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

If this report is not to be made public, please state here why:

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

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

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Deviation from planned efforts for this deliverable: none.

Executive Summary:

The aim of this deliverable is to better understand remote and local forcing of warm and cold events along the equator as well as along the coastal upwelling regions of both hemispheres. This deliverable is mainly based on the analysis of observational data, their statistical analysis, and its interpretation in a dynamical context using idealized and realistic models. Previous work largely relied on the analysis of remote-sensing data (Polo et al. 2008) or model simulations (Richter et al. 2010). They show the impact of equatorial wave propagation and further wave propagation along the coastal wave guide in forcing coastal sea surface temperature variability. However also the local forcing, e.g. via the variability of the South Atlantic anticyclone (also forcing the equatorial waves), plays an important role for the development of Benguela Niños. More recently, Bachèlery et al. (2016) showed, based on a high-resolution model study that the importance of remote vs. local forcing along the Southeast Atlantic wave guide depends on the time scale of variability. By explicitly excluding seasonal variability, they showed that interannual variability is strongly related to equatorial forcing, while intraseasonal variability is dominantly forced locally. Here, we use the available observational database as well as data acquired in the frame of the PREFACE program to study the variability of temperature, salinity and currents in the different upwelling systems, i.e. equatorial upwelling as well as coastal upwelling of both hemispheres. The main results can be summarized as follows:

a) Equatorial variability

A focus of our studies was on the seasonal cycle. Brandt et al. (2016) analyzed the role of equatorial waves in establishing resonant equatorial basin modes. It could be shown that specific baroclinic mode waves are amplified and the superposition of the dominant second baroclinic mode semi-annual and the fourth baroclinic mode annual basin modes could explain the observed semi-annual and annual variability of the Equatorial Undercurrent. Basin modes are forced by the wind stress in the near-equatorial Atlantic, but their amplitude is enhanced by resonance of east- and westward propagating equatorial waves. While these basin modes have maximum amplitude in zonal velocity at the mid-Atlantic equator, they also impact the eastern boundary circulation.

By revisiting the extreme cold event occurring at the equator during boreal summer 2009, local and remote forcing mechanisms were analyzed by Burmeister et al. (2016) based on in-situ and remote-sensing data. The results suggest that the local forcing via meridional advection is of minor importance for the 2009 cold event and the remote forcing via westward propagating Rossby waves north of the equator, its reflection, and following eastward propagation of equatorial Kelvin waves played a dominant role. Higher baroclinic mode waves were of particular importance.

At the equator at the eastern boundary, intraseasonal cold events were observed that were associated with unusual atmospheric conditions including an early onset of the monsoon. The forcing of these events involve a shallower thermocline associated with the arrival of the Kelvin wave from the west as well as intraseasonal southerly wind intensification.

b) Southern hemisphere eastern boundary variability

First moored velocity observations of the Angola Current at 11°S revealed the existence of a mean southward flow in the upper 200 m superimposed by pronounced semi-annual and annual variability (Kopte et al. 2017). Dynamically, these seasonal velocity fluctuations can be explained by the remote forcing from the equatorial Atlantic. As shown by Brandt et al. (2016) the seasonality of zonal velocity at the equator is dominated by resonant equatorial basin modes. However, the off-equatorial lobes of these equatorial basin modes are associated with meridional velocity fluctuation along the eastern boundary largely contributing to the observed seasonal variability of the Angola Current at 11°S.

Along the coastal wave guide further moorings were deployed roughly along the 120 m isobaths at 18°S, 20°S and 23°S. Analysis of the along-shore velocity indicate pronounced intraseasonal variability. Particularly for the northern two moorings, propagation of coastally trapped waves could be identified in the period band between 12 and 45 days. The origin of the forcing of these waves is a topic for further investigations.

On interannual time scales, the most pronounced variability in the Southeast Atlantic is associated with Benguela Niños. Using hydrographic and current data from more than 20 years of observations off Angola acquired within the EAF-Nansen program, the mean and the variability of temperature, salinity and currents in the eastern boundary regime were analyzed. The dataset particularly cover the 1995 and 2011 Benguela Niños that were remotely forced from the equatorial Atlantic as suggested by previous studies. Our analysis reveals substantial differences in the subsurface forcing of surface anomalies during both events with strong subsurface warm anomalies preceding the Benguela Niños in 2011 and no similar subsurface warming occurring during the 1995 Benguela Niño.

A strong but short-lived warm event occurred in the southeastern Atlantic Ocean off Angola and Namibia in January 2016 with SST anomalies reaching up to 2.5°C. The analysis of direct observations aided by a model simulation suggests that the warming was surface intensified and, in contrast to previous Benguela Niños, not linked to equatorial Kelvin wave propagation or a significant reduction in upwelling of cooler subsurface waters. The warm surface layer was characterized by a pronounced negative salinity anomaly, leading to an anomalous thin mixed layer and enhanced stratification. The warm, fresh surface water was advected poleward by southward surface currents, consistent with a weakening in the southerly winds.

c) Northern hemisphere eastern boundary variability

In the northern hemisphere the coastal upwelling in the Gulf Guinea was studied using realistic and idealized model simulations carefully validated against observation (Djakouré et al. 2017). The results suggest that two different generation processes of the coastal upwelling need to be considered: the upwelling east of Cape Palmas which is due to inertia, topographic variations and advective terms effects resulting in important vertical pumping and the upwelling east of Cape Three Points which is principally induced by local winds.

Further to the north the upwelling is studied using experimental data acquired during the UPSEN2–ECOAO campaign (Capet et al. 2017). The main focus was on mesoscale and submesocale processes responsible for the cross-shelf exchange as well as mixing induced by internal gravity waves. The latter process was suggested to be responsible for the sharpness of the front separating upwelling and offshore waters.

Annual and semi-annual cycle of equatorial Atlantic circulation associated with basin mode resonance

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Aim of this study was to dynamically explain seasonal variations in the equatorial Atlantic. The seasonal variability of the tropical Atlantic circulation is dominated by the annual cycle, but semi-annual variability is also pronounced, despite weak forcing at that period. Here we use multi-year, full-depth velocity measurements from the central equatorial Atlantic to analyze the vertical structure of annual and semi-annual variations of zonal velocity. A baroclinic modal decomposition finds that the annual cycle is dominated by the 4th mode and the semi-annual cycle by the 2nd mode. Similar local behavior is found in a high-resolution general circulation model. This simulation reveals that the annual and semi-annual cycles of the respective dominant baroclinic modes are associated with characteristic basin-wide structures. Using an idealized linear reduced-gravity model to simulate the dynamics of individual baroclinic modes, it is shown that the observed circulation variability can be explained by resonant equatorial basin modes. Corollary simulations of the reduced-gravity model with varying basin geometry (i.e. square basin versus realistic coastlines) or forcing (i.e. spatially uniform versus spatially variable wind) show a structural robustness of the simulated basin modes. A main focus of this study is the seasonal variability of the Equatorial Undercurrent (EUC) as identified in recent observational studies (Fig. 1). Main characteristics of the observed EUC including seasonal variability of transport, core depth, and maximum core velocity can be explained by the linear superposition of the dominant equatorial basin modes as obtained from the reduced-gravity model.

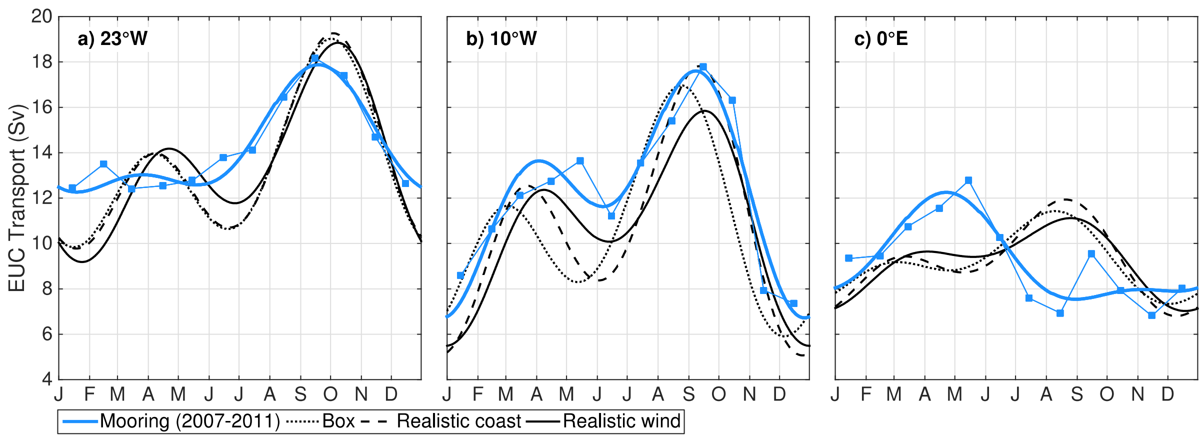

Figure 1: Monthly means (blue squares, thin blue lines) and annual plus semi-annual harmonic cycle of the 30-300 m EUC eastward transport at 23°W (a), 10°W (b), and 0°E (c) from observations taken from October 2007 to June 2011 and as reconstructed with the three different reduced-gravity model simulations: rectangular domain (dotted lines), realistic coastline domain (dashed lines), and realistic wind forcing (solid lines).

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

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The aim of this publication was to identify the remote and local forcing of an extreme cold event at the equator in boreal summer 2009. This event 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 in situ measurements were used in addition to satellite and reanalysis products to investigate the contribution of both mechanisms to the 2009 cold event. The results suggest that meridional advection (to be seen as a local forcing mechanism) 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.

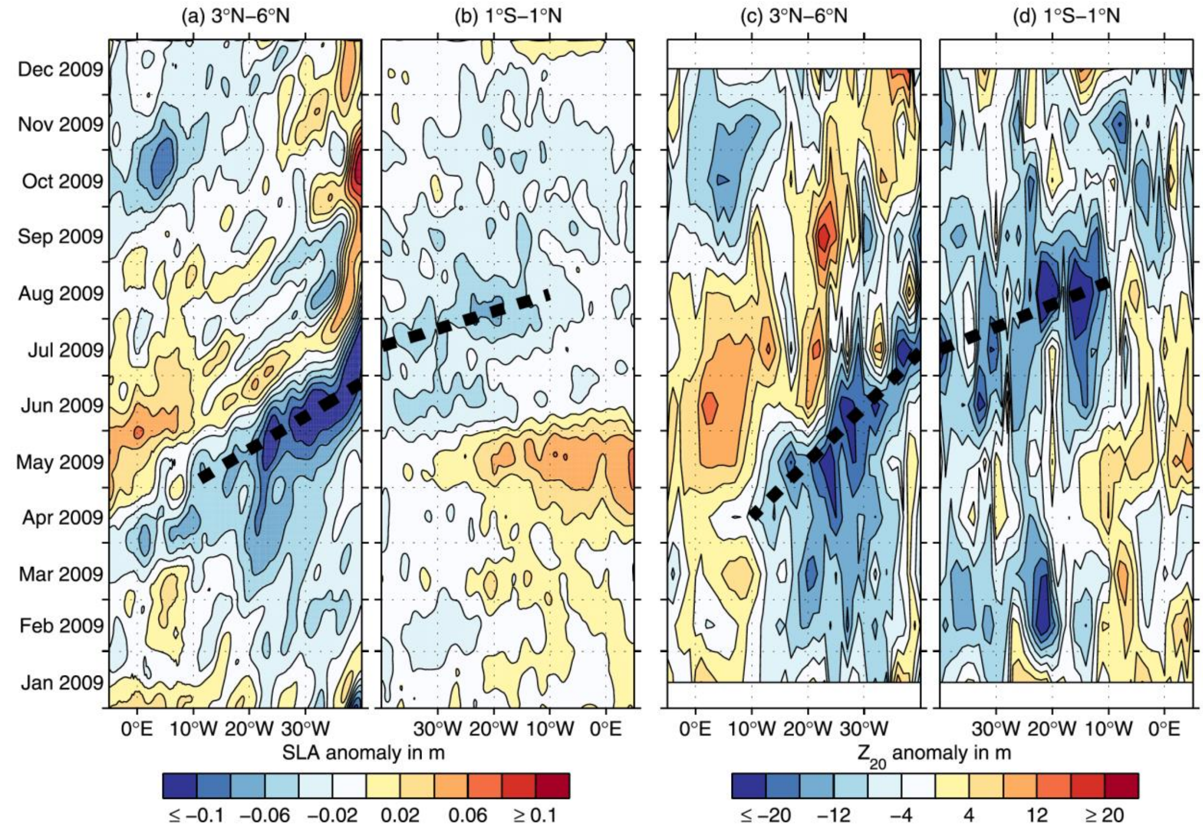

Figure 2: Anomalies of (a, b) sea level anomaly and (c, d) gridded Argo Z20 for the year 2009 with respect to the climatological mean (2005–2012), averaged in the latitude bands (a, c) 3°N–6°N and (b, d) 1°S–1°N. The black-dashed lines represent estimated propagation velocities of the negative anomalies, westward north of the equator and eastward along the equator.

Cold intraseasonal events in spring/summer 2005 and 2006 off Cape-Lopez (Gabon) and their forcing mechanisms, as inferred from numerical simulation and satellite SST data

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In this study, we investigate cold events occurring off Cape-Lopez (slightly south of the equator at the eastern boundary) at intraseasonal scales during spring and summer 2005 and 2006 (Fig. 3) and to which extent they are linked with the equatorial cold tongue. Off Cape-Lopez, shallower thermocline associated to the arrival of the Kelvin wave from the west as well as intraseasonal southerly wind intensification, modulate the strength of the cooling events observed at the equator and around 3°S. In 2005, mechanisms involving Kelvin wave reflection into Rossby waves and enhanced surface westward current (part of the South Equatorial Current) induce westward propagation of cold upwelled waters around 3°S. A particularly strong wind event occurs in mid-May 2005 and causes a strong cooling off Cape-Lopez and in the whole eastern Tropical Atlantic. This event, identified in previous study as responsible for the particularly early onset of the monsoon is characterized by particular and unusual oceanic and atmospheric conditions: it i) has the largest equatorward extension during May over 1998-2008 period; ii) is characterized by a particularly enhanced meridional SST gradient, found to be the earliest and strongest one over 1998-2008; iii) is associated with maximum rainfall in the Gulf of Guinea and in the northeastern Brazil; iv) is responsible for Kelvin wave generation in the western part of the basin.

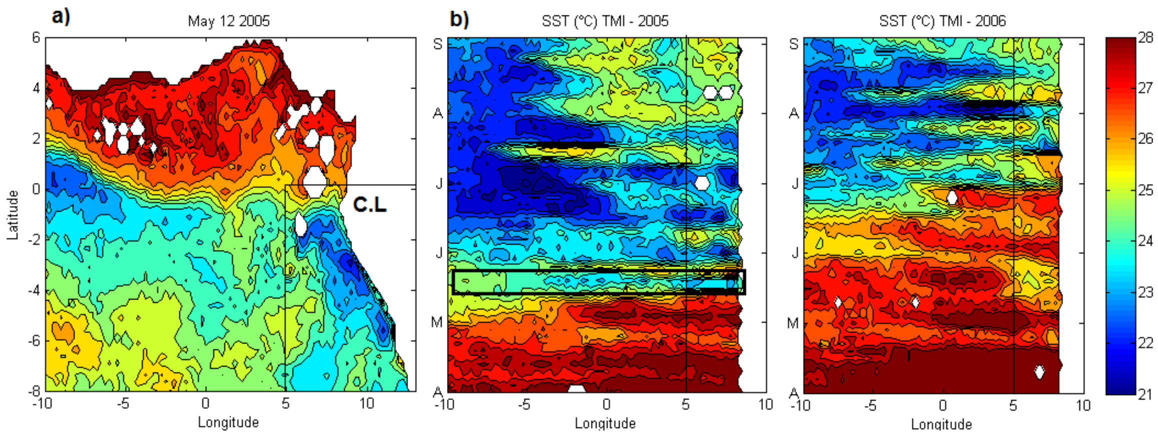

Figure 3: (a) Map of sea surface temperature (SST) (°C) from 3-day TMI data on May 12, 2005. Cape-Lopez is indicated by 'C.L'; (b) time-longitude diagram of SST from April 1 to September 1, 2005 and 2006 from TMI data. The black square indicates the mid-May 2005 event.

The Angola Current – flow and hydrographic characteristics as observed at 11°S

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On of the main aims of PREFACE was to enhance the observing system in the eastern South Atlantic. In this publication we report for the first time direct velocity observations of the Angola Current (AC) at ~11°S taken between July 2013 and October 2015, covering the depth range from 45 to 450 m. The measurements reveal an alongshore flow that is dominated by intra-seasonal to seasonal variability with periodically alternating southward and northward velocities in the range of ±40 cm/s. During the observation period, a weak southward mean flow of 5-8 cm/s at 50 m depth is observed, with the southward current extending down to about 200 m depth (Fig. 4). An extensive set of hydrographic measurements is used to investigate the thermal structure and seasonality in the hydrography of the eastern boundary circulation. Within the depth range of the AC the superposition of annual and semi-annual harmonics explains a significant part of the total variability, although salinity in the near surface layer appears to be also impacted by year-to-year variability and/or short-term freshening events. While this publication focused on a first description of eastern boundary current variability, following publication will address the mechanisms of the variability.

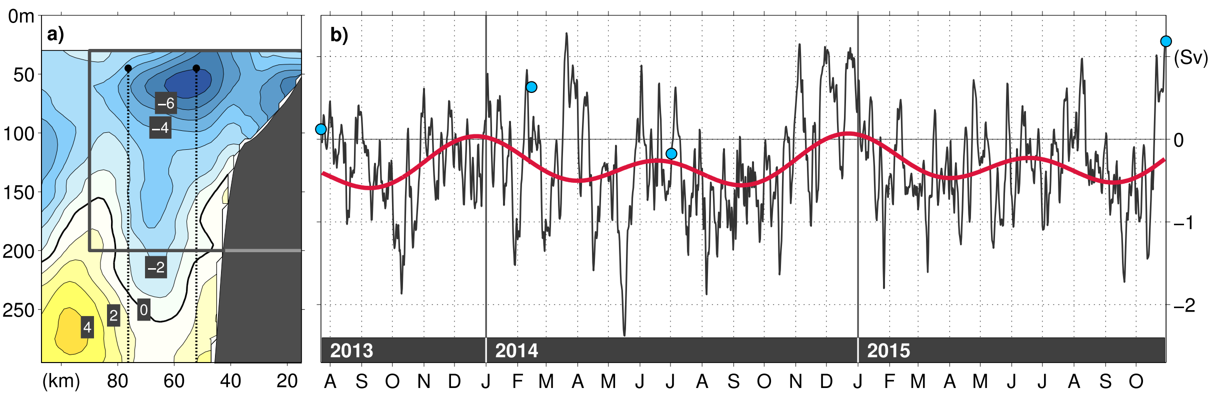

Figure 4: a) Mean alongshore velocity (cm/s) at ~11°S based on the reconstruction of the 3D flow field using mooring and shipboard velocity data. Positive values indicate northward and negative values indicate southward flow. b) Transport time series of the Angola Current at 11°S (black line) obtained by integrating the alongshore velocity from 30 to 200 m depth and from 15 to 90 km offshore (see grey box in a). Red line displays sum of semi-annual and annual harmonic. Blue dots indicate individual transport estimates based on shipboard velocity sections obtained during the mooring period.

Seasonal variability of the Angola Current related to resonant equatorial basin modes

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In this study we want to address the mechanism of semi-annual and annual velocity variability of the eastern boundary current off Angola. Multi-year velocity observations of the Angola Current near 11°S reveal pronounced seasonal variations that are superimposed on a weak southward mean flow. The seasonality is dominated by annual and semiannual oscillations with distinct baroclinic structures. In the equatorial Atlantic these periods were found to be associated with basin mode resonance of the fourth and second baroclinic modes, respectively (Brandt et al. 2016). Here, we investigate whether the observed seasonality at 11°S can be explained by a superposition of equatorial basin modes. Therefore, a suite of reduced gravity models for the tropical Atlantic is employed, each model representing a basin mode simulation for one particular combination of baroclinic mode and forcing period. The model runs cover the first five baroclinic modes with each mode being forced separately by the spatially varying Fourier components of JRA55 wind stress data corresponding to annual and semiannual frequencies (Fig. 5). Model-computed amplitudes are scaled with respect to amplitudes derived from a modal decomposition of surface-to-bottom velocities obtained from an equatorial mooring at 23°W. Model-computed phases are unchanged and are determined by the forcing and model characteristics. At 23°W, the linear superposition of the individual model simulations obtained for the different baroclinic modes are able to reproduce observed annual and semiannual cycles in zonal velocity reasonably well. The large-scale horizontal structure of basin modes indicates their dynamic influence on the eastern boundary circulation of the tropical ocean. The superposition of the model simulations yields consistent baroclinic structures compared to the observed annual and semiannual oscillations of alongshore velocity at 11°S off Angola. Although the model-computed semiannual cycle lacks amplitude at mid-depth, our findings underline the importance of large-scale equatorial dynamics for the seasonal variability of the boundary circulation off Angola.

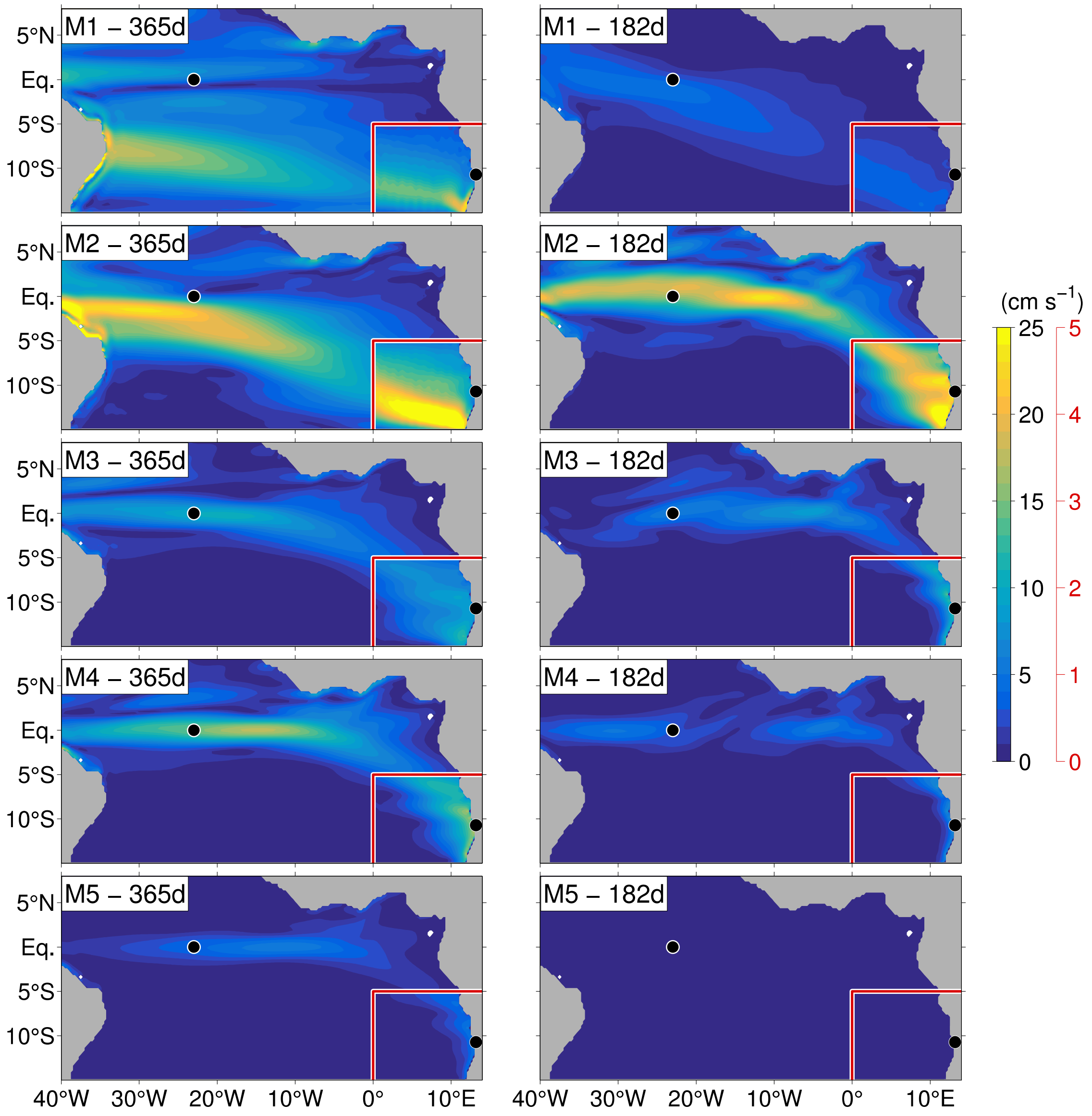

Figure 5: Amplitudes of annual (left) and semiannual (right) cycles of surface zonal velocities for baroclinic modes 1-5. Within the rectangle in the southeastern corner of the domain corresponding amplitudes of meridional velocity are shown (associated with the red color scale). Black dots denote locations of 23°W-Equator and 11°S-Angola moorings.

Low-frequency variability in the alongshore currents and continental shelf waves as revealed by observations along the south-west African coast

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This study investigates the alongshore-current variability along the Namibian shelf based on in situ observations at three different moorings deployed roughly along the 120 m isobath on the Namibian shelf between 18°S (LT18), 20°S (LT20) and 23°S (LT23). For each mooring, we obtained an alongshore velocity time series by decomposing the full spatio-temporal (t-z) alongshore velocity fields into ordinary EOFs. The results showed that the first mode amplitude explains more than 90% of the overall variance and is thought to mirror the alongshore velocity variability very well. The spectral characteristics of the time series were investigated by means of a wavelet method. At all three stations, high common power is seen in a sub-monthly to intra-seasonal band ($(12\ d)^{-1}$ to $(45\ d)^{-1}$)). The seasonal maximum in the wavelet power averaged across this band occurs around July, and a minimum is found in January. The global wavelet power spectrum obtained for the individual time series at each mooring position yields a variety of dominant peaks that spread across the frequency band (Fig. 6). Although most of the investigated time series do not allow conclusions about time scales in the seasonal range, the signal at 20°S shows a dominant semi-annual cycle.

We further calculated the wavelet coherence of the alongshore velocity at LT18 vs. LT20 and LT20 vs. LT23. The analysis shows coherent time series for both segments, albeit coherence is generally stronger for the northern segment. However, a strong difference between the two segments is found for the phase lag. The phase difference of LT18 and LT20 is more or less locked at positive values (LT18 leads LT20). In contrast, the phase difference of LT20 vs. LT23 varies about zero depending on the time and frequency. Only for short periods in the “weather band” the phase difference of the two segments is in good accordance.

The positive phase-locked relation between LT18 and LT20 strongly indicates a dynamical connection between both stations. Such a linkage may be provided by coastally trapped waves (CTWs). Typical phase speeds and wavelengths were estimated from the phase difference of the two stations in this study. In the sub-monthly to intra-seasonal frequency band ($(12\ d)^{-1}$ to $(45\ d)^{-1}$)), phase speeds range from 0.5 m/s to about 4 m/s. The associated wavelength is 1500 to 3100 km (Fig. 7).

Having established typical time and length scales of CTWs in the northern Benguela system and having shown differences in the coherence pattern along the Namibian coast, further emphasis must be put on the origin of these waves.

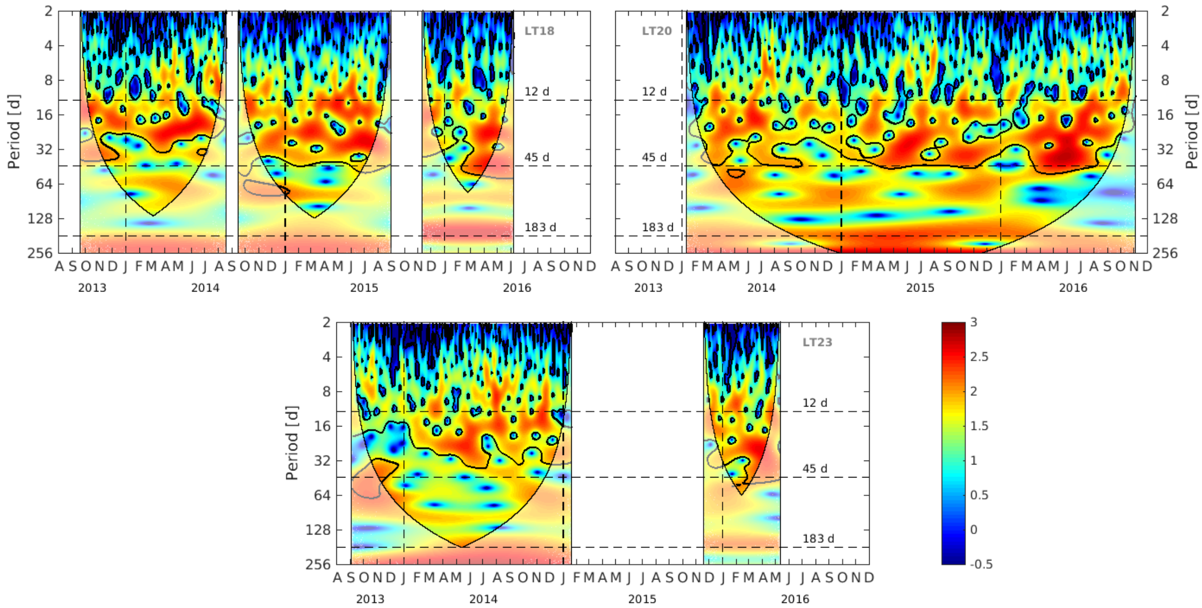

Figure 6: Wavelet power spectrum of the alongshore velocity signal at each station. The cone of influence is indicated. The black contour encloses areas where the wavelet power is above the 95% confidence level.

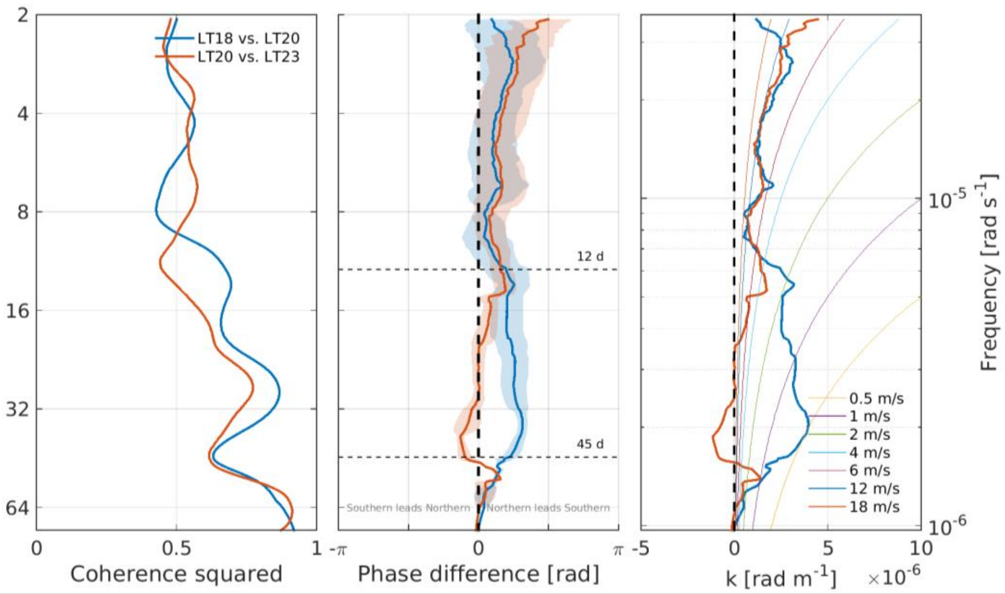

Figure 7: (Left) Global wavelet coherence spectrum of the alongshore velocity for the two segments LT18 vs. LT20 and LT20 vs. LT23 based on concurrent periods across all three stations. (Middle) Angular mean phase difference of the alongshore velocity signal. Shadings give the angular standard deviation. (Right) Estimated wavenumber as function of frequency. Lines of constant phase speeds are also drawn.

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

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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 partly associated with oceanic warming events on intraseasonal to interannual or longer time scale. Large-scale warm anomalies often forced remotely from the equatorial Atlantic were observed at times to propagate southward reaching the Benguela upwelling of Namibia. Such events, also called Benguela Niños, were observed for example in 1995 and in 2011 (Fig. 8). Here we present results from the analysis of a so far not well-explored in-situ dataset that was acquired within the EAF-Nansen program executed by the Food and Agricultural Organization of the United Nations (FAO) and funded by Norwegian Agency for Development Cooperation (NORAD). This dataset provides hydrographic and current data acquired twice a year during the main downwelling and upwelling seasons at the Angolan shelf and continental slope covering the last 20 years or so. For the first time, it was possible to determine the mean seasonal structure of the Angola current from 6°S to 18°S. During austral summer the southward Angola Current is concentrated in the upper 150 m with a northward return flow below. It strengthens from north to south reaching a velocity maximum at about 16°S just north of the Angola Benguela front. During austral winter southward velocities of the Angola Current are weaker, but more deep reaching. On interannual timescales, the analysis of hydrographic data from the EAF-Nansen program reveals remarkable differences in subsurface (about 100 m depth) temperature anomalies: 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. 9). The data are analyzed with respect to previous results mainly based on sporadic in-situ measurements and the analysis of remote sensing data.

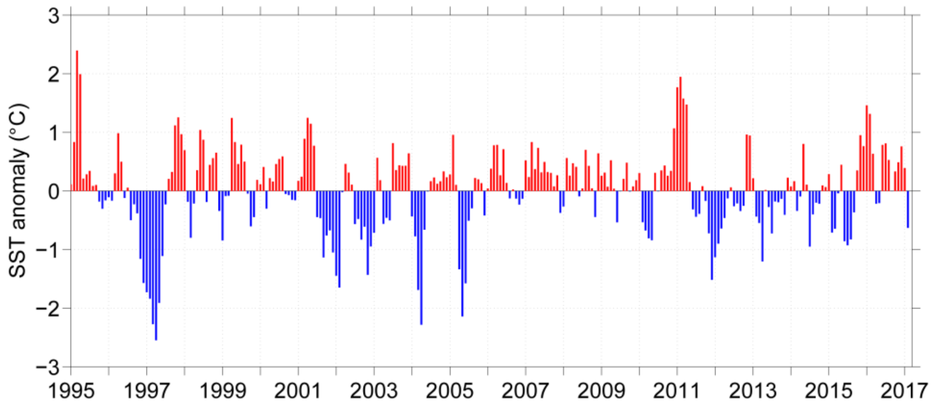

Figure 8: Sea surface temperature (SST) index of the Angola Benguela area (ABA SST index) defined as located between 10°S and 20°S and east of 8°E. The SST anomaly is calculated relative to the mean seasonal cycle.

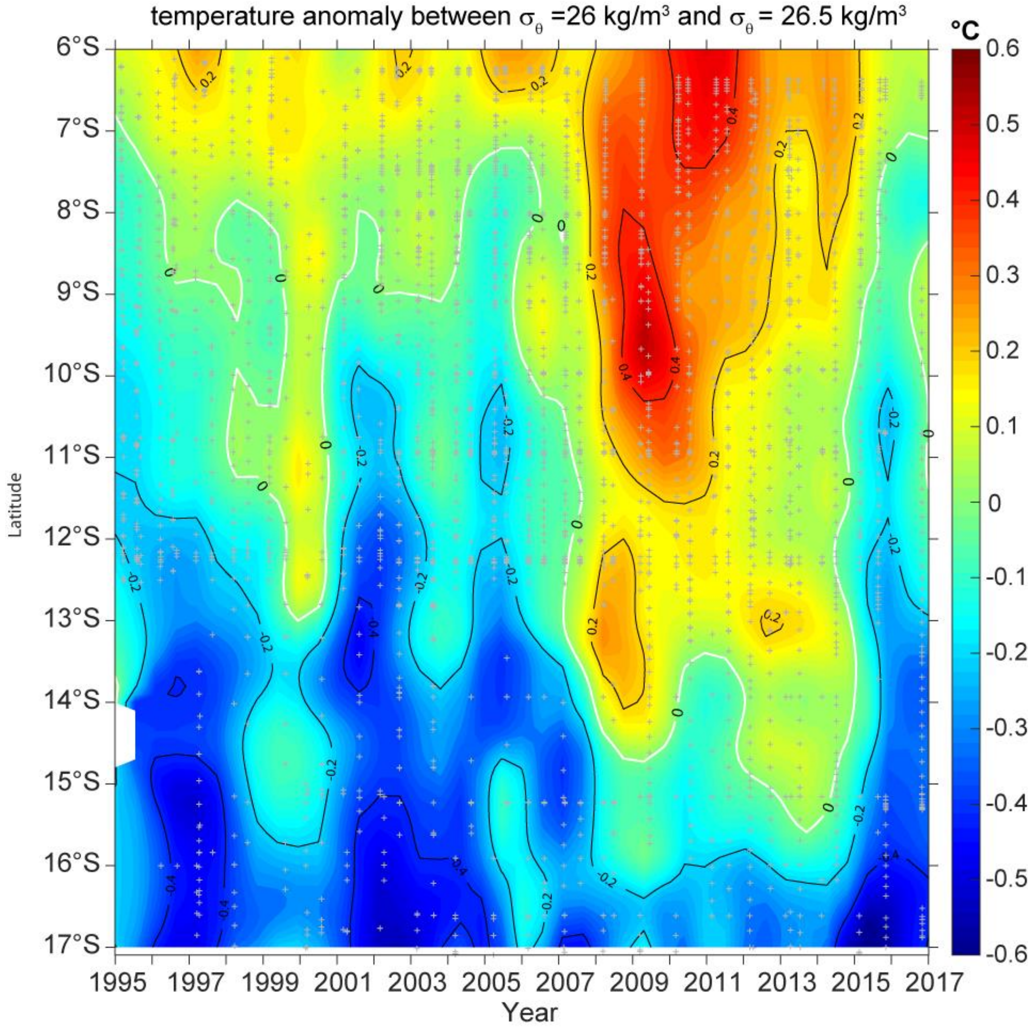

Figure 9: Interannual variability of temperature anomaly along the continental slope off Angola in the upper thermocline. Temperature was averaged between the isopycnal σ_θ = 26.0 kg m^{-3} and σ_θ = 26.5 kg m^{-3}. Altogether, 2987 CTD and underway CTD profiles collected from March 1995 to November 2016 were used. The depth of the upper and lower isopycnal boundary varies between 0 and 100m and between 80 and 250m, respectively.

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

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During the PREFACE period with enhanced observations in the eastern tropical Atlantic, a strong but short-lived warm event occurred. In the Southeastern tropical Atlantic Ocean off Angola and Namibia SST anomalies reached up to 2.5°C in January 2016. The analysis of direct observations aided by a model simulation suggests that the warming was surface intensified and, in contrast to previous Benguela Niño events, not linked to equatorial Kelvin wave propagation or a significant reduction in upwelling of subsurface waters. The warm surface layer was characterized by a pronounced negative salinity anomaly, leading to an anomalous thin mixed layer and enhanced stratification. The warm, fresh surface water was advected poleward by southward surface currents, consistent with a weakening in the southerly winds. With the onset of stronger winds in March 2016, increased mixing erased the warm surface layer, leading to the abrupt termination of the event (Fig. 10).

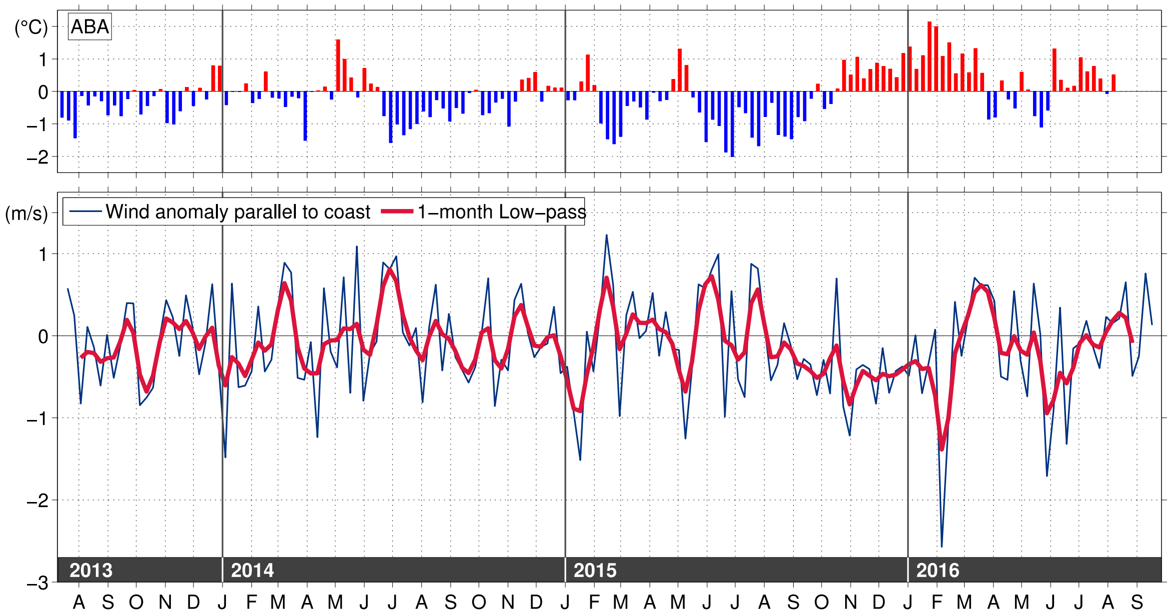

Figure 10: ABA SST index (upper panel, see also Fig. 8) and along-shore wind anomaly averaged between 5°S and 15°S. Prior to the warm event in 2016, southward wind anomalies suggest a southward transport of warm surface waters along the coast. Wind data are from http://www.remss.com/missions/ascat.

Respective roles of the Guinea Current and local winds on the coastal upwelling in the northern Gulf of Guinea

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The northern hemisphere coastal wave guide from the equatorial Atlantic includes the Gulf of Guinea and the western coast of Northwest Africa. Here the northern Gulf of Guinea is studied where oceanic conditions due to the presence of coastal upwelling may influence the regional climate and fisheries (Fig. 11). The dynamics of this coastal upwelling is still poorly understood. A sensitivity experiment based on the Regional Oceanic Modeling System (ROMS) is carried out to assess the role of the detachment of the Guinea Current as a potential mechanism for coastal upwelling. This idealized experiment is performed by cancelling the inertia terms responsible for advection of momentum in the equations and compared with a realistic experiment. The results exhibit two major differences. Firstly, the Guinea Current is found to be highly sensitive to inertia, as it is no longer detached from the coast in the idealized experiment. The Guinea Current adjusts on an inertial boundary layer, the inertial terms defining its lateral extension. Second, the upwelling east of Cape Palmas disappears in absence of the Guinea Current detachment. This is in contrast with the upwelling east of Cape Three Points, which is still present. The results suggest that two different generation processes of the coastal upwelling need to be considered: the upwelling east of Cape Palmas which is due to inertia, topographic variations and advective terms effects resulting in important vertical pumping and the upwelling east of Cape Three Points which is principally induced by local winds. In addition to recent work ruling out the role of eddies, this study clarifies the processes responsible for this coastal upwelling.

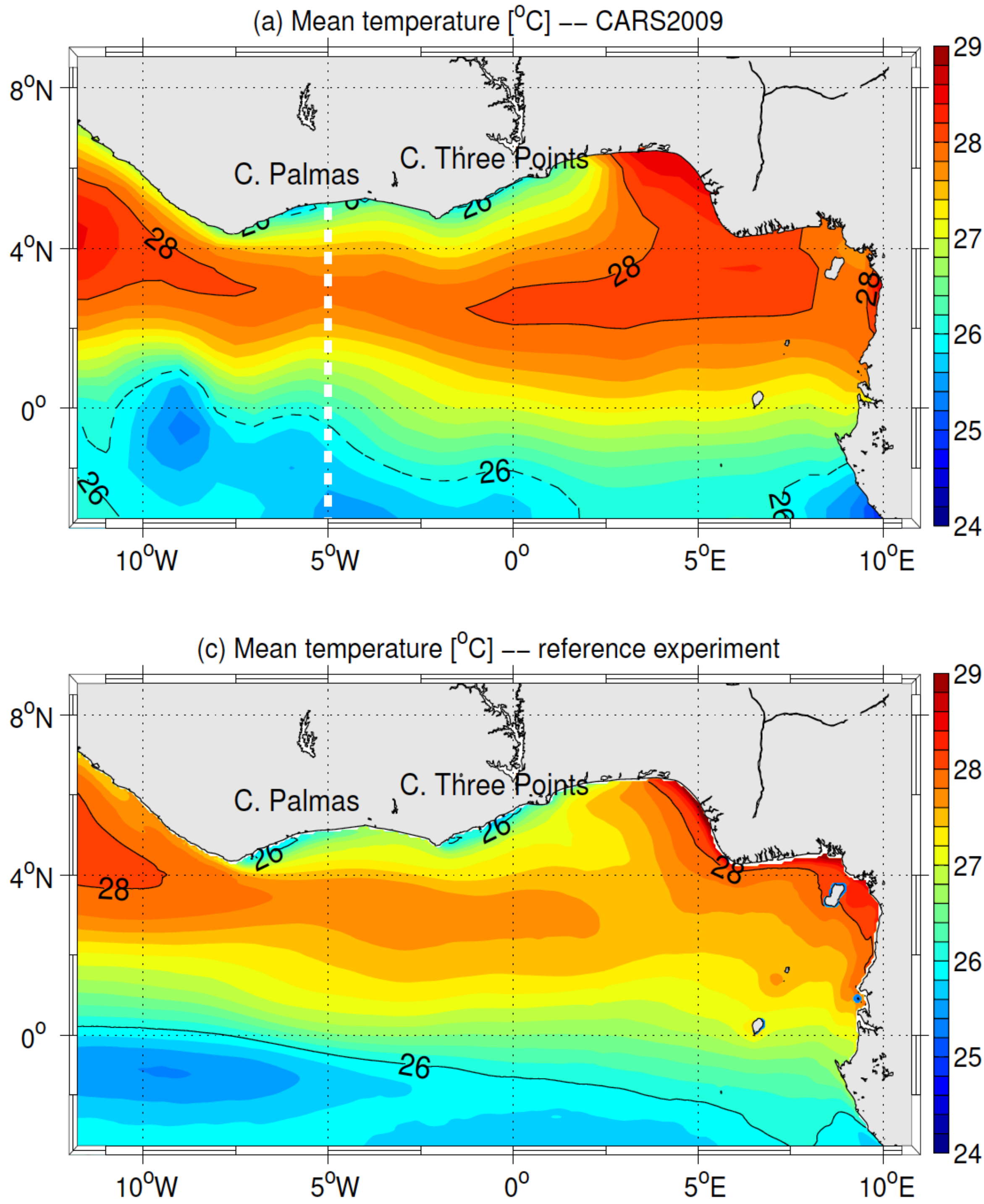

Figure 11: Maps of the spatial distributions of the annual mean SST [°C] in the northern Gulf of Guinea, for CARS (a) and the reference experiment (c). The contour interval is 0.2°C. The model is capable of reproducing the two upwelling cells east of Cape Palmas and east of Cape Three Points.

On the Dynamics of the Southern Senegal Upwelling Center: Observed Variability from Synoptic to Superinertial Scales

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Upwelling off southern Senegal and Gambia takes place over a wide shelf with a large area where depths are shallower than 20 m. This results in typical upwelling patterns that are distinct (e.g., more persistent in time and aligned alongshore) from those of other better-known systems, including Oregon and Peru, where inner shelves are comparatively narrow. Synoptic to superinertial variability of this upwelling center is captured through a 4-week intensive field campaign, representing the most comprehensive measurements of this region to date. The influence of mesoscale activity extends across the shelf break and far over the shelf where it impacts the midshelf upwelling (e.g., strength of the upwelling front and circulation), possibly in concert with wind fluctuations. Internal tides and solitary waves of large amplitude are ubiquitous over the shelf. The observations suggest that these and possibly other sources of mixing play a major role in the overall system dynamics through their impact upon the general shelf thermohaline structure, in particular in the vicinity of the upwelling zone. Systematic alongshore variability in thermohaline properties highlights important limitations of the 2D idealization framework that is frequently used in coastal upwelling studies. The different processes impacting the upwelling system of southern Senegal and Gambia are summarized in the schematic shown in Fig. 12.

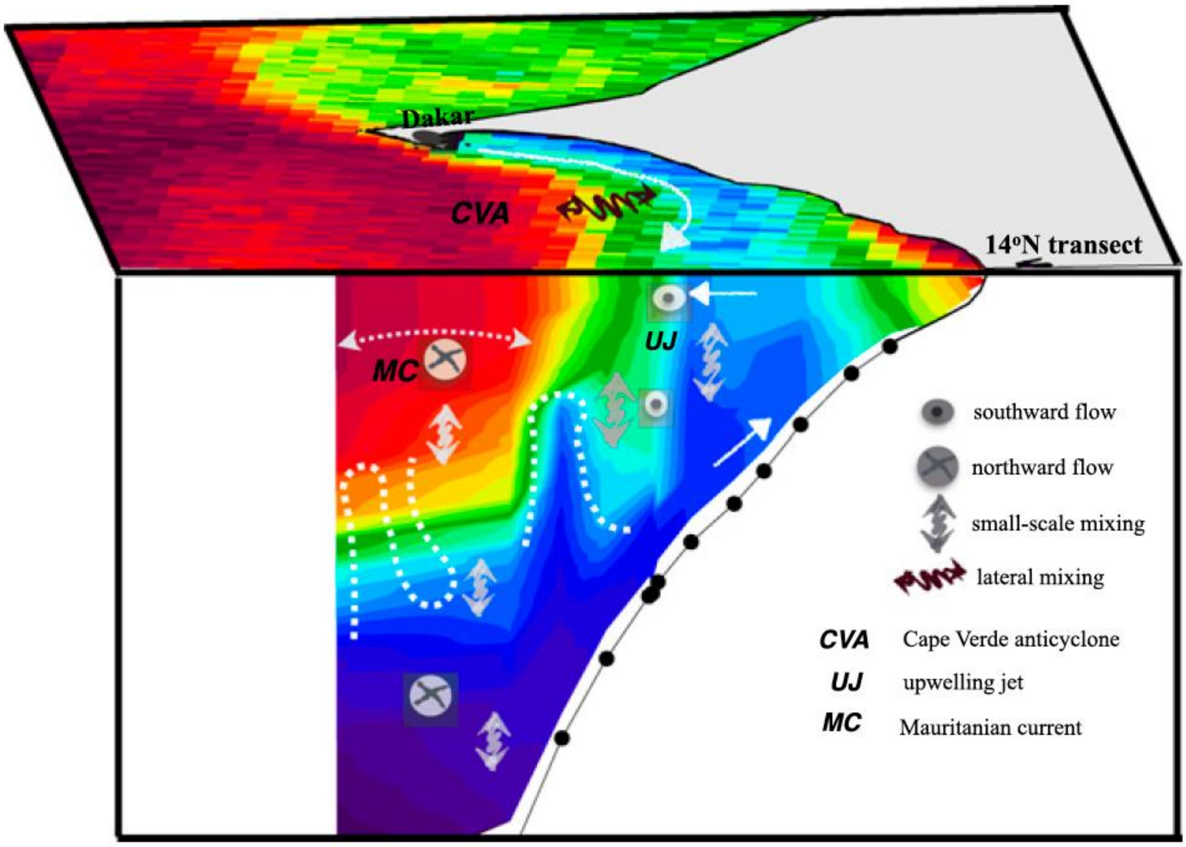

Figure 12: 3D schematic description of the upwelling dynamical and hydrological structure over the southern Senegal shelf, as observed during UPSEN2–ECOAO. The manifestation of upwelling takes the form of a cold SST tongue situated tens of kilometers away the shore. Its position and that of its offshore frontal edge undergo cross-shore displacements influenced by mesoscale disturbances. These mesoscale disturbances presumably arise from instabilities of the current system composed of the poleward flowing MC and the equatorward UJ. One recurrent mesoscale feature is the CVA, which strongly constrained the flow and hydrological conditions in the SSUC during the field experiment. Ubiquitous internal gravity waves over the shelf are implicated in water mass transformation (and associated vertical fluxes of properties) that occur offshore of the upwelling zone. In particular, interior mixing is frequently observed just offshore of the upwelling zone. Inshore of that zone, the classical 2D Ekman cell (onshore flow near the bottom, offshore flow in the surface layer) prevails. Therefore, the position of the upwelling zone may not simply result from the shutdown of the cross-shore Ekman-driven circulation on its inshore flank. Partial evidence suggests that internal gravity wave (IGW) breaking may contribute to the offshore migration of the front during UPSEN2–ECOAO. We hypothesize that the sharpness of the front separating upwelling and offshore waters is primarily controlled by IGW mixing in the front area, as opposed to lateral mixing resulting, for example, from submesoscale frontal dynamics (which has a limited signature in high-resolution SST images).

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