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On Light Absorption Properties off Southeastern China — from Estuarine to Shelf Water

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摘要

本论文研究中国东南近海几种不同特征水体的光吸收特性及其控制机制，包括河口水体—珠江口、沿岸水体—台湾海峡南部、陆架水体—南海东北部，并探讨浮游植物吸收对浮游植物群落结构的指示作用；另外，追踪厦门西海域两次水华过程水体光吸收特征的变动。

就 440 nm 水体吸收而言，珠江口春、冬季最主要成分是非色素颗粒吸收，南海东北部则是浮游植物吸收；夏季台湾海峡南部也以浮游植物吸收为主，但非色素颗粒与 CDOM 二者的贡献与之相当。三个海域吸收组成分别体现河口水体、陆架水体和近岸水体的特征。

南海东北部、台湾海峡南部的非色素颗粒吸收光谱斜率 S_d（350-700 nm）接近，平均分别为 0.0099、0.00912 nm^{-1}，和珠江口的差别较大（~0.00126 nm^{-1}）。

CDOM 的吸收特征与其来源密切相关。冬季珠江口 355 nmCDOM 吸收 $a_g(355)$ 为 0.24-1.93 m^{-1}，低于多数欧美河口水体；与盐度呈线性反相关，在分布上体现珠江口的多口门特征，CDOM 主要为陆源。相应的光谱斜率 S_g(300-500 nm)为 0.0138-0.0184 nm^{-1}，变动小，仅河口与南海陆架间的过渡带低于 0.015 nm^{-1}，同时荧光 EEMs 分析在此发现海源类腐殖质荧光团，过渡带 S_g 的变动可能是河口水和多个海洋水团的混合及其他因素的综合结果。夏季台湾海峡南部 $a_g(355)$为 0.033-0.456 m^{-1}，高于一般大洋水体；其分布基本呈表层低、深层高，总体上与温度反相关，与盐度、浮游植物吸收 $a_{ph}(675)$正相关，说明 CDOM 受陆源的影响小，主要来自现场生产，荧光 EEMs 结果及部分样品在 300-350 nm 的特殊吸收峰现象与之相符。对应的 S_g 为 0.0101-0.0318 nm^{-1}，平均 0.0204 nm^{-1}。

浮游植物吸收(a_{ph})在南海和台湾海峡存在时空变动，主要受控于物理过程。在南海东北部位于珠江口外的一垂直岸断面，春季一场暴雨后，由于河口锋外移，内陆架区表层 $a_{ph}(675)$由 0.002 m^{-1} 升高至 0.050 m^{-1}，B/R 值($a_{ph}(440)/a_{ph}(675)$)由 3.9 降低至 2.5；冬季相同站位表层 $a_{ph}(675)$比春季高 0.002-0.012 m^{-1}，而内陆架区表层 B/R 值（不超过 2.5）低于春季（>3.0），很可能由于强东北季风加强水体垂直混合并驱动粤东沿岸流影响内陆架区。夏季台湾海峡南部沿岸上升流对浮游植物吸收的影响显著：在从南到北的三个沿岸站位，北端较南端表层水温低 3.6 ℃，相应的 $a_{ph}(675)$高出一个数量级（0.038 vs. 0.004 m^{-1} ）。

由浮游植物吸收提取部分浮游植物群落信息有较高的可行性。基于 $a_{ph}(675)$ 估算南海东北部 Chl *a*，表层结果为冬季高、春季低，与遥感结果及文献报道的 SEATS 站位的季节分布模式相似；从 B/R 值推测，春季较之冬季，微微型原核浮游植物（包括蓝藻、原绿球藻）是珠江口外内陆架区更为重要的浮游植物群落组成；冬季浮游植物蓝光波段吸收最大波长红移现象显示，原绿球藻在南海东北部外陆架/大陆坡折区普遍存在。夏季台湾海峡南部两大断面表层的 $a_{ph}(490)/a_{ph}(580)$比值和 Zeaxanthin 占总类胡萝卜素的比例(Zea/T-caro)呈直角双曲线函数关系，据此关系从 a_{ph} 估算两个小断面的表层 Zea/T-caro 分布，结果与 HPLC 色素实测值基本一致，这一发现为未来遥感反演浮游植物吸收、最终获得浮游植物群落结构的一个新指标奠定了重要的基础。厦门西海域水华连续观测过程中，浮游植物吸收特性反映了粒级结构和色素组成上的显著变动；675 nm 归一化浮游植物吸收在 483-532 nm 间的光谱斜率（S_{ph}）和光合辅助色素和光合色素的比例（PPC: PSC)二者呈反相关，但仅当 PPC: PSC <0.65 时，且关系函数会因藻种组成而异；浮游植物吸收二阶导数光谱在特定波段值和 Chl *b*、Chl *c* 和 Fucoxanthin 有强相关。

两度厦门西海域水华过程追踪发现，受水动力的影响，非色素颗粒吸收的变动没有明显规律；CDOM 吸收 $a_g(440)$也仅在 2005 年 6 月强水华事件中变动较大，且和浮游植物吸收 $a_{ph}(440)$有共变趋势。但非色素颗粒吸收光谱斜率 S_d 有随 T-chl *a*（Chl *a*+脱镁色素）升高而降低的趋势，可能与生物碎屑的比例有关；颗粒吸收 $a_p(440)/a_p(675)$比值随 T-chl *a* 的升高而显著下降，可用于指示水华的发生。

关键词 吸收系数；浮游植物；CDOM；珠江口；南海东北部；台湾海峡；水华；群落结构

On Light Absorption Properties off Southeastern China —from Estuarine to Shelf Water

Absorption properties off southeastern China were investigated, including several kinds of regimes such as the Pearl River Estuary (PRE), the southern Taiwan Strait (TWS) and the northeastern South China Sea (NSCS) — a continental shelf water. In addition, a time series of absorption properties as well as algal pigments were measured in the western Xiamen Bay in order to assess temporal variations in absorption properties of various constituents associated with bloom development.

In general, de-pigmented particles dominate the total absorption at 440 nm both in the spring and the winter in the PRE, while phytoplankton dominate in the NSCS. During summer, phytoplankton are the major absorption component in the southern TWS, but the contributions of de-pigmented particles and CDOM can't be neglectable.

The mean absorption spectral slope of de-pigmented particles (S_d, determined between 350-700 nm) in the NSCS is 0.0099 nm^{-1}, similar to that in the southern TWS (0.00912 nm^{-1}), and much smaller than that in the PRE (~0.00126 nm^{-1}).

Absorption properties of CDOM are different in the PRE and the southern TWS, depending on the different sources. Over a 0-33 salinity range, CDOM absorption coefficients at 355 nm, $a_g(355)$ decreased from 1.93 to 0.24 m^{-1} in the PRE in the winter, relatively lower than those in the other American and European estuaries. $a_g(355)$ showed a linear, inverse relationship with salinity, suggesting a freshwater source. High $a_g(355)$ in the vicinity of four outlets demonstrated multiple sources of CDOM. Absorption spectral slopes (S_g), determined between 300-500 nm, ranged from 0.0138 to 0.0184 nm^{-1}. No apparent pattern of S_g for most stations was observed except lower values in the transition zone between the estuary and the South China Sea shelf, where a marine humic-like fluorophore (M) was encountered by fluorescence EEMs analysis. This phenomenon can be interpreted as a mixing process of involving upstream estuarine water and adjacent seawater with different S_g values. In the southern TWS, $a_g(355)$ varied from 0.033 to 0.456 m^{-1} in the summer, a little

higher than those in the open ocean, with S_g ranging from 0.0101 to 0.0318 nm^{-1}. Generally, $a_g(355)$ tended to be low in the surface and high in the deep water, inversed to temperature, covaried with phytoplankton absorption coefficients at 675 nm ($a_{ph}(675)$) and salinity. Moreover, none terrestrial humic fluorophore was detected by fluorescence EEMs analysis. And special shoulders at 300-350 nm existed in the absorption spectra for some samples, likely due to the release/excretion of phytoplankton and zooplankton. It is suggested that CDOM in the southern TWS derives mainly from local production rather than terrestrial source.

Spatial and temporal variations of phytoplankton absorption coefficients (a_{ph}) were observed in the NSCS and the southern TWS, tightly associated with physical processes. a_{ph} was found subject to short time scale and seasonal variabilities in the NSCS. After a rainstorm in the spring, an increase of $a_{ph}(675)$ from 0.002 to 0.050 m^{-1} and a drop of B/R ratio ($a_{ph}(440)/a_{ph}(675)$) from 3.9 to 2.5 accompanied with a decrease of salinity from 34.0 to 26.5 occurred in the surface water at one site on the inner shelf, demonstrating an intrusion of the Pearl River plume onto the inner shelf as a consequence of an episodic event. Surface $a_{ph}(675)$ in the spring was lower than those in the winter at the same stations while B/R ratios were greater than 3.0 contrasting to values less than 2.5 for the inner shelf region. This seasonal pattern was attributed to relatively strong impact of Yue-Dong Coastal Water upon the inner shelf and enhanced vertical mixing owing to the strengthened northeastern monsoon in the winter. During summer in the southern TWS, a_{ph} distribution can be strongly affected by the coastal upwelling. For three coastal stations sampled in succession, $a_{ph}(675)$ increased northward from 0.004 to 0.038 m^{-1} while temperature dropped 3.6 ℃ in the surface water.

Concentrations of Chl *a* in the NSCS were estimated based on $a_{ph}(675)$. Seasonal pattern of surface Chl *a*, high in the winter and low in the spring, is consistent with the remote sensing Chl *a* and that reported in the literatures. According to the variability of B/R ratios, picoprocaryotes were suggested to be an important component of phytoplankton community on the inner shelf in the spring rather than in the winter. Evident bathochromic shifts of the absorption maximum in the blue region

solely found in the winter implicated the presence of *Prochlorococcus* in the outer shelf/slope water. In the southern TWS, the relationship between Zea/T-caro (ratios of zeaxanthin to total carotenoids) and $a_{ph}(490)/a_{ph}(580)$ in the surface water on transects A and B could be described by a rectangular hyperbola function. According to the quasi-quantity relationship above, the surface Zea/T-caro on two small transects, F and G, was calculated. The estimated results were consistent with values determined by HPLC. During blooms in the western Xiamen Bay, the distinct changes in size structure and pigment composition were reflected by phytoplankton absorption properties. Spectral slopes of a_{ph} (S_{ph}), calculated as ($a_{ph}(483)$-$a_{ph}(532)$)/($a_{ph}(675)(483\text{-}532)$), had a linear, inverse relationship with PPC: PSC (ratios of photoprotective carotenoids to photosynthetic carotenoids) when PPC: PSC was less than 0.65, though results were different for samples with PPC: PSC up to 0.65. And the second derivative of a_{ph} at special wavelengths correlated well with Ch *b*, Chl *c* and Fucoxanthin. All of these demonstrate the potential applicability of phytoplankton absorption properties to characterize the temporal and spatial pattern in chl *a* and phytoplankton community structure.

There were no regular variations of de-pigmented particulate absorption coefficients (a_d) during two phytoplankton blooms tracing in the Xiamen bay. CDOM absorption coefficients at 440 nm ($a_g(440)$) only changed significantly in June 2005 and were covaried with $a_{ph}(440)$. However, spectral slopes of a_d (S_d) had a tendency against T-chl *a* (Chl *a*+phaeopigments), which may be related to the proportion of phytoplankton detritus in de-pigmented particles. $a_p(440)/a_p(675)$, ratios of $a_p(440)$ (total particulate absorption coefficients at 440 nm) to $a_p(675)$, dropped evidently with increasing T-chl *a*, which could be used to indicate the phytoplankton bloom.

Key Words absorption coefficient; phytoplankton; CDOM; community structure; Pearl River Estuary (PRE); northeastern South China Sea (NSCS); Taiwan Strait (TWS); bloom

缩写词

a	吸收系数
a_p	总颗粒吸收系数
a_d	非色素颗粒吸收系数
a_{ph}	浮游植物吸收系数
a^*_{ph}	浮游植物比叶绿素 *a* 吸收系数
	chlorophyll-specific absorption coefficient of phytoplankton
a_g	CDOM（有色溶解有机物质）吸收系数
S_d	350-700 nm 的非色素颗粒吸收光谱斜率
S_g	300-500 nm 的 CDOM 吸收光谱斜率
S_{ph}	675 nm 归一化浮游植物吸收在 483-532 nm 的光谱斜率
	$(a_{ph}(483)- a_{ph}(532))/[a_{ph}(675)\times(483-532)]$
B/R	440 nm 和 675 nm 两波段浮游植物吸收系数比值
	$a_{ph}(440)/a_{ph}(675)$
Alloxanthin	别藻黄素
β-carotene	β–胡萝卜素
19'-Butanoyloxyfucoxanthin	19-丁酰基氧化岩藻黄素
Diadinoxanthin	硅甲藻黄素
Dv-chl *a*	二乙烯基叶绿素 *a*
Dv-chl *b*	二乙烯基叶绿素 *b*
Fucoxanthin	岩藻黄素
Neoxanthin	新叶黄素
Peridinin	多甲藻素
Prasinoxanthin	青绿藻素
Zeaxanthin	玉米黄素
Violaxanthin	三色堇黄素
PPC: PSC	光合辅助色素与光合色素的比值

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第一章 绪论

摘要 本章重点介绍浮游植物吸收与 CDOM 吸收的国内外研究现状，总结几十年来的研究进展及存在问题，并在此基础上提出本论文的研究思路和目标。

光对于海洋的重要性，人所共知，它决定海洋热收支平衡，驱动上层水的混合，是浮游植物光合作用、以及物质光化学反应的能量来源。光在海水中的传播本质上是个物理问题，包括吸收和散射行为，取决于海水中的各种颗粒和溶解态物质，特别是浮游植物以及其所衍生的物质，因而这个物理问题深入下去，与生物、化学问题实际上是交织在一起的。卫星水色遥感技术的问世，成为推动这一交叉领域发展的契机，在致力于发展遥感水下算法的物理学者之外，越来越多的生物、化学海洋学领域的学者加入海水中两大类光学活性物质、同时也是生态系统中重要的两个环节—浮游植物色素以及有色溶解有机物质(CDOM)的光学特性研究中，在为算法打下基础之外，也获得了与浮游植物变动、生源要素循环相关的种种过程的新认识。因而我们认为，水体光学特性的研究，应不仅停留在服务于卫星遥感算法的发展，它本身应当被视为一个重要的、并且有遥感应用前景的海洋学参数，可以帮助我们更好地认识海洋学问题，尤其是生态系统与生物地球化学的相互作用问题。

基于这一理念，本论文选择中国东南近海为实验海域，聚焦吸收特性开展研究。以下回顾国内外该领域的进展与现状，而后详述论文的设计思路。

1.1 国内外研究进展

水体光吸收特性用吸收系数 a（m^{-1}）表征，它只与水体中的物质有关，不依赖于水体光场的几何结构，是水体的固有光学性质之一[1]。吸收系数定义为一束平行光透过一无限薄的均匀介质时，光吸收率（A）与介质厚度（△r）的比值：

$$a(\lambda) = \lim_{\Delta r \to 0} \frac{A(\lambda)}{\Delta r}$$

$$a(\lambda) = 2.303 \times OD(\lambda)/r, \qquad (1)$$

其中，OD 表示光学密度（吸光度）。