Oceanologia (2017) xxx, xxx—xxx

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia/

ORIGINAL RESEARCH ARTICLE

# Modeling the ecosystem response to summer coastal upwelling in the northern South China Sea

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Received 19 October 2016; accepted 19 May 2017

**KEYWORDS**
The northern South China Sea;
NPZD ecosystem model;
Summer coastal upwelling;
Coastal ecosystem

**Summary** A coupled three-dimensional physical model and a nitrogen-based nutrient, phytoplankton, zooplankton, and detritus (NPZD) ecosystem model were applied to simulate the summer coastal upwelling system over the continental shelf of northern South China Sea (NSCS) and its impact on hydrographic conditions and ecosystem. The simulated results were comprehensively validated against field and satellite measurements. The model results show that the near shore ecosystem of NSCS has significant responses to the summer coastal upwelling system. The Shantou Coast to the Nanri Islands of Fujian province (YD) and the east of the Leizhou Peninsula (QD) are two main regions affected by NSCS summer coast upwelling. During summer, these two coastal areas are characterized by nearshore cold and high salinity upwelling current. Further, the summer coastal upwelling serves as a perfect nutrient pump, which lifts up and advects nutrient-rich current from deep to surface, from inner shelf to about 30 km outer shelf. This nutrient source reaches its maximum in the middle of July and then begins to decrease. However, the maximum phytoplankton and chlorophyll *a* do not coincide with the maximum nutrients and delay for about 10 days. Because of the intensive seasonal thermocline and the complicated current transporting through Qiongzhou strait, the ecological responding of QD is less pronounced than YD. This study has a better understanding of the physically modulated ecological responses to the NSCS summer coastal upwelling system.


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Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.oceano.2017.05.004

## 1. Introduction

Coastal upwelling is one of the most prominent marine physical processes involving biogeochemical cycles, primary productivity, and fisheries (Prego et al., 2007). Coastal upwelling system is commonly produced by the interaction between favorable winds and the topography (Woodson et al., 2007) and is characterized by bringing cold and nutrient-rich deep water toward the surface while influencing the transport of suspended matters (Freon et al., 2009). Because of its important role in the marine ecosystem, coastal upwelling has been studied worldwide (González-Gil et al., 2015; Ruzicka et al., 2016).

The South China Sea (SCS) is located in the southeast of Asia with an average depth of about 1350 m. It is the largest marginal sea in the world, which stretches $3.5 \times 10^6$ km$^2$ from 23°57′N in the north to the 3°00′N in the south and from 99°10′E in the west to the 122°10′E in the east (Chen et al., 2006). The SCS also supports the most frequent human activity (Li et al., 2014). Our study area — northern South China Sea (NSCS) (Fig. 1) is affected by both natural environment and human activities year-round. In the northern shelf of the NSCS, there are many rivers which input fresh water into it (such as the Pearl River), while the south of the NSCS joins to the SCS. The occurrence of summer coastal upwelling is a regular phenomenon during June to September in the NSCS, and there are two main coastal upwelling regions: Shantou Coast to the Nanri Islands of Fujian province (YD), and the east of the Leizhou Peninsula (QD) (Jing et al., 2008). All of these days, temperature, salinity, dissolved oxygen (DO) and chlorophyll *a* have been regarded as four main indicators for NSCS summer coastal upwelling (Wang, 2013). In order to explore the corresponding environmental changes, a lot of research techniques have been used, such as remote sensing, multivariate statistical analysis, and indicator (silicate) method (Ehlert et al., 2013). However, the influence of the coastal upwelling system on the NSCS ecosystem is still not well understood because of the complex topography, currents and the dynamic climatology (Morton and Blackmore, 2000).

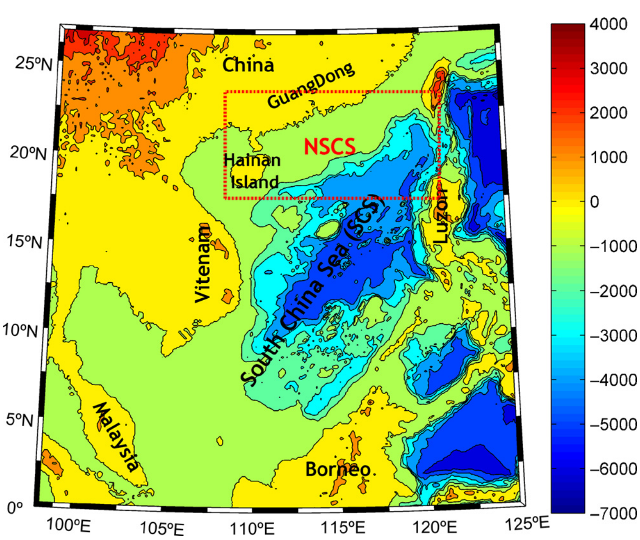


**Figure 1** The northern South China Sea (NSCS) and its physiography; different colors represent the bathymetry of the South China Sea [altitude: m]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

With increasing pressure for a profound understanding of marine ecosystems, numerical modeling becomes a powerful tool for research. Ecological models are ecosystem-based management tools that can be used to forecast ecological impacts. Through their ability to integrate into in situ measurements with the theoretical assumptions of ecosystem response, ecological models can be an effective tool for developing strategies for simulating the environmental changes (Cropper and DiResta, 1999). Coupled physical-biological model can be an efficient approach to study the time dependent three-dimensional responses of the marine ecosystem to the coastal upwelling system, and it can also compensate the time-space restrictions of the earlier studies.

In the paper, the Regional Ocean Model System (ROMS) coupled with a nitrogen-based nutrient, phytoplankton, zooplankton, and detritus (NPZD) ecosystem model was given in the NSCS, and was also constructed and analyzed by discretization, driven condition, and validation methods.

## 2. Material and methods

### 2.1. Model description

The first generation of marine ecosystem models was put forward by Riley (Riley and Stommel, 1949), and constructed as a one-dimensional NP ecological model, which not only put phytoplankton, zooplankton as state variables, but also took photosynthesis, predator-prey relationship, and mineralization into account. It is also the foundation of the NPZD ecological model used in this paper. Compared with the NP model, this NPZD model describes ecosystem structure and functions in more detail, in addition, it is three-dimensional.

The NPZD ecological model is one of the most popular models by virtue of its fewer requirements for parameters and observation data (Heinle and Slawig, 2013). It has successfully simulated many ecological and physical processes in different seas, for instance, the NPZD model was used to illustrate the relationship between changes in the intensity of the spring bloom and changes in the physical forcing in the northeast Atlantic Ocean (Waniek, 2003) and it was also used for simulating the long-term change of planktonic ecosystems in the upstream Kuroshio Current (Li et al., 2015).

The schematic of the NPZD ecological model is presented here (Fig. 2). It describes the evolution of nutrients (*N*), phytoplankton (*P*), zooplankton (*Z*) and detritus (*D*) (Powell et al., 2006). Furthermore, it is a nitrogen-based model and each square in it represents an ecological variable. These ecological variables belong to four submodules corresponding to *N* submodule, *P* submodule, *Z* submodule, and *D* submodule, respectively, and the arrows between the squares indicate directions of energy flows. Nutrients enter the sea through rivers and atmospheric precipitation transport. On one hand, phytoplankton utilizes photosynthesis for compounding organics for its autotrophic growth. But on the other hand, its growth is also limited by light, nutrients, and temperature, etc. Zooplankton is an important linkage