Variations in surface phytoplankton size structure of a cyclonic eddy in the southwest Indian Ocean

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ABSTRACT

Phytoplankton size classes were derived from weekly-averaged MODIS Aqua chlorophyll *a* data over the southwest Indian Ocean in order to assess changes in surface phytoplankton community structure within a cyclonic eddy as it propagated across the Mozambique Basin in 2013. Satellite altimetry was used to identify and track the southwesterly movement of the eddy from its origin off Madagascar in mid-June until mid-October when it eventually merged with the Agulhas Current along the east coast of South Africa. Nano- and picophytoplankton comprised most of the community in the early phase of the eddy development in June, but nanophytoplankton then dominated in austral winter (July and August). Microphytoplankton was entrained into the eddy by horizontal advection from the southern Madagascar shelf, increasing the proportion of microphytoplankton to 23 % when the chlorophyll *a* levels reached a peak of 0.36 mg m^{-3} in the third week of July. Chlorophyll *a* levels declined to < 0.2 mg m^{-3} in austral spring (September and October) as the eddy propagated further to the southwest. Picophytoplankton dominated the community during this spring period, accounting for > 50 % of the population. As far as is known, this is the first study to investigate temporal changes in chlorophyll *a* and community structure in a cyclonic eddy propagating across an ocean basin in the southwest Indian Ocean.

INTRODUCTION

Satellite altimetry and ocean colour data was used to track the origin and development of a cyclonic eddy in the Mozambique Basin (MB) in preparation for an in situ investigation during 17–23 July 2013 (Lamont and Barlow, 2017; Barlow et al 2017). Satellite data continued to be observed during and after the research cruise in order to follow the movement of the eddy towards the Agulhas Current ecosystem over a 4 month period. The satellite chlorophyll data was useful to track changes in surface phytoplankton biomass across the MB, both spatially and temporally. The size distribution of phytoplankton communities plays a key role in the trophic structuring of ecosystems, where communities dominated by larger-sized phytoplankton usually have higher rates of photosynthesis and are able to export organic matter through shorter food chains, while ecosystems dominated by smaller-size phytoplankton are usually characterized by more complex food webs underpinned by stronger microbial activity and recycling of organic material (IOCCG 2014). Thus, observations of phytoplankton size structure are crucial to improve our understanding of marine ecology, biogeochemistry, and ecosystem functioning (IOCCG 2014). More detailed information on the size class composition of phytoplankton in the eddy can be obtained by applying the three-component model of Brewin et al (2010) that computes the fractional contributions of micro- (>20 µm), nano- (2–20 µm) and picophytoplankton (<2 µm) to the overall chlorophyll *a* concentration. The Brewin et al (2010) model has been retuned using in situ pigment data for application to the southern African marine region and used to investigate the changes in seasonal and monthly climatologies of phytoplankton size fractions in various sub-regions (Lamont et al 2018a). In this study, the retuned Brewin et al (2010) model was applied to satellite chlorophyll *a* data for the MB in order to track the fractional variability in phytoplankton size classes in the cyclonic eddy as it propagated towards the east coast of South Africa between June and October 2013. The objectives of the study are to: (1) track the total chlorophyll *a* within the eddy across the Basin to assess variability in phytoplankton biomass; (2) assess changes in the proportions of micro-, nano- and picophytoplankton in relation to seasonal progression through austral winter and spring.

METHODS

A comprehensive description of the retuning of the Brewin et al (2010) model is presented in Lamont et al (2018a, b), together with the final model parameters and statistical assessment of model performance.

Daily maps of Merged Absolute Dynamic Topography (DUACS/AVISO 2014) were used to assess the movement and age of the cyclonic eddy as it propagated across the MB (Figs 1 and 3). The eddy was identified and tracked by means of an eddy detection technique that combines the use of the Okubo-Weiss parameter and closed Sea Surface Height (SSH) contours, as described by Halo et al (2014). Standard weekly-averaged (8-day) chlorophyll a data from MODIS-Aqua (v2018.0), at 4.5 km spatial resolution (NASA 2018) was used to investigate the variations in weekly-averaged chlorophyll *a*, as well as the fractional contributions of micro-, nano-, and picophytoplankton between 18 June and 15 October 2013. The dominance of the various size classes is usually associated with different chlorophyll *a* ranges, where microphytoplankton dominate at high chlorophyll *a*, nanophytoplankton at intermediate chlorophyll *a*, and picophytoplankton at low chlorophyll *a* concentrations (Uitz et al 2006; Aiken et al 2007; Barlow et al 2007). The centre of the eddy was estimated from altimetry data by using the eddy detection technique described above (Halo et al 2014), and values of chlorophyll *a* and the fractional contributions were averaged in a 3x3 pixel window around this location.

To verify the applicability of the re-tuned three-component model (Lamont et al 2018a) for tracking the phytoplankton size structure in the MB eddy, we made use of a transect of HPLC data collected during the passage of the eddy between 17 and 23 July 2013 (Barlow et al 2017). This data is independent of the in situ data used by Lamont et al (2018a) to re-tune the three-component model. The fractions of chlorophyll *a* in the three size classes of phytoplankton were estimated from HPLC data following Brewin et al (2015) and Lamont et al (2018a), consistent with the manner in which Lamont et al (2018a) re-tuned the model. We also made use of the in situ fractions used in Lamont et al (2018a) to parameterize the model, for comparison with the in situ data from the MB eddy. Two relatively clear-sky MODIS-Aqua images (v2018, 4.5 km spatial resolution, NASA 2018) centered on the eddy (on 20 and 24 July 2013) were downloaded from the NASA website (https://oceancolor.gsfc.nasa.gov) and merged (averaged) into a single image, for comparison with the in situ observations (Lamont et al 2018b).

RESULTS & DISCUSSION

The cyclonic eddy was first detected at 26.03^{o}S, 42.82^{o}E on 16 June 2013, where SSH was 0.76 m and geostrophic velocity vectors showed the beginning of circular flow as the eddy split from a larger cyclonic eddy to the west. By 21 June, SSH had decreased to ~0.69 m and geostrophic velocity increased as the emerging eddy moved further southeast to 25.90^{o}S, 42.10^{o}E (Fig 1a). The eddy was clearly distinguished as a separate feature by 29 June, with geostrophic velocities of 0.5–1 m s^{-}1 and a minimum SSH of ~0.5 m and had moved southwest to 26.30^{o}S, 41.60^{o}E (Fig 1b). The eddy continued propagating southwest and by 17–22 July, it was positioned at 27^{o}S; 40.50^{o}E (Fig 1c, d) and had a diameter of about 250 km, at which time it was sampled during the research cruise (Lamont and Barlow, 2017; Barlow et al 2017). Fig 1a–d depicts an apparent extension of the southern extension of the East Madagascar Current (SEMC), with generally westerly flow from 17–29 June shifting to a more southwesterly direction by 17–22 July. However, it is more likely that this westerly to southwesterly flow resulted from the particular spatial structuring and interaction of the intense mesoscale eddy field to the southwest of Madagascar (Fig 1a–d). Of significance is the locality of the cyclonic eddy along the northern edge of this westerly to southwesterly flow (Fig 1a–d).

Elevated chlorophyll a was observed across the southern shelf of Madagascar (26–26.5^{o}S, 44–47^{o}E; Fig 1e). Some of this elevated chlorophyll *a* appears to be advected from the shelf along the northern edge of the SEMC flow towards the eddy (Fig 1e,f,) and then entrained around the perimeter of the eddy by the cyclonic flow during 26 June to 3 July (Fig 1f). Chlorophyll *a* levels had increased to 0.4–0.6 mg m^{-3} within the eddy by 12–19 July, with slightly higher values along the southern perimeter (Fig 1g). Elevated chlorophyll *a* levels within the eddy were maintained through 20–27 July (Fig 1h).

The fractional contribution indicated that nano- and microphytoplankton were dominant on the southern shelf of Madagascar for the period 18 June to 27 July, while picophytoplankton contributed < 20 % (Fig. 2). Similarly, nano- and picophytoplankton comprised the community within the cyclonic eddy over the period 18 June to 3 July but the micro- and nanophytoplankton proportions increased around the periphery of the eddy during 26 June to 3 July (Fig. 2b). Micro- and nanophytoplankton continued to increase within the eddy during 12-19 July and 20-27 July (Fig. 2c, d), with the highest proportion being located around the southern sector over 12-19 July (Fig. 2c). The fractional contribution of picophytoplankton declined over 12-19 July and 20-27 July (Fig. 2k, l) as the micro- and nanophytoplankton proportions increased.

The eddy continued to move further west during August 2013, growing in size as it matured and merged with other cyclonic features, to reach 27°S, 38.5°E by 16 August (Fig 3a). Geostrophic velocity was maintained at 0.5–1 m s^{-1} and the SSH at the core declined to a minimum of 0.38 m, after smaller cyclonic eddies to the north and east merged with the eddy in question . Patchy distribution of chlorophyll *a* within the eddy was observed over 28 July to 12 August and chlorophyll-rich water still seemed to be transported from the southern Madagascar shelf to the eddy. By 13–20 August, chlorophyll *a* within the eddy had declined to 0.2–0.3 mg m^{-3} (Fig 3b). Fractional analysis showed that there was still some microphytoplankton within the eddy during 28 July to 12 August, but this size fraction declined to less than 15% thereafter (Fig 4a). Nanophytoplankton was the dominant fraction in the eddy during August 2013 (Fig 4b), but the picophytoplankton contribution increased from ~35% in the first half of August to ~40% in the second half (Fig 4c).

Southwesterly propagation of the eddy continued through September to mid-October 2013, moving from 27.5°S, 3652°E on 9 September to 28.3°S, 34.1°E by 11 October, close to the Agulhas Current system off the east coast of South Africa (Fig 3c, e). The eddy appeared to be in a declining phase over this period as it decreased in size during its movement towards southern Africa. Chlorophyll *a* levels in the eddy decreased from ~0.25 mg m^{-3} to 0.15 mg m^{-3} over this period, being similar to the surrounding waters in the western sector of the MB (Fig 3d, f). The microphytoplankton fraction in the eddy was very low (Fig 4d, g), with nanophytoplankton declining (Fig 4e, h) and the picophytoplankton contribution increased in September (Fig 4f). In October, the nanophytoplankton contribution declined further (Fig 4h) and picophytoplankton was then the dominant fraction within the eddy (Fig 4i).

Fig 5 shows more detail of the temporal changes in the eddy as it propagated across the MB. The SSH was 0.76 m at the centre when the eddy was formed on 16 June 2013 and decreased steadily to 0.47 m by 22 July. Between 22 July and 5 August, a small increase to 0.53 m was observed (Fig 5a), after which SSH declined sharply to a minimum of 0.38 m on 15 August. This was followed by a steady increase to 0.55 m on 8–11 September. A further decrease in SSH to 0.46 m on 23–26 September occurred, and then SSH increased again to 0.6 m by 11 October and remained stable until the last day (18 October) the eddy was detected (Fig 5a). The mean 8-day chlorophyll *a* levels at the centre of the eddy were 0.21–0.22 mg m^{-3} for 18–21 June and 26 June to 3 July, but increased to a maximum of 0.36 mg m $^{-3}$ by 20–27 July 2013 (Fig 5a). Chlorophyll *a* then decreased steadily to 0.24 mg m $^{-3}$ (21–28 August), followed by a slight increase to 0.26 mg m $^{-3}$ (29 August to 5 September), before it continued to decline, reaching 0.14 mg m $^{-3}$ by 8–15 October (Fig 5a). The size fractionation indicated that pico- and nanophytoplankton comprised most of the community in the centre of the eddy in June 2013, with the nano- fraction becoming dominant through July and August, and the picophytoplankton then dominating in September and October (Fig 5b). The microphytoplankton contribution was low overall and reached a maximum proportion of 23% over 20–27 July when the maximum chlorophyll *a* level was observed in the eddy (Fig 5b).

The application of the three-component model of Brewin et al (2010) to satellite ocean colour data has proven to be useful for tracking the surface phytoplankton community within a cyclonic eddy as it propagated across the MB over a four-month period from mid-June to mid-October 2013. This is the first study to investigate the temporal changes in community structure within an eddy that moves across an ocean basin in the southwest Indian Ocean, and useful quantitative information was obtained on the variability of chlorophyll *a* levels and the proportions of micro-, nano-, and picophytoplankton. Although the community within the eddy was generally similar to the population in the surrounding waters of the MB, in the early stage of development, the eddy was seeded with microphytoplankton from the southern Madagascar shelf by horizontal advection and subsequent entrainment, rather than by vertical uplift of nutrient-rich waters into the euphotic zone as is common in cyclonic eddies. This was due to the particular location of the eddy close to the Madagascar shelf, as well as the spatial structuring of surrounding mesoscale features which served to enhance southwestward flow around the southern tip of Madagascar and export of waters from the shelf.

Overall, the community within the propagating eddy and across the MB was dominated by nanophytoplankton during the austral winter months of July and August, but this changed to picophytoplankton dominance in austral spring during September and October. This suggested that, besides the injection of shelf waters and phytoplankton communities during the interaction of the eddy with the southern Madagascar shelf in July 2013, the most prominent changes in surface phytoplankton communities over the four-month lifetime of the eddy were associated with the seasonal variations from winter to spring and summer. Apart from the satellite observations, there are no phytoplankton measurements within the eddy subsequent to the research cruise in July 2013 (Lamont and Barlow, 2017; Barlow et al 2017) and thus it is not possible to verify using in situ data if such changes indeed took place. Furthermore, additional research in the form of more well-designed in situ studies, together with more detailed and directed analysis of satellite observations and model output, are required to determine if the pattern of variability described in the current study was unique to the MB eddy, or whether it is typical of all long-lived cyclonic eddies within the region.

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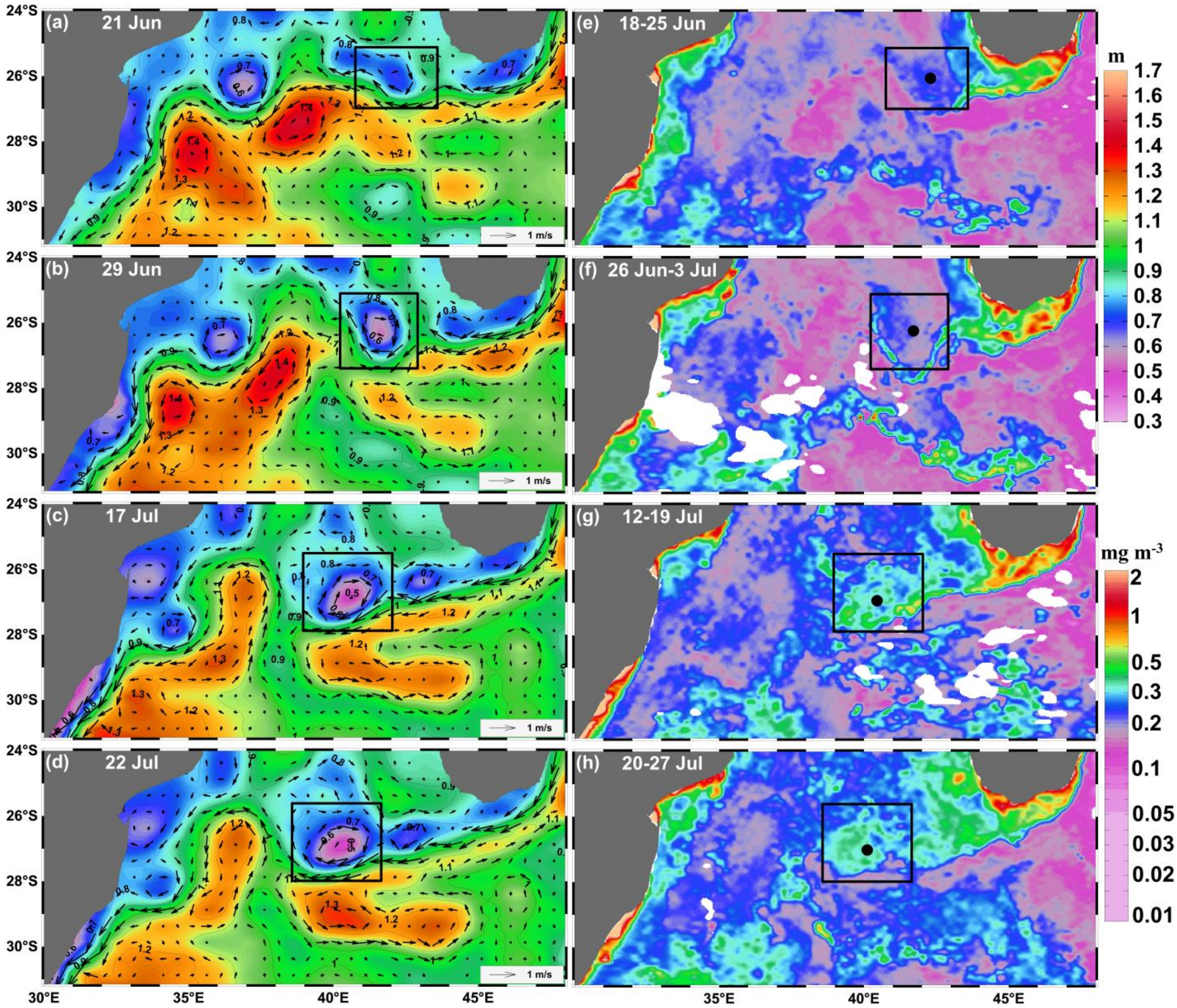

Fig 1. (a–d) Daily Sea Surface Height (colour contours) and geostrophic velocity (black arrows) on selected days for 21 June to 22 July 2013; and (e–h) 8-day MODIS Aqua chlorophyll *a* composites for 18 June to 27 July 2013, over the Mozambique Basin. Black boxes highlight the location of the cyclonic eddy and black dots indicate the centre of the eddy. White areas indicate missing data due to cloud cover.

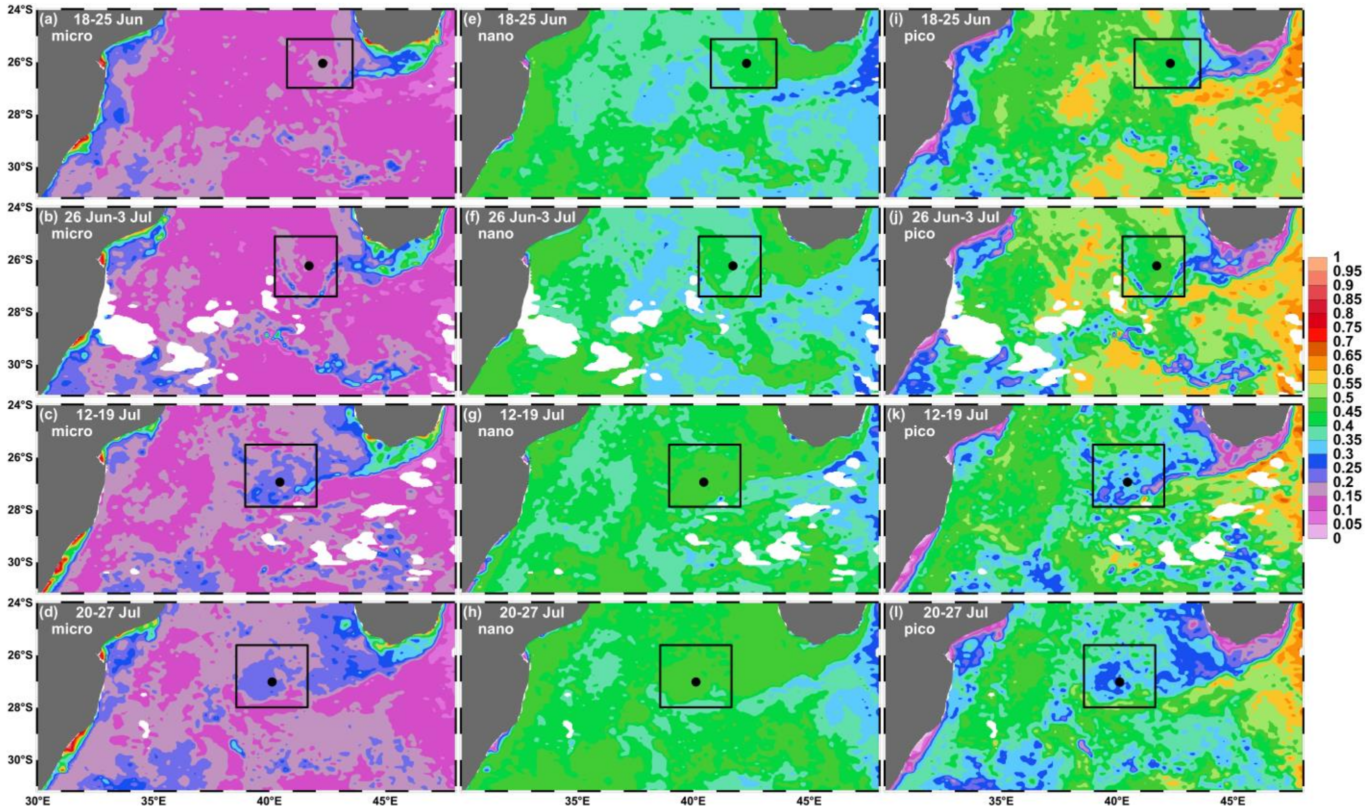

Fig 2. Fractional contribution of (a–d) micro-, (e–h) nano-, and (i–l) picophytoplankton to MODIS Aqua chlorophyll *a* for 18 June to 27 July 2013 over the Mozambique Basin. Black boxes highlight the location of the cyclonic eddy and black dots indicate the centre of the eddy. White areas indicate missing data due to cloud cover.

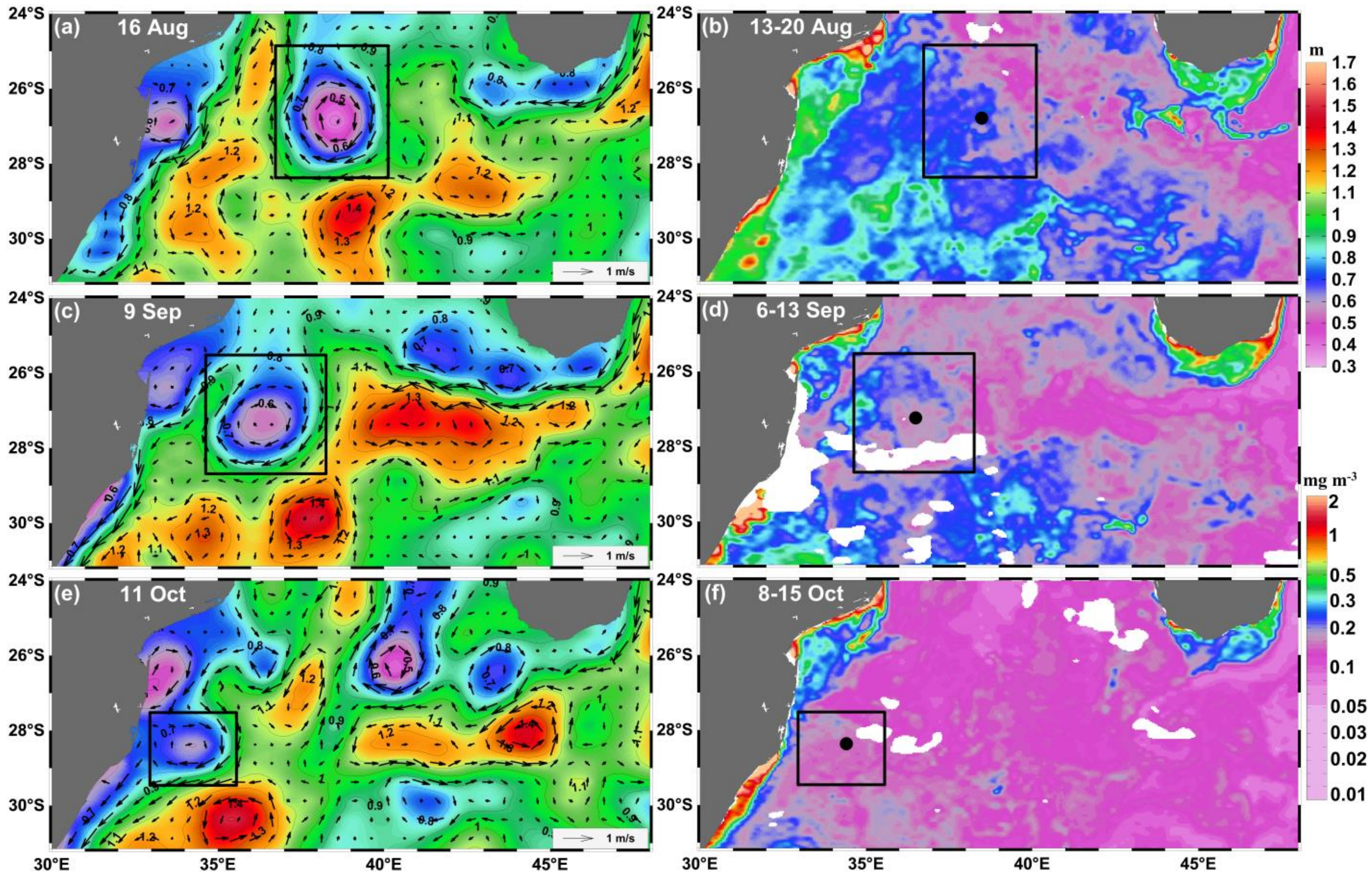

Fig 3. Daily Sea Surface Height (colour contours) and geostrophic velocity (black arrows) on selected days for (a) 16 August, (c) 9 September, (e) 11 October 2013; and 8-day MODIS Aqua chlorophyll *a* composites for (b) 13-20 August, (d) 6-13 September, (f) 8-15 October 2013, over the Mozambique Basin. Black boxes highlight the location of the cyclonic eddy and black dots indicate the centre of the eddy. White areas indicate missing data due to cloud cover.

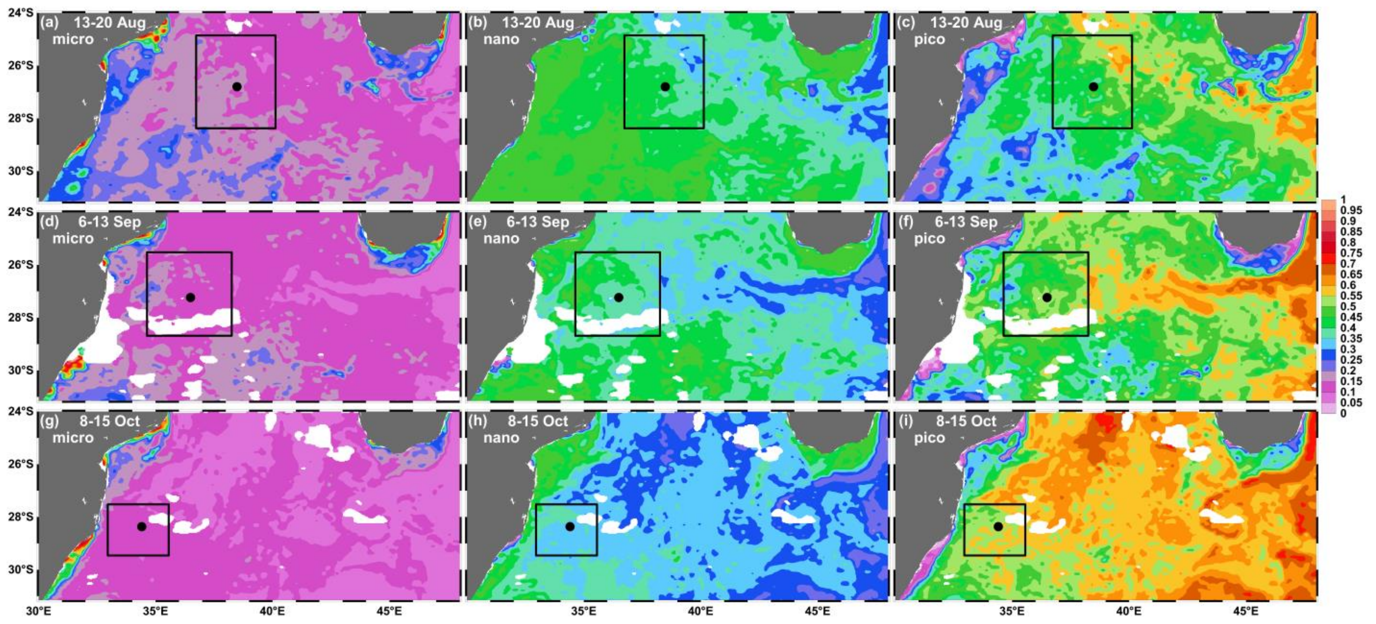

Fig 4. Fractional contribution of (a, d, g) micro-, (b, e, h) nano-, and (c, f, i) picophytoplankton to MODIS Aqua chlorophyll *a* for 13-20 August, 6-13 September and 8-15 October 2013 over the Mozambique Basin. Black boxes highlight the location of the cyclonic eddy and black dots indicate the centre of the eddy. White areas indicate missing data due to cloud cover.

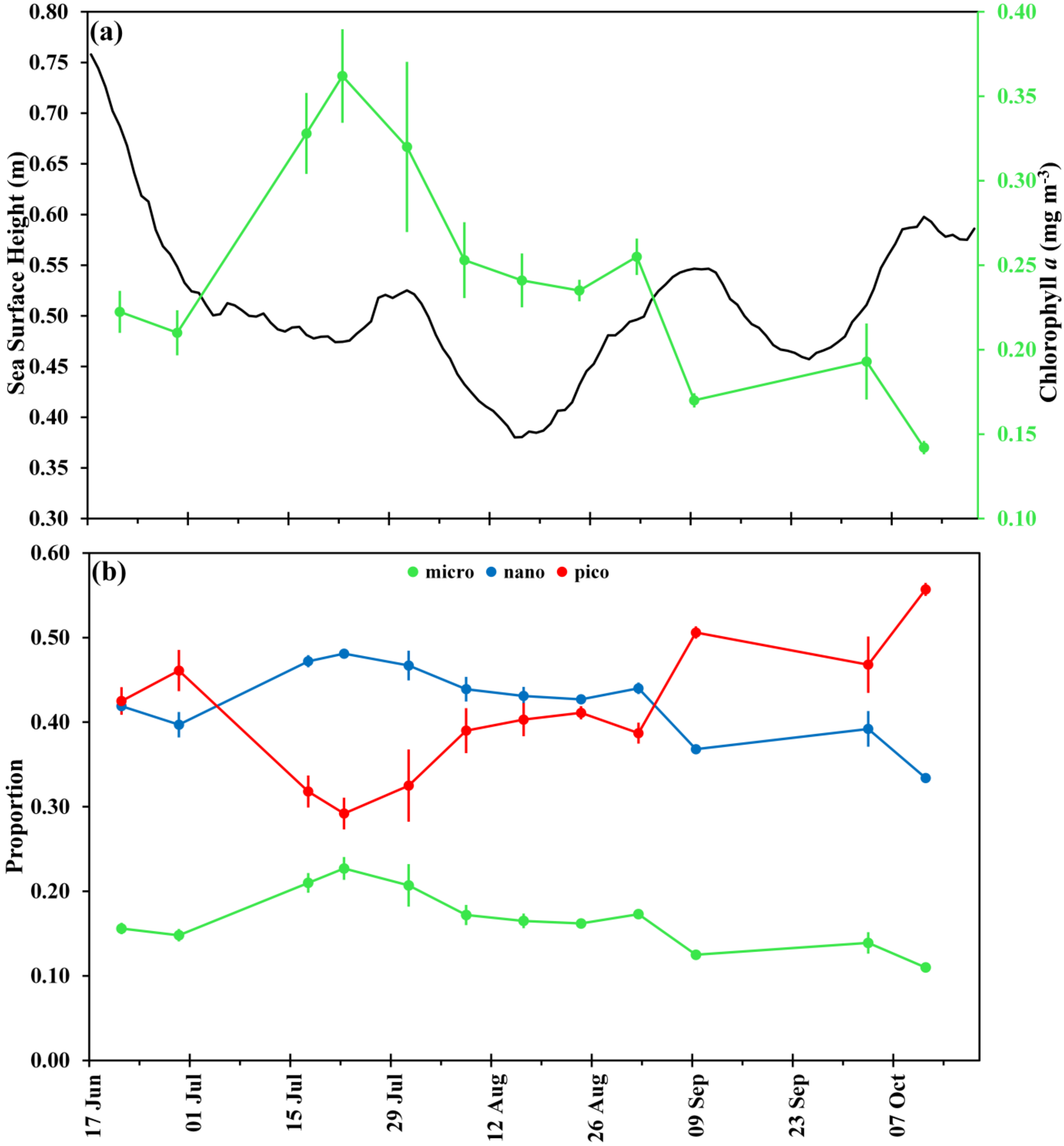

Fig 5. Temporal variation in (a) daily Sea Surface Height (SSH) (black line) and 8-day MODIS Aqua chlorophyll *a* (green line and dots), and (b) the fractional contribution of micro-, nano-, and picophytoplankton at the centre of the cyclonic eddy as it propagated across the Mozambique Basin. Vertical bars indicate the standard deviation of chlorophyll *a* and the fractional contributions of micro- (green dots and line), nano- (blue dots and line), and picophytoplankton (red dots and line) for the 3 x 3 pixel window at the centre of the eddy.