课题编号：2016YFA0601201　　　　　　　　　　　　　　　　　　　密级：公开

国家重点研发计划课题

中期执行情况报告

项目名称：海洋生态系统储碳过程的多尺度调控及其对全球变化的响应

项目牵头单位：厦门大学

课题名称：海洋典型生态系统固碳过程与浮游植物群落结构

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课题牵头单位：（盖章）厦门大学

执行期限：2016 年 7 月至 2021 年 6 月

中华人民共和国科学技术部

2018 年 7 月 20 日

编报要求

一、内容说明

课题中期执行情况报告着重围绕课题任务书的内容，报告课题中期重要进展情况，具体包括课题的总体目标及考核指标实现程度，人员、资金等支撑条件落实情况，课题经费使用情况等，并报告中期执行过程中的重大事项及突出进展。

二、格式要求

文字简练；报告的密级一般与任务书规定的密级相同；报告文本统一用 A4 幅面纸，文字内容一律通过“国家科技管理信息系统公共服务平台”在线填报；报告文本第一次出现外文名称时要写清全称和缩写，再出现时可以使用缩写。

三、编制程序及时间要求

项目中期总结前，由课题承担单位组织课题参与单位编制课题中期执行情况报告，经课题负责人及课题牵头单位审核后，提交项目牵头单位。

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一、总体进展情况

1．课题中期总体进展情况

对照课题任务书的计划目标和各项主要指标要求，简要阐明课题中期进展情况，评述课题中期任务的实施进展状态。

围绕项目的科学问题之一“海洋生态系统固碳和储碳过程的主要调控机制”，课题 1 开展了海洋生态系统固碳的多时空调控机制研究，聚焦浮游植物群落结构变化对固碳的调控作用及其机理，构建基于浮游植物群落结构的初级生产力遥感算法，基于卫星遥感反演得到的浮游植物类群组成信息，研究不同空间和时间尺度上海洋生态系统固碳的变化及其调控机制。

任务书中标明的中期评估指标包括：1）阐明中尺度物理过程对边缘海浮游植物群落结构的影响；2）建立基于光吸收的不同粒级浮游植物固碳遥感模型，构建适用于南海的分类群浮游植物遥感反演算法；3）发表论文 6-8 篇.

根据实施方案，课题组积极开展现场航次观测与实验研究，同时进行历史数据的整合分析，在边缘海浮游植物群落时空格局和环境影响机制、未来演变趋势、浮游植物固碳机理和固碳遥感新方法等取得重要进展，圆满完成了课题的中期目标。主要研究进展如下：

1. 课题组参加了项目联合组织的 2017 年 6 月南海中部航次、2018 年 1 月南海航次，此外，还参加了 2016 年 7-8 月的南海东北部（台湾海峡南部）预研航次、2017 年 7-8 月南海北部和吕宋海峡航次、2017 年 7-8 月南海东北部航次，以及 2018 年 6-7 月南海东北部-吕宋海峡航次等。在航次中开展了浮游植物群落结构、初级生产力、群落净生产力及其调控机制的研究，并且协助其它课题进行真光层和弱光层碳输出以及蛋白质组学的研究。近 2 年来，课题组参加 8 个航次，累计海上观测 190 天，总计 825 人天。收集光合色素样品约 1700 份，初级生产力样品约 1800 份，营养盐样品约 800 份，群落净生产力样品约 1200 份，FastOcean ADP 剖面约 120 次等，总计样品约 5500 份，现已基本测量和分析完毕。

2. 课题组利用自身积累的浮游植物类群和固碳数据以及近 2 年的观测数据，通过应用新理念和统计学方法进行整合分析研究，取得显著进展。（1）阐明了边缘海浮游植物主要类群、丰富种和稀少种子群落的生态位特征，利用群体生态学（synecology）方法阐释了控制不同浮游植物类群分布的调控机制；（2）基于生态位模型，预测了浮游植物群落对海洋变暖和营养盐变化的响应，研究显示未来东海将出现甲藻和硅藻的演替；（3）发展了利用生地化剖面漂流浮标（Bio-Argo）数据估算南海上层海洋群落净生产力的方法，阐明了南海海盆区高时间分辨率的群落净生产力变动特征与调控因子；（4）开展了浮游植物光合固碳机理研究，阐明了自然海区中原绿球藻光合作用能量分配比，初步解析了不同类群浮游植物的光利用特征参数，同时评估和确定了最适合的类群遥感策略，为下一步发展新型初级生产力遥感模型打下了良好的基础；（5）分析了浮游植物分粒级的光合参数，阐释了大粒级浮游植物的饱和光合作用速率和半饱和光强高于小粒级浮游植物的机制，初步建立了基于叶绿素的分粒级初级生产力遥感模型；（6）研究了边缘海叶绿素、初级生产力和新生产力之间的关系，发现了叶绿素季节变化和初级生产力的变动是不耦合的，解析了其上行和下行的调控机制。
3. 在学术交流方面，课题组成员积极参与项目组织的启动会、年度学术研讨会及航次协调会等会议，加强课题内以及与其他课题组的合作交流；课题组还积极参加国内外的学术交流，作为专题召集人共同发起组织 2018 Asia Oceania Geosciences Society Meeting（亚洲大洋洲地球科学大会）海洋科学专题“Carbon Sequestration in Marginal Seas: Regulation and Response to Global

图 1.课题组参加项目召集的 AOGS2018-OS25 专题研究会

Change（Ocean Sciences，OS25）”，来自我国、韩国、台湾地区等学者进行深入交流，共有 7 位课题骨干、博士后和博士生参加了专题交流。同时课题骨干还参加了 2017 Aquatic Sciences Meeting（2 月）、2018 Ocean Sciences Meeting（2 月）、2017 蓝碳国际论坛（11 月）、第十一届海峡两岸海洋科学研讨会（2017 年 7 月）、第五届地球系统科学大会（2018 年 6 月）、“中国生态学学会海洋生态专业委员会第五次代表大会暨第七届全国海洋生态研讨会”（2018 年 1 月）、“中国海洋湖沼学会水环境分会-中国环境科学学会海洋环境保护专业委员会 2017 年学术年会”（2018 年 1 月）等海洋和地球科学领域国际国内大型学术会议，利用大会邀请报告和海报展示课题的最新研究成果，提高课题和项目在国内外的学术影响力。

4. 在科普传播方面，课题组积极参加了厦门市的“厦门国际海洋周”科普文化活动、厦门大学 2016 年和 2017 年度“海洋开放日”活动、2018 年近海海洋环境国家重点实验室及法国塔拉基金会联合举办的“法国 Tara 科考帆船与厦门大学嘉庚号科考船联合活动周”大型公益活动等。2016 年“海洋开放日”活动，课题组以“海洋生物泵”为主题，以“碳在海洋生态系统的传递链”为线

图 2. 课题组参加“法国 Tara 科考帆船与厦门大学嘉庚号科考船联合活动周”海上科普活动

索，向公众科普了海洋初级生产者-浮游植物、浮游动物、海洋生物泵以及全球变化等概念；2017 年 11 月的“海洋开放日”活动，课题组以“海洋浮游生态系统”为主题，在光学显微镜下给小朋友们呈现了多彩形象的浮游生物，并通过超轻粘土捏制藻类、拼图等形式，生动形象地给公众们展示了多姿多彩的浮游生物大世界。2018 年 4 月，在“法国 Tara 科考帆船与厦门大学嘉庚号科考船联合活动周”中，课题组参加了 Tara 科考帆船与嘉庚号联合公众开放、海洋科普展览和中法海洋科学研讨会等系列活动，通过科学报告、科研仪器展览与展报宣传与讲解等方式，宣传与科普项目相关海洋知识与意义。科普活动共吸引了约 16000 的参观人次；此外，课题组还通过项目网站、微信公众号（MARCO_XMU)，以及定期发布项目简报,向大众传播海洋科学知识。

5. 在课题管理方面，通过项目建立的网站（http://marco2016.xmu.edu.cn/）、微信群和项目简报等管理和交流平台，加强课题内以及与其它课题的数据共享与交流。在人才培养方面，共有 17 名博硕士研究生参与课题的研究，其中 6 名研究生已毕业答辩。
6. 已在 Water Research，Environmental Microbiology，Geophysical Research Letters, Remote Sensing of Environment, Progress in Oceanography，Journal of Geophysical Research 等地球科学和环境科学领域的主流刊物上发表学术论文 16 篇，其中 SCI 收录 15 篇，第一标注 11 篇（见论文清单）。

综上，课题组较好地完成了课题的中期目标，提升了对边缘海浮游植物群落结构演变和固碳调控机制的认识，为进一步深入揭示海洋生态系统固碳的调控机制，实现课题和项目的最终目标奠定了良好的基础。

2．课题调整情况

如课题出现超前/迟滞等情况，请详细说明原因、措施及履行相关审批管理制度的情况。

无。

二、取得的重要进展及成果

1．课题中期重要进展及成果

简要介绍课题研究工作的重要进展、阶段性成果（一般不超过3项）及前景。

课题组利用积累的长时间数据集和近2年的现场观测，采用多种先进的观测和分析手段，在边缘海浮游植物群落时空格局、环境影响机制及其未来演变趋势，浮游植物固碳机理和固碳遥感新方法等取得重要进展。

1.1. 深入阐明边缘海浮游植物群落结构演变格局、丰富种与稀少种的生态位特征和环境影响机制

采用基于生态位特征（niche-based）的分析思路，并结合多种统计学、分子生态学等技术手段分析了边缘海不同生态系统以及中尺度暖涡对浮游植物群落的时空格局的影响，阐释不同类群空间格局的环境影响机制。通过不同浮游植物类群生态位特征的研究，可以深入揭示群落变动的生态学机制。

1) 南海浮游植物群落时空格局与实际生态位特征

基于12年光合色素的历史数据，研究发现南海浮游植物的总体分布格局含5种类型：（1）近岸模式，其特征为南海北部近岸区全年以硅藻占绝对优势，并伴随有一定浓度的甲藻（春季）、聚球藻和青绿藻；（2）外海模式，其特征为原绿球藻在整个南海的外海水体都具有较高生物量，尤其在春季和夏季最为明显；（3）表层模式，其特征为聚球藻在整个南海上混合层的生物量都较高，但从春季到冬季逐渐减少；（4）次表层模式，其特征为定鞭藻8型和青绿藻在南海次表层的生物量较高，其中定鞭藻8型的生物量最大层比青绿藻的更深；（5）陆架模式，其特征为南海陆架海区浮游植物群落结构具有高多样性，且季节变化较明显（图3）。

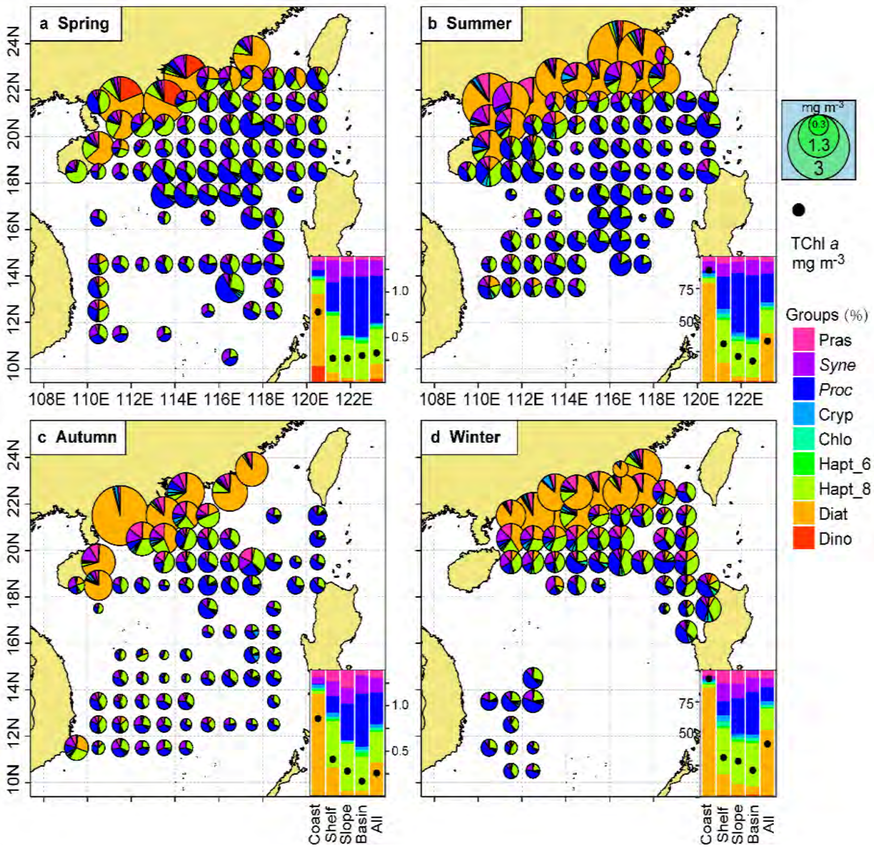

图 3. 基于 2004-2015 年 20 个航次的南海 100 m 积分浮游植物平均生物量和类群结构的季节变化（所有数据在经纬度 1° ×1°内取季节平均）

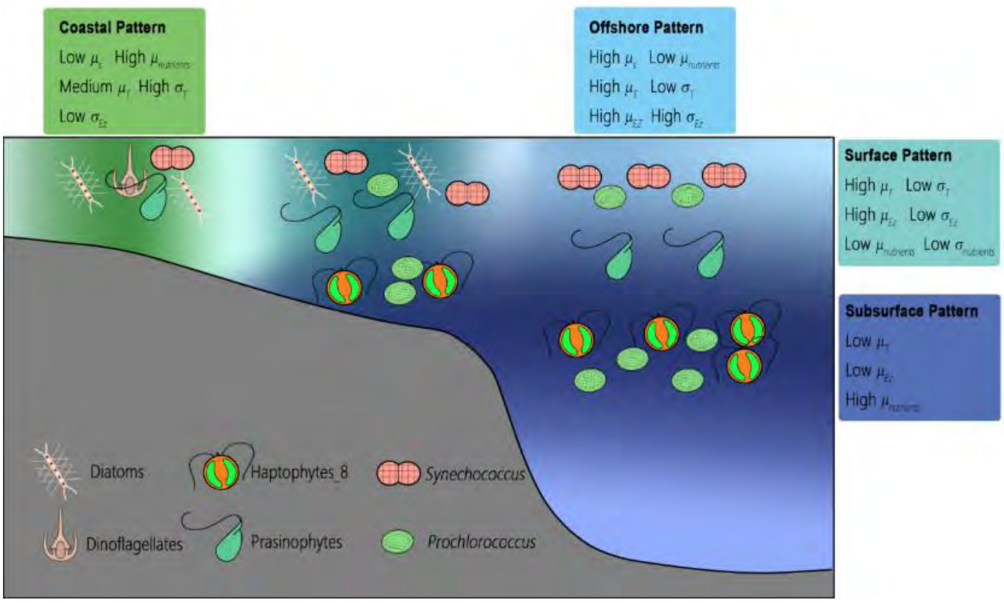

图 4. 基于不同类群的实际生态位平均值和宽度的南海浮游植物空间分布模式

同时，通过 CCA 分析和人工神经网络分析，得到可能的环境主控因子为温度、光照、营养盐和盐度。为探索这些环境主控因子对浮游植物群落结构的调控机制，结合广义加性模型（GAMs）和最大熵模型（MaxEnt）拟合浮游植物各类群在每个环境因子轴上的实际生态位曲线，并计算每条生态位曲线的平均生态位和生态位宽度，以表征浮游植物对环境变化响应的实际生态位特性。结果发现，浮游植物各类群的平均生态位和生态位宽度沿各环境梯度具有明显规律性，表现为中等生态位的宽度较宽，较低或较高生态位的宽度较窄，表明极端环境条件下浮游植物的生态位特异性较强。有些生态位之间相关性非常明显，环境因子之间本身的相关性，在浮游植物的生态位上也能体现出来。这些趋势体现了不同类群在环境因子之间的权衡（trade-off）。进一步将所有的生态位特征做主成分分析和聚类分析，发现这些生态位特征将浮游植物各类群划分为几个明显的类型，且这些类型所对应的浮游植物类群与我们观察到的浮游植物分布趋势基本一致。这些结果表明南海浮游植物群落结构的变化是各类群在温度、光照和营养浓度之间权衡的结果（图 4，Xiao et al.,2018,Progress in Oceanography）。

2) 揭示了西太边缘海上层微微型真核生物丰富种与稀少种子群落差异性分布模式

自然界典型微型生物群落一般由少量丰富种和大量稀少种构成。丰富种基于丰度优势，通常在能量流动和物质循环中起重要作用，历来被认为是生态系统的重要组成部分。近年来，随着高通量测序技术的发展，逐渐揭示出海洋微型生物群落中稀少种也具备重要生态功能。另一方面，丰富种和稀少种子群落由于内在物种组成差异，构建机制可能不同。

以东海和南海的微微型真核浮游生物群落为研究对象，采用 454 高通量测序技术，揭示了这两大边缘海上层水体中微微型真核生物丰富种与稀少种子群落差异性分布模式。在表层水体，丰富种较多受到扩散限制，而稀少种较多受到环境过滤影响；在次表层水体，二者均较少体现环境过滤，而较多受到扩散限制影响（图 5）。此外，丰富种和稀少种子群落均显示出明显季节性差异分布模式（Wu et al., 2017，Environmental Microbiology）。

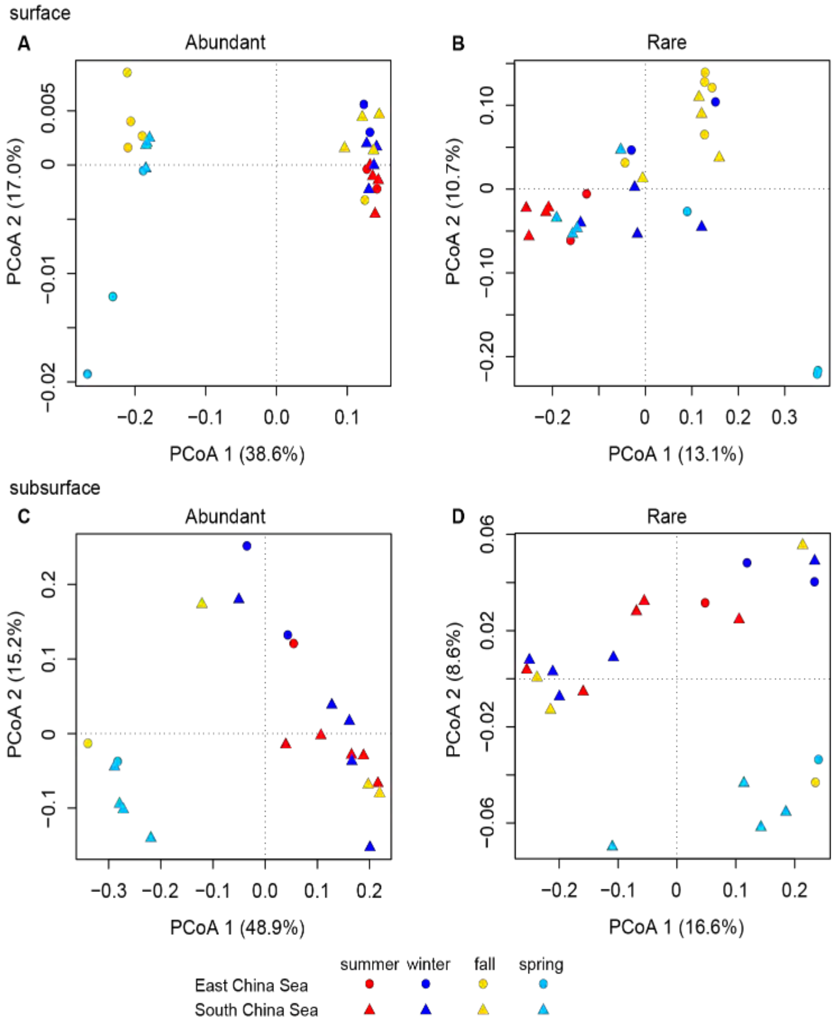

图 5. 基于非加权 UniFrac 距离矩阵的表层（A 和 B）和次表层（C 和 D）丰富种和稀少种子群落主坐标轴分析（PCoA）（基于 100 次有放回随机自抽样平均值）

3) 揭示了南海中尺度涡旋影响下的浮游植物群落结构变动

比较分析了 2007 年 8 月南海北部海盆的 3 个反气旋涡（ACE）影响下的浮游植物生物量和群落结构，并与颗粒有机碳输出通量结合进行不同类群生物泵效率的分析。结果表明，水柱积分叶绿素 a 生物量无明显差异（17.647-18.868 mg m^{-2}），但 ACE 边缘生物量（20.822±3.026 mg m^{-2}）分别高出 ACE 中心和不受 ACE 影响区（对照区）的 1.3 和 1.6 倍。ACE 边缘的高生物量主要由定鞭藻 8 型和原绿球藻增加所贡献。硅藻虽然不是优势类群，但在 ACE 边缘仍然有 2.5 倍的生物量增加（图 6），然而这一增加并未带来边缘生源硅输出通量的增加，反

而是在 ACE 中心生源硅输出通量更高。分析表明这主要是由于 ACE 由边缘向中心的平流输运所致。对优势类群生物量与颗粒有机碳输出相关性分析可知，在生物泵中起主要作用的类群在 ACE 中心、边缘和非 ACE 影响区分别为硅藻、定鞭藻 8 型和原绿球藻。ACE 影响下生物量的增加和群落结构的变动可能提高了生态系统的储碳潜力（Wang et al.,2018，JGR-Ocean, revision）。

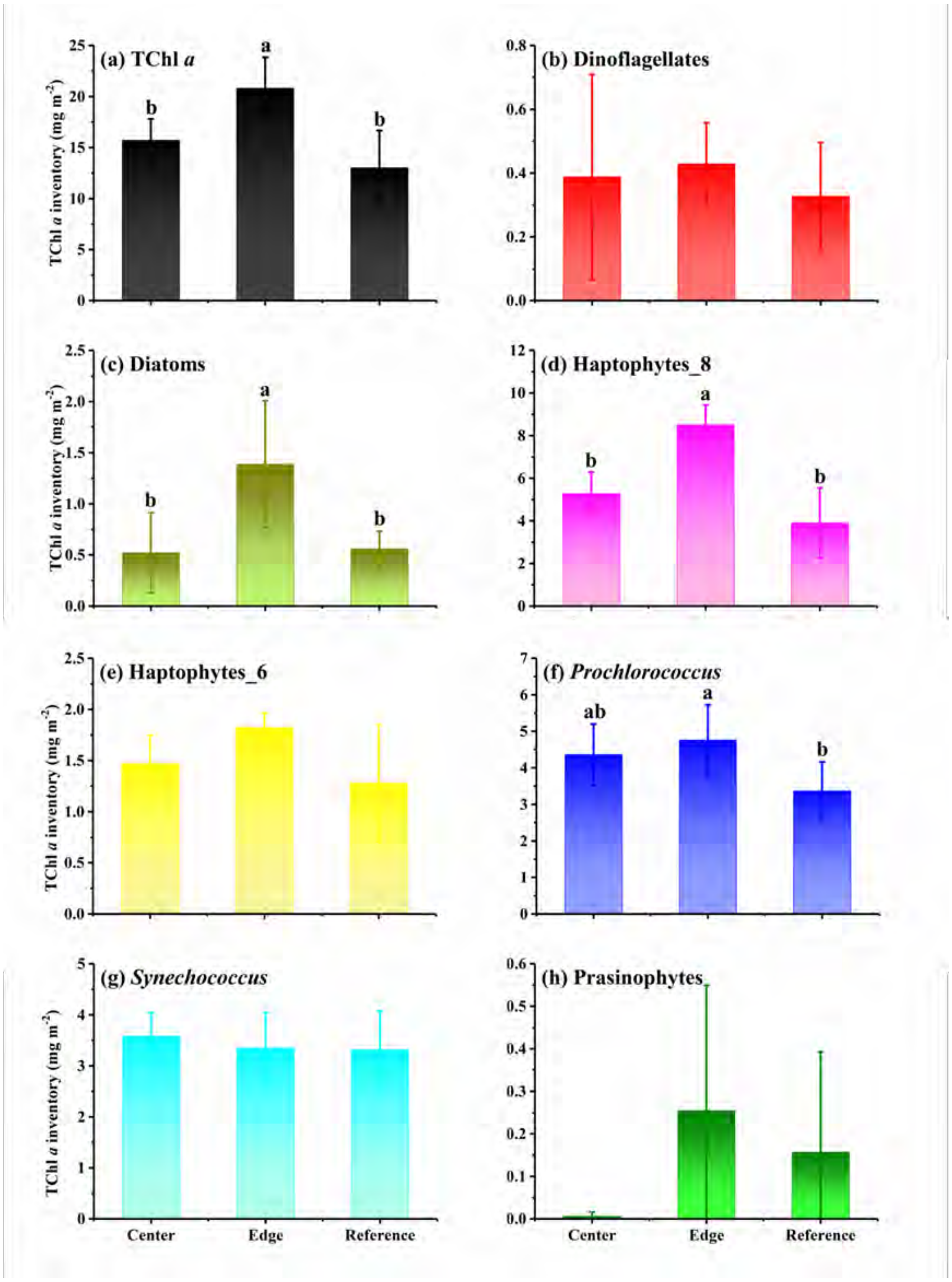

图 6. 南海反气旋涡中心、边缘及对照区浮游植物群落

总叶绿素 a 和主要类群变动

1.2. 利用群体生态学方法揭示全球变化对边缘海浮游植物群落演替的潜在影响及其机制

预测浮游植物群落在全球变暖中的变化是生态学的难题之一。过去的群落生态学主要基于个体生态学（autecology），难以产生一般性原理，利用群体生态学（synecology）的生态位方法可以纠正个体生态学的偏差，可用于预测浮游植物群落对气候变化的响应。

1) 海水变暖和富营养化的双重环境变化对近海浮游植物群落结构的影响

基于东海 14 年（2002–2015 年）累积的 23 个现场航次的 2816 个浮游植物光合色素样本，分别硅藻和甲藻（内陆架水域的优势类群）的特征色素岩藻黄素（Fucoxanthin）和多甲藻素（Peridinin）为研究对象，通过广义线性模型（GLMs）、广义相加混合模型（GAMMs）等多种统计学手段，建立了东海硅藻和甲藻对主要环境因子的响应模式。模型显示，硅藻和甲藻对温度和营养盐（氮、磷及其比值）变化的响应模式不同：硅藻偏好低温和高营养盐，而甲藻对温度和营养盐相对不敏感，但倾向于低磷和高氮磷比的环境。在假设温度和氮磷比（取对数）各升高两个单位的情境下，模型预测东海约 60%的区域将出现硅藻生物量的下降，约 70%的区域甲藻生物量将升高 （图 7）；变化最大的近岸区域硅藻生物量将降低 19%，甲藻生物量将升高 60%（Xiao *et al.*,2018, Water Research）。

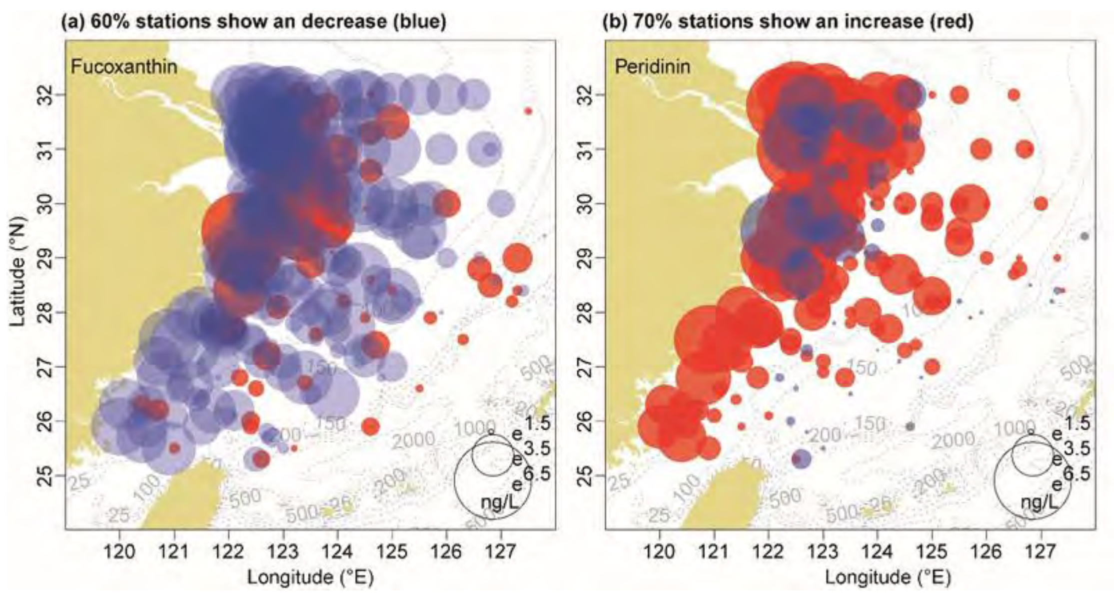

图 7. 模型预测显示在在未来全球变暖和富营养化双重压力下，东海将出现硅藻生物量下降和甲藻生物量升高

2) 构建了基于群体生态学的浮游植物不同类群生态位划分表，预测气候变化背景下南海浮游植物群落演变趋势

基于南海 10 年尺度的浮游植物群落组成数据库，选取易受气候变化影响的上混合层数据，通过有效的数据插值，结合数据降维、排序和分类的多变量方法，建立了浮游植物群落在温度、光照和硝酸盐这三个生态轴上的通用生态位划分方案（图 8）。该生态位划分方案将浮游植物群落划分为三种类型：高光高营养盐、冷型和暖型，其中冷型浮游植物类群的生态位主要通过光强区分，而暖型类群的生态位主要通过营养盐进一步分离。该生态位方案符合一般生态学理论的假设，并证明以往的个体生态学研究结论存在偏差。这种生态位方案可用于预测浮游植物群落对气候变化的响应。

随着全球变暖，海洋上混合层温度和光强增高，营养盐减少，定鞭藻 8 型、青绿藻、隐藻和绿藻这几类冷型浮游植物的相对丰度会降低。硅藻的变化取决于营养条件，在高营养水体中，如近岸、强混合的陆架以及富营养的冲淡水羽流，硅藻会受益于光强的升高，而在中营养和寡营养水体中，如层化的陆架和

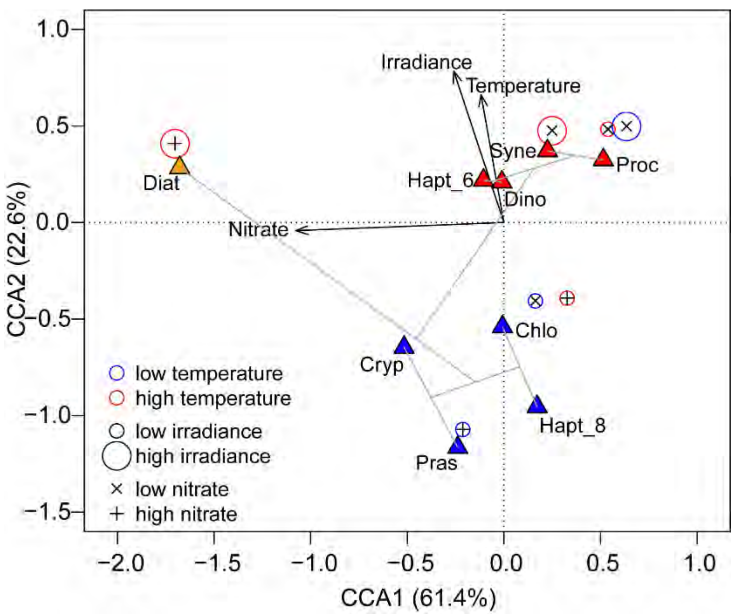

图 8. 浮游植物群落生态位划分方案。根据温度、光照和营养盐的高低水平将南海划分为 7 个有效生态位，通过 CCA 对浮游植物类群在这 7 个生态位内的平均值进行多变量排序，通过聚类分析将排序结果划分为三种类型，分别用橙色、红色和蓝色表示，其中橙色表示高营养盐高光类型，红色表示暖型类群，蓝色表示冷型类群。

寡营养的外海水，其相对丰度都会随营养盐的进一步下降而降低。原绿球藻、聚球藻、甲藻和定鞭藻 6 型等暖型浮游植物的相对丰度会升高。其中原绿球藻和聚球藻可能受益最明显，这两大类群的相对竞争力也取决于环境条件。在中营养水体中，如层化的陆架、强混合的外海水以及中营养的冲淡水羽流，聚球藻的优势大于原绿球藻，而在层化的寡营养水体中，原绿球藻的优势大于聚球藻。

本研究提出了浮游植物对海洋环境变化响应的新认识，并指出基于现场实测大数据库的群体生态学研究是实现通过群落生态学的一般性原理如生态位划分方案预测未来群落变化的有效方法，目前该研究还在进一步完善中。

1.3. 揭示了若干浮游植物固碳机理、初步构建海洋固碳遥感观测新方法

发展包括新型海洋初级生产力遥感算法在内的新方法，用于更准确地观测和评估南海的固碳能力，是课题的核心目标和创新点；探明浮游植物固碳机理，阐释浮游植物群落结构与固碳之间的关联，是更好地认识海洋生态系统固碳变动和调控机制的重要前提，也是发展固碳观测新方法的必经之路；目前该研究已经取得了较好的进展。

1) 阐明了南海海盆区原绿球藻的固碳机理

新型海洋初级生产力遥感算法是将基于光吸收和浮游植物类群分辨的一种新颖的初级生产力模型。发展浮游植物类群的遥感算法和厘清不同类群光合固碳效率是发展这个算法的两个必备条件。原绿球藻是南海海盆浮游植物的优势类群，在夏季的表层甚至次表层叶绿素最大层（DCM），原绿球藻都可占据 50%以上，对自然海区中（非实验室条件）原绿球藻固碳机理的研究，将阐明原绿球藻的光合固碳效率及其影响机制，获得更准确的海盆生态系统固碳遥感关键参数。在 2017 年 6 月份的南海中部航次中，我们在两个连续观测站开展了叶绿素荧光剖面的连续测量和光合固碳速率的同步测定。研究发现：（1）最大光化学效率（Fv/Fm）在混合层内表现出黎明时峰值、白天和夜晚都出现抑制的昼夜变化特征，属蓝藻光合作用的特征，而变化幅度反映了营养盐限制，以及海盆中心和边

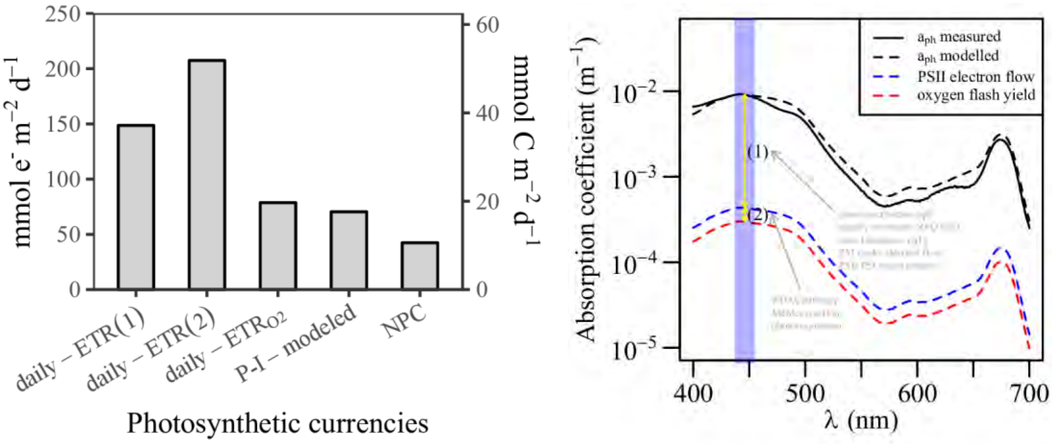

图 9. 南海海盆区原绿球藻光合作用能量分配比，左图：总初级生产和净初级生产的比例；右图：总吸收的光用于光合作用的比例

缘营养盐状态的差异；（2）通过对光合系统 II（PSII）电子传递速率和净初级生产速率的对比，得出海盆中心浮游植物总初级生产和净初级生产比（GOP/NPC）为 3.3/1 或 4.9/1（取决于不同的单位叶绿素 PSII 含量赋值），符合近年来一些研究提出的浮游植物光合作用的一般规律，即浮游植物光合作用最终用于净固碳的能量分配比例较为恒定；但通过与光吸收（浮游植物吸收系数）对比，最终用于进行光合作用（PSII 电子传递或净初级生产）的比例非常小(图 9），显示绝大部分吸收的光以热量的形式散失；我们发现：在自然环境中，PSII 失活或非光化学淬灭在原绿球藻光合作用过程中扮演极其重要的角色（Xie et al., 2018, Frontiers in Microbiology,in press）。

为了确定适用于南海的浮游植物类群遥感算法，需要对不同遥感策略进行研究和评估。课题组成员李忠平教授的实验室曾经发展和评估了吸收系数型算法用于浮游植物色素吸收系数的反演。课题进一步研究和评估了辐亮度型算法，用辐亮度型算法判别甲藻藻华，发现了自然环境中的甲藻垂直迁移现象。通过分析和比较，辐亮度型算法被认为适合于单一种类藻华的研究，而且其前提假设是浮游植物是水体光学特征的单一控制因素，在现实条件下只有藻华时比较接近于这种情景；而吸收系数型算法，是基于浮游植物吸收系数的反演，更加准确也更适合于一般的海洋环境（图 10，Qi *et al.*, 2017，Harmful Algae）。

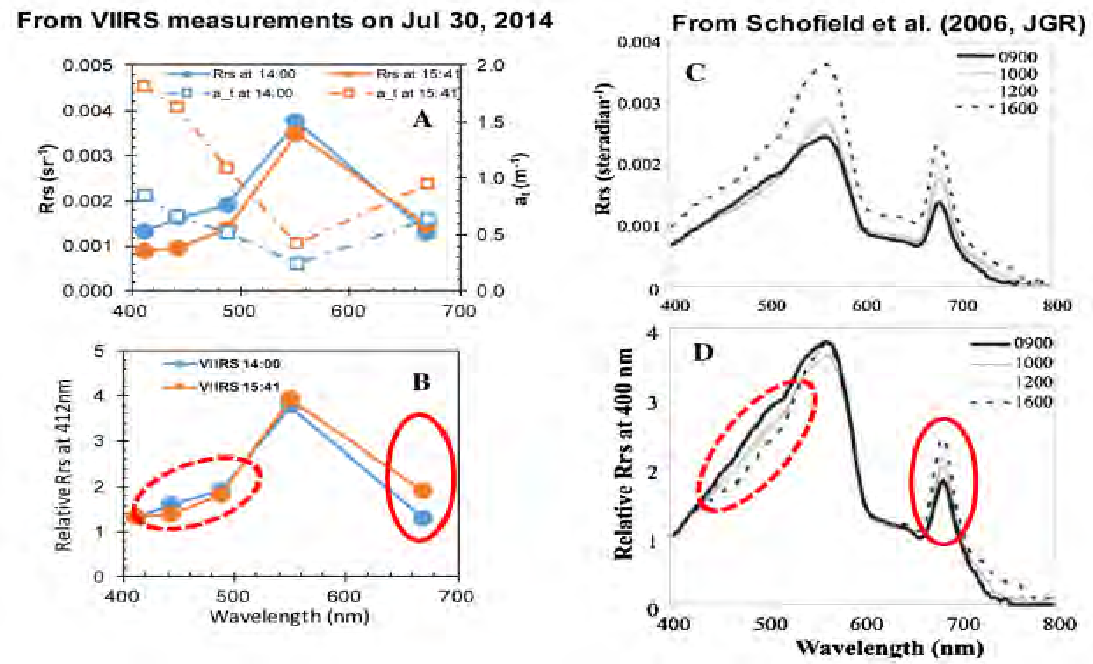

图 10. 光谱特征用于遥感反演甲藻短凯轮藻 *Karenia brevis* 的藻华

2) 利用生地化剖面漂流浮标，揭示南海中部海盆区高时间分辨率的群落净生产力变动特征

群落净生产力是浮游植物初级生产力和群落呼吸的差值，是衡量上层海洋固碳和碳输出潜力的重要指标。BGC-Argo 是一种携带多种光学探头并可用于生地化参数测量的新型剖面漂流浮标，近年来在全球各大海区布放数量越来越多，是一个新兴的研究平台。课题利用厦门大学在南海布放的 BGC-Argo 所测量的水体溶解氧浓度，通过构建模型解析不同物理过程（如海气扩散、气泡注入、夹带效应、垂直扩散）对溶解氧变化的贡献，获得生物活动造成的净氧气变化速率，即群落净生产力。这种原位估算海盆生态系统群落净生产力的方法，其优势是高时间分辨率，可观测到船基采样方法难以捕捉的日变化特征。通过该方法估算得到南海中部海盆上层海洋年群落净固碳 2.7±1.0 mol C m^{-2} yr^{-1}。季节分布上，呈现东北风盛行时期的净群落生产力大于西南季风盛行的月份。其中净群落生产力在一月出现峰值，而夏天甚至短暂异养状态（即群落净生产力小于 0）（图 11）。

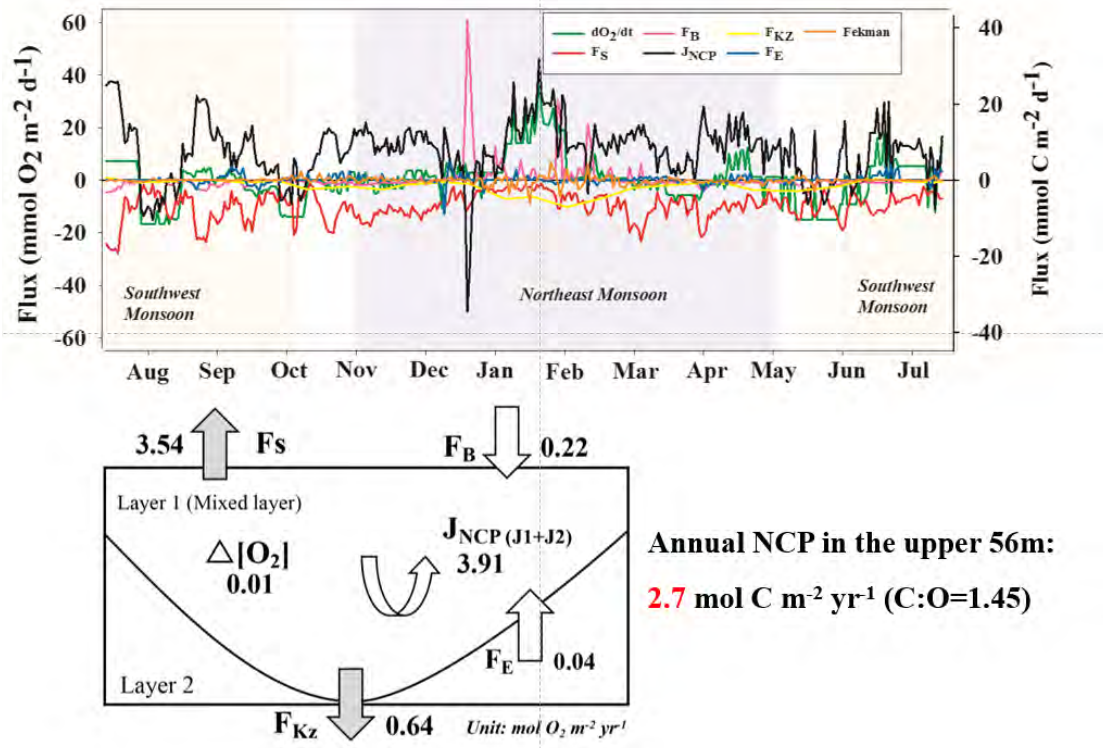

图 11. 南海中部上层海洋净群落生产力和溶解氧通量的各分量随时间的变化

将该方法得到的结果与遥感模型结果相比，基于浮游植物碳的遥感 CbPM-NCP 模型预测值在量值上接近于 BGC-Argo 的结果，但无法重现季节变化特征，而基于遥感叶绿素浓度的 VGPM-NCP 模型相比之下可更好地重现季节变化趋势。BGC-Argo 的方法不受大气校正的影响，同时可以获得卫星遥感观测不到的次表层的生物光学信息。未来期望通过海色卫星和生地化浮标两种平台的互补，发展更加立体全面的海洋生态系统固碳的观测体系(Huang et al.,2018, Deep-Sea Research I)。

3) 南海东北部浮游植物分粒级固碳机理和模型

粒级大小是描述浮游植物形态特征的重要参数，浮游植物的许多功能也与细胞大小有关。浮游植物的粒级结构是较容易测定的参数，研究功能与细胞大小之间的关系，建立相应的模型，可以更好地模拟海洋生态系统结构和功能。课题在现场航次中进行了分粒级光合参数的测量，结果显示大粒级浮游植物的

半饱和光强高于小粒级微微型浮游植物，微微型浮游植物的初始斜率与原绿球藻的比例呈较好的相关关系（图 12）。前人的研究显示大粒级浮游植物具有更高的光耐受性，因此其半饱和光强相对微微型浮游植物高，但这种光耐受性与营养盐利用能力以及营养相关特性之间是一种权衡。初始斜率的变化首先反映了微微型浮游植物具有更高光吸收能力的特征，但是原绿球藻除外。此外通过将两个粒级的半饱和光强分别与环境光强做回归，已初步建立浮游植物分粒级固碳模型。该模型将结合分粒级生物量的模型用于南海浮游植物分粒级固碳量的估算。目前该研究成果正在进一步完善中。

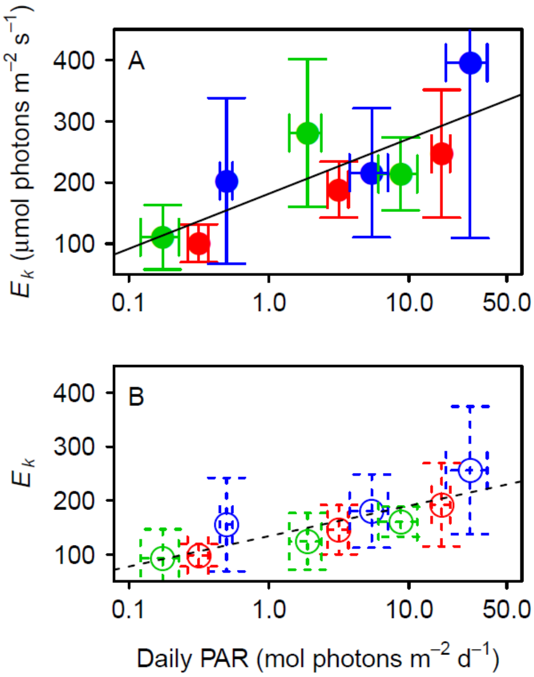

图 12. 南海东北部大粒级（A）和小粒级微微型（B）浮游植物半饱和光强的差异

4) 发现并阐明东海浮游植物生物量和初级生产力季节变化的不耦合关系

东海是世界上最大的边缘海生态系统之一。基于东海叶绿素、浮游植物类群组成、初级生产力和新生产力的数据。我们发现东海初级生产力和新生产力的相关性强，而与叶绿素之间虽然存在显著相关，但数据较离散。这主要是因为叶绿素和浮游植物碳生物量之间存在不确定性。而且，叶绿素现存量也受到浮游动物摄食作用的下行控制，因此叶绿素与初级生产过程之间并非是简单的

线性关系。为进一步解析东海浮游植物叶绿素和初级生产力之间的异同，我们进一步分析了东海初级生产力与叶绿素、颗粒有机碳（POC）、新生产力、浮游植物类群结构等其它参数的关系。研究发现，东海叶绿素季节变化与初级生产力的变动是不耦合的。在夏季的陆架海区初级生产力较高，但叶绿素浓度并不是很高，优势类群为微型粒级的浮游植物。冬季则相反，生产力水平较低，但叶绿素生物量相对不低，优势类群则以硅藻等大粒级浮游植物为主（图 13，Liu et al. JGR-Biogeosciences，revision）

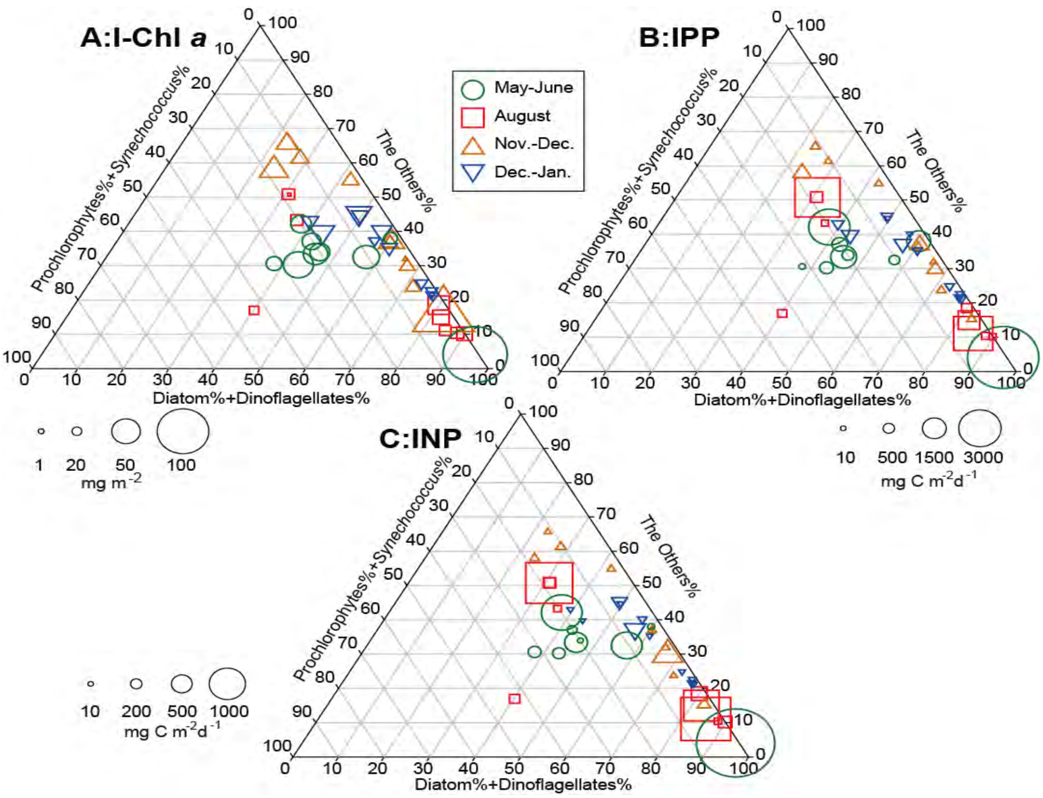

图 13. 东海水柱积分叶绿素、初级生产力和新生产力在四个季节与浮游植物类群结构的关系

2. 预期社会经济效益

重点阐明对学科/行业产生的重要影响，对社会民生、生态环境、国家安全等的作用，以及研究成果的合作交流、转移转化和示范推广情况，人才、专利、技术标准战略在课题中的实施情况等。

通过本项目科研、教育和科普等活动，课题在学科研究与基础科学发展、学术人才培养和社会民生方面做出了重要的贡献：

1) 对本学科产生重要的影响。以本项目主题和科学问题归纳的"海洋生态系统储碳与全球变化"入选中国科协 2018 年重大科学问题和工程技术难题。2018 年 5 月 27 日，中国科协在第 20 届中国科协年会闭幕式上发布了 2018 年 60 个重大科学问题和工程技术难题。"海洋生态系统储碳与全球变化"主题是由海洋生态专业委员会组织专家撰写、遴选与推荐，该主题的入选，彰显了本项目的创新性与重要性，扩大了项目在学科与社会的影响力。
2) 在学术研究方面，课题在海洋浮游植物类群分布和调控机制、浮游植物光合固碳机理和海洋生态系统固碳观测和评估新方法的研究上取得了重要的进展，获取了一批高质量的科研数据，发表了一批高质量的学术论文，建立了新方法，对海洋生态系统固碳领域科学问题的解答和学术研究的发展做出了一定的贡献。课题一还通过组织与参加国内外高层次学术会议，促进学术交流与传播，增加学术影响力。
3) 在团队建设和人才培养方面，课题依托于国内一流高校厦门大学，厦大具有完善的本科生-硕士生-博士生-博士后培养体系，在导师的指导下，通过承担课题的关键任务，课题一的博士后和博士研究生们迅速成长，以高质量的成果贡献于课题和项目。其中，博士后出站 2 人，毕业研究生 6 名，包括 2 个博士研究生，为社会贡献一批有国际化视野和研究潜力的高质量人才。
4) 在社会民生与公众教育方面，课题依托相关海洋论坛、海洋专题展览和海洋文化活动，将课题成果以简单易懂的形式向大众传播，提高公众的海洋意识。课题多次参与了厦门市的"厦门国际海洋周"、厦门大学"海洋开放日"

以及“嘉庚号-塔拉号（法国）”等科普活动，提高了课题的社会影响力，为促进社会民生发展、公民科学素质提升做出了一定的贡献。

三、课题人员及经费投入使用情况

1．人员及经费投入情况

对照课题任务书阐述课题及课题资金（包括专项经费、自筹经费等）到位情况、课题资金单独核算情况、预算调剂情况、支出情况和经费使用监督管理情况、人员投入情况等。

课题一于 2016 年 8 月收到项目到款 378 万，其中直接费 336.6 万，间接费 41.4 万。截止 2018 年 6 月 30 日，总支出为 368.66 万，其中设备费 3.81 万，材料费 47.41 万，测试化验加工费 4.06 万，燃料动力费 170.55 万，国内差旅费 21.29，会议费 8.10 万，国际合作交流费 10.90 万，出版文献费 2.66 万，劳务费 56.09 万，专家咨询费 2.39 万，间接费 41.40 万（其中绩效 14.25 万）。另有 9.34 万试制设备费已支出，7 月 15 日冲账，故课题实际支出为 378 万，占到位经费的 100%。

预算调整情况：预算中编制了两台漂浮式沉积物捕获器（单价 36.2 万/台，总价 72.4 万），在项目实际运行当中发现：目前普遍使用的商品化的捕获器大多为锚系沉积物捕获器(Mooring sediment trap)，不适合在近岸和水团运动大的海域用来收集沉降颗粒。而个别境外实验室制作的漂浮式沉降颗粒捕获器仅可以获得单一的颗粒样品，缺点是设备组装效率低、拓展性能差，且无法同时获得与沉降颗粒有机碳通量相匹配的其他类型样品、参数和映像资料等，因此无法满足海洋生态研究中对于沉降颗粒样品、数据参数和科学实验需求。为了使目前的漂浮式沉降颗粒捕获器更加便捷，具有更强的拓展性能，更好地满足海洋生态学科学研究需求，我们急需一种可拓展的，可用于沉降颗粒捕获、摄影和培养的新型沉积物捕获器，满足更多种类的样品、数据需求。在参考现有文献和与境外实验室合作交流成果经验，自主设计和制作了一套漂浮式沉积物捕获器（目前已经在申请国家发明专利），更加符合我们的科研需求，目前已在

台湾海峡和南海投放并成功采集样品。同时，它的造价远低于同类商品化产品，仅 10 万/套。因此 2018 年 5 月将预算中的 10 万元设备购置费调整为试制设备费，根据项目的进展情况，后续将继续试制一台沉积物捕获器以服务该项目。

厦门大学根据财政部、教育部、科技部等国家相关部门得政策规定设置了人事处、财务处、审计处、科技处、教育处、资产与后勤事务管理处、实验室与设备管理办公室、基建处、研究生院等行政管理机构，配制了相应得管理人员并制定了相关职责。从预算管理、资金管理、合同管理、资产采购、审批报销、资产管理等方面制定了内部控制制度。每个课题经费均分配独立的经费卡号、独立核算，严格按照预算和相关管理规定进行各项额度的网络控制。同时，厦门大学实行“统一领导，分级管理，责任到人”的科研经费管理体制和“分级报账，集中核算”的会计核算体制。厦门大学财务处，下设处办公室、计划管理科、基建财务科、国库支付管理科、财务科、会计科、漳州校区财务办、翔安校区财务办。各二级单位的配置 2ー3 名财务人员，负责本单位的报账工作和对本单位的收支业务编制会计凭证后，将书面的会计凭证及附件提交财务部的财务科进行复核确认后进行记账处理，编制会计报表。厦门大学根据《高等学校会计制度》规定进行会计核算。（1）厦门大学在资产管理方面制定了《厦门大学贵重仪器设备管理办法》（厦大资产〔2001〕5 号）及《厦门大学仪器设备管理办法》（厦大资产〔2001〕4 号）。厦门大学仪器设备管理，实行统一领导、分级管理、管用结合的原则。资产管理处为校一级物资主管部门，在校长领导下，统一管理全校教学、科研、行政、医院等事业单位的物资工作；各院、系、 部、处为二级使用管理单位。（2）财务档案管理方面，有完善的档案管理办法，课题财务资料归档及时，装订规范，财务资料的保存有效完整。会计档案资料保存办公大楼 4 楼的会计档案室。

课题一前两年共投入了 316 人月（合为 26 人年），其中高级职称 4 人，博士后 3 人，中级 1 人，初级 1 人，博士研究生 9 人，硕士研究生 8 人。

2．课题经费拨付情况

课题牵头单位向课题承担单位、课题承担单位向课题参与单位拨付中央财政资金情况。

无。

3．人员及经费实际调整情况

如出现课题人员的调整，以及经费未及时到位、停拨、迟拨等特殊情况，请详细说明原因、措施、履行相关审批管理制度以及整改等情况。

无。

四、课题配套支撑条件情况

阐述各主要研究任务的配套支撑条件落实及调整变化情况。如有调整变化，请说明调整变化对完成课题目标的影响和作用。

课题承担单位厦门大学为该研究提供了调查航次、海上实验、室内研究与分析所需要的仪器设备等条件，为本课题的实施提供了有力支撑。

厦门大学科考船“嘉庚号”（排水量，3600 吨）于 2017 年 4 月 1 日抵达厦门港交付使用。本项目利用“嘉庚号”于 2017 年 6 月和 2018 年 1-2 月分别执行南海中部和中北部的科考航次；在航次科考中，课题收集了大量的浮游植物类群和固碳数据，并且利用叶绿素荧光仪和同位素示踪方法对浮游植物光合作用的昼夜变化进行研究，揭示了自然海区中原绿球藻的光合作用能量分配比等。“嘉庚号”科考船是本课题收集现场数据、开展过程机理研究和布放相关科研仪器的关键支撑平台。

厦门大学于 2016 年 9 月新布放的生地化剖面浮标（BGC-Argo）和 2017 年 6 月航次中布放的水下滑翔机，成功地收集了大量的物理海洋学和生物地球化学数据，这些数据将有利于课题研究海洋生态系统固碳，满足课题科研活动的需求。

五、组织实施风险及应对情况

阐述课题在组织实施过程中，面对外部政策、组织管理、研发变化和知识产权等方面的风险以及应对措施。

课题在项目组的统筹下，针对外部政策、组织管理和研发变化方面进行了风险管理。

在外部政策方面，依托项目组针对航次执行过程中可能涉及的争议海域问题，可能受国家外交政策和周邻国家政策的影响，进行了风险的预估和应对。充分准备航次预案，及时报外交部审核与备案，保障科研活动的正常执行。

在组织管理方面，在项目组的统筹管理下，通过邮件交流、参与项目定期协调会和专题研讨会等，保障课题和项目组间的充分协调和沟通；在课题内部，通过课题成员间定期的会面，数据在课题内部的共享和课题成员在具体科学问题上的合作等，保障课题科研活动的顺利进行和获得高质量的研究成果。

在研发变化方面，自然科学基础研究存在不确定性的风险，课题依托项目组，通过报告科研进展、预期结果和存在问题等，向项目专家组咨询，在专家组的指导下，针对问题适当调整研究内容或计划进度，保障课题研发内容的完整性和核心科研目标的实现。

六、课题组织实施中的重大问题及建议

无。

七、任务书中有特殊约定或其他需要说明的事项

无。

附件：发表论文清单和首页

共发表论文 16 篇，其中 SCI 收录 15 篇，第一标注 11 篇，第二标注 1 篇，其他标注 4 篇。

1. Wupeng Xiao#, Xin Liu#, Andrew J. Irwin, Edward Laws, Lei Wang, Bingzhang Chen, Yang Zeng, Bangqin Huang*, 2018, Warming and eutrophication combine to restructure diatoms and dinoflagellates, ***Water Research***, 128:206-216. 1 区，6.942（第一标注）
2. Wupeng Xiao, Lei Wang, Edward A. Laws, Yuyuan Xie, Jixin Chen, Xin Liu, Bingzhang Chen, Bangqin Huang*, Realized niches explain spatial gradients in seasonal abundance of phytoplankton groups in the South China Sea, 2018, ***Progress in Oceanography,*** 162：223-239. 2 区，3.391（第一标注）
3. Wenxue Wu, Ramiro Logares, Bangqin Huang* and Chih-hao Hsieh*, 2017, Abundant and rare picoeukaryotic sub-communities present contrasting patterns in the epipelagic waters of marginal seas in the northwestern Pacific Ocean. ***Environmental Microbiology,*** 19(1): 287-300. 2 区，5.395（第一标注）
4. Lin Qi, Chuanmin Hu*, Mengqiu Wang, Shaoling Shang, Cara Wilson, 2017, Floating algae blooms in the East China Sea, ***Geophysical Research Letters***, 11:501-509. 1 区，4.339（第一标注）
5. Shaoling Shang*, Zhongping Lee*, Lianghai Shi, Gong Lin, Guomei Wei and Xueding Li, Changes in water clarity of the Bohai Sea: Observations from MODIS. ***Remote Sensing of Environment***， 2016，186: 22-31. 1 区，6.265（第一标注）
6. Yuyuan Xie, Edward Allen Laws, Lei Yang, Bangqin Huang*, 2018, Diel patterns of variable fluorescence and carbon fixation of picocyanobacteria *Prochlorococcus*-dominated phytoplankton in the South China Sea basin, ***Frontiers in Microbiology,*** Accepted，2 区，4.019（第一标注）
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9. Lin Qi*, Chuanmin Hu, Brian B. Barnes and Zhongping Lee, 2017, VIIRS captures phytoplankton vertical migration in the NE Gulf of Mexico. ***Harmful Algae***, 66: 40-46. 3 区，3,087 （第一标注）
10. Lina Wang, Weiran Pan*, Wei Zhuang, Xiao-Hai Yan*, Victor Klemas, 2018, Analysis of seasonal characteristics of water exchange in Beibu Gulf based on a particle tracking model, ***Regional Studies in Marine Science***, 18, 35-43. SCI，1.152（第一标注）
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12. Zhida Huang, Wei Zhuang*, Hailong Liu and Jianyu Hu*, 2018，Subduction of a low-salinity water mass around the Xisha Islands in the South China Sea, ***Scientific Reports***, 8:3074，DOI:10.1038/s41598-018-21364-3. 3 区，4.122. （第二标注）
13. Shaoling Shang*, Zhongping Lee*, Gong Lin, Chuanmin Hu, Lianghai Shi, Yongnian Zhang, Xueding Li, Jingyu Wu and Jing Yan, 2017, Sensing an intense phytoplankton bloom in the western Taiwan Strait from radiometric measurements on a UAV. ***Remote Sensing of Environment***, 198: 85-94. 1 区，6.265（其它标注）
14. Lin Qi*, Zhongping Lee, Chuanmin Hu and Menghua Wang, 2017, Requirement of minimal signal-to-noise ratios of ocean color sensors and uncertainties of ocean color products. ***Journal of Geophysical Research: Oceans***, 122(3): 2595-2611. 2 区，2.939 （其它标注）

15. Jianwei Wei*, Zhongping Lee and Shaoling Shang, 2016, A system to measure the data quality of spectral remote sensing reflectance of aquatic environments. ***Journal of Geophysical Research: Oceans***. 121: 8189–8207. 2 区，2.939（其它标注）
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Warming and eutrophication combine to restructure diatoms and dinoflagellates

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ABSTRACT

Temperature change and eutrophication are known to affect phytoplankton communities, but relatively little is known about the effects of interactions between simultaneous changes of temperature and nutrient loading in coastal ecosystems. Here we show that such interaction is key in driving diatom-dinoflagellate dynamics in the East China Sea. Diatoms and dinoflagellates responded differently to temperature, nutrient concentrations and ratios, and their interactions. Diatoms preferred lower temperature and higher nutrient concentrations, while dinoflagellates were less sensitive to temperature and nutrient concentrations, but tended to prevail at low phosphorus and high N:P ratio conditions. These different traits of diatoms and dinoflagellates resulted in the fact that both the effect of warming resulting in nutrients decline as a consequence of increasing stratification and the effect of increasing terrestrial nutrient input as a result of eutrophication might promote dinoflagellates over diatoms. We predict that conservative forecasts of environmental change by the year 2100 are likely to result in the decrease of diatoms in 60% and the increase of dinoflagellates in 70% of the surface water of the East China Sea, and project that mean diatoms should decrease by 19% while mean dinoflagellates should increase by 60% in the surface water of the coastal East China Sea. This analysis is based on a series of statistical niche models of the consequences of multiple environmental changes on diatom and dinoflagellate biomass in the East China Sea based on 2815 samples randomly collected from 23 cruises spanning 14 years (2002–2015). Our findings reveal that dinoflagellate blooms will be more frequent and intense, which will affect coastal ecosystem functioning.

1. Introduction

Anthropogenic eutrophication and global warming have dramatic impacts on marine phytoplankton and are likely to continue for many centuries (Doney et al., 2012; Hallegraeff, 2010; Karl and Trenberth, 2003). Eutrophication is a major problem in many coastal ecosystems and has resulted in large phytoplankton blooms and the expansion of low-oxygen dead zones (Anderson et al., 2002; Edwards et al., 2006). Warming affects phytoplankton in two fundamentally different ways: directly through the effect of warming on metabolic rates and indirectly through physical mixing, which affects nutrient availability (Lewandowska et al., 2014). Simultaneous warming and eutrophication will have complex consequences because of interactions between the processes that are driven by nutrient supply and metabolic rates. There is accumulating evidence that the intensity of the response differs considerably across taxa; these changes may therefore cause a shift in phytoplankton community structure (Barton et al., 2016; Edwards and Richardson, 2004; Irwin et al., 2012; Wells et al.,

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Realized niches explain spatial gradients in seasonal abundance of phytoplankton groups in the South China Sea

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ABSTRACT

A basic albeit elusive goal of ocean science is to predict the structure of biological communities from the multitude of environmental conditions they experience. Estimates of the realized niche-based traits (realized traits) of phytoplankton species or functional groups in temperate seas have shown that response traits can help reveal the mechanisms responsible for structuring phytoplankton communities, but such approaches have not been tested in tropical and subtropical marginal seas. Here, we used decadal-scale studies of pigment-based phytoplankton groups and environmental conditions in the South China Sea to test whether realized traits could explain the biogeographic patterns of phytoplankton variability. We estimated the mean and breadth of the phytoplankton realized niches based on responses of the group-specific phytoplankton composition to key environmental factors, and we showed that variations of major phytoplankton groups in this system can be explained by different adaptive trade-offs to constraints imposed by temperature, irradiance, and nutrient concentrations. Differences in the patterns of trade-offs clearly separated the dominant groups from one another and generated four sets of realized traits that mirrored the observed biogeographic distribution patterns. The phytoplankton realized niches and their associated traits that we characterized in the present study could help to predict responses of phytoplankton to changes in environmental conditions in the South China Sea and could be incorporated into global biogeochemical models to anticipate shifts in community structure under future climate scenarios.

1. Introduction

Marine phytoplankton play key roles in the global carbon cycle, accounting for about one-half of net global primary productivity (Falkowski et al., 1998; Field et al., 1998). Phytoplankton species can be grouped into functional groups that reflect diverse, multi-dimensional niches characterized by a variety of environmental factors, including nitrogen, phosphorus, silicate, iron, light, temperature, and grazers (Edwards et al., 2013). Changes in the relative abundance of functional groups and their realized niches affect biogeochemical cycles such as the microbial loop, biological pump, and major elemental cycles (Litchman et al., 2015). Thus, understanding the ecological niches of different functional groups and their interaction is central to predicting how diverse global environmental changes will affect phytoplankton communities and ultimately alter biogeochemical cycles.

Phytoplankton niches are usually defined based on both laboratory experiments and field observations. Laboratory experiments use physiological parameters, such as sensitivity to changes in nutrient concentrations, light, temperature, and salinity, to mechanistically construct a niche model that is then related to current environmental conditions to derive a maximal distribution range (Litchman and Klausmeier, 2008; Litchman et al., 2012; Litchman et al., 2015). This approach can provide mechanistic explanations for the predicted patterns. One drawback is that physiological parameters measured for a limited set of species may not be representative of the realized niches occupied by phytoplankton communities in the real ocean (Irwin et al., 2012). Niches estimated from the field have been based on observational data of phytoplankton distributions and associated environmental data using statistical models (Wiens et al., 2009; Litchman et al., 2012). Such statistical models represent realized niches of species or

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Abundant and rare picoeukaryotic sub-communities present contrasting patterns in the epipelagic waters of marginal seas in the northwestern Pacific Ocean

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Summary

In this work, they compared patterns of abundant and rare picoeukaryotic sub-communities in the epipelagic waters (surface and 40–75 m depth subsurface layers) of the East and South China Seas across seasons via 454 pyrosequencing of the V4 region of 18S rDNA. They also examined the relative effects of environmental filtering, dispersal limitations and seasonality on community assembly. Their results indicated that (i) in the surface layer, abundant taxa are primarily influenced by dispersal limitations and rare taxa are primarily influenced by environmental filtering, whereas (ii) in the subsurface layer, both abundant and rare sub-communities are only weakly influenced by environmental filtering but are strongly influenced by dispersal limitations. Moreover, (iii) abundant taxa exhibit stronger temporal variability than rare taxa. They also found that abundant and rare sub-communities display similar spatial richness patterns that are negatively correlated with latitude and chlorophyll *a* and positively correlated with temperature. In summary, environmental filtering and dispersal limitations have different effects on abundant and rare picoeukaryotic sub-communities in different layers. Thus, depth appears as an essential variable that governs the structuring patterns of picoeukaryotic communities in the oceans and should be thoroughly considered to develop a more comprehensive understanding of oceanic microbial assemblages.

Received 30 May, 2016; revised 2 November, 2016; accepted 8 November, 2016. *For correspondence: E-mail bqhuang@xmu.edu.cn (B. Huang): Tel, +86 592 2187783; Fax, +86 592 2180655 OR E-mail chsieh@ntu.edu.tw (C.-H. Hsieh): Tel, +886 2 33669745; Fax, +886 2 33669746.

Introduction

The majority of natural microbial communities seem to be composed of a few abundant taxa with ubiquitous distributions and a large number of rare species with restricted distributions (Pedrós-Alió, 2006; Logares *et al.*, 2015). Abundant microbes account for the majority of biomass and carbon cycling in ecosystems (Pedrós-Alió, 2012); thus, studying this community component is crucial to understand ecosystem functioning. However, recent studies have increasingly emphasized the importance of rare biota (Lynch and Neufeld, 2015), which include numerous metabolically active organisms (Campbell *et al.*, 2011; Debroas *et al.*, 2015). For instance, Pester *et al.* (2010) found that a rare bacterial species plays a crucial role in sulphate reduction in a peatland, and Musat *et al.* (2008) showed that a rare anaerobic phototrophic bacterial species is the primary facilitator of nitrogen and carbon cycling in Lake Cadagno. Moreover, even in highly diverse ecosystems, the rare biota supports critical ecological functions (Mouillot *et al.*, 2013); thus, the loss of rare species could have serious ecological consequences (Pendleton *et al.*, 2014).

Over the last decade, high-throughput sequencing has allowed researchers to analyse rare biota; thus, an increasing number of studies have compared abundant and rare taxa in various ecosystems (Logares *et al.*, 2014; Gong *et al.*, 2015; Liu *et al.*, 2015). Nevertheless, studies assessing the dynamics between abundant and rare marine picoeukaryotes (< 3 μm in size) remain scarce.

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Floating Algae Blooms in the East China Sea

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Key Points:
- An unprecedented massive floating algae bloom in the East China Sea is discovered, which appears to be Sargassum horneri
- The bloom is thought to be a result of increased water temperature, light, and expanded seaweed aquaculture along the ECS coast
- Bloom origin is traced back to coastal waters off Zhejiang coast, with a "hot spot" identified, yet other origins cannot be ruled out

Supporting Information:
- Supporting Information S1

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Abstract A floating algae bloom in the East China Sea was observed in Moderate Resolution Imaging Spectroradiometer (MODIS) imagery in May 2017. Using satellite imagery from MODIS, Visible Infrared Imaging Radiometer Suite, Geostationary Ocean Color Imager, and Ocean Land Imager, and combined with numerical particle tracing experiments and laboratory experiments, we examined the history of this bloom as well as similar blooms in previous years and attempted to trace the bloom source and identify the algae type. Results suggest that one bloom origin is offshore Zhejiang coast where algae slicks have appeared in satellite imagery almost every February–March since 2012. Following the Kuroshio Current and Taiwan Warm Current, these "initial" algae slicks are first transported to the northeast to reach South Korea (Jeju Island) and Japan coastal waters (up to 135°E) by early April 2017, and then transported to the northwest to enter the Yellow Sea by the end of April. The transport pathway covers an area known to be rich in *Sargassum horneri*, and spectral analysis suggests that most of the algae slicks may contain large amount of *S. horneri*. The bloom covers a water area of ~160,000 km^2 with pure algae coverage of ~530 km^2, which exceeds the size of most *Ulva* blooms that occur every May–July in the Yellow Sea. While blooms of smaller size also occurred in previous years and especially in 2015, the 2017 bloom is hypothesized to be a result of record-high water temperature, increased light availability, and continuous expansion of *Porphyra* aquaculture along the East China Sea coast.

Plain Language Summary A massive floating algae bloom in the East China Sea was first captured in Moderate Resolution Imaging Spectroradiometer satellite imagery in mid-May 2017. Both its size and location are unprecedented. Several means have been used to identify the algae type and bloom origin, including the use of multisource satellite imagery, numerical particle tracing experiments, and laboratory experiments. While multiple origins are possible, the bloom could be tracked to Zhejiang coastal waters where the "initial" algae slicks back in February were transported to the northeast following the Kuroshio Current and Taiwan Warm Current to reach South Korea (Jeju Island) and Japan coastal waters by early April 2017, and then transported to the northwest to enter the Yellow Sea by end of April. Spectral analysis and historical field surveys suggested that the bloom may be dominated by *Sargassum horneri*, while expanded seaweed aquaculture and record-high water temperature and increased surface light may have contributed to the unprecedented bloom, which covered a water area of ~160,000 km^2 with pure algae coverage of ~530 km^2, both exceeding the maximum size of most Ulva blooms in the Yellow Sea.

1. Introduction

Since 2008, blooms of the green macroalgae *Ulva prolifera* (often called green tides) have occurred every May–August in the western Yellow Sea (YS) off the Shandong Peninsula, China. These blooms have been studied extensively using remote sensing, field and laboratory measurements, and numerical models (Bao et al., 2015; Hu et al., 2010; Keesing et al., 2011; Lee et al., 2011; Shi & Wang, 2009; Son et al., 2015; Wang et al., 2015; Xing et al., 2015; many others). The blooms have been attributed to *Porphyra yezoensis* (a species of *Porphyra*) seaweed aquaculture in Subei Shoal (Figure 1) where 90% of China's *P. yezoensis* aquaculture is located. *Ulva* usually grows on the *P. yezoensis* aquaculture rafts. During harvest, *Ulva* is released from the rafts, and then advected to the western YS where rapid growth occurs under favorable temperature, light, and nutrient availability, leading to massive blooms (maximum daily coverage ≥ 500 km^2 since 2013; Qi et al., 2016). Although the exact reasons for the annual fluctuations in bloom sizes have not been fully explained, the bloom origin and ecological factors affecting algae growth have been well studied and understood (Hu et al., 2010; Keesing et al., 2011; Liu et al., 2010; Wang et al., 2015; Zhang et al., 2014, others).

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Changes in water clarity of the Bohai Sea: Observations from MODIS

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ABSTRACT

Water clarity, which is commonly and widely represented by the Secchi depth (Z_{sd}), is an important quality parameter for all aquatic environments. To evaluate the variation of water clarity of the Bohai Sea (BHS) in the past decade (2003–2014), Z_{sd} is derived from MODIS-Aqua ocean color data with an innovative mechanistic model. The resulted Z_{sd} product from MODIS is found within 23% differences of match-up in situ measurements that span a range of 2–12 m. Based on this validated MODIS Z_{sd} product of the BHS, valuable findings regarding water clarity of the BHS over the period of 2003–2014 are obtained for the first time. For the central BHS, the climatological mean Z_{sd} in August of 2003–2014 (3.9 m) is found strikingly lower than that observed in situ in August of 1982–1983 (8.7 m), 1959–1979 (8–12 m) and 1972–1987 (8–14 m). This implies substantial deterioration of water clarity in the central BHS after the late 1980s, an unpleasant byproduct of rapid economic development in the BHS surrounding regions initiated in the mid-1980s. On the other hand, no significant variations in Z_{sd} in the central BHS is detected for the period of 2003–2014, suggesting deterioration of water clarity of this water body is not continued. Results from this effort highlight the value of both the analytically-derived Z_{sd} product and satellite ocean color remote sensing in monitoring water quality of coastal seas.

1. Introduction

The Bohai Sea (BHS) is a large (77,000 km^2) and shallow (~18 m on average) semi-enclosed marginal sea surrounded by one of the heavily industrialized and densely populated regions in China (Fig. 1) - the "Bohai-Rim Economic Circle." The BHS includes three bays (Bohai Bay, Laizhou Bay and Liaodong Bay), which serve as primary receivers of >17 rivers (e.g., Zhang et al., 2007). Among these rivers, the Yellow River is the largest and empties itself into the Laizhou Bay with an annual discharge at the magnitude of 10^{10} m^3 and an annual sediment load estimated at 10^9 tons (Milliman and Meade, 1983). The Bohai Strait, with maximum water depth of ~70 m, is the only channel allowing water mass exchanges between the BHS and the neighboring Yellow Sea (YS) (e.g., Xu et al., 2009). The BHS is also under the influence of monsoons, with strong northerly winds prevailing in winter and weak and less persistent southerly winds in summer (Lee and Chao, 2003).

Following the economic reform in the "Bohai-Rim Economic Circle" initiated in 1985 (http://baike.baidu.com/view/48598.htm), various impacts on the BHS water, resulting from the intense urbanization and rapid industrialization, have emerged. The BHS receives ~40% of the direct discharged sewage from the entire country every year, although it takes up just 2.6% of the sea area of China (China Environment Yearbook, Volume 4). In the meantime, most rivers discharging into the BHS have been dammed for the purposes of irrigation and municipal water supply (Fuggle and Smith, 2000). It was suggested that the damming of rivers has resulted in the increasing trend in dissolved inorganic nitrogen, temperature, and salinity in the BHS over 1960–1996 (Ning et al., 2010). Fishery biomass in 1998 was only ~5% of that in 1959, accompanied by a decreasing trend of primary productivity from 1959 to 1998 (Tang et al., 2003). Bottom acidification was observed in the western BHS in summer 2011. It has been suggested that the acidification was induced by remineralization of local biogenic organic matters originating from frequent harmful algae blooms and intensive aquaculture (Zhai et al., 2012). In general, it has been recognized that the BHS ecosystem is being rapidly degraded (Gao et al., 2014; Liu et al., 2011; Xu, 2011).

However, while these changes in the ecosystem of the BHS over the past decades are of serious concern, the current status and the change in water quality over time have not been characterized in detail. One of the key water quality parameters is water clarity, which not only affects our visual perception of the water environment, but also provides important information on light availability to the aquatic ecosystems.

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Diel Patterns of Variable Fluorescence and Carbon Fixation of Picocyanobacteria *Prochlorococcus*-Dominated Phytoplankton in the South China Sea Basin

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The various photosynthetic apparatus and light utilization strategies of phytoplankton are among the critical factors that regulate the distribution of phytoplankton and primary productivity in the ocean. Active chlorophyll fluorescence has been a powerful technique for assessing the nutritional status of phytoplankton by studying the dynamics of photosynthesis. Further studies of the energetic stoichiometry between light absorption and carbon fixation have enhanced understanding of the ways phytoplankton adapt to their niches. To explore the ecophysiology of a *Prochlorococcus*-dominated phytoplankton assemblage, we conducted studies of the diel patterns of variable fluorescence and carbon fixation by phytoplankton in the oligotrophic South China Sea (SCS) basin in June 2017. We found that phytoplankton photosynthetic performance at stations SEATS and SS1 were characterized by a nocturnal decrease, dawn maximum, and midday decrease of the maximum quantum yield of PSII ($F_v(')/F_m(')$, which has been denoted as both F_v/F_m and F'_v/F'_m) in the nutrient-depleted surface layer. That these diel patterns of $F_v(')/F_m(')$ were similar to those in the tropical Pacific Ocean suggests macro-nutrient and potentially micro-nutrient stress. However, the fact that variations were larger in the central basin than at the basin's edge implied variability in the degree of nutrient limitation in the basin. The estimated molar ratio of gross O_2 production to net production of carbon (GOP:NPC) of 4.9:1 was similar to ratios reported across the world's oceans. The narrow range of the GOP:NPC ratios is consistent with the assumption that there is a common strategy for photosynthetic energy allocation by phytoplankton. That photo-inactivated photosystems or nonphotochemical quenching rather than GOP accounted for most of the radiation absorbed by phytoplankton explains why the maximum quantum yield of carbon fixation was rather low in the oligotrophic SCS.

Keywords: diel variation, variable fluorescence, primary production, photosynthetic parameters, *Prochlorococcus*, South China Sea basin, nutrient limitation, photosynthetic energetic stoichiometry

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Net community production in the South China Sea Basin estimated from *in situ* O_2 measurements on an Argo profiling float

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ABSTRACT

For the first time, the net community production (NCP) was estimated over a complete annual cycle in the basin of the South China Sea (SCS) using *in situ* oxygen measurements from an Argo profiling float and an oxygen mass balance model. The annual NCP from July 2014 to July 2015 was estimated to be 2.7 mol C m^{-2} yr^{-1} (calculated to the deepest winter mixed layer depth of 56 m), with the uncertainties ranging from 0.9 ~ 2.2 mol C m^{-2} yr^{-1}. NCP estimates followed a monsoonal pattern with higher values in the cold season (November to April) when northeast monsoon prevailed and low values in the warm season (June to September) when this area was dominated by the southwest monsoon. Most of the net heterotrophic events occurred in the warm season. The magnitude and seasonal pattern derived from our results agree with previous export production studies based on discrete measurements. Comparison with satellite-derived NCP revealed that the results derived with NPP from Carbon-based Production Model (CbPM) were closer to the Argo measurements than the results derived with NPP from Vertically Generalized Production Model (VGPM) in magnitude; while the VGPM-based approach did a better job in reproducing the seasonal cycle of NCP in this area. This novel approach provides the possibilities to study the carbon cycle in the SCS with a much higher temporal and spatial resolution, as well as more insights for metabolic state in the oligotrophic subtropical gyres.

1. Introduction

The biological transfer and export of organic carbon from the surface ocean into the deep sea, commonly referred to as the marine biological pump, plays an important role in regulating the atmospheric CO_2 level (Sigman and Boyle, 2000; Ciais et al., 2013). At steady state, the magnitude of net community production (NCP), defined as the gross primary production minus the community respiration, equals to the amount of biologically-produced organic matter available for export and hence can be regarded as one of the best proxies to quantify carbon export efficiency of marine biological pump (Del Giorgio and Duarte, 2002; Ducklow and Doney, 2012).

Whether the metabolic state in the oligotrophic subtropical gyres is autotrophic or heterotrophic is still under extensive debate (Ducklow and Doney, 2012; Duarte et al., 2013; Williams et al., 2013): shipboard based incubation (*in vitro*) approaches (mostly light-dark bottle incubations) tend to yield heterotrophy whereas most results from incubation-free (*in situ*) methods suggest autotrophy in these oligotrophic waters. The major cause for this discrepancy probably lies in the biases associated with one or both types of methodologies (*in vitro* and *in situ*). Also, it can be induced by sampling bias (*e.g.* the two different methods measured NCP at different time and/or locations). The controversy over the sign of NCP cannot be easily solved due to the complicated controlling mechanisms on NCP, which is not only affected by the local primary production, but also related to the dynamics of trophic status and dissolved organic carbon distribution (Arístegui and Harrison, 2002; Serret et al., 2015). If there is some mechanism to deliver semi-labile organic matters from coastal areas to the ocean gyre, the persistent heterotrophic state of the oligotrophic ocean gyre suggested by the *in vitro* measurements could be real (Duarte et al., 2013).

Satellite-based algorithms have been widely utilized to determine the global distribution of NCP and/or particulate export production. Westberry et al. (2012) calculated global NCP using empirical relationships between *in vitro* photosynthesis /respiration and Carbon-

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Spatial and seasonal distributions of photosynthetic picoeukaryotes along an estuary to basin transect in the northern South China Sea

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The spatial and seasonal distributions of marine photosynthetic picoeukaryotes (PPEs) and the underlying structuring mechanisms are not well understood. Here, we performed Fluorescent *in situ* hybridization associated with tyramide signal amplification along an estuary to basin transect in the northern South China Sea (SCS) across three seasons (spring, summer and autumn). We disentangled the PPE assemblage variances by combining these data with the results obtained in our previous study conducted in winter to evaluate the relative importance of environmental, spatial and temporal effects. Our results showed that Mamiellophyceae was the most abundant class and accounted for an average of 33.1% (spring), 34.2% (summer) and 30% (autumn) of the depth-integrated picoeukaryotic abundances in different seasons. Prymnesiophyceae species were widely detected across the three seasons, and Pelagophyceae species were remarkably abundant in the chlorophyll maximum depth in summer. Bolidophyceae represents an important PPE class and made considerable contributions (up to 25.4% in autumn) to the depth-integrated picoeukaryotic abundances. Moreover, the PPE assemblages were significantly explained by purely environmental (6.5%) and purely temporal (42.7%) components, and they were also explained by a weak and non-significant spatial component (1.9%). In summary, our results provide insights into PPE distributions that are differently influenced by environmental, spatial and temporal components in the northern SCS.

KEYWORDS: FISH-TSA; mamiellophyceae; prymnesiophyceae; pelagophyceae; bolidophyceae; metacommunity; variation partitioning

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VIIRS captures phytoplankton vertical migration in the NE Gulf of Mexico

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ABSTRACT

In summer 2014, a toxic *Karenia brevis* bloom (red tide) occurred in the NE Gulf of Mexico, during which vertical migration of *K. brevis* has been observed from glider measurements. The current study shows that satellite observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) can capture changes in surface reflectance and chlorophyll concentration occurring within 2 h, which may be attributed this *K. brevis* vertical migration. The argument is supported by earlier glider measurements in the same bloom, by the dramatic changes in the VIIRS-derived surface chlorophyll, and by the consistency between the short-term reflectance changes and those reported earlier from field-measured *K. brevis* vertical migration. Estimates using the quasi-analytical algorithm also indicate significant increases in both total absorption coefficient and backscattering coefficient in two hours. The two observations in a day from a single polar-orbiting satellite sensor are thus shown to be able to infer phytoplankton vertical movement within a short timeframe, a phenomenon difficult to capture with other sensors as each sensor can provide at most one observation per day, and cross-sensor inconsistency may make interpretation of merged-sensor data difficult. These findings strongly support geostationary satellite missions to study short-term bloom dynamics.

1. Background

Karenia brevis, a toxic algae responsible for most harmful algal blooms (red tides) in the Gulf of Mexico (GOM), is known to migrate vertically with diel cycles to maximize its use of light and nutrients. This phenomenon has been observed and studied numerous times in laboratory cultures (Heil, 1986; McKay et al., 2006; Schaeffer et al., 2009; Levandowsky and Kaneta, 1987; Hand et al., 1965; Hunte, 1986; Kamykowski and Mccollum, 1986; Kamykowski et al., 1988, 1992) and from field measurements (Kerfoot et al., 2004; Schofield et al., 2006). Laboratory studies are, however, under controlled environments that may not represent realistic environmental conditions. Additionally, the limited field measurements of vertical migration only documented the behavior of *K. brevis* at one station, and thus are limited in both space and time. On the other hand, while satellite remote sensing provides synoptic and frequent measurements, most ocean color satellites can only observe the subtropical and tropical oceans at most once a day, making it impossible to observe such diurnal changes unless multiple satellites are combined. One possible exception may be the Visible Infrared Imaging Radiometer Suite (VIIRS, 2012 – present), as its wide swath (3060 km) occasionally allows for two observations during a day at a given location in subtropical oceans.

Between July – September 2014, a *K. brevis* bloom occurred in the NE GOM off Florida's Big Bend region, during which several studies documented the bloom size, intensity, and temporal evolution from field and remote sensing observations (Hu et al., 2015; Qi et al., 2015; Elhabashi et al., 2016). The bloom reached a maximum size of about 7000 km^2 by late July, with maximum *K. brevis* concentration of >1 million cells L^{-1}. Field measurements using a glider suggested vertical migration of *K. brevis* inside the bloom (Hu et al., 2016). At a speed of 0.5–1 m h^{-1}, *K. brevis* started to move upward from a depth of 8–10 m around sunrise, and started to move downward from a depth of ~2 m around sunset. Although *K. brevis* vertical migration was observed in the field at synoptic scale (~30 km) in several consecutive days, the glider measurement was still limited in both space and time due to its slow motion (e.g., about 400 m an hour).

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Analysis of seasonal characteristics of water exchange in Beibu Gulf based on a particle tracking model

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HIGHLIGHTS

- The residence time in the whole gulf does not vary much between summer and winter.
- The residence times in six sub-regions exhibit a large seasonal difference.
- Water movement in the gulf follows the circulation patterns.
- Currents from Qiongzhou Strait and the south opening help in refreshing the gulf.

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ABSTRACT

The seasonal characteristics of water exchange in Beibu Gulf are investigated based on a particle tracking model. The gulf is divided into six sub-regions in order to better understand the exchange processes and water movement in the gulf. The residence time is computed for each sub-region, and the results show that the whole gulf has a small seasonal variation, with 66 days in winter and 71 days in summer, while the sub-regions exhibit a large seasonal difference with short residence times in summer. Water exchange curves indicate water movement in the gulf follows the circulation patterns. In winter, the water particles move cyclonically and accumulate near the western coast of the gulf. The current flows entering the gulf are dominated by the westward flow from the Qiongzhou Strait. The influence area of this flow can extend to the Vietnam coast. In summer, water particles from the coastal area tend to move offshore and undergo strong mixing in the center of the gulf. The northward current flow from the south opening becomes the dominant flow, with a large influence area in the eastern part of the gulf.

1. Introduction

Beibu Gulf is a semi-enclosed gulf located in the northwestern South China Sea (SCS), with an average depth of about 40 m and a maximum depth less than 100 m. The total area of the gulf is approximately 128 000 km^2. Beibu Gulf is recognized as one of the four largest fishing grounds in China, because of abundant marine life and year-round warm water temperatures. The gulf water is characterized by three major water masses (Chen, 1986), the coastal water supplied by nutrient-rich discharges from numerous rivers along the northern and western coast, the mixed water formed by the current flow from the Qiongzhou Strait (QS), and the sea water coming from the south wide opening between Hainan Island and Vietnam. Water exchange among these water masses has a significant impact on the species composition and distribution in the gulf, providing a greatly diverse marine life. For example, the intrusion of high-salinity and high-temperature water from the SCS contributes to different migration pathways of Paragyrops edita in Beibu Gulf (Chen and Qiu, 2005). Consequently, the study of water renewal and related exchange processes can help us better understand the distribution of biological resources and the formation of fishing grounds, and help provide scientific support for proper management of the ecosystem.

Lagrangian particle tracking methods are very useful tools to investigate and model the transport pathways and mixing processes (Dias et al., 2001; Perianez and Elliott, 2002; Perianez, 2004, 2005; Ninto and Garcia, 1996; Wroblicky et al., 1998; Saxton and Jacobson, 1997). In particular, Random-Walk Particle Tracking (RWPT) models that calculate particle pathways with advection and random displacement are well suited for water exchange studies (Suh, 2006; Zheng et al., 2003; Bilgili et al., 2005; Dimou and Adams, 1993; Signell and Butman, 1992; Liu et al., 2011; Oliveira and Baptista, 1997). When studying large areas, the basic idea is to divide the study area into several zones, and estimate water

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海洋生态系统储碳过程的多尺度调控及其对全球变化的响应

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摘　要　海洋是地表系统中最大的碳库，在全球碳循环中起着举足轻重的作用，显著影响地球气候系统。生物泵和微型生物碳泵是海洋储碳的两个重要途径，其储碳效率在很大程度上决定了海洋和大气中的碳库变动，是碳增汇的关键过程。本项目目标是阐明海洋固碳过程和储碳机理，诠释海洋酸化对固碳和储碳的影响，建立古海洋沉积碳库变动与全球变化的关联，深入揭示海洋生态系统储碳过程的多尺度调控机理。项目将从现代生物地球化学过程入手，研究不同层级水平上海洋生态系统的固碳过程、储碳机制及其对海洋酸化的响应；并结合不同沉积系统近2000年来的碳库变动，以及工业革命以来高分辨率的海水温度、pH值和碳库记录，探讨海洋碳库变动对自然变化和人类活动的响应机制，阐明生物泵和微型生物碳泵储碳的调控机理。项目的实施将显著提升我国在海洋碳循环和储碳机制研究领域的国际地位，为我国制定应对气候变化和实施海洋碳增汇政策提供科技支撑。

关键词：海洋储碳　海洋生物泵　微型生物碳泵　海洋酸化　沉积碳库记录　全球变化

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1　项目研究背景与意义

海洋碳循环是全球碳循环的关键环节，也是当今全球变化科学前沿领域之一。自工业革命以来，海洋吸收了约48%的人为排放CO_2，是地表系统中最大的碳库，亦是吸收人为排放CO_2最大的汇区（Libes，2009）。生物泵和微生物碳泵是海洋吸收CO_2的主要途径，前者是浮游植物利用通过光合作用将海水中的无机碳转变成颗粒有机碳，通过自身沉降和浮游动物摄食，并最终向深层海洋传输的过程；后者则是通过微型生物的作用将活性的溶解有机碳转化为惰性有机碳，从而增加在海洋中的停留时间。作为海洋储碳的重要途径，生物泵一直是海洋碳循环的核心研究内容之一，而新近提出的微型生物碳泵亦是近年来碳循环的热点研究主题（Jiao et al.，2011）。

研究表明，海洋吸收CO_2导致海洋酸化，研究已经证实酸化进程的持续发展将会对现有许多海洋生物造成重大威胁（Busch et al.，2015）。但遗憾的是，至今尚未有报道指出这种威胁是否会影响（甚至已经影响了）海洋的碳汇潜力？全球变化（如酸化、变暖）对海洋储碳能力的影响如何？这是急待解决的重大基础科学问题。造成这种认识不足的根本原因还是对以生物群落主导的海洋储碳过程及其调控机理仍然有许多不明之处（Busch et al.，2015）。

利用古环境与古气候重建来探讨海洋沉积碳库（储碳记录）与气候环境变化的关联是当今全球变化的热点研究课题（Jiao et al.，2010；Wang et al.，2014）。近10多年来，人们开始关注近现代人类活动，如陆源输入特别是人为营养输入对近岸沉积物

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Subduction of a low-salinity water mass around the Xisha Islands in the South China Sea

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Based on three climatologically observed temperature and salinity datasets (i.e., GDEM-V3, SCSPOD14 and WOA13), this paper reports a low-salinity (~34.32) water mass in the subsurface-to-intermediate layer around the Xisha Islands in the South China Sea. This water mass mainly subducts from the surface layer into the intermediate layer, characterized by a relatively low potential vorticity tongue extending from the bottom of mixed layer to the thermocline, and accompanied by a thermocline ventilation in spring (especially in April). The potential dynamics are the joint effects of negative wind stress curl, and an anticyclonic eddy triggered by the inherent topographic effect of the Xisha Islands, reflecting that downward vertical motion dominates the subduction. Despite lacking of the homogenous temperature and density, the low-salinity water mass is to some extent similar to the classic mode water and can be regarded as a deformed mode water in the South China Sea.

The South China Sea (SCS) is the largest semi-enclosed marginal deep sea located west of the North Pacific (NP) (Fig. 1), and its circulation patterns are associated with East Asian monsoon and Kuroshio intrusion. Much work has been done on a variety of dynamic processes in the SCS, including the vertical three-layer (cyclonic-anticyclonic-cyclonic) circulation structure, the SCS meridional overturning circulation, water exchanges in the Luzon Strait, mesoscale eddies and internal waves[1–13]. Analysis of Levitus dataset indicated a thermocline ventilation in the northern SCS in winter, leading to the detrainment of surface mixed layer water into the seasonal thermocline and subsequent southward migration of this water mass due to basin-scale cyclonic circulation[14]. However, whether the mixed layer water further subducts into the main thermocline remains unclear.

The large-scale subduction is the transfer of fluid from the surface mixed layer of the ocean into the interior thermocline, which is quantified by the subduction rate measured by the volume flux of fluid per unit area entering the thermocline from the mixed layer[15,16]. The subduction process is achieved through either shallowing of the mixed layer, lateral transfer of fluid across the sloping mixed layer base, or through vertical motion. In an eddying ocean, the net subduction rate incorporates both Eulerian-mean and eddy contributions[16–18]. The additional eddy-induced subduction can be regarded as the rectified transfer of a water mass from the mixed layer into the thermocline by an eddy-induced "bolus" velocity[19]. Recently, observations presented that subduction caused by an anticyclonic eddy (AE) is comparable in magnitude to that by the mean flow[18]. These suggest that eddies play a significant role in the total subduction. Similar to the NP, lots of mesoscale AEs in the SCS[9,10] will favor for the subduction formation.

In our study region (Fig. 1), our goals are to explore a subduction of low-salinity water mass which has been rarely reported before, and to preliminarily analyze the potential dynamic mechanisms for its formation, by using climatologically observed datasets. The present study will provide clearer insight into the circulation dynamics, ecological effect and climate change in the SCS.

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Sensing an intense phytoplankton bloom in the western Taiwan Strait from radiometric measurements on a UAV

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ABSTRACT

Rapid assessment of algal blooms in bays and estuaries has been difficult due to lack of timely shipboard measurements and lack of spatial resolution from current ocean color satellites. Airborne measurements may fill the gap, yet they are often hindered by the high cost and difficulty in deployment. Here we demonstrate the capacity of a low-cost, low-altitude unmanned aerial vehicle (UAV) in assessing an intense phytoplankton (*Phaeocystis globosa*) bloom (chlorophyll concentrations ranged from 7.3 to 45.6 mg/m^3) in Weitou Bay in the western Taiwan Strait. The UAV was equipped with a hyperspectral sensor to measure the water color with a footprint of 5 m at every 30 m distance along the flight track. A novel approach was developed to obtain remote sensing reflectance (R_{rs}) from the UAV at-sensor radiometric measurements. Compared with concurrent and co-located field measured R_{rs} (14 stations in total), the UAV-derived R_{rs} showed reasonable agreement with root mean square difference ranging 0.0028–0.0043 sr^{-1} (relative difference ~20–32%) of such turbid waters for the six MODIS bands (412–667 nm). The magnitude of the bloom was further evaluated from the UAV-derived R_{rs}. For the bloom waters, the estimated surface chlorophyll *a* concentration (*Chl*) ranged 6–98 mg/m^3, which is 3–50 times of the *Chl* under normal conditions. This effort demonstrates for the first time a successful retrieval of both water color (*i.e.*, R_{rs}) and *Chl* in a nearshore environment from UAV hyperspectral measurements, which advocates the use of UAVs for rapid assessment of water quality, especially for nearshore or difficult-to-reach waters, due to its flexibility, low cost, high spatial resolution, and sound accuracy.

1. Introduction

Phytoplankton blooms are natural phenomenon. Those blooms of particular note over decades, which adversely affect the health of ecosystems and human beings as well as the "health" of local and regional economies, are named harmful algal blooms (HABs) (Hallegraeff, 1993). Various techniques have been developed to help monitoring and early warning of HABs (Babin et al., 2005). Besides *in situ* observations, optical sensors onboard satellites were used to observe HABs and estimate concentrations of phytoplankton over broad regions – or generally termed as remote sensing approach. This technique is based on that there is a dramatic change of water color during these events due to significantly elevated phytoplankton concentrations, and a wide range of schemes have been developed for the utilization of satellite measurements (*e.g.*, Ahn and Shanmugam, 2006; Carder and Steward, 1985; Hu et al., 2005; Kurekin et al., 2014; Qi et al., 2016; Shang et al., 2014a; Sourisseau et al., 2016; Stumpf et al., 2003; Wynne et al., 2005). For instance, a chlorophyll anomaly technique that uses the increase in chlorophyll concentration of 1 mg/m^3 from the mean of the previous 60 days (Stumpf et al., 2003) was found very effective (>80%) for the detection of *Karenia brevis* blooms along the southwest Florida coast (Tomlinson et al., 2004). Based on field measurements of remote sensing reflectance and cell counts, the feasibility of using multispectral and hyperspectral approaches for detecting blooms of *Phaeocystis globosa* was assessed (Lubac et al., 2008). Using either total absorption or water-leaving reflectance field data, an algorithm was proposed to retrieve cell counts of *Phaeocystis* blooms in the southern North Sea waters (Astoreca et al., 2009). A novel floating algae index was developed, that employs the medium resolution (250 and 500 m) MODIS reflectance data at 645, 859, and 1240 nm, to identify locations of cyanobacteria blooms occurring in Taihu Lake, China (Hu et al., 2010). An HAB risk classification method, which employs a fully

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AGU PUBLICATIONS

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RESEARCH ARTICLE

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Key Points:

- Minimal signal-to-noise ratio for ocean color measurements quantified for the first time
- Noise-induced uncertainties in ocean color data products also quantified at different spatial and temporal scales
- Results provide support for sensor design and data interpretation in studying ocean changes in response to climate variability

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Requirement of minimal signal-to-noise ratios of ocean color sensors and uncertainties of ocean color products

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Abstract Using simulations, error propagation theory, and measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS), we determined the minimal signal-to-noise ratio (SNR) required for ocean color measurements and product uncertainties at different spatial and temporal scales. First, based on typical top-of-atmosphere (TOA) radiance over the ocean, we evaluate the uncertainties in satellite-derived R_{rs} in the visible wavelengths (ΔR_{rs}(vis)) due to sensor noise in both the near-infrared (NIR) and the visible bands. While the former induces noise in R_{rs}(vis) through atmospheric correction, the latter has a direct impact on R_{rs}(vis). Such estimated uncertainties are compared with inherent ΔR_{rs}(vis) uncertainties from in situ measurements and from the operational atmosphere correction algorithm. The comparison leads to a conclusion that once SNR(NIR) is above 600:1, an SNR(vis) better than 400:1 will not make a significant reduction in product uncertainties at pixel level under typical conditions for a solar zenith angle of 45°. Then, such uncertainties are found to decrease significantly in data products of oceanic waters when the 1 km pixels from individual images are binned to lower spatial resolution (e.g., 4 km) or temporal resolution (e.g., monthly). Although these findings do not suggest that passive ocean color sensors should have SNR(vis) around 400:1, they do support the argument for more trade space in higher spatial and/or spectral resolutions once this minimal 400:1 SNR(vis) requirement is met.

1. Introduction

Uncertainties in satellite ocean color data products are important parameters to define data quality, thus having direct impact on local, regional, and global studies. High uncertainties at image pixel level lead to low image quality to track ocean features or to study changes at fixed locations. High uncertainties at regional or global scale make it difficult to study ocean changes in response to climate variability because changes in the vast oceans may be very small even at decadal scale (e.g., 5–20%) [*Behrenfeld et al.*, 2001; *Antoine et al.*, 2005; *Gregg et al.*, 2005]. Thus, understanding sources of uncertainties is important in order to reduce them to improve data quality for a variety of applications. In the past, requirements on data product uncertainties at pixel level have been generally accepted by the ocean color community to be <5% in the satellite-retrieved remote sensing reflectance (R_{rs}, sr^{-1}) in the blue bands over clear waters and <35% in the satellite-retrieved chlorophyll *a* concentration (Chl, mg m^{-3}) also for clear waters [*Hooker et al.*, 1992]. This is because the former is the lower boundary from atmospheric correction [*Gordon*, 1997], while the latter was once regarded as the uncertainties in laboratory Chl estimates. Corresponding to these requirements, uncertainties in data products have been evaluated using different approaches, including (1) direct comparison with field measurement [e.g., *Gregg and Casey*, 2004; *McClain et al.*, 2004; *Bailey and Werdell*, 2006; *Marrari et al.*, 2006; *Mélin et al.*, 2007; *Antoine et al.*, 2008; *Zibordi et al.*, 2009; *Wang et al.*, 2009; *Maritorena et al.*, 2010; *Cannizzaro et al.*, 2013; *Moore et al.*, 2015; many others]; (2) statistics using satellite data alone [*Hu et al.*, 2013] or cross-sensor comparisons [*Zibordi et al.*, 2006; *Barnes and Hu*, 2015; *Hu et al.*, 2013] to avoid uncertainties embedded in field measurements. These assessments have led to different findings depending on locations (i.e., open ocean or coastal water), data ranges, and methods used in the assessments.

Such uncertainties in satellite-derived data products can come from several sources, including radiometric calibration, atmospheric correction, and other correction algorithms to estimate remote sensing reflectance

AGU PUBLICATIONS

JGR

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RESEARCH ARTICLE

10.1002/2016JC012126

Key Points:
- A QA system is developed for spectral remote-sensing reflectance
- The system consists of a reference and a score metric
- It is applicable to both remotely sensed and in situ ocean color data

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A system to measure the data quality of spectral remote-sensing reflectance of aquatic environments

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Abstract Spectral remote-sensing reflectance (R_{rs}, sr^{-1}) is the key for ocean color retrieval of water bio-optical properties. Since R_{rs} from in situ and satellite systems are subject to errors or artifacts, assessment of the quality of R_{rs} data is critical. From a large collection of high quality in situ hyperspectral R_{rs} data sets, we developed a novel quality assurance (QA) system that can be used to objectively evaluate the quality of an individual R_{rs} spectrum. This QA scheme consists of a unique R_{rs} spectral reference and a score metric. The reference system includes R_{rs} spectra of 23 optical water types ranging from purple blue to yellow waters, with an upper and a lower bound defined for each water type. The scoring system is to compare any target R_{rs} spectrum with the reference and a score between 0 and 1 will be assigned to the target spectrum, with 1 for perfect R_{rs} spectrum and 0 for unusable R_{rs} spectrum. The effectiveness of this QA system is evaluated with both synthetic and in situ R_{rs} spectra and it is found to be robust. Further testing is performed with the NOMAD data set as well as with satellite R_{rs} over coastal and oceanic waters, where questionable or likely erroneous R_{rs} spectra are shown to be well identifiable with this QA system. Our results suggest that applications of this QA system to in situ data sets can improve the development and validation of bio-optical algorithms and its application to ocean color satellite data can improve the short-term and long-term products by objectively excluding questionable R_{rs} data.

1. Introduction

Remote-sensing reflectance (R_{rs}, units: sr^{-1}) is defined as the ratio of water-leaving radiance (L_w, units: µW cm^{-2} sr^{-1} nm^{-1}) to downwelling irradiance just above the surface (E_s, units: µW cm^{-2} nm^{-1}). R_{rs} is a critical optical property for deriving water's optical and biogeochemical properties that include chlorophyll *a* concentration [*O'Reilly et al.*, 1998], colored dissolved organic material (CDOM) absorption coefficient and particulate backscattering coefficient [*IOCCG*, 2006; *Lee et al.*, 2002; *Mannino et al.*, 2008; *Wei and Lee*, 2015], etc. Reliable retrieval and appropriate interpretation of these properties, to the first order, demand accurate R_{rs} data.

R_{rs} cannot be directly measured in the field or obtained remotely, rather derived from two properties (L_w and E_s) obtained independently. Errors in R_{rs} data from field measurements can be related to instrument platforms, strategies of deployment, data processing as well as the ambient environments [*Bailey et al.*, 2008; *Hooker et al.*, 2002; *Mueller et al.*, 2003; *Toole et al.*, 2000; *Zibordi et al.*, 2002]. The in-water approach measures the in-water downwelling irradiance (E_d, units: µW cm^{-2} nm^{-1}) and upwelling radiance (L_u, units: µW cm^{-2} sr^{-1} nm^{-1}) separately, and then the in-water radiance is propagated to right above the water surface to obtain the water-leaving radiance. The known sources of measurement uncertainty could originate from instrument calibrations [*Bailey et al.*, 2008; *Wei et al.*, 2012], instrument self-shading effect [*Gordon and Ding*, 1992], wave-focusing effects [*Wei et al.*, 2014; *Zibordi et al.*, 2004], propagation of L_u(z) to L_w [*Wei et al.*, 2015], and reflection or shading noise from the ship hull. On the other hand, R_{rs} data from the above-water approach are likely subject to uncertainties due to sea surface reflection [*Lee et al.*, 2010a; *Mobley*, 1999], bidirectional reflectance distribution function (BRDF) [*Lee et al.*, 2011; *Morel and Gentili*, 1996; *Voss and Morel*, 2005], sky cloudiness, sun glints, and white caps [*Gordon and Wang*, 1994a]. The skylight-blocked approach (SBA) [*Lee et al.*, 2013; *Tanaka and Sasaki*, 2006] can directly measure L_w (then R_{rs}), but to some degree it is also subject to self-shading error. In addition to these systematic errors, there are likely unidentified errors and uncertainties or artifacts during field observations resulted from uncontrollable field environment.

Visibility: How Applicable is the Century-Old Koschmieder Model?

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(Manuscript received 31 March 2016, in final form 23 August 2016)

ABSTRACT

Koschmieder proposed that visibility is inversely proportional to the extinction coefficient of air, and this model has been widely adopted during the past century. Using radiative transfer theory, the authors present a general relationship for the law of contrast reduction and point out that the Koschmieder model is workable only to situations when a common-size object can be viewed tens of kilometers away. However, the Koschmieder model is not applicable for viewable distances of hundreds of meters when the angular dimension of an object is significantly greater than the eye resolution of the human being. The authors further separate the term "visible" into "simple detection" or "detectability" and "clear identification" or "identifiability" and point out that the Koschmieder model is applicable to identifiability, but not necessarily for detectability. In addition, the way of calculating contrast is revised to follow the concept of brightness constancy. The results of this effort advocate the measurement and distribution of detectability in harsh weather conditions, as such data offer more useful and important information for daily life.

1. Introduction

Our lives are strongly dependent on information, big or small, aged or new, because it forms the basis of sound decision-making. We use a suite of advanced technologies and instruments, from microscopic to macroscopic, to collect a broad range of information from human activities to the Earth system. However, our eye–brain system, the oldest "imaging instrument," is still the most used and indispensable in our daily lives. With this system, events or objects are constantly observed and whether an object is visible or not impacts decision-making and management. Subsequently, the term "visibility" has been used to provide a quantitative representation of this information throughout the past decades.

However, there is no unified definition of visibility, although it is usually referred to as the distance of "an object will be just *visible*" (Duntley 1948b, p. 237; Malm et al. 1980; Middleton 1947), as adopted by the International Civil Aviation Authority (ICAA). On the other hand, the World Meteorological Organization (WMO) defines visibility as "the length of path in the atmosphere required to reduce the luminosity of a collimated beam to 5% of its original value." Apparently, the former definition involves human perceptions, while the latter is simply a measure of atmospheric properties without human involvement. Consequently, the two visibility measurements may not provide consistent results.

During daylight hours (or the photopic regime), the visibility of an object to our eyes depends on a host of factors (Duntley 1948b). For instance, if an object is too small (i.e., smaller than the resolution of our eyes), then it is not perceivable. Similarly, if the object's color and brightness are similar to the background (e.g., creatures with camouflage capabilities), then it is also not (or hardly) visible. If the medium (air or water) is murky (e.g., dense fog or severe dust storms), then an object will also be imperceptibly visible even at close distances. With a focus on the quality of the medium and to have visual ranges observed at different times or at different locations comparable (Dabberdt and Eigsti 1981; Doyle and Dorling 2002; Ma et al. 2011; Majewski et al. 2015), visibility V_{cvt} (km) in the classical visibility theory

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附表 2

国家重点研发计划课题中期执行情况信息表

一、课题基本情况

课题名称	海洋典型生态系统固碳过程与浮游植物群落结构		
课题编号	2016YFA0601201		
密级	☑公开 □秘密 □机密 □绝密		
课题承担单位	厦门大学	单位性质	大专院校
课题负责人	黄邦钦	参加单位数	1
课题类型	☑基础前沿 □重大共性关键技术 □应用示范 □其他		
课题进展情况	☑按计划进行 □进度超前 □进度拖延 □进度停顿 □申请调整或撤消		
与项目内其他课题/ 应用单位/企业合作 状况	☑信息交流 □技术咨询 □研发合作 □成果转化 □实现产业化		
课题实施情况	☑达到预期指标 □超过预期指标 □未达到预期指标		

二、课题中期经费及人员投入情况（经费单位：万元）

总经费			专项经费					自筹经费		
预算数		到位数	预算数	到位数	是否按计划拨付课题承担单位		执行数	预算数	到位数	执行数
1260.00		378.00	1260.00	378.00			368.66			
总人数	其中女性	高级职称	中级职称	初职称级	其他人员	博士	硕士	学士	其他学历	总人年
25	5	4	1	1	3	6	10	9	0	27
人才情况	院士	千人计划	万人计划	百人计划	长江学者	青年长江学者	杰青	优青	海外引进人才数	
	0	1	0	0	0	0	1	0	0	

三、课题中期目标及考核指标完成情况

课题目标	成果 名称	成果类型	考核指标				考核方式（方法）及评价手段	中期实际 完成指标 状态
			指标名称	立项时已有指标值/状态	中期指标值/状态	完成时指标值/状态		
通过开展现场观测和甲板模拟实验，阐明浮游植物群落结构变化对固碳的调控作用及其生理生态学机制；构建基于不同类群浮游植物光合作用量子系数的新型海洋初级生产力遥感算法，提高固碳估算的准确度；结合现场观测、生物光学浮标（Bio-Argo）与水下滑翔机（Glider）原位观测和卫星遥感观测，阐明南海浮游植物类群组成和固碳在不同空间和时间尺度上的演变特征及其调控机制，揭示海洋生态系统固碳的多时空调控机制。	1：海洋生态系统固碳和储碳过程的调控机制 …	☑新理论 □新原理 □新产品 □新技术 ☑新方法 □关键 部件 □数据库 □软件 □应用解决方案 □实验装置/系统 □临床指南/规范 □工程工艺 □标准 ☑论文 □发明 专利 □其他__________	指标 1.1 海洋生态系统固碳的调控机制	对边缘海浮游植物群落结构在中尺度和亚中尺度物理过程的响应机制认识不足； 现行基于叶绿素的海洋固碳遥感模型存在较大问题，也缺乏分粒级和分类群的算法	阐明中尺度物理过程对边缘海浮游植物群落结构的影响； 建立基于光吸收的不同粒级浮游植物固碳遥感模型,构建适用于南海的分类群浮游植物遥感反演算法； 发表论文6-8 篇。	提升对浮游植物群落结构和固碳调控机制的认识； 发展基于光吸收的新型海洋固碳遥感算法； 提升对固碳在不同时空尺度的变化和调控机制的认识； 发表论文15-20 篇； 提交遥感产品数据库。	论文 方法 数据库	较为系统地阐明了中国主要边缘海-南海和东海浮游植物群落主要类群的时空格局、微微型真核生物丰富种与稀少种的生态位特征和调控机制；阐释了南海浮游植物群落对中尺度暖涡的响应及其生态效应； 利用群体生态学方法揭示全球变化对边缘海浮游植物群落演替的潜在影响及其机制； 阐明了南海海盆优势浮游植物类群-原绿球藻的光合作用能量分配比，初步揭示不同类群浮游植物光利用特性，为发展新型海洋固碳遥感算法奠定良好的基础； 初步发展了一些利用海色卫星和生地化剖面漂流浮标研究浮游植物类群和评估海洋生态系统固碳的方法； 发表论文 16 篇，其中 SCI 收录 15 篇，第一标注 11 篇。

科技报告考核指标	序号	报告类型	数量	提交时间	公开类别及时限	是否按计划提交科技报告
	1	年度执行情况报告	1	2017 年 12 月	延期 3 年公	是
	2	中期执行情况报告	1	2018 年 8 月	延期 3 年公	是

其他目标与考核指标完成情况	

四、课题中期实现经济社会效益情况

获得企业标准数			获得行业标准数		
获得国家标准数			获得国际标准数		
申请发明专利项数		1	获得授权发明专利项数		
其中国外			其中国外		
申请其他各类专利项数			获得授权其他各类专利项数		
其中国外			其中国外		
毕业研究生数		6	发表科技论文数		16
其中博士生		2	其中 SCI、EI 收录数		15
取得软件著作权数			出版专著数		
取得的新理论、新原理数			取得的新技术、新工艺、新方法数		1
取得的新产品、新品种、新装置 数			示范、推广面积数（亩）		
获得新药（医疗器械）证书数、临床批件数			获得临床指南、规范数		
新建生产线数			新建示范工程数		
培训农民数			培训技术人员数		
获得国家级科技奖励数			获得省部级科技奖励数		
成果转让数（项）		成果创产值(万)		成果创税收(万)	
成果转让收入(万)		成果创利润(万)		成果创出口额(万)	