Langa, A.; Calil, P.:

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First published online by Springer: 13.11.2019

DOI: 10.1007/s10236-019-01311-0

[https://dx.doi.org/10.1007/s10236-019-01311-0](https://dx.doi.org/10.1007/s10236-019-01311-0)
On the role of physical processes on the surface chlorophyll variability in the Northern Mozambique Channel

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Abstract

Contrary to others subtropical regions, surface chlorophyll in the Northern Mozambique Channel is characterized by higher concentrations in winter than in summer. **Wind stress and surface net heat flux modulate the seasonal cycle of the mixed layer depth with impacts on the surface chlorophyll.** Therefore, a suite of sensitivity experiments is used in order to evaluate the importance of these forcing fields on the seasonality of the mixed layer depth and, consequently, the surface chlorophyll variability. The winter bloom is triggered by negative surface heat fluxes, where cooling at the surface induces mixing and entrainment of nutrients at the base of the nutricline and light is not limiting. Winds enhance the winter bloom by uplifting additional nutrients and diluting subsurface chlorophyll into the surface layer. In the summertime, weaker wind stress and positive heat fluxes inhibits vertical mixing. As a consequence, the surface layer is depleted in nutrients and a deep chlorophyll maximum is formed. **Analysis of top-down control on phytoplankton biomass reveal that zooplankton abundance increases in a near-linear proportion with phytoplankton biomass despite the deepening of the mixed layer depth.** This suggests that the phytoplankton stock in the Northern Mozambique Channel is also controlled by the grazing, given that zooplankton biomass is not directly affected by the deepening of mixed layer depth during wintertime.

Key words: Wind stress, surface net heat flux, Mixed Layer Depth, deep chlorophyll maximum, surface chlorophyll, Mozambique Channel

1. Introduction

The circulation in the northern Mozambique Channel (NMC) is driven mainly by the South Equatorial Current (SEC), which moves from the northern tip of Madagascar toward mainland Africa where it bifurcates at, approximately, 10°S. One branch moves equatorward and forms the East African Coastal Current (EACC) while the other branch flows poleward and becomes the Mozambique Current (MC) (Sætre and Da Silva, 1984). Using satellite altimetry and an eddy-resolving model, Backeberg and Reason (2010) found that the region is also under the influence of anticyclonic eddies which result from instabilities of the SEC. These eddies interact with the Mozambican coastal boundary current yielding speeds of, approximately, 2.0 m s$^{-1}$ (Ullgren et al., 2016).

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Apart from the remote forcing from the equatorial region, the NMC is also under the influence of local winds. The wind regime in the region is an extension of the northern Indian Ocean monsoons, where the wind blows from the northeast (NE) during austral summer and from the southwest (SW) during austral winter (Saetre and Da Silva, 1982). Maximum wind speeds occur between June and July during the SW monsoon reaching 15 m s\(^{-1}\), while the NE monsoon is characterized by wind speeds of, approximately, 10 m s\(^{-1}\), prevailing from August to April (Malauene et al., 2014). The intensification of wind forcing linked to the seasonal monsoon variability in the north Indian Ocean is known to have important physical and biogeochemical implications in the upper ocean (Banse and English, 2000; Wiggert et al., 2002; Prasad, 2004). For instance, the seasonal variation of SST has been associated with the reversing monsoons in the Gulf of Tokin (Tang et al., 2003) and in the Arabian Sea (Prasad, 2004). Based on a modeling study, Wiggert et al. (2000) found cold SST and low surface chlorophyll concentrations in the Arabian Sea as a result of intense mixing caused by strong winds during austral winter (June - September). More recently, Roxy et al. (2016) found a relatively low correlation between surface chlorophyll and wind stress which suggests that other factors may have a significant role on phytoplankton variability in the region.

High chlorophyll values in the Mozambique Channel have been associated with episodic coastal upwelling and subsequent offshore advection (Malauene et al., 2014) as well as with mesoscale eddies (José et al., 2014). Previous modeling studies in the Mozambique Channel highlighted the seasonality of surface chlorophyll (e.g. Koné et al. (2009); Tew-Kai and Marsac (2009)). Koné et al. (2009), for example, used a biogeochemical model to analyze the timing of phytoplankton blooms in the entire Indian Ocean. However, their model failed to reproduce the bloom in the Mozambique Channel due to the coarse resolution (1/2\(^{\circ}\)) which does not accurately represent the mesoscale activity. José et al. (2014) used a relatively higher model resolution (1/6\(^{\circ}\)) but still found discrepancies in terms of the magnitude of surface chlorophyll concentrations, when compared to climatological data.

The seasonal signal of surface chlorophyll in the NMC, with higher concentrations in winter than in summer, suggests that the reversion of the wind, from northward in summer to southward in winter, modulates the biogeochemistry in the region. It is known that surface chlorophyll is strongly dependent on processes that control the Mixed Layer Depth (MLD) with the wind and heat fluxes having a significant role (Chiswell et al., 2015). In this study, we used the Regional Ocean Modeling System (ROMS) coupled to the Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES) model in order to assess the role of the wind stress and the net heat fluxes on the MLD variability and the seasonal cycle of surface chlorophyll in the NMC. Several sensitivity experiments with different surface forcing are performed in order to evaluate the relative importance of each forcing on the seasonal evolution of surface chlorophyll in the NMC.

2. Methods

2.1. Model description

ROMS is an hydrodynamic model based on free-surface, split-explicit, terrain-following vertical coordinates (Shchepetkin and McWilliams, 2005). The model solves the primitive equations taking into considerations hydrostatic and Boussinesq approximations. The unresolved vertical mixing processes are parameterized following a non-local K-Profile Parameterization - KKP (Large et al., 1994).

PISCES is a biogeochemical model designed to simulate the first trophic levels of the marine ecosystem and the biogeochemical cycles of carbon and of the main nutrients (Aumont et al., 2003; Aumont and Bopp, 2006). The model simulates 24 prognostic variables including two phytoplankton (diatoms and nanophytoplankton), and two zooplankton (mesozooplankton and micro-zooplankton). The growth rate of phytoplankton is limited by the availability of five different nutrients: nitrate, ammonium, phosphate, silicate and iron. Differently from nanophytoplankton which requires minimum nitrogen and/or phosphorus availability, diatoms have a higher demand on silicate and iron concentrations to growth (Sunda and Huntsman, 1995). Constant Redfield ratios are imposed for Carbon, Nitrogen and Phosphorus and are kept...
Figure 1: (a) GEBCO Bathymetry 30 arc-sec interpolated into ROMS for parent grid and child grid (box). The contours represent isobaths of 500 and 2500 m. (b) Annual mean surface currents derived from ROMS showing the SEC (South Equatorial Current), SEMC (Southern Equatorial Madagascar Current), EACC (East African Coastal Current), MC (Mozambique Current), AC (Agulhas Current) following the schematic representation by Schouten et al. (2003). The boxes in (b) indicate the geographic limits of the sampling areas used in our analysis.
constant in the model for all living compartments. The model contains three non-living compartments: semi-labile dissolved organic matter (with timescales ranging from weeks to several years), small and large particles. Nutrients in PISCES come from three different external sources which includes atmospheric dust deposition, rivers and sediment mobilization.

In order to analyze the effects of the increased resolution in the Mozambique Channel, we use a one-way nesting procedure (Debreu et al., 2008). The parent domain with 1/4° horizontal resolution extended from 5.1°N to 50°S of latitude and between 5.1°W and 79.3°E of longitude (Fig. 1-a). The child domain with 1/12° horizontal resolution extended from 5.3° to 32.9°S of latitude and between 34° and 68.1°E of longitude (Fig. 1-a-box). Both model grids have 40 sigma-coordinate vertical levels, using the following values for vertical stretching parameters: $\theta_s=6.0$, $\theta_b=0.0$ and $hc=10$ m. The topography for both configurations is from the General Bathymetric Chart of the Oceans (GEBCO-2014; www.gebco.net) product and has been smoothed to avoid pressure-gradient errors over steep topography using the ROMSTOOLS package (Penven et al., 2008).

The Comprehensive Ocean -Atmosphere Data Set (COADS; Da Silva et al. (1994)) data used to force the model consists of monthly climatological sea surface heat and salt fluxes interpolated into the ROMS grid. Other surface fields used to force the model are sea surface temperature (SST) obtained from the Advanced Very High Resolution Radiometer Pathfinder (AVHRR; Casey and Cornillon (1999)) and wind field from the QuikSCAT scatterometer (Liu et al., 1998). Atmospheric dust deposition was obtained from Tegen and Fung (1995). Boundary conditions for both physical and biochemical properties for the parent grid were derived from the World Ocean Atlas (WOA2009; Conkright et al. (2002)). The child configuration was run for 5 years after a 16 year spin-up time of the parent grid. The last four years of our simulations were used for our analysis by constructing monthly averages. Satellite data are used to validate our model results of sea surface height and sea surface chlorophyll. Vertical sections of temperature, salinity and nitrate are compared against climatological data, described in the next section.

### 2.2. Data products

Sea level data is obtained from Mean Sea Level Anomalies (MSLA) distributed by AVISO (www.aviso.oceanobs.com). MSLA is derived from the sol multimissions d’ALTimetrie, d’Orbitographie et de localisation precise/Data unification and Altimeter combination System (Ssalto/Duacs) processing which integrates available data from all altimeter missions: HY-2A, Saral/AltiKa, Cryosat-2, OSTM/Jason-2, Jason-1, Topex/Poseidon, Envisat, GFO, ERS 1-2. MSLA consists of gridded geostrophic velocity anomalies ($u$, $v$) at 1/4° horizontal resolution. For details on data processing the reader is referred to the AVISO website. Daily averaged MSLA were downloaded for the period of 2006 to 2012 and used to calculate the Eddy Kinetic Energy (EKE).

Surface chlorophyl is obtained from the Moderate Resolution Imaging Spectro-radiometer (MODIS) chlorophyll product for the period between 2002 and 2012 distributed by NASA (http://oceancolor.gsfc.nasa.gov). The dataset is a level-3 standard mapped image chlorophyll-a with daily temporal resolution and 4.6 km spatial resolution. The chlorophyll concentrations were used to construct a monthly mean by averaging each daily pixel over the sampling period. The third dataset includes hydrological and nutrients observations from the Commonwealth Scientific and Industrial Research Organization (CSIRO) Atlas of Regional Seas (CARS2009). CARS2009 is generated from all available oceanographic data to produce a climatology at 1/2° horizontal resolution and on 79 standard vertical levels (www.cmar.csiro.au/cars). In our study we used temperature, salinity and nitrate from CARS2009 to validate the model outputs.

We also used the Ocean Mixed Layer Depth climatology dataset, which is computed from observational data obtained from the National Oceanographic Data Center (NODC) and from the World Ocean Circulation Experiment (WOCE) database (Boyer Montegut et al., 2006; Mignot and de Boyer Montegut, 2006).
The global MLD is built upon all vertical high resolution measurements from different instruments such as expendable bathythermograph (XBT), conductivity-temperature-depth probes (CTD), and profiling floats (PFL) covering the period from 1941 to 2002. The MLD dataset used in our study is estimated using a reference depth of 10 m and the temperature criterion of 0.2 °C absolute difference from surface. The dataset consisted of a monthly climatology with horizontal resolution of 2°x2°.

3. Results and Discussion

3.1. Model Validation

3.1.1. Sea Surface Circulation

In order to show the dynamical and bio-geochemical consistency of our simulations, we compare the EKE derived from the AVISO Altimetry with that calculated from both parent and child domains (Fig. 2). Larger values of EKE indicate regions of intense mesoscale activity. Both child and parent simulations are able to capture the general aspects of the sea surface height variability when compared to the altimetry. Specifically, the region of large EKE near the Mozambique coast which results from the southward propagation of mesoscale eddies through the channel (de Ruijter et al., 2002; Harlander et al., 2009). However, the low resolution (parent) simulation underestimates EKE (≈ 10³ cm² s⁻²) by almost 50% when compared to that derived from the altimetry (≈ 2*10³ cm² s⁻²). The embedded (child) simulation, on the other hand, shows a very good agreement with the remotely sensed data, but small differences in the magnitude are observed, with the modeled EKE being slightly higher. This may result from the relative smoothness of the altimetric product. Based on current profiles from ship-mounted Acoustic Doppler Current Profiler and currents from drifters, Ullgren et al. (2016) highlighted that surface currents in the Northern Mozambique may be underestimated by altimetry due to its coarse resolution (1/3°). Another important improvement in the simulation with higher spatial resolution is the pathway of smaller eddies originating from eastern Madagascar, passing through the southern tip of the island and moving toward the coast of Mozambique. These eddies from Madagascar encounter those from the Mozambique Channel at approximately 28°S, and contribute to the formation of the Agulhas Current. The geographic location and EKE magnitude is consistent with the observed pathway from AVISO Altimetry. This variability is hardly seen in the model with coarser resolution, highlighting the importance of mesoscale processes in the surface circulation in the Mozambique Channel.

3.1.2. Temperature, Salinity and Nitrate

The performance of the annual modeled temperature, salinity and nitrate in the Northern Mozambique Channel is evaluated at a zonal section at 13 °S from 42 ° to 44 °E. Vertical profiles of annual mean temperature are compared against observations from the CARS2009 climatology (Fig. 3). Both parent (Fig. 3-a) and child (Fig. 3-d) simulations are in good agreement with observations in a climatological sense (Fig. 3-g), showing the permanent thermocline located between 100 to 300 m deep. However, SST values from both model simulations are slightly higher (<1°C) than the observations. This could be related to the impact of high frequency winds on SST, which is not accounted in the climatology forcing used in the model. Overall, the higher resolution model shows a slight improvement in reproducing the vertical temperature structure.

The vertical distribution of annual mean salinity shows maximum values (35.3 PSU) at approximately 250 m depth for observations (Fig. 3-h). A similar pattern is observed in the child domain (Fig. 3-e) where maximum values of 35.15 PSU are located from 200 to 300 m depth. The geographic location of the higher salinity values is confined between ~43.5°E and 44°E in the observations, while in the child domain it is extended from ~ 43°E to 44°E of longitude. Despite small differences in magnitude and geographic
Figure 2: Annual mean values of Eddy Kinetic Energy (EKE) representing the surface circulation in the Mozambique Channel. The data corresponds to EKE derived from: (a) AVISO; (b) parent domain; and (c) child domain. Higher values of EKE indicate regions of intense mesoscale activity, characterized by interaction between anti-cyclonic and cyclonic eddies.
Both cyclonic and anticyclonic eddies with a mean lifespan of approximately 3 months, are common features in the NMC (Collins et al., 2014). In cyclonic eddies, isotherms are deflected upward, upwelling deeper, nitrate-rich waters into the surface layer. Lower values of nitrate vertical flux at the surface may result from biological activity, where nitrate-rich upwelled waters by cyclonic eddies into the euphotic zone are consumed by primary producers as they made available. Conversely, anticyclonic eddies characterized by a deeper nutricline within their cores and a shallower nutricline in their edges (Calil and Richards, 2010). The strength of the so-called eddy pumping (cf. Falkowski et al. (1991); McGillicuddy Jr and Robinson (1997)) varies depending on the size, age and formation mechanism of the eddy. Mesoscale eddies are thus important not only in the vertical transport of nutrients but also in the asso-

Figure 3: Comparison of principal oceanic properties between observations and model in the Northern Mozambique Channel. The figure shows annual means of Temperature (a,d,g); Salinity (b,e,h); and Nitrate (c,f,i) obtained from zonal vertical profiles at 13°S section.
ciated horizontal transport of shelf waters into the open ocean (José et al., 2014).

Overall, ROMS captures, on a climatological sense, the variability of temperature, salinity and nitrate in terms of magnitude and spatial variation, which allows us to investigate the physical processes that drive the seasonal variability of surface chlorophyll in the Northern Mozambique Channel. The better agreement between the high resolution run and the observations shows the importance of mesoscale eddies in the nitrate redistribution in the region.

3.1.3. Time-Latitude variations of surface chlorophyll

To illustrate the seasonal cycle of the surface chlorophyll in the Mozambique Channel, chlorophyll concentrations were obtained from the regions between latitudes 12 - 14°S, 18 - 20°S and 22 - 24°S, respectively for North, Center and South and between longitudes of 42 - 44°E (North) and 40 - 42°E (Center and South) (see Fig. 1-b). These open ocean regions were chosen so that the connection between wind stress and net heat flux on the chlorophyll variability may be investigated, away from the influence of coastal processes. Time-latitude variation of monthly mean surface chlorophyll concentrations within the selected regions from the model output and observations from MODIS are shown in Fig. 5. The seasonal evolution of the MODIS chlorophyll concentration in the northern Mozambique Channel shows a peak of $\sim 0.15 \text{ mg Chl m}^{-3}$ during the austral winter (June to August) and minimum values of $\sim 0.10 \text{ mg Chl m}^{-3}$ in austral summer (November to January). The same pattern is seen in both model experiments (parent and grid domain), but with slight differences in concentration and spatial variation. The child domain presented values of the surface chlorophyll higher than MODIS during winter ($\sim 0.22 \text{ mg Chl m}^{-3}$), but very small concentration over the summer period ($\sim 0.05 \text{ mg Chl m}^{-3}$). The seasonal changes of surface chlorophyll of both model runs are similar to MODIS, but the maximum concentration was relatively lower ($\sim 0.13 \text{ mg Chl m}^{-3}$) in the parent domain than the child domain and MODIS. A similar seasonal signal of surface chlorophyll is seen in the central and southern regions of the Mozambique Channel, with surface chlorophyll increasing southward both observations and model simulations, particularly in the child grid. The differences in surface chlorophyll concentrations between the two model (parent and child) configurations is attributed to the increased horizontal resolution. As model resolution is increased, these effects are better resolved and
an increase in chlorophyll is observed.

Both model resolutions failed to reproduce the concentration of surface chlorophyll during summer time (50% less than observed in MODIS). **This can be due to a number of reasons.** First, we are comparing modeled, surface chlorophyll concentrations with chlorophyll concentrations estimated from MODIS. These are generally understood as an average chlorophyll concentration in the first optical depth (approximately, 50 m in open ocean). Surface modeled chlorophyll concentrations may not be exactly the same quantity. In addition, nutrient depletion after the winter bloom due to stratification may lead to an underestimation of the modeled surface phytoplankton concentrations when vertical mixing is strongly suppressed. Better agreement between observations and biogeochemical models require significant tuning of model parameters based on available observations.

In this study we used default parameters for the PISCES configuration in the Mozambique Channel. A separate study would be necessary in order to optimize the parameters in biogeochemical model for the region. Ideally, such parameters should be based on observational studies, which are scarce in the region. This makes this task unfeasible at present. One could tune the parameters so that surface chlorophyll concentrations are somewhat in better agreement with the observations, but these would be at the risk of obtained seemingly correct results for the wrong reasons (Franks, 2009). Therefore, we opted for maintaining the default parameters which have been validated from global PISCES model runs (Aumont and Bopp, 2006).

3.1.4. Spatial and temporal variability of surface chlorophyll at 13°S

The spatial and temporal trend of surface chlorophyll is also analyzed longitudinally at 13°S of latitude, between the coastal areas of Mozambique (41.5°E) and Madagascar (49°E) (Fig. 6). Surface chlorophyll concentrations in the child domain show a small increase in the coastal region of Madagascar during winter as in MODIS. As in the latitudinal analysis, a surface chlorophyll concentration in child is slightly higher during winter than the parent configuration and MODIS. Contrary to MODIS and child, the parent configuration shows a slight decrease in surface chlorophyll concentrations with longitude and also underestimates the chlorophyll concentration in both seasons. This zonal trend in surface chlorophyll concentrations is likely associated with the lack of cyclonic eddies near the shelf of Madagascar that affect chlorophyll variability locally. In the middle of the channel were eddies make their pathway toward central part of the Mozambique Channel, these features that are well represented in child, seems to induce the phytoplankton growth. During summer, MODIS also shows an increase in chlorophyll concentration in the coast of Madagascar but this trend is not reproduced by the model. Suggesting that the river input which is not included in the model should explain these differences between satellite estimation and both model configurations in the coast of Madagascar. River flow my also increase sediments load in coastal area which may lead to an overestimation of surface chlorophyll concentration by satellite. The higher resolution (child) simulation represents more accurately the spatial and temporal variability of surface chlorophyll in the NMC. Therefore, from now on we will focus our analysis on the child configuration.

3.1.5. Seasonal variation of the Mixed Layer Depth (MLD)

We analysed local wind stress and surface net heat fluxes (Fig. 7-a) in order to understand their impact on MLD in the NMC. Spatio-temporal variability of MLD over the NMC area derived from the model (Fig. 7-c) is compared against observational data (Fig. 7-b). Modeled MLD were calculated using the reference depth of 10 m and the temperature criterion of 0.2°C absolute difference from the surface, the
Figure 5: Time-latitude evolution of surface chlorophyll correspondent to the boxes representing the three subregions of the Mozambique Channel (see Fig.1b) for: MODIS (a-c); parent domain (d-f); and child domain (g-i). Both MODIS and model shows a peak in chlorophyll concentrations in winter and minimum values during summer.
Figure 6: Longitudinal variation of surface chlorophyll at 13°S of latitude between the coastal areas of Mozambique and Madagascar in the Northern Mozambique Channel, showing the spatial trends of MODIS (blue line and dotted, for summer and winter, respectively), child (magenta line and dotted, for summer and winter, respectively) and parent (black line and dotted, for summer and winter, respectively)
same criteria as in the climatological data from the de Boyer-Montégut product. During winter, stronger wind stress (0.07 N m$^{-2}$) and negative net heat flux (-85 W m$^{-2}$) are responsible for the deepening of the MLD. In summer the situation reverses, with moderate wind stress (-0.03 N m$^{-2}$) and large, positive heat fluxes (>100 W m$^{-2}$), the MLD is shallower. The model displayed the same seasonal variation as in the observations, but values of the MLD differ slightly in magnitude and spatial distribution. As the horizontal resolution (child) increase, the values of maximum MLD and the correspondent spatial variations during winter are lightly higher when compared to the results from the coarser configuration model (parent, not shown) and observations. This suggests that mixing processes associated with the wind stress and negative net heat flux in winter may be enhanced by the mesoscale eddies in the child configuration.

3.2. The role of wind stress and net heat flux on the seasonal cycle of chlorophyll

The MLD is an important parameter in the ocean surface as it modulates vertical exchanges of properties as well as influence vertical migration and light penetration. Therefore, to a large extent, the MLD modulates surface chlorophyll concentrations. In the NMC, maximum chlorophyll concentrations occur in winter, when the MLD is deeper while minimum concentrations occur during summertime when the MLD is shallower. In this subsection, we examine the relationship between MLD and nutricline in modulating the surface chlorophyll in a cross-shore transect at 13°S located between 42 and 44°E in the NMC. Two additional simulations were performed in order to evaluate the individual role of wind stress and surface net heat flux, on the MLD in the region. The simulations forced with suppressed wind stress (NOWIND simulation) and surface net heat flux (NOHEAT simulation) are compared to the 'control' run (CTL) which is the simulation forced with monthly climatological wind stress and net heat flux. The remaining forcing fields remained unaltered. We compare one year of simulation for CTL, NOWIND and NOHEAT, each one restarted from the fifth year of the parent and child configurations. The aim is to
obtain the local response of the dynamics and biogeochemistry to these forcings. The large-scale circulation is imposed in all simulations via the boundary conditions from World Ocean Atlas.

The change in wind stress values by dividing the climatological wind by one hundred in the NOWIND experiment did not change the pattern of the large scale and mesoscale features in the domain, except for a relative weakening of surface speed of SEC and EKE values, when compared to CTL. This is because the large scale circulation in the model depends mostly on the boundary conditions. Coastal upwelling in some regions of the Mozambique Channel may be affected in NOWIND as a result of the decreased wind stress. However, upwelling verified in the western part of North Madagascar is not associated to the wind stress but to the strong northward current associated with the large anticyclonic eddy (Pripp et al., 2014).

The time evolution of a vertical profile averaged over the NMC area defined in Fig.( 1-b) indicates that chlorophyll concentrations increase between the months of January and May, with maximum values of \(~0.20 \text{ mg Chl m}^{-3}\) located between 40 m and 140 m depth(Fig. 8-a). This pattern coincides with periods of shallower MLD (\(~20 \text{ to } 30 \text{ m}\)). From June to September, increased winds and negative surface net heat flux induce vertical mixing and a deepening of the MLD. Nutrient-rich waters are brought up to the surface and induce an increase in surface chlorophyll concentrations (\(~0.20 \text{ mg Chl m}^{-3}\)) as the phytoplanktonic community is not light-limited at this location. When the MLD starts shoaling at the end of winter, vertical mixing is inhibited and the surface mixed layer becomes nutrient-limited, leading to a decrease in chlorophyll concentrations to their minimum values at the surface (\(~0.05 \text{ mg Chl m}^{-3}\)). The depth-horizon (40 - 100 m) and concentration of the deep chlorophyll maximum (DCM, \(~0.30 \text{ mg Chl m}^{-3}\)), which develops from early spring to late autumn, are similar to in-situ data measured in the western tropical Indian Ocean (George et al., 2013). The depth of the nutricline varied between 50 to 100 m, except from October to December where the nutricline deepens while the MLD shoals.
Fig. 8 (b) is the same as Fig. 8 (a), but for the NOWIND simulation. The pattern of the chlorophyll distribution is similar to the CTL, except for the magnitude of the winter peak of chlorophyll which shows lower values. This sensitivity experiment shows that the net heat flux triggers the winter chlorophyll peak, where cooling induces nutrient entrainment and erodes the DCM. This suggests that the surface net heat flux contributes for the timing of the seasonal signal of surface chlorophyll of the winter bloom in the NMC, the so called turbulence-shutdown hypothesis (Chiswell et al., 2015). The depth of nutricline in this experiment varied between 50 and 100 m as in the control run, but with slightly differences in the seasonal pattern, especially in November.

The NOHEAT run shows a shift in the seasonal signal of chlorophyll from the winter toward the end of the year resulting in higher surface chlorophyll concentrations (∼ 0.30 mg Chl m$^{-3}$) between August and November (Fig. 8-c). With the absence of the net heat flux, the wind stress erodes the high stratification layer from the beginning of the simulation. The continuous erosion of the stratification is shown by the progressive deepening of the MLD. The absence of restratification induced by positive heat fluxes in late winter allows the winds to keep eroding the thermocline throughout the year. This causes an unrealistic constant supply of new nutrients into the surface layer and an increase in surface chlorophyll concentrations.

As in CTL, the NOWIND and NOHEAT runs also indicate that there is a close relationship between the variation of the MLD and the nutricline. Similar to CTL, the deepening of both the MLD and the nutricline in both NOWIND and NOHEAT allows more nutrients to be available for phytoplankton growth and thereby induce an increase of surface chlorophyll concentrations. Deeper nutricline and MLD in NOHEAT when compared to CTL and NOWIND favored DCM formation (> 0.30 mg Chl m$^{-3}$) at around 60 m depth.

The decrease in chlorophyll concentrations in NOWIND shows that the winter peak depends on wind stress and subsurface chlorophyll concentrations in the region. The importance of wind stress in regulating the magnitude of the surface chlorophyll is further evidenced in the NOHEAT run, where the subsurface chlorophyll concentration is higher when compared to NOWIND and CTL. The prominent subsurface chlorophyll concentration in NOHEAT is also upwelled to the surface.

Changes in the magnitude and seasonal signal of subsurface chlorophyll seen in CTL, NOWIND and NOHEAT may be detailed by the model diagnostics averaged over the MLD (Fig. 9). Vertical and horizontal advection, vertical mixing as well as entrainment of nitrate are larger during winter in the control run, explaining the winter peak of chlorophyll concentrations. In NOWIND, the MLD still deepens and the vertical mixing increases during winter following the seasonal cycle of the heat fluxes. Stratification and reduced winds in NOWIND inhibit vertical nutrient transport which results in lower surface chlorophyll concentrations. In NOHEAT, moderate wind stress in summer deepens the MLD allowing vertical transport and mixing of nutrients which increased the phytoplankton growth in the period.

Fig. 10 shows the changes of nitrate concentrations and temperature in CTL and the two sensitivity experiments. Higher surface nitrate concentrations of approximately ∼ 0.1 µmol N L$^{-1}$ stimulate the high chlorophyll concentrations in the CTL and NOHEAT model experiments, respectively, in winter and summer. However, surface chlorophyll concentration is slightly higher in NOHEAT (∼ 0.30 mg Chl m$^{-3}$) than in CTL (∼ 0.20 mg Chl m$^{-3}$). On the other hand, surface concentrations of nitrate in NOWIND are reduced when compared to CTL and NOHEAT. Maximum isopycnal displacements are about 60 - 70 m in CTL and NOWIND during winter.
Figure 9: Model diagnostics of nitrate averaged over the MLD: (a) horizontal advection; (b) vertical mixing term; (c) vertical advection; and (d) entrainment rate. Legend: CTL (solid line), NOWIND (dashed line) and NOHEAT (circle-dotted line).

Figure 10: Time-depth evolution of nitrate concentrations and temperature in the Northern Mozambique Channel. The upper panel corresponds to nitrate concentrations: (a) CTL, (b) NOWIND and (c) NOHEAT simulations. The lower panels correspond to temperature: (d) CTL, (e) NOWIND and (f) NOHEAT simulations.
3.3. Impact of trophic interactions on the seasonal chlorophyll variability

The above analyses indicate that the winter maximum of surface chlorophyll in the NMC depend on the deepening of the mixed layer depth. The time evolution of a vertical profile of phytoplankton biomass mimics that of chlorophyll concentrations. Phytoplankton biomass increases between the months of January and May, with maximum values of $> 0.5$ mmol C m$^{-3}$ located between 30 and 120 m depth (Fig. 11-a). As explained in the section 3.2, the winter peak in chlorophyll concentrations at the surface is triggered by intense vertical mixing between the months of June and September, due to negative surface heat fluxes. The deepening of MLD (Fig. 8-a) induces entrainment of nutrients (9-d) which stimulates phytoplankton growth from the base of the nutricline, leading to a surface peak during the wintertime. This suggests that phytoplankton cells are brought up to the surface and contribute to enhance surface chlorophyll concentrations with the deepening of mixed layer in winter. As in CTL, phytoplankton biomass in the NOWIND and NOHEAT experiments also show similarities with the time evolution of vertical profile of chlorophyll concentrations (Fig. 11- b & c). In NOWIND the biomass of phytoplankton decreases throughout the year, including wintertime. On the other hand, the peak of phytoplankton biomass changes from winter months to spring in NOHEAT.

Next, we analyse how the seasonal variability of the vertical mixing caused by winds and heat fluxes influences the vertical distribution of the two classes of both phytoplankton and zooplankton biomass over the euphotic zone.

The question we try to answer is the following: is the increase in phytoplankton biomass during winter due to a reduction of grazing by zooplankton in the water column? Here, we also used the two sensitivity experiments, NOWIND and NOHEAT, together with the CTL run (see 3.2) to better understand the role of the MLD variability on the vertical distribution of plankton biomass in the region. The surface biomass in the CTL run is about 2 times higher during winter than in summer, for both small (nano-phytoplankton) and big (diatoms) sizes of phytoplankton in the region. Nano-phytoplankton biomass is higher than the concentrations of diatoms, indicating that small phytoplankton (nano-phytoplankton) are mostly responsible for the seasonal variability of phytoplankton biomass in the region (Fig. 12, a-b).
The two simulated zooplankton sizes, micro- and meso-zooplankton, increase in proportion to phytoplankton abundance, despite the deepening of the MLD. However, a relative delay of approximately two months is verified in the peak of micro-zooplankton biomass, which takes place in September. Meso-zooplankton is the main grazer in the region and follows the signal of both classes of phytoplankton biomass with the maximum values in July (Fig. 12, c-d). Suggesting that the deepening of the MLD in the NMC has a minor effect on diluting zooplankton biomass in the water column. The near-linear increase of grazing pressure on phytoplankton by zooplankton suggests that the phytoplankton stock in the Mozambique Channel is also controlled by zooplankton.

4. Concluding remarks

In this study we used a regional hydrodynamic model coupled with a biogeochemical model at two horizontal resolutions in order to investigate the physical processes and the main nutrient (nitrate) driving the seasonal cycle of surface chlorophyll in the Northern Mozambique Channel. The embedded simulation was more effective in representing the surface circulation as well as the surface chlorophyll variability in the Mozambique Channel. Maps of Eddy Kinetic Energy shows that at higher resolution mesoscale activity is better reproduced in the Mozambique Channel, showing good agreement with the remotely sensed altimetry data. Annual mean values of surface chlorophyll ranged between 0.10 and 0.15 $mg \text{ Chl m}^{-3}$, for the child configuration and MODIS, except near the coastal area of Madagascar where the model underestimates the concentrations of surface chlorophyll. The parent configuration shows different trends and underestimates the surface chlorophyll concentrations ($> 0.10 \: mg \text{ Chl m}^{-3}$) when compared to observations and the child configuration. The better agreement between the child simulation and the observations shows the importance of the model resolution in reproducing physical processes such as vertical mixing and, consequently, the chlorophyll pattern in the Mozambique Channel.
Several model experiments were performed in order to investigate the mechanisms controlling the annual cycle of surface chlorophyll in the NMC. In addition to wind stress, surface net heat flux is an important physical forcing in the region as it also modulates the seasonal cycle of the MLD with impacts on the surface chlorophyll. In this study we demonstrate that a substantial amount of nutrients entrains into the euphotic zone in winter as a response to the deepening of the MLD which was linked to heat loss at the surface. Under mixed conditions, light winds blowing are sufficient to enhance the uplift of nutrients from the base of the nutricline to euphotic zone, therefore stimulating phytoplankton growth. The peak in surface chlorophyll concentration seen during winter, is also due to upwelled phytoplankton from subsurface waters to the surface layer. During austral summer, under strong stratification, phytoplankton growth is confined to the subsurface layer, leading to the formation of a deep chlorophyll maximum. Chlorophyll concentrations of approximately $\sim 0.20 \text{ mg Chl m}^{-3}$ remained stable within the upper 100 m depth when phytoplankton emerges into the surface during the winter peak of surface chlorophyll.

The combined effect of surface net heat flux and wind stress on chlorophyll variability is further evidenced in NOWIND experiment. Simulated surface chlorophyll concentrations in the NOWIND decreased during winter as a result of weaker vertical advection of nitrate from the base of the nutricline, while the seasonal signal characterized by a small increase in chlorophyll concentrations in winter is maintained as a consequence of heat loss at the surface which deepened the mixed layer depth.

In addition to the seasonal cycle of nutrients input, the temporal change of surface chlorophyll in the region is also a consequence of the interaction between phytoplankton and zooplankton in the water column. The seasonal cycle of surface chlorophyll results from an increase in phytoplankton biomass, which is dominated by nano-phytoplankton. Zooplankton seems to have a greater impact on the seasonal variability of phytoplankton biomass in the region. Zooplankton biomass is not affected by the deepening MLD during wintertime.

Understanding the physical mechanisms that control the seasonal cycle of chlorophyll is important to predict the biogeochemical response to physical forcing. The present study helps to delineate strategies for better management of marine living resources under climate change scenarios, with respect to the strengthening of winds and the sea surface temperature rise in the Indian Ocean.

Acknowledgements

This work was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Progama de Pós-graduação Ciência para o Desenvolvimento (CAPES-PGCD) scholarship, which is a collaboration between Ministério da Educação, Brazil and Instituto Gulbenkian de Ciência, Portugal. The first author thanks Rodrigo Mogollón for his useful suggestions. The second author thanks Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil, Bolsa de Produtividade em Pesquisa (Process 306971/2016-0).

A. Appendix: Validation

This section is for additional validation of the model results used in this work. It is organized by the following order: (i) Vertical profiles of temperature, salinity and nitrate in the Northern Mozambique Channel; (ii) Seasonal Variation of Sea Surface Temperature (SST) and the difference of SST between the model and observations; and (iii) Seasonal variation of Sea Surface Salinity (SSS) and the difference of SSS between the model and observations. The seasonal variation of SST and SSS are for the whole grid domain. For the vertical profiles, we used climatological data from CARS2009 (www.cmar.csiro.au/cars). For comparison between SST and SSS data of ROMS and observations, additional datasets are used. The descriptions of the additional datasets used in this section are below. Model realism on seasonal variation of nitrate for the whole domain were not included because of the scarcity of observational data. Overall, ROMS capture much of the seasonal and spatial variability when compared to observational data.
A.1. Vertical profiles of temperature, salinity and nitrate

The model performance on the seasonal scale is evaluated quantitatively using Taylor Diagram for the summer (December, January and February) and winter (June to August) seasons (Fig. 13). The analysis corresponds to the vertical profiles of temperature, salinity and nitrate in the Northern Mozambique Channel (see Fig. 1-b, for geographic location). Both ROMS configurations, parent (dotted line) and child (dashed line), are compared to observational data from CARS (continued line). The blue lines correspond to the averaged data of the winter period, while the black lines are of the summertime. Vertical profiles of temperature, salinity and nitrate in the child domain are better compared to CARS. Parent also follows the pattern of observations, although slight differences in magnitude, especially for temperature and salinity. For instance, parent superestimate the values of temperature and salinity in the upper 100 m depth during winter. In summer, both parent and child superestimate the salinity in the first layers. Nitrate varies slightly from summer to winter season in the upper layers (0 - 100 m) in both parent and child, with an increase in the concentrations during the wintertime. Taylor diagram indicate that temperature and nitrate \((\text{NO}_3)\) derived from the model are in better agreement with observations in summertime (middle panels) as in wintertime (lower panels). Contrary, modeled salinity shows weaker agreement with observations especially in summer for both parent and child, but in winter the comparison is better for the two configurations.

A.2. Sea Surface Temperature (SST)

The model results of SST are compared to monthly averaged data from Moderate Resolution Imaging Spectro-radiometer (MODIS) SST product for the period of 2002 and 2014. This observational dataset is distributed by NASA (http://oceancolor.gsfc.nasa.gov). The dataset is a level-3 standard mapped image of SST with daily temporal resolution and 4.6 km spatial resolution. High SST values from the model during summer followed by intermediate values in fall within the Mozambique Channel, are well compared to MODIS, despite ROMS superestimates SST. During winter and spring time, when temperature drops to lowest values, the model underestimate the SST, especially in the northern part of the Mozambique Channel (Fig. 14). The maximum difference between the model and observation occur in summer and winter and rarely exceed +/- 1 degree Celsius in major part of the domain (Fig. 15).

A.3. Sea Surface Salinity (SSS)

To validate the Sea Surface Salinity (SSS) from the model, we used the data obtained from climatological dataset - the Indian Ocean HydroBase (IOHB). The dataset consists of a 1° x 1° gridded climatology designed especially for the Indian Ocean (Kobayashi and Suga, 2006). The modeled SSS is in agreement with the observations in terms of spatial and temporal variability in the domain, except in the coastal area of Northern Madagascar Island (Fig. 16). In this particularly region of the northern Mozambique Channel, a tongue of lower SSS is well reproduced by ROMS in summer. ROMS also indicate that during the fall time, the contribution of SEC in lowering salinity as stated by DiMarco et al. (2002) is well reproduced in the entire region of NMC. The model superestimate SSS values in about 0.2 \(\text{PSU}\) within the Mozambique Channel with focus to the summertime. However, during winter period, SSS from ROMS is better compared to observation, with the difference falling in less than 0.2 \(\text{PSU}\) in the vast domain (Fig. 17).
Figure 13: Vertical profile of temperature (Temp. - a), salinity (Sal. - b), and nitrate (NO$_3$ - c). Continued line corresponds to observational data from CARS, dashed line is for the child domain, and dotted line is for parent. Blue lines are from winter while black lines are from summer periods. The red dots represented by letters A, B and C in the Taylor diagram, corresponds to observations, parent and child, respectively. Panels in the middle are for the analysis in summer, while lower panels are for winter time.
Figure 14: Comparison of Sea Surface Temperature (SST) between ROMS (upper panels) and MODIS (lower panels), at seasonal scale in the Mozambique Channel. The analysis from ROMS corresponds to Child and the data is derived from monthly mean SST of the last 5 years simulations. MODIS is a monthly mean data averaged from daily SST for the period between the years of 2002 and 2014. ROMS capture much of the seasonal and spatial variability as SST from MODIS. Summer months (December, January and February) are warmer, followed by the fall months (March, April and May). Winter (June, July and August) is the coldest season and spring (September, October and November) is the season with intermediate SST. Colors are in [°C].

Figure 15: Seasonal mean differences of averaged Sea Surface Temperature (SST) between ROMS and MODIS. Positive values indicate that ROMS superestimates SST in the domain, while negative values corresponds the regions where ROMS underestimates SST. Colors are in [°C].
Figure 16: Same as Fig. 14, but for Sea Surface Salinity (SSS). Contour colors are in $PSU$.

Figure 17: Same as Fig. 15, but for Sea Surface Salinity (SSS). Contour colors are in $PSU$. 

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References


