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# Managing emerging fisheries of the North Kenya Banks in the context of environmental change

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ABSTRACT

The North Kenya Banks have long been considered an important emerging fishery with the potential to spur economic growth for local fishing communities. As a regionally important extension to the otherwise narrow East African continental shelf, the North Kenya Banks remain under studied with implications for efforts to develop a sustainable fisheries management strategy. The local marine ecosystem is known to be strongly influenced by wind driven upwelling processes with seasonal variability driven by the changing monsoon seasons being of particular importance. Nevertheless, the Western Indian Ocean is warming due to anthropogenic climate change with evidence indicating reduced ocean productivity in future. How the ecosystem of the North Kenya Banks will respond is currently uncertain but is of great importance due to the significance of coastal fishery resources to coastal communities, and growing Blue Economy initiatives to exploit the North Kenya Banks fisheries more widely. There is, however, limited knowledge of the processes influencing productivity over the North Kenya Banks regions and currently there is no management plan in place to sustainably manage the fishery resources. Here, information about the North Kenya Banks fisheries are examined in relation to environmental processes and threats from climate change impacts with suggestions for future research and management directions.

## 1. Introduction

In Africa, Kenya's tropical coastal zone is characterized by a narrow continental shelf that widens at the northern part near the Somalian border where it extends to about 60 km offshore. The wider part of the continental shelf is referred to as the North Kenya Banks (Morgans, 1959), and since its initial identification has long been viewed as a potentially important fishing ground. Marine fishing in Kenya, however, is predominantly conducted on a small scale and is artisanal (McClanahan and Mangi 2004; Samoilys et al., 2011a; FAO, 2020), with artisanal fishers largely unable to reach the outer shelf waters of the North Kenya Banks (NKB; Onyango et al., 2021). It is estimated that about 3100 small artisanal fishing boats operate in Kenya's nearshore waters (GOK, 2016). Nevertheless, small-scale fisheries generally constitute the pillar of coastal livelihoods, are significant in the provision of coastal food security and in supplying 95% of the country's total marine catch (ASCLME, 2012). Increased sustainable exploitation of marine resources is considered advantageous and in particular, growth of the Blue Economy in Africa (World Bank and United Nations Department of Economic and Social Affairs, 2017), is leading Kenyan Government initiatives to expand domestic fishing into the NKB region (Kenya Vision 2030 initiative). At the same time there is still considerable uncertainty regarding the environmental conditions of the NKB, of the environmental controls on the biological productivity of these waters, as well as questions over the extent to which, or even if, the region can be safely exploited and whether the NKB really can be viewed as the 'next frontier' for food security (Aloo et al., 2014; Munga et al., 2012).

Kenya's marine environment is already under pressure from a

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rapidly growing coastal population, estimated in 2000 to be about 3 million (Obura, 2001), but by 2019 had reached almost 4 million (GOK, 2019), and from overfishing, habitat destruction, and weak governance (Japp 2012; Aloo et al., 2014), which together impact the long-term viability and sustainability of the coastal fisheries (McClanahan and Mangi 2004; Samoilys et al., 2011a). The impacts of these local stressors are further exacerbated by the growing impact of climate change (Graham et al., 2007). Climate change is projected to impact marine biogeochemical and oceanographic processes ultimately altering ecosystem dynamics (Jebri et al., 2020; Jacobs et al., 2020a). However, whilst climate change is expected to directly impact Kenyan fisheries, associated ecosystem biodiversity and ultimately impact livelihoods, considerable uncertainty remains around the future timing and severity of these impacts (Jacobs et al., 2021).

Alongside efforts to increase fishing intensity are efforts to develop a sustainable fisheries management strategy for the North Kenya Banks. However, knowledge of the various system components (Fig. 1), for which there is currently a lack of information, hinder this ambition. In this study we provide an overview of Kenyan marine fisheries and fisheries management, with a focus on the North Kenya Banks, and review existing environmental knowledge for this region before assessing how climate change may impact local marine ecosystems and fisheries. We conclude with identification of critical research gaps that should be addressed for improved management and long-term planning purposes.

## 2. Materials and methods

General observations and data on the North Kenya Banks region and its fisheries were collated from the literature, Fisheries and Agriculture Organization (FAO) databases and from the Kenya Fisheries Service and are used to provide an overview of the marine fisheries sector, new emerging fisheries and their relationship to the North Kenya Banks region.

Phytoplankton and zooplankton distributions are presented to illustrate productivity gradients across the North Kenya Banks region with data provided by the Kenya Marine and Fisheries Research Institute (KMFRI). Information on sampling strategies and sampling methodologies is provided in KMFRI (2018).

Predictions of climate change impacts up to 2100 are based on recent model analyses reported by Jacobs et al. (2021) and that study should be consulted for full methodological details. Maps showing the connectivity of the North Kenya Banks to the wider Western Indian Ocean region are based on Lagrangian particle tracking model experiments analogous to those described by Popova et al. (2019).

Satellite derived chlorophyll and sea surface temperature data are used to provide climatological monsoon season and annual mean conditions. Satellite chlorophyll-a concentrations were acquired from the Ocean-Colour Climate-Change Initiative (OC–CCI) project (http://www.esa-oceancolour-cci.org/), at a spatial resolution of 4 km and as monthly means for the period January 1998 to December 2018. This product is considered the most consistent timeseries of multi-satellite (MODIS-Aqua, SeaWiFS and MERIS and VIIRS) global ocean colour data available (Racault et al., 2017). Monthly composites are used here to derive climatological means. Satellite chlorophyll-*a* may be overestimated in shallow optically complex Case II waters, where suspended sediments and/or coloured dissolved organic matter do not covary in a predictable manner with chlorophyll-*a* (IOCCG 2000). As the majority of the Kenyan coastal area comprises Case-I waters, this issue would affect only a very narrow coastal band (i.e., areas shallower than ~30 m).

The SST data used in this study are the reprocessed L4 product acquired from the *Operational-Sea-Surface-Temperature-and-Sea-Ice-Analysis* (OSTIA). This is a multi-satellite global dataset obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu/services-portfolio/access-to-products/) as daily means from 1998 to 2018 at a spatial resolution of 5 km. Monthly and climatological means over the Kenyan coastal waters were calculated for the period 1998–2018. Further details are provided in Jebri et al. (2020).

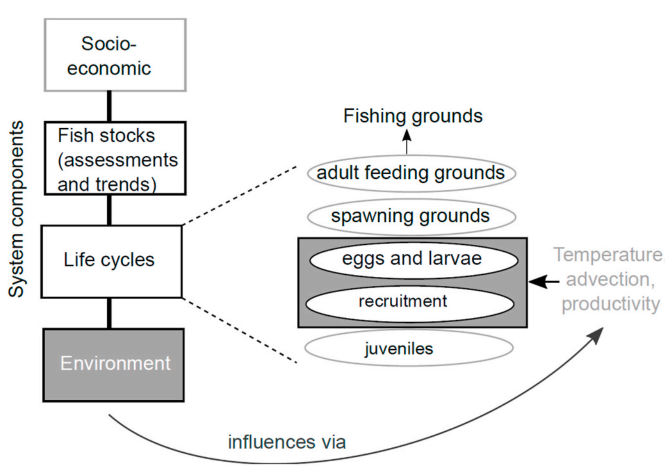


**Fig. 1.** Illustrative schematic of the information needed to develop and manage the North Kenya Banks fisheries for betterment of coastal livelihoods and blue economy. Grey shading used to emphasize environmental influences.

## 3. Marine fisheries in Kenya

### 3.1. General overview

The marine fishery sector is broadly divided into a coastal inshore fishery, which is predominantly artisanal and subsistence based, and an offshore or Exclusive Economic Zone (EEZ) fishery, which is commercial and largely the preserve of foreign fishing vessels targeting tuna. The coastal fishery directly supports about 60,000 people, including fishers and fish processors, and as of 2018 realized an annual production of 24,800 MT (FAO, 2020). Despite its potential marine fish catch in Kenya represents <5% of national fish catch totals with the freshwater sector being dominant (Fig. 2). Yet it is argued that the magnitude of the marine fisheries catch is underestimated and the marine fishery is more important than realized (Le Manach et al., 2015). Using the catch reconstruction approach developed by the Sea Around Us initiative, Le Manach et al. (2015) reported a total domestic catch of almost 985,000 tons for the period 1950–2010, which was 2.8 times higher than the official catch reported to the Food and Agriculture Organization (FAO) of the United Nations. The total reconstructed catch included catches from the industrial, artisanal, recreational, and subsistence fishing sectors and showed that the artisanal sector (i.e., small-scale commercial) was dominant accounting for 64% of the total historic catch with subsistence fishing representing 27%; industrial 5%, and recreational 4%. Furthermore, it was estimated that around 86% (845,000 tons) of the total catch from 1950 to 2010 was taken within the coastal fisheries.

The low national marine fishery production level is attributed to the narrowness of the continental shelf and the use of conventional artisanal fishing methods that allow only for shallow water fishing mainly inside the fringing reef (McClanahan 2010; Samoilys et al., 2011a). In recent years however, the marine fishery sector has experienced a sustained increase in production attributed to an increase in offshore small-scale fishing mainly taking place over the North Kenya Banks (FAO, 2020). Whilst this increase may partially be due to improved access to offshore waters by the mechanized fishing fleet, it appears also to have been driven by a decline in reef fisheries forcing mechanized vessels into deeper waters (Le Manach et al., 2015). The offshore waters of the wider North Kenya Banks region are perceived as holding great potential yet they remain generally under-exploited by domestic fishers (ASCLME, 2012; Fondo et al., 2014; Onyango et al., 2021), though this is now starting to change.

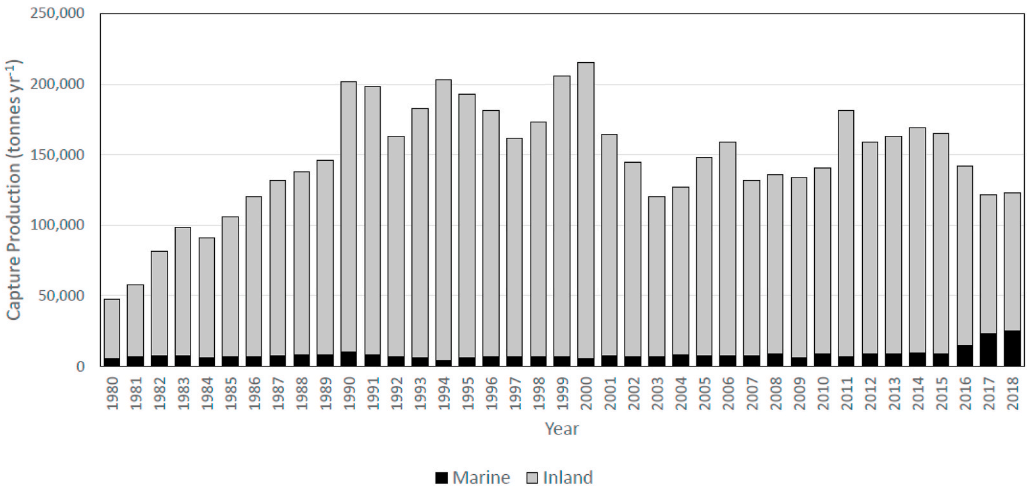


**Fig. 2.** Kenyan fisheries capture production per year by inland (grey) and marine (black) sectors showing a steady increase in marine capture production since 2015. Figure reproduced from data reported by FAO Fisheries Statistics (http://www.fao.org/fishery/facp/KEN/en).

### *3.2. Marine fishery grounds and gear types*

Artisanal fishing is conducted widely along the entire Kenyan coastline but is generally confined to within a few miles of the fringing coral reef network found along Kenya's coast (Fig. 3). The major fishing grounds are located at Kiunga, off Lamu islands, near the Tana River mouth, within Ungwana Bay, the Malindi area, which includes the offshore NKB, Shimoni, Vanga, Funzi Island and the coral reef areas on the southern border (Fondo, 2004; Munga et al., 2012). Productive coastal waters near to major rivers and easily accessible coral reefs generally tend to receive the greatest focus from fishers.

The coastal artisanal fisheries are multi-gear, multi-species, landed widely along the Kenyan coast and considered difficult to effectively monitor (McClanahan and Mangi, 2004; Samoilys et al., 2017). A high diversity of gear types is used throughout the fisheries (Samoilys et al., 2011b), though the use of basket-traps, gillnets, and hook and line gears are dominant across the region (Okemwa et al., 2009; Samoilys et al., 2011b; Onyango et al., 2021; Osuka et al., 2021). Use of several now illegal gear types or fishing practices (e.g. beach seine, spear gun, blast fishing) continues (Samoilys et al., 2017; Osuka et al., 2021). Longline fishing is less common but where used catches a wide range of species including the tunas; yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), and albacore (*Thunnus alalunga*), the billfishes striped marlin (*Tetrapturus audax*), black marlin (*Makaira indica*), blue marlin (*Makaira nigricans*), shortbill spearfish (*Tetrapturus angustirostris*), sailfish (*Istiophorus gladius*), and swordfish (*Xiphias gladius*), the sharks including thresher shark (*Alopias vulpinus*), black shark (*Carcharhinus melanopterus*), hammerhead shark (*Sphyrna zygaena*), tiger shark (*Galeocerdo cuvier*), and mako shark (*Isurus glaucus*), dolphinfish (*Coryphaena hippurus*), barracuda (*Sphyraena* spp.), rainbow runner (*Elagatis bipinnulatus*), moonfish (*Lampris regius*), and wahoo (*Acanthocybium solandri*) (GOK 2008; Kimani et al., 2018). Domestic longlining activity is small compared to the activities of foreign vessels operating within the EEZ.

The demersal finfish fishery involves over 13,000 fishers operating from 197 landing sites (Fig. 3) with about 80% of vessels being non-motorized (GOK 2016). The mode of propulsion is dominated by sails (43%) and paddles (40%) with minor representation by outboard engines (10%), poles (5%), and inboard engines (2%) (Kimani et al., 2018). Annual demersal finfish landings are variable between years (Fig. 4), but the fishery is considered to be experiencing an upward trend in landings (Kimani et al., 2018). Large increases in recent years however reflect changes in monitoring methodologies (Kimani et al., 2018) as well as increased adoption of fishing technologies to target the offshore pelagic fishery (GOK 2016).

Prawn trawling in the Malindi–Ungwana Bay area (inshore NKB region) is a regionally important marine fishery with an annual trawl catch that ranges between 300 and 600 mt (Kimani et al., 2018). The prawn trawling grounds lie between latitudes 3° 30′S and 2° 30′S and longitudes 40° 00′N and 41° 00′N spanning between Malindi and Ungwana Bay. Five penaeid prawn species are commonly captured in the artisanal and commercial catches. These include the Indian white prawn, *Fenneropenaeus indicus*; Giant tiger prawn, *Penaeus monodon*; Speckled shrimp, *Metapenaeus Monoceros*; Green tiger prawn, *Penaeus semisulcatus*, and Kuruma prawn, *Marsupenaeus japonicus*. *P. monodon* and *F. indicus* (Kimani et al., 2018). Although prawns are the target fishery within Ungwana Bay the region is also highly productive supporting a multispecies fishery within the artisanal fishing grounds. This productivity may be linked to inputs from the Tana River (Mutia et al. pers comm.).

### *3.3. Stock assessments*

Stock assessment surveys for Kenyan waters have been infrequent and the marine capture fisheries potential is largely unknown (Maina 2012; Fondo et al., 2014). Initial surveys conducted in the 1950s yielded promising results (Williams, 1956, 1958, 1963) with the first survey off Malindi-Ungwana Bay in 1958 indicating an annual potential of 5000 tonnes of fish (Morgans 1959). Until very recently, the most extensive stock assessment surveys were those conducted by *R/V Dr Fridtjof Nansen* between 1980 and 83 (Mbuga, 1984). These surveys investigated the abundance and distribution of fish to depths of 700 m along the entire Kenyan coast using trawls and hydro-acoustic techniques estimating a total annual production of between 150,000 and 300,000 metric tonnes per annum (Iversen 1983; Iversen and Myklevoll 1984; Maina 2012), an estimate that has long guided fisheries policy. New hydroacoustic surveys conducted in 2017 (KMFRI, 2017) project an annual yield of 240,000 metric tonnes for Kenya's EEZ considering a 20% extractable fishery. However, despite its potential the size of marine fishery capture in Kenya remains small (Fig. 2; FAO, 2020). Near-shore artisanal fisheries may have a potential yield of 12,000 to 20, 000 tonnes per annum but estimates are highly uncertain (Odero, 1984; FAO, 1990; Maina 2012).

### *3.4. North Kenya Banks fishery*

The NKB is an expansive area of the continental shelf of approximately 4325 km$^2$ lying between 2 and 4°S. The NKB supports multiple fisheries and appears highly productive on seasonal timescales (Jacobs

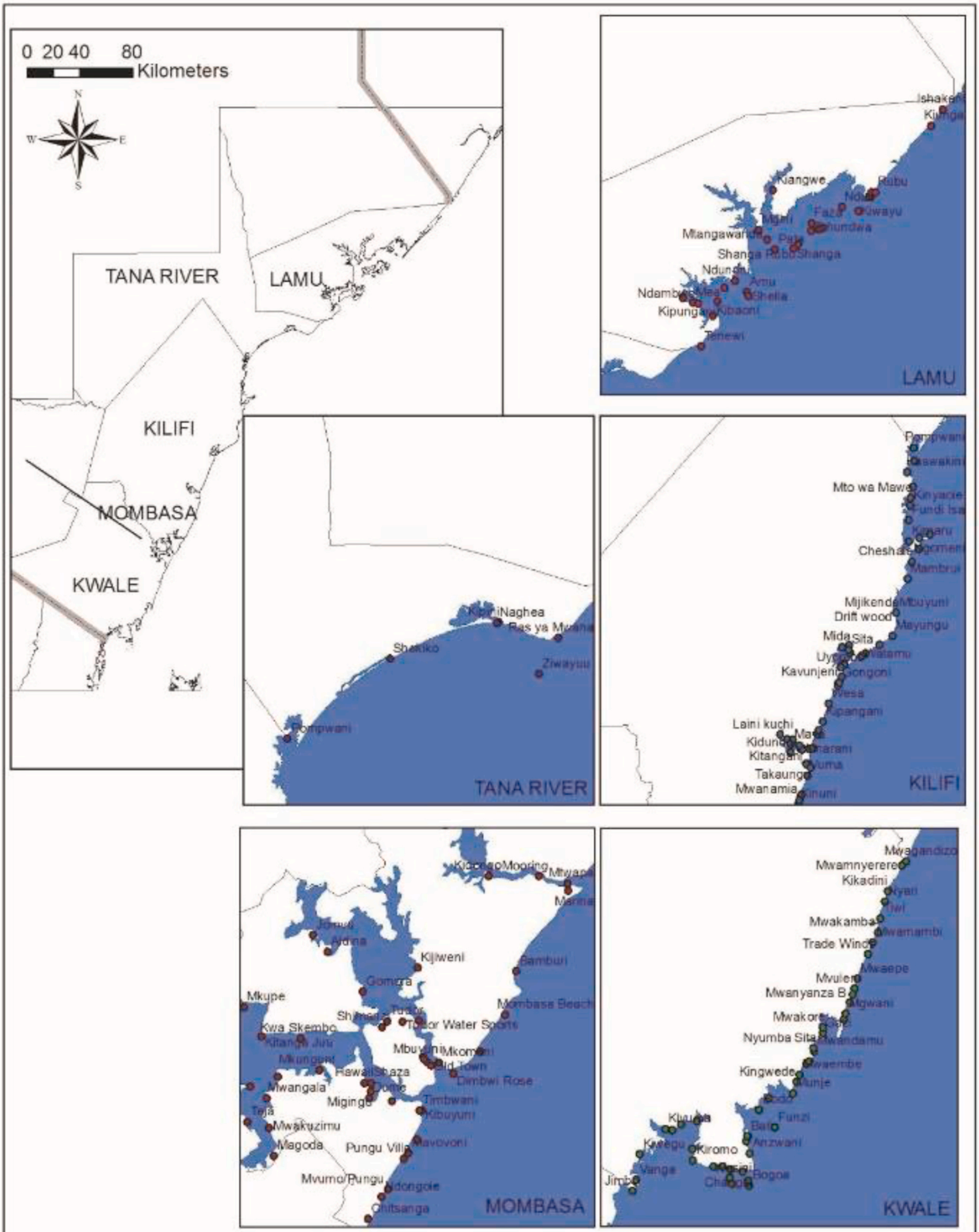


**Fig. 3.** Designated fish landing sites in Lamu, Tana River, Kilifi, Mombasa and Kwale counties. Inset map shows respective distribution of coastal counties and Mombasa city (Reproduced from GOK 2016).

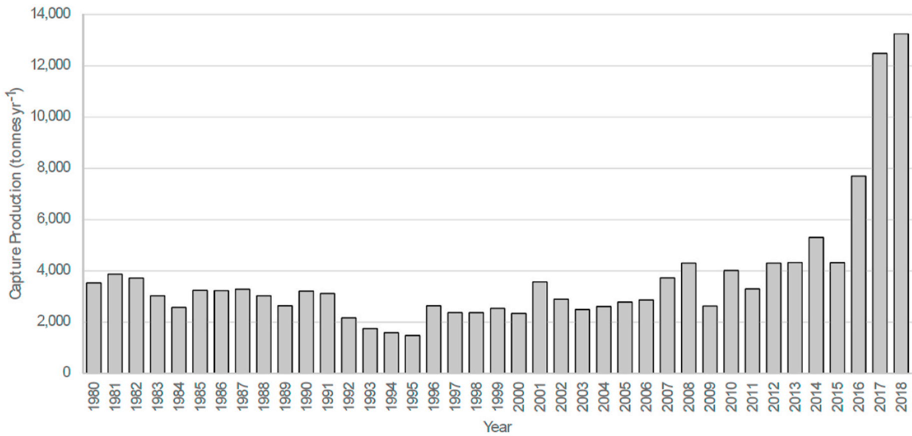


**Fig. 4.** Annual demersal finfish landings from 1980 to 2018. Figure reproduced from data reported by FAO Fisheries Statistics.

et al., 2020b). In particular the area is known as an important spawning ground for yellowfin tuna during the northeast monsoon (NEM) season (Marsac, 2013; KMFRI, 2018). According to a recent hydroacoustic survey the NKB has a pelagic fish density of about 21 ton km$^2$ – which translates to a total stock of 401,520 ton for the area of the NKB (KMFRI, 2017) or approximately one-third of the total stock estimated for Kenya's entire EEZ waters (~1.2 M mt; KMFRI 2017).

### 3.4.1. *Artisanal handline fishery*

The NKB artisanal deep-sea demersal handline fishery is multi-species and operates in the region between 2°5′– 3°00′S, 40°45' – 40° 57′E. Handline fishing is carried out primarily in the 100–400 m depth range. The target pelagic species include, *Thunnus albacares*, *Thunnus obesus*, and *Xaphius Gladys,* while demersal species include, *Argyrops spinifer, Epinephelus flavocaeruleus, Epinephelus poecilonotus, Lutjanus sanguineus, Etelis coruscans, Pristipomoides filamentosus, and Pristipomoides sieboldii.* These species are highly valued and are usually sold to factories for further processing and transport to the national markets although some is sold on the local markets. Artisanal fishing occurs mainly during the dry, calm NEM season (October–March) when winds are weaker and fishers feel safer at sea (Nakken 1981; Hoorweg et al., 2009).

### 3.4.2. *Deepwater fleets*

Fishing by vessels from Distant Water Fishing Nations (DWFN) also occurs within the NKB region and more generally within the Kenyan EEZ. They are drawn by the fact that Kenyan waters are situated within the rich tuna zone of the Western Indian Ocean (WIO) where about 25%

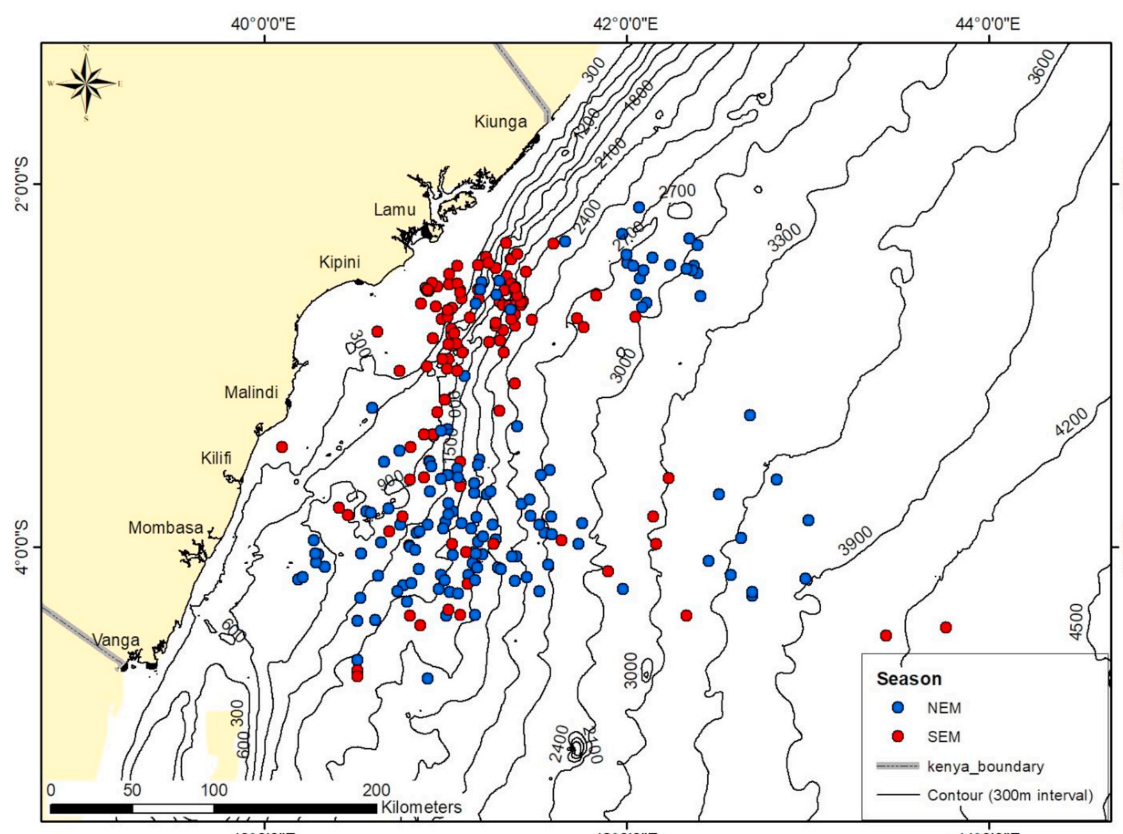


**Fig. 5.** Longline fishing vessel locations during the SEM and NEM seasons. Reproduced from KMFRI (2017).

of the world's tuna is harvested (FAO, 2016). To manage this, the Kenya Fisheries Service (KeFS) undertakes fishery monitoring activities and has licensed 44 vessels (38 foreign and 6 national) with installed on-board tracking transponders (Pramod, 2018) to fish within waters of the Kenyan EEZ; though the number of vessels actively fishing varies significantly between years. KeFS monitors commercial fishing activities within Kenya's marine waters by logbook returns as well as deploying observers on board the vessels. Data from the logbook returns for the longline fishing vessels is beginning to reveal the spatiotemporal variability of productive fishing zones within the Kenyan EEZ, and in particular the singular importance of the NKB region. Observer data for the period 2016–2017 reveals distinct seasonal foci for the longline vessels during the southeast monsoon (SEM) and NEM seasons (Fig. 5). Such data indicate intensified fishing effort over the NKB during the SEM whereas during the NEM fishing takes place further south along the shelf break. Such movements of the fishing fleet likely reflect seasonal changes to upwelling intensity along the NKB (Jacobs et al., 2020b; Jebri et al., 2020) with implications for the location of the best fishing grounds.

Despite the dominance by foreign vessels leading to the export of tuna catches, tuna fisheries do play an important role in the socio-economic development of the country (Wekesa and Ndegwa, 2011). This is particularly important during the SEM season when catch rates are higher (Fig. 6; Kimani et al., 2018) and fishing effort more likely to be focused on the NKB (Fig. 5). In 2010, for example, artisanal landings of 180 tons of tuna were realized by domestic fishers, a single local longliner landed 137 tons (Wekesa and Ndegwa, 2011), and recreational game fishing for tuna and billfishes landed a further 60 tons with most of this caught in the vicinity of the NKB. Artisanal and other domestic tuna landings though remain small compared to the quantities captured by foreign commercial vessels operating in Kenya's EEZ which for the year 2007 caught and exported over 16,500 tons of tuna and tuna-like species (ASCLME, 2012).

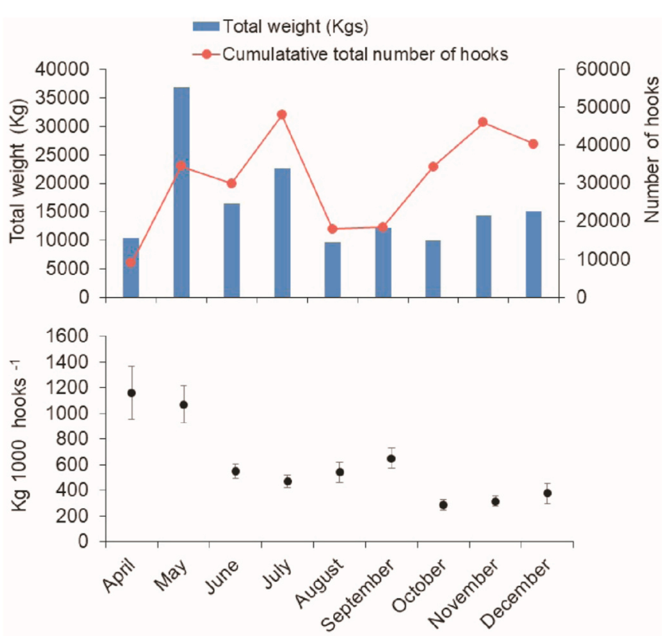


**Fig. 6.** Temporal trends of commercial longline fish catch in the Kenyan EEZ of which the North Kenya Banks is an important component. (a) longline pelagic catches and fishing effort and (b) the standardized catch rates (Kg/1000 hooks) in Kenya's EEZ during April–November 2016. Note that the longline pelagic catch is higher during the SEM (May, 35,000 kg) than during the NEM months (November, 15,000 kg) despite greater fishing effort during the NEM (50,000 vs 25,000 hooks). Reproduced from Kimani et al. (2018).

### 3.4.3. *Deepsea crustacean fishery*

Deep water taxa are poorly studied both off Kenya and across the wider WIO region yet preliminary investigations reported by Everett et al. (2015a) suggest that the steep slopes of the NKB host several crustacean species of commercial interest including the deep-water shrimps *Penaeus marginatus*, *Heterocarpus woodmasoni* and *Heterocarpus tricarinatus* and the deep-water crab *Chaceon macphersoni*, and deep-water lobster *Metanephrops mosambica, Nephrops stewartia,* and *Puerulus angulatus*. Commercial prospects for large-scale fishing of deep-water crustaceans however are considered limited due to the low abundances of species in Kenyan waters (Everett et al., 2015b). Nevertheless, fisheries observer data shows targeted fishing for crustaceans along the margins of the NKB is slowly increasing with the catch emerging as a small though important high-end export product (Fig. 7).

## 3.5. *Management of marine fishery resources*

### 3.5.1. *National fisheries*

Management of the national marine fisheries is complicated by its artisanal open-access nature and extensive transboundary connectivity (Aloo et al., 2014). Existing management structures were developed to address local disputes between commercial and artisanal fishers (e.g. Malindi Ungwana Bay management plan) or in response to rapid habitat destruction. There is no comprehensive management plan for the small and medium pelagic fisheries. However, a National Tuna Fishery Development Strategy exists which aims to increase the benefits of the tuna fishery in the Kenya EEZ for the local economy.

### 3.5.2. *Transboundary shared fisheries*

Neighboring countries, in this case Tanzania and Somalia, have their own resource management regimes which can pose complications in the management of a shared fishery resource. To resolve this the Kenyan and Tanzanian Governments, via Kenya Wildlife Service (KWS) and the Tanzania Marine Parks and Reserves Unit (MPRU) initiated a process to develop a coastal and marine Trans-Boundary Conservation Area (TBCA) between the Republic of Kenya and the United Republic of Tanzania with the objective of better managing their shared marine resources.

### 3.5.3. *Internationally shared fisheries*

Elsewhere, the presence of an internationally shared migratory fishery in Kenyan waters, in this case tuna, involves a complicated management regime that requires an agreement between Kenya and an international governing body. Kenya lies within the Tuna belt and is a member of the Indian Ocean Tuna Commission (IOTC), and as a member shares fisheries data and information to enable species specific stock assessments for the Indian Ocean in order to facilitate effective management. Kenya is also a member of the South West Indian Ocean Fisheries Commission (SWIOFC) whose goal is management of other (non tuna) trans-boundary fisheries resources.

### 3.5.4. *Management challenges*

In the absence of a comprehensive management plan for the small and medium pelagic fishery, the objectives of the government of Kenya are addressed indirectly through numerous and various policy documents, legislations and Acts (Table 1; Kamau et al., 2009; Church and Obura, 2004; FAO, 1990; Japp 2012). Notable are the National Oceans and Fisheries Policy 2008, The Prawn Fishery Management Plan 2010, Fisheries (Beach Management Units) Regulations, 2007 and the Fisheries Management and Development Act 2016, though there are many more (Table 1). There exist also other specialized fishery management instruments driven by private stakeholder interests (Maina, 2012). These include but are not limited to; Tuna Fisheries Alliance of Kenya (TUFAK); Kenya Fish Processors and Exporters Association (AFIPEK). There have also been recent regional and national initiatives aimed at specific fisheries and environment matters including the Agulhas and

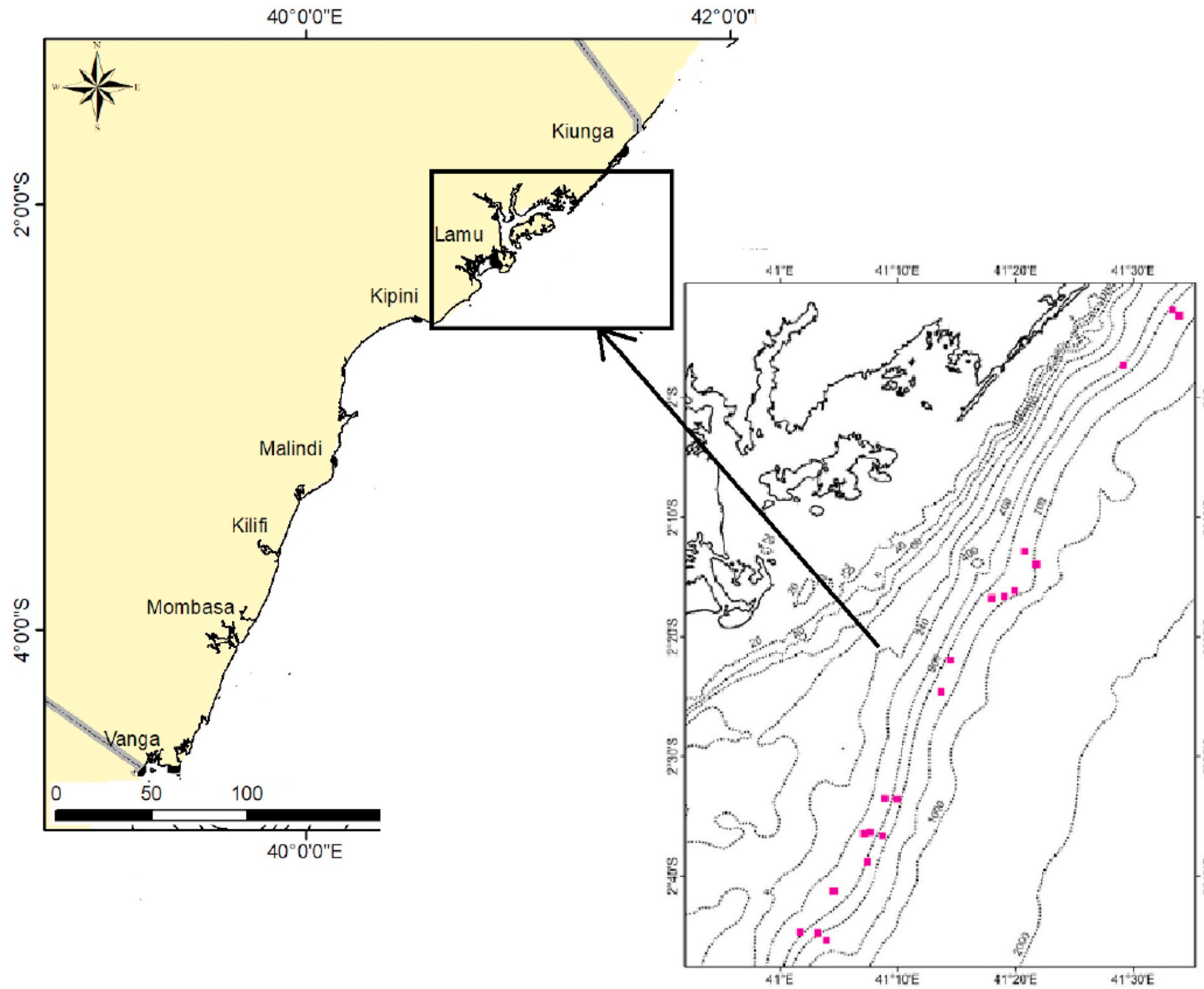


**Fig. 7.** Illustration of how observer programs can be used to identify deep-water fishing grounds along the edges of the North Kenya Banks. In this example observer data on deep-water crab pot locations are shown which indicate targeted placement between 300 and 700 m depth (Data from Kenya Fishery Service (KeFS) observer program, 2020).

Somali Currents Large Marine Ecosystems Programme (ASCLME programme); WIOLab project (UNEP) and the South Western Indian Ocean Fisheries Project (SWIOFP); and the Kenya Coastal Development Project.

As a result of the complex legislative arena within which fisheries management currently operates and the lack of a central national management plan, a number of challenges to effective management and growth of the sector have been identified (e.g. Japp 2012; Aloo et al., 2014), which include i) The high number of fish landing sites, which makes monitoring and data collection difficult, time consuming and expensive, ii) The expansive EEZ which has not been effectively studied nor have catches from this region been adequately quantified, iii) Uncontrolled fishing by Distant Water Fishing Nations, iv) Willful destruction of artisanal fishing gears by large commercial trawlers, v) Inadequate capacity by artisanal fishers to exploit the offshore fish stocks, vi) Lack of adequate information about offshore marine fish stocks, vii) Compliance and enforcement problems and viii) lack of a management plan directly addressing the small and medium pelagic fishery along the Kenyan coast.

In addition to the practical issues of fisheries management, efforts to understand responses by the fisheries to natural seasonal-to-decadal variability as well as to predict how the region may change in the future remain limited. The local marine environment is historically under sampled and the links between fisheries and environmental variability are only just beginning to be understood.

## 4. Blue economy and marine food security

Despite the small size of Kenya's marine fisheries they are of strategic value due to the large role the sector plays in supporting livelihoods and food security. For coastal communities, small-scale fishing is essential to welfare by providing both income and nutrient-dense food. National average fish consumption as a proportion of total animal protein intake is around 7.3% in Kenya, which is low in comparison to other WIO countries such as Tanzania and Seychelles with 22.5% and 49.7% respectively (FAO, 2018). However, recent studies (Cinner and Bodin, 2010; Taylor et al., 2019) have found a high level of dependence by coastal communities on fish contrasting markedly with the national-level statistics for Kenya. The majority of fishers in the marine sector (77%) consume at least part of their catch, which includes semi-industrial small-scale commercial (SSC) fisheries such as the *Mshipi* (handline) fishery (WIOFish, 2020; Breuil and Grima, 2014; Taylor et al., 2019). This finding illustrates the significance of marine fisheries on both direct (nutrition) and indirect (monetary) food security of coastal communities.

The marine fishing capacity of around 3100 small scale fishing craft realizes an annual production of 24,800 mt worth KES 4.6 billion (around US$42 million in 2020 exchange rate) (Kimani et al., 2018). Of the five coastal counties, Kilifi reported the highest marine artisanal landings in 2015 with 12,211 mt representing 51 percent of total

**Table 1**
Kenyan Government Acts, legislations and policy documents relevant to marine fisheries management.

| Year | Acts, Legislations or Policies | Description |
|---|---|---|
| 1989 | Maritime Zones Act, Chapter 371, 1989 (Revised, 2012) | Act of Parliament consolidating the law relating to the territorial waters and the continental shelf of Kenya including the establishment and delimitation of the exclusive economic zone |
| 1991 | Fisheries Act CAP 378, 1991 (Revised, 2012) | Act of Parliament to provide for the development, management, exploitation, utilization and conservation of fisheries |
| 1999 | Environmental Management and Coordination Act (EMCA) 1999 | Act of Parliament to provide for the establishment of an appropriate legal and institutional framework for the management of the environment |
| 2004 | Fisheries (Foreign Fishing Craft) (Amendment) Regulations, 2004. (Legal Notice No. 20.) | Amendment of regulations concerning licence fees for foreign fishing craft operating in Kenyan waters |
| 2007 | Fisheries (Beach Management Units) Regulations, 2007 | Regulations to establish and administer beach management units for each fish landing site with the objectives of strengthening management of fish-landing stations, fishery resources and the aquatic environment |
| 2007 | Fisheries safety of fish, fishery products and fish feed Regulations, 2007 (Legal Notice No. 170.) | Regulations to control the safety of fish, fishery products and fish feed and specify health requirements for the production and placing on the market of (particular) fish products |
| 2008 | National Oceans and Fisheries Policy 2008 | Policy document introducing a coordinated framework for addressing the challenges facing the fisheries sector with the overall aim of guiding sustainable development of the fisheries sector |
| 2008–2030 | Kenya Vision 2030 | Long-term national development plan that also incorporates development of fisheries related infrastructure and strengthening of monitoring, control and surveillance systems. |
| 2009 | Merchant Shipping Act, 2009 | Act of Parliament formalizing registration and licensing of Kenyan ships – including fishing vessels |
| 2009 | National Environmental Action Plan 2009–2013 (NEAP) | National plan that highlights priority themes and activities necessary for achieving sustainable development and sustainable environmental management including marine fisheries |
| 2010 | The Prawn Fishery Management Plan 2010 | Management Plan to ensure the continuation of a biologically sustainable and economically viable prawn fishery and protection of the prawn fishery and habitat over the long term |
| 2010 | Constitution of Kenya Act (2010 | Includes provisions to enact protection of the environment and natural resources in order to establish a durable and sustainable system of development, including fisheries |
| 2011 | Integrated Coastal Zone Management (ICZM) Action Plan for Kenya | Promotion of sustainable development in the coastal zone in line with the principles of the new (2010) constitution and objectives of Kenya Vision (2030) |
| 2012 | National Environment Policy, 2012 Revised Draft # 4 April 2012 | The policy seeks to provide a framework for an integrated approach to planning and sustainable management of Kenya's environment and its natural resources. |
| 2015–2030 | Kenya National Adaptation Plan 2015–2030 | National management plan with a focus on integrating climate change adaptation into national and county level development planning and budgeting processes |
| 2016 | Fisheries Management and Development Act | Act of Parliament to provide for the conservation, management and development of fisheries and other aquatic resources to enhance the livelihood of communities dependent on fishing and to establish the Kenya Fisheries Services |
| 2018–2022 | National Climate Change Action Plan 2018–2022 | National plan to ensure alignment between climate change actions with the Government's development agenda |

landings (KMFSED, 2020). In 2015, Gross Marine Product (GMP), a measure of the ocean's annual economic value, and Gross Domestic Product, a measure of the monetary value of all finished goods and services, indicated Kenya was the second largest economy (measured by GDP) in the WIO region and the 5th largest ocean economy (measured by GMP). Kenya's ocean economy was worth an estimated US$2.4 billion in 2015, equating to 4% of total GDP (Obura et al., 2017).

Fisheries however account for only 1.8% of Kenya's ocean income, with the largest ocean sector in terms of annual value being tourism. The government of Kenya has prioritized the blue economy component of its Kenya Vision 2030 development agenda with recent estimates suggesting the annual economic value of goods and services in the blue economy could be worth around US$4.4 billion (UNDP, 2018). The inclusion of blue economy initiatives began in May 2016 when Kenya established a Blue Economy Committee, and the State Department of Fisheries was renamed to the State Department for Fisheries and the Blue Economy. The blue economy sector plan includes the Kenya Marine Fisheries and Socio-Economic Development Project (KMFSED), a five-year project beginning in 2020.

Approximately 80 percent of Kenya's total marine products come from coastal waters and reefs with the remaining 20 percent from offshore fishing (KMFSED, 2020). With the artisanal sector being characterised by small crafts, fishers are restricted to near-shore waters including reefs, estuaries, and lagoons where a lack of governance has affected near-shore fisheries resulting in resource overexploitation and habitat degradation (Japp 2012; Aloo et al., 2014). Pressure points on marine resources include the open access nature of near-shore and territorial waters coupled with the use of destructive fishing gear and the limited alternative or complementary livelihoods for coastal communities. To address these issues Kenya has begun implementing measures via national fisheries regulations, national fisheries management plans (FMP), and local co-management area (CMA) plans to manage fishing effort in both the artisanal and commercial sectors (KMFSED, 2020).

Industrial fishing in territorial and offshore waters also faces governance issues due to Illegal, Unreported, and Unregulated (IUU) fishing. It is estimated that Kenya loses up to US$100 million annually to IUU fishing (Benkenstein, 2018), a finding that elevated the elimination of IUU in Kenyan waters to high on the list of blue economy priorities. The Kenya Coastal Development Plan (KCDP) subsequently led to the development of a monitoring, control, and surveillance (MCS) strategy that is currently being used to monitor licensed foreign-flagged vessels operating within the EEZ. Part of Kenya's blue economy strategy priorities include increased marine fisheries production with the aim of increasing value and income throughout the value chain (KMFSED, 2020). Appropriate fish landing and processing facilities are however currently lacking, heightened by the closure of Mombasa's tuna processing facility in 2013. In addition, catches by licensed offshore industrial fishing vessels (longline and purse seine vessels) are typically landed outside of Kenya, and few Kenyans are currently employed in this sector. Consequently, the economic value generated from the industrial catch is minimal and restricted to the collection of license fees. New regulations now require fishing vessels to land part of their catch in Kenya and the Tuna Fishery Strategy (GOK 2013) is part of an attempt to increase the presence of domestic operators in the industrial offshore sector in Kenya, whilst also including plans to refurbish the Mombasa processing facility.

Expansion plans within the blue economy strategy, such as those to increase marine fisheries production, are being developed with sustainable management use of resources in mind. With the Kenyan government acknowledging that climate change impacts will add pressure to marine resources, the need to increase resilience measures to better support the most vulnerable communities in their transition to alternative and climate-resilient livelihoods has been recognized. A subcomponent of the KMFSED project therefore includes a subsection on Enhancing Governance of Marine Fisheries and Blue Economy (KMFSED, 2020). This component aims to increase the benefits derived from Kenya's marine resources within the blue economy while ensuring the long-term sustainability of those resources is not compromised. This will be done by strengthening fisheries policy and related legislation, Marine Spatial Planning (MSP), and strengthening the management of priority fisheries. The priority fisheries identified are deep-water snapper fisheries of the North Kenya Banks, small-scale purse seine (ring net), small-scale line-caught tuna, shallow water prawn, octopus, and the inshore/creek basket trap fishery. The implementation of fishery improvement projects for these selected fisheries incorporates activities to improve stocks and ecosystems, and strengthen their climate resilience (such as stock assessments and habitat spatial assessments), with the overarching goal being to improve socio-economic benefits to the fishing communities.

## 5. Oceanography of Kenyan coastal waters

The upper-ocean circulation of the tropical western Indian Ocean responds strongly to the monsoon winds, with the South Equatorial Current (SEC), the East African Coastal Current (EACC), the Somali Current (SC) and the South Equatorial Counter Current (SECC) dominating the regional flow (Fig. 8). Southern and central Kenyan waters are strongly influenced by the EACC which flows northwards year-round extending into northern Kenyan and Somalian waters during the SEM months. The EACC is generally nutrient poor and its waters exhibit low rates of productivity (Painter, 2020). Northern Kenya is also seasonally impacted by the SC which flows southwards during the NEM months (November to February), reversing during the SEM in response to changes in large-scale atmospheric pressure gradients over the WIO (Duing, 1977). The NKB are located where the southward flowing SC meets the northward flowing EACC during the NEM season with the confluence of these two currents feeding into the SECC (Fig. 8).

The EACC flows northwards along the Kenyan coast with peak velocities of around 2 m s $^{-1}$ and a transport in the top 100 m of ~15 Sv (Leetmaa et al., 1982). During the SEM, when the SC reverses and the EACC extends northwards towards Somalia, surface currents are accelerated by strengthening winds and estimated transports of 27 Sv in the top 100 m have been reported (Leetmaa et al., 1982). During the NEM current speeds and transports are reduced (Manyilizu et al., 2016; Semba et al., 2019). Strong vertical mixing due to surface forcing has been suggested to homogenize the upper ocean and the EACC is generally characterized with well mixed physical and chemical properties (Smith, 1982; Ochumba, 1983). Upwelling events along the Kenyan coast, particularly shelf edge upwelling, occur during the NEM (Jacobs et al., 2020b) and can be bathymetrically enhanced over the NKB (Johnson et al., 1982). In addition, eddies and wakes can enhance vertical mixing due to interaction of the strong current and the complex bathymetry (Ochumba, 1983). Upwelling events are characterized by widespread reductions in sea surface temperature and elevations in surface chlorophyll-a concentrations in the vicinity of the NKB region (Jacobs et al., 2020b), with the exact location and magnitude of the upwelling-driven increases in chlorophyll-*a* characterised by strong interannual variability (Jacobs et al., 2020a,b). In-situ observations demonstrating enhanced primary productivity at this time remain limited. Seasonal acceleration of the EACC also induces dynamic uplift upwelling along much of Tanzania and Kenya (Jebri et al., 2020), supporting and enhancing primary productivity at this time.

The Somali Current, which flows as an intense western boundary current, differs from other western boundary currents by reversing direction with the changing monsoon seasons. There are few direct estimates of the Somali Current transport and most are now several decades old. During the NEM Bruce and Volkman (1969) estimated a volume transport of between 20 and 28 Sv as the SC flows southwards where it crosses the equator contrary to geostrophic assumptions assuming zero

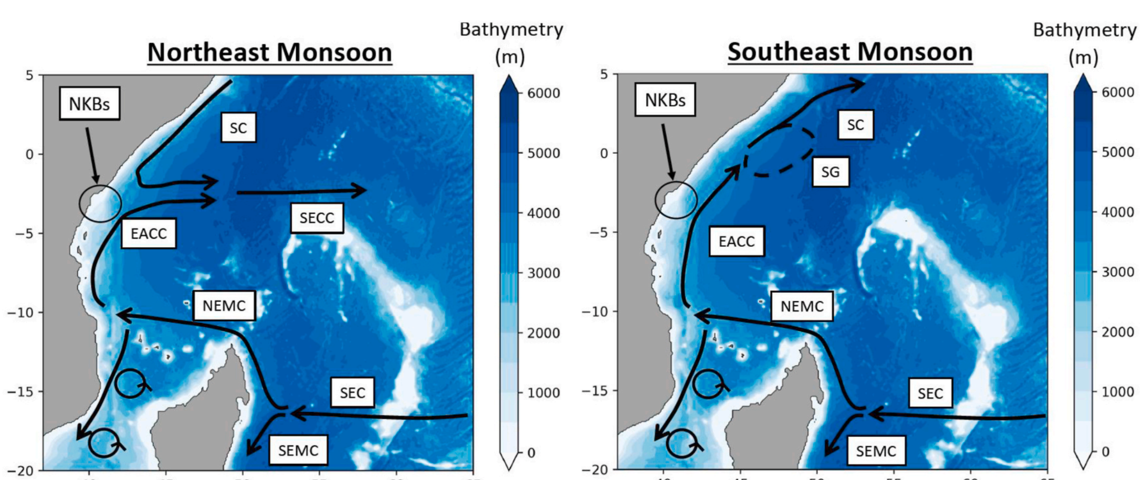


**Fig. 8.** Regional circulation of the WIO region during the Northeast and southeast monsoon periods. The North Kenya Banks (NKBs) are indicated by the thin black circle.

mean flow. Leetmaa et al. (1982) meanwhile observed a volume transport of only 3 Sv as the SC flowed southwards during the NEM with a velocity between 0.5 and 1 m $s^{-1}$. Duing (1970) reported that the maximum depth influenced by the reversal of the current direction was around 400 m. Duing and Szekielda (1971) subsequently reported large changes in the volume transport ranging from 0 to 60 Sv in response to the monsoonal reversal in current direction, whilst Bruce (1970), estimated the total volume transport during the SEM, when the SC flows northwards, as 48 Sv for the 0–200 m depth range and 74 Sv for the 0–1000 m depth range. Notably, larger transport estimates during the SEM are influenced by the latitudinal extension of the EACC at this time.

In situ hydrographic data from the NKB region remain limited. Observations collected by the *R/V Dr. Fridtjof Nansen* cruises in 1982–1983 remain some of the most detailed observations available for the outer NKB region (Groeneveld and Koranteng, 2017). Data from these cruises typically indicates an absence of strong hydrographic gradients either along or perpendicular to the coast, broadly homogenous upper ocean conditions and a thermocline positioned between 100 and 150 m. Salinity down to 500 m depth is generally within the range 35.0–35.3.

### 5.1. Nutrients and phytoplankton

Marine productivity in Kenyan coastal waters is highly dependent on the influence of the monsoon seasons (McClanahan, 1988; Kaunda, 2009; Mwaluma, 2011). Elevated phytoplankton biomass has been reported in coastal waters during the NEM (Kaunda, 2009; Mwaluma et al., 2003), a period of upwelling (Jacobs et al., 2020b; Jebri et al., 2020), which subsequently promotes an increase in zooplankton abundance, particularly from February (late NEM) through to August (SEM) (Kaunda, 2009; Mwaluma, 2011; Mwaluma et al., 2003). Detailed studies of the plankton along the Kenyan coast are scarce, the size-class distribution rarely studied - though picoplankton likely dominate the phytoplankton (Painter 2020; Painter et al., 2021) - and phenological studies limited. Recent observations from the SEM period indicate higher phytoplankton biomass in shallow shelf waters compared to deeper offshore sites, with a bloom of the diatom *Chaetoceros* sp. driving much of the spatial variability (KMFRI, 2018, Fig. 9). These recent observations also indicate the effects of higher nutrient loads from land-based sources on near-coastal phytoplankton abundances (Fig. 9; KMFRI, 2018). Dominant phytoplankton species found along the Kenyan coast during both monsoon seasons include the Cynobacteria *Ocillatoria* sp. and diatoms *Chaetoceros* sp. and *Rhizosolenia* sp. Other common species were *Bacteriastrum* sp. *Protoperidinium* sp., *Coscinodiscus* sp., *Alexandrium* sp., and *Ostreopsis* sp. (Imbayi et al., 2019; KMFRI, 2018; Kromkamp et al., 1997; Wickstead, 1961).

Mean chlorophyll-*a* concentrations along the East African coast including Kenyan waters are typically <0.3 μg $L^{-1}$ rising to average concentrations of 0.4–0.5 μg $L^{-1}$ over the North Kenya Banks (Painter 2020). Seasonally however, surface chlorophyll-*a* concentrations can be far higher over the NKB reaching >3 μg $L^{-1}$ during exceptional upwelling periods and surface chlorophyll-*a* concentrations typically peak in January–February (Jacobs et al., 2020b).

Zooplankton exhibit high spatial variability in both shelf and EEZ waters (KMFRI, 2018). Common species include Cyclopoids *Oithona* sp., *Oncaea* sp. and *Corycaeus* sp. which appear geographically wide spread (Smith et al., 1992; Hitchcock et al., 2002) and the calanoid copepods *Neocalanus* sp. and *Calanoides carinatus* which are associated with upwelling areas in northern Kenya and Somalian waters (Smith et al., 1992; Hitchcock et al., 2002). High densities of calanoid copepods have been observed along the northern coast of Kenya near Lamu during the NEM season (Fig. 10). Previously however, Osore et al. (2004), noted latitudinal variations in the zonal distribution along the Kenyan coast showing that *Candaciidae* were more abundant during the SEM period than in the NEM period. Abundances also decreased with depth from a maximum of 880 individuals per 100 $m^3$ at the surface to a minimum of 10 individuals per 100 $m^3$ in deeper layers. *Candaciidae* were least abundant between 400 and 800 m, which coincided with the depth of minimum oxygen concentration (Heip et al., 1995).

Nutrient observations for the East African coastal region also remain limited. Painter (2020) reported mean annual surface nutrient

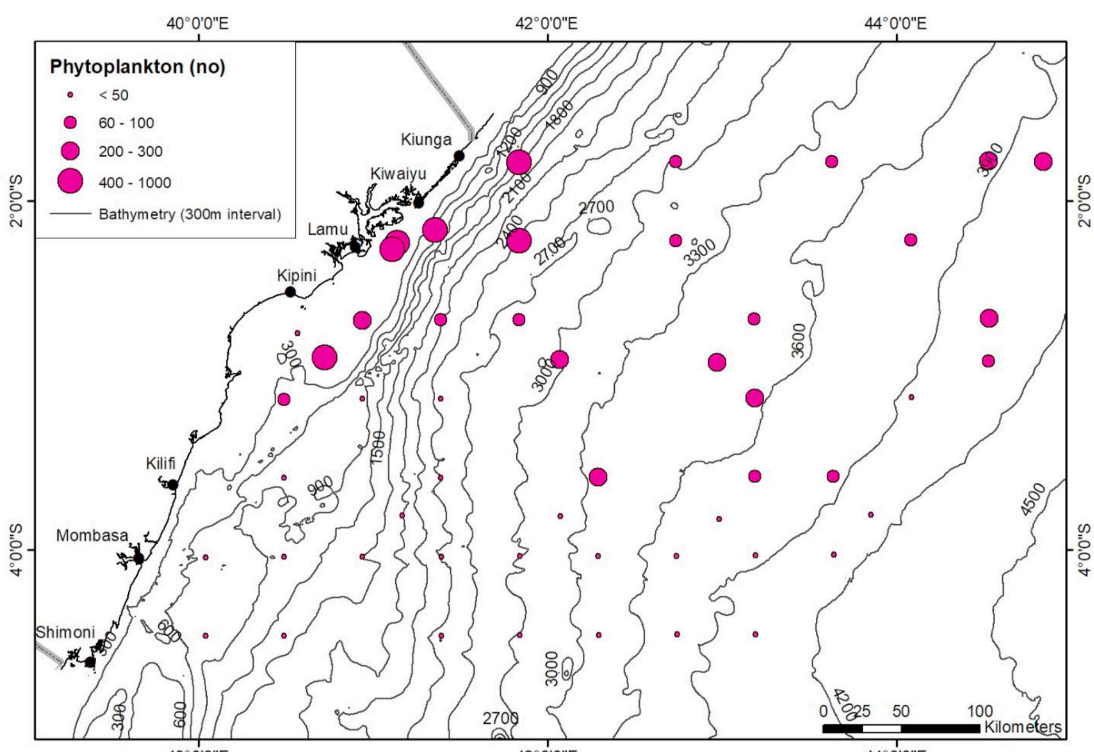


**Fig. 9.** Distribution of phytoplankton (cells $m^{-3}$) in Kenya's Territorial waters and EEZ. Data obtained during December 2016 and February 2017 RV. *Mtafiti* cruises. See KMFRI (2018) for further details.

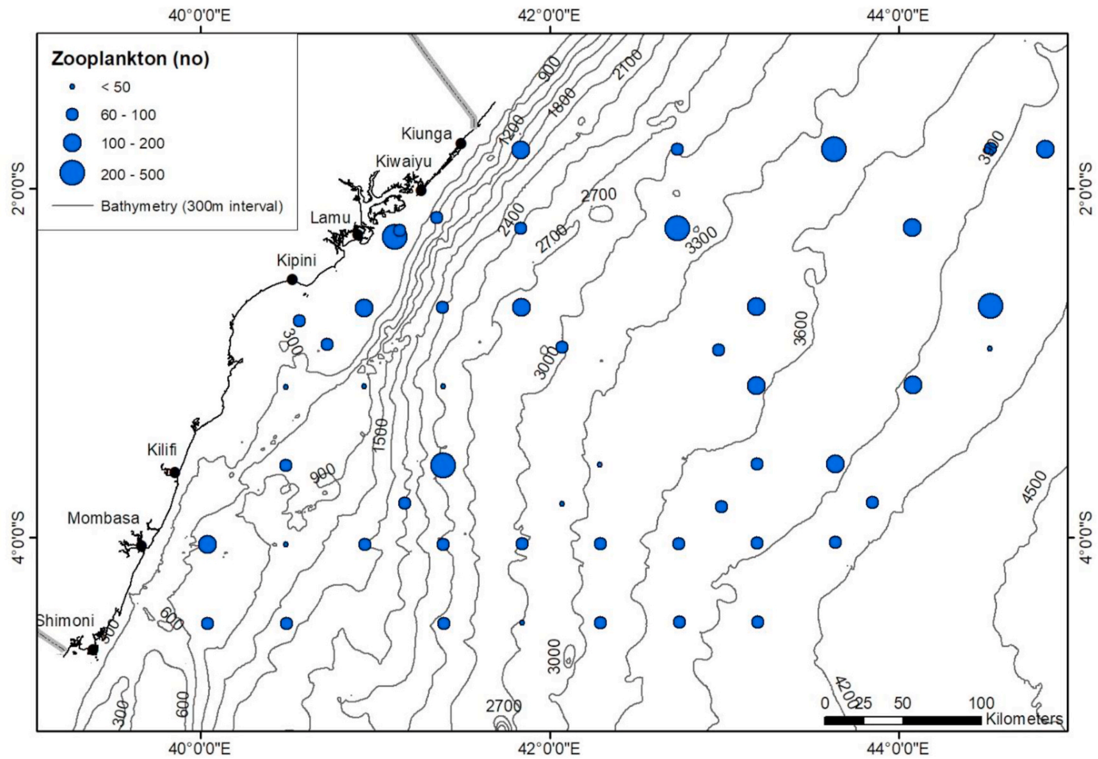


**Fig. 10.** Distribution of zooplankton (no. $m^{-3}$) in Kenya's Territorial waters and EEZ. Data obtained during December 2016 and February 2017 RV. Mtafiti cruises. See KMFRI (2018) for further details.

concentrations for the EACC of ~0.2 μmol $NO_3^-$ $L^{-1}$, 0.18 μmol $PO_4^{3-}$ $L^{-1}$, and ~3.7 μmol Si $L^{-1}$, noting that there was also significant spatial and temporal variability in reported measurements. Conditions over the North Kenya Banks appear more variable. Babenerd and Boje (1973) noted a latitudinal gradient in $PO_4^{3-}$ concentrations which increased northwards with concentrations peaking at >0.3 μmol $L^{-1}$ in North Kenyan waters. Similarly, Goosen et al., (1997) reported phosphate concentrations in Kenyan waters ranging from ~0.1 to 0.66 μmol $L^{-1}$ during the SEM and intermonsoon (Nov) period whilst Kromkamp et al. (1997) reported a narrower range of 0.1–0.35 μmol $L^{-1}$. Away from estuaries and river outflows surface $NO_3^-$ concentrations are generally reported as being <0.1 μmol $L^{-1}$ along the Kenyan coast (Kromkamp

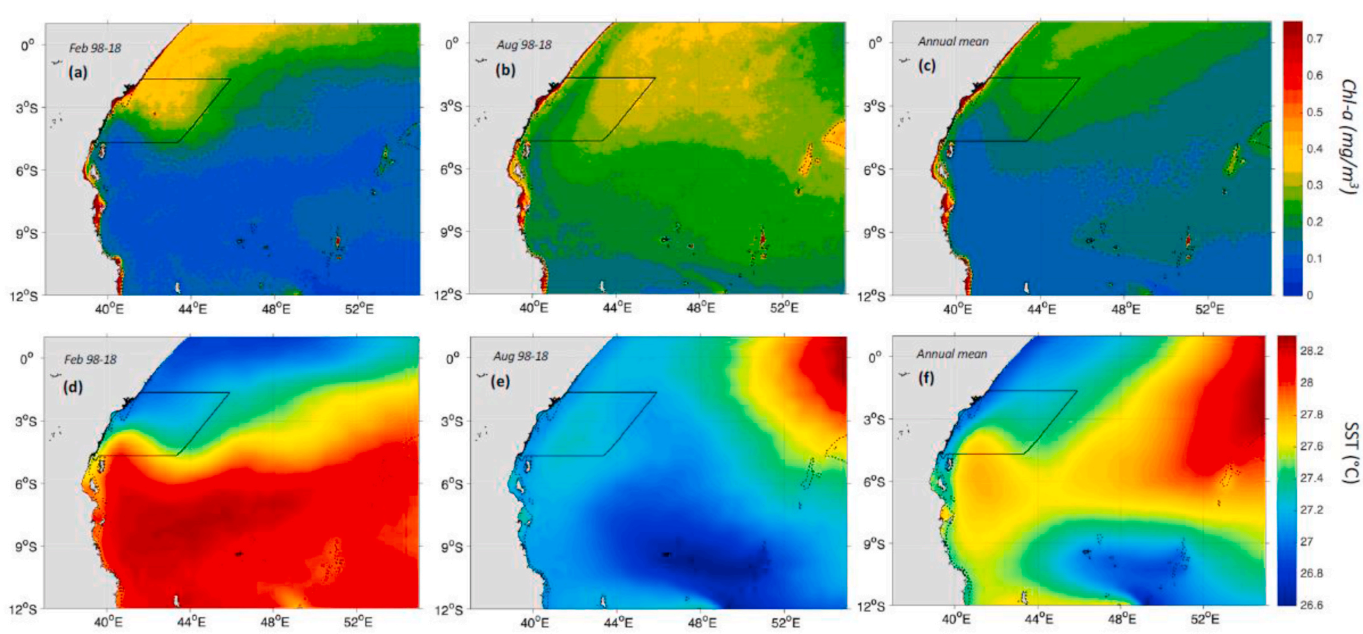


**Fig. 11.** Satellite Chlorophyll-a (in mg/$m^3$) during climatological **(a)** February (Northeast monsoon) and **(b)** August (Southeast monsoon) and as **(c)** annual mean. Satellite SST (in °C) during climatological **(d)** February (NEM) and **(e)** August (Southeast monsoon) and as **(f)** annual mean. The climatological period used for SST and Chlorophyll-a covers 1998–2018. The dashed black line indicates the 200 m isobath and the solid black line contour indicates the Kenyan EEZ as defined by https://www.un.org/depts/los/LEGISLATIONANDTREATIES/STATEFILES/KEN.htm.

et al., 1997). Van Couwelaar (1997) however reported a concentration of 0.5 μmol $L^{-1}$ specifically for the North Kenya Banks for July (SEM), whilst Obura (2001) and Nguli (1995) both suggested typical concentrations of <2–3 μmol $L^{-1}$ for shallow shelf waters. All studies indicate typical Si concentrations of around 3 μmol $L^{-1}$. There are no studies reporting a complete annual cycle of nutrient concentrations for the North Kenya Banks region.

## 6. Influence of the environment on life cycles and Kenyan fisheries

### 6.1. Key productivity drivers of Kenyan coastal waters

With advances in satellite observations and high-resolution modelling, it has become possible to assess the state of ocean productivity and how it varies over the long term; especially in coastal areas where *in-situ* observations remain limited. Remotely sensed chlorophyll-*a* fluorescence (Chl-a, a proxy for phytoplankton biomass at the sea surface) and Sea Surface Temperature (SST) for the Kenyan coastal zone reveal significant variability between monsoon seasons. Spatial distributions of Chl-a and SST for climatological annual mean conditions and during the climatological months of February and August, which are considered representative of the NEM and SEM periods, are presented in Fig. 11. Notable, are the strong contrasts in SST and Chl-a between the monsoon seasons with this contrast only poorly represented within the mean annual SST and Chl-a fields (Fig. 11). Importantly, the seasonal representations show reductions in SST and elevations in Chl-a concentrations, relative to the immediate surrounding waters, over the NKB region during the NEM and along much of the coastal band from Tanzania to Kenya during the SEM. This reduction in SST and increase in Chl-a is indicative of seasonally enhanced productivity processes driven by upwelling of cool, nutrient rich waters. Few studies however, have investigated upwelling in Kenyan coastal waters with Johnson et al. (1982), Smith (1982) and Bakun et al. (1998) indicating the presence of upwelling over the NKB during the NEM. Factors causing this upwelling include current-bathymetry interactions (Johnson et al., 1982) and prevailing wind fields (Bakun et al., 1998). The importance of the NEM winds on upwelling over the NKB was further confirmed by Varela et al. (2015). However, recent work by Jacobs et al. (2020a), also highlights the importance of the position of the SC and EACC confluence zone for initiating upwelling over the NKB.

Whilst productivity along the Kenyan coast appears less intense during the SEM than during the NEM surface Chl-a values are still enhanced compared to the offshore zone (Fig. 11e and f). According to Jebri et al. (2020), this enhanced productivity during the SEM results from acceleration of the EACC by the southerly SEM winds which in turn induces dynamic uplift upwelling and enhanced westward advection of nutrient rich waters from northern Madagascar towards the East African coast. Furthermore, an additional mechanism contributing to enhanced primary productivity during the SEM was proposed by Bakun et al. (1998) who found evidence of enhanced vertical mixing based upon an analysis of the wind speed cube index.

Though riverine inputs are suspected as being an important source of dissolved nutrients for productivity over the NKB the evidence remains equivocal. The Tana River, Kenya's largest, discharges close to the NKB and outflow is highest during the intermonsoon periods (i.e. March–April and October–November) (McClanahan, 1988). This outflow has been observed to promote elevated phytoplankton biomass and high biological productivity in near-shore waters (Munga et al., 2012, 2014; Mutia et al., pers. comm.) but indications of an influence on the outer NKB region appear unlikely (Mutia et al. pers comm.). The Tana river also discharges about 6.8 million tons of sediment annually (Kitheka et al., 2005), which, based on studies elsewhere (e.g. Nixon 1981; Farias 2003), are likely to act as a source of nutrients to the overlying water column particularly following periodic perturbations of shallow unconsolidated sediments though this has yet to be directly observed for the NKB.

The persistent strong flows and stratified nature of the NKB environment also provide ideal conditions for internal hydraulic control, which promotes opportunities for further mixing over steep or rapidly changing topography particularly from internal lee waves (Vlasenko et al., 2013; Hosegood et al., 2019) and hydraulic jumps (Palmer et al., 2013; Nash and Moum, 2001). Internal wave generation and hydraulic jumps over shelf sea banks have been shown to produce sufficient mixing to produce vertical flux of nutrients that promote enhanced local primary productivity (Sharples et al., 2009) and influence fish distribution and behaviour relative to the timing of internal wave driven mixing (Embling et al., 2013).

### 6.2. Monsoonal influence on the NKB fishery

The major commercial fish stocks include pelagic and demersal species. Pelagic species include Clupeidae, Scombridae, Carangidae, Mullidae and Leiognathidae while dermersal fishes include Lujanidae, Lethrinidae, Sphyraenidae, Pomadasyidae, Elasmobranchs, Rays and Skates (Darracott, 1977; Nzioka, 1979; Birkett, 1979; Kimani et al., 2018). Temperature is the dominant control on fish distribution patterns in the Indian Ocean (Cohen, 1973) thus local oceanographic conditions influence the spawning behavior of many fish in Kenyan coastal waters (Nzioka, 1979; Ochumba, 1983; Kaunda-Arara, 2009; Mwaluma, 2011). Fish availability and breeding activity are normally linked to biological productivity (Nzioka, 1979; McClanahan, 1988). For some of the major commercial species however, spawning is not restricted to a specific time period and many species may be aseasonal breeders (McClanahan, 1988) while others breed only during the intermonsoon period (Nzioka, 1982). Most studies typically show that reproduction is highest during the NEM for both pelagic and demersal fishes (e.g. McClanahan, 1988). In nearshore coastal waters calm conditions during the NEM season likely provide optimum conditions of food and temperature, which ensures greater survival of larvae (Kaunda et al., 2009). In support, Mwaluma (2011) found fish larval abundances to be strongly influenced by the monsoon seasons with the highest growth rates of larvae and juveniles during the NEM when sea surface temperatures and zooplankton abundances were highest. Lowest growth rates were observed between May and July during the SEM season when temperatures were lowest. Temperature and zooplankton abundance were identified as being the most important biophysical parameters to influence larval abundance (Mwaluma 2011).

Spawning habits may also be influenced by the NKB environment. Spawning of *T. albacares* (yellow fin tuna) was reported between June and December within inshore coastal waters, with large shoals of very small tuna reported in February during the NEM (Darracott, 1977). In contrast, along the east coast of Madagascar *T. alalunga* (Albacore tuna) and *K. pelamis* (Skipjack) spawn later between November and January (Grandea et al., 2014; Dhurmeea et al., 2016), whilst between north Madagascar and the equator spawning by *K. pelamis* and *T. albacares* has been reported between November and May (Conrad and Richards, 1982). Other fish species including the sardines *Sardinella albella* and *S. gibbosa* have been reported to spawn in September/October (Okera 1973).

The spawning patterns of demersal fish are also variable. Nzioka (1979) observed spawning between January–March (NEM to on-set of the intermonsoon) and August–November (end of SEM to intermonsoon) for several demersal fish species (Lutjanidae, Lethrinidae, Mullidae, Scaridae and Serranidae) around the NKB. Darracot (1977) meanwhile found the spawning period for the multispecies demersal stock generally began in August/September continuing through to February with fish recovering in March/May.

As well as influencing the spawning behavior of key fish species there is also a pronounced influence of the monsoon on fish catch. Generally, there is reduced artisanal fishing effort, perhaps by as much as a third, during the SEM due to stronger winds and poorer conditions at sea

(Hoorweg et al., 2009; Onyango et al., 2021) despite evidence for larger catches at this time. Industrial longline fishing activity generally reports higher cumulative catches during the SEM months between April and June (777 ± 71 kg/1000 hooks) compared to the NEM months (300–400 kg/1000 hooks) (Kimani et al., 2018). Among the sardines (Clupeidae) the round Herring *Etremeus micropus* is known to produce large catches (e.g. 152–244 kg/h) during the SEM (Birket, 1977). Indian mackerel (*Rastrelliger kanagurta*) also occasionally yields 50 kg/h offshore (Ochumba 1983). Herring species important in the pelagic fishery include *Herklotsichthys* sp., *Sardinella* sp. *Hilsa* sp. and *Pellona* sp. All are neritic and fished mainly in response to the rainy season and the NEM (Ochumba, 1983). Notably, *Sardinella longiceps* thrives in areas of upwelling and can be a useful indicator of biologically rich waters (Losse, 1968; Okera, 1973; Marsac, 2013). Somewhat fortuitously, in July 2020 a large sardine run occurred in Lamu (Fig. 12), comparable to the major sardine run that occurs off the East Coast of South Africa from May to June (O'Donoghue et al., 2010; van der Lingen et al., 2010) suggesting that large sardine catches may also be possible during the SEM.

### 6.3. Circulation connectivity, larval dispersal and recruitment

Larval dispersal pathways are important for annual recruitment rates but also because of the uncertainty over how climate change may alter dispersal pathways. The WIO exhibits some of the strongest circulation connectivity in the world (Popova et al., 2019), and this plays a crucial role in determining the connectivity and retention characteristics of Kenya's coastal zone. For example, East African fisheries have a relatively low yield compared to what one might expect given high production rates for oceanic tuna, whilst short retention timescales in coastal habitats are believed to play in important role in limiting fisheries catches (Bakun et al., 1998). Bakun et al. (1998) hypothesized a triad of conditions that are necessary for fisheries to thrive: i) enrichment (of nutrients, for example from strong upwelling systems), ii) concentration (e.g. convergence and frontal structures), and iii) retention (of larvae). The third part of this triad is controlled by circulation connectivity.

Lagrangian particle-tracking model experiments, analogous to those described in Popova et al. (2019), reveal little retention of waters in the Kenyan coastal zone. Fig. 13 shows the downstream connectivity pathways from the Kenyan coastal zone for all Januaries (representing the NEM) and Julys (representing the SEM) for the 2000–2009 period. The impact of the reversal of the SC is apparent, with northward trajectories and rapid advection via the EACC/SC dominating in July, whereas particles are advected out to sea in January. In both monsoon seasons retention on the Kenyan shelf is low with even particles advected northwards onto the Somalian shelf in July rapidly lost to the open ocean after ~10 days. The Kenyan shelf cannot therefore be considered as self-seeding.

In addition to the downstream connectivity assessment it is also possible to assess how Kenyan waters are connected upstream and how larval dispersal seeds Kenyan waters (see Popova et al., 2019 for details). Tracking model particles backwards in time to find their origins for January and July reveals rather different connections during the different monsoon periods (Fig. 14). In January during the NEM (Fig. 14a), particle trajectories reaching the southern third of the Kenyan coast can be traced back via the EACC and North East Madagascar Current (NEMC) to the tip of Madagascar and in some cases to the Mozambique Chanel. This contrasts with the northern third of the Kenyan coastal zone (Fig. 14c) which shows that particles originate in Somalian waters, with connectivity to the EACC/NEMC significantly reduced. The middle third of the Kenyan coastal zone (Fig. 14b) shows an intermediate picture with particle trajectories originating from both

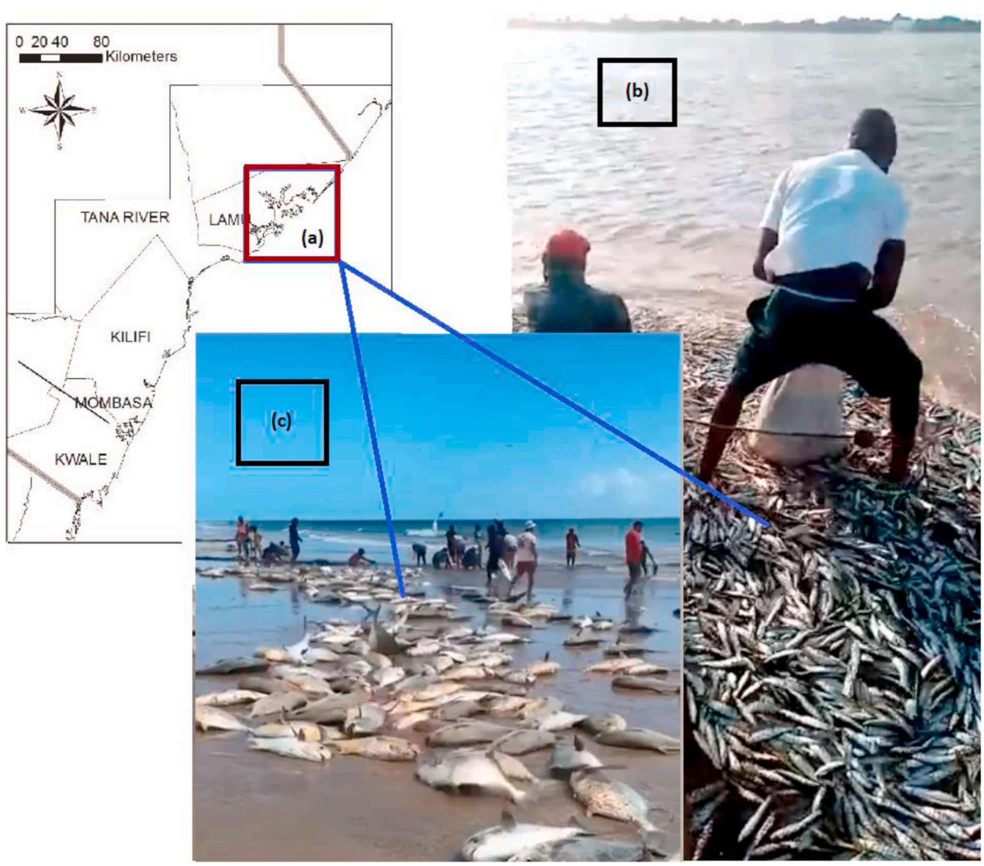


**Fig. 12.** A sardine run event in July 2020 experienced at Lamu during the South East Monsoon; a) Lamu area; lies within the North Kenya Bank; b) small pelagic fish beached at Lamu c) predator fish beached alongside small pelagic at Lamu.

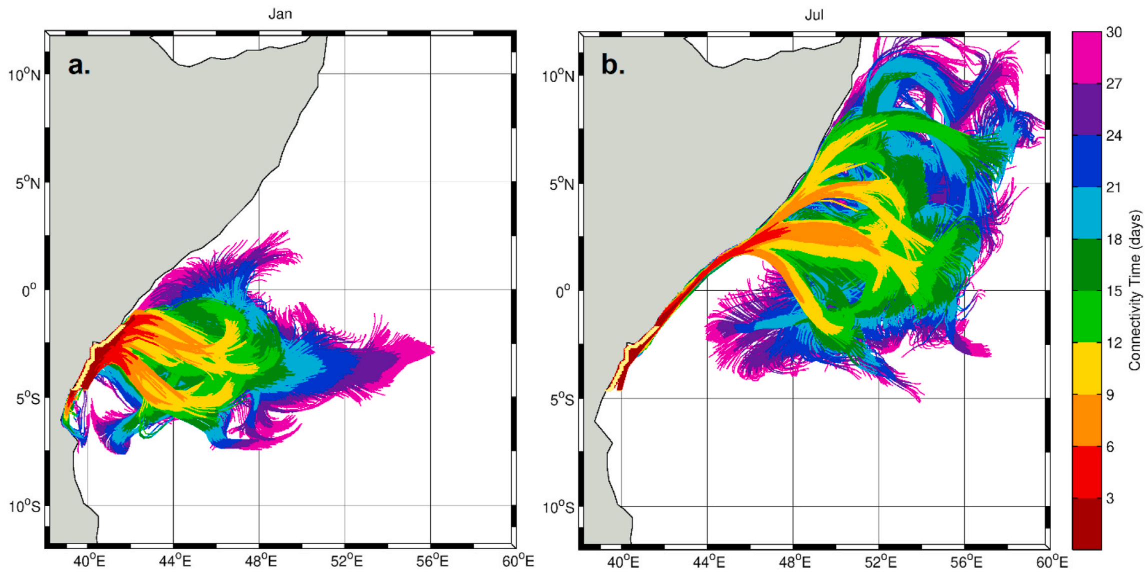


**Fig. 13.** FORWARD tracked Lagrangian experiments from Kenyan coastal zone to their downstream locales in **a.** January and **b.** July 2000–09. Particle release locations are indicated by the pale yellow strip. Colours denote connectivity timescale: e.g. it takes a virtual particle 9 days to get from its release location to the end of the orange part of the trajectory. Details of model methodology presented in Popova et al. (2019). Lagrangian particle tracking model results are available from the Zenodo repository at https://zenodo.org/search?page=1&size=20&q=4580830%20. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

southern and northern source regions. Results for July, representing the SEM (Fig. 14d–f), indicate particles reaching all parts of the Kenyan coastal zone are exclusively sourced from the south via the EACC and NEMC. Such results demonstrate that upstream connectivity between the Kenyan coastal zone and Somalian waters is limited to just the northern part of the Kenyan coastline and only during the NEM season when the Somali upwelling is not active (de Castro et al., 2016).

## 7. Climate change impacts on Kenyan marine ecosystems and fisheries

Climate change is expected to impact marine ecosystems and fishing industries in multiple and complex ways and its onset is expected (and already observed) to be heterogeneous across the oceans. Thus, climate-proofing fisheries policies is a challenging task that requires information on both long-term projections of the key climate change stressors and near-term impacts, which would allow business operational decisions to be made. The longer term projections of the large-scale stressors for the tropical Indian Ocean that are likely to impact Kenyan waters are relatively well reported (Parvathi et al., 2017; Popova et al., 2016; Jacobs et al., 2021) and include large-scale warming (reaching up to 5 °C by the end of the century under the high emission RCP8.5 scenario), strengthening of stratification and weakening of upwelling leading to the reduction of surface and near surface nutrients and associated decline of primary production (mostly during the NEM); continuing ocean acidification and deoxygenation, all of which are damaging for marine ecosystems. However, more regionally specific dynamical changes and how they will evolve over the course of the next few decades are still outside of predictive modelling capabilities. In particular, how the position and the strength of the SC-EACC confluence zone, which drives the NKB shelf break upwelling and impacts fish catches (Jacobs et al., 2020a,b), would evolve under the accelerating impact of global warming is one of the key factors that needs to be understood to ensure that the fisheries policies developed for the NKB and wider Kenyan EEZ are climate-proof. This upwelling feature presents a particular challenge for climate impact assessments, as it is known to be highly variable at interannual timescales, changing its strength, location and extent; and in an extreme case (during the 1997-98 El Niño) migrating into the EEZ of neighboring Tanzania (Jacobs et al., 2020a). High resolution climate change projections (Jacobs et al., 2021) suggest strengthening of the SC and EACC during the SEM and weakening during the NEM, with the resulting impact on the regional upwelling systems, including the NKB upwelling, remaining uncertain.

Another challenging and highly dynamic climate impact stressor that Kenyan fisheries will be facing as early as the decade 2020-30 is marine heatwaves (MHW, Fig. 15). Defined more broadly than coral bleaching indices widely used in the WIO (Hobday et al., 2018; Obura, 2005), MHW have already caused devastating impacts on marine ecosystems in some regions (Wernberg et al., 2016; Hughes et al., 2017; Sanford et al., 2019). High resolution ocean projections conducted under the high emission RCP8.5 scenario (Jacobs et al., 2021) in line with other modelling studies (Frolicher et al., 2018; Oliver et al., 2019) suggest that MHW will increase their frequency, intensity and duration over the next two decades in such a way that by ~2040 whole years may be considered as a single continuous heatwave. However, the onset of such heatwaves will likely not be homogeneous across the region, and in the vicinity of the NKB upwelling the onset of MHW is projected to be delayed by 10 or even 15 years relative to the surrounding region. Thus, upwelling of cooler waters in the vicinity of the NKB may act as a refuge for some of the fish species of the region.

In addition to driving opposing changes in surface currents, changes in the monsoonal winds are also projected to impact regional rainfall. The region has already experienced a decline in rainfall during the April–May inter-monsoon long-rainy season (William and Funk, 2011). Other studies indicate a continued reduction in rainfall during the long-rains while also suggesting that rainfall may increase during the NEM season (Monerie et al., 2012; Lee and Wang, 2014), which could increase the likelihood of drought and flooding respectively. Such changes are important for the coastal region where changes in riverine input to the coastal zone could affect local nutrient concentrations and productivity (Shaghude pers. comm). In Ungwana Bay, where the Tana River mouth is located, increased rainfall has been linked to elevated chlorophyll-*a* concentrations (Mutia et al. pers comm.).

The key to understanding how climate change will impact this complex socio-ecological system lies in analyzing high quality fisheries data in the context of seasonal and interannual dynamics of the key driving factors (Fig. 1). More specifically understanding the roles of seasonally reversing monsoon currents and associated upwelling

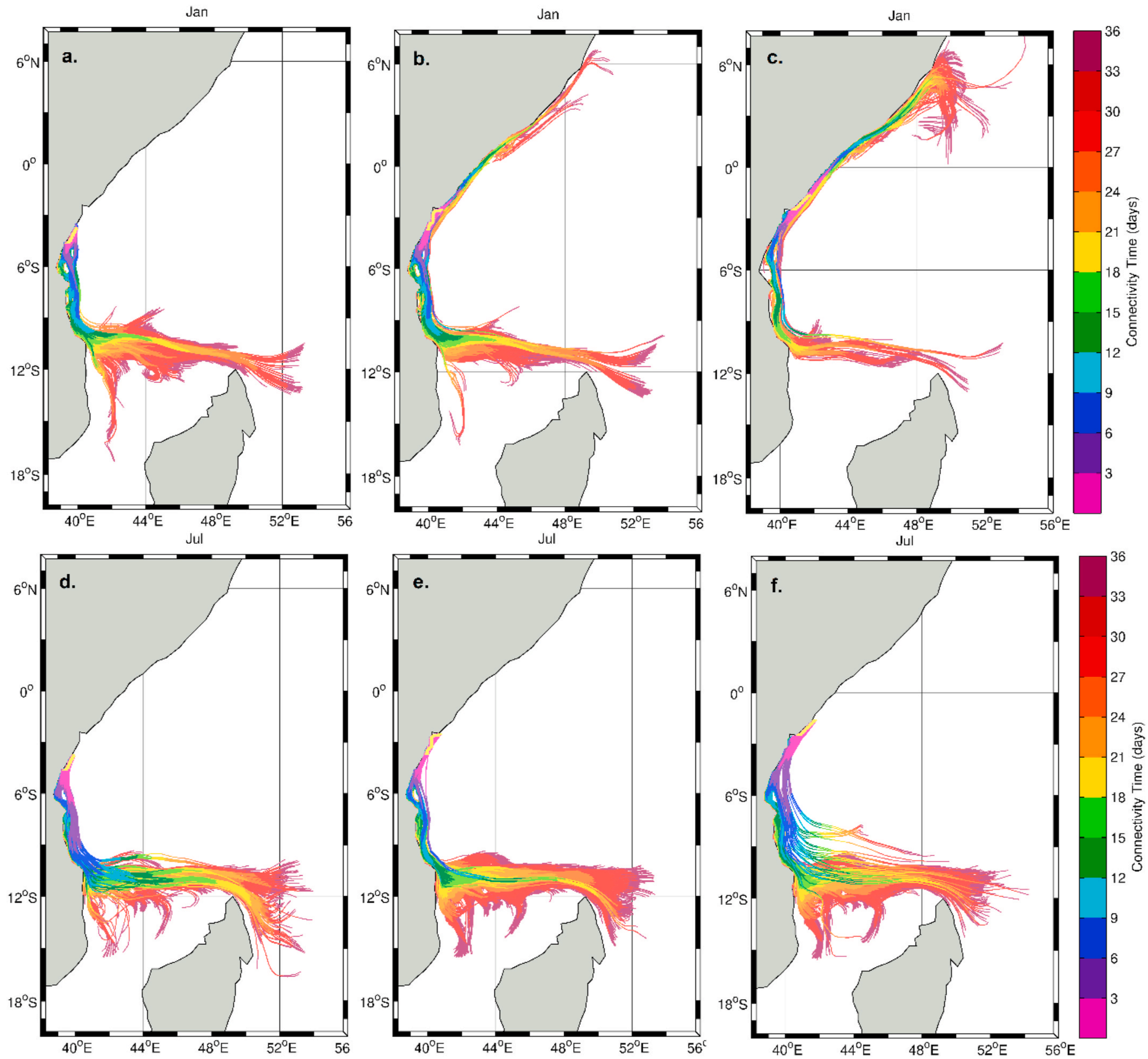


**Fig. 14.** BACKWARD tracked Lagrangian trajectories from the Kenyan coastal zone to their sources. In this case, the coastal zone has been split into southern (**a** and **d**), middle (**b** and **e**) and northern (**c** and **f**) sections, for January (**a-c**) and July (**d-f**) 2005–2014. Note that Somali waters are only connected to the northern parts of the Kenyan coastal zone, and only in January: i.e. the Somalia-Kenya connectivity does not occur during the Somali upwelling. Details of model methodology presented in Popova et al. (2019). Lagrangian particle tracking model results are available the Zenodo repository at https://zenodo.org/search?page=1&size=20&q=4580674.

systems, as well as understanding the causes of variability within the NKB upwelling remain central objectives for future work. However, while remote sensing information presents a cost effective and reliable dataset to analyse the dynamics of these waters under accelerating climate change impacts, a major and urgent investment is needed in improving fisheries records in the region to facilitate climate change adaptation and risk management in existing and, especially, emerging fisheries.

## 8. Key knowledge gaps

The NKB have long been considered an important emerging fishery with the potential to spur economic growth for local fishing communities (Wickstead, 1961; Maina, 2012). Under Blue Economy initiatives to increase exploitation of marine resources however there is increased urgency to formulate effective management plans for the NKB to sustain those resources. One of the key difficulties facing this endeavor is that expanding the fishery offshore essentially equates to creating a new fishery without a previous history of coping with strong seasonal and interannual variability of the key oceanographic features which control recruitment and retention of the key commercial species. Such a previous history would have built up skills and approaches to cope with the strong environmental variability typical of the NKB region. Without such skills, a risk-based management approach becomes essential. Effective resource utilization also requires increased research on the spatial and temporal distribution of the pelagic fishery as well as undertaking more fundamental environmental research. Currently, there exists only scant information on the ecological status and drivers of this

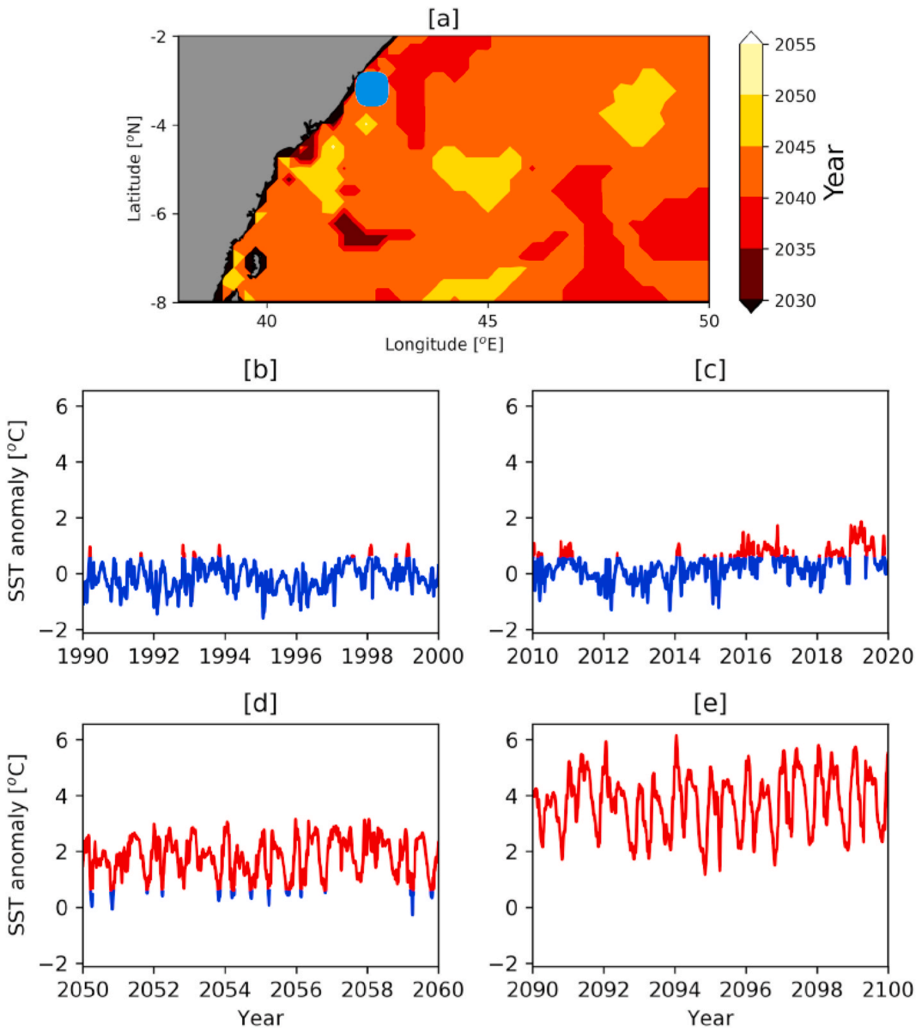


**Fig. 15.** Marine Heat Wave (MHW) projected impacts for the offshore Kenyan waters including a) Model projections of when year-long MHWs will appear in offshore Kenyan waters, b-e) Daily SST anomalies for a single point in the Kenyan EEZ (3°S, 42°E; indicated by blue circle in panel a) for the periods b) 1990-99, c) 2010–19, d) 2050-59 and e) 2090-99. Red lines in panels b–e indicate when a MHW is projected to occur. Details of the model and the model runs are reported in Jacobs et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

emerging fishery resource and limited management structures to adequately manage the fishery going forward (Maina 2012; Kimani et al., 2018). Well managed fisheries also present opportunities for achieving national sustainable development goals (SDG) including poverty eradication (SDG 1), wealth creation and economic growth (SDG 8) and sustainable use of marine resources (SDG14) (UN, 2015). Moreover, this huge potential is a critical vehicle for the achievement of the Kenya Vision 2030 development plan (Aloo, 2009), which is implemented through five-year Medium-Term Plans (MTPs), currently implementing MTP 2018–2022, and within which are embedded the sustainable development goals. In seeking to meet these challenges however several key knowledge gaps must be overcome.

### 8.1. Critical ocean drivers influencing fisheries

The NKB are influenced by multiple upwelling mechanisms that have been shown to be highly variable in time and space (Jacobs et al., 2020b, 2021; Jebri et al., 2020). Only recently was it shown that the confluence zone between the EACC and SC, which is critical to seasonal upwelling at the NKB, can migrate southwards into the Tanzanian EEZ under the influence of particularly strong El Nino events (Jacobs et al., 2020a). Such variability in mechanisms that are critical controls on local productivity has the potential for significant socio-economic impact at a national level yet study of the impact on fisheries has barely begun. It is, therefore, imperative to equip the emergent fishery of the NKB with the appropriate information (e.g. Fig. 1) and solutions to adapt to relatively short-term changes impacting functioning of the system from seasonal to interannual timescales.

### 8.2. Biomass, species composition and exploitation rates

The North Kenya Banks has a rich demersal fishery that requires improved monitoring and assessment to better understand fish stocks, reproductive cycles, and the pressures that current fishing activity places upon them. Infrequent stock assessments, uncertainties over historic exploitation rates and limited information about other fisheries (e.g. pelagic or deep-water fisheries) all conspire to prevent establishment of reliable baselines which remain a key step towards development of a fishery management plan specifically for the NKB region.

### 8.3. Bathymetry and the role of canyons

The NKB ecosystem comprises several ridges of deep-sea canyons with a rich fishery biomass at the crescent. The unique topographic formations combined with fast flowing boundary currents have a dramatic influence on the physical processes in the area impacting the vertical supply of nutrients which sustain primary production. Seamounts and accreted sediments are also assumed to play a role in many biogeochemical processes within the NKB region yet the benthic environment is poorly studied and whilst a few studies have examined bathymetric influences on the local circulation, these are now several decades old and reassessment is urgently needed.

### 8.4. Terrestrial and riverine inputs

The Tana River discharges about 7 M tons of sediment and >4000 M $m^3$ of freshwater annually. The extent and impacts of fresh water, sediment and nutrient input on the wider NKB ecosystem are largely unknown but widely inferred within the literature. The receiving waters of Ungwana Bay contain rich biodiversity and host important fisheries. Sediments are derived from agriculturally rich catchment areas and are assumed to be rich in nutrients and organic matter. Identifying transport pathways and quantifying associated nutrient fluxes and impacts on marine productivity are critical first steps towards understanding the role that terrestrial inputs may have on the NKB ecosystem.

### 8.5. Impact of climate change on productivity

Although the general long-term (centennial-scale) trends of the key climatic stressors in the tropics (such as ocean warming, increased stratification and reduction in primary production) are becoming clear from the work of the Intergovernmental Panel on Climate Change (IPCC, 2018), very few regional management or policy decisions are influenced by change over such long temporal scales. The emergent fishery of the NKB will have to cope with, and make operational decisions based on, shorter-term environmental fluctuations while adapting to the longer-term background trends of anthropogenic climate change. In particular, the seasonally varying dynamics of the monsoon winds coupled with the irregular periodicity and influence of El-Niño and the Indian Ocean Dipole provides for dramatic inter-annual variability in regional upwelling and subsequently poor predictability of productivity of the NKB ecosystem. Long-term climatic trends indicating reduced productivity imply less productive fisheries, but how less productive and when this reduced productivity may become problematic for coastal communities are not well known. In addition, high-resolution, multi-decadal regional forecasts that permit strategic planning and sustainable management of national fishing efforts are highly desirable.

## 9. Recommendations

The socio-economic potential of Kenya's marine and coastal fisheries has not been fully realized. A contributing factor is insufficient research of offshore fisheries via a lack of investment that has further exacerbated poorly developed marine management structures and supporting infrastructure. Whilst Kenya's marine fishery resource is largely dependent on monsoonal variability intricately tied to the accelerating impact of anthropogenic climate change, successful development and future management of the NKB fishery will require development of climate change adaptation measures. To facilitate this, robust oceanographic and fisheries studies are urgently required to enable development of sustainable marine and fisheries management measures and to quantify the impacts of increasing human pressures on this natural resource.

The high socio-economic potential of the North Kenya Banks has been recognized at the national level, notably in President Kenyatta's address during Africa's first Sustainable Blue Economy conference in Nairobi in 2018. The President noted that Kenya's Blue Economy could easily contribute three times its present share to the gross domestic product, create jobs and bring prosperity to millions of Kenyans. To facilitate this growth, investment is urgently required to support regional and local marine and fisheries management of the NKB, which itself requires immediate efforts to increase understanding of the current state and functioning of the NKB ecosystem. Sustainable management of the NKB requires adoption of a marine management framework that follows a standards-based approach to address the identified gaps in current knowledge, to constrain baseline conditions against which on-going change and increasing pressures can be assessed and to better enable forecasting of the impact of current human pressures on future environmental conditions. Given the economic potential of this resource, securing and maintaining a healthy ecosystem is dependent on effective stakeholder engagement and communication with coastal communities. A clear communication strategy is also required that is sympathetic to socioeconomic, cultural and demographic status across communities and stakeholders to ensure optimal engagement.

## Author contributions

JK was the lead author and with SP responsible for coordination of all contributions. Section 2 was coordinated by JK (with contributions from SFWT, MJR, EK, EM, SP), Section 3 was coordinated by SP (with contributions from MP, JW, JM, JK), Section 4 coordinated by FJ (with contributions by SK, EP, JM, JK), section 5 coordinated by ZJ (with contributions by FJ, EP), and section 6-7 coordinated by JK (with contributions from SP, MP, JW, ZJ, FJ). All authors made important contributions to the contents of the paper. All authors revised and approved the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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