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Cross shelf hydrographic and hydrochemical conditions and their short term variability at the northern Benguela during a normal upwelling season

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ABSTRACT

Cross shelf hydrographic and hydrochemical conditions were investigated during the seasonal maximum of upwelling in the northern Benguela upwelling system. The study combines in situ observations, remotely sensed data and results of a regional 3-dimensional numerical model. In situ observations were recorded along a cross shelf transect off Namibia starting at 20°S 13°E, repeated five times during 16 August 2011 until 19 September 2011. Comparison of wind forcing and sea surface temperatures during the time of the expedition with long-term climatological data as well as the index of intensity of the Benguela upwelling indicates "normal" upwelling conditions in austral winter 2011 in the northern Benguela. Small scale temporal (days) and spatial (km) variability is high during the upwelling season, primarily caused by highly variable wind forcing and dynamics of mesoscale structures like eddies and filaments as found in remotely sensed data. This mesoscale dynamics impact the applicability of a conceptual 2-dimensional circulation model, i.e. a linear succession along the cross-shelf transect. Therefore, an age proxy for surface water was constructed based on oxygen and heat fluxes during the first aging period and on salinity and heat fluxes during the second phase. The application of an age proxy instead of distance to shore successfully validates the succession concept. Furthermore, the investigation of the upwelling strengths by analytical and circulation models verified their dependence on coastal- and curl driven upwelling processes with the onshore dominance of coastal upwelling. In the investigated time period, offshore, curl driven upwelling dominated with a maximum located on the shelf.

1. Introduction

Wind forced upwelling is one of the most important processes to connect the deep ocean with the euphotic layer and plays an important role in the global cycle of carbon and nutrients (Ianson and Allen, 2002; Muller-Karger et al., 2005). Although upwelling systems cover only a small fraction of the ocean surface they contribute disproportionally to the global primary production and host many of the major commercially used fish stocks (FAO, 2012). The Benguela upwelling system is one of the large Eastern Boundary upwelling systems (EBUS) that are associated with the highest primary production in the world ocean (e.g. Carr, 2002; Carr and Kearns, 2003). The productivity of Eastern Boundary upwelling systems responds sensitively to changes in physical forcing caused by climate variability (Bakun, 1990; Bakun et al., 2010). Thus, understanding ecosystem functioning in upwelling areas is of overall interest for managing and protecting these valuable marine areas.

Upwelling of nutrients into the euphotic zone is the initial process of the trophic chain in upwelling systems. Upward directed vertical movement at the base of the surface layer (H_{mix}) brings nutrient-rich water into contact with the sea surface, where this water and the dissolved nutrients become part of the actively mixing surface layer. As such, the nutrient supply to the surface layer is a result of the combined action of a vertical upwelling movement of water masses and mixing. Vertical velocity at the base of the surface layer corresponds to a divergence of the horizontal transport within this layer. There are two mechanisms to generate this divergence (Fennel and Lass, 2007). The first is related to the existence of a coast as a natural physical boundary for the cross shore surface transport. Coastal upwelling is governed by the alongshore wind stress near the coast. It is confined to a coastal band with a width of a baroclinic Rossby radius (Charney, 1955; Yoshida, 1955; Fennel, 1999). Coastal upwelling is affected by Kelvin waves that leave a steady state in their wake and reduce the upwelling. Moreover they export the upwelling signal poleward. In the inviscid case, i.e. when frictional effects are neglected, the upwelling ceases completely after the arrival of the Kelvin waves. Therefore only temporal variations of

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the wind field can excite new upwelling events (Fennel, 1999). The second upwelling mechanism is Ekman pumping, where the vertical velocity w at the bottom of the mixed layer (H_{mix}) depends on the curl of the local wind stress τ:

$$w|_{z=H_{mix}} = \frac{\mathrm{curl}\,\tau_z}{\rho f} \quad \text{with}\,\mathrm{curl}\,\tau_z = \left(\frac{\partial\tau^{(y)}}{\partial x} - \frac{\partial\tau^{(x)}}{\partial y}\right) \tag{1}$$

where ρ is the water density, and f is the Coriolis parameter. Contrary to the Ekman divergence driven upwelling, wind stress curl driven upwelling is not affected by Kelvin waves (Fennel, 1999). This fact illustrates the importance of wind stress curl in upwelling systems since this mechanism is able to maintain upwelling independent of Kelvin waves.

The importance of both upwelling processes for marine systems has been extensively discussed in the recent years (Fennel, 1999; Fennel and Lass, 2007; Jin et al., 2009; Renault et al., 2009; Albert et al., 2010; Veitch et al., 2010). Pickett and Paduan (2003) estimated upwelling due to Ekman transport and pumping in the California current system. Their results suggest that Ekman pumping is nearly as important as upwelling driven by the alongshore winds. However, there exists no estimation on the vertical velocity related to both upwelling mechanisms in the Benguela system so far.

Rykaczewski and Checkley (2008) have shown that the vertical upwelling velocity plays an important role in the size distribution of phytoplankton and in the availability of suitable food for higher trophic levels. Curl driven upwelling favors the smaller phytoplankton species, which are the preferred food for small pelagic fish.

In this paper the results of a field study are presented, that is focused on cross shelf matter transports and plankton succession in the upwelled water along its pathway from the coast towards the open ocean. The experiment was carried out in the northern Benguela upwelling system (BUS) during the seasonal maximum of wind forcing. The BUS off southwestern Africa is one of the four major upwelling systems in the world oceans (Carr and Kearns, 2003; Chavez and Messié, 2009). The BUS consists of a northern and a southern part, separated by the Lüderitz upwelling cell at 27°S (Duncombe Rae, 2005). Both systems are closely connected, but behave differently with respect to wind forcing, seasonality of upwelling, ventilation of the shelf area, and many other aspects (Cury and Shannon, 2004). The northern boundary of the BUS is formed by the Angola Benguela frontal zone (ABFZ) at approximately 15°S to 17°S (Shannon et al., 1987). The southern boundary of the BUS is the Agulhas retroflection zone near the Cape of Good Hope. In the northern BUS the wind forcing has a strong seasonal cycle. Winds are strongest during austral winter months — July, August, and September. During summer (December to March) the trade winds relax. Due to the spatial structure of the wind field the wind stress curl driven vertical current component is positive (upward directed) in a 200 to 300 km wide band along the entire Namibian coast (Bakun and Nelson, 1991; Lass and Mohrholz, 2008; Risien and Chelton, 2008; Fennel et al., 2012).

The amount of nutrients lifted into the euphotic layer depends on both the upwelling intensity and the nutrient content of the source water mass, usually from the central water layer. The northern BUS is the transition area between two different central water masses of the south Atlantic (Duncombe Rae, 2005; Mohrholz et al., 2008), the South Atlantic Central Water (SACW) and the Eastern South Atlantic Central Water (ESACW). Both water masses have different nutrient and dissolved oxygen content. In the Angola Gyre the properties of SACW are modified before it is transported poleward into the BUS by the Angola current and its extension the poleward undercurrent. SACW is nutrient enriched, but oxygen depleted. ESACW originates from the Cape Basin and is well ventilated, but contains less nutrients than the SACW (Mohrholz et al., 2008). ESACW is the dominant water mass in the BUS during the main upwelling season in austral winter, whereas in summer SACW spreads southward up to the Lüderitz upwelling cell. The seasonal change in central water mass distribution at the Namibian shelf is controlled both by the seasonal variation of trade winds off Namibia and by remote forcing from the equatorial Atlantic (Lass and Mohrholz, 2008).

The main processes in upwelling ecosystems are often treated in frame of 2-dimensional conceptual models of cross shelf circulation and plankton succession. The cross shelf circulation consists of an offshore transport in the surface layer, maintained by Ekman transport and mesoscale dynamics (Kostianoy and Zatsepin, 1996), and an onshore directed compensation flow below the mixed layer. Biological production, biogeochemical processes and fluxes through the boundaries change the properties of upwelled water along the pathway towards the open ocean.

Following the 2-dimensional approach, in situ observations were carried out along a cross shelf transect in the northern Benguela at approximately 20°S, referred to as the SUCCESSION transect. This specific region is often depicted as the northern Namibian cell (e.g. Hardman-Mountford et al., 2003) and was selected since there the alongshore variability of wind forcing and shelf bathymetry is weak. Thus, it is assumed that cross shelf processes dominate the observed structures. In reality the wind driven surface circulation is three dimensional. It also consists of longshore currents and is overlayed with advection components of mesoscale dynamics (filaments, eddies, etc.). Mesoscale dynamics contributes significantly to the offshore export of nutrients (Gruber et al., 2011; Gutknecht et al., 2013). However, on average the upwelled water spreads towards the northwest. Therefore, the measurements along the cross shelf transect represent a projection of the real advection onto the transect. In a simplified view cross shelf matter transports and plankton succession can be described using the distance to the coast as a measure of water mass age. Water masses are younger close to the coast and older further offshore, but this simple concept is impacted by mesoscale structures, like eddies and filaments. The mesoscale dynamics complicate the investigation of both temporal and spatial succession of the plankton community and biogeochemical conditions along the cross-shelf transect because, among others, they depend on the water age. To overcome this problem an age proxy for surface water was constructed based on oxygen and heat fluxes during the first aging period and on salinity and heat fluxes during the second phase. By applying the age proxy instead of distance to shore, the measurements of the interdisciplinary data were successfully rearranged to study the succession of different processes.

This paper deals with the analysis of wind forcing, hydrographic and hydrochemical conditions and the impact of mesoscale dynamics during the annual maximum of upwelling in the northern Benguela. It supplies the basis data and background information for the detailed and specialized investigations of various trophic levels carried out in the interdisciplinary field experiment “SUCCESSION”.

2. Material and methods

The used data set consists of in situ measurements carried out during the cruises MSM18/4 and MSM18/5 with the R/V Maria S. Merian, remote sensing data, and results of a regional 3-dimensional coupled hydrodynamic–biogeochemical model of the Benguela upwelling system (Herzfeld et al., 2011; Schmidt and Eggert, 2012).

In situ sampling of hydrographic and hydrochemical parameters was carried out along the SUCCESSION transect across the northern Namibian shelf between approximately 20°S and 22°S (Fig. 1). The transect was directed perpendicular to the coast and covers the shelf, the shelf break, the continental slope and partly the continental rise. At this latitude the bottom topography depicts a double shelf break at 200 m and at 400 m depth, with coastal distances of 60 km and 110 km respectively. In this paper we use the term “shelf” for the entire area within 400 m water depth. The continental slope extends offshore to 250 km distance from the coast. Between 16th August and 19th September 2011 the transect was worked five times to obtain information about the variability of