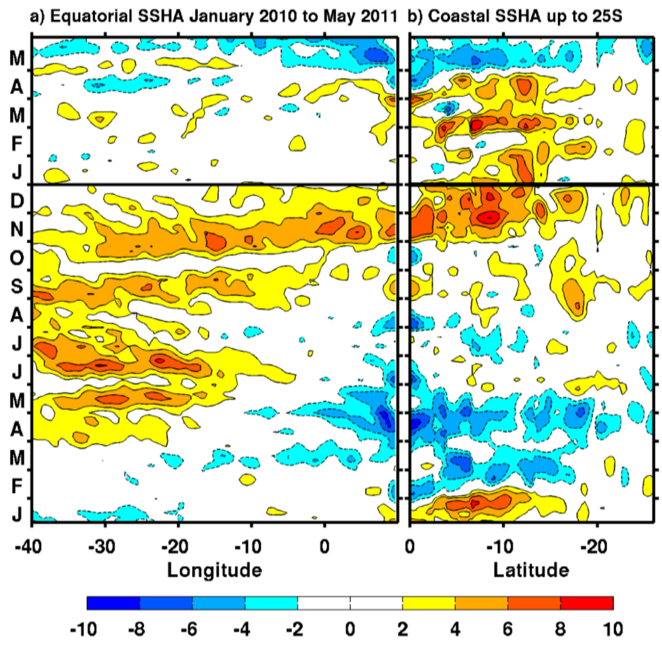

Fig. 16: Hovmøller diagram of detrended altimetry derived sea surface height anomalies (SSHA, in cm) from monthly climatology along the equator (averaged over 1°S to 1°N, left) from 40°W to the African coastline and along the Southern African coast (averaged from the coast to 1° offshore, right) from 0°S to 25°S from January 2010 (bottom) to May 2011 (top).

Mixed layer heat and salinity budgets during the onset of the 2011 Atlantic cold tongue

Michael Schlundt[1], Peter Brandt[1,2], Marcus Dengler[1], Rebecca Hummels[1], Tim Fischer[1], Karl Bumke[1], Gerd Krahmann[1], Johannes Karstensen[1]

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The mixed layer (ML) temperature and salinity changes in the central tropical Atlantic have been studied by a dedicated experiment (Cold Tongue Experiment, CTE) carried out from May-July 2011. The CTE was based on two successive research cruises, a glider swarm, and moored observations. The acquired in-situ datasets together with satellite, reanalysis, and assimilation model data were used to evaluate box-averaged ML heat and salinity budgets for two sub-regions: 1) the western equatorial Atlantic Cold Tongue (ACT) (23°-10°W) and 2) the region north of the ACT. The strong ML heat loss in the ACT region during the CTE was found to be the result of the balance of warming due to net surface heat flux and cooling due to zonal advection and diapycnal mixing. The dominant role of diapycnal mixing in ML cooling could be confirmed by sparse shipboard microstructure measurements. The northern region was characterized by weak cooling and the dominant balance of net surface heat flux and zonal advection. A strong salinity increase occurred at the equator, 10°W, just before the CTE. During the CTE, ML salinity in the ACT region slightly increased. Largest contributions to the ML salinity budget were zonal advection and the net surface freshwater flux. Diapycnal mixing played a minor role. In the region north of the ACT, the ML freshened at the beginning of the CTE due to precipitation, followed by a weak salinity increase. Zonal advection changed sign contributing to ML freshening at the beginning of the CTE and salinity increase afterward.

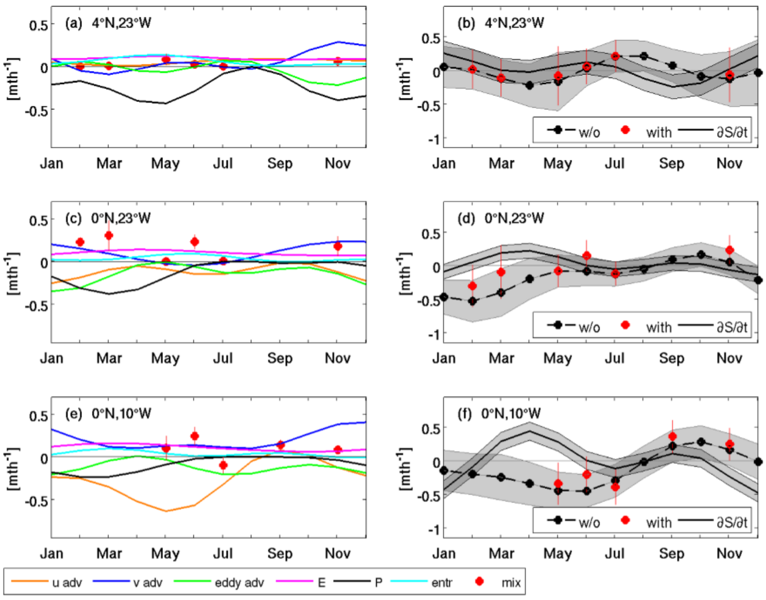

Fig. 17: Seasonal cycles of the contributing terms to the mixed layer salinity budget (left panels) and the comparison of local salinity tendency and the sum of the contributing terms (right panel) at three poitions. The different contributions in the left panels are zonal (u adv), meridional (v adv), and eddy (eddy adv) salinity advection, evaporation (E), precipitation (P), entrainment (entr), and diapycnal mixing (mix). Black dashed-dotted lines (right panels) are the sum without diapycnal mixing and red dots are the sum with diapycnal mixing.

Eastern boundary circulation and hydrography off Angola – building oceanographic capacities in Southwestern Africa

Pedro Tchipalanga[1], Marcus Dengler[2], Peter Brandt[2,3], Robert Kopte[2], Marisa Macuéria[4], Paulo Coelho[4], Marek Ostrowski[5] and Noel S. Keenlyside

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The eastern boundary region off Angola encompasses a highly productive ecosystem important for the food security of the coastal population. The fish-stock distribution, however, undergoes large variability on intraseasonal, interannual and longer time scales. These fluctuations are partly associated with large-scale warm anomalies which are often forced remotely from the equatorial Atlantic and propagate southward reaching the Benguela upwelling off Namibia. Such warm events, named Benguela Niños, occurred in 1995 and in 2011. Here we present results from an under-explored extensive in-situ dataset that was analyzed in the framework of a capacity building effort. The dataset was acquired within the Nansen Programme executed by the Food and Agricultural Organization of the United Nations and funded by the Norwegian Agency for Development Cooperation. It consists of hydrographic and velocity data from the Angolan continental margin acquired biannually during the main downwelling and upwelling seasons over more than 20 years. The mean seasonal changes of the Angola Current from 6°S to 17°S are presented. During austral summer the southward Angola Current is concentrated in the upper 150 m. It strengthens from north to south reaching a velocity maximum just north of the Angola Benguela Front. During austral winter the Angola Current is weaker, but deeper reaching. On interannual timescales, the hydrographic data reveals remarkable variability in subsurface upper ocean heat content (Fig. 18): While the 1995 Benguela Niño showed no particular signal at subsurface, the 2011 Benguela Niño was preceded by a strong subsurface warming of about 2 year duration (Fig. 18).

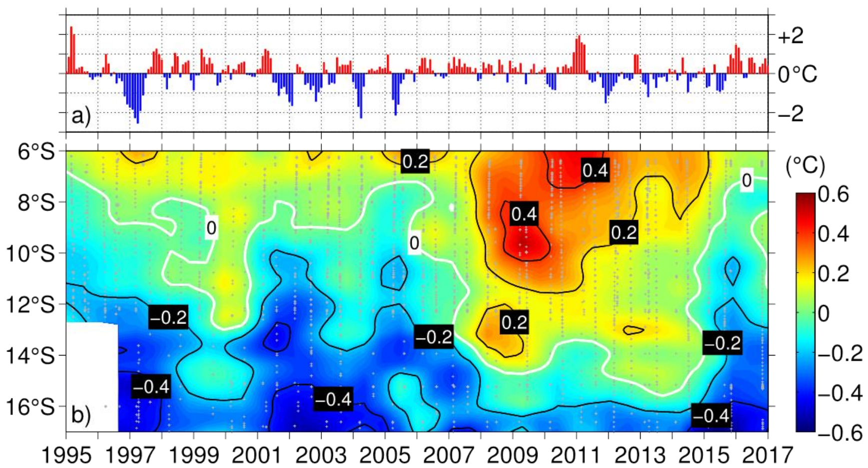

Fig. 18: Upper panel shows Angola Benguela Area (ABA) sea surface temperature index from 1995 to 2017 determined from NOAA-OISST. Lower panel depicts interannual variability of temperature anomaly along the continental slope off Angola in the upper thermocline. Temperature was averaged between the isopycnal σ_θ=26.0 kg m^{-3} and σ_θ=26.5 kg m^{-3}. Altogether, 2987 CTD and uCTD profiles collected from March 1995 to November 2016 were used.

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