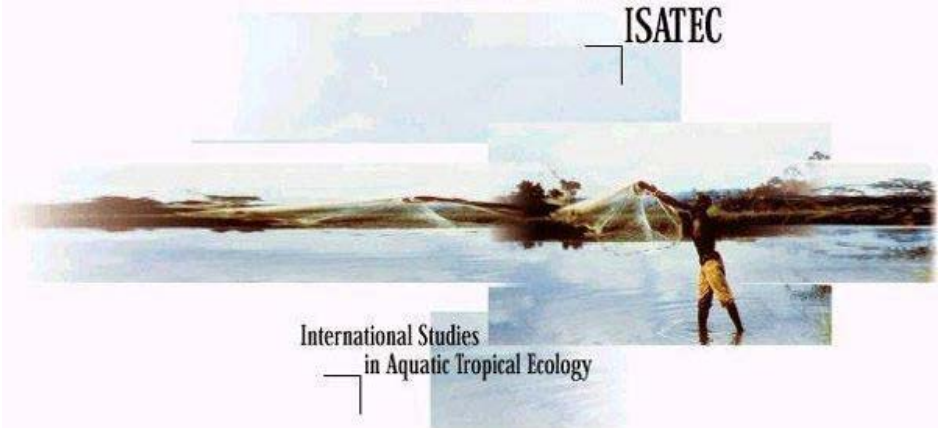

Temporal Variability in the Inshore Particle Fluxes of the Benguela Current Upwelling System of Namibia

by

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August 2014

Temporal Variability in the Inshore Particle Fluxes of the Benguela Current Upwelling System of Namibia

A thesis submitted in partial fulfillment of the requirements for the degree

Master of Science

In

Tropical Aquatic Ecology

by

Victor Miti Libuku

International Studies in Aquatic Tropical Ecology
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Statement according to §10 (11)

Allgemeiner Teil der Masterprüfungsordnungen der Universität Bremen vom 27. Oktober 2010 (General Section of the Master Examination Regulations of the University of Bremen from 27 October 2010):

Hereby I (*Victor Miti Libuku*) declare that I have written this Master's Thesis by my own and without any assistance from third parties.

Furthermore, I confirm that no other sources and resources have been used than those indicated in the thesis itself and that all quotations are marked.

Bremen, 15 August 2014 _____

Table of Content

List of Acronyms

BUS – Benguela Upwelling System
EBUS – Eastern Boundary Upwelling Systems
ESACW – East South Atlantic Central Water
SACW – South Atlantic Central Water
SST – Sea Surface Temperature
N-BUS – Northern Benguela Upwelling System
S-BUS – Southern Benguela Upwelling System
PPR – Primary Productivity Required
Chl a – Chlorophyll a

List of Tables and Figures

Acknowledgements

I would like to express my humble gratitude to:

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Dedication

Namasiku Mubiyana and Chika Libuku

&

Mulela Libuku

Abstract

The particle flux is key process of the biological pump that transports carbon from the atmosphere to the ocean's interior and controls the distribution of nutrients in the ocean. Within this work a particle flux study was conducted in the Benguela upwelling system to determine the particle flux rates on the shelf and better understand the flux drivers on the upwelling system. Particle fluxes were intercepted with a Hydrobios MST-12 time series sediment trap at a water-depth of 60 m off Walvis Bay at the Namibian coast. We could show that the sediment traps were effective in this environment and the particle fluxes ranged between 243 and 4790 mg m^{-2} day^{-1}. Bimodal fluxes were observed on the Benguela shelf with the highest fluxes in austral spring. The main contributor to the fluxes was opal indicating the domination of diatoms on the shelf. Calcium carbonate only increased in the second flux maximum after the upwelling season due to an increase in nutrients from a pulse of SACW during the upwelling season. Lithogenic matter was higher on the shelf than reported in offshore studies with maxima of 468 mg m^{-2} day^{-1}. A direct relationship between wind stress and fluxes (wind maxima preceding flux maxima by 3 months) was observed and there was an inverse relationship between wind SST and fluxes. SST decreased due to an increase in wind stress during the upwelling season thus proving to be a good upwelling indicator, and when winds subsided, SST began to rise. Productivity and consequently fluxes, in the Benguela were determined to be driven by winds and the contribution of SACW during upwelling. Therefore an increase in upwelling favorable winds would not increase fluxes if SACW contribution does not increase too. Lithogenic matter played an important role as ballast and was funneled into the Atlantic via dry riverbed channels which open up into the Atlantic.

1. Introduction

Introduction

A central task to better understand the global carbon cycle was to study the physicochemical and biological conditions that control the regional variations of particle fluxes and the strength of the organic carbon pump (Berger et al., 1989; Flohr et al., 2014). The biological carbon pump is the term used for the production of organic carbon from dissolved carbon dioxide (CO_2) in the surface mixed layer of the ocean and its transport into the large CO_2 reservoir of the ocean beneath the mixed layer (Volk & Hoffert 1985). The air-sea CO_2 flux is controlled by the pCO_2 difference between the ocean and the atmosphere. If CO_2 is used by primary producers mainly phytoplankton during photosynthesis the pCO_2 decreases and that favors the CO_2 uptake by the ocean. The produced organic matter forms aggregates such as marine snow and fecal pellets (Burd and Jackson, 2009). These particles are exported from the euphotic zone into the deep ocean. This so-called particle flux is a key process of the biological pump that transports carbon from the atmosphere to the ocean's interior. When exported to surface sediments carbon is stored for long periods of time.

Berger et al. (1989) estimated that about 25% of biologically produced carbon leaves the euphotic zone in high production areas such as the coastal upwelling areas, whereas only 10% of carbon is exported in the oligotrophic open-ocean areas of the subtropical gyres. Therefore much scientific interest has been focused on high production regimes, whereas the subtropical gyres have been considered as large ocean deserts due to chronic nutrient depletion and low standing stocks of organisms (Berger, 1989). Furthermore, it is assumed that where primary production is high, a larger proportion of the organic carbon produced by photosynthesis is lost from the surface layer via sedimentation and removed from the atmosphere on geological time-scales (Berger et al., 1989; Eppley and Peterson, 1979).

The Benguela upwelling system is, together with the Peru, Californian, and Canary systems, one of the four major coastal upwelling systems and among the most productive regions of the World Ocean (Giraudeau et al., 2000) Carr, 2001). Being a major site of enhanced productivity, the Benguela Upwelling System (BUS) has been proposed to play a crucial role in the control of the oceanic carbon budget and atmospheric CO_2 levels

(Sarnthein et al., 1988). This high level of primary productivity of the Benguela supports an important global reservoir of biodiversity and biomass of zooplankton, fish, sea birds and marine mammals (Shannon and O'Toole, 2003).

Due to increased terrestrial heating caused by global warming, upwelling favorable winds will intensify and lead to increased productivity of eastern boundary upwelling systems (Bakun et al., 2010). Since increased productivity is assumed to results in increased fluxes (Berger et al., 1989), degradation of this organic matter in the water columns and the sediment may lead to more anoxic conditions and sulfur eruption events (Monteiro et al., 2008) which are not favorable for the fisheries and biodiversity in this upwelling system.

Despite its assumed sensitivity to global change, its high productivity, and its potential role in the global carbon cycle particle fluxes have been measured only during four studies in the Bengueal upwelling system (Wefer & Fischer, 1993; Treppke, 1996; Giraudeau, 2000; Monteiro et al., 2006). Three out of the four studies were conducted at the continental margin (Wefer & Fischer, 1993; Treppke, 1996; Giraudeau, 2000) and only one was carried out on the shelf were upwelling takes (Monteiro et al., 2006, (Lutjeharms et al., 1991). Upwelled water is carried offshore by filaments extending more than1000 kilometers offshore. Considering the assumed sensitivity of costal upwelling systems to global changes and the fact that physicochemical and biological conditions that control the particle flux in the Benguela upwelling systems remain still not fully understood we conducted a particle fluxes stuffy on the Namibian shelf in the year 2013.

2. Hypotheses

Purpose of Study

The sediment trap experiment was carried out in the Benguela Upwelling System shelf to obtain a better understanding of the mechanisms, which control particle fluxes in the upwelling system and to better understand the response of the Benguela Upwelling System to climate changes.

Hypotheses

The working hypotheses for my study were:

i) Wind-driven upwelling controls productivity and particle fluxes.

   Wefer and Fischer (1993) argue that the second seasonal flux peak is due to upwelling but cannot explain the first peak by upwelling.

ii) Sea surface temperature and sea water temperature can be used as an indicator for upwelling.

   Decreases in sea surface temperatures have been used in previous studies to denote upwelling.

iii) Particle fluxes are directly linked to chlorophyll a concentrations indicating productivity.

   Particle fluxes are supposed to be an indication of surface productivity (Fischer et al., 2000).

iv) Productivity and therewith particle flux will increase during the intensification of upwelling in the course of global warming.

   Bakun et al. (2010) state that due to increased terrestrial heating caused by global warming, upwelling favorable winds will intensify leading to increased productivity of eastern boundary upwelling systems.

3. Materials & Methods

Materials and Methods

Study Area

The study was conducted in the Benguela Upwelling System (BUS) of Namibia. The Benguela is one of the four major eastern boundary upwelling systems (EBUS) of the world, it extends from 34°S 28°E (near East London) to 5°S 12°E off Cabinda in Angola. Along with the Canary, Humboldt and California eastern boundary upwelling systems, these EBUS contribute approximately 25% of the Primary Productivity Required (PPR) to sustain global fisheries, however, the BUS is the most productive EBUS with a mean annual primary productivity of 1.25 kg C m^{-2} y^{-1} (Carr, 2001; Hutchings *et al*. 2009; Pauly and Christensen, 1995; Shannon and O'Toole, 2003). The Benguela waters are cool due to upwelling induced by strong south-easterly trade winds that cause a strong offshore Ekman transport of surface water masses, resulting in a north to north-westward flow of the current along the coast (Nelson & Hutchings 1983). The BUS is separated into a northern and a southern subsystem (N- and S-BUS) at about 26°S by the strong Lüderitz upwelling cell, which acts as a perennial barrier (Duncombe Rae, 2005).

The Benguela Current is dominated by two water masses; the Eastern South Atlantic Central Water (ESACW) and the South Atlantic Central Water (SACW), the ESACW is dominant in the S-BUS, whereas the N-BUS consists of a mixture of ESACW and SACW (Duncombe Rae, 2005; Mohrholz et al., 2008). The SACW and the ESACW are in principle of the same origin, however the ESACW mixes with the Indian Ocean Central Water at the Agulhas Retroflection in the Cape Basin, before it enters the BUS from the south, whereas the SACW is carried equator ward into the tropics, by the Brazil Current after confluence with the Malvinas (Falkland) Current, from where it is introduced into the BUS from the north (Gordon, 1981; Gordon et al., 1987). As it travels through the tropics the SACW gets older and is enriched in nutrients as well as depleted in oxygen, due to the respiration of organic matter that is exported from the more sunlit tropical surface ocean into the subsurface waters (Mohrholz et al., 2008).

Studies done by Mohrholz and others, between January 2004 and September 2005 off Walvis Bay in the N-BUS revealed that the inflow of SACW and ESACW has a pronounced seasonality (Mohrholz et al., 2008). During the peak upwelling season between May and October, when south-easterly trade winds are prevalent along the Benguela, the ESACW dominates the subsurface water-mass, whereas during the austral summer when the poleward undercurrent strengthens, the SACW can contribute up to 80 % to the subsurface water mass (Mohrholz et al., 2008; Monteiro et al., 2008).

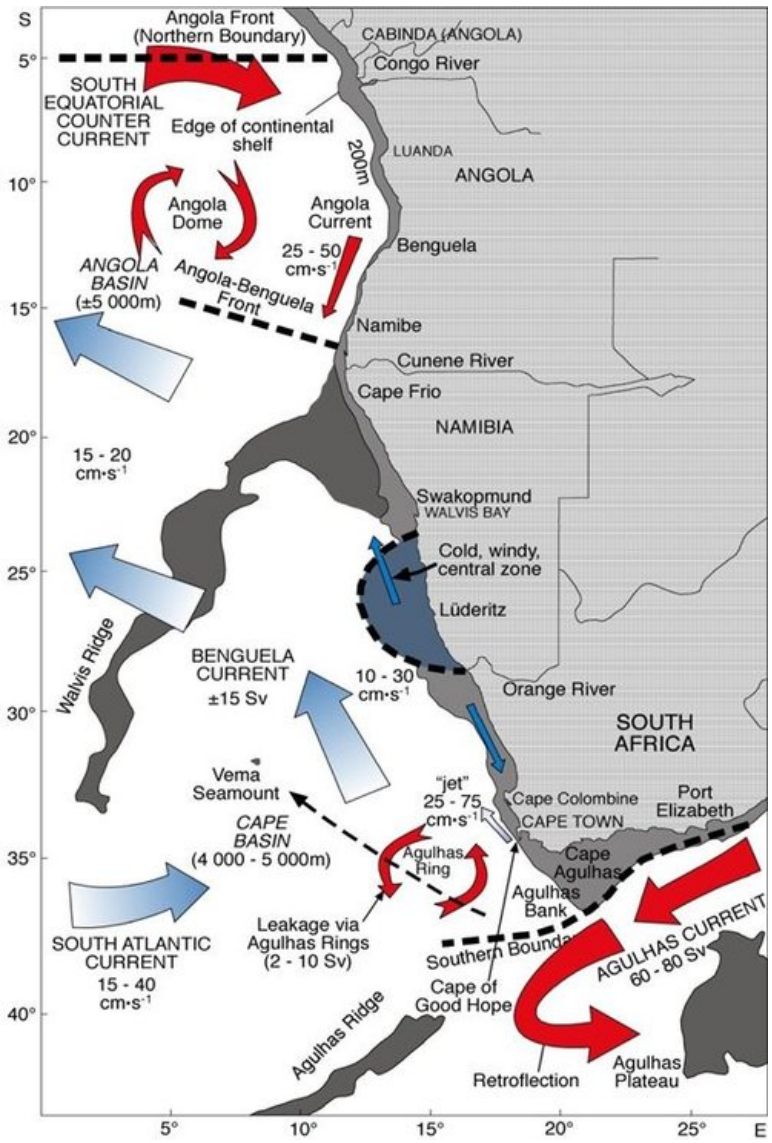

Figure 1: External and internal boundaries of the Benguela Current Large Marine Ecosystem, bathymetric features and surface (upper layer) currents, adapted from Shannon and O'Toole (2003), (source http://genus.zmaw.de/).

Materials and Methods

Sediment trap samples

A Hydrobios MST-12 time series sediment trap with a collection area of 0.015 m^2 was deployed from January to December 2013 at 23°01.350'S 014°01.667 'E in the eastern Atlantic Ocean (Figure 2). The trap was deployed at a depth of 57 m in 130 m deep water and set at 30 day sampling intervals (Table 1). However the January to February 2013 sample bottle was lost during deployment and therefore there is no data for the first month.

Table 1: Rotation schedule of sediment trap with the start and stop date of each sampling period.

Start Date	Stop Date		Duration [days]
20-01-13	18-02-13	Feb	30
19-02-13	20-03-13	Mar	30
21-03-13	19-04-13	Apr	30
20-04-13	19-05-13	May	30
20-05-13	18-06-13	Jun	30
19-06-13	18-07-13	Jul	30
19-07-13	17-08-13	Aug	30
18-08-13	16-09-13	Sep	30
17-09-13	16-10-13	Oct	30
17-10-13	15-11-13	Nov	30
16-11-13	15-12-13	Dec	30

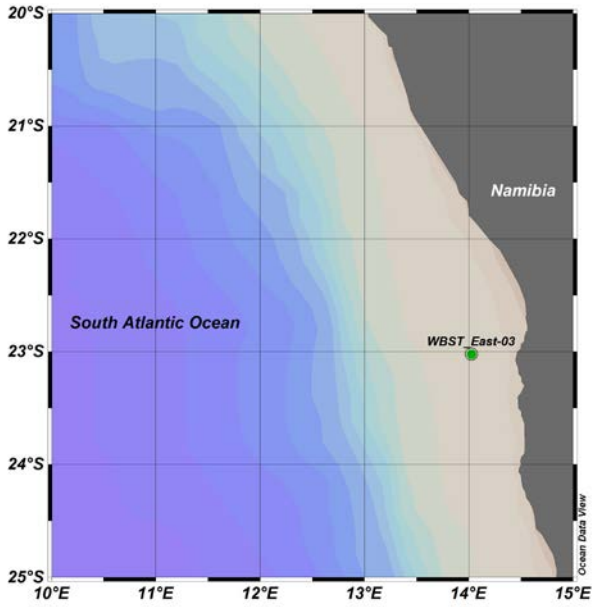

Figure 2: Positon of Sediment trap moorin (WBST East-03) on the Benguela shelf.

Prior to deployment, the sample bottles were filled with Milli-Q water, also 70 g/L NaCl and 3.3 g/L $HgCl_2$ were added in order to minimize diffusive processes and retard microbial activity in the trapped material.

Samples once retrieved were stored at 4°C. The samples were then macroscopically analyzed for their composition, before being sieved through a 1mm mesh nylon sieve to exclude zooplankton that had been able to swim through the trap entrance baffle into the sample bottles. The > 1 mm fraction contained mostly pteropods and copepods, of which a large amount consists of swimmers and it was thus not included in calculations of total fluxes. The swimmers on the 1 mm sieve were gently washed with a small volume of filtered seawater to dislodge any <1 mm material entrapped on the sieve; smaller copepods were picked with forceps from the <1 mm fraction because they are active swimmers. The <1 mm sample fractions were split into aliquots by a high-precision rotary splitter (McLane WSD-10), then filtered on pre-weighed Nuclepore filters of 0.45 mm pore size and dried at 40 ºC for 72 h.

The dried sediment on the filter was then weighed and scraped from the filter, crushed and homogenized with an agate mortar and pestle into a fine powder. The dry mass was used for calculating the total fluxes and for component analyses.

Analytical methods

Total Carbon, Total Nitrogen and Total Organic Carbon

The homogenized powder sediment was weighed into 9 mm tin cups for total carbon and total nitrogen as well as into 9 mm silver cups (pre-combusted at 550°C) for total organic carbon analyses. The total organic carbon samples were acidified three times with 1N NaCl to remove any inorganic carbon. The acidified samples were dried at 40ºC for 24 h, and then subsequently acidified further.

Total carbon and total nitrogen as well as total organic carbon were measured by flash combustion using a Carlo Erba Science 1500 CNS Analyser in the Biogechemical Laboratory of the University of Hamburg. For calibration acetanilide (C: 71.09 %; N: 10.36 %) was used as a standard. The standard deviation of the duplicate analyses was 0.15% for carbon and 0.005% for nitrogen. Total inorganic carbon was calculated as the difference between total carbon and total organic carbon.

Biogenic Opal

The biogenic silica was extracted from sediment samples with an alkaline solution and then the dissolved silicon concentration in the extract was measured by molybdate-blue spectrophotometry (Mortlock and Froelich, 1989). Biogenic opal extraction and measurements were executed in the Biogeochemical Laboratory of the University of Hamburg.

About 1 mg of sample material was weighed into 20 ml PE scintillation bottles. Then 1 ml HCl was added in order to remove calcium carbonate and the sample was dried overnight. Once completely dry, 1 ml H_2O_2 was added to the sample in order to remove organic compounds and it was dried again overnight.

10 ml of 7% Na_2CO_3 was added and the bottles were closed and heated at 85°C for 5 hours. Exactly 0.2 ml of the sample was taken up and transferred into bottles containing 10 ml Milli-Q water. Subsequently 0.1 ml ammonium heptamolybdate was added and the sample was shaken. After waiting 30 min, 0.1 ml oxalic acid and 0.1 ml ascorbic acid were added and the sample was shaken again. Finally after waiting for 60 min, the blue complex was measured photometrically at 800 nm using a Dr. Braun photometer. The

photometer was calibrated against a Merck Silicon standard solution with 1000 mg L^{-1} Si. All samples were measured twice with a relative error of less than 5%.

Satellite Data

Satellite data of Sea Surface Temperature (SST) and Chlorophyll a (Chl a), were obtained from the Giovanni website (http://disc.sci.gsfc.nasa.gov/giovanni) in monthly averages.

Mooring Data

Temperature, salinity and oxygen measurements were obtained from sensors on another nearby mooring by Dr. Volker Mohrholz of the Leibniz Institute for Baltic Sea Research, Rostock -Warnemünde (IOW), deployed in the vicinity of our sediment trap mooring (23.00 °S and 14.05 °E). Percent SACW was determined by Dr. Volker Mohrholz using measured temperature and salinity from the moored sensors.

Wind Data

Wind data were obtained from the National Marine Information and Research Centre in Swakopmund Namibia where hourly wind speed and direction data are recorded. Monthly averages were obtained from these data and used to calculate wind stress along the coast:

$$\tau = r * Cd * v^2 \ [kg\ m^{-1}\ s^{-2}]$$

Where: r = air density (1.22 kg m^{-3})

Cd = drag coefficient (0.0013)

v = speed of wind component parallel to the coast (m s^{-1}) at 10 m above a surface (at Walvis Bay this is the south-north component)

The south-north component was calculated as:

$$Cns = \cos(wd) * ws$$

Where: wd = wind direction

ws = wind speed

Negative wind stress was wind stress in the north to south direction, opposing the south to north component of the wind stress that favors upwelling.

4. Results

Results

The total particle fluxes ranged between 243 and 4790 mg m^{-2} day^{-1} and showed two distinct maxima over the course of the study in 2013. One of the flux maxima occurred in August. However the highest fluxes with up to 4790 mg m^{-2} day^{-1} were recorded in October/November (Figure 5).

The major component of the fluxes was biogenic opal which contributed an average of 61% to the flux mass composition over the duration of the study. Except in the first 3 months of the study biogenic opal was also the major contributor to the monthly fluxes (Figures 3 & 4)

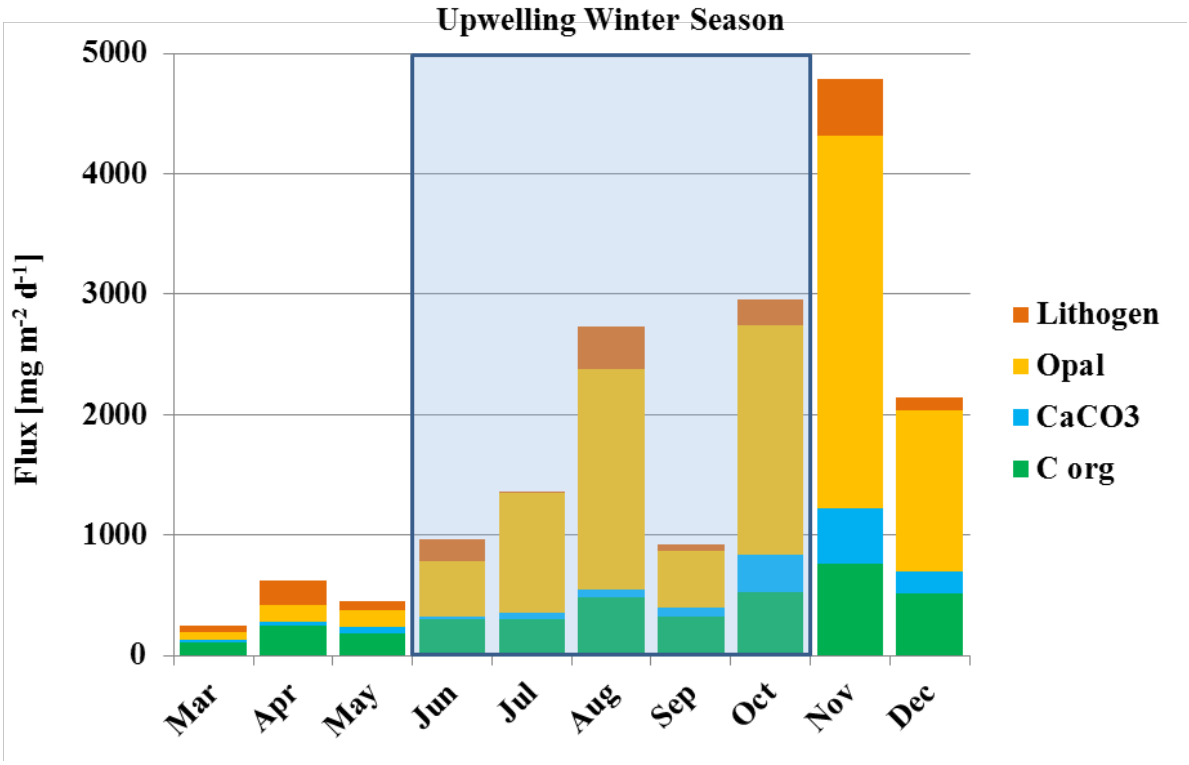

Figure 3: Monthly calculated fluxes and their composition in the Benguela shelf area in 2013.

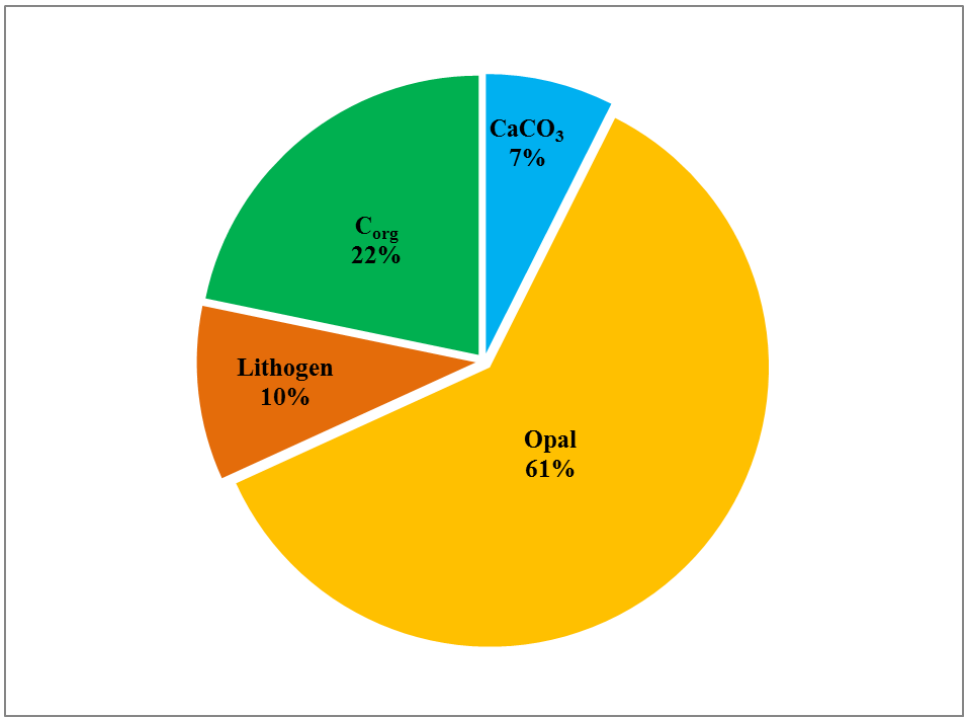

Figure 4: Average flux composition from March 2013 to December 2013.

Organic carbon fluxes ranged between 110 and 760 mg m^{-2} day^{-1}. Organic carbon had a similar trend to that of the overall fluxes in that two organic carbon maxima were also observed. The highest organic carbon fluxes were seen in October/November 2013. Biogenic opal ranged between 61 and 3096 mg m^{-2} day^{-1} and just like organic carbon had pronounced peaks during the two overall flux maxima with the highest opal also being observed during the October/November flux maximum. Calcium carbonate only had one pronounced peak which appeared in the later of the two overall flux maxima. There was a more than six fold increase in calcium carbonate from September to November, when calcium carbonate levels rose from 75 to 465 mg m^{-2} day^{-1}. Calcium carbonate ranged between 19 and 465 mg m^{-2} day^{-1}. Lithogenic matter fluxes ranged between 3 and 468 mg m^{-2} day^{-1}. They also had a similar trend to the overall particle fluxes but there was one other less pronounced lithogenic flux peak which did not coincide with any of the biological flux peaks (Figure 5).

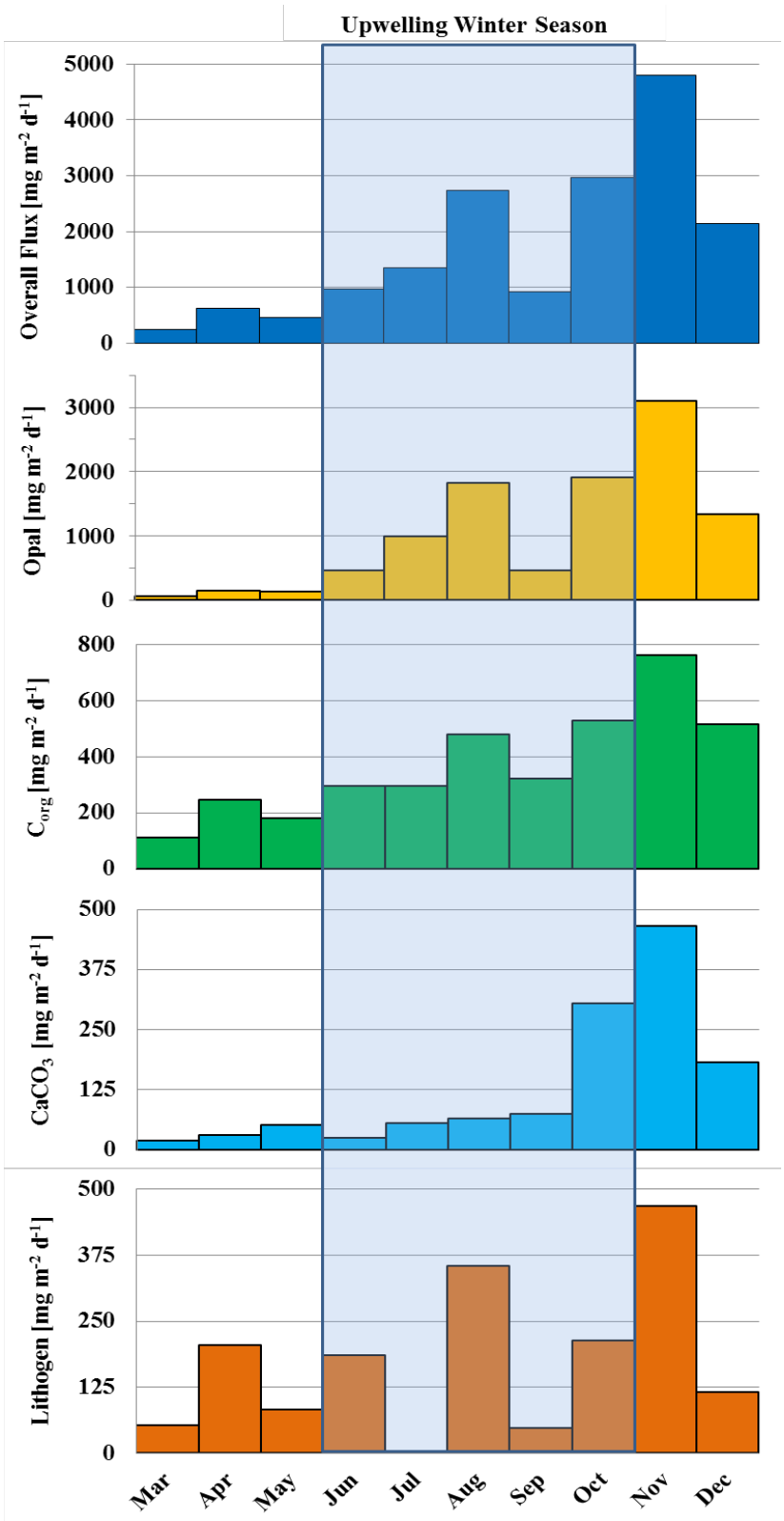

Figure 5: Overall flux and the calculated composition of biogenic opal, organic carbon, calcium carbonate and Lithogenic fluxes in the Benguela shelf area in 2013.

The south-north component of wind stress ranged between -0.008 and 0.005 kg m^{-1} s^{-1}. Positive or upwelling favorable wind stress began in April. By May wind stress along the coast had reached its first maximum of the year. However the wind stress dropped in June and only began to increase in July. Wind stress reached the second and highest maximum by August and from there onwards began to decline.

SST ranged between 13 and 18 °C. SST had already started decreasing from the beginning of the study in March, but the lowest SST was in September, one month after the highest south-north wind stress. The correlation between SST and wind stress had an r^2 = 0.44. A month after wind stress began to decrease temperatures began to rise. Sea water temperature at 90 m only began to decrease from June.

Sea water temperature at 90 m had a 1 °C range. Just like SST, sea water temperature at 90 m was also lowest one month after the highest wind stress and began to increase thereafter, but the relation between wind stress and sea water temperature at 90 m had an r^2 = 0.0598 (Figure 6).

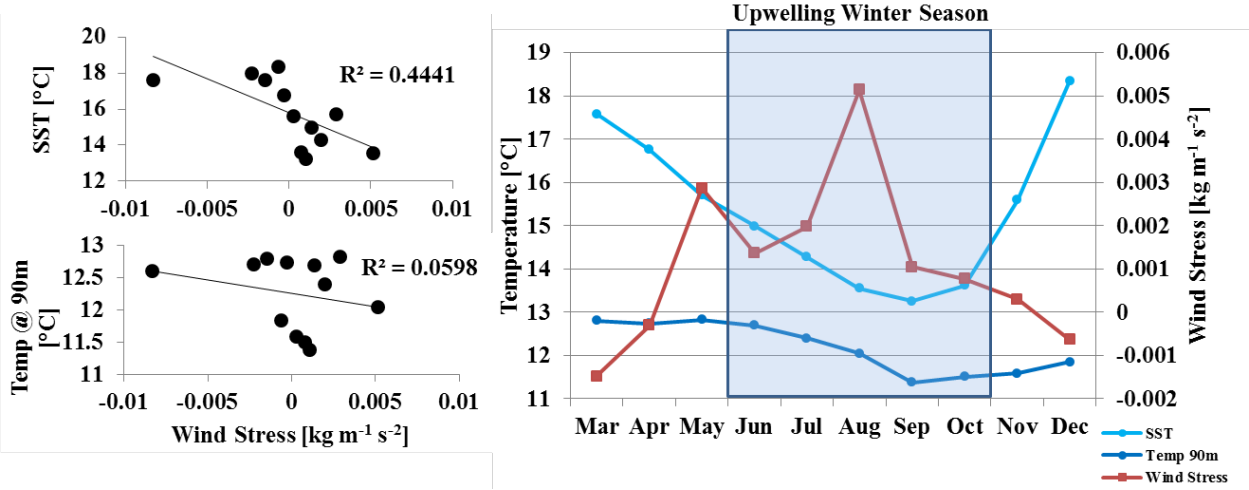

Figure 6: Wind Stress, SST and Temperature at 90 m of Northern the Benguela Upwelling System and their correlation, in 2013.

Chl-a concentrations ranged between 2.8 and 10.4 mg m^{-3}. It had three maximum peaks but only two occurred during the course of the study. The highest peaks were in February and June and the lowest of the 3 peaks was in October. Chlorophyll a did not show a similar trend to that of organic carbon and the correlation between the two had an r^2 = 0.0699. Even shifting chlorophyll a concentrations forward by up to 2 moths did not

improve the relation between chlorophyll a and organic carbon. There was no relation between Chlorophyll a and SST (r^2 = 0.0054) and also between Chlorophyll a and Wind Stress with an r^2 = 0.0019 (Figures 7, 8 & 9).

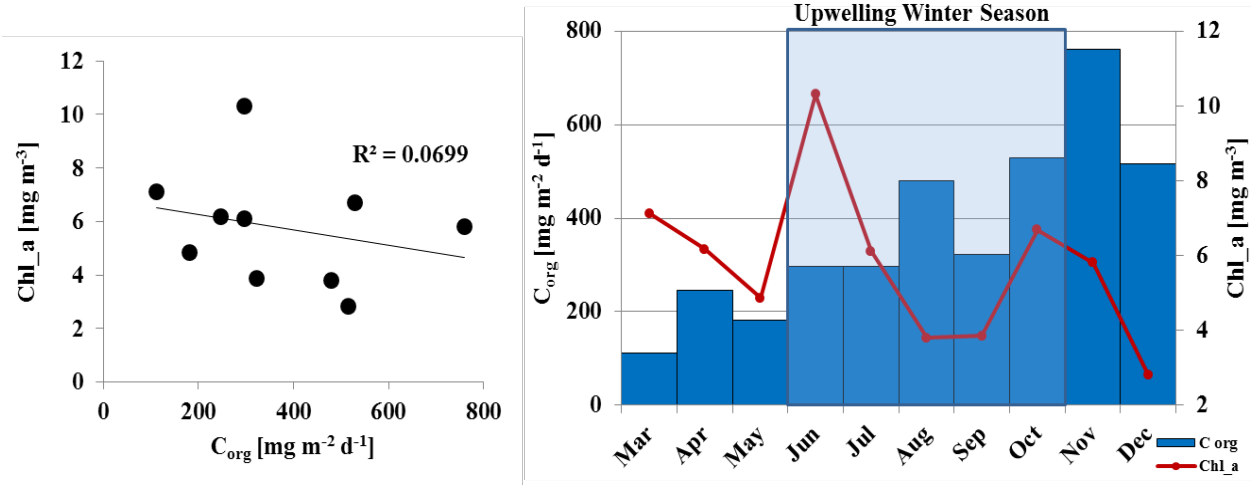

Figure 7: Chlorophyll a and organic carbon in the Benguela, and their correlation in 2013.

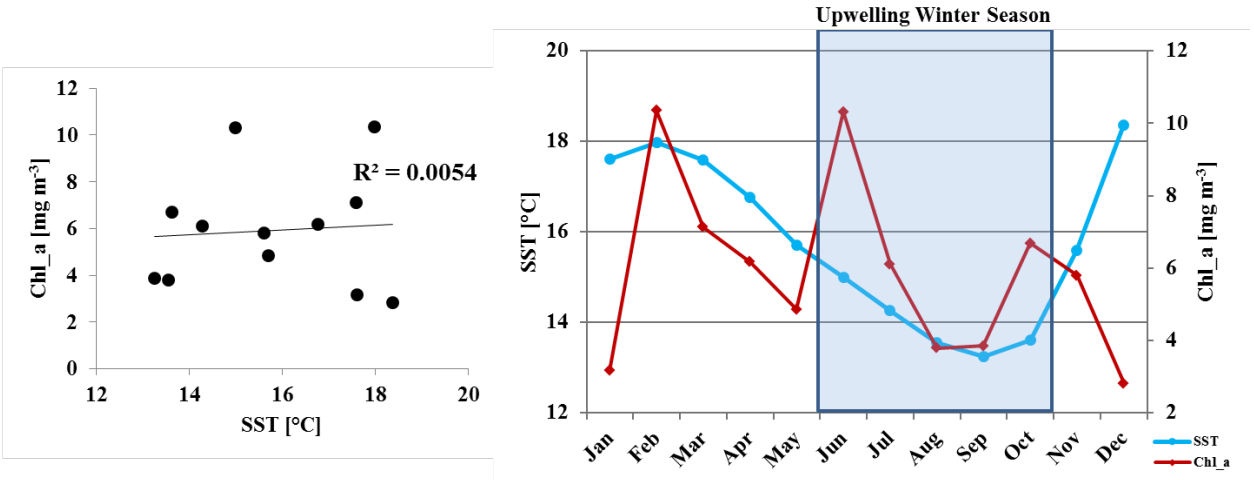

Figure 8: Chlorophyll a concentrations and SST of the Benguela, and their correlation in 2013.

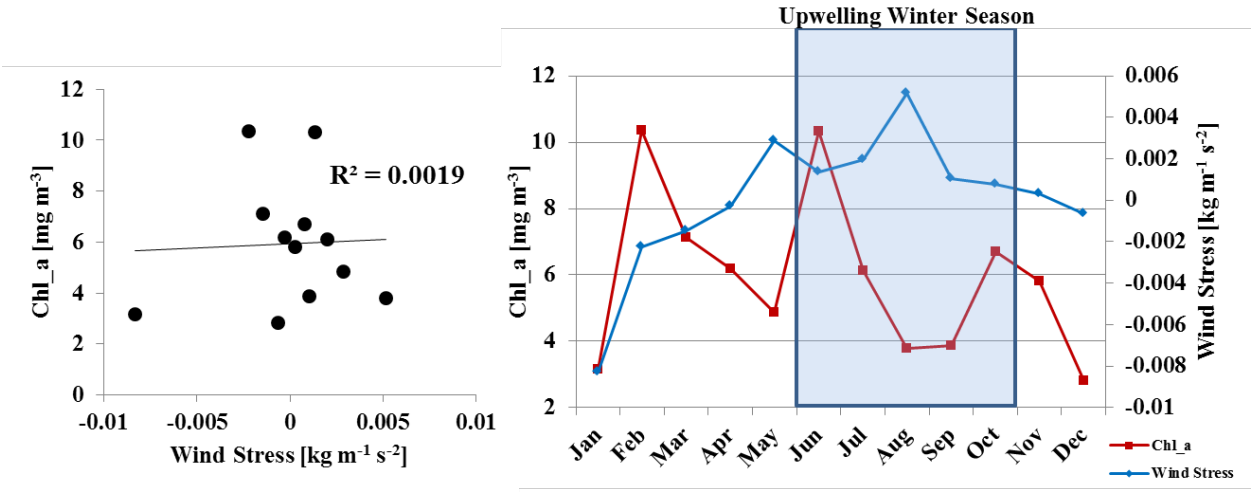

Figure 9: Chlorophyll a concentrations and Wind Stress of the Benguela, and the correlation between the two, in 2013.

On the same timeline wind stress seemed not to be related to organic carbon fluxes with a correlation of r^2 = 0.0057. But a 3 month forward shift of wind stress, yielded a correlation with an r^2 of 0.8469. This indicated a delayed relationship between wind stress and particle fluxes (Figures 10).

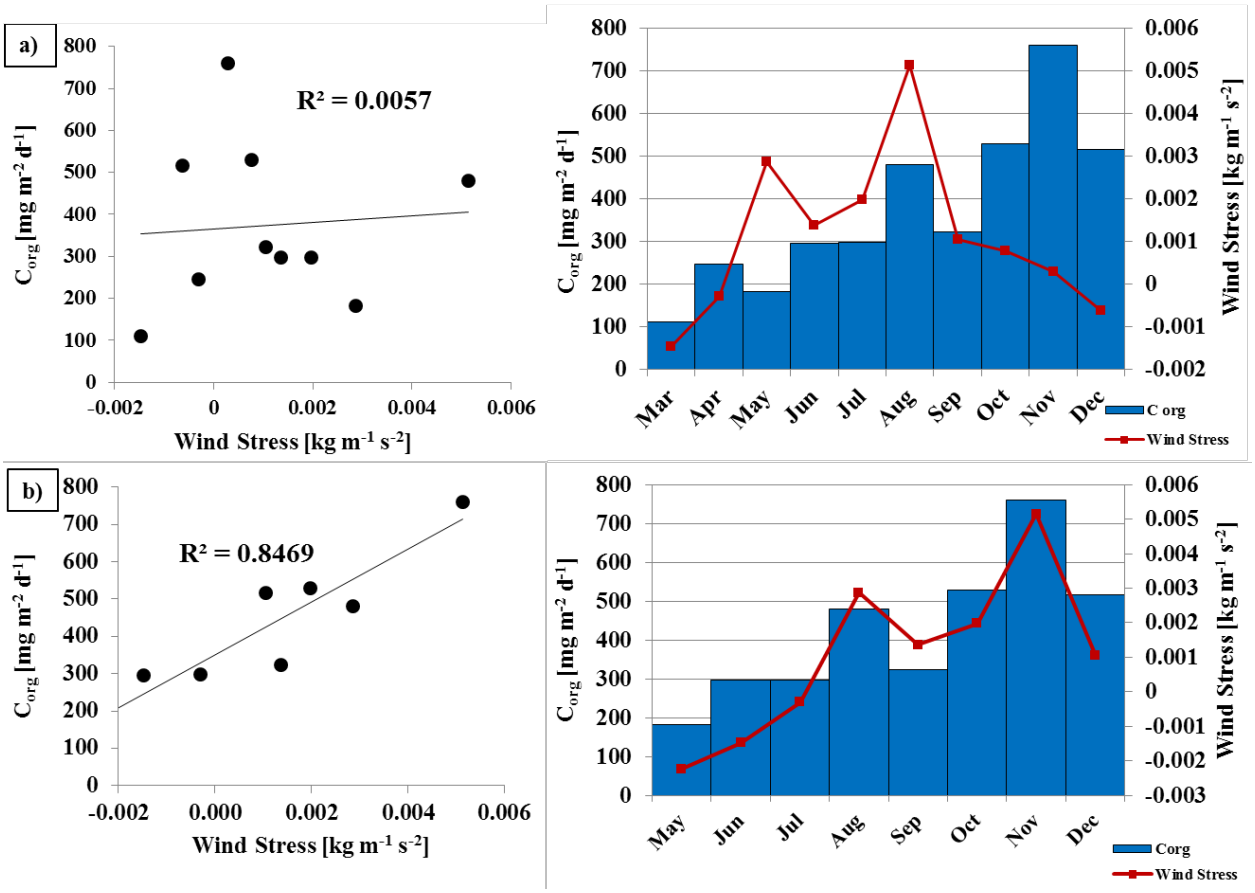

Figure 10: Wind Stress and Organic Carbon Fluxes of the Benguela Shelf Area, and their correlation, in 2013 a) before a 3 month forward shift in wind stress b) after a 3 month forward shift in wind stress.

The percentage of SACW in the overall Benguela water mass composition ranged between 24% and 54% SACW. SACW began to decrease from May and was lowest in August, but there was a pulsate increase in % SACW in September and October and then it began to decrease again (Figure 11). A negative relationship was found between % SACW composition and organic carbon fluxes with $r^2 = 0.5768$.

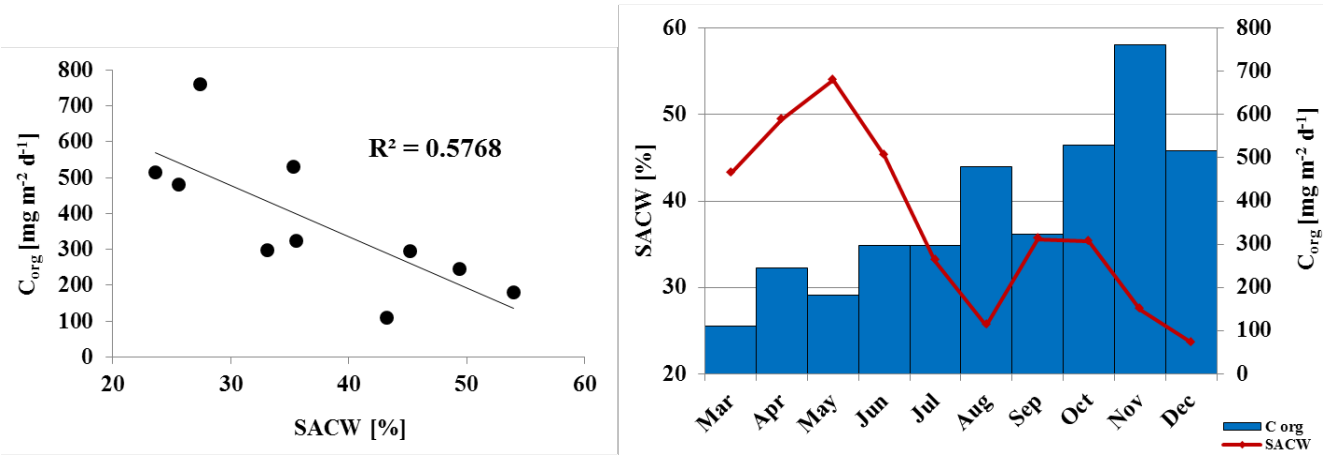

Figure 11: Percentage SACW and organic carbon of the Benguela, and their correlation, 2013.

SST had a negative relationship to organic carbon which was only noticeable with a 2 month forward shift in SST. The correlation between the two changed from $r^2 = 0.0321$ to $r^2 = 0.7546$ when SST was shifted 2 months forward (Figure 12).

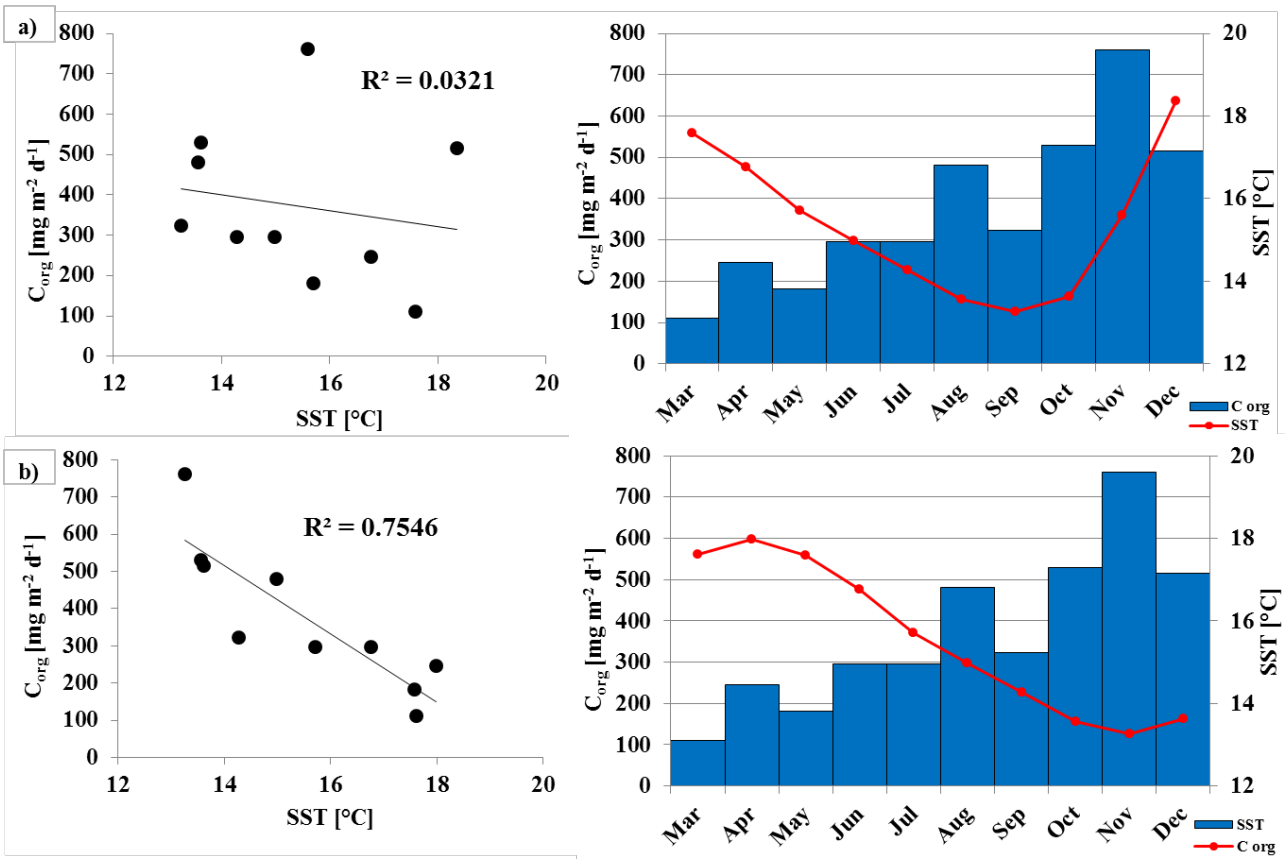

Figure 12: SST and organic carbon and their correlation in 2013 a) before a 2 month forward shift in SST and b) after a 2 month forward shift in SST.

5. Discussion

Discussion

The upwelling season in the Benguela is from June to October. Particle fluxes in the Northern Benguela Upwelling system shelf area depicted two seasonal maxima, one in austral winter and another in austral summer. These are understood to be the same kind of maxima found in previous studies (Wefer and Fischer, 1993 and Fischer et al., 2000). The presence of sediment in the sediment trap sample bottles as well as the notable trend in particle fluxes over the study period is a clear indication that the sediment traps are efficient in shelf area particle flux studies. It is also an indication that the sediment traps have no technical bias as they record similar trends to those seen offshore. The second flux maximum occurs just at the end of/ outside the upwelling season, but it is caused by upwelling during the upwelling season because there is a delay from the time upwelling takes place to primary production which consequently leads to particles sinking. Fischer and others (2000) suggested this delay to take 2-3 months from primary production to the fluxes being recorded at the sea floor due to long range offshore transport by filaments. We found also a 2-3 month delay period between the SSTs, wind stress and organic carbon particle fluxes. Since our study was done on the shelf at a depth of 60 m, long range offshore transport is not a factor. The only factors involved in these 2-3 months are upwelling, primary production and the subsequent sinking of particles.

Biological fluxes

Biogenic opal was the highest contributor to particle fluxes indicating that the major contributing primary producers were diatoms which have silicate containing shells. This is a typical situation of inshore waters, that diatoms are the dominant primary producers (Barlow et al., 2006). Calcium carbonate was however not very high throughout most of the year except in the second particle flux maximum where concentrations are seen to increase six fold indicating a slight change in the primary producing community composition. Opal concentrations however were still high so this shows that it was not a total shift in the dominant primary producers but rather an addition to the primary producer community diversity. The organic carbon concentration increased during the

second flux maximum because of an increase in primary producers which is shown by an increase in biogenic opal.

Lithogenic Fluxes

Lithogenic matter fluxes were also significantly higher on the shelf (468 mg m^{-2} day^{-1}) as opposed to what offshore (40 mg m^{-2} day^{-1}) studies showed, indicating that there is in fact an input of terrestrial sediment into the Benguela opposing conclusions by Wefer and Fischer (1993) that lithogenic input into the Benguela is insignificant. Lithogenic particle flux peaks in April, August and November coincided with organic carbon particle flux peaks indicating a relationship between organic carbon fluxes and lithogenic matter input from land, supporting the theory that lithogenic matter act as ballast to sinking particles (Ittekkot 1991; Ittekkot et al., 1993).

However the way by which sand from land is transported to the ocean may be the reason why offshore studies in the Benguela only recorded small fluxes of lithogenic matter (Wefer and Fischer, 1993). Unlike with the great Sahara dust plumes which are blown as large sand clouds over the northern Atlantic, in the Benguela the sand is funneled through dry riverbed channels that open up into the southern Atlantic. Figure 12 shows a satellite image taken on 21 July 2013 during the upwelling season and there one can see that the terrestrial dust input into the Atlantic is only at designated places which are associated with dry river beds further inland. Therefore the sand blown in from land does not always make it far off shore but a considerable amount makes it to the shelf area (Figure 13).

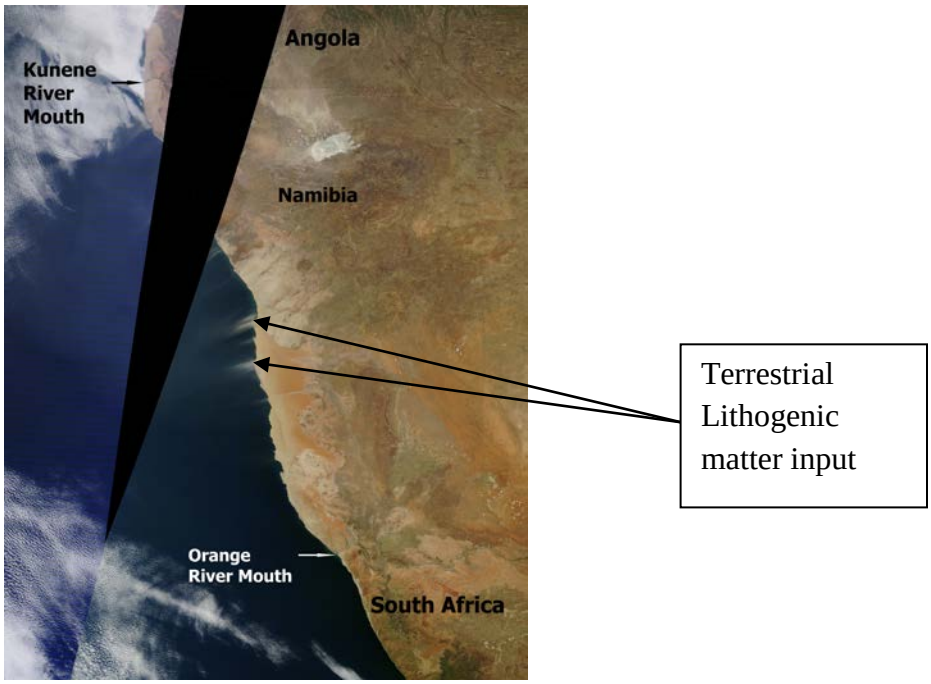

Figure 13: Sand storm in the Benguela off Namibia on 21 July 2013, picture taken from https://earthdata.nasa.gov/labs/worldview/

Furthermore lithogenic fluxes increased with increasing organic carbon fluxes. Satellite imagery observations of sand storms off Namibia show that even though sand storms were highest in July, the August lithogenic matter flux does not exceed that of November where organic carbon fluxes were highest. Indicating that not only does marine snow use lithogenic matter as ballast for faster sinking but that lithogenic matter also depends on the availability of organic matter to be able to sink when blown into the ocean.

Wind stress and Temperatures as Upwelling indicators

South-easterly trade winds drive upwelling in the Benguela (Nelson and Hutchings, 1983) and this could be seen by an increase in the south-north component of wind stress along the Namibian coast and a subsequent decrease in SST of the Atlantic. Winds subsided again half way through the upwelling season followed by increases in SST showing that the trade winds drive upwelling of cold waters. The inverse relationship between wind stress and SST had an r^2 of 0.44 indicating the significance of winds in driving upwelling.

Sea water temperature at 90 m however was not as affected as SST by wind stress. Sea temperature at 90m only varied within a range of 1 °C, while the range for SST was 5 °C indicating a more intense influence by trade winds on surface temperatures. Even though sea water temperature at 90 m was also lowest in the same month as the lowest SST, it was not correlated to wind stress, with an r^2 of 0.06. Therefore it was not affected much by wind stress and cannot be used as an upwelling indicator.

Surface productivity and Organic fluxes

Although particle fluxes are known to be a reflection of surface productivity (Fischer et al., 2000) which is indicated by chlorophyll a concentrations, chl-a concentrations during the time of the study did not show a trend that was similar to that of particle fluxes. Chl-a concentrations showed 3 peak maxima which if they translated to particle fluxes would in fact have shown higher organic carbon before the upwelling season as opposed to during or immediately after the upwelling season. This would mean that upwelling does not play a role in the productivity of the system. Nonetheless it is a well-known phenomenon of upwelling systems that the upwelling brings up nutrient rich waters (Calvert and Price, 1971) that cause high primary production when they enter the photic zone. Chl-a had a low correlation ($r^2 = 0.07$) to organic carbon fluxes, even after time shifts chl-a had no close relation to particle fluxes. This could have brought doubt to the results of the study, were it not that chl-a was not related to SST ($r^2 = 0.0054$) and wind stress ($r^2 = 0.0019$) as well. The fact that the highest chl-a concentrations were not during the upwelling season, when productivity is supposed to reach its climax, leads to the conclusion that chl-a concentration readings from the satellite data were not well reflecting the system's productivity.

This could either be due to the patchiness of algal blooms or the sparse coverage of the satellite (Chavez, 1995) leading to inconsistent readings. Also because satellites cannot take measurements during cloud cover or haze (Moses et al., 2009) this could affect the readings as several days of data can be missed.

According to, Kutser (2004), the main limiting factor for remote sensing estimates of chlorophyll concentration of a water body is the depth of penetration at which the signal that can be detected by a remote sensing sensor is originated. Implying that subsurface chl-a cannot be read by the satellite sensor.

Also, the fact that we have an increase in calcifying primary producers during the upwelling season could mean that this change in primary producer community composition affects satellite readings. The composition may affect readings in the sense that satellites may read the same chlorophyll a concentration in a cocolithophore to be lower than in a diatom probably due to the calcite in cocoliths which may cause a higher light scatter than the silicate in diatoms. Balch et al., (2005) state that in typical non-bloom situations, backscattering of light by suspended coccoliths routinely accounts for 10–20% of all visible backscattered light from the sea and this percentage can exceed 90% in coccolithophore blooms when the concentration of calcite is much higher.

Wind stress and organic carbon

When plotted on the same time line, wind stress seemed to have very little relation to organic carbon fluxes with an $r^2 = 0.0057$, but after a time shift of wind stress 3 months forward, there appeared a close relationship between the two which had an $r^2 = 0.8469$. This relationship was not obvious at first because there is a lag between the time when the trade winds induce upwelling to the time the resultant productivity of the upwelling is seen at the depths of the sea as particle flux. Andrews and Hutchings (1980), state that the rate of upwelling in the Benguela is statistically related to wind data.

After the time shift it was explicit that the wind stress maxima and the organic carbon maxima were the exact time apart, even when wind stress was seen to decrease in September the same trend was also observed in the organic carbon flux. This agrees with findings by Treppke et al., (1996), who observed that fluxes were directly related to wind stress variations.

This confirms that trade winds are one of the drivers of productivity through upwelling and consequently particle fluxes in the Benguela.

SACW and organic carbon

The SACW had a higher contribution to the Benguela water mass composition before the upwelling season and began to decrease by the start of the upwelling season. There was a negative relationship between SACW and organic carbon which may be easily concluded that SACW must decrease in order for particle fluxes to increase. However this may be a misleading conclusion as SACW decreases because of an increase in ESACW which is brought into the Benguela from the south by the trade winds that cause upwelling. SACW is nutrient rich (Mohrholz et al., 2008) compared to ESACW so it should enhance the system's productivity, but since SACW is also devoid of oxygen, productivity is hampered. Therefore only when there is a mixture of both nutrient rich SACW and oxygen rich ESACW (Mohrholz et al., 2008) is productivity optimized and flux increases. There was a notable pulse of SACW during the upwelling season which when combined with the upwelled ESACW could also be a contributing factor to the increased fluxes towards the end of and immediately after the upwelling season. This pulsate addition of nutrient rich SACW during the upwelling season may be the reason why the abundance of both diatoms and calcifying primary producers could both increase at the same time without a decline in the other. Therefore if upwelling favorable winds were to intensify, the amount of ESACW in the upwelling system would increase thus making the system nutrient poor and productivity would decrease. But also domination by SACW due to a decrease in upwelling favorable wind intensity could lead to an anoxic system since SACW is oxygen reduced.

SST and organic carbon

Sea surface temperature also had no obvious close relation to organic carbon until after a time shift, because of a lag phase between the time the cooler waters are upwelled and the time when the productivity begins, then translated to particle flux. The inverse relationship found between SST and flux agrees with similar findings by Treppke et al., (1996).

Comparison with previous work

Organic carbon levels recorded on the shelf are higher than those recorded offshore in studies by Wefer and Fischer (1993) and those recorded on the continental slope by Giraudeau (2000) who reported maximum organic carbon fluxes of 47.7 and 16.1 mg m^{-2} day^{-1} respectively, compared to 760 mg m^{-2} day^{-1} observed on the shelf. A study done on the shelf area by Monteiro and others in 2006, they reported maximum organic carbon fluxes of ~100 mg m^{-2} day^{-1}, which is still far less compared to fluxes observed in this study but this was because they only considered the fraction of less than 200 µm. Therefore there is higher production that takes place on the shelf which is seen by high shelf area fluxes, but shelf area flux dynamics are little understood.

In a study done by Wefer and Fischer (1993), they explained the second flux maximum that occurs immediately after the upwelling season that it was solely caused by upwelling which could be seen by a drop in SST 3 months earlier. They argued that, particles had a 3 month delay in sinking due to the great depth they have to travel to reach the bottom (Figure 14). But since the same maximum is seen in our studies which are at a shallower depth and at the same time as was seen by Wefer and Fischer (1993), it casts doubt upon this 3 month lag phase suggested by Wefer and Fischer (1993). Also by suggesting this 3 month lag phase between upwelling productivity and fluxes it becomes difficult to explain the austral spring flux maximum with the same argument as there is no upwelling seen 3 months prior to the austral autumn maximum.

In addition since there is more lithogenic matter on the shelf area, one would expect particles on the shelf to sink even faster due to more ballast. Therefore if the delay was due to sinking speed, the maximum would be observed much earlier on the shelf compared to offshore. By considering water mass composition one may be able to explain both maxima much better, however the study by Wefer and Fischer (1993) did not consider the influence of water mass composition and this may explain their conclusion.

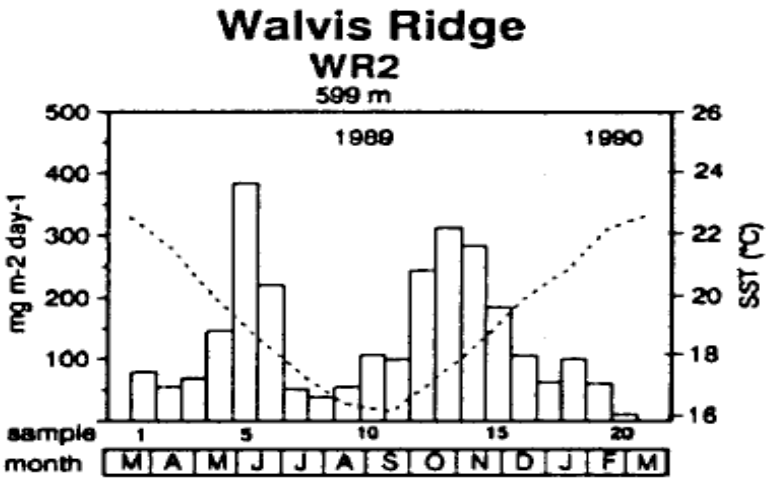

Figure 14: Total fluxes at the Walvis Bay ridge in the Benguela between 1988 and 1989, adopted from Wefer and Fischer (1993)

6. Conclusion & Outlook

Conclusion

The use of a Hydrobios MST-12 time series sediment trap on the Namibian shelf was sufficient to collect meaningful particle flux data in this area and can therefore be used in future studies in such an environment. Diatoms are the dominant primary producers on the shelf area and they constitute a large part of the flux composition on the shelf. Calcifiers increased six fold in abundance during the upwelling season but their presence does not reduce the diatom abundance.

Lithogenic matter composition is quite significant on the Benguela shelf and is supplied into the ocean through the dry riverbed channels. Lithogenic matter on the shelf is higher than those reported offshore by previous studies.

Sea surface temperature can be used as an indicator for upwelling since sea surface temperatures do decrease during the upwelling season. The decrease in SST is related to an increase in south-north wind stress caused by southeasterly trade winds during the upwelling season.

Chlorophyll a satellite data were not a good primary productivity indicator because the data were not related to organic carbon fluxes and physical parameters responsible for upwelling such as wind stress and sea surface temperature. On the other hand wind stress and SST were closely related to the organic carbon flux. Chlorophyll a satellite data were not suitable to be used in this study because of their inconsistency.

SACW appeared to have a negative relationship to flux but this may be because SACW is highest before the upwelling season when productivity is low and reduces because more ESACW is brought into the Benguela from the south. Also a combination of SACW and ESACW is what optimizes productivity and increases fluxes during upwelling. Domination by only ESACW due to intensification of winds may lead to a less productive system, whereas domination by SACW could lead to an anoxic system.

The particle flux trends observed on the shelf were similar to those observed in other studies offshore and on the continental slope, with two flux maxima being observed, one in austral autumn/winter and another in austral spring.

Hypotheses

With respect to my hypothesis it can be concluded that wind-driven upwelling is one of the factors controlling the productivity and particle fluxes in the Benguela upwelling system along with SACW contribution. This therefore does not support the assumption that productivity and therewith particle flux will increase during the intensification of upwelling in the course of global warming unless there is a concurrent increase in percent SACW.

Contrary to sea water temperatures at 60 m water-depth, sea surface temperature can be used as an indicator for upwelling whereas chlorophyll a satellite data appear not to be not a good indicator for primary productivity.

Outlook

The Benguela shelf, being a major sight of primary productivity which supports a globally important reservoir of biodiversity (Shannon and O'Toole, 2003) and a locally and internationally important fisheries sector, needs to be better understood to better deal with any problems that may arise in the system. This study was just a glimpse into the little understood, but very important shelf area of the Benguela, further studies and monitoring are therefore recommended to better understand the system.

I also recommend that the Hydrobios MST-12 time series sediment trap be used in particle flux studies done in this area as it is effective. However for future studies I recommend that chl-a measurements should be done in the vicinity of the sediment trap mooring during the time it is deployed to obtain a clearer understanding of primary production. The mooring should also be equipped with buoy to measure not only sea water temperature in the deeper part of the water column but as at the sea surface. Comparative studies on different sites at the same time would also help in better understanding the dynamics of particle fluxes on the shelf area.

7. References

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M-103/1 WBST_East-03																						
Mooring Position: 23°01.350'S 014°01.667 'E																						
Mooring at 57 m Water Depth, Water Depth 130 m																						
					Flux [mg m^{-2} d^{-1}]		Measurements and calculations only for fraction <1 mm													Cup Chemistry			
	Start	Stop		Duration [d]	>1 mm	<1 mm	C_{tot} [%]	N_{tot} [%]	C_{org} [%]	$CaCO_3$ [%]	Opal [%]	Lithogen [%]	C_{tot} [mg m^{-2} d^{-1}]	N_{tot} [mg m^{-2} d^{-1}]	C_{org} [mg m^{-2} d^{-1}]	$CaCO_3$ [mg m^{-2} d^{-1}]	Opal [mg m^{-2} d^{-1}]	Lithogen [mg m^{-2} d^{-1}]	del 15N [o/oo]	Sal PSU	O_2 [mg/l]	pH	Organic Matter [mg m^{-2} day^{-1}]
#01	20-01-13	18-02-13	Feb	30	Bottle lost during deployment																		
#02	19-02-13	20-03-13	Mar	30	45.91	243.71	26.18	3.09	25.25	7.69	25.07	21.78	63.80	7.53	61.55	18.75	61.10	53.08	5.60	32.50	7.91	4.40	110.7838
#03	21-03-13	19-04-13	Apr	30	174.13	624.84	22.46	2.74	21.87	4.88	23.09	32.66	140.32	17.10	136.66	30.50	144.29	204.06	5.02	62.50	6.99	3.05	245.9917
#04	20-04-13	19-05-13	May	30	27.04	454.78	23.53	3.53	22.16	11.43	30.54	18.14	107.03	16.05	100.79	51.98	138.87	82.50	5.63	30.40	7.31	2.95	181.4192
#05	20-05-13	18-06-13	Jun	30	324.80	967.64	17.33	1.96	17.01	2.60	47.63	19.14	167.66	18.96	164.64	25.14	460.90	185.25	6.82	50.00	6.65	2.68	296.3535
#06	19-06-13	18-07-13	Jul	30	346.27	1352.44	12.68	1.46	12.19	4.11	73.77	0.18	171.52	19.72	164.86	55.54	997.66	2.50	6.20	36.00	7.02	3.70	296.7469
#07	19-07-13	17-08-13	Aug	30	429.76	2732.33	10.05	1.02	9.77	2.37	67.04	13.01	274.62	27.93	266.84	64.89	1831.64	355.49	5.04	57.50	6.58	2.50	480.3072
#08	18-08-13	16-09-13	Sep	30	113.07	918.91	20.52	2.33	19.53	8.23	51.36	5.26	188.53	21.39	179.45	75.66	471.94	48.31	5.73	36.50	7.08	3.09	323.0042
#09	17-09-13	16-10-13	Oct	30	133.18	2961.16	11.17	1.26	9.93	10.30	64.59	7.23	330.73	37.36	294.15	304.86	1912.63	214.20	5.13	32.80	7.12	2.62	529.4633
#10	17-10-13	15-11-13	Nov	30	159.07	4790.53	9.98	1.23	8.82	9.72	64.64	9.77	478.31	58.86	422.43	465.63	3096.47	468.05	5.94	35.20	7.13	2.36	760.3808
#11	16-11-13	15-12-13	Dec	30	65.04	2145.96	14.37	2.07	13.35	8.50	62.10	5.37	308.42	44.36	286.54	182.32	1332.65	115.22	6.76	33.10	7.59	0.20	515.7681
Average							16.83	2.07	15.99	6.98	50.98	13.25	223.09	26.93	207.79	127.53	1044.81	172.87	5.79	40.65	7.14	2.76	374.02

	SST [°C]	C_{org} [mg m^{-2} d^{-1}]	Wind Stress [Kg m^{-1} s^{-2}]	Chl_a [mg m^{-3}]	Temp 90 m [°C]	SACW [%]
Jan	17.606		-0.00831	3.164	12.61004	39.50295
Feb	17.986		-0.00224	10.355	12.71415	43.24156
Mar	17.583	110.78	-0.00148	7.13	12.80237	43.20237
Apr	16.762	245.99	-0.0003	6.172	12.73848	49.42199
May	15.704	181.42	0.002868	4.857	12.82795	53.97498
Jun	14.988	296.35	0.001365	10.318	12.69971	45.2327
Jul	14.274	296.75	0.001979	6.117	12.39703	33.10759
Aug	13.557	480.31	0.005142	3.793	12.04461	25.62501
Sep	13.256	323.00	0.001051	3.856	11.38052	35.56891
Oct	13.62	529.46	0.00077	6.694	11.5037	35.30561
Nov	15.598	760.38	0.000296	5.804	11.58728	27.43146
Dec	18.36	515.77	-0.00064	2.814	11.84516	23.60571