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A physical–biological coupled aquaculture model for a suspended aquaculture area of China

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ABSTRACT

A three-dimensional physical–biological coupled aquaculture model is developed to study the aquaculture carrying capacity of kelp in Sungo Bay, a typical aquaculture site in China with intensive suspended raft aquaculture. In the aquaculture model, the hydrodynamic module builds on the Princeton Ocean Model by adding two types of drags due to the aquaculture facilities at surface and kelp in water column. The biological module simulates the renewal of dissolved inorganic nitrogen (DIN), the cycle of phytoplankton biomass, and the growth of kelp, while the contribution of bivalves' excretion to DIN is set to a constant derived from observations. Thus, the coupling between the growth of kelp and the current variation can be studied by adding drags in the layers reached by kelp. The simulated magnitude and vertical profile of currents agree well with observations. The suspended aquaculture causes a reduction in the average speed of surface current by 40%, decreasing the water exchange with the open sea. The simulation results also show that the seasonal and spatial variations of the DIN concentration and phytoplankton biomass are clearly controlled by the distributions of different species. The estimation of DIN budgets of different periods shows competition between kelp and phytoplankton. The primary source of nutrients for the growth of kelp in Sungo Bay is the DIN from the open sea, and the aquaculture obstruction is the main reason for the deficient DIN in the kelp culture area. The final kelp production decreases from the mouth to the end of the bay, consistent with the spatial variation of water exchange rate. Numerical experiments have been carried out by increasing the aquaculture density of kelp from 0.8 to 1.5 times of the current value. Obtained results indicate that the optimal average density is 0.9 times of the current value.

1. Introduction

Fisheries and aquaculture are both important ways of seafood production in China. For example, the consumption of seafood in 2008 in China was 25 million tons and the predicted demand will reach about 40 million tons in 2020. However, marine fish stocks are decreasing in the last decades. The increasing demand of seafood production will rely more on aquaculture and the intensive aquaculture could be an important method to address the challenge. Considered that aquaculture production in a coastal bay is limited, a sustainable aquaculture method needs to be established for supporting a long-term and stable supply. In 1934, Errington first introduced the concept of "carrying capacity" to aquaculture (Kashiwai, 1995) that was also applied to administration of water quality and tourism, etc. (Duarte et al., 2003). With respect to aquaculture, carrying capacity is described as the standing stock at which the annual production of the marketable cohort is maximized (Bacher et al., 1998). Accurate estimation of the carrying capacity is an important step for sustainability in aquaculture.

Suspended aquaculture is popular in semi-closed bays with aquaculture activities in China. Kelp and bivalves could grow in cages, nets, or other containers hung from floats or rafts. Thus, suspended aquaculture can be considered as an integrated system that includes the cultivated species, facilities (buoys, ropes and rafts) and the environment. Various types of ecosystem models have been developed to estimate the carrying capacity of such systems. Energy-balanced models are generally based on the balance between depletion and renewal of nutrients and food (Grant, 1996; Wildish and Kristmanson, 1997). For example, Fang et al. (1996a, b) estimated the carrying capacity of kelp and bivalves in Sungo Bay of China (the study area of this work) based on the balance of DIN and organic carbon. These models have two limitations: 1) only single species being considered and 2) the complexity of biological and physical

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processes being not included. Box models including more complicated biological processes can be used to predict the growth of more than one species and estimate carrying capacity (Grant et al., 2007; Nunes et al., 2003; Raillard and Ménesguen, 1994; Zhu et al., 2002). However, these box models oversimplify the flow and its potentially important interactions with nutrients and food availability for cultivated species. It is not surprising that these models cannot simulate details of flow variability, neither the effects of species and facilities on hydrodynamic.

Generally, flows tend to slow down in suspended aquaculture areas because of the extra drags caused by the suspended system. Based on observations, Grant et al. (1998) estimated that the drag due to the mussel raft aquaculture was about 30 times of that for a bare substrate. Pilditch et al. (2001) observed a reduction by 40% of current passing through suspended scallop aquaculture from the average surrounding values. In New Zealand, Gibbs et al. (1991) estimated that the current within longline mussel aquaculture was about 70% of that in the surrounding areas. Boyd and Heasman (1998) carried out a comprehensive study on the effects of suspended aquaculture on tidal currents. They reported that the current within the rafts depended on rope spacing and current speed and could be reduced by a factor of 6.

Overall, it is important to couple hydrodynamic processes into carrying capacity models. By using a two-dimensional model Grant and Bacher (2001) estimated a reduction by 41% in the water exchange rate by increasing the bottom friction in Sungo Bay with intensive suspended aquaculture. This suggested that neglecting the physical barriers could lead to a significant overestimation of the water exchange rate and the renewal of nutrient and food. The same was true for the aquaculture carrying capacity. Using the same approach, Duarte et al. (2003) found that Sungo Bay was being exploited close to its environmental carrying capacity; however, an optimized distribution of aquaculture may further increase the yield.

The suspended aquaculture causes not only decreases in the magnitude, but also changes in the vertical profile of current. In order to study the hydrodynamics under the influence of aquaculture activities in Sungo Bay, two field campaigns were carried out in April and July 2006 (Fig. 1). Fig. 2 compared the typical vertical profiles of tidal current at station Xunshan in Sungo Bay and at station A1 in the southern Yellow Sea (observed in December 2005) without aquaculture. In April when kelp in Sungo Bay reached its maximum length, the current at the surface layer had only half the magnitude in the middle layer, and led the bottom layer by up to 2 h; the maximum current speed occurred in the lower part of the water column (Fig. 2a). In common area without aquaculture (taking observations at station A1 as an example), the maximum tidal current occurred at the surface and decreased gradually toward the bottom; the bottom current led that at the surface (Fig. 2b). Clearly, the aquaculture activities caused significant changes in current structure in Sungo Bay. The aquaculture-induced drags have both spatial and temporal variations. Spatial variations are caused by horizontal distributions of aquaculture, and temporal variations are caused by the changing kelp length associated with growth.

In this study, a three-dimensional model was modified by including two types of drags to study the dynamic coupling between physical and biological processes in Sungo Bay. Accurate magnitude and vertical structure of current were predicted by the model. Reasonable annual cycles of DIN concentration, phytoplankton biomass and kelp production were obtained and discussed.

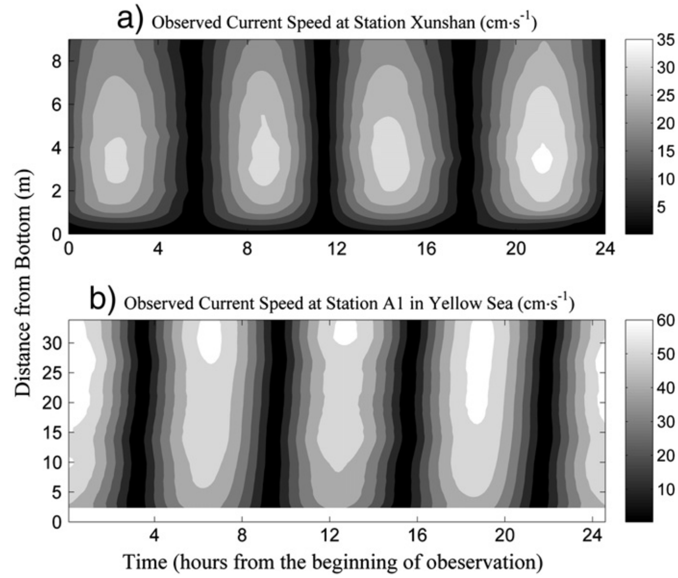

Fig. 2. Observed vertical profiles of tidal current over 25 h at (a) station Xunshan in April 2006 (measured with 500 kHz SONTEK ADP) and (b) station A1 in March 2005 (measured with 600 kHz RD ADCP).

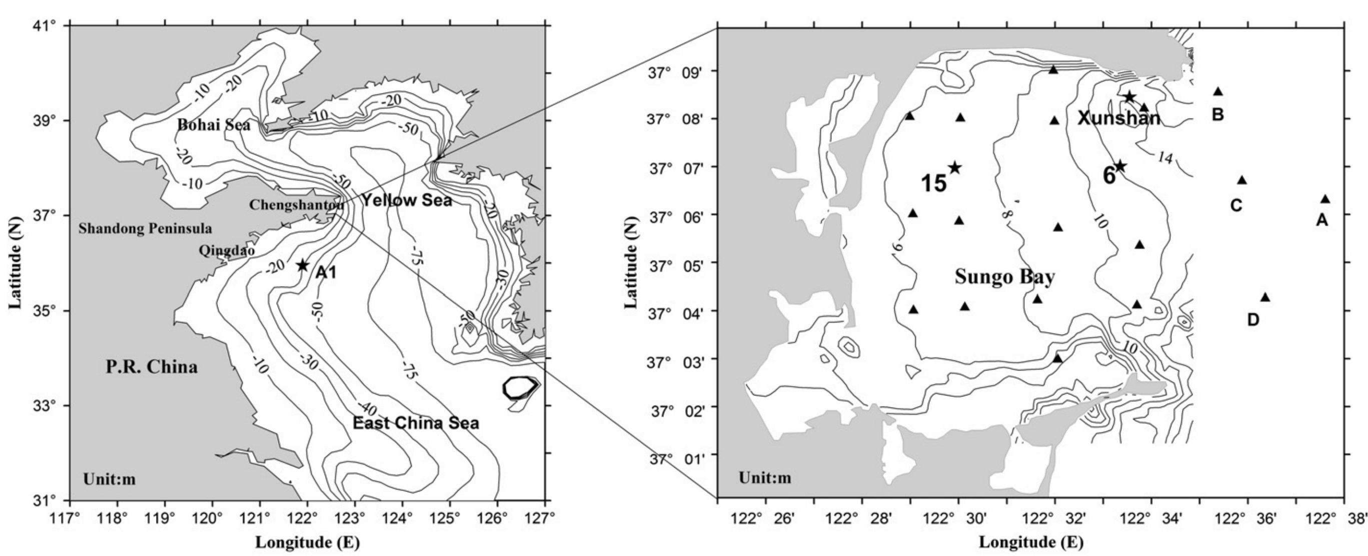

Fig. 1. The location and topography (in m) of the study area. The observational stations are marked by stars. Stations Xunshan, 6 and 15 are located inside Sungo Bay; station A1 is located in the southern Yellow Sea. Observational data at stations within Sungo Bay (marked by triangles) in November, 2006 are used to provide initial conditions of state variables. Data collected at stations A, B, C and D in January, April, July and November of 2006 are used to construct the boundary forcing for the model.