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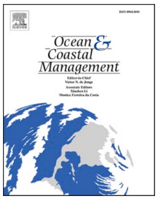

Productivity driven by Tana river discharge is spatially limited in Kenyan coastal waters

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ABSTRACT

The Tana River is the longest river system in Kenya (~1000 km) and contributes ~ 50% of the total river discharge to Kenyan coastal waters. The river discharges significant amounts of nutrients and sediments, reaching ~24,000 tons per day during the rainy season (March–April), into Ungwana Bay (North Kenya Banks). The bay is an important habitat for high-value *Panaeid* prawn species which sustain important small-scale fisheries, semi-industrial bottom trawl prawn fisheries, and is the livelihood mainstay in the surrounding counties. In this study we analysed >20 years of satellite-derived chlorophyll-a observations (Chl-a, an index of phytoplankton biomass), along with *in situ* river discharge and rainfall data, to investigate if the Tana River discharge is a major driver of local phytoplankton biomass in Ungwana Bay and for the neighbouring Kenyan shelf. We find that during the rainy inter-monsoon (March–April), a significant positive relationship ($r = 0.63$, $p < 0.0001$) exists between river discharge and phytoplankton biomass. There is a clear time-lag between rainfall, river discharge (1-month lag) and local chlorophyll biomass (2-months lag after discharge). Unlike offshore waters which exhibit bi-annual chl-a peaks (0.22 mg m^{-3} in February, and 0.223 mg m^{-3} in August/September), Ungwana Bay displays a single peak per annum in July (2.51 mg m^{-3}), with indications that river discharge sustains phytoplankton biomass for several months. Satellite-derived observations and Lagrangian tracking simulations indicate that higher Chl-a concentrations remain locally within the bay, rather than influencing the broader open waters of the North Kenya Banks that are mainly impacted by the wider oceanic circulation.

1. Introduction

1.1. Riverine discharge and coastal environments

Global fisheries production has been shown to be a function of nutrient-enrichment processes including vertical mixing, coastal upwelling, tidal mixing, land-based runoff and freshwater input (Benson, 1981; Gillson, 2011). Riverine outflow has an important influence on coastal ecosystems mainly because of the temporal variability of the incoming river loads (Erzini, 2005; Halliday et al., 2008;

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González-Ortegón et al., 2010; Munga et al., 2012). According to Drinkwater and Frank (1994), the freshwater outflow impacts circulation patterns and alters existing physicochemical parameters including nutrients which ultimately influence primary production (Ndungu, 2009). Subsequently, these parameters affect species migration patterns, spawning habitat, species diversity, water quality and distribution and production of lower trophic levels. In response, the abundance and distribution of many marine fish and invertebrate stocks exhibit large temporal fluctuations (Bakun et al., 1982; Hamilton, 1987; Gillson, 2011). For example, Sutcliffe, (1973) and Galindo-Bect et al. (2000) have demonstrated positive correlations between freshwater discharge and the spatio-temporal variation of fish catch. Of course, the seasonal variations of these processes are also significantly influenced by the broader climate regime (McClanahan, 1988).

Studies on river plumes using remote sensing methods have been carried out in various parts of the world. For example, the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) on board the 2nd generation METEOSAT has been used to map the total suspended sediments of the Sabaki River plume (Ndungu, 2009), while suspended matter from the Mississippi River plume has been studied using the Moderate Resolution Imaging Spectroradiometers (MODIS) on Aqua (Shi and Wang, 2009) and Terra-1 (Walker et al., 2005). Moreover, remote sensing data coupled with *in situ* data, and more recently modelled data, have been valuable for quantifying the influence of river plumes on seagrass and coral reef habitat in the Great Barrier Reef (Devlin et al., 2015). SeaWiFS ocean colour measurements have also been used to investigate inter-annual, monthly, and weekly variations in Chlorophyll-a (Chl-a) on the Louisiana shelf and to assess relationships with river discharge, nitrate load, and hypoxia (Walker and Rabalais, 2006). Massoti et al. (2018) utilized *in situ* hydro-chemical data and MODIS - SeaWiFS ocean colour observations as a proxy of river plumes and phytoplankton biomass from 2000 to 2014, and documented the temporal co-variability of river discharge, plume area, nitrate and phosphate export and Chl-a in the coastal waters off Central Chile.

1.2. *Kenya rainfall and the Tana River*

Climate variation in the Western Indian Ocean (WIO) is controlled by the large-scale monsoon winds, with their characteristic seasonal reversal from the Northeast to the Southeast. They define four seasons over the region: the northeast monsoon (NEM) from December to February, the Southeast monsoon (SEM) from May to September, and two inter-monsoon periods (Schott and McCreary, 2001; Jebri et al., 2020). The first inter-monsoon period presents the so-called long rains from March to April (occasionally lasting to mid-May), while the second inter-monsoon season is characterized by short rains between October and November; due to the north-south migration of the Intertropical Convergence Zone (ITCZ) over the region twice a year (Okoola, 1999). During the long rainy season, highest river flows are experienced while low flows are experienced during the dry seasons (June to September and January to February). (McClanahan, 1988; Tamooh et al., 2012; Njogu and Kitheka, 2017).

The Tana River is the largest river in Kenya and drains into the WIO through the expansive Ungwana Bay at Kipini in Lamu County (Fig. 1), which lies between latitudes 3.5°S and 2.5°S and longitudes 40.0°E and 41.0°E on a widening continental shelf with expansive trawl grounds (Munga et al., 2012). Ungwana Bay is a complex network of mangrove swamps, tidal creeks (estuaries) and floodplains. Upstream, the Tana River passes through the mountainous areas of the Aberdare ranges, by Mount Kenya and the Nyambene Hills of central Kenya, and flows through semiarid flood plains, ending up at the large delta at Ungwana Bay (Langat et al., 2017). Draining a large catchment area of ~120,000 km^2 and stretching over 1000 km from the high rainfall, heavily cultivated central Kenyan highlands to the WIO, the Tana River contributes approximately 50% of Kenya's total river discharge (Kitheka et al., 2005; Tamooh et al., 2012, 2014).

Fig. 1. True colour map showing the location of the Tana River and its outflow into Ungwana Bay (north coast of Kenya). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

A series of hydroelectric power (HEP) dams have been constructed along the Tana River including the Kindaruma Dam (1968), the Kamburu Dam (1975), the Gitaru Dam (1978), the Masinga Dam (1981), and the Kiambere Dam (1988) (Adams and Hughes, 1986; Galadin et al., 2006; Langat et al., 2017). These have modified the flow of the river including its annual sediment load (Kitheka et al., 2005). According to Kitheka et al. (2005) and Kitheka and Mavuti, (2016), the Tana River discharges between 60 and 750 $m^3 s^{-1}$. Maximum discharge occurs in May and coincides with the long rains (March to May). Another, smaller, peak occurs in November and coincides with the short rains (October to December). The river's volume reduces as it flows into the lower Tana basin due to the damming in the upper Tana basin (Kitheka et al., 2005; Okuku et al., 2018). Consequently, sediment loads have shown a distinct reduction over time with a clear difference before (1968–1988) and after damming. Between 1950 and 1957, before the construction of the Seven Forks Hydroelectric dams, the sediment load of the Tana was as high as 8.7×10^6 ton yr^{-1} (Ongwenyi, 1979). After damming, Kitheka et al. (2005) reported sediment loads of 6.8×10^6 ton yr^{-1} between 2002 and 2003, while Njogu and Kitheka (2017) recorded sediment loads of 7.1×10^6 ton yr^{-1} from 2010 to 2012.

1.3. *Ungwana Bay fisheries*

The significance of the Tana River for local coastal ecosystems and the even wider shelf, has long been advocated but not proven. In spite of being the longest river in Kenya and releasing around 50% of Kenya's total river discharge, the impact of freshwater, nutrient and sediment inputs to Northern Kenyan coastal waters remain poorly understood. In fact, it is largely because the spatial extent of any impacts are themselves unclear that anecdotal statements persist in the literature regarding the significance of the Tana River discharge for productivity over the NKB. As the main receiving area, Ungwana Bay is expected to be strongly impacted by the Tana River discharge, with localized disturbances to salinity and nutrient fields and reductions in water column optical clarity due to increased turbidity. Coral distribution maps along the Kenyan coast indicate a general absence of coral reefs in this region (UNEP-WCMC, 2010), suggesting environmental conditions may be less than optimal. Ungwana Bay is also a biodiversity-rich area that hosts a nationally significant prawn fishery (KMFRI, 2018). Studies have shown that prawn abundance, distribution and even species composition are strongly linked to the Tana River outflow (Ruwa et al., 2001; KMFRI, 2007; Munga et al., 2013, 2016). The prawn fishery remains the only fishery in Kenya to be covered with a management plan, implemented in response to resource conflicts and high bycatch (KMFRI, 2018). Part of the management plan includes a seasonal closure of the fishery between November and March (NEM) when spawning of penaeid prawns takes place (Munga et al., 2013). Resumption of fishing in April coincides with increased regional rainfall yet there is little information available on the link between increased river discharge, following the seasonal rainfall, and coastal productivity. As the timing and occurrence of enhanced primary production and/or input of organic matter via sedimentary pathways may be significant for resident prawn populations, understanding the impact of the Tana River remains key to supporting and developing existing management plans. Furthermore, delineating the extent of the impact of Tana river nutrient input on the productivity of the wider shelf is important for the development of the management plans for the offshore fisheries, and in particular an emerging NKB fishery (Kamau et al., 2021).

The small-scale Ungwana Bay prawn fishery is a mainstay livelihood for the people within the Tana River and Kilifi Counties. This fishery provides food, employment and income besides being an important ecological and biodiversity hotspot for fish and birds (Abila, 2010; Munga et al., 2016; Dzoga et al., 2019). Based on the most recent catch assessment survey data of 2013–2014, total annual landings from this fishery are ca. 363.5 ton with Ungwana Bay contributing up to 40% of the catch. With the current estimated average value for prawns of Kenya Shilling (KES) 350 per kg (US$ 3.4), this fishery generates up to KES 127 million (US$ 1.234 million) per annum nationally (Kromkamp et al., 1995; Fulanda, 2003; Kitheka et al., 2005; Munga et al., 2012; Mkare, 2013). The estuary ecosystems along this coast support the Ungwana Bay prawn fishery, which is the only place where prawn trawling is practiced in Kenya (Fulanda, 2003; Munga et al., 2016). Little however is known on the role, if any, of the Tana River and the estuarine and mid-shelf environments and marine ecosystems.

The objective of this study was to determine the influence of the Tana River outflow on the surrounding marine waters, and in particular on phytoplankton biomass. As with similar studies, we used a combination of methods that made use of *in situ*, remote sensed and modelled data to explore the river's influence. These included 20 years of *in situ* rain and river discharge, satellite chlorophyll, and outputs from a numerical ocean model that was used to track particle trajectories which highlighted the flow of riverine water in the ocean.

2. Materials and methods

2.1. *Study area*

Ungwana Bay opens onto the North Kenya Banks (NKB), an expansive area approximately 45 km wide and 180 km long which represents the largest expanse of continental shelf along the East African coastline (Morgans, 1959; Johnson et al., 1982; Jacobs et al., 2020). The NKB are where the opposing Somali and East African Coastal Currents (EACC) meet during the NEM, referred to as Somali-Zanzibar Confluence Zone (SZCZ), which is characterized by upwelling and high productivity (Jacobs et al., 2020). The location of the Tana Estuary and Ungwana Bay in relation in Kenya is shown in Fig. 1.

2.2. *River discharge data collection and analysis*

The Tana River has two main sub-watersheds referred to as upper and middle, where five hydro-electric dams exist. The Water Resources Management Authority (WARMA) has been managing and collecting long-term daily river discharge data based on gauge height and rating curve since 1941 at the Garissa Gauging Station (Langat et al., 2017). This station is located ~250 km upstream of the Tana River Delta (Leauthaud et al., 2013). WARMA has also been recording the monthly total rainfall at 10 stations within the upper and middle Tana River basin (Langat et al., 2017). These records provide the only long-term rainfall data available in the region and have been used in several previous works (e.g. Tamooh et al., 2012; Geeraert et al., 2015; Langat et al., 2017). In this study monthly river discharge ($m^3 s^{-1}$) and precipitation (mm) data for the period 1997 to 2016 are used, from which monthly means (climatologies) were calculated and presented in Fig. 2. For a detailed description on the WARMA precipitation and river discharge data, see Langat et al. (2017).

2.3. *Remote sensed chlorophyll-a data collection and analysis*

Satellite chlorophyll-a observations (mg m^3) used in this study were extracted from the ESA Ocean Colour Climate Change Initiative (OC–CCI) dataset, version 3.1, available from https://esa-oceancolour-cci.org/(Sathyendranath et al., 2018). The OC-CCI data are a level 4 multi-satellite product based on observations from the MERIS, MODIS, VIIRS and SeaWiFS sensors. The dataset was created by band-shifting and bias-correcting all observations to match those from SeaWiFS, with merging the resulting individual datasets and computing per pixel uncertainty estimates. Data were provided on a daily basis for the global ocean from 1997 to 2017 at a spatial resolution of 4 km. Satellite-derived chlorophyll measurements have known limitations, particularly concerning shallow sediment rich waters. The OC-CCI product used in our study was derived using the multi-chlorophyll algorithm approach (Jackson et al., 2017; see Section 4.0 for more

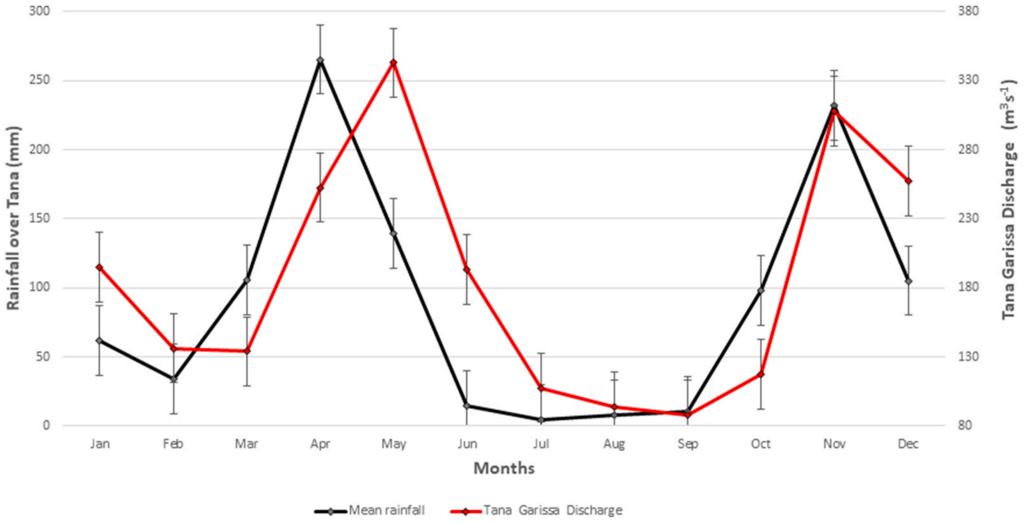

Fig. 2. Monthly climatology of *in situ* rainfall measurements from 10 WRA stations in the upper Tana River sub basin (black), and Tana River the discharge (red) measured at Garissa Gauging Station 4G01, during the period 1997–2016. Bars denote standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

details). This is currently the most complete and consistent time-series of ocean colour available (Racault et al., 2017).

Our analysis focused on monthly averages generated from the daily observations for Ungwana Bay and adjacent offshore regions (see boxes in Figs. 3 and 4). The study area involved coastal and shallow regions, where remotely-sensed chlorophyll observations are known to have limitations (IOCCG, 2000). For instance, in shallow optically-complex Case II waters, suspended materials including sediments, particulate matter, and/or dissolved organic matter, do not necessarily covary in a predictable manner with chlorophyll concentrations (IOCCG, 2000). In such environments, scattering by suspended sediments and underwater reflectance from shallow seabed regions may result in relatively high water-leaving radiance in near-infrared wavelengths, leading to over-estimation of chlorophyll concentrations. Although the OC-CCI product used a multi-chlorophyll algorithm approach (Jackson et al., 2017), the remotely-sensed ocean colour observations over the study region may still be influenced by the above factors, resulting in overestimated chlorophyll concentrations in coastal waters and/or very shallow near-shore waters (<30 m) along the East African coast.

Currently, due to the lack of adequate *in situ* chlorophyll data within Ungwana Bay*,* validation of the satellite-derived ocean colour products is not possible. Painter (2020) provides the most comprehensive and up-to-date review of available chlorophyll concentrations in the western tropical Indian ocean, confirming the lack of chlorophyll observations within Ungwana bay to assess the accuracy of satellite observations. However, past literature provides some useful information supporting the use of ocean colour remote sensing in the study area. Bouillon et al. (2007) sampled the river waters and the mangrove lagoons up to a few km offshore within Ungwana bay, during the period of maximum river discharge and chlorophyll concentrations (April 2004). The reported *in situ* chlorophyll concentrations were on average ~2 mg m^{-3} (their Figs. 3 and 4), which appear to be in line with the satellite-derived ones reported here (Fig. 3). Furthermore, Bouillon et al. (2007) reported that Particulate Organic Carbon (POC) to Chl ratio is inversely correlated with salinity, indicating that the Chlorophyll contribution to the suspended material becomes increasingly important moving from the river mouth (fresher water) to off-shore in the bay (more saline waters) (their Fig. 8). Both results support our interpretation of satellite chlorophyll concentrations within Ungwana bay, which covers tens of km off the coast. These conclusions seem to be further supported by our Fig. 4, which shows that the correlation between river discharge and chlorophyll concentration is significant everywhere within Ungwana bay except for a very narrow band near the coast (only few pixels, hence few Km off-shore). This band is where river suspended matter is expected to have the maximum impact on the quality of remotely sensed chlorophyll. Thus, this feature indicates that our results from within the bay were most likely unaffected by the impact of river suspended matter, which remains limited to waters near the shore.

2.4. Spatial correlation analysis

To assess the influence of riverine nutrient inputs on phytoplankton dynamics, a least square linear regression analysis was computed between the time series of monthly river discharge and monthly-averaged surface chlorophyll concentrations. The analysis was based on the average time series of chlorophyll concentration within the Ungwana Bay region (black box in Fig. 3). To retrieve more detailed information on the spatial extent and spatial distribution of such correlation, the individual time-series from each pixel of the OC-CCI domain was used over a large area covering Ungwana Bay and the surrounding regions (39–44°E and 4-0°S).

While the onset and early development of the phytoplankton bloom is expected to be directly influenced by the riverine nutrient intrusions (in otherwise nutrient-limited waters), its decay is likely controlled by other factors (i.e. grazing; nutrient recycling rates etc.). Because of that, we focused our correlation analysis only on datasets from January to May for each year (the period of maximum river discharge values), which defines the period of growth before the peak and subsequent decay of the main summer phytoplankton bloom.

A sensitivity analysis was performed with different time lags between the two time series. Positive correlations were found with up to a 2-month lag, but the strongest (highest) was found when no time lag was applied. This suggests that the initial phytoplankton response to riverine nutrient inputs occurs fairly quickly within a few weeks after the discharge. Only results from the immediate response (no time lag) between river discharge and chlorophyll concentrations (i.e. chlorophyll observations were correlated to river discharge observations from the same month) are presented in this study.

The analysis returned a two-dimensional distribution of the Pearson correlation coefficient, which was used to investigate the spatial patterns of chlorophyll response to riverine discharge. The associated distribution of p-values (computed based on the null hypothesis that the slope is zero, using Wald Test with t-distribution of the test statistic) were also analysed to assess the significance of the observed Pearson

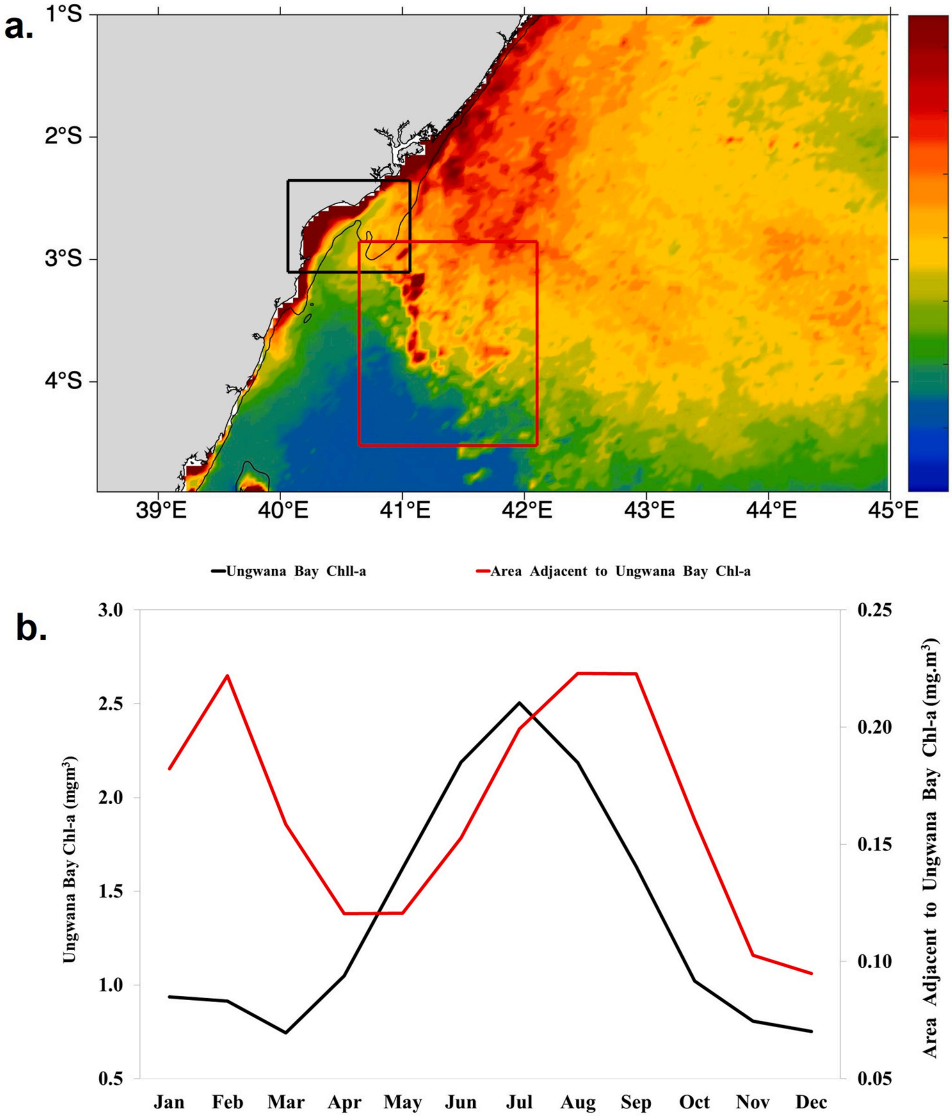

Fig. 3. (a) Map showing satellite-derived chlorophyll concentration in February 2003 (used as an example). Black line shows 200 m isobath. (b) Climatology of chlorophyll-a in Ungwana Bay (black box) and the adjacent offshore (red box) area for the period 1997–2017. Note the different scales in the y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

coefficient distribution.

2.5. Numerical modelling

Output from the Nucleus for European Modelling of the Ocean (NEMO) model (Madec, 2014) was used to perform a series of offline particle tracking experiments to investigate the seasonal and interannual variability of advective pathways from the mouth of the Tana River. A 1/12° horizontal resolution run of NEMO (ORCA0083-N006) was used. This run of NEMO is a global eddy-resolving global z-level model, with 75 depth levels and a non-linear free surface, coupled to the LIM2 ice model (Fichefet and Maqueda, 1997; Goosse and Fichefet, 1999). The model was run as a forced hindcast from 1958 to 2015, using forcing from the DRAKKAR Forcing Set (DFS 5.2), and based on ERA40 reanalysis data (Brodeau et al., 2010). This forcing includes 6-hourly winds, humidity and atmospheric temperature. Daily means are used for longwave and shortwave radiative fluxes, and monthly means are used for precipitation. Climatological data is used for riverine freshwater flux, taken from CORE2 reanalysis (Timmermann et al., 2005; Brodeau et al., 2010). The output from this run was saved as 5-day means. The 3-dimensional mean velocities (u, v, w) were used to drive the particle tracking experiments.

The Ariane particle-tracking software (Blanke and Raynaud, 1997) was used to perform offline Lagrangian experiments, with virtual particles released in the vicinity of the Tana River mouth and advected based on the NEMO model velocities. For each experiment, 2048 particles were initialized at the ocean surface over 8 model grid cells (256 particles per model grid cell, approximately 3 particles per km^2) and tracked for 20 days (see Fig. 5 for the study area). Ariane uses a bi-linear interpolation of the input velocity fields to analytically solve for particle transport within model grid cells, with particle position output at a daily frequency. Experiments were performed monthly for 15 years between years 1995 and 2009. Particle trajectories from each monsoon season were then analysed to investigate how the seasonal shift in modelled ocean currents influences oceanic advective pathways from the mouth of the Tana River.

3. Results

3.1. Rainfall and Tana River discharge

The seasonal variation of rainfall over the Upper Tana sub-basin and

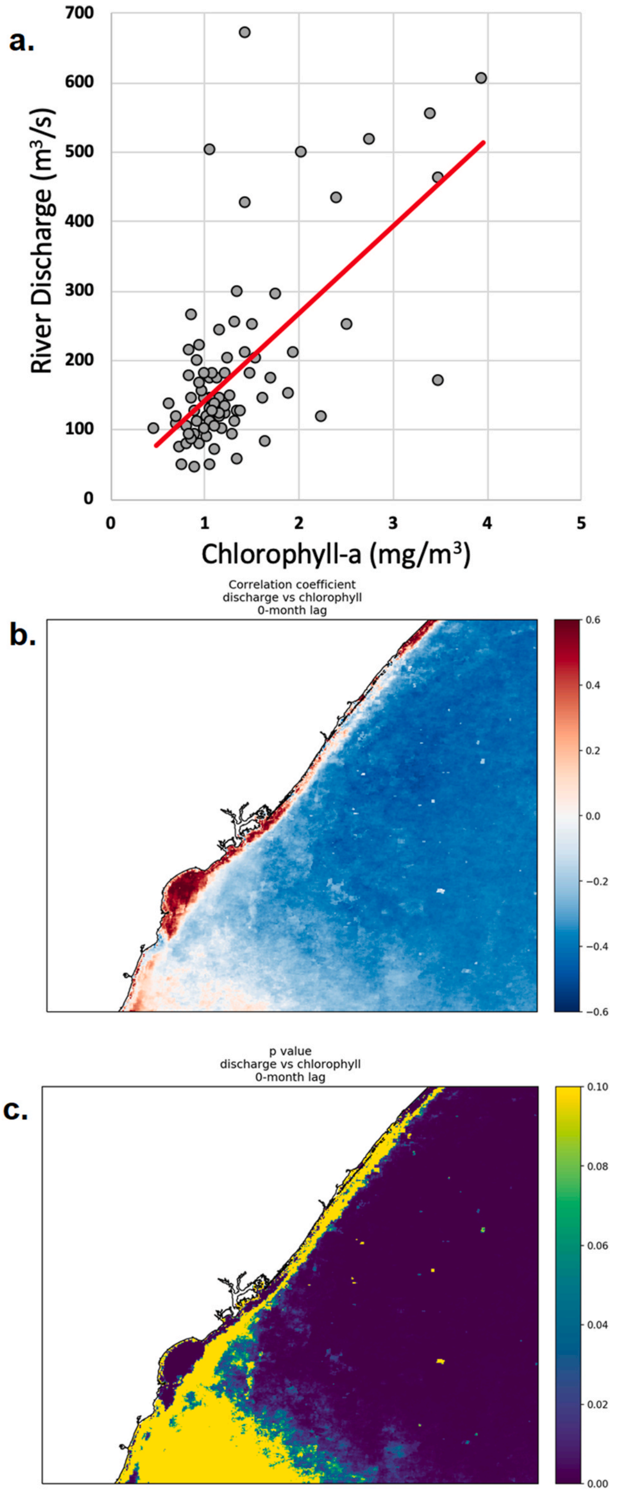

Fig. 4. (a) Scatter plot showing the correlation ($r = 0.63$, $p < 0.0001$) between monthly mean Tana River discharge and satellite-derived chlorophyll-a concentrations in the vicinity of Ungwana Bay (black box in Fig. 3a) for each January–May period between 1999 and 2016. (b) Map showing the Pearson correlation between chlorophyll-a concentration for each pixel and the Tana River discharge for the same time series. (c) p-values for each pixel in Fig. 4b. Correlations are not considered significant for pixels where $p > 0.05$.

outflow from the Tana River mouth is shown in Fig. 2. A bimodal distribution for both climatologies is presented, with error bars indicating standard errors. The intensity of the precipitation and discharge are both greater during the long rainy season (March–May) with rainfall peaking at 265 mm during April. A second peak of 232 mm is experienced in November. The first peak in river discharge lags the initial rainfall peak by one month, with an outflow of 343 $m^3\ s^{-1}$ occurring in May. The second outflow peak in November (308 $m^3\ s^{-1}$) coincides with the rainfall peak, though remains high (257 $m^3\ s^{-1}$) during December despite the decline in rainfall. The lowest precipitation and river discharge rates were found from July until September.

3.2. *Chlorophyll-a*

Satellite observations of chlorophyll-a concentrations were analysed in Ungwana Bay area and adjacent offshore region, highlighted in Fig. 3a. For each region, a climatology of chlorophyll-a concentrations was calculated based on the period 1997 to 2017 (Fig. 3b). For Ungwana Bay (black box, Fig. 3a), chlorophyll-a concentrations reveal a single peak during July. Chlorophyll gradually increases from March to July peaking at 2.51 mg m^{-3}, and then diminishes, two months after the peak Tana discharge. By comparison, the chlorophyll-a climatology for the offshore region (red box, Fig. 3a) has two peaks; the first occurring in Aug–Sep (0.223 mg m^{-3}) and a second peak in February at 0.222 mg m^{-3}. Note that even the minimum Ungwana Bay chlorophyll-a concentration in Ungwana Bay (0.744 mg m^{-3}) in March is greater than either of the offshore peaks.

3.3. *Correlation analysis*

River discharge was correlated with the spatially averaged chlorophyll concentrations in Ungwana Bay for each month between January and May over the period 1999–2016 (Fig. 4a). Chlorophyll concentrations in Ungwana Bay (black box, Fig. 3a) were found to be significantly correlated with the Tana discharge ($r = 0.63$, $p < 0.0001$, $n = 90$). To further investigate the spatial distribution of this correlation, a similar correlation analysis was undertaken using the chlorophyll time series from each pixel within the OC-CCI domain for January–May (Fig. 4b). The resulting spatial distribution of the Pearson coefficient shows the strongest positive correlations (>0.6 occurring within Ungwana Bay and along the coast to the north of the bay. Positive correlations were also observed south of the bay, whereas negative correlations generally characterize the outer shelf and offshore regions. To assess the significance of the observed Pearsons coefficients, the p-value for each correlation was also computed (Fig. 4c). This shows that the positive correlations between river discharge and chlorophyll concentrations within Ungwana Bay and north of the bay are significant ($p \leq 0.05$) whilst in waters south of the bay correlations were insignificant ($p > 0.5$). The sharp transition from strongly positive correlations to zero correlation (Pearson coefficient ~ 0) approximately at the 200 m isobath (see Fig. 4b), suggests that the influence of the Tana River is strongly localized to inshore waters, particularly the shallower waters of Ungwana Bay.

3.4. *Numerical modelling of surface currents*

Lagrangian analysis of modelled advective pathways from Ungwana Bay is presented in Fig. 5. Illustrative examples of the particle-tracking results for a typical year (i.e., January, April, July and October of 2009) are shown. These months illustrate the surface circulation downstream from Ungwana Bay during the NEM, SEM and intermonsoon seasons. Significant differences in the advective pathways are evident during the NEM and SEM. During the NEM (Fig. 5a; January), particles are rapidly carried away from the coastline and removed from the continental shelf within a week. At this time the confluence, and subsequent deflection of, the Somali Current and EACC

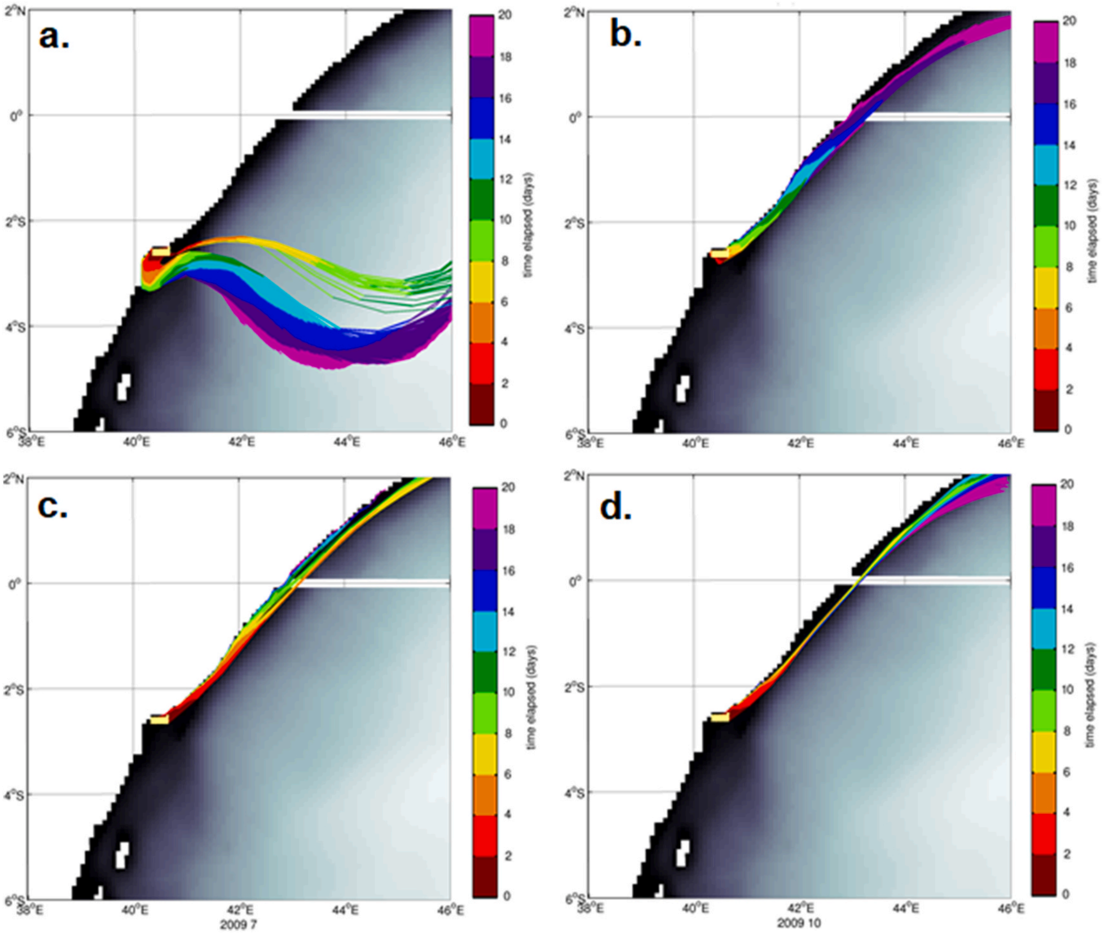

Fig. 5. Trajectories of particles initialized near the mouth of the Tana River (yellow box) during (a) January (NEM), (b) April (inter-monsoon), (c) July (SEM) and (d) October of 2009, chosen as an illustrative example of a typical year. Colour of trajectory denotes time since initialization. Background greyscale shows the bathymetry. Note the rapid off-shelf advection during the NEM regime, contrasting with on-shelf retention and northward advection during the SEM and inter-monsoon seasons. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

drives seasonal upwelling in the region (Jacobs et al., 2020) and this confluence appears responsible for the eastward (offshore) advection of virtual particles. This contrasts with trajectories during the SEM (Fig. 5c; July) when particles typically remain on the shelf for a longer period and are advected northward. The Lagrangian experiments also reveal on-shelf, northward transport during the inter-monsoon periods (Fig. 5b and d respectively).

4. Discussion

Whether seasonality in the Tana River outflow impacts primary production locally within the receiving waters of Ungwana Bay, or more widely across the NKB is not well understood despite the bimodal hydrological cycle (comprising long rains between March and May, and short rains occurring between October and December) having been long known (e.g. McClanahan, 1988; Tamooh et al., 2012; Njogu and Kitheka, 2017). Here we have shown that Tana River discharge impacts phytoplankton biomass and hence productivity within Ungwana Bay (Fig. 4), and this influence is mainly restricted to near-shore waters whilst also extending northwards along the Kenyan coast due to the prevailing oceanic circulation (Fig. 5). The impacted areas are thus distinct from the broader NKB region, which is upwelling-driven (Jacobs et al., 2020). This suggests that an important distinction can be drawn between inshore river-influenced (within Ungwana Bay and near-shore waters) and off-shelf upwelling-influenced areas, which has implications for the management of these two regions.

In this study, satellite derived chlorophyll-a concentrations were investigated over Ungwana Bay and the neighbouring offshore region. Strong positive correlations with Tana River discharge were found in Ungwana Bay, with lower positive correlations extending northwards along the coast. Such a spatial pattern agrees with the LANDSAT era study by Brakel (1984), which identified coastally-trapped sedimentary plumes emanating from this river. In addition, our findings are broadly supported by Kitheka (2002) who suggested that the discharge of terrigenous sediments and nutrient-laden freshwater by the Tana (and neighbouring Sabaki) Rivers were likely explanations for why Ungwana Bay contained the richest and most productive fishery along the Kenyan Coast. Here we have to mention that satellite-derived chlorophyll concentrations have acknowledged weaknesses in shallow coastal waters (see methods for further details). Thus, satellite algorithms should be validated and calibrated to account for local conditions. For instance, a ground-truth comparison with several *in situ* observations of similar spatiotemporal distribution should occur. However, *in situ* validation efforts have not been possible for Ungwana Bay, primarily due to the lack of adequate *in situ* data. We stress that significant efforts should be put towards phytoplankton biomass and production data collection, that could ultimately lead to more accurate satellite observations in these optically complex waters.

Lagrangian particle tracking experiments demonstrated the seasonality of downstream connectivity from Ungwana Bay. During the NEM (January, Fig. 5a) the particle trajectories show advective pathways perpendicular to the coastline and can be attributed to the eastward water movement after the confluence of the southward Somali Current and the weaker northward EACC (Jacobs et al., 2020; Todd, 2020). This confluence zone drives an upwelling system over the NKB, which causes the second (February) peak in productivity in offshore waters (Jacobs et al., 2020). However, during the first inter-monsoon period (April, Fig. 5b), northward movement of productive (perhaps nutrient-rich) waters is apparent. This provides one potential explanation for the statistically significant positive correlations between Tana discharge and productivity along the coast to the north of Ungwana Bay. Ungwana Bay is turbid in the vicinity of the Tana River (Munga et al., 2013), and nutrient-rich waters advected northward along the coast (as seen in Lagrangian experiments) could potentially contribute to productivity in these areas, away from the sediment-laden waters of Ungwana Bay into less turbid areas where light limitation does not determine primary productivity (Tilstone et al., 2011).

While this paper focuses on elucidating the present-day drivers of Ungwana Bay productivity, it is important to note that climate change is expected to have a substantial impact on hydrology and subsequently on estuaries on both a global and regional scale (Funk et al., 2010). Some of the effects that would arise from climate change would be varying precipitation, which would affect freshwater supply. Nakaegawa and Wachana (2012) predicted that mean annual rainfall in the Tana basin will increase by ~15% by the end of the 21st century, with river discharge predicted to increase significantly between November and March. Further, the affected freshwater supply would have an impact on estuarine communities, e.g. prawns (Adamack et al., 2012). The increased sediment load, nutrients and the phytoplankton biomass might be important for the prawn fisheries (Munga et al., 2012; Thoya et al., 2019). However, further research is required to assess this speculation, as other potential explanations exist. For instance, although the Tana River contributes greater than half of the total river discharge into the Kenyan sector of the WIO (Kitheka et al., 2005), it would be expected that continual runoff along the rest of the coast should peak at the same time as Tana River discharge, potentially supplying nutrients to drive this increased productivity independently of the Tana. Without appropriate baseline studies it remains challenging to assess the true impact that the Tana River has on coastal water productivity. An early study on coastal sediment plumes from the Tana River revealed a pronounced seasonal cycle in the appearance, intensity and spatial distribution of such plumes (Brakel 1984), suggesting seasonal impacts on productivity. Whilst productivity impacts were not investigated, the general conclusion that Tana River sediment plumes are more likely to be coastally trapped features rapidly advected along the coast has largely been overlooked in more recent literature.

It is of great importance that the increased sediment load, nutrients and phytoplankton biomass regulated by the Tana River, could have relevance for the local fisheries. Mwaluma et al. (under review) showed that the highest concentrations of fish larvae are found inshore on the Kenyan shelf particularly in the vicinity of Ungwana Bay and further north towards Lamu. Many of these species are fished on the NKB and it is possible that these larvae take advantage of the high coastal productivity in the Ungwana Bay region whilst developing. Once juvenile, they will forage on larger prey further offshore. Of particular relevance is the prawn fishery. Munga et al. (2013) showed that five penaeid prawn species are found in depths shallower than 10 m in the Ungwana Bay region, with their distribution influenced by habitats created by the Sabaki and Tana Rivers. These prawns are fished by local small-scale fishers, but previously by trawlers (Fulanda et al., 2011). While species do have lifecycle variations, all penaeid prawns use the offshore (deeper) coastal areas for adult feeding and spawning, and the nearshore and estuarine waters for post-larval and juvenile development. Gleason and Wellington (1988) demonstrated that phytoplankton play an important part of the natural diet of penaeid prawn particularly during the post-larval and early juvenile stages. Munga et al. (2013) also noted that small-sized *Metapenaeus monoceros* and *Penaeus monodon* individuals were abundant during their SEM survey, suggesting spawning (certainly of these two species) occurs in the inter-monsoon period between March and April. Interestingly, this coincides with the first Tana River peak discharge (Fig. 2), and given our results (Fig. 3), could imply that the 1-year life cycle of these prawns is aligned with the Ungwana Bay bloom. This dependence has significance in that bloom biomass regulated by freshwater discharge, will probably be reflected in prawn recruitment (Adamack et al., 2012). If the forecast of future precipitation for this region is correct (Nakaegawa and Wachana, 2012), then this could bode well for the local fishery. However, water extraction for urbanization and agriculture from the river would have the opposite effect.

In summary, interest in the Ungwana Bay rivers, estuaries and on the coastal environment seems to have started with work done by Brakel (1984), publishing the first descriptions of rainfall, river discharges and the dynamics of the freshwater river plumes in the coastal ocean. Since then focus has strongly been on the precipitation, streamflow, discharge and sedimentation (Kitheka et al., 2005; Tamooh et al., 2012, 2014; Leauthaud et al., 2013; Geeraert et al., 2015; Langat et al., 2017; Njogu and Kitheka 2017; Okuku et al., 2018), while little attention has been given to climate change (Nakaegawa and Wachana, 2012) and river threats and management challenges (Kitheka and Mavuti, 2016). In parallel there have also been efforts to better understand the marine fisheries within Ungwana Bay – one of East Africa's most important fishing and habitat areas sustaining bottom trawl commercial and resident-migrant artisanal fisheries (Fulanda 2003; Fulanda et al., 2011; Munga et al. 2012, 2013, 2016; Dzoga et al., 2019). However, we note that none of these studies elucidate the connection between the life cycle of these species and the environment. Our study is the first to show that the Tana River is a major driver of local coastal production, which is likely to strongly impact the Ungwana fisheries with possible implications for fisheries recruitment in the offshore NKB region.

In conclusion, our analysis of spatiotemporal correlations of Tana River discharge and satellite chlorophyll-a observations demonstrate that the influence of the Tana River on NKB productivity is limited to coastal waters. This conclusion is further supported by modelled advective pathways demonstrating that offshore advection during the NEM does not coincide with the peak productivity of Ungwana Bay. In short, the Tana River is a key driver of productivity in Ungwana Bay, but influence over the outer NKB is unlikely. This has policy implications for the management of both Ungwana Bay and the NKB. While the NKB are likely to be impacted by oceanic warming and by the position and strength of the confluence zone between Somali and East African Coastal Currents (Jacobs et al., 2020; Kamau et al., 2021), the riverine-influenced areas may primarily be impacted by changes in large-scale precipitation patterns and anthropogenic factors (including upstream agricultural practices and operation of existing hydroelectric dams). In particular, decisions affecting the use of the Tana River should consider downstream impacts on marine productivity and hence, potentially, the sustainability of Ungwana Bay and coastal fisheries. Based on these findings, a number of policies and management acts could be refined and conjoined in the management and conservation of the Tana River as well as Ungwana Bay. Specifically, these include The National Wildlife Conservation and Management Policy April 2017; The environmental Management and co-ordination (Amendment) Act, 2015; and the Integrated Coastal Zone Management (ICZM) Policy Draft December 2013. While a specific management plan exists for the prawn fishery in Ungwana Bay, there is currently no such plan in place that specifically covers the NKB region. The results presented here show that Tana discharge is an important driver of productivity in Ungwana Bay, but suggest that a management plan for the NKB region should primarily consider oceanic drivers of productivity.

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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