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Inter-annual variability of upwelling off the South-Vietnamese coast and its relation to nutrient dynamics

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ABSTRACT

It is the general consensus that the South China Sea (SCS) is influenced by the El Niño southern Oscillation (ENSO). Off southern Vietnam, coastal upwelling is one of the major features of the SCS, which is consequently influenced by the ENSO. However, the processes behind this influence are under discussion. It is the general thesis that the inter-annual changes of the monsoon wind cause the changes of the strength of the upwelling. This thesis has been tested and it is discarded. Instead it can be shown that the wind stress is not the main cause for the impact of the ENSO. Therefore, also nutrient dynamics must be completely re-evaluated.

This study investigates in the circulation and the hydrographical situation during the summer 2003 and 2004, an El Niño and a normal year, respectively. The influence of the circulation on the new biological production based on vertical nutrient fluxes is estimated. Numerical modelling is used to study the circulation inside the SCS. The results of the simulation discover two different states of the horizontal circulation: During the first state an anticyclonic circulation dominates the region. During the second state the cyclonic circulation in the north and the anticyclonic circulation in the south build the dipole. Two cruises during the summer 2003 and summer 2004 verify the two states of the simulated circulations. The ENSO influence on the summer circulation is by tending towards the first state in the summer after an El Niño, while during normal summers the second state is dominant.

Against earlier findings, this study features one new major key of the ENSO influence on the temperature distribution and primary production in the western SCS: This influence is not via the vertical velocities, but due to the different horizontal circulations. In the dipole circulation pattern, the decreased horizontal velocities cause longer residence times which come along with the increase in the efficiency of the upwelling. In this study, for the first time, the advection of the pronounced different water masses of the northern and southern SCS is considered. The different water masses support an important preconditioning of the nutrient concentrations in the water column. An experiment, which compares primary production with and without this preconditioning proves that the originating water masses moving into the upwelling region control the primary production.

Horizontal advection explains the substantial contributions of the strong ENSO signal in the region. Not the regional Ekman drift currents, but the basin wide horizontal circulation explains the inter-annual changes of the vertical nutrient uplift during the summer. It can be shown that the dipole circulation is an almost perfect nutrient pump for new production.

1. Introduction

Coastal upwelling is one related process, which moves cold and particularly nutrient-rich water towards the surface. It is one of the most important physical processes for primary production. Coastal upwelling is the cause of some of the most productive fishery areas in the world, which are the basis for the availability of food and the economic power in these areas.

The Vietnam Upwelling Area (VUA) is located off south-central Vietnam, between 10°30′N and 12°N. In a country like Vietnam, with a coastline of more than 3000 km and more than 40 million people living at the coast an upwelling region is of enormous relevance in the economic development — although the VUA stretches only over one small part of the coast. In this region are the greatest temperature and chlorophyll anomalies inside the South China Sea (SCS). Moreover in this region starts the well discussed offshore jet (Wyrtki, 1961).

The region is illustrated in Fig. 1: Upwelling can be found exactly in the area north of the Sunda Shelf, where the shallow and wide shelf exchanges to a deep and narrow shelf. In Fig. 1 the brown dashed lines represent the crestline of one asymmetric ridge at the edge of the Sunda Shelf and the crestline of the second asymmetric ridge off Cam Ranh. Between these two rises a canyon-like structure can be found. Based on the topographic variability, the VUA contains four sub-regions, by the means of boxes in Fig. 1. Northernmost, in the region

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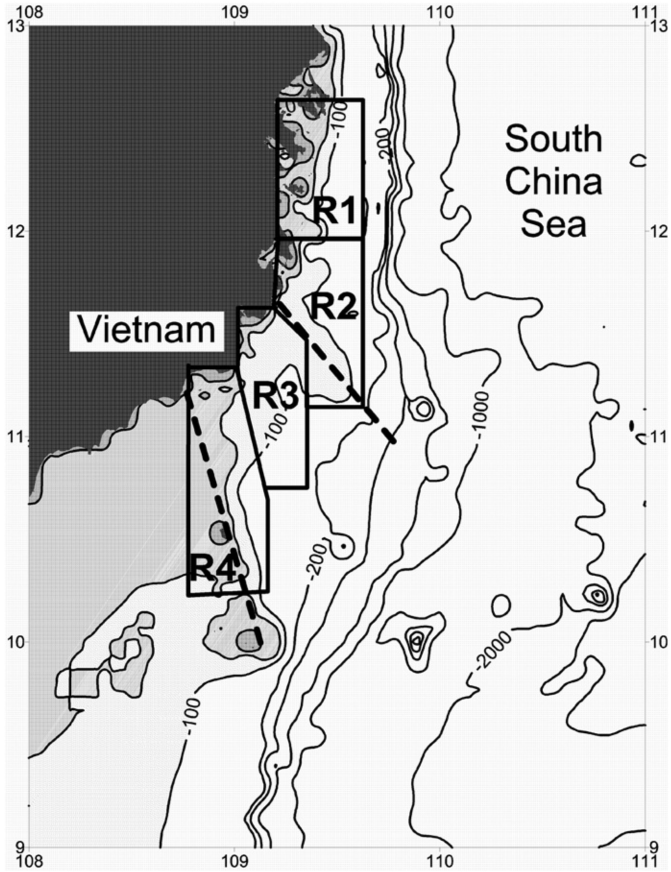

Fig. 1. Topography of the "Vietnam Upwelling Area": The dashed lines depict the crestline of the Sunda Shelf and a ridge near Cam Ranh; the boxes represent the four sub-regions (R1, R2, R3, and R4) of the upwelling area.

off Nha Trang (R1), a deep and homogeneous shelf can be taken as a topographic undisturbed region. The region off Cam Ranh (R2) represents a strong change of the alongshore shelf topography which is typified by the northern ridge. The canyon-like structure is the main morphological feature of the region Phan Rang (R3). The southernmost region, off Hoa Da (R4), is formed by the ridge at the margin of the Sunda Shelf.

This study focuses on the two years 2003 and 2004. Thereby, the summer 2003 is related to a weak El Niño in the Pacific during the preceding winter, whereas the summer 2004 is related to a quasi-neutral ENSO state. During both years, an interdisciplinary cruise was carried out in the VUA, on the results we drawn here. Additionally we use hydro-numerical simulations, and estimate the governing processes in the VUA in relation to the ENSO.

Ning et al. (2004) investigated in the seasonal distributions of phytoplankton in the SCS and identified a coupling of physical–chemical–biological processes. In the SCS, coastal upwelling is the most important physical processes amplifying the primary production (Liu et al., 2002). Our results allow us to discuss the nitrate based new production in order to understand them and their abundance in the sense of intra- and inter-annual variability. This study tries to get the biological processes consistent with the physical processes, in order to understand possible influences of the ENSO on the new production in this region.

For the comprehensibility of the text, the circulation of SCS is summarised at the beginning in the form of a short review. Next, the hydrodynamic model, the in-situ observations and the simplified method to estimate primary production is presented. Based on the results of the simulation and the in-situ observations, this study analyses the regional circulation in the VUA. Finally, the influence of the hydrodynamic situation on the nitrate fluxes and new production is estimated and discussed.

2. The circulation of the South China Sea

As the basis for understanding the text, a short review of the investigation in the circulations of the South China Sea (SCS) is collated. The SCS and the associated atmosphere are one part of the East Asian monsoon system (Wyrtki, 1961). The wind stress of East-Asian monsoon drives the circulation of the SCS. Accordingly, as the monsoon system the SCS undergoes the seasonal cycle. The simplified cycle of the SCS means a cyclonic circulation during winter and an anticyclonic circulation during summer.

The first investigations in the SCS were carried out by Dale (1956) and Wyrtki (1961). Both deduced the surface currents from ship drift data and prevailing wind data. Pohlmann (1987) applied the first prognostic baroclinic three-dimensional circulation model to simulate the SCS circulations during the winter and summer monsoons, more or less the same did Mao et al. (1992). Li et al. (1992a,b,1994), Liu and Su (1992), Zeng et al. (1989) and Zeng et al. (1992) used two-dimensional numerical models to calculate the monthly or seasonal mean SCS circulation. Shaw et al. (1999), Morimoto et al. (2000) and Hwang and Chen (2000) extracted the circulation from the sea surface elevation in the SCS using the Topex/Poseidon altimeter data. The first three-dimensional model, running over a longer timescale, was that of Shaw and Chao (1994). Wu et al. (1998) performed an EOF-analysis on the basis of the model results originating from Shaw and Chao (1994). Summarizing these former studies, almost all observations and models cited reflect the general seasonal circulations, i.e., a mean cyclonic circulation in winter and a mean anticyclonic circulation in summer.

In the most former studies, investigating in the processes of the SCS, it is the consensus, that the monsoon wind, represented by both the monsoon wind stress and its curl is the major cause for the patterns and the strength of the surface circulation. Apparently, during winter the northeast monsoon moves the surface water northwestward, resulting in some compensatory southward movements in the western SCS. The result is the strong cyclonic circulation in the western basin. Wyrtki (1961) was the first one who observed the strong westward intensification. The estimated current velocities can reach more than 75 cm/s in the western boundary current. During winter monsoon this southward directed western boundary current follows the shelf-edge from 18°N to 5°N as the eastern part of the cyclonic circulation.

During the southwest monsoon, the circulation is a bit more complex. Then the circulation is anticyclonic in the southern basin. The strong western boundary current along the Vietnamese coast south of 12° N is established. In this season it is directed northward as westward part of the anticyclone. However, at 12° N the boundary current separates from the coast and builds the eastward jet, which partly re-circulates to the south further offshore.

Several publications (e.g., Metzger and Hurlburt, 1996; Shaw et al., 1999; Wu et al., 1999; Wang et al., 2003) describe the cyclonic eddy during summer, which is located north of the point of separation (12° N). During summer the dipole structure in the western part of the SCS, with the pronounced confluence zone of two western boundary currents is established, exactly in that area where the Vietnam Upwelling Area (VUA) is located. Wang et al. (2006) investigated the dipole pattern with satellite observations of sea surface height anomalies (SSHA) and model studies. According to them, the dipole structure begins in June, peaks in August and September, and disappears in October. Moreover, they show that the strength of the wind stress curl is responsible for the generation and maintenance of the dipole structure and the variability of the dipole lag about 40 days behind the wind field (Wang et al., 2006).

The detailed physical processes of dipole causing separation of the boundary current are subject of ongoing discussion. Gan and Qu