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硕士学位论文

海洋生产力调控因子：西北太平洋与南海为例

On the marine productivity: cases in the North Western Pacific and South China Sea

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摘要

海洋生产力相关过程 (初级生产力、新生产力、再生生产力) 是海洋生态系统物质循环和能量流动的重要基础, 是调节大气 CO₂ 水平和全球气候的关键过程。海洋生产力与营养盐的供给和氮营养盐组成紧密相关, 中尺度物理过程 (冷涡、暖涡) 通过改变海表营养盐状态对生产力产生重要影响, 因此, 系统研究不同海区以及中尺度过程下的海洋生产力过程, 对深入理解海洋生产力, 揭示海洋生产力对全球气候的调控具有重要意义。

本研究通过同时应用 ¹³C、¹⁵N 等多种人工同位素标记示踪技术, 在 2014 年春季和夏季, 分别调查了西北太平洋和南海海区的生产力相关过程。本次研究建立了酸性过硫酸钾氧化法测量颗粒有机碳 (POC) 的 ¹³C 方法; 同时运用了碱性过硫酸钾氧化-细菌还原法测量颗粒有机氮 (PON) 的 ¹⁵N 技术, 显著降低了目前最为普遍的元素分析仪-稳定同位素质谱仪联用技术的检测限, 大幅节约了同位素标记培养所需的水量需求。

本研究在 2014 年春季西北太平洋南部寡营养盐海区 (30°N 以南) 和北部富营养海区 (30°N 以北) 针对中尺度物理过程开展了初级生产力和新生产力的调查。结果显示, 北部海区的颗粒物浓度、初级生产力和新生产力均显著高于南部。在南部寡营养盐海区, 暖涡 (反气旋) 中心的初级生产力和新生产力积分分别为 61.3, 13.2 mmol C m⁻² d⁻¹, 分别比暖涡外缘小 15%, 38%。南部寡营养盐海区硝酸盐不足, 中尺度暖涡加剧了硝酸盐的匮乏。然而, 北部富营养盐海区表层营养盐浓度较高, 硝酸盐不再是生产力的限制因子, 生产力相关过程对中尺度涡的响应结果与南部海域不同。北部海区冷涡 (气旋) 中心的新生产力积分为 35.0 mmol C m⁻² d⁻¹, 比暖涡 (反气旋) 中心小 48%, 冷涡中心的初级生产力积分为 259.2 mmol C m⁻² d⁻¹, 比暖涡中心大 43%。显然, 中尺度涡的演变和环境因子如氮营养盐组成、温度等的改变历史, 可能影响浮游植物群落及其吸收, 进而影响初级生产力和新生产力。中尺度过程的变化和影响是复杂的, 本研究发现西北太平洋表层叶绿素 (Surf-Chl *a*) 与新生产力积分 (INP) 之间具有很好的正相关关系,

因此提出简单的拟合方程 ($INP=12.76 \cdot [Surf-Chl\ a]-0.10$) 来模拟和预测研究海区 INP。这一拟合结果的控制机制研究尚不清晰,有待于在未来的研究中进一步验证和深入理解。

2014 年夏季,南海航次通过高垂直分辨率的采样调查研究了三个站位的初级生产力(无机碳吸收)、新生产力(硝酸盐吸收)和再生生产力(铵盐吸收)情况。在南海同时测得三种生产力数据的尚属首次,在全球大洋中同时测得三种生产力数据的文章也屈指可数。结果显示,初级生产力为 $59.5-89.7\text{ mmol C m}^{-2}\text{ d}^{-1}$,硝酸盐吸收为 $14.4-45.2\text{ mmol C m}^{-2}\text{ d}^{-1}$,铵盐吸收总体较小为 $2.5-8.7\text{ mmol C m}^{-2}\text{ d}^{-1}$ 。硝酸盐吸收与铵盐吸收积分数据显示硝酸盐吸收对初级生产力的贡献比铵盐吸收大。硝酸盐吸收与铵盐吸收的垂直分布特征不同,与硝酸盐跃层位置显著相关。铵盐吸收主要发生在硝酸盐跃层以上,而硝酸盐吸收速率高值发现于硝酸盐跃层位置。硝酸盐跃层越浅,真光层以下提供的硝酸盐越多,对应真光层初级生产力和硝酸盐吸收的积分值越大。并且,硝酸盐和铵盐的吸收速率之和小于无机碳吸收,说明铵盐和硝酸盐不足以构成浮游植物所有氮源,小分子有机氮如尿素、氨基酸等再生氮源可能对于寡营养海域生产力有重要贡献。

关键词: 初级生产力; 新生产力; 再生生产力; 中尺度涡; 同位素技术

Abstract

Marine biological productivity, including primary, new and regenerated productivities, controls elemental and energy flows in the surface oceans. The magnitude and efficiency of biological productivity, so called “biological pump”, regulate the atmospheric CO₂ levels, thus, the global climate. Marine productivity is largely determined by nutrient supply rate and compositions therein. Mesoscale eddies have been proved to have profound effects on nutrient distribution in the euphotic zone. Therefore, the researches under environments with various nutrient supply intensities are of great importance revealing the role of marine productivity on the global climate.

This study applied stable isotope (¹³C and ¹⁵N) tracer techniques to investigate the marine production in the spring of North Western Pacific Ocean and the summer of South China Sea. A wet oxidation method was established to measure ¹³C in particulate organic carbon (POC), of which water demand was significantly reduced; meanwhile, the method also lower down the detection limit of carbon isotope when compared with the high temperature oxidation by EA-IRMS (element analyzer -isotope ratio mass spectrometer).

In the North Western Pacific in March and April of 2014 we measured primary production and new production under the influence of mesoscale processes. According to nutrient levels, we separate the area into northern nutrient-replete and southern oligotrophic zones by 30°N. Compared with those in the southern zone, the particulate organic carbon and nitrogen (POC and PON) concentration, primary production, and new production were significantly higher in the northern zone. In the southern oligotrophic region, the integrated primary and new production in the anticyclonic eddy were about 15% and 38%, respectively, lower than those in non-eddy waters, where low nitrate was further drew down by converged warm water.

On the contrary, in the northern zone where nitrate was no longer the limit factor we found the integrated nitrate uptake rate was significantly higher (about 48%) in anticyclonic eddies than that in the cyclonic eddy. The mean primary productivity in the center of anticyclone eddy was about 43% lower than that in the cyclonic eddies. The mechanisms controlling primary and new productions were not a simple function of nitrate. The high primary production and the low new production in cyclonic eddy with high level of nutrient suggested that renewable nitrogen (e.g. ammonium, amino acid and urea) served as more important nitrogen source than nitrate. The evolutionary stage of the mesoscale eddy and associated environmental factors might synergistically affect phytoplankton community and the nitrogen sources and in turn, the marine productivity. In the study region, we established an empirical model by using the surface chlorophyll concentration to predict the integral new production ($INP=12.76 \cdot [Surf-Chl\ a]-0.10$).

In this study we investigated the primary production, new production and regenerated production in the summer of the South China Sea. It is the first report of all three kinds of production at one time in the South China Sea. Our results showed that the depth-integrated primary production (inorganic carbon uptake) was 59.5-89.7 $\text{mmol C m}^{-2} \text{d}^{-1}$, integrated new production (nitrate uptake) was 14.4-45.2 $\text{mmol C m}^{-2} \text{d}^{-1}$, integrated regenerated production (ammonium uptake) was 2.5-8.7 $\text{mmol C m}^{-2} \text{d}^{-1}$. The contribution of nitrate uptake to primary production was higher than that of ammonium uptake. The maximum nitrate uptake rate was generally located at the base of the thermocline near the nitracline. However ammonium uptake mostly appeared in depth shallower than the nitracline. When the nitracline was shoaling, we observed higher integrated primary production and new production in the euphotic layer. Nevertheless, nitrate and ammonium uptake rates (converts into carbon via Redfield ratio) cannot support the total inorganic carbon uptake suggesting that extra nitrogen sources besides ammonium and nitrate were required to sustain the phytoplankton community. Small organic molecules such as amino acids and urea

might have contributed to the marine productivity in the South China Sea.

Key words: Primary production; New production; Regenerated production; Mesoscale eddies; Isotope tracer techniques

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第一章 绪论

1.1 生产力的定义及研究进展

1.1.1 初级生产力、新生产力和再生生产力的定义及三者之间关系

1960年 Menzel 和 Ryther 首次利用 ^{14}C 测定了寡营养盐海区的初级生产力，随后的研究发现初级生产力的季节变化与上层水体的层化和混合程度有关，这影响了营养元素的供应，因此 Dugdale 和 Goering 于 1967 年首次提出了 ^{15}N 的实验方法，并定义了新生产力和再生生产力。新生产力即初级生产力中与新氮源（包括 NO_3^- 和 N_2 等）有关的那部分生产力；再生生产力为初级生产力中与铵，更确切的是与再生氮源有关的那部分生产力。

研究全球尺度的初级生产力方法有两个，一个是同位素（ ^{14}C 或 ^{13}C ）培养实验（Menzel et al., 1961; Dugdale et al., 1967），培养时要注意痕量金属的污染，用洁净培养方式与先前实验比较结果相差几倍之多。另一种方法就是从卫星遥感测量海洋颜色，从而得出海洋近表层水域的叶绿素含量（Behrenfeld et al., 1997）。当水体清澈浮游植物是吸光主体，蓝绿光与叶绿素量基本相关，遥感技术准确度高。但是在沿岸地区由于溶解有机物的吸光，导致遥感算法不准确。而且海洋辐射主要是与上层 10-20 m 深的水层有关，因此遥感结果并不能说明整个水体的情况。

随着研究发展，新生产力和再生生产力概念的很多条件得到重新思考，定义不断被丰富完善。这一定义提出后，短时间的 ^{15}N 培养成为测量新生产力、再生生产力的唯一方法，而营养盐来源二分法建立在稳态的条件下，浮游植物（包括浮游动物摄食的那部分）沉降离开真光层的量应当与硝酸盐吸收、固氮和其他真光层以外的氮元素的吸收相等，这就带来了时间尺度上的问题（Platt et al., 1989）。固氮作用产生的氮作为一种很重要的氮源一直没有被忽略，而且研究显示束毛藻生物量的周转很快，但是由于技术问题直到十九世纪中期固氮才开始被认真评估。在真光层硝化作用的贡献是不能忽略的（Dore and Karl, 1996），表层水体中硝酸

盐 ^{15}N 的同位素稀释 (Lipschultz, 2001) 说明在层化水体硝酸盐被再循环。再生生产来自摄食者的排泄和溶解有机氮的再矿化, 当然现在研究表明部分溶解有机氮也可以被浮游植物直接同化 (Bronk and Glibert, 1993)。另外, 铵的同位素稀释的测量实验可以校正铵吸收的速率, 说明在马尾藻海存在快速的铵循环 (Lipschultz, 2001)。Eppley 和 Peterson (1979) 根据新生产力和再生生产力的概念提出 f-ratio 即新生产力与初级生产力的比值, 用来衡量生物泵的效率。他们的研究发现在初级生产力低于 $200 \text{ mg C m}^{-2} \text{ yr}^{-1}$ 时, f-ratio 与初级生产力之间线性相关, 随后 f-ratio 渐进 0.5 这一恒定比值。由于低浓度铵的测量问题导致大洋再生生产力数据很少, Lipschultz (2001) 同时测得三种生产力, 结果显示在春季生物量暴增时期几乎 90% 以上的初级生产力由新生产力贡献而来, 秋季营养盐匮乏再生生产力大于新生产力速率, 两者之和不足初级生产力的 50%。

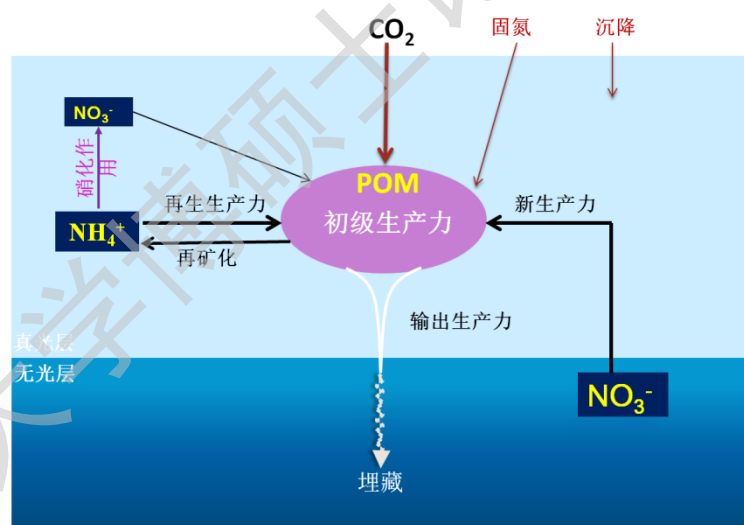
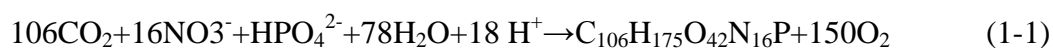


图 1-1 初级生产力、新生产力和再生生产力概念图

Fig.1-1 Concept of primary production, new production and regenerated production

浮游植物利用不同的氮源通过光合作用将无机碳、氮、磷固定成为有机物的方程式如下:



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