Estuarine, Coastal and Shelf Science 164 (2015) 425–432

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Simulating the vertical dynamics of phosphate and their effects on the growth of harmful algae

Haruo Yamaguchi*, Koji Sai

Faculty of Agriculture, Kochi University, Nankoku, Kochi 783-8502, Japan

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
9 June 2015
Accepted 30 July 2015
Available online 5 August 2015

Keywords:
Harmful algae
Phosphate
Simulation
One-dimensional model
Stratification
Vertical mixing

ABSTRACT

A large amount of inorganic phosphate (P_i) is required for harmful planktonic algae to proliferate extensively in enclosed coastal regions. However, P_i in surface euphotic waters is typically deficient during warm season when the waters are stratified. Mixing events that redistribute the large amount of P_i in bottom waters can therefore have large ecological effects, making understanding such events important. In this study, we simulated the vertical dynamics of P_i in an enclosed coastal region, Uranouchi Inlet, Japan, and discuss their potential effects on harmful algal blooms using algal growth kinetics. Our results indicated that our one-dimensional model is capable of reproducing empirically observed variations in the water column of the inlet. In simulations, during the warm season, the water column became vertically stratified when the wind velocity was weak (less than 2.4 m s^{-1}), but mixed completely within 20 h under a strong wind (over 6 m s^{-1}). The flux of P_i from the lower to the upper layer during such a mixing event was calculated to be 0.472–2.22 μmol L^{-1} day^{-1}, two orders of magnitude higher than under stratified conditions (0.00230–0.0108 μmol L^{-1} day^{-1}). Our analyses demonstrated that the concentration of P_i vertically supplied within one day during such mixing events has a great potential for supporting the massive proliferation of harmful algae such as *Chattonella antiqua* and *Heterocapsa circularisquama*.

1. Introduction

Aquaculture is emerging as a revolution in agriculture of global importance to humankind (Duarte et al., 2007). However, aquaculture farms in enclosed coastal regions of temperate areas are threatened by blooms of harmful algae such as *Chattonella* spp. (*Chattonella antiqua*/*Chattonella marina*/*Chattonella ovata*, Raphidophyceae), *Heterocapsa circularisquama*, and *Karenia mikimotoi* (Dinophyceae). These harmful blooms can cause serious economic damage to the aquaculture industry, sometimes of over ¥1 billion ($10 million), by killing both cultured and wild fish (Okaichi, 2004; Hoagland and Scatasta, 2006).

Harmful algae require nitrogen (N) and phosphorus (P) for proliferation. Of them, the major P source in the surface waters of enclosed coastal regions is inorganic phosphate (PO_4^{3-}, hereafter P_i) and its concentration is usually insufficient to cause algal blooms during the warm season (Nakamura et al., 1989b; Yamaguchi et al., 2004; Kittiwanich et al., 2006). In contrast to the surface waters, the bottom waters contain a large amount of P_i, because of ongoing P_i regeneration and P_i release from sediments (Iizuka, 1972; Hopkinson and Wetzel, 1982; Shirota, 1989; Yamamoto et al., 1998; Patel et al., 2000; Yanagi et al., 2004). Hopkinson and Wetzel (1982) reported that P_i regeneration in benthic environments in the near shore zone of the Georgia Bright, USA, can supply approximately 53% of the daily phytoplankton P requirement. During the warm season, however, the vast P_i reservoir in bottom waters is rarely carried up to the euphotic layer, due to stratification of the water column.

Vertical mixing of the water column in coastal regions sometimes occurs, usually associated with heavy rainfall, strong winds, or both (Fogel et al., 1999; Yanagi et al., 2004; Fawcett et al., 2007; Lucas et al., 2014). As a consequence of such mixing events, P_i sometimes increases in surface waters (Patel et al., 2000; Yanagi et al., 2004; Tsuchiya et al., 2013; Lucas et al., 2014). Marine ecologists have shown that this vertically supplied P_i typically promotes the proliferation of planktonic algae in the surface waters (Fogel et al., 1999; Shiah et al., 2000; Yanagi et al., 2004; Fawcett et al., 2007; Tsuchiya et al., 2013; Lucas et al., 2014). Yanagi et al. (2004) analyzed a vertical mixing event in Harima-Nada in 1978 and

---

* Corresponding author.
E-mail address: yharuo@kochi-u.ac.jp (H. Yamaguchi).

http://dx.doi.org/10.1016/j.ecss.2015.07.043
0272-7714/

found that a strong wind of over 4 m s^{-1} on 22 July 1978, might have disrupted the stratification of the water column, carrying nutrients (nitrogen and phosphorus) up into the surface layer and triggering blooms of *C. antiqua*.

Several studies have simulated changes in water column stratification in coastal regions using box and/or numerical models, and have reported the vertical dynamics of phosphorus (often called 'fluxes') on annual or seasonal timescales (Hashimoto and Takeoka, 1998; Kittiwanich et al., 2006, 2007; Koriyama et al., 2013). Most coastal bodies of water are connected to rivers, to the ocean, or to both. Such connections will lead to an influx of riverine or oceanic waters into the body, resulting in large changes in salinity and P_i concentration. We consider it difficult to simulate the changes in the water column stratification and P_i concentration, and also to evaluate the quantity of vertically supplied P_i in most coastal regions.

The Uranouchi Inlet, located on the south coast of Shikoku in western Japan, has a narrow area (0.2 km wide, with a depth of approximately 4 m) and a depth of approximately 20 m at central region, and is rarely supplied by any major river (Fig. 1). Furthermore mass aquaculture is practiced in this small enclosed inlet, but it possesses eutrophic bottom waters (Munekage and Kimura, 1990; Patel et al., 2000). Such a situation frequently causes harmful algal blooms during the warm season. This inlet is thus well suited for evaluating the vertical transport dynamics of P_i in an enclosed coastal region and subsequent effects on harmful algal blooms.

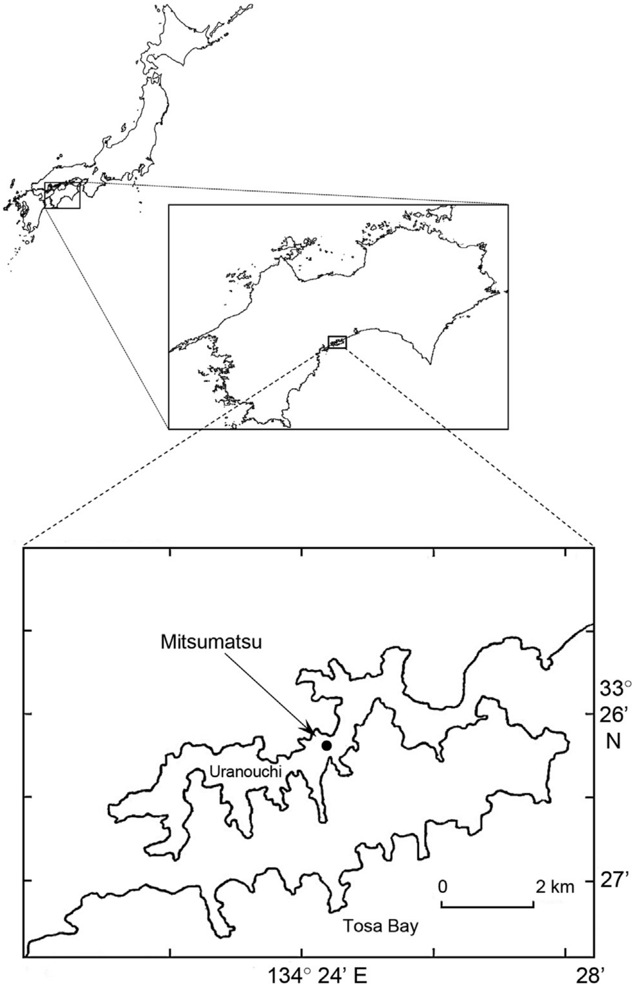

Fig. 1. The sampling location of Mitsumatsu in Uranouchi Inlet.

The present study developed a one-dimensional model of the Uranouchi Inlet capable of simulating the vertical stratification of its water column at multilayer level and changes due to vertical mixing. Using this model, we evaluated the quantity of P_i supplied vertically from the bottom layer to the surface waters, on a daily timescale. Using the known growth kinetics of several representative harmful algal species, we then evaluated the ecological potential effects of the vertical redistribution of the P_i reservoir on the development of blooms of harmful algae when the water was disturbed.

2. Materials and methods

2.1. Derivation of the vertical one-dimensional model

A vertical one-dimensional (1-D) diffusion model was developed to estimate the vertical mixing of a water column based upon diffusion equations for water temperature T (°C) and salinity S with the addition of a heat storage term. In this model, advection was ignored because vertical velocity was assumed to be zero. The bottom topography of the Uranouchi Inlet was described by a model parameter A_z, representing the horizontal area (m^2) of waters at depth z (m) in the inlet. The effects of factors such as tributary rivers and precipitation were ignored. Under these conditions, the 1-D diffusion equations were

$$\frac{\partial T}{\partial t} = \frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z K_v \frac{\partial T}{\partial z}\right) - \frac{1}{\rho_w c_{wp} A_z}(A_z q_z) \tag{1}$$

and

$$\frac{\partial S}{\partial t} = \frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z K_v \frac{\partial S}{\partial z}\right), \tag{2}$$

where K_v is the vertical diffusion coefficient (m^2 s^{-1}), q_z is the heat flux (W m^{-2}) at depth z, ρ_w is the water density (kg m^{-3}), and c_{wp} is the specific heat of water (J kg^{-1} K^{-1}) by Bromley's method (Bromley et al., 1967), as shown in Table 1. The q_z was modeled using an equation from Dake and Harleman (Dake and Harleman, 1969),

$$q_z = [(1-\alpha)S_d] \times e^{-\eta z}, \tag{3}$$

where α is the albedo of water, S_d represents the intensity of incident short-wave radiation (W m^{-2}), and η is the extinction coefficient. In general, η is related to transparency D_s (m) measured at the Inlet by following equation;

$$\eta = \frac{1.7}{D_s}. \tag{4}$$

The boundary conditions at the surface and bottom are very important for estimating the vertical mixing and stratification of

Table 1
Parameters for the water temperature diffusion equations used in this study.

Symbol	Full text	Unit	Value
α	Albedo of water		0.06
σ	Stefan–Boltzmann constant	W m^{-2} K^{-4}	5.67×10^{-8}
ε	Emissivity		0.96
C_H	Bulk transfer constant for latent heat		1.3×10^{-3}
C_E	Bulk transfer constant for sensible heat		1.3×10^{-3}
c_{ap}	Specific heat at the standard pressure	J kg^{-1} K^{-1}	1.005×10^{3}
α_w	Coefficient of thermal expansion of water	$degree^{-1}$	0.21×10^{-3}
c_{wp}	Water's specific heat	J kg^{-1} K^{-1}	4.171×10^{3}
κ	Kármán constant		0.41