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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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Comments on deviations:

Deviation occurred due to the ongoing involvement of the main author in the EAF Nansen Programme with many survey days at sea of the research vessel Dr. Fridtjof Nansen. The slow unreliable internet access onboard precluded systematic access to the data required to perform analyses and to download and timely read the publications prepared by other authors involved in this deliverable. This institutional obligation on the main author was not foreseen, and as other parts of the project did not depend directly on the deliverable we didn't seek an alternate lead author.

Executive Summary:

The aim of this deliverable is to better understand ocean climate variability effects on environmental conditions and small pelagic fish populations off West Africa during the last 30 years. The deliverable is based on the analysis of observational environmental and fisheries data and their interpretation in the upwelling regions along West tropical Africa seaboard of both hemispheres. The results from the northern hemisphere include also results of the modelling work. Previous studies, based on observations before the 1990s have established baseline understanding of climatic mechanisms controlling variability of small pelagic resources of the tropical West Africa, mainly sardinella species. Various aspects of ecology and biology of these species have been relatively well understood [*Binet*,

1988; *Boëly*, 1980; *Boley and Fréon*, 1980; *Conand*, 1976; *Cury and Fontana*, 1988; *Fréon*, 1986; *Ghéno and Fontana*, 1981]. The variability of commercial landings in relation to climatic patterns through 1960-1980 was reasonably well documented [*Binet et al.*, 1991; *Pezennec and Bard*, 1992; *Pezennec and Koranteng*, 1998; *Roy and Reason*, 2001]. Here, we use the newer fisheries data and integrate information on climatic variability from satellites, surveys and models to describe impact of climate on fluctuations of tropical pelagic fish resources during the last three decades, and, in some cases, to disentangle the previously unconsidered climatic mechanisms driving this variability. The main results can be summarized as follows:

a) Angola and the Eastern Gulf of Guinea

A focus of our studies was on explaining the fluctuations in the estimated biomass of sardinella from 1994-2014 by climatic processes inducing stress in the coastal habitat of these fish in the Eastern Gulf of Guinea. The main analysis was concentrated in the Angolan coastal region because of the data availability, but the interpretation is extended to the entire region. Ostrowski and Bazika-Sangolay (2016) analysed results of multiple surveys in the Angolan upwelling region, concluding that the enrichment, planktonic food concentration and retention of their spawning products, i.e. the "ocean triad" [*Bakun*, 1996], occurs in the nearshore areas of that upwelling region under windless conditions. The study of sardinella biomass evolution and sea surface temperature (SST) variability nearest to the Angolan coast by Ostrowski and Barradas (2018) has revealed the major recruitment events of *Sardinella aurita* in 2006-2007 and 2012. Both events occurred one year after a strong upwelling season. However, the two events differed in the location of the sardinella coastal nurseries. During 2006-2007 juvenile fish were exclusively found in the Congo-Gabon regions. Off Angola only old fish was caught, suggesting an increase in biomass due to the adult migration, consistent with the previous observations. In 2012, in contrast, juvenile fish were massively caught down to 14°S, suggesting a southward shift of the recruitment areas into the Angolan waters. The result shows that within the seasonal habitat driven by remote forcing (to the north of 12°-13°S) favourable conditions for the southward shift of juvenile sardinella occur when a strong upwelling season follows an extreme warm equatorial event during the preceding austral summer. That situation occurred in 2012 when the cold upwelling season preceding the recruitment event happened in the wake of the 2011 Benguela Niño. At the Angola-Benguela Front (ABF, 16°-17°S) temperature is typically too low for sardinella to survive during winter. However, the poleward shift in distribution of these species towards this front during winter has been observed during the interannual warm period 2006-2010.

b) Northwest Africa

Sarre et al. (2018) studied the poleward shift for a number of tropical species in the northwest African upwelling region. *S. aurita* exhibited the strongest shift among the studied species. The northwest African upwelling region exhibits a front similar to the ABF at Cape Blanc, 21°N, characterized by a similar temperature gradient. Compared to the Angolan case where Ostrowski and Barradas (2018) observed the wintertime *S. aurita* distributions at the ABF only during the warm period 2006-2010, off northwest Africa Sarre et al. (2018) observed during the same season a systematic shift of *S. aurita* from 1995 to 2015 by some 270 km into the Sahara Bank, north of Cape Blanc. *S. maderensis*, on the other hand, did not display a significant shift during the same period.

Winds are key driver of sardinella abundance off Senegal and it depends on the state of North Atlantic Oscillation (NAO) (Thiaw et al. 2017). Monthly indices of abundance from commercial statistics indicate two peaks in *S. aurita* abundance, in spring and autumn and one peak in abundance of *S. maderensis* during boreal summer. The difference in the abundance peaks of the two species stem from the change in fishermen strategy. Large *S. aurita* is caught during its bi-annual passage through the Senegalese waters on the annual migration cycle between Guinea and Morocco. *S. maderensis* constitutes the highest catch during summer when large *S. aurita* is away from the Senegalese waters. Interannual trends of sardinella abundance are significantly correlated with the wind-derived upwelling index (offshore Ekman transport), especially in autumn and spring. However, the fluctuations of the two species are explained by different upwelling timing aspects. The *S. maderensis* fluctuations are better correlated to early onsets of upwelling while those of *S. aurita* are better coupled to longer upwelling durations. The authors attribute this to the specific migration patterns. The sedentary *S. maderensis* benefits from early upwelling in the autumn when the migrant is still absent from the Senegalese waters. The longer duration of upwelling season would delay the spring departure of *S. aurita* from the Senegalese waters.

Brochier et al. (2018) demonstrated potential of the modelling approach in studying climate-fish scenarios. These authors studied interannual abundance patterns *S. aurita* off northwest Africa using an individual life-cycle model. The model outputs were validated against available commercial capture data, acoustic survey results and fishermen perception. According to these results, interannual variability of the total biomass off northwest Africa depends strongly on favourable conditions within the nurseries over the Sahara Bank. These conditions in turn depend on intensity of the southward flowing coastal current. The weakening of this current occurred from 1994 to 1998. The Sahara Bank has optimal enrichment and plankton concentration conditions for inshore recruitment of *S. aurita*, but too strong current prevents migration of adult spawners into that area. The weakening of this current led to a peak in the simulated biomass during the same period.

Tiedemann et al. (2017) observed shifts of *S. aurita* spawning areas depending on the season: cold 13°-15°N during cold season and 16°-21°N during warm season. The poleward shift in the spawning areas was thus well correlated with the fish migratory cycle. The peak occurrences of the larvae were observed in the inshore areas. The highest abundances were found during south-easterly wind in the range 5-6 m s^{-1}, supporting the optimal environmental window hypothesis on the existence of the optimum of wind-induced turbulence range, sufficiently strong to maintain a steady upwelling and primary production, but not strong enough to induce larval dispersal and losses [*Cury and Roy*, 1989]

c) The Ivorian-Ghanaian upwelling

Similarly to the eastern Gulf of Guinea fluctuations, small pelagic fish fluctuations in the Ivorian-Ghanaian upwelling system are not related to local wind conditions. Koné et al. 2017 analysed retention conditions of *S. aurita* larvae using a biophysical model of early life-history of *S. aurita*. The result shows the importance of the spawning areas downstream the two principal capes blocking the eastward flowing Guinea Current: Cape Palmas and Cape Three Points. The seasonally-amplified cyclonic eddies created in the lee of these capes and anti-cyclonic eddy in the vicinity of the Niger delta, exhibit retentive properties, trapping eggs and larvae along the coast. The highest simulated retention is observed during the main upwelling season (July-September) and can also occur during the minor upwelling (February-March).

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Complex small pelagic fish population patterns arising from individual behavioral responses to their environment

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Abstract (doi: 10.1016/j.pocean.2018.03.011):

Small pelagic fish (SPF) species are heavily exploited in eastern boundary upwelling systems (EBUS) as their transformation products are increasingly used in the world's food chain. Management relies on regular monitoring, but there is a lack of robust theories for the emergence of the populations' traits and their evolution in highly variable environments. This work aims to address existing knowledge gaps by combining physical and biogeochemical modelling with an individual life-cycle based model applied to round sardinella (Sardinella aurita) off northwest Africa, a key species for regional food security. Our approach focused on the processes responsible for seasonal migrations, spatio-temporal size-structure, and interannual biomass fluctuations. Emergence of preferred habitat resulted from interactions between natal homing behavior and environmental variability that impacts early life stages. Exploration of the environment by the fishes was determined by swimming capabilities, mesoscale to regional habitat structure, and horizontal currents. Fish spatio-temporal abundance variability emerged from a complex combination of distinct life-history traits. An alongshore gradient in fish size distributions is reported and validated by in situ measurements. New insights into population structure are provided, within an area where the species is abundant year-round (Mauritania) and with latitudinal migrations of variable (300–1200 km) amplitude. Interannual biomass fluctuations were linked to modulations of fish recruitment over the Sahara Bank driven by variability in alongshore current intensity. The identified processes constitute an analytical framework that can be implemented in other EBUS and used to explore impacts of regional climate change on SPF

Effect of environmental conditions on the seasonal and inter-annual variability of small pelagic fish abundance off North-West Africa: The case of both Senegalese sardinella

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Abstract (doi: 10.1111/fog.12218):

The objective of this study was to assess the effect of environmental variations on the abundance of *Sardinella aurita* and *Sardinella maderensis* in Senegalese waters in the upwelling system. Monthly data indicating the abundance of sardinella were first estimated from commercial statistics, using Generalized Linear Model from 1966 to 2011. Abundance indices (AIs) were then compared with environmental indices, at the local scale, a Coastal Upwelling Index (CUI) and a coastal Sea Surface Temperature (SST) index, and on a large scale, the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) and the Multivariate El Niño Southern Oscillation Index (MEI), using correlations and times series analyses. The results showed that the abundance of sardinella is determined by a strong seasonal pattern and inter-annual fluctuations. The abundance of *S. aurita* peaked in spring and in autumn, whereas that of S. maderensis peaked in the warm season (July–September). The trend of the sardinella abundance was significantly correlated with the CUI especially in autumn and spring. Interannual fluctuations of *S. maderensis* and *S. aurita* abundance are, respectively, driven by the precocity and the duration of the upwelling season that is attributed to distinct migration patterns. Both sardinella species also respond with a delay of around 4 years to the winter NAO index and the autumn CUI, and the AMO index, respectively, both related to migration patterns. The wide variations in sardinella biomass are caused by variations in environmental conditions, which should be considered in the implementation of an ecosystem-based approach in sardinella stocks management.

Report on the evolution of the Angolan sardinella stock in relation to the seasonal coastally trapped waves climatology and interannual equatorial events 1994-2014

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Extended abstract: (Report and manuscript to be submitted)

The aim of the study is to better understand impact of tropical Atlantic climate on sardinella, the principal fisheries resources along the southeastern tropical Atlantic coasts. A time series of biomass index and fish length frequency distributions of sardinella off Angola obtained from regular acoustic surveys with the Norwegian research vessel RV Dr Fridtjof Nansen during 1994-2014 have been analysed in the context of coastal climate variability derived from satellites.

Acoustic survey methodology is subject to many potential biases; and the interannual trends inferred from such data typically require a validation against robust statistics from fisheries dependent data sources. In the case of Angolan sardinella, until 2008 fisheries statistics is not considered reliable therefore we rely on the acoustic survey derived trends as the indicator of the climate-induced sardinella fluctuations. We link these results to the climate variability under the habitat based hypothesis, which treats small pelagic fish stock fluctuations as the result of adaptive strategies of these fishes to pressures induced by climatic stresses on their habitat. The available acoustic data, compared to the continuous satellite observations, are relatively sparsely sampled in time and are aliased by synoptic-scale behavioural effects in fish. We interpret the observed fluctuations in the sparsely sampled biomass estimates as the effect of the two adaptive strategies of sardinella in which they cope with the seasonal climate extremes: the seasonal migrations of adult sardinella (short-term effects) and the development of juvenile fish in littoral nurseries sheltered from the seasonal climate extremes (population level changes). We separate these two effects in the biomass data by studying in parallel the absence or presence of juvenile sardinella in the catch composition during the respective surveys.

Unique to the Angolan ecosystem is the forcing controlling the seasonal and interannual climate variations affecting the coastal habitats of sardinella. The annual march of climatic conditions in this habitat is controlled by seasonal coastally trapped waves emanating from the equatorial region. Upwelling seasons favourable to fish recruitment are interspaced with periods of harsh conditions during the passage of seasonal downwelling propagations. Favourable conditions to recruitment are dominated by the above class of environmental forcing and not by local wind conditions and not by wind-induced upwelling. The two major periods of the rising biomass trends during the studied period were observed during 2005-2007 and 2011-2012. We find that climatic scenarios leading to the biomass increase during the above two periods were linked to the passage of cold interannual equatorial events along the Angolan coastal waveguide. The increase of fish biomass occurred one year after the passage of such anomalies. In contrast, we find that the extreme warm anomalies, termed the Benguela Niños cause fluctuations in fish availability to fisheries, but not inducing strong changes at the population level. However, a combination of warm events with decadal scale warming was found to be instrumental in expanding juvenile nurseries towards the southern range the sardinella distribution at the Angola Benguela Front. *S. aurita* and *S. maderensis* are characterized by different environmental preferences and this is reflected in the analysed data. Nonetheless, the

southward juvenile habitat expansion is being observed for both species. Interannual equatorial episodes appear to initiate these changes.

Owing to the progress in the recent years, including the contributions of PREFACE, equatorial interannual events are nowadays becoming predictable (based on satellites and mooring arrays deployed in the equatorial region) several months ahead before they strike the Angolan coast. The climate - sardinella scenarios identified in this report may thus be helpful in adopting the predictions of equatorial events in improving the management of Angolan sardinella fisheries.

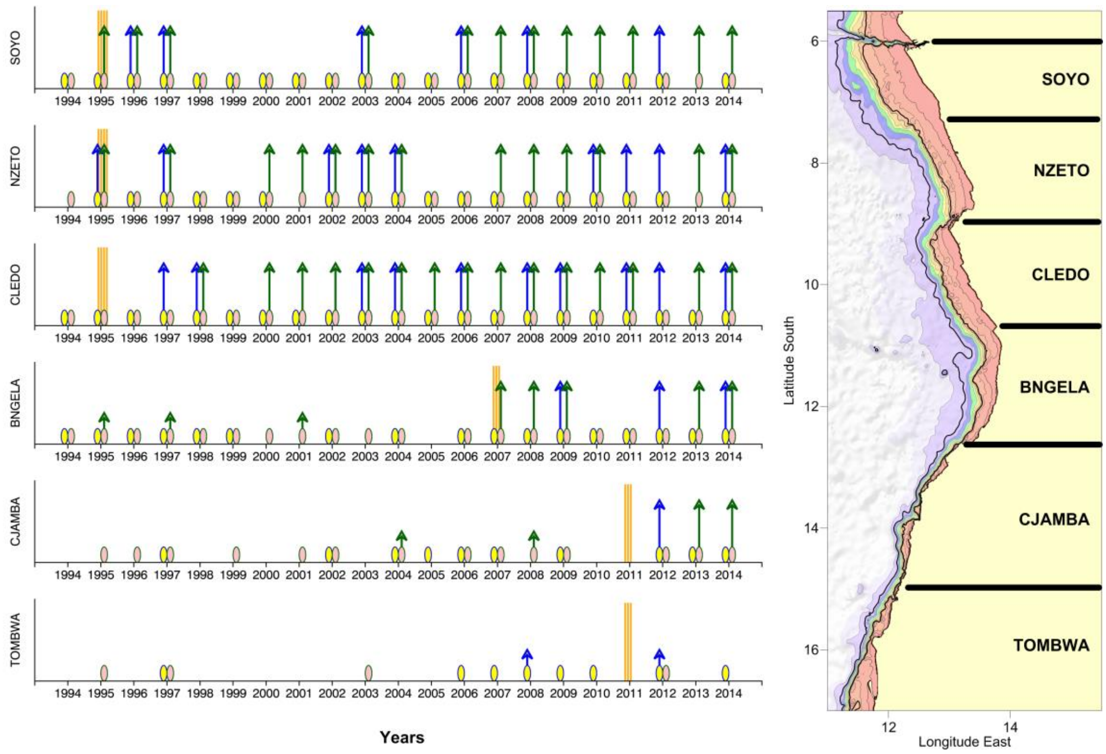

Figure 1. A demonstration of southward progression of regions where juvenile sardinella has been found between 1994 and 2014. The figure shows the incidence of juvenile sardinella (< 15 cm TL) in the trawls of Dr Fridtjof Nansen during winter surveys 1994-2014 by sub-regions along the Angolan coast. The ovals indicate the presence of adult fish in the trawls from the same regions (yellow – *S. aurita*, pink *S. maderensis*). The blue and green arrows denote incidence during a given survey of juvenile *S. aurita* and *S. maderensis*, respectively. The arrows of half-sized if the incidence occurred during an isolated year. The map showing the regions is shown to the right.

Intense warming causes a spatial shift of small pelagic fish: early warning for food security in North-West Africa

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Extended abstract: (Under review: PROOCE_2018_19)

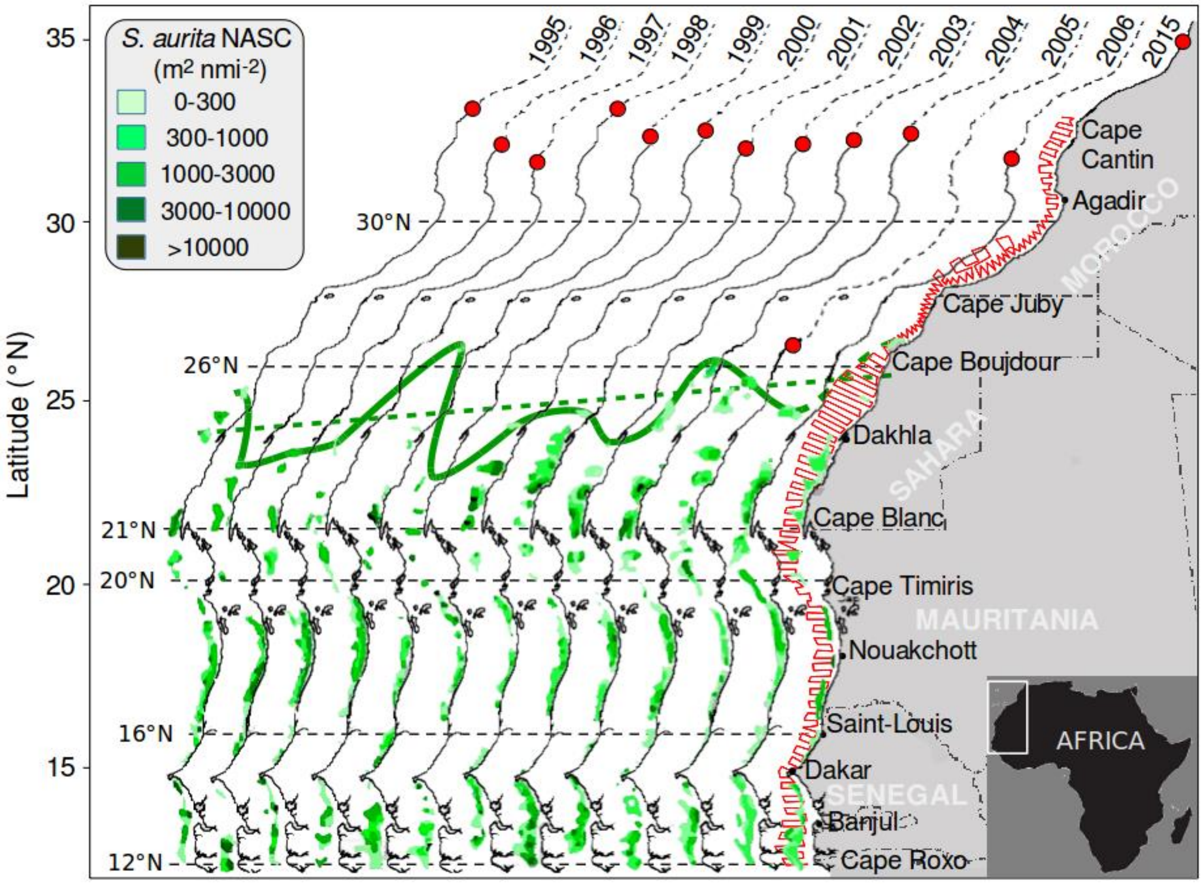

Figure 2. Northward trend in the distribution of sardinella, along their habitat extension from Cape Roxo (Senegal) to Cape Boujdour (Morocco), from 1995 to 2015 based on annual acoustics surveys. Fish density (nautical area backscattering coefficient 'NASC' expressed in m^2 nmi^{-2}) is indicated by different intensities of green. The northern limit of detection identified by fishing operations is shown as a dark green line. Red circles indicate the northernmost latitude in which vessels operated each year. Red lines show typical acoustic transects. This distribution includes the two sardinella species (*Sardinella aurita* and *Sardinella maderensis*), with *S. aurita* being the main contributor to the

north of 20 °N.

Along the coast of North-West Africa, fish supply is important at both socio-economic and cultural levels. Reports by fishermen emphasise changes in the distribution of fish species important for food security. Northward shifts in the distribution of sardinella and other species have been attributed to a warming trend and the redistribution of upwelling intensity and productivity. As a result, the abundance of sardinella along the coast has increased in the subtropics and fallen in the intertropical region. Independent observational time series confirm a robust northward shift in *Sardinella aurita* since 1995, which we attribute to the intense warming of this region, where the greatest increase in sea surface temperature of all tropical regions is found. The spatial shifts in biomass of several hundred kilometres observed during the last 20 years are of the same order of magnitude as those recorded for surface isotherms in the sub-regional pelagic habitat of sardinella. Such changes are an important policy consideration for food security management in several West African countries.

Climate variability and small pelagic fish: Population dynamics of small pelagic fish off the Namibian coast in the last 30 years

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Report

Introduction

Although variations in pelagic fish populations are initiated by climate-induced changes in oceanographic conditions, trophic interactions of the species with other ecosystem components tend to shape the status of their populations. Small pelagic fish act as a conduit through which energy flows from the producers, usually photosynthesising micro-organisms, to the top predators that feeds directly on the small pelagic fish or on other life forms that previously fed on the small pelagic fish. Such interactions will eventually determine the status of the fish populations, whereby lack of food for the early life stages of small pelagic fish would negatively impact their recruitment while good recruitment would eventually lead to increases abundance of the later life stages of both the small pelagic species as well as those of their predators. Small pelagic fish include Sardine (*Sardinops sagax*), redeye round herring (*Etrumeus whiteheadi*), Cape anchovy (Engraulis encrascicolus), all which are exclusively small pelagic fish, as well as Cape horse mackerel (*Trachurus capensis*), which are classified as small pelagic fish at younger ages but tend to become somewhat demersal with age. In spite of their demersal behaviour horse mackerel was shown to perform diel vertical migrations between the pelagic and demersal zones depending on time of the day. Another species of horse mackerel, the Cunene horse mackerel (*Trachurus trecae*) is also occasionally encountered along the Namibian coast, particularly in the extreme northern part of the coastline during the summer months, coinciding with the intrusion of the warm Angolan current waters onto the Namibian shelf.

On the Namibian coast small pelagic fish has also been exposed to intensive fishing which has also contributed to shaping their populations. Cape horse mackerel make up the most abundant pelagic species and the one supporting the largest fishery by volume. The Namibian Cape horse mackerel fishery came into existence by the 1960's at the time that the species was mainly targeted by the Midwater fleet of the USSR and other Eastern bloc fleets from Bulgaria and Romania. A purse-seine fishery targeting juvenile horse mackerel for the production of fishmeal was also introduced in 1971. Some horse mackerel is also caught as bycatch in the demersal hake and monk fisheries. Of the true small pelagic fish only sardine has a dedicated fishery with the other species only being caught as bycatch of both the sardine and horse mackerel directed purse seine fisheries. Sardine is mainly targeted for canning. The purse seine fishery that targeted juvenile horse mackerel for fishmeal production has been discontinued since 2014.

This report summarises trends in population dynamics of horse mackerel with respect to survey biomass and abundance and commercial catches.

Abundance

Survey biomass estimates fluctuated with wider error bars for the 1991 to 1998 dataset and narrower error bars for the 1999 to 2015 dataset (Figure 3). The survey biomass index show a cyclical behaviour where it remain above a million tonnes for a number of years, before dropping to below the million tonnes mark but above 500,000 tonnes and remain there for about 2 years before shooting up again or increasing gradually to above one million tonnes. Horse mackerel biomass was the highest (just below 2,000,000 tonnes) in 1998 and 1999 and the lowest (just above 500,000 tonnes) in 2006 and 2007. There was no survey in 2008, and the biomass estimated in 2009 was more than twice that estimated in 2007 the survey biomass index was above the 1,000,000 mt level up to the end of the survey period in 2015. Despite the issues concerning comparability between the two survey series the general biomass trend was relatively consistent.

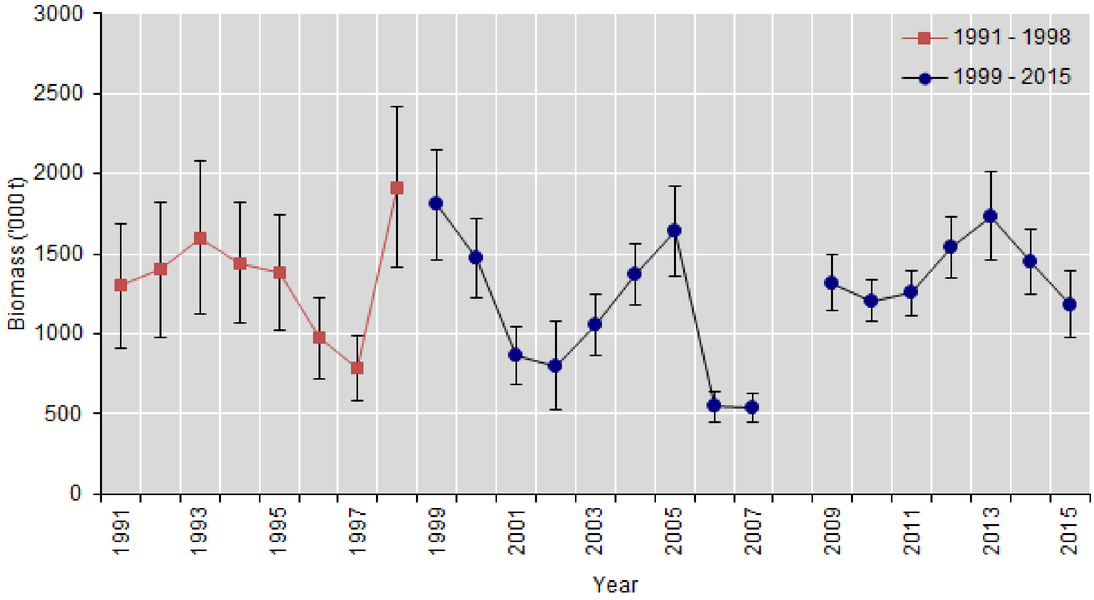

Figure 3 Biomass of horse mackerel during the Nansen surveys (1991 – 1998) and the Namibian national surveys (1999 – 2015)

Length frequency distributions obtained from the survey samples from 1999 to 2015 are shown in Figure 2. The 1999 length frequency distribution consisted of about 3 modes, including a prominent smaller fish mode at 6 cm, midsize fish at 21 cm and larger fish at 26 cm and the fish ranged in length from 2 to 39 cm TL. In 2000 **the** length frequency distribution was bimodal with modes at 14 cm and 20 cm, and the range of lengths extended between 6 and 39 cm. The 2001 length frequency distribution was also bimodal with modes at 13 cm and 18 cm, and a length range from 2 to 31 cm. The 2002 length frequency distribution was bimodal and the modes were situated at 14 cm and 18 cm, with lengths ranging from 10 to 36 cm. The 2003 length frequency had a single mode at 20 cm TL, although a hint of a size group can be observed with a modal length of 10 cm. The 2003 length range extended from 3 to 32 cm. A single mode was observed in the length frequency

distribution of 2004 at 16 cm TL, and the range of lengths was from 5 to 42 cm. In 2005 the length frequency distribution was bimodal with modal lengths of 12 and 24 cm, and the range of the size distribution extended from 3 to 32 cm. The 2006 length frequency distribution had 3 modes at 9, 12 and 18 cm and the lengths ranged from 3 to 27 cm. In 2007 a bimodal length frequency distribution was obtained with modal lengths of 6 and 16 cm, ranging in lengths from 3 to 36 cm. In 2009 there were 4 modes in the length frequency distribution, and this were situated at 6, 10, 18 and 21 cm, within the lengths ranging from 3 to 33 cm. The 2010 length frequency distribution contained 3 modes at 8, 12 and 20 cm and the range of the lengths was from 3 to 36 cm. Two modes were observed in the length frequency distribution for 2011 at 7 and 20 cm, with the lengths ranging from 2 to 33 cm. Three modes were observed in the 2012 length frequency distribution at 7, 14 and 20 cm and the range of the lengths was from 2 to 30 cm. A bimodal length frequency distribution was observed in 2013 with modal lengths of 10 and 22 cm in a length range of 3 to 31 cm. The 2014 length frequency distribution contained 4 modes with modal lengths of 5, 13, 17 and 22 cm and the fish ranged in length from 2 to 31 cm. Four modes were also distinguished in the length frequency distribution obtained in 2015 and the modal lengths were 4, 10, 16 and 21 cm. The 2015 lengths extended from 2 to 30 cm. During 2006 to 2009 the bigger fish made up the predominant size group, although a size group made up the very small fish of <10 cm TL could be distinguished. The group of fish <10 cm TL also persisted longer on the surveys between 2010 and 2015 (Figure 4).

Landings

Annual horse mackerel landings were variable and the highest landings of about 400,000 tonnes recorded in 1993 (Figure 5). Relatively constant annual landings, hovering around 250,000 tonnes, were recorded between 1998 and 2006 after which the landings dropped to about 150,000 tonnes in 2007 and 2008. Landings then started picking up gradually since 2009 and continued increasing into the present. Thus, there were three periods of high landings interspersed with about two years of low landings where this cycle was repeated after every ten years. Thus, ten years of higher or increasing landings were followed by two years of low landings.

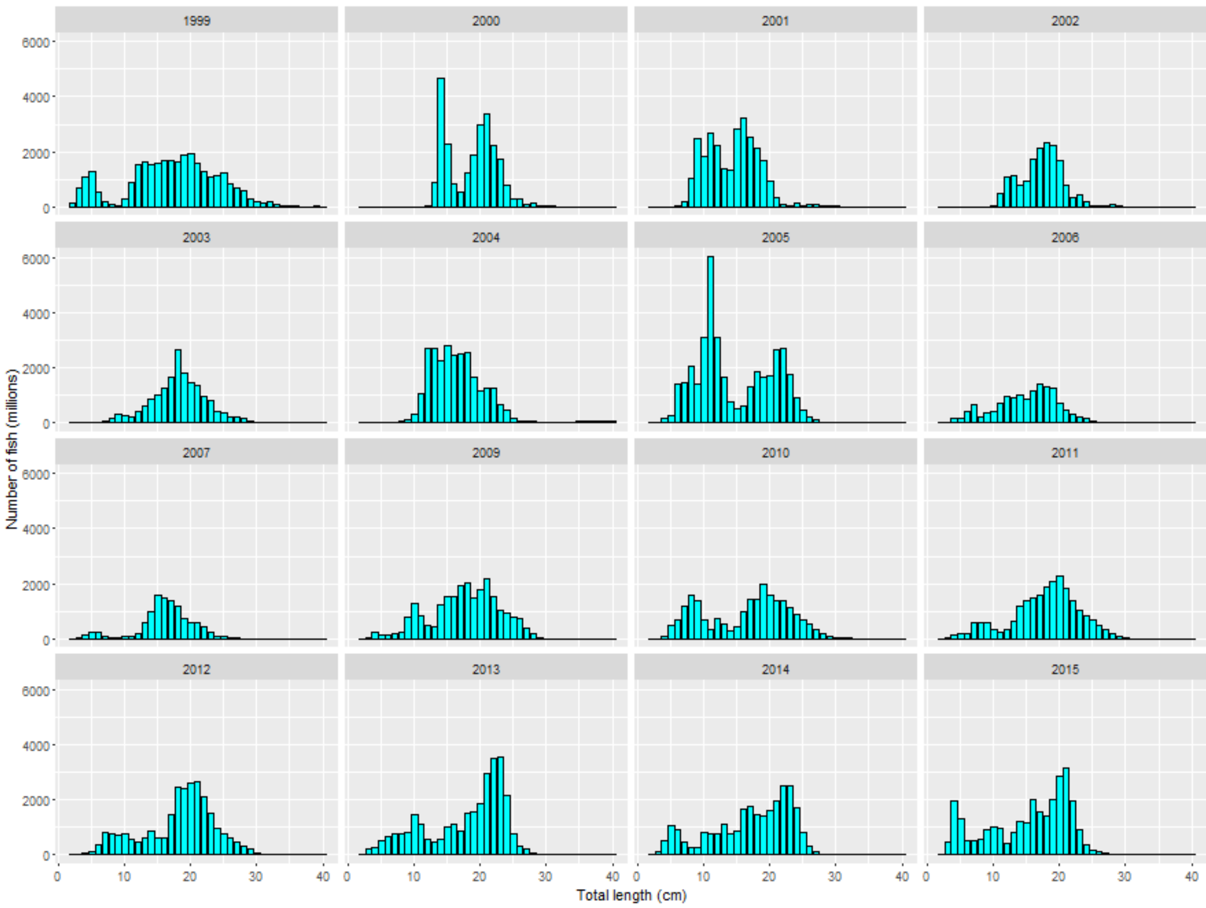

Figure 4 Abundance of horse mackerel during the Namibian national surveys (1999 – 2015)

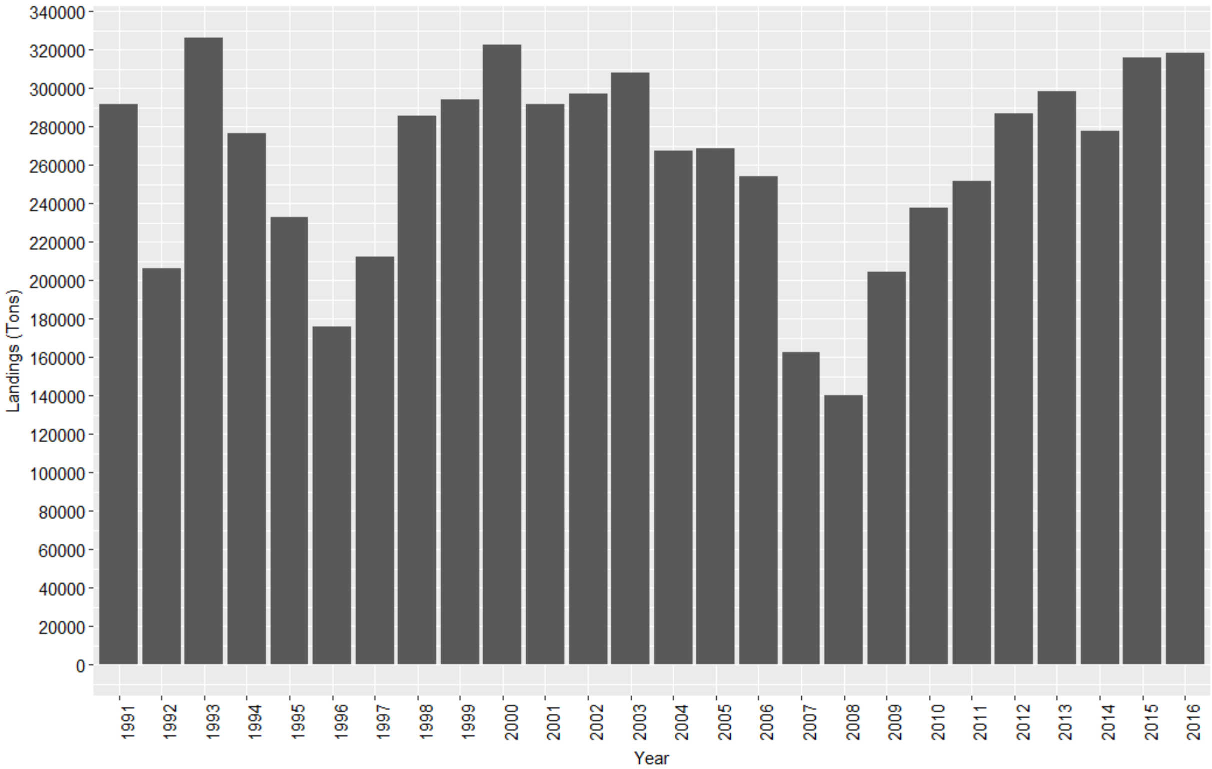

Figure 5 Abundance of horse mackerel during the Namibian national surveys (1999 – 2015)

Spatial distribution of main clupeid species in relation to acoustic assessment surveys in the continental shelves of Senegal and The Gambia

A. Sarré[1], J-O, Krakstad[2], P. Brehmer[1,3], E.M. Mbye

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Abstract (doi: 10.1051/alr/2017049):

This work compiles hydroacoustic recordings and catch data over Senegambia (Senegal and The Gambia) from assessment surveys on the major clupeid species to identify sources of bias in abundance estimates caused by their horizontal distribution. The latitudinal distribution of small pelagic fish is often well known, while their “across shelf” distribution on the continental shelf is less understood. The southern part of the Senegambian shelf has a wide shallow water (< 10 m) area that makes up 20% (1500NM^2) of the total shelf surface, while the northern part accounts for 3% (200NM^2). These areas are not assessed by conventional fisheries acoustics surveys and therefore increase the uncertainty of the assessment of these species. Our findings show that this likely introduces a bias in the assessment of *Sardinella maderensis* , while for *S. aurita* no major estimation-error is caused by their horizontal distribution. The data confirm that *Ethmalosa fimbriata* and *Ilisha africana* are challenging to assess by conventional surveys, due to their mostly inshore distribution. We emphasise the usefulness of assessing *S. aurita* through fisheries independent hydroacoustic surveys, and propose alternative methods to survey shallow water areas to reduce biases in biomass estimates and distribution mapping.

On physical mechanisms controlling inshore aggregations of small pelagic fish in a tropical upwelling system

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Abstract (doi: 10.1109/RIOAcoustics.2015.7473621):

Acoustically determined fish distribution pattern from bi-seasonal pelagic fish surveys conducted off Angola indicate for the seasonal contrasts in the spatial organization of the sardinella (*Sardinella spp.*) aggregations. During austral winter, the distributions are dominated by contiguous aggregations, aligned with the inshore areas shallower then 50 m while during austral summer the aggregations are more scattered and spread across the entire continental shelf length. Bi-seasonal acoustic surveys on this stock were conducted during 1994-1998 and 2011-2014. We have compared oceanographic data collected during these surveys with cross-shelf multi-frequency acoustic images constructed from the collected echogram segments in an attempt to asses an impact of the seasonally varying physical conditions on the observed changes in fish distributions patterns. The oceanographic regimes off Angola are remotely controlled by coastally trapped Kelvin waves. The main upwelling season takes place from June to August. The hydrographic and meteorological observations evidence that this upwelling it is characterized by the elevated thermocline and the presence of the cold water pool close to the sea surface despite of the absence of the upwelling favorable coastal wind. The acoustic imagery reveals the omnipresence of the first mode internal solitary waves in the water column. Under these conditions, the observed continuous pelagic fish aggregations are generally located inshore of a shallow front induced by the internal wave breaking, which is located in the depth range of 40-60 m. The concomitant drop in the surface temperature and the rise in the fluorescence suggest that this front is the hot-spot of the planktonic food concentrations. On the basis of these observations, we conclude that in the windless upwelling region of the southeastern tropical Atlantic (6°30’-13° S), it is the internal waves and their breaking which are likely to be a major factor controlling the ocean triad: enrichment, concentration and retention - of the physical mechanisms that control small pelagic fish populations in these waters

Contrasted optimal environmental windows for both sardinella species in Senegalese

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Abstract (doi: 10.1111/fog.12257):

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We investigate *Sardinella aurita* and *Sardinella maderensis* recruitment success relative to the variability of oceanographic conditions in Senegalese waters using generalized additive models (GAM). Results show that recruitment of both species is marked by a strong intra-annual (seasonal) variation with minimum and maximum in winter and summer, respectively. Their interannual variations are synchronous until 2006 (recruitment decreasing), while from 2007 there is no synchrony. The model developed shows that sardinella recruitment variability is closely related to the tested environmental variables in the study area. However, the key environmental variables influencing the recruitment success are different for both species: the Coastal Upwelling Index and the sea surface temperature for *S. aurita* and *S. maderensis*, respectively. We report that recruitment success of *S. aurita* and *S. maderensis* are associated with distinct ranges of sea surface temperature, upwelling intensity, wind-induced turbulence, concentration of chlorophyll-a and north Atlantic oscillation index. Considering food security and socio-economic importance of both stocks, we recommend that consideration is given to the environmental variability in the small pelagic fish national management plans, particularly in the context of climate change.

Studying the contribution of different fishing gears to the Sardinella small-scale fishery in Senegalese waters

O. Diankha[1,], H, Demarcq[2], M., Fall[3], D. Thiao[3], M. Thiaw[3], B. A., Sow[4], B.A., A.T., A.T. Gaye[1], P. Brehmer[3,5]

Abstract (doi: 10.1051/alr/2017027):

[1]Université Cheikh Anta Diop (UCAD), Ecole Supérieure Polytechnique, Laboratoire de Physique de l'Atmosphère et de l'Océan Siméon Fongang (LPAO-SF), BP 5085, Dakar-Fann, Senegal. [2]Institut de Recherche pour le Développement (IRD), UMR 248 MARBEC (Marine Biodiversity, Exploitation and Conservation) CS 30171, 34203 Sète, France. [3]Institut Sénégalais de Recherches agricoles (ISRA), Centre de Recherches Océanographiques de Dakar-Thiaroye, PRH, BP 2241 Dakar, Senegal. Université Assane Seck de Ziguinchor (UASZ), [4]Laboratoire d'Océanographie, des Sciences de l'Environnement et du Climat (LOSEC), Département de Physique, UFR Sciences & Technologies, BP 523 Ziguinchor, Senegal. [5]Institut de Recherche pour le Développement (IRD), UMR 195 Lemar (Laboratory of Marine Environment). BP 1386 Hann, Dakar, Senegal (published paper: Diankha et al. 2017).

This study investigated variations of landings of two key species, *Sardinella aurita* and *Sardinella maderensis*, in Senegalese waters over a ten-year period (2004– 2013). Using generalized additive models, it was found that fishing gear played a major role in explaining differences in monthly landings for both species (51– 71% deviance explained). Its effect was more significant in the southern part of Senegal. Fishing effort (number of trips) accounted only for 4– 18% of variability in landings. Purse seine (PS) fishing was the most important contributor to the landings of both species. In addition, in the southern area, surrounding gillnet fishing was also important for *S. maderensis* . Modeling results showed that the relationship between monthly effort and landings was generally positive and leveling off, while it was dome shaped for PSs and surrounding gillnets. Thus, when estimating fishing effort indices for management in Senegal, it is necessary to account for differences in fishing gears and the non-linear relationship between fishing effort and landings.

Reproductive Biology of Sardinella sp. (*Sardinella aurita* and *Sardinella maderensis*) in the South of Morocco.

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(published: Baali et al. 2018).

Abstract (doi: 10.3923/pjbs.2017.165.178):

Background and Objective: *Sardinella* sp. has gained much attention lately because of its biomass increase, which might be the result of climatic changes occurring across the Atlantic sea. Little information is known about reproduction of these species particularly in the Moroccan Atlantic area. The objective of the this study was to explore some aspects of the reproductive biology of *Sardinella* in the South of Atlantic Moroccan coast. **Materials and Methods:** Monthly samples were collected during the period between February, 2015 and January, 2016 in the area between Cape Boujdor and Cape Blanc. The data collected concerned the measure of the total length, the weight, the gonad weight as well as the sex and maturity stages. The $\chi 2$ test was used to compare the differences between both sexes and the ANOVA test was adopted to analyze the data variation. **Results:** *Sardinella* sp. is a gonochoristic fish. The overall female to male ratio was not statistically different for both species ($\chi 2$ = 0.68 for *Sardinella aurita* and $\chi 2$ = 1.04 for *Sardinella maderensis*), although it varied seasonally and according to the length of the fish. The monthly changes in the gonadosomatic index and the macroscopic characteristics of gonads showed that round *Sardinella* in the South of Morocco spawns between February and July and between November and December with a spawning peak on April. For the flat *Sardinella*, it spawns between February and March and in July with a spawning peak on July. Females round *Sardinella* reach first sexual maturity at a smaller size than males (26.17 and 26.78 cm, respectively). Concerning the flat *Sardinella*, it was the opposite. Males reaching sexual maturity are smaller than females (20.75 and 21.76 cm, respectively). **Conclusion:** It is concluded that the size at first maturity revealed that mature females in the South of Moroccan Atlantic Ocean were smaller than males for the round *Sardinella* and the opposite was observed for the flat *Sardinella*. The spawning of *S. aurita* presented a pick in April and for *S. maderens*is in July. As a shared stock these findings will be used for stock assessment in the North West Africa area.

Does upwelling intensity determine larval fish habitats in upwelling ecosystems? The case of Senegal and Mauritania

M. Tiedemann[1,] T., H, Fock[1], P. Brehmer[2,3], J. Döring[4], C. Möllmann[5]

Abstract (doi: 10.1111/fog.12224):

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European sardine (*Sardina pilchardus*) and round sardinella (*Sardinella aurita*) comprise two-thirds of total landings of small pelagic fishes in the Canary Current Eastern Boundary Ecosystem (CCEBE). Their spawning habitat is the continental shelf where upwelling is responsible for high productivity. While upwelling intensity is predicted to change through ocean warming, the effects of upwelling intensity on larval fish habitat expansion is not well understood. Larval habitat characteristics of both species were investigated during different upwelling intensity regimes. Three surveys were carried out to sample fish larvae during cold (permanent upwelling) and warm (low upwelling) seasons along the southern coastal upwelling area of the CCEBE (13°–22.5°N). *Sardina pilchardus* larvae were observed in areas of strong upwelling during both seasons. Larval habitat expansion was restricted from 22.5°N to 17.5°N during cold seasons and to 22.5N during the warm season. *Sardinella aurita* larvae were observed from 13°N to 15°N during cold seasons and 16–21°N in the warm season under low upwelling conditions. Generalized additive models predicted upwelling intensity driven larval fish abundance patterns. Observations and modeling revealed species-specific spawning times and locations,that resulted in a niche partitioning allowing species' co-existence. Alterations in upwelling intensity may have drastic effects on the spawning behavior, larval survival, and probably recruitment success of a species. The results enable insights into the spawning behavior of major small pelagic fish species in the CCEBE. Understanding biological responses to physical variability are essential in managing marine resources under changing climate conditions.

Larval fish assemblages across an upwelling front: Indication for active and passive retention

M. Tiedemann[1,] T., P. Brehmer[2,3]

Abstract (doi: 10.1016/j.ecss.2016.12.015):

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In upwelling areas, enrichment, concentration and retention are physical processes that have major consequences for larval fish survival. While these processes generally increase larval survival, strong upwelling can also increase mortality due to an offshore transport of larvae towards unfavorable habitats. In 2013 a survey was conducted along the Senegalese coast to investigate the upwelling effect with regard to larval fish assemblages and possible larval fish retention. According to water column characteristics two distinct habitats during an upwelling event were discriminated, i.e. the inshore upwelled water and the transition area over the deepest part of the Senegalese shelf. Along the two areas 42,162 fish larvae were collected representing 133 species within 40 families. Highest larval fish abundances were observed in the inshore area and decreasing abundances towards the transition, indicating that certain fish species make use of the retentive function of the inner shelf area as spawning grounds. Two larval fish assemblages overlap both habitats, which are sharply delimited by a strong upwelling front. One assemblage inhabited the inshore/upwelling area characterized by majorly neritic and pelagic species (Sparidae spp., Sardinella aurita), that seem to take the advantage of a passive retention on the shelf. The second assemblage consisted of a mix of pelagic and mesopelagic species (Engraulis encrasicolus, Carangidae spp. and Myctophidae spp.). Some species of the second assemblage, e.g. horse mackerels (Trachurus trachurus and Trachurus trecae), large finned-lantern fish (Hygophum macrochir) and foureyed sole (Microchirus ocellatus), revealed larval peak occurrences at intermediate and deep water layers, where the near-ground upwelling layer is able to transport larvae back to the shelf. This indicates active larval retention for species that are dominant in the transition area. Diel vertical migration patterns of S. aurita, E. encrasicolus and M. ocellatus revealed that a larval fish species may adapt its behavior to the local environment and do not necessarily follow a diurnal cycle. Field observations are essential to be integrated in larval drift models, since the vertical and horizontal larval distribution will have major consequences for survival. Comprehending larval survival mechanisms is necessary for the ultimate goal to understand and predict recruitment.

A biophysical model of *S. aurita* early life history in the northern Gulf of Guinea

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Abstract (doi: 10.1016/j.pocean.2016.10.008):

S. aurita is the most abundant small pelagic fish in the northern Gulf of Guinea. Its reproduction and recruitment depend crucially on environmental conditions. We developed a biophysical model of *S. aurita* early life history by coupling offline an individual-based model with the regional oceanic modeling system (ROMS). We used this model to investigate the main factors driving variability in eggs and larval dispersal and survival in the northern Gulf of Guinea. Precisely, individuals were released from different spawning areas along the coast and tracked for a period of 28 days corresponding to their planktonic phase. Individuals that remained in the coastal recruitment areas at an age more than 7 days, at which they can supposedly actively retain themselves in a favorable area, were considered as recruited. Simulation results show the importance of the spawning areas around Cape Palmas and Cape Three Points where cyclonic eddies trap eggs and larvae along the coast, preventing their advection offshore by the Guinea Current. The spawning period also plays a key role in the recruitment success, with highest coastal retention obtained during the major upwelling period (July–September). We find that a second retention peak can occur during the minor upwelling period (February–March) when larval mortality due to temperature is included in the model. These results are in general agreement with knowledge of *S. aurita* reproduction in the northern Gulf of Guinea.

What drives the spatial variability of primary productivity and matter fluxes in the north-west African upwelling system? A modelling approach

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Abstract (doi: 10.5194/bg-13-6419-2016):

A comparative box analysis based on a multi-decadal physical–biogeochemical hindcast simulation (1980–2009) was conducted to characterize the drivers of the spatial distribution of phytoplankton biomass and production in the north-west (NW) African upwelling system. Alongshore geostrophic flow related to large-scale circulation patterns associated with the influence of coastal topography is suggested to modulate the coastal divergence, and then the response of nutrient upwelling to wind forcing. In our simulation, this translates into a coastal upwelling of nitrate being significant in all regions but the Cape Blanc (CB) area. However, upwelling is found to be the dominant supplier of nitrate only in the northern Saharan Bank (NSB) and the Senegalo-Mauritanian (SM) regions. Elsewhere, nitrate supply is dominated by meridional advection, especially off Cape Blanc. Phytoplankton displays a similar behavior with a supply by lateral advection which equals the net coastal phytoplankton growth in all coastal regions except the Senegalo-Mauritanian area. Noticeably, in the Cape Blanc area, the net coastal phytoplankton growth is mostly sustained by high levels of regenerated production exceeding new production by more than twofold, which is in agreement with the locally weak input of nitrate by coastal upwelling. Further offshore, the distribution of nutrients and phytoplankton is explained by the coastal circulation. Indeed, in the northern part of our domain (i.e. Saharan Bank), the coastal circulation is mainly alongshore, resulting in low offshore lateral advection of nutrients and phytoplankton. Conversely, lateral advection transports coastal nutrients and phytoplankton towards offshore areas in the latitudinal band off the Senegalo-Mauritanian region. Moreover, this latter offshore region benefits from transient southern intrusions of nutrient-rich waters from the Guinean upwelling.

Dynamics of a “low-enrichment high-retention” upwelling center over the southern Senegal shelf

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Abstract (doi: 10.1002/2017GL072789):

Senegal is the southern tip of the Canary upwelling system. Its coastal ocean hosts an upwelling center which shapes sea surface temperatures between latitudes 12∘ and 15∘N. Near this latter latitude, the Cape Verde headland and a sudden change in shelf cross-shore profile are major sources of heterogeneity in the southern Senegal upwelling sector (SSUS). SSUS dynamics is investigated by means of Regional Ocean Modeling System simulations. Configuration realism and resolution ($\Delta x \approx 2$ km) are sufficient to reproduce the SSUS frontal system. Our main focus is on the 3-D upwelling circulation which turns out to be profoundly different from 2-D theory: cold water injection onto the shelf and upwelling are strongly concentrated within a few tens of kilometers south of Cape Verde and largely arise from flow divergence in the alongshore direction; a significant fraction of the upwelled waters are retained nearshore over long distances while travelling southward under the influence of northerly winds. Another source of complexity, regional-scale alongshore pressure gradients, also contributes to the overall retention of upwelled waters over the shelf. Varying the degree of realism of atmospheric and oceanic forcings does not appreciably change these conclusions. This study sheds light on the dynamics and circulation underlying the recurrent sea surface temperature pattern observed during the upwelling season and offers new perspectives on the connections between the SSUS physical environment and its ecosystems. It also casts doubt on the validity of upwelling intensity estimations based on simple Ekman upwelling indices at such local scales.