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台湾海峡叶绿素 *a* 对海洋环境多尺度时间变动的响应研究
Response of Chlorophyll *a* Concentrations to Multi-scale
Environmental Variations in the Taiwan Strait

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摘要

全球变化的区域响应，是一个备受关注的热点问题。迄今的研究表明，海洋环境与生态系统在不同的区域可能出现完全不同的时间变化规律。台湾海峡是季风控制的近海环境，具有典型性。因而本论文选取台湾海峡为研究区域，倚重具备时间序列优势的遥感数据并结合现场调查，以叶绿素作为生态指标，聚焦生态系统对环境变动响应这一科学问题，揭示所研究海区多时间尺度的变化规律及其与赤道太平洋 ENSO 指数变化规律的异同，并探讨其成因。

首先，为构建一有效的遥感叶绿素长序列数据，利用 2004 年冬季和夏季的现场叶绿素对台湾海峡和南海北部的 SeaWiFS (Sea-viewing Wide Field-of-view Sensor)和 MODIS (Moderate-resolution Imaging Spectroradiometer)标准叶绿素产品 (Chl) 进行验证。验证结果表明，在台湾海峡，除了冬季外，SeaWiFS Chl 基本可以反映真实的叶绿素时空分布形态；SeaWiFS 和 MODIS Chl 无论从其统计结果上看，还是从其反映 Chl 时空变动趋势上看，都没有显著区别，MODIS 可以接续 SeaWiFS 构成时间序列。

其次，在短期尺度上，发现风是决定冬季台湾海峡海表层温度逐日变动的关键因素，以温度法 ($SST \leq 17^{\circ}\text{C}$) 和温度空间距平法 ($\leq -1^{\circ}\text{C}$) 表征的浙闽沿岸水影响面积的逐日变动与东北季风风应力显著相关，二者的相关系数 r^2 分别达到 0.90 和 0.91。夏季，表征浮游植物生物量的叶绿素浓度的短期变化与近岸上升流活动亦有很强的相关性，不过叶绿素高值区的出现有可能滞后低温区 1-2 天；很可能是因西南季风空间分布的南北差异，使得海峡西南、西北近岸上升流过程出现不一致的短期变动趋势，并导致近岸叶绿素高值出现的时间也南北不同。

在季节尺度上，台湾海峡叶绿素的季节分布存在显著的空间区域化现象，可分为北部和中部的春秋双峰型、西南部的夏季单峰型以及东南部的季节变动不显著型等三类。这一空间差异与季风驱动下水文动力场的季节演变有着密切关联，春、秋季富含营养盐、低温的浙闽沿岸水与寡营养的南海暖水在海峡内共同存在海洋锋，夏季上升流事件在局部区域时有发生，这些过程对海峡内营养盐补充和生物活动起着相当重要的调控作用。

在年际尺度上,以遥感海表层温度和叶绿素作为指示,首先揭示了 El Niño 盛期的 1997-1998 冬季台湾海峡发生了高温、低营养盐、低叶绿素的强暖事件,表层水温高出历史平均值 1.4°C,高叶绿素面积减小一半,暖冷水面积比值比往年增加 25%,这一异常现象很可能是由该年东北季风减弱、富含营养盐的沿岸冷水减弱进而寡营养暖水入侵增强所致。同时发现 1985-2005 年这 21 年间台湾海峡夏季近岸上升流引发的低温区年际变动相当显著,其强弱变动规律与沿岸风应力高度相关,并且面积最大或最小的年份与 ENSO 事件影响夏季风最强或最弱的年份基本一致。在可获得遥感叶绿素数据的 1998-2005 年期间内,无论是叶绿素浓度还是高叶绿素区面积,均以 2004 年为最低,其高叶绿素区面积仅为 2005 年的一半,与该年的弱沿岸风应力、弱上升流和低营养盐的观测结果相一致。但 8 年观测期间的 Chl 年际变动趋势与沿岸风应力没有出现显著的相关关系,说明上升流并不是叶绿素年际变动唯一的控制因素。

关键词 海表层温度; 叶绿素; 上升流; 季风; El Niño; 年际变动; 遥感; 海洋水色; 台湾海峡

Response of chlorophyll *a* concentrations to multi-scale environmental variations in the Taiwan Strait

Regional response to global climate change has received increasing attention, where temporal changes in marine ecological environments may differ from place to place. The Taiwan Strait (TWS) represents a typical coastal ocean under the influence of seasonal monsoon, therefore was chosen as the study area to show the spatial-temporal variability of the surface chlorophyll *a* concentrations (Chl) and their relationship with environmental forcing and ENSO index. Specifically, based on multi-sensor satellite data and *in situ* measurements, we have examined the variability of Chl and its response to environmental forcing at short-term, annual and inter-annual scales in the TWS.

First, in order to establish a long-term, synoptic and accurate dataset, chlorophyll *a* concentration (Chl) data products from the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) and MODIS (Moderate-resolution Imaging Spectroradiometer) satellite sensors were validated using concurrent *in situ* data collected from three cruise surveys in winter and summer 2004. The results showed that the satellite Chl data product is generally accurate for most of the waters where Chl ranges between 0.1 and 10 mg m⁻³, with overall RMS (root mean square) error in log scale smaller than 0.35 and absolute percentage RMS error between 60% and 170% for the open ocean and most of the shallow (<30m), coastal regions, respectively. There was no large systematic error or significant bias in either satellite data set, and SeaWiFS and MODIS showed similar spatial and temporal patterns as well as nearly identical Chl (0.1 < Chl < 4 mg m⁻³). Therefore, satellite Chl was believed to represent the true biological state of the surface ocean.

Then, analysis of the QuikScat wind and AVHRR Sea Surface Temperature (SST) showed that wind played a key role in the short-term SST variations in winter (2-8 January 2002), when distribution of the Zhe-Min Coastal Water, defined by SST ≤ 17°C, was highly correlated ($R^2 \sim 0.90$) with the strength of the northeast

monsoon. During summer 1998, the extent of eutrophic waters (SeaWiFS Chl $>1 \text{ mg m}^{-3}$) was highly correlated with cold upwelling waters, but with a lagging time of 1-2 days. The temporal changes of upwelling events were found different in the northern and southern TWS, and the duration of one upwelling event in the western TWS in August was estimated to be about 12 days. It appears that two distinctive northern and southern upwelling systems in the western TWS were connected with, and affected by, the East China Sea (ECS) and the South China Sea (SCS), respectively.

On seasonal scales, Chl distribution showed significant spatial heterogeneity, which can be generally described by the spring-autumn double-peak in the north and middle of the TWS, summer peak in the southwest, and non-significant peak in the southwest. This spatial heterogeneity is closely related to the wind-driven seasonal hydrodynamic changes in this region. During spring and autumn, nutrient-rich, low temperature Zhe-Min coastal water co-existed with the nutrient-poor but warm waters from the SCS, while during summer upwelling events often occurred at regional scales. These processes modulated the nutrient budget as well as biological processes.

On inter-annual scales, high-SST, low-nutrient, and low-Chl were found in the TWS during the El Niño event in winter 1997-1998. Average SST was $\sim 1.4^\circ\text{C}$ higher normal, and the area of eutrophic waters (Chl $>1 \text{ mg m}^{-3}$) was halved, accompanied with nutrient-poor waters in the mixed layer. These observations are consistent with a diminished advection of the cold and eutrophic Zhe-Min Coastal Water, and, concomitantly, an expansive intrusion of the warm and oligotrophic South China Sea Warm Current/ Kuroshio Branch Water to the TWS as the northeast monsoon was weakened.

Moreover, temporal patterns from the Empirical Orthogonal Function (EOF) analysis showed that the upwelling strength in summer fluctuated from year to year, which was confirmed by field observations. Such patterns showed covariance with the alongshore component of the wind stress (upwelling favorable). It seemed that the maximum and minimum area of upwelling-associated surface cold water could be influenced by the El Niño and La Niña events. Although the low-Chl pattern in 2004 was found consistent with low-wind stress, weak upwelling, and low nutrient during

that year, for the entire 8-year period between 1998 and 2005 no significant correlation was found between Chl interannual variability and along-shore wind stress. Hence, upwelling was not a unique factor to control Chl distributions at interannual scales.

Key Words Sea surface temperature; chlorophyll *a*; upwelling; monsoon; El Niño; Inter-annual variability; remote sensing; ocean color; Taiwan Strait

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厦门大学博硕士学位论文摘要

第一章 前言

海洋环境变动是多时空尺度的复杂过程^[1,2]。从跨越的时间尺度上讲,有数十年的年代际、数年的年际,有季节、月,还有日、时、分、秒等不同周期。从空间尺度上讲,大到上千、万公里的洋流系统,中到上百、千公里的涡旋、锋面、上升流系统,小到几米、几十米的混合、湍流过程。受其影响,海洋生物的分布也具有很高的时空变异度^[3,4,5]。可以说,生物活动的时空变异在某种程度上或多或少都与其生存环境及其变动密切相关,其时空分布格局也往往是各种物理-生物过程时空匹配的结果^[6,7]。如,在大尺度上,与洋流对应的生物过程多和各种水团分布有关;在中尺度上,决定生物行为的关键物理过程主要有锋面、涡旋和上升流;在小尺度上,湍流混合可能起着决定性作用。Denman 和 Powell^[7]曾指出只有时空尺度真正匹配时,物理和生物过程的耦合作用才最有效率。比如,对于浮游植物的日变动而言,表面波(其时间尺度只有几秒)可能比潮汐(时间尺度半天左右)的作用要小得多。Daly 和 Smith^[4]则认为:在小尺度上,生物过程如垂直迁移、摄食等行为对浮游植物的现存量 and 分布的影响可能更大些;而在大、中尺度上,物理过程对生物群落的结构和分布格局的调控作用就显得更为重要。无论如何,确定这些敏感且复杂的物理、生物过程的变动及其对海洋生态动力学的影响不仅是 GLOBEC(全球海洋生态动力学研究)所关注的科学问题之一,而且理解这些过程的耦合作用及其多尺度时空变动规律及机制,对于研究食物网动力学、生物地球化学循环、气候变化的响应以及渔业资源生产都具有十分重要的意义。

全面理解海洋生态系统的物理-生物过程的耦合作用需要拥有不同时空尺度的大量数据,卫星遥感由于其在时空观测频度上无可比拟的优越性,目前已成为一个不可或缺的数据源。至今已被广泛应用于海洋学研究的遥感资料主要包括风、海表层温度(SST)、海面高度和叶绿素 a(Chl)等参数。其中,覆盖时间最长的为 SST 和 SSH(海面高度异常)这两个最基本的物理参数,已积累了近 30 年和 15 年的数据。作为生态响应唯一表征的叶绿素水色数据积累时间最短,所以,近年来,为尽可能地获取更长序列的可覆盖全世界各海区的叶绿素数据集,多源水色传感器数据的融合正日益成为研究热点^[8]。这些遥感时序列数据结合船

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