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Seasonal and interannual phytoplankton dynamics and forcing mechanisms in the Northern Benguela upwelling system

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A B S T R A C T

Seasonal phytoplankton blooms are one of the key features of the productive northern Benguela upwelling system (nBUS), however they are not well described thus far. In this study twelve years (2000–2012) of in situ chlorophyll-a data from a monitoring transect off the Namibian coast were analysed to assess the long-term and seasonal variability in chlorophyll-a as a measure of phytoplankton biomass and the occurrence of phytoplankton blooms. On the shelf, low chlorophyll-a concentrations were identified in 2001/2002, 2005/2006, and 2011/2012. The concentrations on the shelf were highest in 2008/2009 and 2010/2011. Major phytoplankton blooms defined at chlorophyll-a concentrations >18 mg m^{-3} occurred in five of the 12 years (2002/2003, 2004/2005, 2008/2009, 2009/2010 and 2010/2011) while minor blooms (>13 mg m^{-3}) occurred in almost every year. The calculated climatology of the chlorophyll-a time series revealed a clear seasonality. Three chlorophyll-a maxima typically develop inshore over the year: an austral winter peak (August), an early austral summer peak (December) and a late summer/autumn peak (April). The analysis of synoptic hydrographic, nutrient and wind data revealed three different forcing mechanisms that all initiate an influx of nutrients into the surface mixed layer.

1. Introduction

The northern Benguela upwelling system (nBUS) is one of the most productive marine ecosystems worldwide, even when compared to the other large upwelling systems in the Pacific, the California Current and the Humboldt Current (Carr and Kearns, 2003; Lachkar and Gruber 2012). The nBUS is situated in the central part of the Benguela Current Large Marine Ecosystem (BCLME). Coastal upwelling in the nBUS is driven by quasi-permanent strong along-shore south-east trade winds (Lass and Mohrholz 2008; Lachkar and Gruber, 2012). Seasonal patterns in the wind field do occur and periods of reduced upwelling occur in the case of warm water intrusion from the tropical Angola Basin (occurring in summer/autumn), a phenomenon known as the Benguela Niño (extreme warm water intrusion during summer/autumn), which has similar characteristics as the El Niño in the Pacific (Shannon et al. 1986, Bartholomae and Van der Plas, 2007, Monteiro et al. 2008).

This ecosystem with high phytoplankton productivity of diatoms, dinoflagellates and small flagellates, sustained a rich marine fisheries sector during the 1960s and 1970s. Since then the catches for commercially important species declined tremendously due to overfishing (Cury and Shannon, 2004; Alheit and Bakun, 2010; Finney et al., 2010; Boyer and Boyer, 2012). Furthermore, independent of direct human impacts, the BUS is also suggested to react directly to global climate change, specifically to changes in atmospheric forcing (Bakun, 1990; Bakun et al., 2010). These changes might affect regional and local environmental patterns negatively and influence the already fragile fisheries industry with possible repercussions for the local economy.

To assess the state of the marine environment and to aid the management of sustainable fisheries, monitoring programs were already set up in Namibia in the 1970s. Two monitoring programs, SWAPEL (South West Africa Pelagic Egg and Larvae survey) and "Cape Cross", included measurements of a large number of oceanographic variables including chlorophyll-a (Chl-a) concentration and phytoplankton abundance down to species level (Reyssac, 1973; Visser et al., 1973). Unfortunately, these programs stopped after the collapse of the fisheries sector in the 1970s (Kollmer, 1958; Visser et al., 1973; Vavilova, 1990).

A remote sensing monthly time series of Chl-a estimate, produced by the Coastal Zone Color Scanner (CZCS), was the first long-term phytoplankton related data set for the nBUS. It was measured with the Nimbus 7 satellite and showed the BUS's dynamics at an interannual time scale from 1978 to 1985 (Weeks and Shillington, 1994). Only since 1999/2000, a regular monthly oceanographic monitoring program started again along the central coast off Namibia, sampling quasi monthly on the 23°S transect and quarterly on the northern 20°S

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transect (Bode et al., 2014). Additional to temperature, salinity and oxygen concentration, the measured parameters include nutrients (nitrate, nitrite, phosphate, ammonium and silicate), Chl-a concentration and phytoplankton and zooplankton abundance.

The aim of this study was to identify the physical and chemical drivers of the spatial and temporal distribution of phytoplankton biomass, which are critical to the understanding of the functioning of this coastal shelf ecosystem and, thus, also essential for fisheries management in Namibia. The nBUS, as well as other coastal upwelling systems, is susceptible to strong phytoplankton blooms due to the natural upwelling of nutrient rich water into the euphotic zone of the water column. To be able to show the significance of the variability of phytoplankton phenology and intensity, long time series of in situ phytoplankton information is needed. We analysed a 12 year (2001–2012) time-series of monthly in situ Chl-a data along the 23°S transect of the Namibian oceanographic monitoring program and used Chl-a as a proxy of phytoplankton biomass. Remote sensing Chl-a data have been used in the past (Weeks and Shillington 1994, Demarcq et al., 2007), but this is the first attempt to use long term in situ data in the nBUS. Although remote sensing gives a holistic view over the coast of Namibia, cloud cover and the inability to resolve the Chl-a algorithm close to the coast and within the water column may lead to a biased phenology. We examined synoptic wind, hydrographic and nutrient data to reveal the main drivers for the phytoplankton distribution and consequently high biomass bloom development and decay with associated low oxygen and sulphide events. This study contributes to an improved understanding of the spatial and temporal variability in this coastal shelf ecosystem and is valuable for categorization of long-term changes, fisheries and climate change.

2. Materials and methods

2.1. Area of investigation

The 23°S transect is situated off Namibia in the nBUS on the downstream side of the main Lüderitz upwelling cell at 27°S. It is located in a transition area influenced by both nutrient rich and oxygen poor South Atlantic central water (SACW) from the Angola Gyre in the north and well-oxygenated but nutrient poor Eastern SACW (ESACW) from the south (Bartholomae and van der Plas, 2007; Mohrholz et al., 2008). The 23°S line off Walvis Bay was chosen by the NatMIRC (National Marine Information and Research Centre) monitoring program as the primary monitoring transect as it is in the centre of the nBUS and because the Namibian shelf has the highest concentration of diatomaceous mud in this region, indicating maximum primary production (Bremner, 1983, Inthorn et al. 2006). The Walvis Bay area is also an important breeding ground for commercially valuable pelagic fish. Furthermore, a long-term environmental data set exists for this transect. The 23°S transect consists of nine stations between 2 nm and 70 nm, covering the entire shelf from the coast to the shelf edge with bottom depths between 39 and 371 m (Fig. 1, Table 1).

2.2. Sampling, sample preparation and measurements

Wind, temperature and nutrient data have been used to examine possible physical and chemical drivers of the long-term and seasonal Chl-a patterns.

2.2.1. Wind data

We used remotely sensed wind stress data (23.1°S, 13.9°E) from the Quick Scatterometer (QuikSCAT) and the Advanced Scatterometer (ASCAT) (Bentamy and Fillon 2012) for the periods of January 2000 to November 2009 and March 2009 to November 2013, respectively. The spatially gridded, daily-averaged wind fields were derived from the Asia-Pacific Data-Research Centre (http://apdrc.soest.hawaii.edu/). From the wind data, we calculated monthly mean values and a monthly climatology of coast parallel wind stress that reflects upwelling and Ekman transport. Since the data from the different scatterometers are known to exhibit a persistent bias (Bentamy et al. 2012), we calculated two climatologies, one from each dataset of the scatterometers.

2.2.2. Water temperature

Oceanographic data were obtained by using a Seabird or SEACAT CTD with Niskin bottles attached to a rosette. The CTDs were regularly serviced and externally and internally calibrated. The accuracy of the temperature data is $+/-0.005$ K. In situ temperature data (surface to 100 m water depth) for the period January 1999 until December 2012 were used. The 13 °C isotherm temperature at 15 m water depth was used as a measure of upwelling intensity (Hagen et al., 2001), whereas the 14 °C (Bartholomae and van der Plas, 2007) and 16 °C isotherms were used as thresholds to describe thermocline strength, i.e. the stratification of the water column. In situ temperatures at 15 m depth were utilized for the surface temperature plot in order to exclude a direct surface radiation effect, especially during summer.

2.2.3. Dissolved inorganic nutrients

Data for nitrate and silicate concentrations were available from 2000 to 2004 at water depths corresponding to the Chl-a sampling. The water samples for nutrient analysis taken during each CTD cast were filtered on board through a 0.45 μm cellulose acetate membrane filter and frozen until further analysis ashore. Nutrient concentrations were measured with a Bran and Luebbe Traacs 800 autoanalyser according to the standard colorimetric nutrient analysis method (Grasshoff et al., 1999).

2.2.4. Chlorophyll a

Approximately 3400 samples for Chl-a analysis were taken on the 23°S line in the upper 30 m of the water column from January 2001 until December 2012 (Table 2). Surveys were planned to be

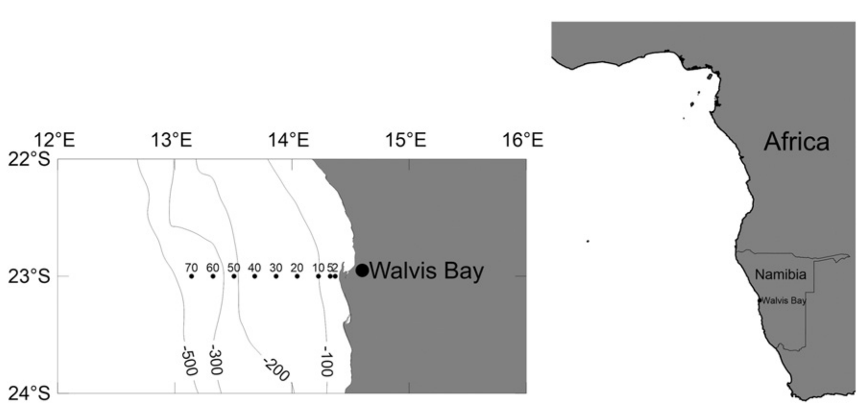

Fig. 1. Map of study area and 23°S transect off the coast of Namibia.