Available online at www.sciencedirect.com
SCIENCE DIRECT®

Estuarine, Coastal and Shelf Science 65 (2005) 351–360

ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ECSS

Modeling the effect of freshwater inflows on the development of spring blooms in an estuarine embayment

Do-Seong Byun [a,b,*], Xiao Hua Wang [a], Deirdre E. Hart [c], Yang-Ki Cho [b]

[a] *School of Physical Environmental and Mathematical Sciences, University of New South Wales at Australian Defence Force Academy, Canberra, ACT 2600, Australia*
[b] *Faculty of Earth Systems and Environmental Sciences/Institute of Marine Science, Chonnam National University, Gwangju 500-757, Republic of Korea*
[c] *Department of Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*

Received 8 November 2004; accepted 2 June 2005
Available online 10 August 2005

Abstract

Low vertical mixing rates are a key physical condition associated with the development of phytoplankton spring blooms in coastal and ocean waters. Vertical mixing rates in shallow coastal regimes are decreased not only by thermal stratification but also by haline stratification due to river runoff.

In this paper, the main physical processes involved in the onset of phytoplankton spring blooms are examined in a tide-dominated estuarine embayment, characterized by weak current velocities, using a 1-D ecosystem model (the European Regional Seas Ecosystem Model) coupled with a 3-D physical model (the Princeton Ocean Model coupled with a sediment transport model) via the off-line method. Simulation results show that a reduction in vertical mixing, caused by the episodic input of buoyant, freshwater inflows from a reservoir during the period of neap tides, is the main physical controlling process on the occurrence of spring algal blooms. Furthermore, sensitivity tests using: (1) layered and (2) depth-averaged monthly vertical eddy diffusivity values reveal that the timing of phytoplankton spring blooms in the model is strongly affected by the parameterization of vertical diffusivity.

Keywords: spring blooms; haline stratification; freshwater discharge; vertical mixing; sea-surface cooling; Korea

---

1. Introduction

Marine phytoplankton bloom dynamics between winter and spring are significantly affected by the reduction in vertical mixing rates caused by changes in light availability (Cloern, 1991; Townsend et al., 1992). In general, an increase in solar radiation due to seasonal changes in the solar elevation leads to a reduction in vertical mixing and thermal stratification in the water column in the mid to high latitudes.

Since the early work of Gran and Braarud (1935), the relationship between "mixing depth" and "critical depth" has commonly been used as an indicator for the onset of phytoplankton spring blooms (e.g., Sverdrup, 1953; Smetacek and Passow, 1990; Nelson and Smith, 1991). The original concept of "critical depth" is defined by Gran and Braarud (1935) as the depth at which the gross primary production in the water column is equal to the total respiration by the plankton.

Sverdrup (1953) pioneered the quantification (parameterization) of critical depth as a function of light intensity alone, based on several assumptions, including

---

[*] Corresponding author. Faculty of Earth Systems and Environmental Sciences/Institute of Marine Science, Chonnam National University, Gwangju 500-757, Republic of Korea.
E-mail address: dsbyun@hanmail.net (D.-S. Byun).

0272-7714/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2005.06.012

a sufficient supply of nutrients and the presence of adequate turbulence. In his simple analytical model, Sverdrup's critical depth is a function of average daily light intensity and compensation light intensity. Sverdrup maintained that a net increase in the phytoplankton biomass in the water column occurred in early spring when the depth of the surface mixed layer was less than the "parameterized critical depth". He pointed out that the presence of thermal and/or haline stratification, which affects the thickness of the surface mixed layer, is a "necessary physical condition" for the onset of springtime phytoplankton blooms.

The formation of thermal stratification has been accepted as an essential physical condition for the occurrence of spring phytoplankton blooms in open waters (e.g., Riley, 1957; Nelson and Smith, 1991; Tett and Walne, 1995; Ruardij et al., 1997) and coastal waters (Azumaya et al., 2001). However, as Sverdrup (1953) speculated, spring phytoplankton blooms have also been observed in association with salinity stratification: in South San Francisco Bay by Cloern (1984) and in the Gulf of Maine by Townsend and Spinrad (1986). On the other hand, Townsend et al. (1992) and Eilertsen (1993) observed spring phytoplankton blooms in neutrally-stable clear shelf waters, environments in which physical conditions lead to excessive phytoplankton growth relative to respiration due to the relatively slow vertical excursion rates and deep light penetration. The latter observations have been supported through a simple growth-diffusion model simulation by Huisman et al. (1999). It should be noted that Sverdrup's analytical model lacks the fundamental concept of the "residence time" of phytoplankton in the photic and aphotic zones, a parameter which depends on rates of vertical mixing.

The studies mentioned above imply that vertical mixing is a main controlling factor for the development of spring phytoplankton blooms in open and coastal waters. In open waters (i.e. clear-water environments), seasonal variability (from winter to spring) in the rates and depth of vertical mixing is fundamentally affected by the formation of thermal stratification. Occasionally, spring phytoplankton blooms develop in a neutrally-stable, clear-water column due to clarity and low vertical mixing rates. Unlike in open seas, in tidally-dominated coastal regimes with freshwater inflows the rates of vertical mixing and the depth of the surface mixed layer in spring are influenced by thermal and haline stratification as well as by spring–neap tidal cycles (Legendre, 1981; Cloern, 1991). In tidally-dominated, turbid, coastal environments, vertical mixing rates are also affected by suspended sediment-induced stratification in the bottom boundary layer (Byun and Wang, 2005).

In this paper, we use a 1-D ecosystem model to examine the major controlling physical process for the onset of phytoplankton spring blooms in a tide-dominated turbid estuarine embayment, the Youngsan River Estuarine Bay (YREB). The YREB is located on the western tip of the southwest coast of Korea (Fig. 1). Tidal characteristics are described as mixed, but predominantly semidiurnal (the tidal form factor, the ratio of diurnal ($K_1 + O_1$) to semidiurnal amplitudes ($M_2 + S_2$), is 0.28) with mean spring and neap tidal ranges of approximately 6 m and 3 m, respectively (Byun et al., 2004; Cho et al., 2004). The YREB is a unique system which functions either as an estuary or as a bay depending on the operation of the water-gates on the Youngsan River Estuary. For most of the time, the YREB operates as a semi-enclosed embayment system, functioning as an estuary only when the water-gates on the Youngsan River Estuary are episodically opened. It should be noted that such freshwater discharge events are usually conducted in less than an hour during low tide conditions.

2. Ecosystem model configuration

The 1-D ecosystem model consists of a 1-D biogeochemical model (the European Regional Sea Ecosystem Model, ERSEM) coupled with a 3-D physical model (the Princeton Ocean Model, POM, integrated with a sediment transport model) through the off-line technique (Fig. 2). The 1-D ERSEM, a generic biomass-based biogeochemical model, simulates the biogeochemical dynamics of the coupled pelagic–benthic system. The biological state variables (i.e. carbon (C), nitrogen (N), phosphorus (P) and silicon (Si)) are aggregated into the biological functional groups which comprise trophic levels. The organisms in the model are expressed as vectors of C, N, P, and Si, each of which varies vertically and with time due to hydrodynamics. Three main biological functional groups are identified: the primary producers (phytoplankton), the consumers (zooplankton) and the decomposers (bacteria). The primary physiological processes associated with these organisms (Blackford and Radford, 1995) are: (1) for primary producers, assimilation, respiration, nutrient uptake, exudation, lysis and sedimentation; (2) for consumers, predation, excretion, respiration, mortality and nutrient release; and (3) for decomposers, respiration, nutrient uptake and release, mortality and assimilation of both detritus and dissolved matter. Each of these functional organic groups is further divided according to their morphological and physiological characteristics (e.g., cell size, feeding behavior, growth and respiration rates and uptake preferences), as illustrated in Fig. 3. Net primary productivity in the coupled model is primarily determined by physical and biochemical factors (i.e. solar radiation, nutrients, temperature, turbulence and intracellular nutrient storage). Refer to the following studies for a more detailed description of the biological functional groups: Varela et al. (1995) and Ebenhöh