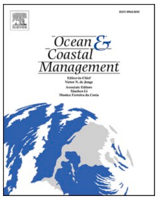
Ocean and Coastal Management 197 (2020) 105322

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: http://www.elsevier.com/locate/ocecoaman



The small pelagic fishery of the Pemba Channel, Tanzania: What we know and what we need to know for management under climate change

Baraka Sekadende[a], Lucy Scott[b], Jim Anderson[c], Shankar Aswani[d], Julius Francis[e], Zoe Jacobs[f], Fatma Jebri[f], Narriman Jiddawi[g], Albogast T. Kamukuru[h], Stephen Kelly[f], Hellen Kizenga[g], Baraka Kuguru[a], Margareth Kyewalyanga[g], Margaux Noyon[i], Ntahondi Nyandwi[g], Stuart C. Painter[f], Matthew Palmer[f], Dionysios E. Raitsos[j,l], Michael Roberts[f,i], Sévrine F. Sailley[j], Melita Samoilys[k], Warwick H.H. Sauer[d], Salome Shayo[a], Yohana Shaghude[g], Sarah F.W. Taylor[f], Juliane Wihsgott[f], Ekaterina Popova[f,*]

[a] *Tanzania Fisheries Research Institute, Dar Es Salaam, Tanzania*
[b] *South African Environmental Observation Network, Egagasini Node, Cape Town, South Africa*
[c] *Independent, United Kingdom*
[d] *Rhodes University, Grahamstown, South Africa*
[e] *Western Indian Ocean Marine Science Association, Zanzibar, Tanzania*
[f] *National Oceanography Centre, Southampton, SO14 3ZH, United Kingdom*
[g] *Institute of Marine Sciences, University of Dar Es Salaam, Tanzania*
[h] *Department of Aquatic Sciences and Fisheries Technology, University of Dar Es Salaam, Tanzania*
[i] *Nelson Mandela University, Port Elisabeth, South Africa*
[j] *Plymouth Marine Laboratory, Plymouth, PL1 3DH, United Kingdom*
[k] *CORDIO East Africa, Mombasa, Kenya*
[l] *Department of Biology, National and Kapodistrian University of Athens, Athens, Greece*

ABSTRACT

Small pelagic fish, including anchovies, sardines and sardinellas, mackerels, capelin, hilsa, sprats and herrings, are distributed widely, from the tropics to the far north Atlantic Ocean and to the southern oceans off Chile and South Africa. They are most abundant in the highly productive major eastern boundary upwelling systems and are characterised by significant natural variations in biomass. Overall, small pelagic fisheries represent about one third of global fish landings although a large proportion of the catch is processed into animal feeds. Nonetheless, in some developing countries in addition to their economic value, small pelagic fisheries also make an important contribution to human diets and the food security of many low-income households. Such is the case for many communities in the Zanzibar Archipelago and on mainland Tanzania in the Western Indian Ocean. Of great concern in this region, as elsewhere, is the potential impact of climate change on marine and coastal ecosystems in general, and on small pelagic fisheries in particular. This paper describes data and information available on Tanzania's small pelagic fisheries, including catch and effort, management protocols and socio-economic significance. Then, incorporating the rapidly improving understanding of the region's oceanography resulting from the application of remote sensing and oceanographic modelling, the paper undertakes the most complete assessment to date of the potential impacts of climate change on the small pelagic fishery of the Pemba Channel. Pathways of climate change impact are explored and crucial knowledge gaps, both in terms of the fishery itself and the wider ecosystem, are identified in order to guide future research activities. Although we analyse small pelagics in the specific context of the Pemba Channel, the key challenges identified in the analysis are likely to be relevant to many small pelagic fisheries in coastal nations heavily dependent on living marine resources.

1. Introduction

Small pelagic fish, often referred to as 'bait-fish' or 'forage fish', are a group of species that are characterised by their relatively short lifespans, rapid growth, large biomass, strong shoaling (or schooling) behaviour and highly variable population dynamics. In terms of habitat, small pelagic species are *epipelagic*, inhabiting the upper 200 m of coastal zones and oceans, and are capable of significant horizontal and vertical mobility. Depending on the family, they are found in both near-shore and continental shelf environments and are characterised, as a group,

---

[*] Corresponding author.
E-mail address: e.popova@noc.ac.uk (E. Popova).

https://doi.org/10.1016/j.ocecoaman.2020.105322
Received 11 May 2020; Received in revised form 30 July 2020; Accepted 31 July 2020

by their size range of ~7 cm–~25 cm in length (e.g. Freon et al., 2005).

Small pelagics have a special place in the food security of the poor coastal populations of the developing countries, being generally more affordable, available and accessible than other fish species. This is particularly true for tropical coastal populations as they witness the increasing degradation and collapse of their reef fisheries. Although small pelagic fish are frequently regarded as a lower value product in the international food trade, predominantly resulting in fishmeal, they are often consumed by the poorest populations, and provide direct local employment (e.g. Isaacs, 2016). In addition, the important role of the small pelagics for local food security is often assured by the fact that trading them on the global market is very challenging as the post-harvest handling of this high fat content fish with no cold chain (refrigeration facilities) often does not meet the minimum hygiene standards. Thus, the artisanal small pelagic fisheries present an important case where the food security of the poor in developing countries is not compromised by the need for income from the foreign trade as in the case of the higher value species (Isaacs, 2016).

Small pelagics are the target of some of the globally most important single fisheries and, although the precise definition of what species are defined as 'small pelagic' varies, in 2014 a total global catch of an estimated 25 million tonnes was landed, representing about 30% of the global marine catch (FAO, 2018). More specifically, the catch of the so-called 'HAS' grouping, of approximately 44 species of Herring, Anchovy and Sardines was an estimated 15million tonnes (Mt) in 2014 (Kripa et al., 2019). It is important to note that HAS species, while sharing similar characteristics, do not all have the exact same environmental preferences or display the same responses to environmental change. Optimal temperature, salinity, depth, degree of migratory behaviour and prey preferences all differ, particularly between the Engraulidae (Anchovy) and the Clupeidae (Herring and Sardines). In general, anchovies are significantly more vulnerable to environmental change than sardines (Bakun, 2017).

In the major industrial-scale small pelagic fisheries, notably in the south-east and north-east Pacific Ocean, and the eastern Atlantic, a substantial proportion of the catch is processed into fishmeal for aquaculture or fish-oils as food supplements. Data from the FAO (Food and Agriculture Organization of the United Nations) indicates that in 1993, 65% (or ~23 Mt) was used for non-food products but by 2014 that figure had reduced to less than half (48% or ~13 Mt), thereby increasing the resources available for direct human consumption (Barange et al., 2017). In 2006, the aquaculture sector consumed 68% of the total global fish meal production and nearly 90% of the total fish oil production, representing a total of 16.6 Mt of small pelagic species (Tacon and Metian, 2008). However, smaller, artisanal-scale pelagic fisheries in developing countries make an important and, in some cases, growing contribution to the food security of both coastal and inland communities. Over the last two decades the contribution of small pelagic species to total fish food supply in Africa has been relatively constant at between 30 and 38% (Barange et al., 2017).

The sensitivity of small pelagics to natural environmental forcing implies that they will be equally sensitive to marine environmental forcing that is a result of anthropogenic climate change.

However, projections of climate change and its impact on fishery biomass are, at present, conducted in a framework of global models with only a large-scale representation of ocean dynamics and ecosystems. Such models are not yet able to provide the level of accuracy needed for country-scale decision-making (Cisneros-Mata et al., 2019). Downscaling research outputs to a smaller sub-region or country is challenging, exacerbated by the fact that the understanding of fluctuations in small pelagic populations and their environmental drivers outside of the major upwelling systems is, in any case, limited. This is especially pronounced along the coastlines of developing countries, although their importance to the food security of the coastal population makes it imperative to be able to do so. The Tanzanian coast is no exception; while our understanding of the environmental drivers of small pelagic biomass is at an early stage (Anderson and Samoilys, 2016), current knowledge suggests a tight coupling to monsoonal cycles of productivity, rainfall patterns and interannual variations in primary production.

The small pelagic fishery (Fig. 1) is one of the most important fisheries in Tanzania, making a substantial but probably under-estimated contribution to coastal livelihoods and food security (Mayala, 2016). The official fisheries data indicate that the small pelagic fishery accounts for approximately one third of the total fish catch of mainland Tanzania (SWIOPF, 2012) and 21 percent of the total catch in Zanzibar (FAO, 2014). It is important to note that the total catch estimate is likely to be an underestimate, as suggested by the FAO's work on restructuring catch estimates (Buitel, 2015). Preliminary estimates from a small pelagics research programme implemented by the Tanzania Fisheries Research Institute (TAFIRI) under the South West Indian Ocean Fisheries Governance and Shared Growth (SWIOFish) programme also suggest that official catch estimates for this group are significantly under-estimated (Kashindye and Anderson pers.comm). Despite the apparent importance of this fishery, limited research has so far been conducted into the abundance of the small pelagics, their key regional environmental drivers and potential impacts of the climate change.

The inherent variability of small pelagic populations implies that capture fisheries based on their productivity may be somewhat unreliable, precarious and even *fragile enterprises* for both fishers and investors (Beverton, 1983; Pitcher, 1995). The latter implies that, ideally, management strategies should be in place that allow small pelagic fisheries to adapt to such oscillations, but this appears not to be the case, neither in Tanzania nor elsewhere. For example, Mullon et al. (2005, cited by Kripa et al., 2019) analysed 50 years of fisheries landing data from the FAO, which revealed that of the 161 stocks in the HAS group, 38 (28%) have shown collapses. It is apparent that small pelagic species are especially difficult to manage (Beverton, 1983, 1990; Pinsky and Byler, 2015).

In this study we consider the Zanzibar Archipelago, which consists chiefly of the islands of Pemba and Unguja, situated 20–40 km offshore of mainland Tanzania. In particular, we focus on the Pemba Channel, in which the deepest part is approximately 800 m deep and ~50 km wide. It is located north of Unguja Island and separates Pemba Island from the mainland. The Pemba Channel is characterised by a deep oceanic setting with direct connectivity to the open ocean but also with adjacent coastal areas that host important coral reef and mangrove habitats that are also exploited by a number of fisheries. The fast-flowing current speeds that are typical of this channel indicate low retention rates and short residence times, but the channel is also considered to be part of a larger scale coastal upwelling system, receiving only limited riverine nutrient inputs.

The aim of this paper is to describe what is known about the Pemba Channel small pelagic fishery and its environmental drivers, discuss the contribution of the small pelagic fish to food security, and identify the knowledge gaps that need to be filled in order to improve the resilience of this fishery to the impact of climate change. Although this study analyses the small pelagic fish in the local context of the Pemba Channel, the key challenges identified in the analysis are likely to be relevant to many small pelagic fisheries in coastal nations heavily dependent on living marine resources.

2. The ecology of small pelagic fish

2.1. Environmental sensitivity

Small pelagics are highly sensitive to their marine environment throughout their life history (Beverton, 1983; Alheit et al., 2009). They have specific tolerance windows for their environmental conditions (e.g. temperature, salinity, oxygen, pH), which define their bioclimatic envelope (Pearson and Dawson, 2003). For example, oxygen levels impact growth of fish and the maximal size a fish can reach (Pauly, 2019). As the pelagic environment gets warmer, the oxygen demand of the fish (to

Fig. 1. Small pelagic fishery of Tanzania: a) Unloading small pelagic fishing vessels: Mangapwani, Unguja/Zanzibar, United Republic of Tanzania (Credit: Jim Anderson); b) Spreading boiled small pelagics to dry: Mkokotoni, Unguja/Zanzibar, Tanzania (Credit: Jim Anderson); c) Small pelagics sun-drying: Mkokotini, Unguja/Zanzibar, Tanzania (Credit: Jim Anderson); d) Small pelagic fishing vessel auctioning catch at Kasera landing site, Tanga Municipality, Tanzania (Credit: Benedicto Kashindye, TAFIRI, Tanzania).

cover metabolic need) will rise leading to the need for the fish to migrate to cooler waters or death. Salinity impacts egg buoyancy and whether hatching will occur at the right depth for optimal survival of the larvae. Larval survival is also influenced by the immediate and proximal availability of food sources (plankton) and survival is greatest when food supply *matches* peak production of larvae (the *match-mismatch* theory of Cushing, 1990). Similarly, ocean turbulence will determine planktonic density (Cury and Roy, 1989), while certain oceanographic features will act to retain larvae within the habitat of a species such that the larvae are able to recruit to adult populations (Lobel and Robinson, 1986). Lasker (1975) concluded that anchovy larvae required a certain duration of stability in their environment, sometimes referred to as 'Lasker windows', in order to be able to secure sufficient food particles to pass through the critical early growth phase. Failure of such *Lasker windows* to remain open for the minimum duration, due to storm events for example, could result in cohort recruitment failure (Bakun, 2010).

The sensitivity of small pelagic populations to their environment is observed over a range of temporal scales. The distribution of a shoal or even a sub-population of adult small pelagics may be strongly affected by localised variations in sea surface temperature (SST) over a period of hours to a few weeks (Bender et al., 1984). Longer-term abundance has been shown to follow decadal oscillations of SST (Lehodey et al., 2006) and primary production (Peck et al., 2013). Thus, fisheries landings fluctuations in the Mediterranean Sea showed significant year-to-year correlations with SST for nearly 60% of the species, and the majority (~70%) were negatively related (Tzanatos et al., 2014). A time-series of data of fish-scale deposits from the Santa Barbara Basin, off California, shows how the species assemblage underwent dramatic changes in the relative abundance of Engraulidae and Clupeidae, with an approximate 50–70 year periodicity associated with wider ecosystem *regime shifts* (Issacs, 1976).

Population responses to environmental variations can also include life-history adaptations. For example, Agostini (2007) showed that under productive (warm) regimes, Clupeidae in the California Current might live up to 13 years, with an age of maturity of 2–3 years, compared to a maximum age of just 4 years and age of maturity of 1–2 years in an unproductive (cool) environmental regime. By contrast, Engraulidae would live longer in a cooler regime compared to a warmer regime. Engraulidae, being relatively weak swimmers, are generally less mobile than Clupeidae, which can respond to adverse conditions by searching for a more suitable habitat. On the other hand, Engraulidae are capable of rapid population growth in ideal conditions (Bakun, 2017). Highlighting the important differences between the two major families of small pelagics, enables further understanding of the potential response and vulnerability to climate change. Although the two main families may co-occur and share common habitats, there is an evident degree of resource partitioning between them, such as the specific trophic level, food-web length and the origin of their respective diets (Garrido and van der Lingen, 2014). The different morphologies of the feeding apparatus, as well as different feeding behaviour, leads to Clupeidae feeding on smaller zooplankton than Engraulidae; phytoplankton are also more important in the diet of Clupeidae than of Engraulidae. Environmental (and climate) change affecting phytoplankton and zooplankton has the potential to differentially affect these two major families (Checkley et al., 2017).

2.2. *Wasp waist ecosystems*

Small pelagic fishes are generally found in coastal marine ecosystems, and are particularly abundant in upwelling regions, although they can range several hundred kilometres offshore. Such ecosystems are often characterised as 'wasp-waist' systems. That is to say that while lower and upper trophic levels typically comprise a large number and diversity of species, the intermediate level is rather different, with fewer species and lower diversity of species; a far simpler sub-system (Cury et al., 2000). Although two of the major families of small pelagics, the Engraulidae and Clupeidae, have somewhat different feeding strategies related to species and size of prey, they all feed predominantly on zooplankton. Their intermediate trophic level position is ecologically important because they effectively mediate the transfer of energy from lower to higher trophic levels, including to top predators (Cury et al., 2000). In doing-so, they influence the abundance of both predators (in the upper trophic levels) and prey (in the lower, Faurchald et al., 2011). By the same token, their reproductive success, and hence the strength of recruitment to a fishery, has been shown to be negatively correlated to the abundance of zooplankton in their spawning habitat potentially reflecting a decreased predation pressure by zooplankton predators (Agostini et al., 2007).

2.3. *Fishery implications of environmental sensitivity & adaptability*

Crucially, the life-histories and the responses of small pelagic species to environmental change implies that the potential biomass available to a fishery, its species composition and its spatial distribution will also be highly variable (Hunter and Alheit, 1995). This has important livelihood implications for fishers and associated industries, economic implications for investors, and for the types of management strategies that may be applied.

Indeed, Essington et al. (2015) and Pinsky and Byler (2015) have shown that some of the traits that make small pelagic species sensitive to environmental change, also exacerbates their sensitivity to fishing pressure. Research by Pinsky and Byler (2015) suggested a mechanism for this, arguing that the short generation times of fast-growing species implies fewer cohorts in a population and therefore their ability to tolerate environmental change *and* fishing pressure is limited compared to longer-lived species. Therefore, delays in reducing the fishing pressure when environmental change is already having negative effects on a population will only compound those effects. Pinsky and Byler (2015) go on to argue in fact that the collapses of small pelagic fisheries witnessed over the last 50-years were ‘primarily caused by overfishing’ and lags in management response time.

2.4. *The small pelagic fishery resources of Tanzania*

The first surveys of marine fisheries resource abundance in Tanzanian waters were undertaken in 1976/77 by the R/V Professor Mesyatsev using acoustic techniques, with trawl sampling to identify the species assemblage of the acoustic targets. The analysis of data generated from these surveys gave biomass estimates of 16,000 Mt for January; 2,000 Mt for March; 20,000 Mt for early July; 12,000 Mt for late July and 18,000 Mt for November. However, it is not clear what species these estimates refer to. In the trawl catches taken during the same surveys there were catches of sardines and anchovies, but they did not predominate over large areas (Birkett, 1979).

Further acoustic surveys were undertaken by R/V Dr Fridtjof Nansen in 1982/83, again supported by trawl surveys to verify the acoustic targets. The estimated biomass of fish observed in mid-water over the entire Tanzanian shelf was 101,000 Mt for June/July 1982, 66,000 Mt for November/December 1982 and 57,000 Mt for May 1983 (Saetersdal et al., 1999). In general, the three surveys recorded a relatively low biomass of pelagic resources. These figures also include pelagics with *Sardinella sirm*, *S. gibbosa*, *S. albella* and *S. leiogaster* being the most abundant and widespread Clupeoids in the shallower areas.

Overall, the data from the first Nansen survey show that pelagic species comprised 18% of trawl catches in waters less than 20 m depth, 16% in 20–50 m depth and 44% in water of 50–200 m depth. Results were highly variable in the subsequent surveys (9–22% across all depths) (Iversen et al., 1984).

The most recent acoustic survey in April 2018, was conducted by the new R/V Dr Fridtjof Nansen (launched in 2017) during the intermonsoon season with substantially lower biomass estimates being recorded. The estimate for the area off Mafia Island was 516 Mt and the estimate for the Zanzibar Channel was 6,532 Mt although the very low densities detected during the survey may cast some doubt on the strength of the raised biomass estimates. No pelagic species were observed in the Pemba Channel, but the level of sampling effort that took place in the Channel is not clear (IMR, 2018).

There are no within season stock assessments using acoustic techniques, and the schooling nature of most small pelagic species makes resource assessment estimates from catch data difficult, as natural abundance will decrease faster than the ratio of catch vs effort. Good catches in one year therefore might not indicate a successful catch in the following season.

3. Environmental setting

3.1. *Regional circulation*

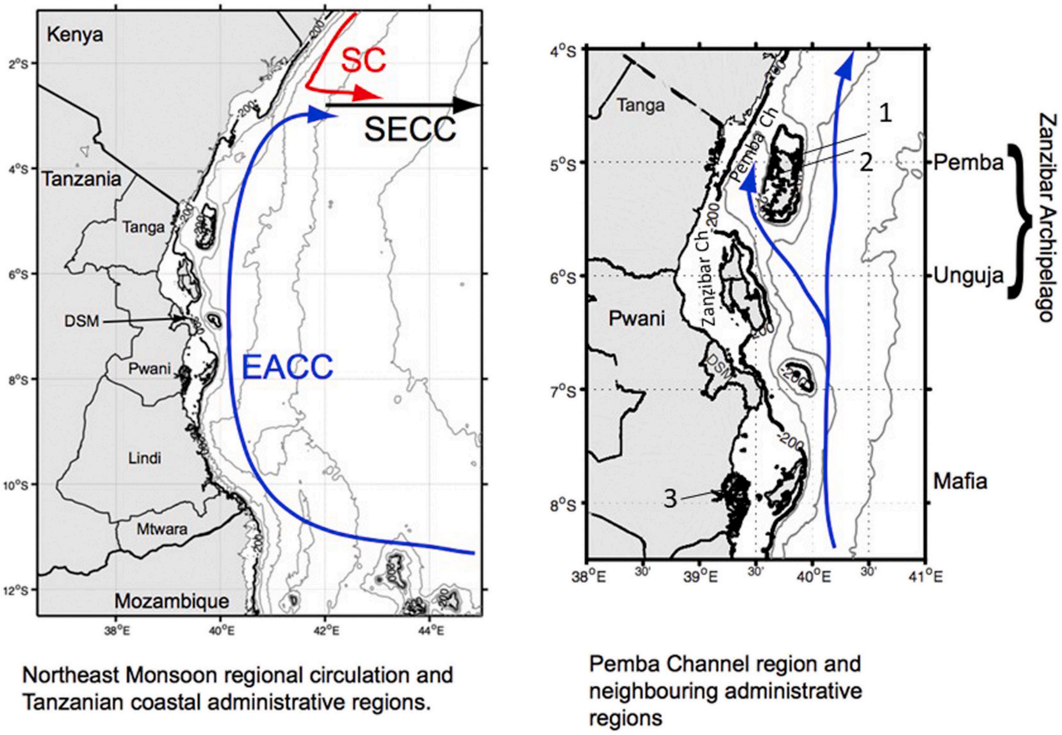
The Western Indian Ocean (WIO) experiences strong monsoon driven seasonality (Schott and McCreary, 2001; Mahongo et al., 2011) which has significant implications for the local circulation along the East African coast (Schott et al., 2009), as well as fish catch (Jury et al., 2010) including the catch of the small pelagics in the Pemba Channel (Jebri et al., 2020). The East African Coastal Current (EACC) is the dominant oceanographic influence on the physical and biogeochemical environment of the Tanzanian coast (Swallow et al., 1991; Nyandwi, 2013, Fig. 2) and flows northwards year-round between the latitudes of ~11 and ~3°S, extending its range northwards into Kenyan and Somalian waters during the South East Monsoon (SEM; April–October).

The SEM is characterised by strong south-easterly winds with speeds of up to 10 m s^{-1} which strengthen and accelerate the EACC to typical velocities of ~1.5–2 m s^{-1} with some of the strongest associated flows experienced within the Pemba Channel (Semba et al., 2019). During the northeast monsoon (NEM; November–March), the seasonally reversed winds are weaker, typically around 6 m s^{-1}, and the reversed southward flowing Somali Current inhibits northward continuation of the EACC beyond southern Kenya, leading to decreased current velocities along the coast of Tanzania (Mahongo and Shaghude, 2014; Mayorga-Adame et al., 2016; Semba et al., 2019).

SSTs range from ~25 °C during the SEM to ~30 °C during the NEM (Shaghude and Byfield, 2012; Mahongo and Shaghude, 2014). Seasonal deepening of the surface mixed layer by 30–60 m or more occurs between monsoon seasons with the deepest mixed layers observed during the SEM months (Hartnoll, 1974). A broad understanding of the impact of the changing monsoon seasons on the general circulation of surface waters, such as the physical characteristics of the upper ocean, the dispersion of shelf waters and associated pelagic organisms does exist, however generally sparse sampling of the region means that many aspects of the finer-scale regional circulation remain poorly constrained (Manyilizu et al., 2014; Swallow et al., 1991; Shaghude et al., 2002) and there is only limited information on the associated impacts on the ecology and biogeochemistry of these waters (Jury et al., 2010; Mayorga-Adame et al., 2017; Painter, 2020).

3.2. *Chlorophyll a*

Remote sensing observations of surface chlorophyll-*a* (Chl-*a*) reveal a clear monsoon cycle over the deeper off-shelf (Case-I) waters with highest surface Chl-*a* concentrations during the mid-SEM months (July to September) – in agreement with general productivity patterns across the wider WIO (Cushing, 1973; Kyewalyanga, 2015; Painter, 2020). In shallow shelf waters the annual cycle is more complex with studies showing highest Chl-*a* concentrations during the NEM in the coastal waters around Dar es Salaam (Bryceson, 1982; McClanahan, 1988) and in waters around Tanga , or during the SEM around the island of Unguja, along the western coast of Pemba Island and off the Rufiji River Delta (Limbu and Kyewalyanga, 2015; Moto and Kyewalyanga, 2017). Understanding this spatial variability is challenging due to limited in-situ data and the genuine possibility of sub-regional patterns related to natural and anthropogenic influences, whilst satellite retrievals from



Northeast Monsoon regional circulation and Tanzanian coastal administrative regions.

Pemba Channel region and neighbouring administrative regions

Fig. 2. a) Schematic diagram of the ocean circulation during the north-east monsoon and Tanzanian coastal administrative regions; b) Pemba and Zanzibar channels and neighbouring administrative regions. Numbers on the map (b) show: Mcheweni (1) and Mkoani (2) districts; Rufiji River Delta (3); Dar es Salaam is abbreviated as DS.

shallow coastal (Case-II) waters are largely unvalidated for these waters (Peter et al., 2018). In-situ observations indicate a mean annual surface Chl-a concentration of ~0.3 mg/m^3 (ASCLME, 2012), but close to land concentrations can vary significantly, reaching ~19 mg/m^3 in one extreme example (Kyewalyanga, 2002). The vertical distribution of chlorophyll is also poorly described for these waters but a deep chlorophyll maximum, typical of the prevailing tropical conditions, was reported by Barlow et al. (2011) in the waters around Unguja Island. Maximum subsurface chlorophyll concentrations were over twice as high as surface concentrations though the implications for remotely sensed productivity assessments are unclear.

3.3. Nutrients

Tanzanian coastal waters are classified as nutrient poor (ASCLME, 2012), though shelf waters can be mesotrophic in character. Away from the shelf, surface nutrient concentrations are low (NO_3 ~0.1 μmol L^{-1}, PO_4^{3-} 0.2–0.3 μmol L^{-1}, and Si ~4 μmol L^{-1}) whilst NH_4^+ has been shown to be the single most important form of N for phytoplankton production (Mengesha et al., 1999). In coastal waters, which can be influenced by rivers, mangrove forests or agro-industrial and sewage discharges, nutrient concentrations can be considerably higher. Observations of surface NO_3^- and PO_4^{3-} concentrations reaching 54 and 45 μmol L^{-1} respectively close to Dar es Salaam have been reported (Lyimo, 2009), but these have definitive explanations (sewage outflow) and are not indicative of natural conditions. Around Tanga, where there is much less anthropogenic influence, average values for phosphate and nitrate concentrations were found to be 0.21 and 0.34 μmol L^{-1}, respectively . A general distinction may be drawn between neritic waters (sheltered coastal waters) with higher nutrient concentrations, and the off-shelf waters, which are more of oceanic nature. Nevertheless, due to the lack of in-situ measurements, the annual cycle in surface nutrient concentrations and the spatial scales of variability across the region, is yet to be adequately described. Although a general decline in surface nutrients is expected under the influence of further ocean warming and stabilisation of stratification (e.g. Popova et al., 2016), some uncertainty remains with regards to how this general trend might be altered by the WIO region-specific dynamics, and in particular, by the future fate of coastal upwelling systems.

3.4. Primary production

Productivity measurements are limited and generally restricted to shallow coastal waters around the Zanzibar Archipelago (Pemba and Unguja Islands) and near Dar es Salaam. Typical productivity rates are reported between 0.5 and 2 g C m^{-2} d^{-1} but can range from <0.1 to >3 g C m^{-2} d^{-1} (Kyewalyanga, 2015). Limited investigation to date shows that regenerated production dominates over new production with implications for the flow of energy to higher trophic levels (Mengesha et al., 1999). Recent studies examining the annual cycle of productivity report contradictory results and it is not clear how, or if, such observations can be extrapolated more broadly along the Tanzanian coast. For example, Kyewalyanga (2002) reported surface productivity rates along eastern Unguja Island that ranged from 0.04 to ~1 g C m^{-3} d^{-1} over the year of sampling but the same dataset also revealed contradictory seasonal timings of peak productivity between inshore and offshore sites. In a rare study for these waters, Barlow et al. (2011) reported integrated productivity rates of 0.79–1.89 g C m^{-2} d^{-1} at deep water stations around Pemba Island at the end of the SEM period. In that study the variability in productivity rates between stations was attributed to spatially variable stratification and patchy upwelling of nutrients into the mixed layer. Multi-model ensemble of future projections of Chl-a and primary production under RCP8.5 emission scenario show a general decline in the global tropics over the 21st century, with the WIO being one of the regions where this decline is the most pronounced (Bopp et al., 2013).

3.5. Phytoplankton community

The distribution, abundance and seasonal cycle of phytoplankton are considered to be poorly known (Kyewalyanga, 2015). Existing information about the phytoplankton community is dispersed with a significant proportion of relevant information located within grey literature, inaccessible project reports or theses (e.g. Peter, 2013; Ezekiel, 2014). There are no routine monitoring programs, though there are nascent efforts to establish Harmful Algal Bloom (HAB) monitoring capabilities in response to recognised prevalence of HAB species across the region (Hansen et al., 2001; Kyewalyanga and Lugomela, 2001; Tamele et al., 2019). Taxonomic studies typically report 200–300 phytoplankton species within these waters (e.g. Bryceson, 1977; Moto et al., 2018) but investigation of the picoplankton is particularly limited. Reported shifts in the community structure from pico- and nanoplankton to nano- and microplankton dominance suggests that there are important but as yet poorly documented spatial scales of variability and patchiness (Barlow et al., 2011). Although the future of the phytoplankton composition remains highly uncertain (Peters, 2008), warming-induced strengthening of ocean stratification can be expected to favour smaller planktonic species with high surface to volume ratio (Falkowski and Oliver, 2008).

3.6. Zooplankton

Few studies have investigated zooplankton communities within the coastal waters of the East African coast and data from offshore regions are particularly rare. Seasonality has been reported in almost all the major zooplankton groups studied in coastal waters (Wickstead, 1962; Okera, 1974; Bryceson, 1982). Abundances are reportedly greatest during the late NEM and early SEM seasons and occur after peaks in coastal/shelf phytoplankton abundances (Okera, 1974). Salinity, particularly in estuarine waters and in areas of riverine discharge, may influence zooplankton abundances (Tafe, 1990). More recent zooplankton biovolume measurements around Pemba Island have shown some coherence with regions exhibiting higher surface Chl-a concentrations or higher primary production (Roberts et al., 2008; Barlow et al., 2011). The most recent and comprehensive review on zooplankton studies in the WIO region, spanning work between 1975 and 2015, was presented by Huggett and Kyewalyanga (2017). The review found significant variations both seasonally and spatially in zooplankton distribution, biomass and species composition. There is a growing consensus among the climate models that the climate change mediated decline of the oceanic primary production is likely to be amplified throughout the foodweb with more dramatic responses towards top of the foodweb (Kwiatkowski et al., 2018). Thus, a general decline of zooplankton biomass can be expected across the global tropics, Including the EACC region.

3.7. Relevance of local environment for small pelagics (Bakun's triad)

Bakun et al. (1998) noted a contrast between the low coastal fisheries landings and high production rates for oceanic tuna, describing this observation as "The Small Pelagics Puzzle" of the East African coast. The authors hypothesised that an extremely dissipative (low retention) environment led to low small pelagic yields relative to other parts of the world. This led to the proposal of a "fundamental triad" of essential conditions needed to provide a favourable habitat for small pelagics. The Triad argues that in addition to upwelling (as an enrichment process), concentration mechanisms (convergence, frontal structures and water column stability) and processes favouring retention within an appropriate range of habitats are required. Thus, along the East African coast the strong monsoonally reversing circulation, which favours offshore transport acts to disperse rather than retain the passive larval stages of small pelagic fish ultimately leading to low landings.

With the rapid development of i) remote sensing data processing algorithms, ii) high resolution ocean modelling and iii) Lagrangian approaches to the description of ecologically important properties of ocean circulation, it has become feasible to create spatially and temporally resolved maps of all three components of Bakun's Triad and assess how they may be altered by climate change. Although a full numerical study of the Triad dynamics in the WIO is outside the scope of this paper, Fig. 3 shows examples of the three components of the Triad: frontal positions (as a representation of convergence, Fig. 3b, following Miller and Christodoulou, 2014); Lagrangian forward trajectories (as a representation of coastal retention, Fig. 3a, following Popova et al., 2019), and examples of ocean upwelling as depicted by low SST and elevated Chl-a (Fig. 3c–f, following Jebri et al., 2020). This "proof of concept" outcome shows that while upwelling along the Tanzanian coast is a widely occurring phenomenon (Jebri et al., 2020), the other two components (frontal convergence and retention) are indeed low along the Tanzanian coastline in agreement with Bakun's hypothesis. Nevertheless, growing evidence suggests that the ecosystem, including small pelagic fish, responds strongly to upwelling events along the Tanzanian coast, and that interannual variability in the strength of upwelling is well correlated with the catches of small pelagics (Jury et al., 2010; Jebri et al., 2020). Upwelling intensity peaks during both the SEM and NEM, although the mechanisms at play are different during these two periods. During the NEM upwelling is driven by local alongshore winds, while during the SEM the acceleration of the strong along-shelf current results in "dynamic uplift" (Jebri et al., 2020).

One of the key hydrodynamic features of the Pemba Channel relevant to the small pelagic fish is its low retention and strong seasonal changes of the connectivity to upstream areas. Fig. 4 shows model-derived (Popova et al., 2019) advective pathways bringing the surface waters to the eastern (coast of Pemba) and western (mainland) sides of the Pemba channel. The trajectories demonstrate that the residence time of surface waters in the channel is of the order of two days, with the eastern side characterised by lower (1–2 days) residence time than the western side (2–3 days). Furthermore, the eastern side has a predominantly oceanic upstream connectivity, driven by the EACC, while the western side of the channel is of a coastal origin, being formed by the flow closely following the Tanzanian coastline through the Mafia and Zanzibar Channels. This general regime prevails through most of the year with the exception of the peak of the NEM (December–January) when the monsoonal reversal leads to a slowdown of the circulation. During this period, the residence time almost doubles, with complex flow patterns including an upstream connection to the Kenyan shelf waters and some across-channel connectivity which is usually absent during the rest of the year.

4. The small pelagic fishery of Tanzania

4.1. Tanzanian marine fisheries (a background)

The Tanzanian marine fishery is concentrated in inshore waters, over the continental shelf and around the inshore and offshore islands. A surface area of 9980 km^2 was estimated by Iversen et al. (1984) for waters shallower than 500 m, while Jiddawi and Ohman (2002), estimated a total fishable area within the territorial waters of approximately 30,000 km^2. The area of the Exclusive Economic Zone (EEZ) was cited by Breuil and Grima (2014) as being approximately 242,000 km^2.

Important marine resources include coral reef fishes (rabbitfish, groupers, emperors, snappers, goatfish), lagoon, intertidal and sub-tidal species (including octopus, squid and bivalves), large pelagic species (including tunas and tuna-like species), demersal species (including rays, catfish and shrimp), and the small pelagic species (anchovies, herrings, sardines and mackerels) which are the focus of this report (Jiddawi and Ohman, 2002). The artisanal sector is dominant in Tanzania, accounting for approximately 95% of all catches (Jiddawi and Ohman, 2002) and although these figures are relatively old, there has not been any development of a domestic semi-industrial or industrial

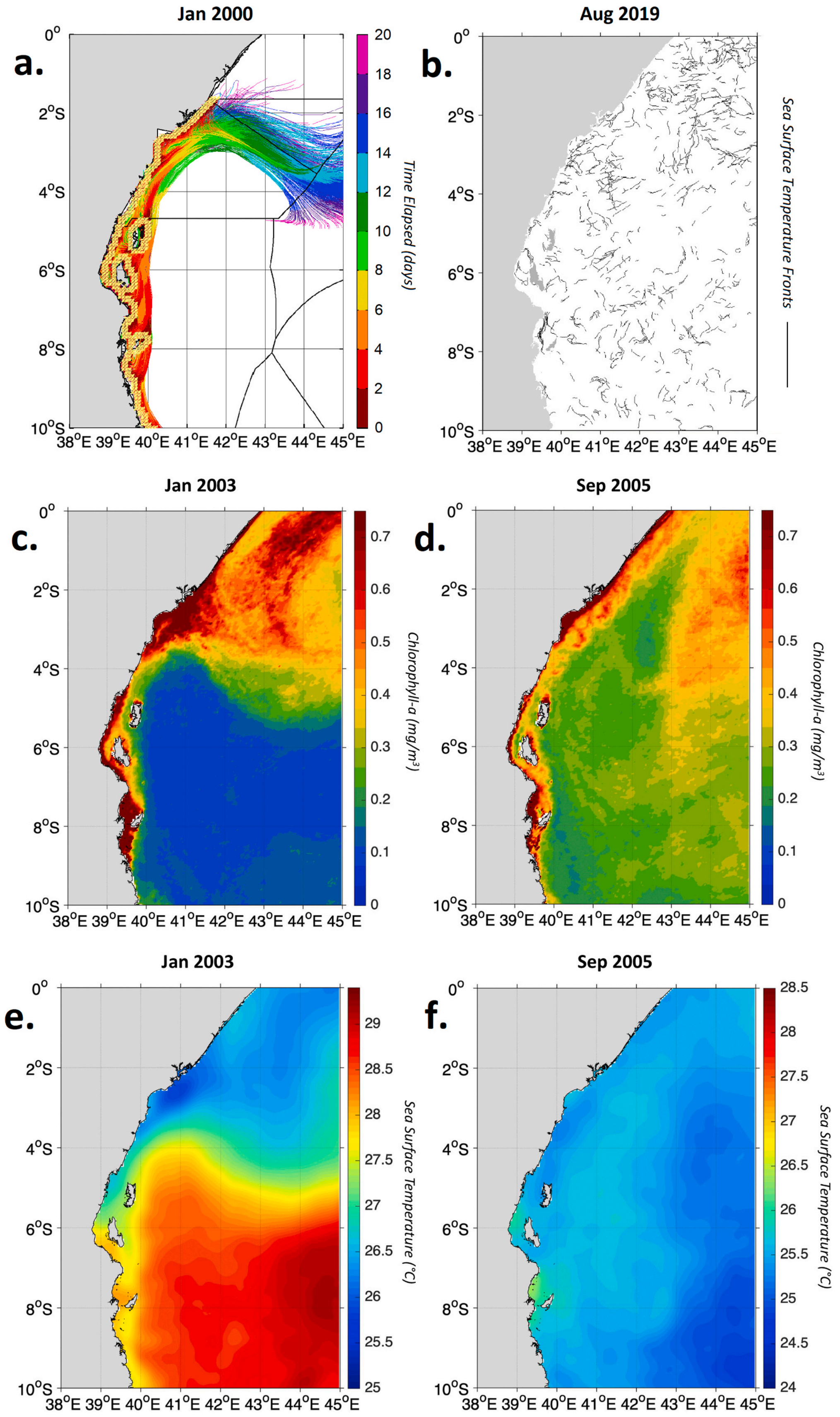


Fig. 3. Illustration of the Bakun's triad for the coast of Tanzania. **a**) lagrangian trajectories showing low (6–8 days) retention timescales of the Tanzanian coastline (following Popova et al., 2019). The colour of the trajectories indicate the time in days for the surface waters to be advected away from the coastal zone, termed on the colour bar as the "time elapsed" (January 2000 is used as an example); b) location of the frontal zones detected by the Miler et al. (2009) algorithms (example of 16–19 2019 Aug is used); c-f - examples of upwelling along the Tanzanian coast during the Northeast monsoon (Jan 2003) and Southeast monsoon (Sep 2005) as inferred from satellite observations of Chl-a (c,d) and SST (e,f), following Jebri et al., 2020. January 2003 and September 2005 are chosen as an illustration of strong upwelling events. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

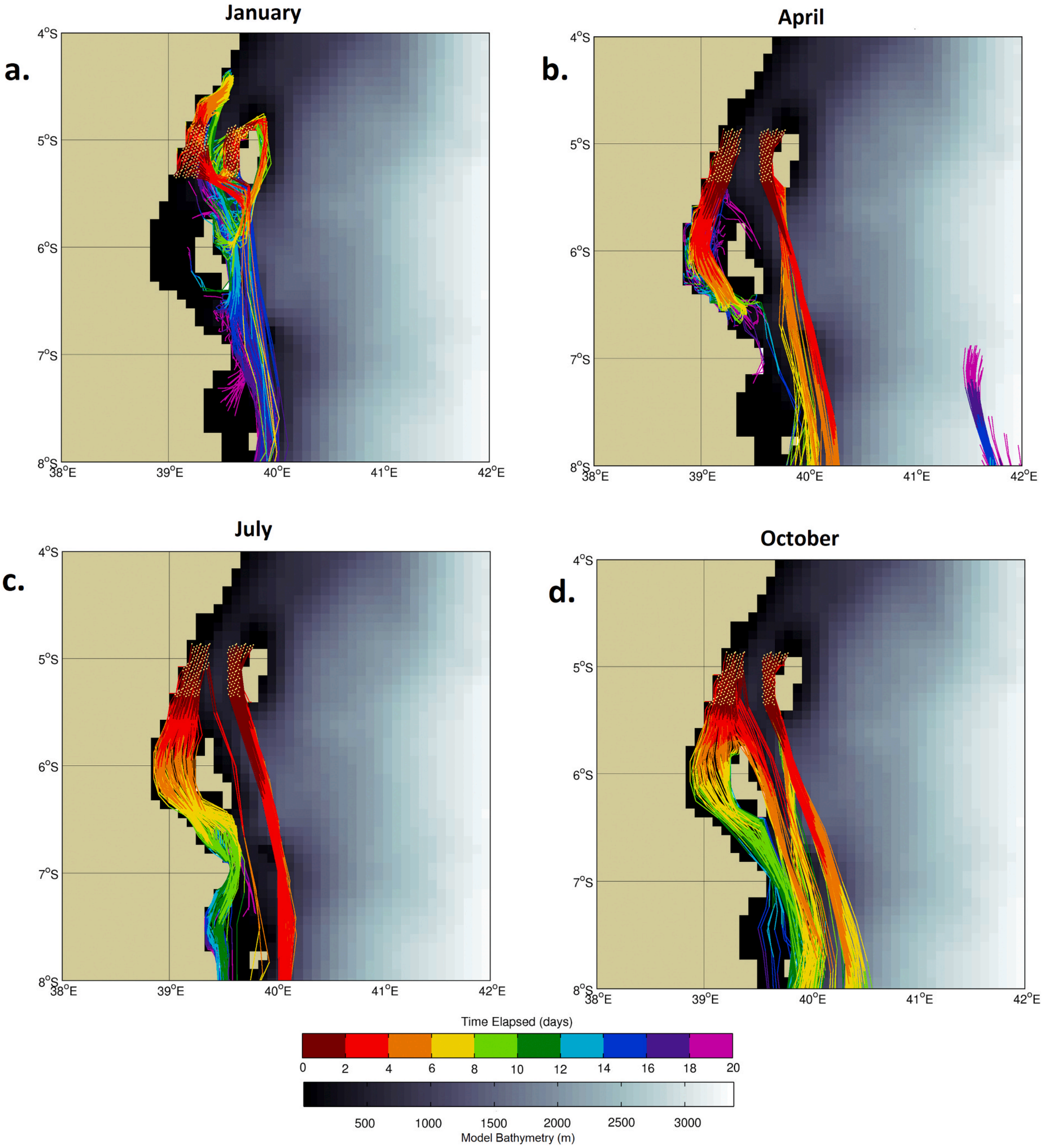


Fig. 4. Lagrangian trajectories showing residence time and upstream connectivity of the coastal zones of Pemba Channel for January (a), April (b), July (c) and October (d). The colour of trajectories indicates the time in days, that it takes the surface waters to arrive to Pemba Channel, termed on the colorbar as the "Time elapsed". Trajectories are numerical model derived (Popova et al., 2019), with year 2008 shown as an illustration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fishery since 2002.

In the WIO as a whole, the catch of small pelagics makes up just over 5% of the total marine catch, which is very small on a global scale (Bakun et al., 1998). Despite this, the percentage of small pelagic fishes in the inshore marine catch in Tanzania, is important, contributing to approximately 27% of marine coastal landings in the mid-2000s in Zanzibar (Anderson and Samoilys, 2016, citing national statistics), to 40% in 2013 (Breuil and Bodiguel, 2015).

The marine fisheries of mainland Tanzania are managed by the Ministry of Livestock and Fisheries Development (MLFD) and those of Zanzibar by the Department of Fisheries Development (DFD) in the Ministry of Livestock and Fisheries (MLF). There is currently no institutional mechanism to support collaboration between the authorities that manage shared stocks of small pelagics, although such a mechanism, the Deep-Sea Fishing Authority (DSFA), does exist for the offshore tuna fisheries (Breuil and Bodiguel, 2015).

Tanzanian fisheries are technically open access but there are arguably some *de facto* user rights in the artisanal fishery whereby permission to temporarily reside is sought by migrant fishers from host community representatives, who may allocate areas where the migrants can camp (known as *dago* in East Africa) (Jiddawi and Ohman, 2002; Wanyonyi et al., 2016). Migrant fishers are also expected to register with district fisheries officers but, overall, these fishing rights are not clearly defined. And although fishing licenses are issued, they have never been intended to be used to control entry into the fishery but are purely administrative in purpose. In fact, migrant fishers are an important feature of East African fisheries culture, the Kojani fishers (from north-east Pemba Island), for example, are a particularly well-known group. Migration may be of a seasonal duration or more short-term. Inevitably though, migration leads to localised increases in fishing effort at certain times of the year, as well as representing a challenge for community-based management initiatives (Jiddawi and Ohman, 2002). Attitudes to migrant fishers tend to be mixed, with the negative impact being the competition for resources, but there are positive features including cash injections to the (host) local economy (Anderson and Samoilys, 2016; Mayala, 2018).

Historically, the management of fisheries resources was based on a top-down model but over the last two decades there have been a number of initiatives to increase the participation of local communities in the management process (MLFD, 2013) The current vehicle for local involvement is the village-level Beach Management Units (BMUs) on the mainland and the Village Fisheries Committees (VFCs) in Zanzibar. In recognition of the scale of marine ecosystems, the community-based approach has been further developed on the mainland to include Collaborative Fisheries Management Areas (CFMAs), that include multiple BMUs under their auspices. Although these management initiatives have some partial successes the local institutions face many challenges as effective fisheries management entities (Shalli and Anderson, 2013; Mwangamilo and Anderson, 2013; MLFD, 2013). But they have persisted in various forms since the late 1990s and are developing a degree of momentum, assisted by relatively consistent funding from development partners.

4.2. The small pelagic fishery - in brief

The small pelagic ring-net fishery, in its current form dates back to 1961, when it was introduced by Greek fishery entrepreneurs and it was initially known as the *Greek Method* (Losse, 1964). Fishing vessels, *dhows* and so-called *boti,* are plank-built and typically range in length from ~7 m to ~11–15 m although the majority (90%) are <11 m (van der Knaap, 2013). The vessels are powered by either inboard or outboard engines; non-motorised dugout canoes are also used in the very small-scale nearshore gillnet component of the fishery. *Dhows* and *boti* fix lamps (kerosene, on-board generator and/or battery powered) to the gunwales of their vessels to attract shoals of fish and use large ring-nets (a form of purse-seine net) to capture the fish. Although the light-aggregation technique has been widely used throughout the world and across many fisheries for millennia, the reason *why* it works is still debated and is likely to be a combination of behavioural responses of both fish and plankton (Khanh et al., 2018). Seine nets, scoop nets, cast nets, traps and (illegal) beach seines are also used in certain shallow, near-shore habitats (Jiddawi and Ohman, 2002; Samoilys et al., 2011; MLFD, 2013). Some enterprises also use *ngwanda*, which are similarly vessels to the *boti* but are deployed without nets; they act as light boats to attract fish before a *dhow* or *boti with a* net (usually part of the same enterprise) is called over to catch the fish. A crew of 10–20 fishers are employed, depending on the size of the vessel and the number of sets per night typically ranges from 1 to 4, with a few outliers.

Small pelagic fishing is largely scheduled around the cycle of the moon, with night fishing using the lights taking place mostly during the 15–20 darkest nights of the lunar cycle when the marginal effect of the lights is at its highest. A few smaller vessels may operate throughout the lunar cycle. Fishing duration varies from 4 to 12 h with an average of at least ~7.5 h for mainland Tanzania (Kashindye & Anderson pers. comm.). The monsoon winds have some influence on fish landings. During the NEM, landings are thought to be greater since winds are less strong, the sea is relatively calm and fishing grounds are more easily accessible (Breuil and Bodiguel, 2015). During the SEM, air temperatures are lower, winds are stronger, and the sea-state is more dangerous, reducing the access of artisanal fishers to fishing grounds, and thus fish landings are lower (Jiddawi and Ohman, 2002). Catch Per Unit Effort (CPUE) does not appear to show a strong seasonal pattern but can be highly variable at any time (Kashindye & Anderson pers. comm.).

4.3. The small pelagic fishery - Tanzania mainland

Probably the first catch surveys in Tanzania were undertaken by Losse (1964, 1966; 1968) and Whitehead (1965, 1972). These surveys found the major species were *Dussumieria acuta* (Rainbow sardine), *Herklotsichthys quadrimaculatus* (Spotted herring), *H. spilurus* (Common herring), *Sardinella longiceps* (Indian oil sardine), S. gibbosa (Golstripe sardinella), *Amblygaster sirm* (Spotted sardinella), *Stolephorus punctifer* (Bucaneer anchovy), *S. commersonnii* (Commerson's anchovy and *Engraulis (Stolephorus) indicus* (Indian anchovy).

The most recent species-level catch survey work, currently being undertaken by TAFIRI under the SWIOFish programme, is seeking to address the critical lack of information about the ecology of these species in Tanzanian waters. Preliminary analyses indicate that the dominant species are *E.devisi, S. punctifer, Spratelloides gracilis, D.acuta, R. kanagurta, Decapterus kurroides, S. commersonnii* and *A. sirm*. The TAFIRI data suggests that, overall, Engraulidae are the dominant family in the total catch, with three species accounting for 51% of the estimated total landings on the mainland, with Clupeidae (four species) comprising 26% of the landings, Scombridae 7% (one species) and Carangidae 6% (one species). However, the same data appear to indicate significant spatial and temporal variation in the species composition of the catches. For example, the Engraulid *E. devisi* seems to dominate the catch in Kilwa and Bagamoyo landing sites, although it does not appear to feature to the same extent in landings at the more northerly site of Tanga. This may be explained by the differences in the types of marine habitat adjacent to each of those sites or it may be some sampling anomaly; further analysis is needed to confirm these initial observations. A temporal variation manifests in substantially greater proportion of *E. devisi* in the catches in Kilwa during the months of April to July (during the SEM) and then again from October (Kashindye and Anderson pers. comm.). The major landing site of Tanga on the other hand is dominated by the Engraulids *Stolephorus commersonnii* and *S. punctifer* and by the clupeids *D. acuta* and *S.gracilis*. Again, there is significant seasonality apparent in the relative species composition.

Frame surveys (a census of fishers, vessels and gears) are periodically carried out and published by the Ministry of Agriculture and Fisheries of mainland Tanzania. Although not all reports are directly comparable, reflecting differences in the approaches, terminologies and definitions employed in each census, they do suggest important changes (both increases *and* decreases) in fishing effort directed at small pelagics over time. However, these apparent changes are not only likely to reflect actual changes in fleet dynamics, but also the effect of season on fleet distribution, the level of training and support provided to the district level enumerators during a frame survey, as well the very important methodological differences across the surveys. Comparing the 2007 frame survey and data from a one-off small pelagic survey in 2013, for example, the number of vessels targeting small pelagics increased from 1432 (825 *dhows*, 607 *boti*) to 1955 (van der Knapp, 2013). In terms of the number of fishers, a figure of ~20,000 was reported in 2000, while the 2013 survey reported only 10,791 '*licensed fishermen for pelagic fish*' (van der Knapp, 2013). The 2016 frame survey reported 1032 ring-nets while the 2018 survey, which did not report the number of vessels by fishery-type, reported a total of 525 ring nets, employed by between 11,288 and 12,220 fishers (depending on how interprets the collated data) (MALF, 2018). The most recent potential effort data, made available in early 2020 from district fisheries officer records, suggests a total of 666 ring-net vessels. The 2018 survey indicated that Tanga Region (situated along the western shore of the Pemba Channel) accounts for up to 45% of fishers targeting small pelagic species on the mainland.

In 2013 the estimated total marine fish production for the mainland was 52,846 Mt, a figure based on the national sampling programme at

22 landing sites along the coast, with an annual catch of small pelagics of ~13,000 to 21,000 Mt. Within these data, there have been apparent shifts in both catch and effort between landing sites, perhaps aligning with market opportunities, with the city of Dar es Salaam in particular showing significant increases in estimated landings (statistics from Fisheries Development Division, cited in Anderson and Samoilys, 2016).

More recent data generated from the SWIOFish research programme, suggest a potentially different picture. Depending on which frame survey data are applied to raise the sample CPUE data (from 2019), one can generate total catch estimates for small pelagics for the mainland of between 92,000 Mt (2019 CPUE raised by 2013 frame survey data), 49,000 Mt (raised by 2018 frame survey data) and 57,000 Mt (raised by counts of ring-net vessel numbers from early 2020). The considerable uncertainty related to total vessel numbers active in the fishery and their distribution along the coast (and therefore operating across different fishing grounds) is an issue that requires some sort of resolution.

4.4. *The small pelagic fishery - Zanzibar archipelago*

In many ways, the small pelagic fishery of Zanzibar is indistinguishable from that of the mainland. The fishery generally operates in many of the same fishing grounds, uses the same types of vessels and gears, and therefore likely catches the same species. The extent of these similarities will be confirmed by the outputs of the current SWIOFish programme, which includes a Zanzibari component to the small pelagic research. In Zanzibar, the majority of small pelagic fish are caught, landed and processed on the west coasts of Unguja and Pemba Island (Breuil and Bodiguel, 2015).

In terms of total nominal fishing effort, the number of fishers has increased substantially from 18,618 in 2002 to 49,312 in 2016 (ASCLME, 2012; DFD, 2018). This is more than a doubling of fisher numbers in 14 years, although the proportion of this fishing effort allocated to the capture of small pelagics is not clearly understood, and the overall numbers are highly uncertain. Overall, the number of fishing vessels has risen from 7664 in the 2009 frame survey to 9650 in 2016, an increase of 25%. In terms of the distribution of these new vessels along the coasts of the two main islands, the data show important increases for Mkoani and Micheweni districts (on Pemba Island and both situated on the Pemba Channel) and North A district, which covers the northern extent of Unguja Island (DFD, 2018).

In Zanzibar, catches of small pelagics appear to have fluctuated significantly, with lows of just 80 Mt in 1978, 600 Mt in 1986, but more recently catch values ranged from an estimated 6,000 Mt in 2005, followed by less than 2,700 Mt in 2012 (Fig. 5), with most of the changes attributed to the change in the proportion of Engraulidae in the catch (Jiddawi and Ohman, 2002; Anderson and Samoilys, 2016).

4.5. *On the accuracy of current catch estimates*

Catch reconstructions of Tanzania's marine fisheries from 1950 to 2005, through the review of grey literature, identification of missing sectors, and validation of FAO figures, showed that actual catches might be nearly double the official estimates. This is partly due to the complete omission of Zanzibar data from national statistics, as well as omission of catches by foot fishers on the mainland and Zanzibar (Jacquet et al., 2010). An updated analysis carried out in 2015 and covering the period 1950–2010, showed the reconstructed catch to be 77% higher than the reported catch (Bultel et al., 2015).

The new catch estimates generated by the reconstructions imply that the marine fishing sector is more important to national food security than was previously appreciated, and that significant efforts towards fishery management need to be made (Jacquet et al., 2010).

4.6. *Management and monitoring of the small pelagic fishery*

Understanding how seasonal environmental variability and long-term climate change may affect small pelagic populations is critical for informing management decisions that will support a sustainable fishery. Climate change has been identified as an issue requiring an adaptation strategy in the management plan for the Tanzanian artisanal fishery for small and medium pelagic fish species (MLFD, 2013).

Some of the shared issues facing the management of small pelagic species on the Tanzanian mainland and Zanzibar include: the need to significantly improve the current statistical approaches and research base of the fishery; managing uncertainty related to the level of exploitation of the fishery; the need to harmonise fishing regulations and management approaches between the mainland and Zanzibar; the reduction of conflicts around migrant fishers; the nature of the participation of fishery stakeholders including community-based organisations; unregulated and unreported fishing related to lack of management and low compliance with licensing and registration initiatives, and the need for a better understanding of the ecology of small pelagic species, and the environmental drivers that affect the variability of populations of these species (Breuil and Bodiguel, 2015; MLFD, 2013).

The potential role of community-based management institutions in the management of small pelagic resources is open to question. This is because of the significant geographic range of the fleet, with the fishery taking place largely outside of the boundaries of local management

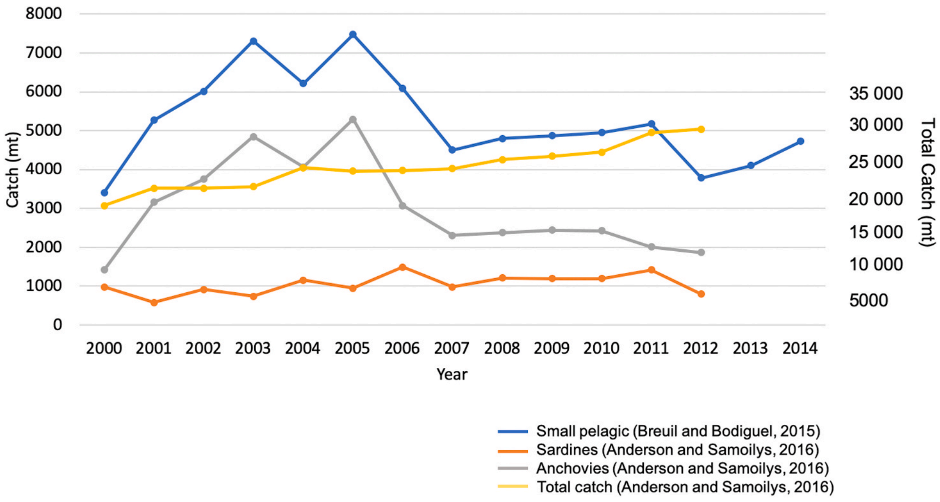


Fig. 5. Catch figures for Zanzibar 2000–2014. Small pelagic catch 2000–2014 (Breuil and Bodiguel, 2015), sardine catch 2000–2012 (Anderson and Samoilys, 2016), anchovy catch 2000–2012 (Anderson and Samoilys, 2016), and total marine catch 2000–2014 (Anderson and Samoilys, 2016).

institutions and the largely commercial nature of this fishery compared to rather more adjacent reef, mangrove and seagrass-based fisheries. An additional complication for the small pelagic fishery is that the vast numbers of fish caught and the complex patterns of landing, handling, processing and sale, make a rigorous sub-sampling protocol necessary, and this is not currently in place on a national scale (Van der Elst et al., 2005; Anderson and Samoilys, 2016). For example, between 2000 and 2012, data from Zanzibar erroneously report anchovies as Clupeids and not Engraulids (Anderson and Samoilys, 2016).

5. The economic and livelihood significance of the fishery

5.1. Socio-economic and cultural significance

For mainland Tanzania, the entire fishery sector accounted for 1.7% of national gross domestic product (GDP) in 2018 (BoT, 2019). It is important to note, however, that the fishery sector in mainland Tanzania is dominated, in catch tonnage and in value (~65%), by just two fisheries in Lake Victoria; for the freshwater pelagic Silver Cyprinid (*Rastrineobola argentea*) and for Nile Perch (*Lates Niloticus*). The contribution of the marine fisheries sector to mainland GDP is actually probably less than 0.25%. In Zanzibar fishing-related activities, an entirely marine-based sector, were provisionally reported to account for 5.2% of GDP in 2018/19 (BoT, 2019). Rather than simply looking at the contribution of the small pelagic fishery to GDP figures, perhaps a more useful approach is to consider the wider livelihood role (ASCLME, 2012).

Regarding nutrition for example, in Tanzania, marine and freshwater fish provides approximately 30%–60% of protein consumed, at 6–8 kg per year per capita on a national basis, and 23–30 kg per capita for Zanzibar (Lange and Jiddawi, 2009; MLFD, 2013). More specifically, marine small pelagic fisheries constitute a major source of this protein in coastal communities, especially for low income households (Van Hoof and Kraan, 2017). The consumption of small pelagics by urban communities has also steadily increased over the last two decades, driven by the diminished demersal and reef fisheries catches caused by overfishing and the use of destructive fishing methods, and responding to the high growth rate of the human population (3% in 2018).

In terms of the wider local economy, in addition to the fishers themselves, the fishery provides employment and income for processors, carriers and transporters, boat builders, firewood and other material suppliers, suppliers of salt, repairers of equipment and gears and, of course, wholesale and retail traders of the fish itself (Breuil and Bodiguel, 2015). Mayala (2018) reported data from Mafia Island (central coastal Tanzania) suggesting the ratio of fishers to the number of people locally employed within the fisheries sector (but other than directly in fishing) was 6:1. The processing and trade of small pelagics along the value chain is mostly, although not exclusively, the domain of women (MALF, 2016a), although they are not involved in primary fishing activities due to the associated risk and other cultural factors (Jiddawi, 2012). Women also cook to provide food for fishers (and others) at the fish landing sites.

The precise mechanics of marketing in the small pelagic fishery vary according to the size and nature of the landing site, with greater or lesser degrees of organization and vertical integration for the purchase, transport, processing, and eventual sale of the fish. A site such as Dar es Salaam (Tanzania's economic capital), where landings are made in a port adjacent to the city's major retail fish market (and other buyers), does not compare to the situation at a village beach site with perhaps just a handful of vessels landing each morning.

In the more rural settings (which represent the majority of landing sites) the fish are mainly auctioned off directly from a vessel (anchored in the shallows) to traders (or their agents). The fish are then carried in large buckets or baskets, often by women (who are paid piece-meal specifically for the task) but also sometimes by boats or small carts drawn by livestock, to be processed. A study at one of Zanzibar's major rural landing sites found that at least 50% of fishers (n = 72) sold directly to traders rather than the general public (and often to specific traders with whom the vessel owner or skipper had some form of agreement in place) and 40% sold to processors (dryers) (Stanek, 2015).

The processing technique varies, depending on species, size, destination market(s) and prevailing environmental conditions although a common feature is that the majority of the processing is undertaken by women. For example, anchovies may be simply spread in a thin layer on the ground and sun-dried, or rapidly cooked in perforated plastic buckets in boiling seawater (with additional salt added) and then sun-dried. Small sardines are often fried for immediate sale, or sun-dried (raw or boiled). Larger sardines are often fried, while mackerels (such as *R. kanagurta*) are gutted, iced and frozen or dried (Breuil and Bodiguel, 2015). Drying is carried out on simple wooden drying racks, on large plastic sheets on the ground, directly on sand and by various forms of smoking. Sun-drying on the ground results in the highest rates of post-harvest loss, particularly due to rain (Mayala, 2018). Although detailed equivalent data is lacking for the marine fishery, the small pelagic processing operations around Lake Victoria are similar, and these operations experience a post-harvest loss of up to 40% (LVFO, 2016). Processing extends the shelf-life of these species, making the produce available all year round and diversifying the opportunities for marketing and sale. This has further promoted the consumption of small pelagics by both the urban and rural communities (Bodiguel and Breuil, 2015).

It is important to note that the processing trade is not necessarily a part-time or small-scale occupation; even on Unguja, individual processors will buy 250–500 kg of fish to process on a single day and in some sites the processors have developed cooperative enterprises to cover the costs of the purchase of the large rectangular metal basins generally used for boilers, buying the large plastic drying sheets, organising the delivery of firewood etc. An interesting indirect effect of fish processing is the pressure it can place on other ecosystems, particularly as the boiling process requires firewood. Firewood to supply the processing at the main sites on the north-west coast of Unguja Island, for example, is brought from forested areas in south Unguja, indicating the increasing sophistication and significance of the trade in small pelagics (Mayala, 2018; Omari Foum pers.comm.).

The economics of the fishery can be precarious. As with most commodities, over-supply, even on a daily basis, can result in high price variability (Jiddawi, 2000). The price is lowest during the rainy season when catches are high while processing options are more limited. With little to no opportunity for sun drying the fish, the only option for processing is frying (Bodiguel and Breuil, 2015). This is, however, a less preferred processing method which lowers the price that people are willing to pay (Breuil and Bodiguel, 2015, Jiddawi pers. obs.). Inevitably, the larger landing sites require relatively large surface-areas (100s of square-metres) of land for the drying of the fish; this land itself is therefore a commodity in the economics of the fishery, with processors renting or leasing areas from local landowners, or from the community. However, the lack of guarantee or security apparent in many of these agreements dissuades individuals from investing in improving their infrastructure, by building fixed drying racks for example (Omari Fuom & Mohammed Suleiman, pers. comm.).

In 2018, 2019, a vulnerability survey was conducted in Unguja and Pemba (Zanzibar) and in Mafia and Tanga (mainland Tanzania) using the integrated framework approach developed by Aswani et al. (2018). A total of 293 households were surveyed in eight coastal communities across these sites. Respondents were asked to list the three most important species for both commercial and subsistence purposes. On average, across the four regions, small pelagics accounted for 23% of the commercially important species listed, and 26% of the vital species for subsistence.

More widely, and in addition to their economic significance, small-scale fisheries in general are of considerable socio-cultural importance. In the 2018/19 vulnerability survey, respondents were asked if they had a fishing *identity* and/or a cultural attachment to fishing. Of those that responded (*n*=*252*), 70% reported a strong cultural bond to fishing. Finally, when asked about how important it was to pass on local knowledge regarding fishing to the younger generations (cultural continuity) 76% believed it to be either “important” or “very important” (*n*=*293*).

5.2. Fisheries exports and food security

The annual gross marine product of the WIO region is estimated to be at least US$20.8 billion (Obura et al., 2017). As international trade has expanded over time, fish exports have become an increasingly important component of fisheries in the WIO. A traditional measurement of food self-sufficiency is assessing the net food trade position of a country, so national food self-sufficiency can be measured by determining if a country is a net exporter of basic foodstuffs rather than a net importer (Clapp, 2017). Tanzania has long been a net exporter of fish. This is an indication of a country either meeting domestic demand and therefore being able to export a surplus, or that prices in markets outside of a country incentivise exports over selling in domestic markets; in the case of Tanzania, it is the latter (Jiddawi, pers.obs.). Tanzania, interestingly, experienced a peak in fish exports during the financial crises of 2008 while GDP growth rate was in decline (World Development Indicators. The World Bank Group, 2020, viewed January 20, 2020, https://databank.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG/1ff4a498/Popular-Indicators).

For the mainland, fisheries export statistics are dominated by Lake Victoria. For example, in comparison to the export value generated from Lake Victoria (est. 124 million USD in 2013) the mainland’s marine fisheries in their totality contribute a relative minor value (est. 7 million USD) (MLFD, 2014). For 2017, the FAO reported a total export value of fishery commodities from Tanzania of 181 million USD (FAO, 2019). In 2014 the European Union purchased 49% of these exports (by volume) and the DRC 18% (MALF, 2016b).

In recent years, important regional export markets for processed marine small pelagics have developed in the Democratic Republic of Congo (DRC), Zambia, Rwanda, Burundi and Malawi. In the Zanzibar study by Stanek (2015), respondents stated that 80% of the processed fish had been sold to agents exporting fish to the DRC. A study on Mafia Island reported profit margins of 15% for local sales of processed sardines, 86% for domestic markets but 130% for sales to regional markets (e.g. to the DRC). Data from the mainland’s 2013 Fisheries Annual Statistics Report indicate a total value of exports of processed (dried) marine small pelagics of 274 Mt with a value of 325,000 USD (MLFD, 2014).

There is little information available on how stakeholders in the fishery - the fishers, processors, traders and investors - have adapted to any past fluctuations in resource availability; nor has there yet been any research into understanding the potential future resilience of the fishery. Furthermore, there are no data on what drives patterns of consumption of small pelagic species (Anderson and Samoilys, 2016). This is a common situation in the developing countries, where catches for some of the most important fisheries are underreported, especially in less regulated, small-scale fisheries (Mills et al., 2011; Pauly and Zeller, 2016). Food security analyses often use national level data (such as food balance sheets and trade balances), as community or household level surveys are time consuming and costly. However, food security on a national scale does not necessarily imply that food security exists on an individual level (Broca, 2002) especially in the case of developing coastal countries with a substantial number of subsistence fishers. Understanding the level of dependence on small scale fisheries for individual and household levels of food security should be an important component in the development of food security policies in countries such as Tanzania (Taylor et al., 2019).

6. Potential impacts of climate change on the small pelagics of Pemba Channel

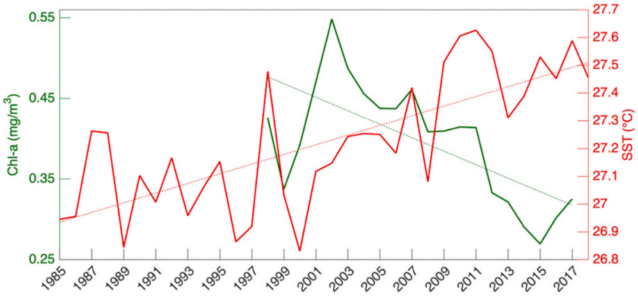
Climate change is likely to impact small pelagic fish via multiple direct and indirect pathways (e.g. Checkley et al., 2017; Brander, 2010). Its onset is expected to be heterogeneous, and the wide range of habitats, behaviours and life history strategies of the small pelagics most likely means that their response to climate change will vary greatly between species and between geographical areas (e.g. Muhling et al., 2017). The potential impacts of climate change on small pelagic species are likely to include distributional shifts in response to changes in temperature (with a general expectation of poleward migration), abundances, composition and phenology of phyto- and zooplankton, ocean deoxygenation and acidification (Checkley et al., 2017; Gittings et al., 2018). Climate change may also indirectly affect small pelagics through its effect on ocean circulation impacting retention and population connectivity and ocean upwelling impacting nutrient supply to the food chain (e.g. Freon et al., 2009). The growth, metabolism, and reproduction of small pelagics can be negatively impacted if the increasing ocean temperature approaches their thermal limits, with early life stages expected to be most vulnerable to the extreme temperatures. It has been suggested that the environmental stress on the early life stages may present a highly vulnerable stage for the persistence of fish species in a warming climate (Faleiro et al., 2016).

Our ability to produce reliable future projections at a regional scale strongly depends on our understanding of the regional driving forces of primary production, circulation patterns and the ecology of the fish species themselves. Spatial distribution of the spawning areas of small pelagics in the boundary upwelling systems is often a result of the dispersal and retention properties of a particular geographical area (Checkley et al., 2009). Thus, Lagrangian properties of the flow, controlling retention, dispersal and connectivity are critical driving mechanisms. However, numerical models providing future projections have not yet reached sufficient resolution to confidently assess possible future changes of the Lagrangian properties at a regional scale, although the first steps in this direction have already been made (e.g. van Gennipp et al., 2016). Projection of changes in fish population and density is made difficult by the need to properly define their bioclimatic envelope in the case of a species-specific model. Another approach is to use size classes to define the community structure (Blanchard et al., 2012) and project growth rate and catch estimates. Two recent global fish production model efforts (Cheung et al., 2018; Lotze et al., 2019) projected change in biomass and/or catch. Under RCP-8.5 it was found that the EEZ of Tanzania could expect a loss in potential catch ranging from 25 to 50% (Cheung et al., 2018); and a loss in biomass of up to 50% (Lotze et al., 2019) by the end of the century.

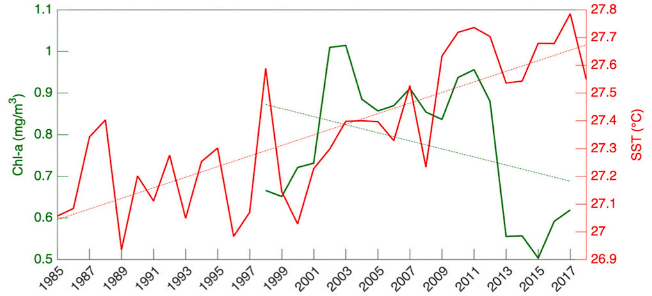
Potential impacts of climate change on the abundance and behaviour of the small pelagics of the Tanzanian coast and, downscaling further, of the Pemba Channel, are expected to be multiple and complex. Our limited understanding of these impacts is exacerbated by the lack of sustained marine observations in the area and of regional biogeochemical models, which can assist in the interpretation of existing variability and regionalization of future trends. However, the first steps towards this understanding can be made based on high-resolution global models put in a context of regional knowledge (Cochrane et al., 2018) and observed multi-decadal variability. Understanding the response of small pelagics to major extreme events may produce a reliable first guess of how the system will respond to climate change. Thus, it has been demonstrated (Jebri et al., 2020) that outside of El-Niño events, intensification of the monsoonal winds over the pathway of the EACC is the key driver of elevated yields of the small pelagic fish along the Tanzanian coast. The mechanism behind this driver lies in the seasonal coastal upwelling which intensifies during both monsoonal periods leading to elevated primary production. However, the mechanisms behind these two seasonal upwellings are different. Thus, in order to attribute the response by small pelagics to underlying environmental drivers, analyses must go beyond annually averaged characteristics, and consider monsoonal seasons separately. Although the AR5 multi-model ensemble projections agree on the general decline of the primary production in the global tropics under the RCP8.5 “business as usual” scenario (Bopp et al., 2013), a strengthening and lengthening of the SEM over the Indian Ocean has also been projected by the IPCC AR5 (IPCC, 2013). Such a change to the monsoonal winds may shift the whole ecosystem towards more frequent and intense upwelling-driven monsoonal phytoplankton blooms with an associated increase in the biomass of the small pelagic fish along the path of the EACC.

Riverine input of nutrients is also an important localised mechanism thought to impact the productivity of small pelagic fish along the Tanzanian coast via its impact on primary productivity and phytoplankton and zooplankton abundance (Anderson and Samoilys, 2016) and one that will likely change in future. Eight main rivers discharge into Tanzanian coastal waters, but only one of these rivers (Pangani) discharges directly into the Pemba Channel. To what extent the terrigenous nutrient supply impacts the primary production of the Pemba Channel remains

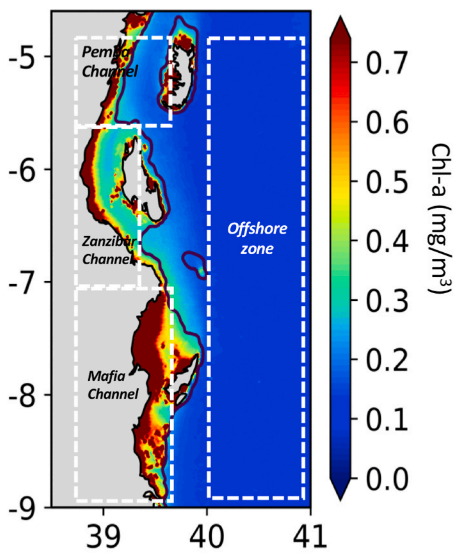
(a) ***Pemba Channel***



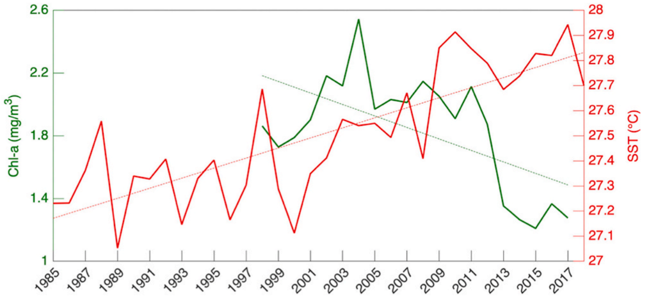
(b) ***Zanzibar Channel***



(e)



(c) ***Mafia Channel***



(d) ***Offshore zone***

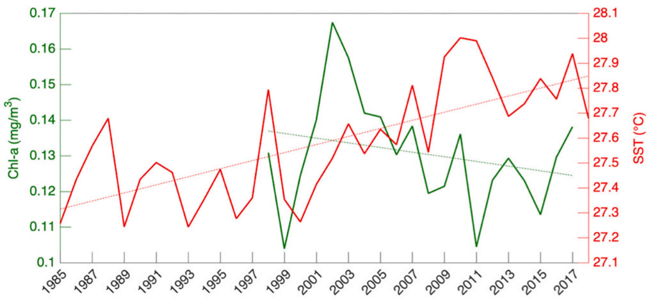


Fig. 6. Annual means of satellite Chl-a in mg/m^3 from 1998 to 2017 and satellite SST in °C from 1985 to 2018 (solid lines) and their long-term linear trends (dashed lines) over the (a) Pemba Channel, (b) Zanzibar Channel, (c) Mafia Channel and (d) Offshore zone as delimited by the white boxes superimposed on (e) the satellite Chl-a total mean for the period 1998–2017.

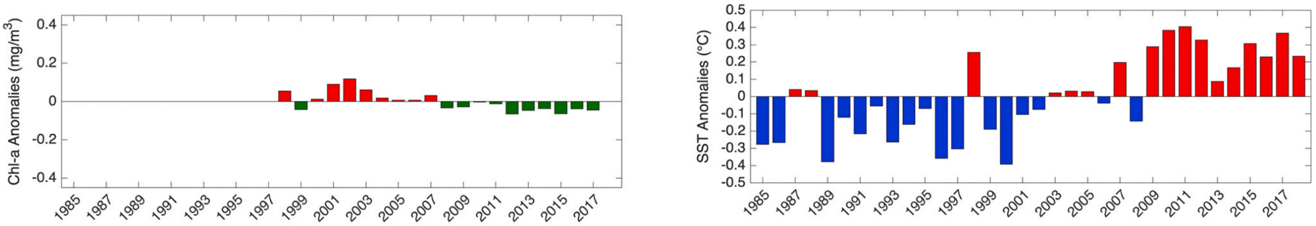
an open question. However in-depth analysis of available remote sensed Chl-a and precipitation may provide an estimate of the riverine flow influenced areas and their possible exposure to future changes in the mean and extreme precipitation during the Indian summer monsoon projected by the CMIP5 models. These models show that despite a projected weaker monsoon circulation, the increased evaporation is expected to lead to greater precipitation overall (IPCC, 2013).

Under RCP8.5 emission scenario, the SST in Tanzanian waters is expected to increase by 3-4 °C by the end of the century (e.g. Popova et al., 2016). In addition to the average temperature increase, short-term extremes such as marine heatwaves are expected to increase in duration and intensity (Frölicher et al., 2018). Marine heatwaves can affect both the behaviours and distribution pattern of fish, with the schools migrating into the deeper waters in search of cooler temperature unless constrained by feeding or physiological traits. Such a change in behaviour may substantially reduce the catchability of these fish by the artisanal fishers with simple gear and boats.

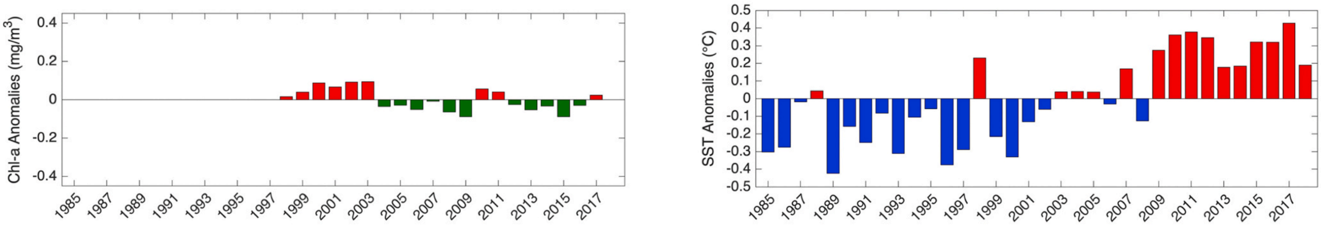
A detailed study on the effect of El Niño on primary production estimated that impacts on phytoplankton tend to be greatest in the tropics and subtropics, encompassing up to 67% of the total affected areas, while showing a decrease of −82 TgC/y in the WIO (Racault et al., 2017). In the background of the key modes of interannual variability such as El Niño, Indian Ocean Dipole (IOD) and decadal-scale variability of monsoonal winds, long term upward temperature and downward Chl-a trends are manifesting themselves in all areas along the Tanzanian coastline (Fig. 6) with an average SST increase of 0.1 °C/decade (accelerating to 0.15 °C/decade during 2010–19) and Chl-a decline of 0.1 mg/m^3/decade in the channels and 0.05 mg/m^3/decade offshore. However, the time series are too short (33 years of SST and 20 years of Chl-a) to exclude the possibility of a reversal of this trend in the next decade due to strong multidecadal variability, as can be inferred from the time series of the SST and Chl-a anomalies (Fig. 7).

It can be hypothesised that due to the substantial (up to 800 m) depth of the Pemba Channel and throughflow of the EACC, the properties of the channel may respond to climate change differently to the shallow Zanzibar (~40 m deep) and Mafia (<10 m deep) Channels. Upwelling-induced cooler temperatures and higher nutrients may provide a delayed onset of the climate change impacts in these areas relative to the

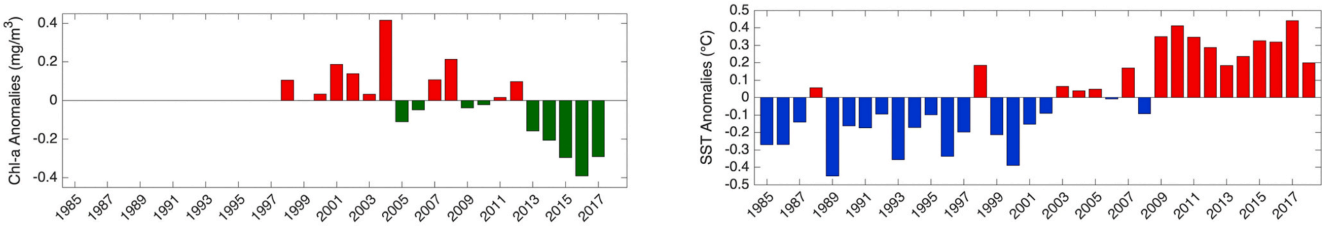
(a) ***Pemba Channel***



(b) ***Zanzibar Channel***



(c) ***Mafia Channel***



(d) ***Offshore zone***

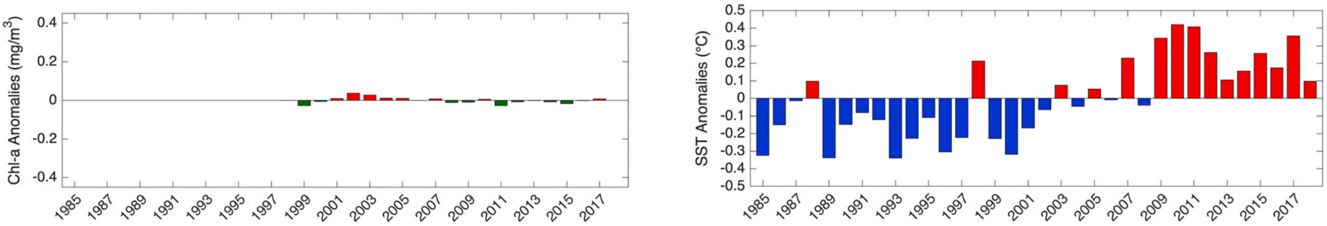


Fig. 7. Satellite Chl-a and SST anomalies over the period 1998–2017 and 1985–2018 respectively over the (a) Pemba Channel, (b) Zanzibar Channel, (c) Mafia Channel and (d) Offshore zone as delimited by the white boxes superimposed on Fig. 7e).

rest of the Tanzanian shelf waters. However, analysis of Figs. 6 and 7 shows that these domains have been responding to the extreme events in synchrony, a situation which may change with the progression of the global warming.

Although the general trends of the ocean temperature and acidification under climate change impacts are clear, the changes to ocean circulation and mixing and their resulting impacts on biogenic nutrients, primary production and higher trophic levels are less well understood. Here again, an observed ecosystem-level response to the extreme events including El-Niño, IOD and anomalous monsoon years present an opportunity for the evaluation of the system-level response. For example, the well understood impacts of elevated SSTs on coral reef ecosystems combined with relatively long-term assessments of coral reef health in the WIO provide good understanding of the impacts of climate change on these ecosystems (Ateweberhan et al., 2012). However, the limited information on the small pelagics fisheries yields and their distributions severely limit our ability for such an assessment.

In conclusion, two key challenges currently obstruct successful predictions of how the dynamics of small pelagic fish may respond to a changing climate. The first involves understanding the response of small pelagic fish to currently occurring or recent extreme events. The second challenge involves our ability to successfully downscale future climate projections to sub-basin scales, resolving not only core annual characteristics such as temperature and primary production, but also more subtle, and more regionally relevant factors such as changes in the ocean circulation and upwelling, frequency and magnitude of marine heatwaves and shifts in the seasonal dynamics of phytoplankton blooms.

7. Conclusions: key research gaps in understanding of the climate change impacts on the future of the small pelagic fishery

Despite decades of intensive research into the population dynamics of small pelagic species around the world, our ability to predict their variability is limited, particularly outside of the major upwelling regions where most research has been concentrated. This in turn limits the possibilities for the sustainable management of this important component of local food security under the combined impacts of climate change and growing fishing pressure. In this section we propose six key research questions that this study identifies as the most critical to improve current capability to predict climate change impacts on the small pelagic fishery of the Pemba Channel.

Question 1. What are the critical local and regional environmental drivers of small pelagic population dynamics and ecology in the Pemba Channel? Small pelagic fish stocks around the globe are prone to strong fluctuations driven in part by environmental characteristics. Although some responses are common among all regions, many regional features remain unique and are rooted in the specifics of the key local oceanographic regimes. Evidence is beginning to emerge of the importance of the intensity of seasonal coastal upwelling systems along the Tanzanian coast and of their interannual variability driven by El-Niño, IOD and anomalous dynamics of the monsoonal winds. However, our understanding of the local environmental drivers is incomplete.

Question 2. What is the current biomass, species composition and exploitation rate of small pelagic species in the Pemba Channel? Identifying a reliable baseline is a key step towards monitoring and understanding future interannual and multidecadal fluctuations of the small pelagic fish. However, information on the catch and effort, abundance, distribution and behaviour of the key species is currently inadequate. Weaknesses in official data and the national statistics systems can undermine the best management efforts. Fish catch statistics in Tanzania are scarce and unreliable, and problems of data capture and monitoring persist due to logistical, institutional and human resource challenges.

Question 3. How does the fishery adapt its inputs and behaviour to changes in biomass? For successful management of a fishery, it is critical to distinguish between impact of fishing pressure and impact of environmental factors. Despite the high fecundity of small pelagics, they are highly vulnerable to exploitation and numerous stocks around the world have declined or even collapsed. It is currently unclear if the small pelagics in Tanzania are exploited at a sustainable level, however the current large catch identified by the SWIOFish project is certainly a cause for concern. Very little is known about the historical responses of the fishery to environmental fluctuations and what strategies were used by fishers to adapt to them reflecting challenges in the collection of fisheries statistics in Tanzania in general.

Question 4. To what extent is it possible to predict fluctuations of small pelagic biomass to provide an early warning system for anomalously low catch years? Mechanistic understanding of the linkages between environmental variables and responses of small pelagics is necessary for the development of the predictive capabilities. Seasonal and interannual variability of the key environmental factors controlling the small pelagic fish stock such as intensification or weakening of coastal upwelling accompanied by strengthening or weakening of phytoplankton blooms, is detectable in near real time by remote sensing in combination with ocean models. Given that a few months lag in the SPF response to such factors or their remote drivers is evident, some short-term prediction can be attempted.

Question 5. Given the uncertainty of climate change projections can we predict the long term future of the most regionally relevant environmental factors? Future projections of climate change stressors and their impacts on biomass are conducted in a framework of global models with a very broad representation of ocean dynamics and ecosystems. How global scale changes translate into regional impacts remains speculative at the present stage of IPCC-class model development. The key challenge facing our ability to provide reliable future projections lies in developing models capable of capturing region-specific dynamics and particularly localised impacts of climate change.

Question 6. Can we predict impact of anthropogenic factors on the small pelagic fish? Anthropogenic factors other than climate change impact and fishing pressure may have either strong direct or indirect impacts on the distribution of small pelagics, especially in semi-enclosed areas of the channels. These include land-based pollution, changes in the nutrient composition of the riverine discharge, intensification of HABs, habitat destruction, development of off-shore structures and deep-sea mining, accelerated coastal development, general degradation of coastal habitats such as mangrove forests, seagrass meadows and coral reefs, and illegal practices such as dynamite fishing.

Addressing the research gaps identified here requires a combination of in-depth studies in marine ecology and oceanography and multidisciplinary approaches to accompany major effort by government and NGOs at collecting fisheries data. Critical roadblocks to achieving this include low levels of scientific capacity, inadequate monitoring programmes, and a poor integration of basic science into fisheries policies. Where policy does exist, little is put into practice through direct management intervention. However, recent developments such as a growing political awareness of the importance of the marine environment to food security and trade, the remote sensing and ocean modelling platform and methodologies and a rise in local, regional and international scientific collaborations (promoted through such agencies as the Western Indian Ocean Marine Science Association (WIOMSA) and the Nairobi Convention) promise to overcome the identified limitations. Developing the capability to access, control, use and interpret multiple data from a range of platforms, may help achieving a step change in the ability to manage and optimally exploit local fisheries.

Author contributions

BS was the lead author and responsible for coordination of all contributions. Section 2 was coordinated by JA (with contributions from LS, BS, BK,SFS,MS,AK), Section 3.1-3.6 was coordinated by SP (with contributions from MN, MK, MP, JW, YS, HK, NN, SS), Sections 3.7 and 6 was coordinated by EP (with contributions from SK, ZJ, FJ, DER, SFS), Section 4 was coordinated by LS (with contributions from JA, ST, WS, BS, NJ,MS,JF), Sections 5 was coordinated by ST (with contributions by NJ, SA,LS, JA). All authors made important contributions to the contents of the paper during numerous workshops and subsequent discussions of the final manuscript.

Broca, 2002, Bryceson, 1977, Agostini, 2005, Ateweberhan et al., 2013, Cochrane et al., 2019, Currie et al., 2013, Falkowski and Oliver, 2007, FAO, 2016, Henson et al., 2017, Manyilizu, 2008, Nguyen and Winger, 2018, Samoilys et al., 2015, Van Gennip et al., 2017

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

This publication was produced with the financial support of the Global Challenges Research Fund (GCRF), UK, in the framework of the SOLSTICE-WIO project, NE/P021050/1 and the project ACCORD (as part of the UK National Capability, Official Development Assistance award NE/R000123/1). ARIANE simulations were performed using the JASMIN data analysis environment (http://www.jasmin.ac.uk) and can be provided upon request. The satellite SST and the Ssalto/Duacs altimeter products were produced and distributed by the CMEMS (http://www.marine.copernicus.eu). We would like to thank the ESA Ocean Colour CCI project for processing and providing the *Chl-a* dataset online at http://www.esa-oceancolour-cci.org/and the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for supplying oceanic fronts data for this study.

References

Broca, S., 2002. Food Insecurity, Poverty and Agriculture: a Concept Paper. Food and Agriculture Organization - Agriculture and Economic Development Analysis Division, Rome.

Bryceson, I., 1977. An Ecological Study of the Phytoplankton of the Coastal Waters of Dar Es Salaam. University of Dar es Salaam. PhD thesis: 560 pp.

Agostini, V.N., 2005. Climate, Ecology and Productivity of Pacific Sardine (*Sardinops sagax*) and Hake (*Merluccius productus*). PhD Dissertation. University of Washington.

Agostini, V.N., Bakun, A., Francis, R.C., 2007. Larval stage controls on Pacific sardine recruitment variability: high zooplankton abundance linked to poor reproductive success. Mar. Ecol. Prog. Ser. 345, 237–244. https://doi.org/10.3354/meps06992.

Alheit, J., Roy, C., Kifani, S., 2009. Decadal-scale variability in populations. In: Checkley Jr., D.M., Alheit, J., Oozeki, Y., Roy, C. (Eds.), Climate Change and Small Pelagic Fish. Cambridge University Press, New York, NY, USA, pp. 312–343.

Anderson, J., Samoilys, M., 2016. Chapter 2: the small pelagic fisheries of Tanzania. In: Anderson, Jim, Andrew, Timothy (Eds.), Case Studies on Climate Change and African Coastal Fisheries: a Vulnerability Analysis and Recommendations for Adaptation Options. FAO Fisheries and Aquaculture Circular No. 1113, Rome, Italy.

ASCLME, 2012. National Marine Ecosystems Diagnostic Analysis, Tanzania. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (Supported by UNDP with GEF Grant Financing), 92pp.

Aswani, S.J., Howard, A.E., Gasalla, M.A., Jennings, S., Malherbe, W., Martins, I.M., Salim, S.S., Van Putten, I.E., Swathilekshmi, P.S., Narayanakumar, R., Watmough, G. R., 2018. An integrated framework for assessing coastal community vulnerability across cultures, oceans and scales. Clim. Dev. https://doi.org/10.1080/17565529.2018.1442795.

Ateweberhan, M., Feary, D.A., Keshavmurthy, S., Chen, A., Schleyer, M.H., Sheppard, C. R., 2013. Climate change impacts on coral reefs: synergies with local effects, possibilities for acclimation, and management implications. Mar. Pollut. Bull. 74, 526–539. https://doi.org/10.1016/j.marpolbul.2013.06.011.

Bakun, A., 2010. Linking climate to population variability in marine ecosystems characterised by non-simple dynamics: conceptual templates and schematic constructs. J. Mar. Syst. 79, 361–373. https://doi.org/10.1016/j.jmarsys.2008.12.008.

Bakun, A., 2017. Progress in Small Pelagic Fish Research in the 3½ Decades since 'Costa Rica'. Presentation to the International Symposium of PICES 'Drivers of dynamics of small pelagic fishresources'. Vancouver, British Columbia, Canada. March 6-11, 2017.

Bakun, A., Roy, C., Lluch-Cota, S., 1998. Coastal upwelling and other processes regulating ecosystem productivity and fish production in the Western Indian Ocean. In: Sherman, K., Okemwa, E.N., Ntiba, M.J. (Eds.), Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability, and Management. Blackwell Science, Malden, MA, pp. 103–141.

Barange, M., Vannuccini, S., Yimin, Y., Beveridge, M., 2017. State of Small Pelagic Fish Resources and its Implications for Food Security and Nutrition. Presentation to the International Symposium of PICES 'Drivers of dynamics of small pelagic fish resources.'. Vancouver, British Columbia, Canada. March 6-11, 2017.

Barlow, R., Lamont, T., Kyewalyanga, M., Sessions, H., van den Berg, M., Duncan, F., 2011. Phytoplankton production and adapation in the vicinity of Pemba and Zanzibar islands, Tanzania. Afr. J. Mar. Sci. 33 (2), 283–295.

Bender, E.A., Case, T.J., Gilpin, M.E., 1984. Perturbation experiments in community ecology: theory and practise. Ecology 65, 1–13.

Beverton, R.J.H., 1983. Science and decision-making in fisheries regulations. FAO Fish Rep. In: Sharp, G.D., Csirke, J. (Eds.), Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources, vol. 291, pp. 919–936, 3.

Beverton, R.J.H., 1990. Small marine pelagic fish and the threat of fishing; are they endangered? (Suppl. A). J. Fish. Biol. 37, 5–16.

Birkett, L., 1979. Western Indian Ocean Fishery Resources Survey. Report on the cruises of R/v PROFESSOR MESYATSEV, December 1975 – June 1976/July 1977 - December 1977. Tech.Rep. Indian Ocean Programme, FAO (26):97 pp.

Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J.I., Holt, J., Dulvyand, N.K., Barange, M., 2012. Potential Consequences of Climate Change for Primary Production and Fish Production in Large Marine Ecosystems. https://doi.org/10.1098/rstb.2012.0231.

Bopp, L., Resplandy, L., Orr, J.C., et al., 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10, 6225–6245.

BoT, 2019. Bank of Tanzania Annual Report 2018/2019, 0067–3757, 246pp.

Brander, K., 2010. Impact of climate change on fisheries. J. Mar. Syst. 79, 389–402. https://doi.org/10.1016/j.jmarsys.2008.12.015.

Breuil, C., Bodiguel, C., 2015. Report of the Meeting on Marine Small Pelagic Fishery in the United Republic of Tanzania. SFFAO/2015/34, IOC-SmartFish Programme. FAO, 96 pp. http://www.fao.org/3/a-bl755e.pdf.

Breuil, C., Grima, D., 2014. Baseline Report Tanzania. SmartFish Programme of the Indian Ocean Commission, Fisheries Management FAO component, Ebene, Mauritius, 43 pp.

Bryceson, I., 1982. Seasonality of oceanographic conditions and phytoplankton in Dar Es Salaam waters. University Science Journal (University of Dar Es Salaam) 8 (1&2), 66–76.

Bultel, E., Doherty, B., Herman, A., Le Manach, F., Zeller, D., 2015. An update of the reconstructed marine fisheries catches of Tanzania with taxonomic breakdown. In: Le Manach, F., Pauly, D. (Eds.), Fisheries Catch Reconstructions in the Western Indian Ocean, 1950–2010. Fisheries Centre Research Reports, vol. 23. Fisheries Centre, University of British Columbia, pp. 151–161, 2, [ISSN 1198–6727].

Checkley Jr., D.M., Bakun, A., Barange, M., Castro, L.R., Freon, P., Guevara, R., Herrick Jr., S.F., McCall, A.D., Ommer, R., Oozeki, Y., Roy, C., Shannon, L., Van der Lingen, C.D., 2009. Synthesis and perspective. In: Checkley Jr., D.M., Alheit, J., Oozeki, Y., Roy, C. (Eds.), Climate Change and Small Pelagic Fish. Cambridge University Press, Cambridge, UK; New York, pp. 344–351.

Checkley, D.M., Asch, R.G., Rykaczewski, R.R., Annual, R., 2017. Climate, anchovy, and sardine. Annual Review of Marine Science 9 9, 469–493.

Cheung, W.W.L., Bruggeman, J., Butenschon, M., 2018. Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. In: Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options. FAO Fisheries and Aquaculture Technical Paper 627.

Cisneros-Mata, M.A., Mangin, T., Bone, J., Rodriguez, L., Smith, S.L., Gaines, S.D., 2019. Fisheries governance in the face of climate change: assessment of policy reform implications for Mexican fisheries. PloS One 14 (10), e0222317. https://doi.org/10.1371/journal.pone.0222317.

Clapp, J., 2017. Food self-sufficiency: making sense of it, and when it makes sense. Food Pol. 66, 88–96.

Cochrane, K.L., Rakotondrazafy, H., Aswani, S., Chaigneau, T., Downey-Breedt, N., Lemahieu, A., Paytan, A., Pecl, G., Plagányi, E., Popova, E., van Putten, E.I., Sauer, Warwick H.H., Byfield, V., Gasalla, Maria A., van Gennip, Simon, J., Malherbe, W., Rabary, Andriantsilavo, Rabearisoa, Ando, Ramaroson, N., Randrianarimanana, V., Scott, L., Tsimanaoraty, P.M., 2019. Tools to enrich vulnerability assessment and adaptation planning for coastal communities in data-poor regions: application to a case study in Madagascar. Frontiers in Marine Science 5. https://doi.org/10.3389/fmars.2018.00505.

Currie, J.C., et al., 2013. Indian Ocean Dipole and El niño/southern oscillation impacts on regional chlorophyll anomalies in the Indian ocean. Biogeosciences 10, 6677–6698.

Cury, P., Roy, C., 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci. 46, 670–680.

Cury, P., Bakun, A., Crawford, R.J.M., Jarre-Teichmann, A., Quiñones, R.A., Shannon, L. J., Verheye, H.M., 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in "waspwaist" ecosystems. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 57, 603–618.

Cushing, D.H., 1973. Production in the Indian Ocean and the transfer from the primary to the secondary level. In: B. Z (Ed.), The Biology of the Indian Ocean. Chapman and Hall, London, pp. 475–486.

Cushing, D.H., 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Adv. Mar. Biol. 26, 250–293.

Department of Fisheries Development (DFD), 2018. Marine Fisheries Frame Survey 2016, Zanzibar. Ministry of Agriculture, Natural Resources, Livestock and Fisheries. SWIOFish project/World Bank, Zanzibar p.55.

Essington, T.E., Moriarty, P.E., Froehlich, H.E., Hodgson, E.E., Koehn, L.E., Oken, K.L., Siple, M.C., Stawitz, C.C., 2015. Fishing amplifies forage fish population collapses. Proc. Natl. Acad. Sci. U.S.A. 112 (21), 6648–6652.

Ezekiel, J., 2014. Temporal and Spatial Variation of Phytoplankton in Rufiji Delta/Mafia Channel, Southern Tanzania. M.Sc. Thesis. University of Dar es Salaam, Dar es Salaam, Tanzania, p. 99.

Faleiro, F., Pimentel, M., Pegado, M.R., Bispo, R., Lopes, A.R., Diniz, M.S., Rosa, R., 2016. Small pelagics in a changing ocean: biological responses of sardine early stages to warming. Conservation Physiology 4. https://doi.org/10.1093/conphys/cow017.

Falkowski, P.J., Oliver, M.J., 2007. Mix and match: how climate selects phytoplankton. Nat. Rev. Microbiol. 5, 813–819.

FAO, 2014. The State of World Fisheries and Aquaculture 2014. Opportunities and Challenges. Rome. 243 pp.

FAO, 2016. The State of World Fisheries and Aquaculture 2016. Contributing to Food Security and Nutrition for All. Rome. 200 pp.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Rome. 227pp.

Fauchald, P., Skov, H., Skern-Mauritzen, M., Johns, D., Tveraa, T., 2011. Wasp-waist interactions in the north sea ecosystem. PloS One 6 (7), e22729. https://doi.org/10.1371/journal.pone.0022729.

Freon, P., Cury, P., Shannon, L., Roy, C., 2005. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: a review. Bull. Mar. Sci. 76 (2), 385–462.

Freon, P., Werner, F., Chavez, F.P., 2009. Conjectures on Future Climate Effects on Marine Ecosystems Dominated by Small Pelagic Fish. https://doi.org/10.1017/CBO9780511596681.016.

Frölicher, T.L., Fischer, E.M., Gruber, N., 2018. Marine heatwaves under global warming. Nature 560, 360–364. https://doi.org/10.1038/s41586-018-0383-9.

Garrido, S., van der Lingen, C., 2014. Feeding biology and ecology. In: Ganias, K. (Ed.), Biology and Ecology of Sardines and Anchovies. CRC Press, Boca Raton, FL, pp. 122–189.

Gittings, J., Raitsos, D.E., Krokos, G., Hoteit, I., 2018. Impacts of warming on phytoplankton abundance and phenology in a typical tropical marine ecosystem. Sci. Rep. 2240.

Hansen, G., Turquet, J., Quod, J.P., Ten-Hage, L., Lugomela, C., Kyewalyanga, M., Hurbungs, M., Wawiye, P., Ogongo, B., Tunje, S., Rakotoarinjanahary, H., 2001. Potentially Harmful Microalgae of the Western Indian Ocean - a Guide Based on a Preliminary Survey. IOC Manuals and Guides No. 41. UNESCO, 108 pages.

Hartnoll, R.G., 1974. The Kunduchi marine biology station. Tanzan. Notes Rec. 74, 39–47.

Henson, S., Beaulieu, C., Ilyina, T., et al., 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nat. Commun. 8, 14682 https://doi.org/10.1038/ncomms14682.Herrick et al. 2009.

Huggett, J.A., Kyewalyanga, M., Groeneveld, J.C., Koranteng, K.A., 2017. Ocean productivity. Chapter: 5 and Appendix, Publisher. In: The RV Dr Fridtjof Nansen in the Western Indian Ocean: Voyages of Marine Research and Capacity Development. FAO, pp. 55–80. Appendix 189-216.

Hunter, J.R., Alheit, J., 1995. International Globec Small Pelagic Fishes and Climate Change Program. Report of the First Planning Meeting on Small Pelagic Fishes and Climate Change Program. La Paz, Mexico, 20–24 June 1994, p. 72.

IMR, 2018. Survey of Regional Resources and Ecosystem off Southeast Africa. Survey no 2018404. Tanzania. 6-18 April 2018. IMR, Bergen, p. pp76.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovern- Mental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.

Isaacs, M., 2016. The humble sardine (small pelagics): fish as food or fodder. Agric. Food Secur. 5, 27. https://doi.org/10.1186/s40066-016-0073-5.

Iversen, S.A., Myklevoll, S., Lwiza, K., Yonazi, J., 1984. Tanzanian Marine Fish Resources in the Depth Region 10-500 M Investigated by R/V "Dr. Fridtjof Nansen". Joint Tanzanian/Norwegian seminar to review the marine resources of Tanzania, Mbegani FDC, Tanzania, 6-8 March.

Jacquet, J., Fox, H., Motta, H., Ngusaru, A., Zeller, D., 2010. Few data but many fish: marine small-scale fisheries catches for Mozambique and Tanzania. Afr. J. Mar. Sci. 32 (2), 197–206.

Jebri, F., Jacobs, Z., Raitsos, D.E., Srokosz, M., Popova, E., Painter, S.C., Kelly, S., Roberts, M., Scott, L., Taylor, S., Palmer, M., Kizenga, H., Shaghude, Y., Wishgott, J., 2020. Interannual monsoon winds variability as a key driver of East African small pelagics. Scientific Reports 10, 13247. https://doi.org/10.1038/s41598-020-70275-9.

Jiddawi, N.S., 2000. Age, Growth, Reproductive Biology and Fishery of *Rastrelliger kanagurta* in Zanzibar, East Africa. PhD Thesis. UDSM, 435 pp.

Jiddawi, N.S., Öhman, M.C., 2002. Marine fisheries in Tanzania. AMBIO A J. Hum. Environ. 31 (7), 518–527.

Jiddawi, N.S., Zanzibar, Tanzania, Torre-Castro, de la, 2012. The artisanal fisheries and other resources in chwaka bay. In: Lymo, T.J. (Ed.), People, Nature and Research in Chwaka Bay, pp. 193–212.

Jury, M., McClanahan, T., Maina, J., 2010. West Indian ocean variability and East African fish catch. Mar. Environ. Res. 70 (2), 162–170.

Knaap, Van der, 2013. Smart Licensing of Artisanal Fisheries in the Coastal Waters of Tanzania (Mainland) with Emphasis on Small Pelagic Fisheries. Smartfish Programme for the implementation of a Regional Fisheries Strategy for the Eastern and Southern Africa – Indian Ocean Region. SF/2014/46. 41pp.

Kripa, V., Mohamed, K.S., Shelton, Padua, Jeyabaskaran, R., Prema, D., 2019. Similarities between Indian oil sardine Sardinella longiceps Valenciennes, 1847 and global sardine fisheries and its management. J. Mar. Biol. Assoc. India 61 (1), 5–18. https://doi.org/10.6024/jmbai.2019.61.1.2053-01.

Kyewalyanga, M.N.S., 2002. Spatial-temporal changes in phytoplankton biomass and primary production in Chwaka Bay, Zanzibar. Tanzan. J. Sci. 28 (2), 11–26.

Kyewalyanga, M., 2015. Phytoplankton primary production (Part IV, (Chapter 16), 213-231). In: UNEP-nairobi Convention and WIOMSA. *The Regional State of the Coast Report: Western Indian Ocean*. UNEP and WIOMSA, Nairobi, Kenya, p. 546.

Kyewalyanga, M., Lugomela, C., 2001. Existence of potentially harmful microalgae in coastal waters around Zanzibar: a need for a monitoring programme?. In: Marine Science Development in Tanzania and Eastern Africa. Proceedings of the 20th Aniversary Conference on Advances in Marine Sciences in Tanzania.

Lange, G., Jiddawi, N., 2009. Economic value of marine ecosystem services in Zanzibar: implications for marine conservation and sustainable development. Ocean Coast Manag. 52 (10), 521–532.

Lasker, R., 1975. Field criteria for survival of anchovy larvae: the relation between inshore chlorophyll maximum layers and successful first feeding. Fish. Bull. 73, 453–463.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J.M., Hare, S.R., Ottersen, G., Perry, R.I., et al., 2006. Climate variability, fish, and fisheries. J. Clim. 19, 5009–5030.

Limbu, S.M., Kyewalyanga, M.S., 2015. Spatial and temporal variations in environmental variables in relation to phytoplankton composition and biomass in coral reef areas around Unguja, Zanzibar, Tanzania. SpringerPlus 4, 646. https://doi.org/10.1186/s40064-015-1439-z.

Lobel, P.S., Robinson, A.R., 1986. Transport and entrapment of fish larvae by mesoscale eddies and currents in Hawaiian waters. Deep Sea Res. 33, 483–500.

Losse, G.F., 1964. A purse seine fishery in East African Coastal waters. Proc.E.Afr.Acad. Vil. II, 88–91.

Losse, G.F., 1966. Fishes taken by purse-seine and dipnet in the Zanzibar Channel. East Afr. Agric. For. J. 50–53.

Losse, G.F., 1968. The elopid and clupeoid fishes of East African coastal water. Jl. E.Afr. Nat.Hist.Soc.natn.Mus. 27 (2), 77–115/.

Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W., Galbraith, E.D., Bopp, L., 2019. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proc. Natl. Acad. Sci. U.S.A. 116, 12907–12912. https://doi.org/10.1073/pnas.1900194116.

LVFO, 2016. State of Lake Victoria Dagaa (*Rastrineobola argentea*): Quantity, Quality, Value Addition, Utilization and Trade in the East African Region for Improved Nutrition, Food Security and Income. Regional Synthesis Report. Lake Victoria Fisheries Organisation.

Lyimo, T.J., 2009. Microbial and nutrient pollution in the coastal bathing waters of Dar es Salaam. Aquat. Conserv. 19, S27–S37.

Mahongo, S.B., Shaghude, Y.W., 2014. Modelling the dynamics of the Tanzanian coastal waters. J. Oceanogr. Mar. Sci. 5 (1), 1–7.

Mahongo, S.B., Francis, J., Osima, S.E., 2011. Wind patterns of coastal Tanzania: their variability and trends. West. Indian Ocean J. Mar. Sci. 10 (2), 107–120.

MALF, 2016. *Marine Fisheries Frame Survey 2016 Report*, Mainland Tanzania. Ministry of Agriculture, Livestock and Fisheries, Fisheries Development Division, The United Republic of Tanzania, 83pp.

Manyilizu, M.C., 2008. Numerical Modelling of Tanzanian Shelf Waters and the Adjacent Ocean. Dept Oceanography, University of Cape Town.

Manyilizu, M., Dufois, F., Penven, P., Reason, C., 2014. Interannual variability of sea surface temperature and circulation in the tropical western Indian Ocean. Afr. J. Mar. Sci. 36 (2), 233–252. https://doi.org/10.2989/1814232X.2014.928651.

Mayala, P.J., 2018. Assessment of Socio-Economic Value of the Small Pelagic Fishery in Mafia Island. United Nations University Fisheries Training Programme, Tanzania. Iceland [final project]. http://www.unuftp.is/static/fellows/document/philipo16prf.pdf.

Mayorga-Adame, C.G., Batchelder, H.P., Spitz, Y., 2017. Modeling larval connectivity of coral Reef organisms in the Kenya-Tanzania Region. Frontiers in Marine Science 4, 92.

Mayorga-Adame, C.G., Ted Strub, P., Batchelder, H.P., Spitz, Y.H., 2016. Characterizing the circulation off the Kenyan-Tanzanian coast using an ocean model. J. Geophys. Res.: Oceans 121 (2), 1377–1399.

McClanahan, T.R., 1988. Seasonality in East Africa's coastal waters. Mar. Ecol. Prog. Ser. 44, 191–199.

Mengesha, S., Dehairs, F., Elskens, M., Goeyens, L., 1999. Phytoplankton nitrogen nutrition in the western Indian Ocean: ecophysiological adaptations of neritic and oceanic assemblages to ammonium supply. Estuar. Coast Shelf Sci. 48, 589–598.

Miller, P.I., Christodoulou, S., 2014. Frequent locations of oceanic fronts as an indicator of pelagic diversity: application to marine protected areas and renewables. Mar. Pol. 45, 318–329.

Mills, D.J., Westlund, L., de Graaf, G., Kura, Y., Willman, R., Kelleher, K., Pomeroy, R.S., Andrew, N.L., 2011. Under-reported and undervalued: small-scale fisheries in the developing world. In: Small-scale Fisheries Management: Frameworks and Approaches for the Developing World. CAB International, Wallingford, Oxfordshire, pp. 1–15.

MLFD, 2013. Management Plan for the Tanzanian Artisanal Fishery for Small and Medium Pelagic Fish Species. Fisheries Resource Development. Ministry of Livestock and Fisheries Development, The United Republic of Tanzania.

Moto, E., Kyewalyanga, M., 2017. Variability of chlorophyll-a in relation to physico-chemical variables in Zanzibar coastal waters. Advances in Ecological and Environmental Research 2 (12), 475–492.

Moto, E., Kywelyanga, M., Lyimo, T., Hamisi, M., 2018. Species composition, abundance and distribution of phytoplankton in the coastal waters off Zanzibar Island, Tanzania. J. Biodivers. Environ. Sci. (JBES) 12 (5), 108–119.

Muhling, Barbara, Lindegren, Martin, Clausen, Lotte, Hobday, Alistair, Lehodey, P., Pérez-Ramírez, Mónica, 2017. Impacts of climate change on pelagic fish and fisheries. In: Phillips, Bruce F. (Ed.), Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis, , first ed.vol. II. John Wiley & Sons Ltd. https://doi.org/10.1002/9781119154051.ch23. Published 2018 by John Wiley & Sons Ltd.

Mullon, C., Freon, P., Cury, P., 2005. The dynamics of collapse in world fisheries. Fish Fish. 6 (2), 111–120.

Mwangamilo, J., Anderson, J.D., 2013. Recommendations for Support to Fisheries Co-management in Tanzania: Mainland Tanzania (Report to the World Bank).

Nguyen, Khanh Q., Winger, Paul D., 2018. Artificial Light in Commercial Industrialized Fishing Applications: A Review, Reviews in Fisheries Science & Aquaculture. https://doi.org/10.1080/23308249.2018.1496065.

Nyandwi, N., 2013. The effects of monsoons on the east african coastal current through the Zanzibar channel, Tanzania. J. Ocean Technol. 8 (4), 65–74.

Okera, W., 1974. The zooplankton of the inshore waters of Dar es Salaam (Tanzania, S.E. Africa) with observations on reactions to artifical light. Mar. Biol. 26, 13–25.

Painter, S.C., 2020. The biogeochemistry of the East African Coastal Current. Progress in Oceanography 186, 102374. https://doi.org/10.1016/j.pocean.2020.102374.

Pauly, D., 2019. A précis of gill-oxygen limitation theory (GOLT), with some emphasis on the eastern mediterranean. Mediterr. Mar. Sci. 20 (4), 660–668. https://doi.org/10.12681/mms.19285.

Pauly, D., Zeller, D., 2016. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat. Commun. 7 (1).

Pearson, R.G., Dawson, T.P., 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecol. Biogeogr. 12, 361–371.

Peck, M.A., Reglero, P., Takahashi, M., Catalan, I.A., 2013. Life cycle ecophysiology of small pelagic fish and climate-driven changes in populations. Prog. Oceanogr. 116, 220–245.

Peter, N., 2013. Phytoplankton Distribution and Abundance along Zanzibar and Pemba Channels. M.Sc. Thesis. University of Dar es Salaam, Dar es Salaam, Tanzania, p. 105.

Peter, N., Semba, M., Lugomela, C., Kyewalyanga, M., 2018. The influence of physical-chemical variables on the spatial and seasonal variation of Chlorophyll-a in coastal waters of Unguja, Zanzibar, Tanzania. WIO Journal of Marine Science 17 (2), 25–34.

Peters, F., 2008. Diatoms in a future ocean — stirring it up. Nat. Rev. Microbiol. 6, 407. https://doi.org/10.1038/nrmicro1751-c1.

Pinsky, M.L., Byler, D., 2015. Fishing, fast growth and climate variability increase the risk of collapse. 282. Proc. R. Soc. B 282, 20151053. https://doi.org/10.1098/rspb.2015.1053.

Pitcher, T.J., 1995. The impact of pelagic fish behaviour on fisheries. Sci. Mar. 59 (3–4), 295–306.

Popova, E., Yool, A., Byfield, V., Cochrane, K., Coward, A.C., Salim, S.S., Gasalla, M.A., Henson, S.A., Hobday, A.J., Pecl, G., Sauer, W., Roberts, M., 2016. From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. Global Change Biol. 22 (6), 2038–2053. https://doi.org/10.1111/gcb.13247.

Popova, E., Vousden, D., Sauer, W.H.H., Mohammed, E.Y., Allain, V., Downey-Breedt, N., Fletcher, R., Gjerde, K.M., Halpin, P.N., Kelly, S., Obura, D., Pecl, G., Roberts, M., Raitsos, D.E., Rogers, A., Samoilys, M., Sumaila, U.R., Tracey, S., Yool, A., 2019. Ecological connectivity between the areas beyond national jurisdiction and coastal waters: safeguarding interests of coastal communities in developing countries. Mar. Pol. 104, 90–102.

Racault, M.F., Sathyendranath, S., Brewin, R.J.W., Raitsos, D.E., Jackson, T., Platt, T., 2017. Impact of El Niño variability on oceanic phytoplankton. Frontiers in Marine Science 4, 133.

Roberts, M.J., Ribbink, A.J., Morris, T., Duncan, F., Barlow, R., Kaehler, S., Huggett, J., Kyewalyanga, M., Harding, R., van den Berg, M., 2008. 2007 Western Indian Ocean Cruise and Data Report: ALG160. African Coelacanth Ecosystem Programme, Grahamstown, South Africa.

Samoilys, M.A., Maina, G., Osuka, K., 2011. Artisanal fishing gears of the Kenyan coast. Mombasa: CORDIO/USAID.

Samoilys, M., Pabari, M., Andrew, T., Maina, G.W., Church, J., Momanyi, A., Mibei, B., Monjane, M., Shah, A., Menomussanga, M., Mutta, D., 2015. Resilience of Coastal Systems and Their Human Partners in the Western Indian Ocean. IUCN ESARO, WIOMSA, CORDIO and UNEP Nairobi Convention, Nairobi, Kenya x + 74pp.

Sætersdal, G., Bianchi, G., Strømme, T., Venema, S.C., 1999. The Dr. Fridtj of Nansen Programme 1975–1993. Investigations of Fishery Resources in Developing countries. History of the Programme and Review of Results. *FAO Fisheries Technical Paper*. No. 391. FAO, Rome, 434pp.

Schott, F.A., McCreary Jr., J.P., 2001. The monsoon circulation of the Indian Ocean. Prog. Oceanogr. 51, 1–123.

Schott, F.A., Xie, S.-P., McCreary Jr., J.P., 2009. Indian Ocean circulation and climate variability. Rev. Geophys. 47. RG1002/2009, 2007RG000245.

Semba, M., Lumpkin, R., Kimirei, I., Shaghude, Y., Nyandwi, N., 2019. Seasonal and spatial variation of surface current in the Pemba Channel, Tanzania. PloS One. https://doi.org/10.1371/journal.pone.0210303.

Shaghude, Y.W., Byfield, V., Maathuis, B.H.P., 2012. Using sea surface temperature to assess coral bleaching risk. In: Mannaerts, C.M.M. (Ed.), GEONETCast-DevCoCast Application Manual, Version 1. University of Twente, Enschede, the Netherlands, pp. 179–194.

Shaghude, Y.W., Wannas, K.O., Mahongo, S.B., 2002. Biogenic assemblage and hydrodynamic settings of the tidally dominated reef platform sediments of the Zanzibar channel, West. Indian Ocean J. Mar. Sci 1 (2), 107–116.

Shalli, M., Anderson, J.D., 2013. Recommendations for Support to Fisheries Co-management in Tanzania: Zanzibar. Report to the World Bank.

Swallow, J.C., Schott, F., Fieux, M., 1991. Structure and transport of the east african coastal current. J. Geophys. Res. 96 (C12), 22245–22257.

SWIOFP, 2012. Mainstreaming Biodiversity in Fisheries Management: a Retrospective Analysis of Existing Data on Vulnerable Organisms in the South West Indian Ocean. A specialist report. A SWIOFP Retrospective Analysis, Durban, South Africa.

Tacon, A.G.J., Metian, M., 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture 285 (1–4), 146–158.

Tafe, D.J., 1990. Zooplankton and salinity in the Rufiji River delta, Tanzania. Hydrobiologia 208, 123–130.

Tamele, I.J., Silva, M., Vasconcelos, V., 2019. The incidence of marine toxins and the associated seafood poisoning episodes in the African countries of the Indian Ocean and the Red Sea. Toxins 11, 58. https://doi.org/10.3390/toxins11010058.

Taylor, S.F.W., Roberts, M.J., Milligan, B., Ncwadi, R., 2019. Measurement and implications of marine food security in the Western Indian Ocean: an impending crisis? Food Security. https://doi.org/10.1007/s12571-019-00971-6.

Tzanatos, E., Raitsos, D.E., Triantafyllou, G., Somarakis, S., Tsonis, A.A., 2014. Indications of a climate effect on Mediterranean fisheries. Climatic Change 122, 41–54.

Van der Elst, R., Everett, B., Jiddawi, N.S., Mwatha, G., Santana-Afonso, P., Boulle, D., 2005. Fish, Fishers and fisheries of the western Indian Ocean: their diversity and status. A preliminary assessment. Philosophical Transactions of the Royal Society 363, 263–284.

Van Gennip, S.J., Popova, E.E., Yool, A., Pecl, G.T., Hobday, A.J., Sorte, A.J.B., 2017. Going with the flow: the role of ocean circulation in global marine ecosystems under a changing climate. Global Change Biol. 23 (7), 2602–2617.

Van Hoof, L., Kraan, Marloes, 2017. Mission Report Tanzania; Scoping Mission Marine Fisheries Tanzania. Wageningen Marine Research (University & Research centre), Wageningen. Wageningen Marine Research report, 66pp.

Wanyonyi, I.N., Wamukota, A., Tuda, P., Mwakha, V.A., Nguti, L.M., 2016. Migrant Fishers of Pemba: drivers, impacts and mediating factors. Mar. Pol. https://doi.org/10.1016/j.marpol.2016.06.009.

Whitehead, P.J.P., 1965. A preliminary revision of the indo-pacific alosinae (pisces: Clupeidae). Bull. Br. Mus.nat. Hist. (Zoo I.) 12 (4), 117–156.

Whitehead, P.J.P., 1972. A synopsis of 'the Clupeoid fishes of India. J. Mar. Biol. Assoc. India 14, 160–256.

Wickstead, J.H., 1962. Plankton from the east african area of the Indian ocean. Nature 162, 1224–1225.