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（SHENGTAI XUEBAO）

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封面图说：冬天低空飞翔的丹顶鹤——丹顶鹤是鹤类中的一种，因头顶有“红肉冠”而得名。是东亚地区特有的鸟种，因体态优雅、颜色分明，在这一地区的文化中具有吉祥、忠贞、长寿的象征，是传说中的仙鹤，国家一级保护动物。丹顶鹤具备鹤类的特征，即三长——嘴长、颈长、腿长。成鸟除颈部和飞羽后端为黑色外，全身洁白，头顶皮肤裸露，呈鲜红色。丹顶鹤每年要在繁殖地和越冬地之间进行迁徙，只有在日本北海道等地是留鸟，不进行迁徙，这可能与冬季当地人有组织地投喂食物，食物来源充足有关。

彩图提供：陈建伟教授　北京林业大学　E-mail：cites.chenjw@163.com

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典型低纬度海区(南海、孟加拉湾)初级生产力比较

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摘要: 南海和孟加拉湾有着相似的纬度范围, 均处于低纬度季风区, 但环境的开放性和水体交换特征有所不同。将南海和孟加拉湾的初级生产力进行对比, 有助于加深人们对低纬度海区生物生产过程的认识。南海有着复杂的物理过程, 存在涡旋、上升流、黑潮、台风和冲淡水等多种现象, 显著地影响着初级生产力大小和时空分布。南海初级生产力有以下几个特点: (1)受冲淡水和沿岸上升流的影响, 沿岸海域常常高于开阔海区; (2)初级生产力的高值通常不出现在表层, 大都出现在次表层; (3)在开阔海区受水体交换(黑潮等)和中尺度现象影响(涡旋)显著。此外, 南海初级生产力的季节变化也比较明显, 但季度变化规律有较强的区域性。孟加拉湾物理环境与南海差别明显, 初级生产力主要受淡水输入、涡旋和光照的影响, 受台风和上升流影响不如南海明显。在沿岸区, 高温低盐水覆盖了沿岸上层水体, 使得混合层较稳定, 抑制了深层富含营养盐水体的涌升补充, 导致初级生产力下降; 光强(悬浮物多、多云天气多)也限制了初级生产力。孟加拉湾开阔海区常常有涡旋形成, 也对初级生产力有一定影响。沿岸区初级生产力南海高于孟加拉湾, 而在开阔海区两者差别不大, 因此整体上南海初级生产力水平高于孟加拉湾。

关键词: 南海; 孟加拉湾; 初级生产力

A comparison study on primary production in typical low-latitude seas (South China Sea and Bay of Bengal)

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Abstract: The Bay of Bengal (BOB), the largest bay in the world, forms the northeastern part of the Indian Ocean. Both the BOB and the South China Sea (SCS) were influenced by monsoon seasonally with similar latitude range. Primary productions (PP) of the two seas and their influencing factors were reviewed in this paper. The spatial distributions of PP and their environmental regulation mechanisms showed obvious differences between the two seas. Complicated physical phenomena could be found in the SCS, such as mesoscale eddies, coastal upwelling, Kuroshio, typhoon and river discharges. River discharges (especially those from the Pearl River and the Mekong river) and coastal upwelling (e.g. the

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Eastern Guangdong upwelling) bring abundant nutrients to the coastal waters in the southwest monsoon period, and result in the stimulation of phytoplankton growth. Mesoscale eddies (cold eddy or warm eddy) have different physical structures from adjacent waters, and can influence the nutrients availability. Kuroshio intrusion (characterized as warm and oligotrophic waters) and typhoon can also regulate PP in the SCS. Various physical processes could potentially control nutrient supply in the euphotic layer, and consequently influence the spatial and temporal variation of PP in the SCS. In the BOB, copious rainfall and river discharge often decreased salinity in the upper layers during summer, and sea surface temperature was warmer than in the SCS, leading to strong stratification in the upper layer. Weak wind over the Bay was unable to erode the strongly stratified surface waters; thereby the wind-driven vertical mixing was restricted within a shallow depth. This inhibits any possible introduction of nutrients from deeper water below the mixed layer into the upper layer. Meanwhile, suspended solids from the discharges and cloudy weather decreased light availability and therefore limited phytoplankton growth. In the near-shore area, river discharge and coastal upwelling can enhance PP in the SCS, while stratification in the BOB can inhibit algal growth in the euphotic zone, so PP in the coastal waters of SCS was higher than that in the BOB. In the open sea area, PP in the SCS is supposed to be close to that in the BOB. As a whole, PP in the SCS is evaluated to be higher than in the BOB.

Key Words: South China Sea; Bay of Bengal; primary production

初级生产力是自养生物通过光合作用或化学合成制造有机物的能力,是生态系统的起点和生物海洋学的研究基础[1]。初级生产力受多种因素的影响,既有物理因素(主要包括温度、光强、水团扰动等),又有化学因素(营养盐、痕量金属)和受生物因素(微型浮游动物摄食、细菌等)的影响[2]。

低纬度海区常常受季风影响,表层水温较高,有着恒定的温跃层和较深的真光层。南海和孟加拉湾具有典型的热带海洋特征,有着相似的纬度范围(5°—25°N),受季风影响明显,但环境的开放性和水体交换特征有明显区别[3],将南海和孟加拉湾的初级生产力进行对比,有助于加深我们对低纬度海区的认识。本文对近年来南海、孟加拉湾的初级生产力研究结果进行综述,重点探讨初级生产力的影响因素,以期深入了解低纬度海区生物生产过程。

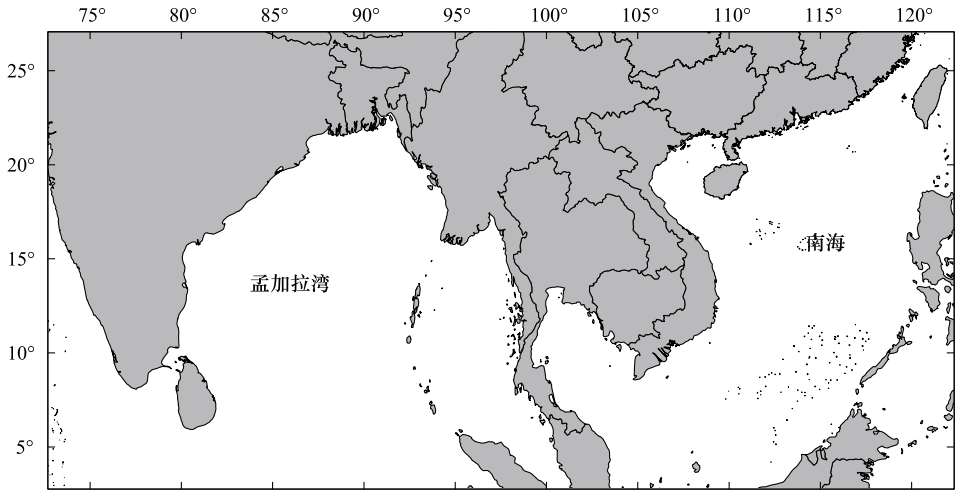

图 1　南海和孟加拉湾的地理位置

Fig. 1　Location of South China Sea and Bay of Bengal

1　南海初级生产力

南海面积约 $3.5\times10^6 km^2$,分别经台湾海峡、吕宋海峡、巴拉巴克海峡、卡里马塔海峡和马六甲海峡等与东

海、太平洋、苏禄海、爪哇海和印度洋等相通,但由于这些海峡大多宽度较窄,水深较浅,只有较宽的吕宋海峡海槛深度超过 2000 m,所以南海自身具有很高的封闭性[4]。Wyrtki[5]利用早期的资料,描绘了南海基本环流型,并指出季风变化是环流型季节转换的原因。季风和黑潮是南海环流 2 个主要的驱动力,它们对南海大尺度环流和中尺度现象都起着十分重要的作用[6]。近年来,国内外学者对南海物理过程进行了较多研究[7-14],南海存在着径流、上升流、涡旋、黑潮和南海暖流等物理现象,而复杂多样的物理过程对海洋浮游植物的初级生产带来了诸多影响。

南海叶绿素 *a* 和初级生产力的研究始于 20 世纪 80 年代,主要集中在叶绿素 a 和初级生产力的时空分布、垂向变化、生物与物理过程耦合等方面[15-27],部分研究结果见表1。南海初级生产力有以下几个特点:(1)在水平分布上,沿岸海域高于开阔海区[15-16],这是由于沿岸海域常常受冲淡水(珠江、湄公河)和上升流(琼东上升流、粤东上升流等)等影响[26-27];(2)在垂直分布上,初级生产力的高值通常不出现在表层,大都出现在次表层,这与表层强光,叶绿素 a 最大层以及营养盐的垂向分布有关[20-26];(3)在开阔海区受水体交换(黑潮等)和中尺度现象(涡旋)影响显著[17, 28]。

整体上南海初级生产力季节变化比较明显,冬季最高,春季逐渐降低,夏季初期开始回升,八月份出现较小峰值,秋季回落后逐渐升高回到冬季的状况[20, 25]。南海不同区域季度变化模式不同,深水海盆区初级生产力的浮动相对较小;台湾海峡南部和广东沿岸附近和北部湾初级生产力终年较高;吕宋岛西北附近海域初级生产力峰值在冬季;越南东部和湄公河口附近海域冬季和夏季均存在较高初级生产力[20, 25]。

表 1 南海初级生产力部分研究结果

Table 1 Partial result of Primary production in South China Sea

时间 Time	纬度(N) Latitude	经度(E) Longitude	初级生产力/(mgC $m^{-2}d^{-1}$) Primary production	参考文献 Reference
2004 夏季(2004, Summer)	21.5°—22°	113°—120°	870±260	[15]
2004 夏季	15°—20°	114°—119°	370±140	[15]
2004 冬季(2004, Winter)	21.5°—22°	113°—120°	820±40	[15]
2004 冬季	15°—20°	114°—119°	530±210	[15]
1998 夏季	6°—22°	108°—120°	390±340	[24]
1998 冬季	6°—22°	108°—120°	550±410	[24]
2008 夏季	17.5°—23.5°	109°—120°	225±137	[26]

初级生产力的影响因素有着较强的地域性和各因素间的交互作用性,本节重点探讨物理因素(上升流、径流、涡旋、台风等)对初级生产力的影响(图 2)。

珠江和湄公河是南海周边国家的主要河流,西南季风期间向南海输入了大量淡水[9]。径流携带大量的营养盐,促进了沿岸区浮游植物生长,提高了初级生产力[27]。珠江冲淡水常常向东运动到 116°E,上层水体被冲淡水所覆盖,显示出低温低盐的特性,径流常常在河口形成羽状峰,且锋面的特征及水流受风驱环流的影响,初级生产力出现高值[26-27]。

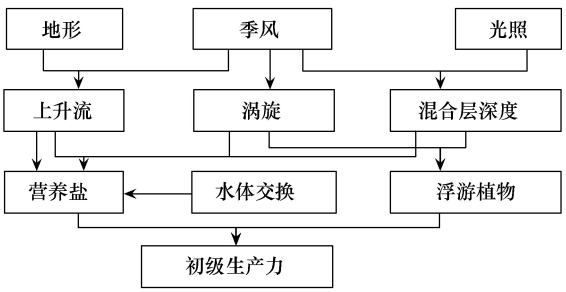

图 2 南海初级生产力的环境调控机制

Fig. 2 Environmental modulation of primary production in SCS

由于埃克曼效应,风引起表层海水的离岸运动,促使深层水的涌升补充,形成沿岸上升流。南海上升流系统具有多个中心,如粤东、琼东、吕宋西南部和越南东部流等[10-11]。深层低温水向上涌升,带来了较为丰富的营养盐,如在汕头海域、琼州海峡东侧常常出现低温中心和高初级生产力[27, 29]。

海洋中的涡旋是气旋式或反气旋式海洋环流,它的存在不仅会改变水体的温盐结构,而且调节真光层营

养盐含量,进而影响浮游植物生物量和生产力。气旋式涡旋(冷涡)中心海水自下而上运动,使海面升高,将下层冷水带到上层较暖的水中,使涡旋内部的水温比周围海水低;反气旋式涡旋(暖涡)中心海水自上而下运动,使海面下降,携带上层的暖水进入下层冷水中,涡旋内部水温比周围水温高[12, 19]。2005 年春末,吕宋海峡冷涡内部初级生产力为 1090 $mgCm^{-2}d^{-1}$,新生产力为 670 $mgCm^{-2}d^{-1}$,而冷涡外部初级生产力为 590 $mgCm^{-2}d^{-1}$,新生产力为 250 $mgCm^{-2}d^{-1}$,显示了冷涡对初级生产力的提升作用,而黑潮区的新生产力仅为 120 $mgCm^{-2}d^{-1}$[17],证明黑潮水体具有低初级生产力特征。

热带风暴或者是台风,能引起海洋水体的垂直混合和上升流形成[30]。垂直混合过程及由此引起的上升流能将海洋深层冷水区中营养盐泵送到真光层并引起浮游植物的旺盛生长[31]。台风“鹦鹉”经过南海北部后,表层水温降低了 3℃,强风和强降雨导致珠江冲淡水强度是同期平均强度的五倍,加上水体垂直混合和上升流等因素,在珠江口外侧诱发藻华[32-33]。热带风暴启德(Kai-Tak)在 2003 年掠过我国台湾岛以南巴林塘海域后,在此风暴为期 3 d 停留期间,Kai-Tak 使海表叶绿素 a 浓度增加了近 30 倍[31]。

此外,黑潮对南海初级生产力的影响,高温低盐水体进入南海,一定程度上降低了南海的初级生产力[17]。

2　孟加拉湾初级生产力

孟加拉湾位于印度洋北部,是世界第一大海湾,面积约 217 万 km^2,西临印度半岛,东临中南半岛,北临缅甸和孟加拉国,南与印度洋相交,经马六甲海峡与南海相连[34-35]。印度和缅甸的一些主要河流(恒河、布拉马普特拉河等)均流入孟加拉湾,湾内著名的岛屿包括斯里兰卡岛、安达曼群岛、尼科巴群岛等[34]。孟加拉湾表层水体主要受常年盛行的季风以及印度洋的影响,西南季风主要盛行于每年的 6—12 月份向孟加拉湾每年贡献约 80% 的降雨,随着 10 至 1 月份东北季风的加强,西南季风开始减弱[36]。近年来学者们对孟加拉湾浮游植物生物量和初级生产力展开了较多研究[37-44],部分研究结果见表 2。

表 2　孟加拉湾初级生产力部分研究结果

Table 2　Primary production in Bay of Bengal

时间 Time	纬度 N Latitude	经度 E Longitude	初级生产力/($mgC\ m^{-2}d^{-1}$) Primary production	参考文献 Reference
2001-07—08	9°—20°	80°—88°	40—520	[41]
2002-09—10	8°—20°	80°—88°	182—513	[39]
2003-04—05	8°—20°	80°—88°	155—427	[39]
2002-07—08	11°—21°	80°—89°	沿岸 350±225; 远岸 251±177	[42]
2001-12	11°—21°	80°—89°	沿岸 252±210; 远岸 231±150	[42]
2001-04	11°—21°	80°—89°	沿岸 308±120; 远岸 303±95	[42]
2010-04—05	10°	83°—91°	199—367	[44]

在西南季风和秋季季风转换期间,沿岸和开阔海域水柱叶绿素 *a* 相差不大,但水柱初级生产力有一定变化,秋季季风转换期间水柱初级生产力变化范围为 180—512 $mgCm^{-2}d^{-1}$,西南季风期间为 90—520 $mgCm^{-2}d^{-1}$[37]。每年的 3—4 月(西南季风前),东印度沿岸流带来了表层富含营养盐的冷水,提升了沿岸的浮游植物生物量和生产力;在 7—8 月(西南季风期),沿岸上升流也刺激了浮游植物生长,但并没有高生产力出现(均值约 300 $mgCm^{-2}d^{-1}$),这是因为多云天气造成了浮游植物初级生产的光限制[38]。Madhu[42]对孟加拉湾初级生产力的季度研究结果显示:在沿岸区,夏季初级生产力最高,其次是春季季风转换期,冬季最低;在开阔海区,春季季风转换期初级生产力最高,其次是夏季,冬季最低。

孟加拉湾物理环境与南海差别明显,受台风和上升流的影响不如南海明显,初级生产力主要受淡水输入、涡旋和光照的影响。孟加拉湾淡水来源包括降水和径流,印度东岸附近年降水量高达 1 m, 安达曼海及其北部沿岸区域年降水量甚至超过 3 m,大量的海表淡水通量和河流径流量使孟加拉湾成为印度洋盐度最低的区域[35]。由于降水大大超过蒸发作用,加之大量淡水注入,夏季湾北部层化明显,并出现障碍层,使孟加拉湾处于较稳定的层结状态[36-37]。冬季淡水径流量虽然大大减少, 在湾北部表层仍出现层化, 并产生逆温现

象[39-42]。湾内海水盐度由沿岸向外部海域逐步升高,高温低盐水覆盖了沿岸上层水体,使得混合层较稳定,抑制了营养盐的抽吸,抑制了浮游植物生长和高初级生产力。

淡水输入带来了数以亿吨的河流物质,水体悬浮物含量增加,降低了水体的透明度,加上多云和阴雨天气较多,使得光强和光强可利用性不高,抑制了初级生产力[39]。孟加拉湾开阔海区常常有涡旋形成,暖涡和冷涡的出现会改变水体运动,进而影响水柱中的营养盐的分布,改变了水柱中叶绿素 *a* 含量和初级生产力的大小[40-44]。

3 初级生产力对比

初级生产力高低主要由物理过程和营养盐调控,而营养盐浓度受物理和生物过程支配,不同的物理过程使得两个海区营养盐的时空分布特征差异明显,导致初级生产力的差异。在沿岸区,南海受上升流和冲淡水影响,营养盐得到了有效补充,刺激了浮游植物生长,初级生产力水平较高,而孟加拉湾由于受高温低盐水覆盖了沿岸上层水体,层化现象抑制了营养盐的抽吸,加上光强的限制,导致初级生产力下降[42, 44],因此在沿岸区,南海初级生产力水平高于孟加拉湾。在开阔海区,南海与孟加拉湾初级生产力相差不大,海水层化明显,营养盐无法进入上层水体,常常限制浮游植物生长,导致了低初级生产力。综上所述,南海初级生产力水平整体上高于孟加拉湾,两海区初级生产力具体影响因素见表3。

表3 孟加拉湾和南海初级生产力影响因素归纳

Table 3 Summary of influencing factor on PP in Bay of Bengal and South China Sea

海区 Area	影响因素 Influencing factor
孟加拉湾 Bay of Bengal	沿岸区域主要受冲淡水(层化)和光影响(透明度、多云)较大;开阔海区受涡旋影响较大
南海 South China Sea	中部深海区受涡旋影响;沿岸区受冲淡水和沿岸上升流影响较大;东北部受黑潮和涡旋影响较大;台风也有一定影响

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