Remote Sensing of Environment 112 (2008) 3248–3270

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

SeaWiFS sensing of hazardous algal blooms and their underlying mechanisms in shelf-slope waters of the Northwest Pacific during summer

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ARTICLE INFO

Article history:
Received 27 November 2007
Received in revised form 3 April 2008
Accepted 5 April 2008

Keywords:
Remote sensing
Hazardous algal blooms
RCA-chlorophyll
OC4-chlorophyll
SeaWiFS
Sea surface height
Multi-satellite altimeter
QuikSCAT
Northwest Pacific (NWP)

ABSTRACT

RCA-chlorophyll (red tide index chlorophyll algorithm — RCA) estimates from the SeaWiFS, sea surface height (SSH) variations/geostrophic currents from the multi-satellite altimeters, sea surface temperature (SST) from the NOAA-AVHRR, and wind speed/direction from the QuikSCAT are used in conjugation with field observation data to first describe comprehensively the occurrences of various hazardous algal blooms (HABs) and their underlying mechanisms and link to nutrient enrichment during the summer (June–September) in shelf-slope waters off the Northwest Pacific (NWP) covering China, Korea, Japan and Russia (perhaps this is the first satellite-based study in Russia). These datasets provide a coherent view of the summertime evolution of HABs and related physical processes in the above regional segments with four common dynamic regions: coastal cold/estuary water zones, upwelling zones next to the coast, repeated meanders/eddies, and frontal regimes induced by the Kuroshio and its tributaries. Summer HABs numerically dominated by dinoflagellates and diatoms (only in few cases) were initiated in these hydrodynamically active coastal regions and subsequently transported throughout their coastal and oceanic ranges by major currents and eddy systems. As a consequence, dense and colossal blooms displayed mean RCA of >7 mg m^{-3} and TBCA (total bloom covered area) of >20×10^3 km^2, which limits the research vessels to observe concomitantly their spatially explicit phases together with physical oceanographic features in such large regions. Less dense and spatially disbanded blooms were characterized by mean RCA of <3 mg m^{-3} and TBCA of < 8×10^3 km^2. Besides those of the nutrient-abundant zones, high blooms coincided with the coastal upwelling and cyclonic eddy regimes that followed SST minimum and large negative SSH along with favorable phase of winds. By contrast, relatively low mean RCA were consistent with the fronts and anticyclonic meanders revealing moderate-high SSH fields along with variable winds blown off the NWP coast. These anticyclonic meanders, on some occasions, when nutrient-containing coastal water setoff higher chlorophyll biomass and major currents gained force in August, straddled the continental margin, entraining high chlorophyll water from the coast and from the adjacent cyclonic eddies (and upwelling) located nearby into their outer rings that formed a conveyer-belt system of transport to inject coastal blooms into the deep-sea (e.g., East Sea) region of the NWP. The above findings based on satellite data combined with field hydrographic/bloom observation data evidently illustrated richness of the response of summer HABs to the surface circulation and nutrient enrichment processes in shelf-slope waters off the NWP coast.

1. Introduction

Continental shelf-slope waters of the Northwest Pacific (NWP) (covering China, Korea, Japan and Russia) in recent decades have undergone a remarkably troubling transformation to more mesotrophic and eutrophic conditions by which there is appearance, persistence and epidemic of summer algal blooms causing fish mortality, shellfish poisoning, physiological impairment, and numerous ecological and health impacts (Table 1). Such blooms of microscopic marine algae producing different forms of hazardous effects on marine organisms and human are therefore broadly termed as “hazardous” algal blooms (HABs). For what is known about HAB occurrences in the NWP region, NOWPAP (2005) supports a widespread belief that summer HABs are increasing in frequency and severity owing to nutrient enrichment of shelf-slope waters supplied either anthropogenically or naturally (Anderson et al., 2002) or owing to climate oscillations and climate change impacts (Edwards et al., 2006; Sellner et al., 2003). Arising from growing concerns of such an increase in the occurrence of HABs, a number of national, regional and international programs namely the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) (http://ioc.unesco.org/hab/GEOHAB.htm), the Northwest Pacific Action Plan (NOWPAP) (http://www.nowpap.org/), the Korean Harmful Algal Bloom Research Group (KORHAB) (http://ioc.unesco.org/hab/HAN29_Final_comp.pdf), have hence recently been implemented to

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0034-4257/$ – see front matter
doi:10.1016/j.rse.2008.04.002

Table 1
The summer HAB species composition in NWP waters (1998–2006)

Region	Dominant species	Maximum cell density (cells l^{-1})	Area (km^2)	Damage
Bohai Sea, Yellow Sea, East China Sea and South China Sea (east)	**Noctilula scintillans* (Df)	2.0×10^7	6300	No data
	**Ceratium furca* (Df)	1.25×10^9	10,000	Fish kill
	**Prorocentrum dentatum* (Df)	No data	10,000	Fish kill
	Alexandrium tamarense (Df)	No data	No data	Fish kill
	**Alexandrium catenella* (Df)	No data	No data	Fish kill
	Gymnodinium sanguineum (Df)	No data	170	Fish kill
	**Gymnodinium catenatum* (Df)	No data	No data	No data
	Exuviaella marina (Df)	8.1×10^6	No data	No data
	Leptocylindrus danicus (Da)	No data	770	No data
	**Karania mikimotoi* (Df)	No data	3200	No data
	Eucampia zoodiacus (Da)	2.3×10^6	No data	No data
	Mesodinium rubrum (Ci)	No data	100	No data
	**Skeletonema costatum* (Da)	No data	1000	Fish kill
	Paralia sulcata (Da)	No data	No data	No data
Korean Sea	**Cochlodinium polykrikoides* (Df)	4.8×10^4	>100	Fish kill
	**Prorocentrum minimum* (Df)	3.0×10^4	>100	No data
	**Gymnodinium sanguineum* (Df)	1.5×10^4	>100	No data
	**Heterosigma akashiwo* (Rap)	9.96×10^4	>100	No data
	**Skeletonema costatum* (Da)	3.0×10^4	>100	No data
	Noctilula scintillans (Df)	2.0×10^4	>100	No data
	Prorocentrum dentatum (Df)	4.5×10^4	>100	No data
	Alexandrium tamarense.(Df)	3.0×10^4	>100	No data
Japan Sea (including remote islands)	**Gymnodinium mikimotoi* (Df)	3.2×10^4	No data	Fish kill
	**Nactiluca scintillans* (Df)	1.0×10^4	No data	Fish kill
	**Cochlodinium polykrikoides* (Df)	1.9×10^4	No data	Fish kill
	**Heterosigma akashiwo* (Rap)	7.9×10^4	No data	Fish kill
	**Gymnodinium sanguineum* (Df)	1.0×10^4	No data	No data
	**Skeletonema costatum* (Da)	8.37×10^4	No data	No data
	Mesodinium rubrum (Ci)	0.8×10^4	No data	No data
	Alexandrium catenella (Df)	No data	No data	Fish kill
	Ceratium furca (Df)	No data	No data	Fish kill
Russian Sea	**Nactiluca scintillans* (Df)	0.2×10^4	No data	No data
	**Prorocentrum minimum* (Df)	1.5×10^4	No data	No data
	**Heterosigma akashiwo* (Rap)	2.5×10^4	No data	No data
	Oxyrrhis marina (Df)	2.010^4	No data	No data
	Skeletonema costatum (Da)	1.5×10^4	No data	No data
	Ditylum brigthwellii (Da)	0.15×10^4	No data	No data
	Pseudo-nitzschia pungens (Da)	0.18×10^4	No data	No data
	Chattonella globosa (Rap)	0.6×10^4	No data	No data

Star marks indicate the high frequency species and no star marks indicate the relatively low frequency species. The bloom species recorded rarely are not shown here. Abbreviations for four groups of phytoplankton are as follows: Da — Diatoms, Df — Dinoflagellates, Ci — Ciliates, Rap — Raphidophytes (CNRR 2005; JNRR, 2005; KNRR 2005; NOWPAP, 2005; RNRR, 2005).

understand the features and mechanisms underlying the population dynamics of HABs, and to improve and develop management and amelioration strategies.

Historical records from the NWP region show that summer HABs are mostly dominated by the causative microorganisms of the dinoflagellates and diatoms (NOWPAP, 2005 and references therein). In the 1960s the abundance and spatial distribution of these HABs were restricted to small coastal areas, but recently they have become more abundant and frequent throughout the coastal and offshore areas although this trend is not homogeneous and is restricted to specific habitat types. After the first observation of *Noctilula scintillans* and *Skeletonema costatum* in Zhejiang province of the East China Sea (ECS) in 1933 (Fei, 1952), several studies reported evidences of *Ceratium furca*, *Karenia digitata*, *Prorocentrum dentatum*, *Karania mikimotoi* and *Mesodinium rubrum* blooms throughout the ECS and its neighboring South China Sea (SCS) and Bohai Sea (BS) domains, where their peak apparently delayed from south to north, i.e., from April to June in the SCS, June to August in the ECS, and July to September in the BS (NOWPAP, 2005; Tang et al., 2006a; Yang & Hodgkiss, 2004; Yin, 2003; Zhao et al., 2003). In the Korean Sea domain downstream side of East China, *Cochlodinium polykrikoides* has been noted as a major bloom-forming organism (compared to several other causative organisms) associated with socio-economic and ecological issues in the recent times (KNRR, 2005). On the other hand, *Alexandrium tamarense*, *Alexandrium catenella*, *Gymnodinium mikimotoi* (with highest cell density 117,980 cells ml^{-1} in Kyushu coastal areas in July 2002), *Heterosigma akashiwo*, *C. polykrikoides*, *N. scintillans* and some minor species have had devastating effects on a natural community and led to serious economic losses for the aquaculture fish industries in Japan (south west) (Fukuyo et al., 1990; JNRR, 2005; Yamamoto et al., 2002; Yuki & Yoshimatsu, 1989). In Russian coastal waters (especially Primorye), HAB events were registered sporadically from summer and had the species of four taxonomic groups of phytoplankton diatoms, dinoflagellates, raphidophytes and euglenophytes, with no records of fish mortality and other health impacts (RNRR, 2005).

Understanding of regional- and global-scale variability in HABs has been limited by in-situ sampling confined to point measurements from ship-based surveys. Remotely sensed ocean color data acquired with satellite sensors (e.g., Sea-viewing Wide Field-of-view Sensor, SeaWiFS) are the best identified alternatives for providing temporally resolved synoptic views of ocean regions over long periods of time (Holligan, 1985; Keafer & Anderson, 1993; Steidinger & Haddad, 1981; Tester et al., 1991). There have been numerous satellite-based studies of the NWP HABs that have used the SeaWiFS standard chlorophyll-*a* (hereafter chlorophyll-*a* is referred to as Chl) from generic atmospheric correction and bio-optical algorithms, NOAA-AVHRR sea surface temperature (SST) and QuikSCAT wind data in conjugation with in-situ data to describe these blooms. In the SCS, ECS and BS, Tang et al. (2002, 2003, and 2006b) identified several high Chl features from the SeaWiFS data and made attempts to correlate these features with the SST and wind to explain the underlying mechanisms to their time- and space-scales of variation. They stressed that, dense, more