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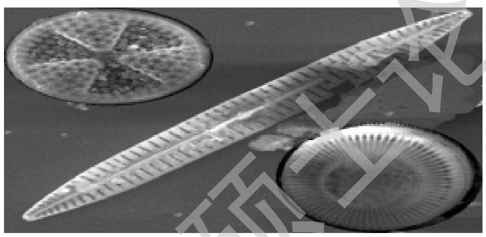
DECADAL CHANGE IN DIATOM AND OTHER SILICEOUS ALGAE PRODUCTION AND CARBON CONTENTS IN EAST CHINA SEA AND SOUTH CHINA SEA, CHINA



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Abstract

It has been decades that climate change becomes a major issue in scientific communities. Scientists have been trying to elucidate the climate change and its impact on the ecological stability and its direct and indirect influence on human lively hood, however, due to its complexity and erratic way of species responses, it has not been easy to show the reaction of ecosystems. Diatoms are eukaryotic algae that have been commonly used as environmental change indicator species due to its well preserving cell wall in the sediment and immediate reaction to environmental changes. The abundance and compositions of diatoms intrinsically linked to changes in the thermal–physical dynamics of nutrients and light in the water column. Consequently, for the last couple of decades diatom has been used to analyse past climate change and future predictions. Thus, this thesis focuses on the impact of recent climate changes and anthropogenic impact and its consequent implication on two large marginal seas of Western north Pacific Ocean, East China Sea (ECS) and South China Sea (SCS). In order to study recent (decadal and interdecadal) climate change and anthropogenic pressure and its consequent implication on biological productions three sediment cores; core QD21a, core DH3-5 and core DH5-3 of 48cm, 22cm and 47cm were collected from Leizhou Peninsula of SCS, mid shelf of ECS and inner shelf of ECS at location of N 20^{o}85.765` and E $111^{o}$18.16833`, 29°59.981′N and 124°30.0848′E， and N 28°26.1591′and E 122°11.0745′, respectively. After collection and arrival at laboratory, each sediment core sample was sliced in to every two centimeter interval and approximately 0.5 cm of the outer rim of each sediment slab was trimmed off to minimize contamination between layers then stored under refrigerator ($-20^{o}C$) until next laboratory analyses. Basically, diatom species composition, diatom abundance (in valve/g dry weight sediment, v/gdw), diatom frustule dissolution index (F_i), ratio of relative planktonic diatom abundance to total diatom abundance (Plan:Tabn), total organic carbon (TOC) content, total nitrogen (TN) content and molar TOC:TN ratio were investigated for all of the three sediment core samples. Additionally, nutrient concentration and pigment signature of ECS inner shelf sediment core were analysed. At the same time various regional and local climatic variable indices such as Pacific Decadal Oscillation (PDO) index, El Niño Southern Oscillation (ENSO) index, Western North Pacific Summer Monsoon (WNPM) index and East Asian Summer Monsoon (EASM) index were investigated to study the correlation between sediment preserved diatom production and climate changes.

Sedimentation rate of Leizhou Peninsula core was 0.53cm^2/g/yr, which shows that each centimeter represent about 2 years and the whole sediment core contains about 90 years of record. Leizhou Peninsula is the most productive site of the three sampling locations regarding to TOC content, whereas inner shelf of ECS has the highest sediment diatom abundance. The observed highest TOC content in Leizhou Peninsula most probably attributed to the fact that it is located in upwelling site. However, for observed diatom abundance and TOC discrepancy between the three cores, other factors such as diatom species-specific/differential preservation and sediment particle size could reasonably create significant variation. On the other hand, inner shelf core of ECS has the highest sedimentation rate, which is attribute to high sediment loading of Yangtze River (YR) and its location more near to shore area. Sedimentation rate of inner shelf ECS core was 0.94cm^2/g/yr, which shows that each centimeter represent about one year and which gives the whole sediment core representing about 47 years of record. Whereas, sedimentation rate of mid shelf ECS core was 0.28cm^2/g/yr, which show each centimeter represent about 4 years and the whole sediment core covers about 79 years of record.

From Leizhou Peninsula core sample, 87 algal taxa belonging to 25 genera were identified, with 25% (20 species) of the species from the genus *Coscinodiscus*. Diatom abundance averaged 16099v/gdw and varied from 2304 to 67788v/gdw. TOC content averaged 0.56% and varied from 0.345% to 0.855%. Generally, TOC showed erratic increment for the last century in decadal scale. The ratio of Plan:Tabn averaged 0.21 and varied from 0.12 to 0.45, with most values are below 0.3, which implies tychoplanktonic or benthic diatoms dominated the diatom assemblage. F index value averaged 0.49 and varied from 0.15 to 0.802, indicating moderate sediment diatom preservation. However, similar to inner shelf and mid shelf ECS sediment core, dominant and bloom forming but weakly silicified and fragile species such as *Skeletonema* and *Rhizosolenia* are totally disappeared from sediment. These indicate species-specific or differential frustule dissolution is a very crucial factor that determines quantity (abundance) and quality (type of species) of sediment preserved diatoms in both SCS and ECS. For the period after 1960`s, diatom abundance increased coinciding with increased ratio of Plan:Tabn and increased F index. These and the co-occurrence of observed larger diatom *Cyclotella striata* and other large diatom species endowed with robust frustule after 1960`s suggest that the climate change occurred after 1960`s through increasing of SST most probably have had significant role to decrease preservation of small sized diatoms. On the other hand, the distinct encroachment of warm, tropical and productivity indicative species, *Thalassionema nitzschioides*, and the sharp decrement of *C.striata* after 1960`s is the reflection of East Asian marginal seas response to 1970`s regime shift that were recorded all over the world. TOC:TN molar ratio averaged 7.1 and varied from 5.45 to 9.06, showing dominance of oceanic or autochthonous primary production.

From mid shelf sediment core of ECS, a total of 85 algal taxa belonging to 25 genera were identified, with 30% (25 species) of the species from the genus *Coscinodiscus*. Absolute diatom abundance averaged 15940v/gdw and varied from 476v/gdw to 77910v/gdw. TOC averaged 0.33% and varied from 0.19% to 0.42%. Total nitrogen averaged 0.063% and varied from 0.049% to 0.08%. TOC:TN (molar weight) ratio averaged 6.47 and varied from 2.74 to 9, showing sediment preserved organic matter predominantly originated from oceanic production, while the lower boundary indicate the presence of organic matter degradation.

From inner shelf sediment core of ECS, 135 algal taxa belonging to 37 genera were identified, with 23% (30 species) of the species from the genus *Coscinodiscus*. *Coscinodiscus* was the most dominant genus preceded by *Pleurosigma*, *Trachyneis* and *Nitzschia*. Diatom absolute abundance averaged 78073v/gdw and showed irregular variation with depth varying from 40902v/gdw to 144770v/gdw. The patterns of ENSO and PDO changed clearly during the year 1976/1977. Similarly, normalized diatom abundance showed more or less similar patterns with ENSO and PDO, indicating that these two regional climate variables together with Western North Pacific Summer Monsoon (WNPM) and East Asian Summer Monsoon (EASM) had greater influence on modulating diatom/phytoplankton abundance and species composition. TWINSPAN showed there were three distinct periods where diatom assemblages that may be explained by changes in the extent and intensity of anthropogenic and climatic pressures. These three periods were, prior to 1982, between 1982 and 2002, and after 2002. Diatom species like *Thalassiothrix longisima*, *Chaetoceros* spp., *Cyclotella striata* and *Coscinodiscus radiatus* dramatically decreased starting from 2004 together with the decrease of nutrients like Aluminum (Al), Iron (Fe), extractable phosphorus (P) and total phosphorus (TP) and ratio of TOC:TN. Whereas, *Thalassionema nitzschioides*, *Paralia sulcata* and *Tryblioptychus cocconeiformis* noticeably increased after 2002. TOC:TN (molar weight) ratio averaged 4.54 and varied from 1.92 to 6.37, showing both the dominance of ocean produced organic matter and high degree of degradation. F index ranges from 0.516 to 0.92 averaging 0.7. Generally, the F index evaluated for the whole assemblages showed good preservation of diatom valve. Relatively better diatom preservation were observed from 2002 to 2011 and from 1964 to 1978. After 2002 TOC:TN together with P, TP, Al and Fe rapidly decrease which was probably related to Three Gorges Dam (TGD) construction. Similarly, for the period after 2000, diatom abundance and almost all identified pigment signatures increased, possibly due to both decreased sediment and freshwater input from YR due TGD construction, which ultimately increase light availability.

Peridinin, a pigment mainly harbored by dinoflagellates, increased after 1980`s in conjunction with prevailed warm phase and increased SST. Generally, in decadal scale, the relative production of dinoflagellate pigment to chlorophyll-*a* has been increasing for the last five decades. Fucoxanthin, diatom indicator pigment, showed no significant increment before and after 1980`s, however, its concentration dramatically increased after 2002. Similarly, the concentration of all pigments drastically increased for the period after 2002, that coincides with prevailed warm phase and TGD constructions, which presumably blocked considerable amount of sediment particles otherwise that had been precluding phytoplankton light availability. Furthermore, the impact of TGD construction reflected by significant increment of mean Chl-*a* concentration from 5.39 to 25.76 for the period 1980-2000 to 2002-2011, showing increment by 377%. For the same period mean phytoplankton carbon increased from 0.245 to 1.03, showing increment by 320%. The F index showed that diatom dissolution is important factor that determine the quantity and quality of diatom community, thus any further studies in the application of diatom frustule in these two seas environmental assessment would be much better to consider diatom dissolution.

One species of Protozoa , *Pinaciophora marina* cfwas identified, which is belong to Choanozoa (Phylum), Cristidiscoidea (Class), Nucleariida (Order), Nucleariidae (Family), Pinaciophora (Genus), and it is a new to China`s microplankton taxon record. Silicoflagellates were very rare for mid shelf and Leizhou Peninsula sediments, however their abundance in inner shelf of ECS sediment was relatively higher. Thus, this thesis focuses on the analyses of silicoflagellates from inner shelf of ECS. Silicoflagellates represented by four species, from which *Dictyocha fibula* and *Octactis speculum* are the dominant. The total abundance of silicoflagellates averaged 1423 v/gdw and varied from 144v/gdw to 3668 v/gdw. Generally, their abundance follows the long-term pattern of diatom abundance, implying the two taxon responding to the environment in similar manner.

Key words: Benthic diatom, dissolution index, East China Sea, planktonic diatoms, primary productivity, South China Sea

摘要 (Abstract in Chinese)

近几十年来，气候变化始终是科学界的一个主要议题。科学家一直在尝试解释气候变化这一现象，阐明其对生态稳定性以及直接和间接地对人类活动造成的影响。然而，由于生态系统的复杂性和不稳定的物种响应方式，要准确阐明生态系统对气候变化的响应并不容易。硅藻是一种真核浮游藻类，由于其细胞壁能在沉积物中保存以及其对环境变化的即时反应，常被作为环境变化的指示物种。硅藻的丰度和种类组成与水体中营养盐以及光照的热物动力学变化具有内在联系。因此，在过去的几十年中，硅藻被用于以往气候变化的分析以及未来气候的预测。本文主要研究了近年来的气候变化和人类活动对北太平洋西部两大边缘海域所造成的影响。分别从中国南海的雷州半岛（N 20º85.765`，E 111º18.16833`）、东海的中陆架（N 29°59.981′，E 124°30.0848′）和内陆架（N 28°26.1591′，E 122°11.0745′）采集了三个沉积物柱样 QD21a, DH3-5 以及 DH5-3，样品长度分别为 48cm，22cm，47cm。在实验室将柱样每隔 2cm 分层切段，每层在环面的边缘切下约 0.5cm 舍去，以减少层间污染，储存于-20 ℃冰箱中待用。首先，分析获得三个柱样的硅藻种类组成，硅藻丰度（细胞/克沉积物干重，v/gdw），硅质壁溶解指数（Fi），浮游硅藻相对丰度与硅藻总丰度之比（Plan:Tabn），总有机碳（TOC）含量，总氮（TN）含量，TOC 与 TN 摩尔比等基础数据；其次，对东海内陆架的沉积物样品进行营养盐浓度和色素特征分析。同时，还对不同地区的气候变量指数，例如，太平洋年代际振荡（PDO）指数，厄尔尼诺南方振荡（ENSO）指数，西北太平洋夏季季风（WNPM）指数以及东亚夏季季风（EASM）指数等进行了研究，以得到沉积物硅藻与气候变化之间的相互关系。

雷州半岛柱样的沉降速率是 0.53 cm^2/g/yr，这表明每 1cm 大约代表 2 年，整个柱样记录了大约 90 年。就 TOC 含量而言，雷州半岛是三个采样地点中最具生产力的，而东海内陆架具有最高丰度的沉积物硅藻。雷州半岛最高的 TOC 含量很可能与其地处上升流有关。硅藻物种特异性/硅质壳保存程度以及沉积物粒度等其他因素则可能造成三个柱样间硅藻丰度和 TOC 含量的差异。另一方面，东海内陆架的柱样沉降速率最快是由于长江的高泥沙装载以及较为近岸的地理位置。东海内陆架的柱样的沉降速率是 0.94 cm^2/g/yr，这表明每 1cm 大约代表 1 年，整个柱样记录了大约 47 年。东海中陆架的柱样的沉降速率是 0.28 cm^2/g/yr，这表明每 1cm 大约代表 4 年，整个柱样记录了大约 79 年。

雷州半岛的柱样中，经鉴定得到硅藻 25 属 87 种，其中 25%（20 种）的种类属于圆筛藻属。硅藻丰度为 2304 到 67788 v/gdw，平均 16099 v/gdw。TOC 含量为 0.345% 到 0.855%，平均 0.56%。TOC 含量在上个世纪呈现不平稳的年际增长趋势。Plan:Tabn 比为 0.12 到 0.45，平均 0.21。大多数 Plan:Tabn 比值低于 0.3，这表明附着/底栖硅藻占优势地位。F 指数为 0.15 到 0.802，平均 0.49，这表明沉积物中保存完整的硅藻约占一半。与东海内陆架和中陆架的柱样相似，在雷州半岛的沉积物中完全没有发现硅质化程度较弱的赤潮种骨条藻（*Skeletonema*）和根管藻（*Rhizosolenia*）。这表明物种或硅质壁溶解的特异性是影响南海和东海沉积物硅藻丰度及种类组成的重要因素。20 世纪 60 年代以后，随着 Plan:Tabn 比和 F 指数的上升，硅藻丰度也在不断上升，还能检测到一些具有厚硅质壁的较大的硅藻细胞如条纹小环藻（*Cyclotella striata*）。这些现象表明，20 世纪 60 年代以后气候发生了变

化。最有可能是由于海表温度（SST）的升高而造成了小个体硅藻的减少。另一方面，温热带生产力指示种，菱形海线藻（*Thalassionema nitzschioides*）的大量出现以及条纹小环藻（*C.striata*）的锐减反映了东亚陆缘海对于 70 年代全球稳态转换的响应。TOC/TN 摩尔比为 5.45 到 9.06，平均 7.1，这表明了海洋或原始初级生产的主导地位。

东海中陆架的柱样中，共鉴定得到硅藻 25 属 85 种，其中 30%（25 种）的种类属于圆筛藻属。硅藻绝对丰度为 476 到 77910 v/gdw，平均 15940 v/gdw。TOC 含量为 0.19% 到 0.42%，平均 0.33%。总氮含量为 0.049%到 0.08%，平均 0.063%。TOC/TN（分子量）比为 2.74 到 9，平均 6.47，这表明沉积物中的有机物主要来源于海洋生产，而较低的下限则说明了有机物降解的存在。

从东海内陆架的柱样中，共鉴定到硅藻 37 属 135 种，其中 23%（30 种）的种类属于圆筛藻属。圆筛藻属超过了斜纹藻、粗纹藻、菱形藻等属，占据最优势地位。硅藻绝对丰度随深度呈不规则变化，为 40902 到 144770 v/gdw，平均 78073 v/gdw。ENSO 指数和 PDO 指数的模型在 1976-1977 年间发生了明显变化。同样，硅藻的标准丰度或多或少显示出了与 ENSO 指数和 PDO 指数模型的相似性，这表明 ENSO、PDO、WNPM 以及 EASM 这几个区域气候变量对硅藻/浮游植物丰度和种类组成的调节具有较大影响。TWINSPAN 分析结果表明，硅藻集群可以分为三个不同时期，这可能是由人类活动范围和强度的变化以及气候的压力造成的。这三个时期分别是：1982 年之前，1982-2002 年之间以及 2002 年之后。从 2004 年开始，伴随着铝、铁、磷等营养盐以及 TOC/TN 比的降低，某些硅藻急剧减少，如长海毛藻（*Thalassiothrix longisima*），角毛藻（*Chaetoceros* spp.），条纹小环藻（*Cyclotella striata*），辐射列圆筛藻（*Coscinodiscus radiatus*）等。然而，菱形海线藻（*Thalassionema nitzschioides*），具槽帕拉藻（*Paralia sulcata*）以及卵形褶盘藻（*Tryblioptychus cocconeiformis*）在 2002 年之后却显著增多。TOC/TN 比值（分子量）为 1.92 到 6.37，平均 4.54，这表明了海洋生产有机物的主导地位以及高度的有机物降解。F 指数为 0.516 到 0.92，平均 0.7，这表明硅藻细胞壁保存得较为完好。2002-2011 年以及 1964-1978 年之间，硅藻细胞壁保存得相对较好。2002 年之后，TOC/TN 比以及磷、铝、铁等营养急剧降低，这很可能与三峡大坝的建设有关。同样，2000 年之后的这段时期，硅藻丰度以及几乎所有色素的浓度都在升高，这可能是由于三峡大坝的建设造成了来自长江的沉积物和淡水输入的减少，从而最终导致了可用光的升高。

多甲藻素是一种主要的甲藻色素。20 世纪 80 年代之后，随着暖期的来临和海表温度的升高，多甲藻素逐渐增多；在过去的五年中，甲藻色素相对于叶绿素 a 呈上升趋势。墨角藻黄素是一种硅藻指示色素；在 20 世纪 80 年代前后，墨角藻黄素都没有明显的增多，而在 2002 年之后，浓度却急剧升高。同样，所有色素的浓度在 2002 年之后的这段时期都大幅升高。这与暖期的来临以及三峡大坝的建设发生在同一时期，很可能因此封堵了大量本会造成浮游植物可用光受阻的沉积物颗粒。此外，叶绿素 a 的平均浓度从 1980-2000 年

这段时期的 5.39 显著升高到了 2002-2011 年这段时期的 25.76，升高了 377%，这也反映了建设三峡大坝的影响。同一时期，浮游植物的平均碳含量从 0.245 升高到 1.03，升高了 320%。F 指数表明硅藻硅质壳的溶解是确定硅藻群落质（种类组成）和量（细胞数）的重要因素，因此，将硅藻溶解这一因素纳入考虑范畴，对于进一步将硅质壁应用于这两个海洋环境的评估来说是很重要的。

经鉴定得到原生动物界、Choanozoa 门、Cristidiscoidea 纲、Nucleariida 目、Nucleariidae 科、Pinaciophora 属中的 1 个中国新纪录种 *Pinaciophora marina* cf。硅鞭藻在中陆架和雷州半岛的沉积物中极少见到，而在内陆架的沉积物中丰度相对较高。因此，本文主要对内陆架沉积物中的硅鞭藻进行分析。硅鞭藻主要包括 4 个种，其中小等刺硅鞭藻（*Dictyocha fibula*）和 *Octactis speculum* 占优势地位。硅鞭藻的总丰度为 144 到 3668 v/gdw，平均 1423 v/gdw。硅鞭藻的丰度通常遵循硅藻丰度的长周期模式，这表明这两种藻对于环境具有相似的响应方式。

关键词：底栖硅藻， 溶蚀度指数，东海，浮游硅藻，初级生产力，南海

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List Abbreviation/symbols

β-car……………………………………………………β-carotene

CCD……………………………………………………Carbonate Compensation Depth

CJCW………………………………………….Changjiang (i.e., the Yangtze River) Cold Water

CRS…………………………………………………….Constant Sedimentation Rate

Chl-*a* and TChl-*a*……………………………………Chlorophyll-*a* and total Chlorophyll-*a*

DCA…………………………………………………….Deterended Correspondence Analysis

DMF……………………………………….......N,N-dimethyl ammonium naphthalene acetic acid

D and DD……………………………………….Diatoxanthin and Diadinoxanthin

ECS…………………………………………………...East China Sea

EASM…………………………………………….…...East Asian Summer Monsoon

Eqn………………………………………………….….Equation

ENSO…………………………………………………..El Niño Southern Oscillation

ECSCC………………………………………………...ECS Coastal Current

Fuc………..…………………………………………... Fucoxanthin

HAB…………………………………………………….Harmful Algal Blooms

HPLC…………………………………………………High Performance Liquid Chromatography

ITCZ…………………………………………………..Intertropical Convergence Zone

KC……………………………………………………Kuroshio Current

MEI…………………………………………………..Multivariate ENSO Index

NAO…………………………………………………North Atlantic Oscillation

NCEP……………………. National Centers for Environmental Prediction/Department of Energy

NOAA/CDC.. ……………………………..National Oceanic and Atmospheric Administration

P and TP………………………………………Extractable and Total Phosphorus, respectively

PDO…………………………………………………..Pacific Decadal Oscillation

Per …………………………………………………… Peridinin

Plan:Tabn……………………………Relative abundance of planktonic diatom:total abundance

RDA……………………………………………………Redundancy Analysis

SCS …………………………………………………South China Sea

SCSSM…………………………………………………South China Sea summer monsoon

SSP…………………………………………………… Sea Surface Pressure

SST……………………………………………………Sea Surface Temperature

TCD …………………………………………………...Total Diatom Carotenoid

TC, TN and TOC ……………………………..Total Carbon, Total Nitrogen, and Total Organic carbon, respectively

TWC…………………………………………………………...Taiwan Warm Current

WPWP …………………………………………………….Western Pacific Warm Pool

WNPM……………………………………………………Western North Pacific Monsoon

YRE………………………………………………………Yangtze River Estuary