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MODIS-based Monthly Dataset of Particulate Organic Carbon Flux in the Bottom of the Global Ocean Euphotic Layer (2003–2018)

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Abstract: The research on the flux of particulate organic carbon (POC) in the bottom of ocean euphotic layer is of great significance for understanding and evaluating ocean organic carbon pumps and ocean carbon cycles. POC flux is the product of e-ratio and net primary production (NPP). The accuracy of seven classic e-ratio estimation models was first evaluated by using the *in situ* POC flux and NPP products in this paper. Then the e-ratio of global ocean from 2003 to 2018 was calculated with the estimation model established by Dunne (2005a) and the monthly MODIS products with a spatial resolution of 9 km, which include sea surface temperature (SST), Chlorophyll concentration (Chl) and euphotic zone depth (Zeu). On this basis, we developed a MODIS-based monthly dataset of POC flux in the bottom of the global ocean euphotic layer (2003-2018) combined with the marine NPP data of Tao *et al*. (2019). This dataset is monthly data with a spatial resolution of 9 km. Each data file includes two parameters, poc_flux and pe_ratio, the former is POC flux and the latter is e-ratio. The dataset is stored in '.hdf' format and consists of 192 files, with a data volume of 13.3 GB (compressed into 16 files, 4.48 GB).

Keywords: global ocean; particulate organic carbon flux; monthly data

Dataset Availability Statement:

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb.2020.09.02.V1.

1 Introduction

In the ocean, the transfer of carbon from the surface to the deep water mainly includes physical process and biological process, among which the biological process is called marine biological carbon pump (BCP)[1]. BCP not only has profound influence in regulating global atmospheric CO_2, but also is an important indicator for studying global carbon cy-

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cle[2]. The flux of particulate organic carbon (POC flux) in the bottom of the ocean euphotic layer directly reflects the efficiency of BCP[3], therefore, one of the most important methods for studying BCP is to measure POC flux. Traditional methods for measuring POC flux include the sedimentation trap method[4] and radioisotope ^{234}Th decay method[5], but the high cost and complicated instrument operations make these methods unable to obtain long time series *in-situ* POC flux of global ocean. In addition, some ecosystem models and earth system models are emerged by researchers to estimate POC flux[6,7], which have made constructive contributions for understanding the internal mechanism of POC flux. However, calculating continuous POC flux simulation data on a global scale requires lots of *in-situ* and auxiliary data as input, which is difficult to obtain. The large-scale observation and short revisit period characteristics of satellite remote sensing enable continuous observation of global ocean. Early studies have shown that the ratio of the output POC flux in the bottom of the ocean euphotic layer to net primary production (NPP) is similar to the ratio of "new productivity" to "total productivity"[8,9], which directly links POC flux to NPP, and provides a new approach to estimating POC flux based on remote sensing satellites.

Based on remote sensing data such as sea surface temperature (SST), Chlorophyll concentration (Chl), euphotic zone depth (Zeu) and etc., researchers have developed a series of models for estimating e-ratio to calculate the global ocean POC flux[9–13]. At present, the research on the temporal and spatial variations of POC flux is mostly concentrated on local waters such as the Indian Ocean, the South Ocean and the Pacific Ocean, and the analysis of long time series POC flux of global ocean is insufficient. To provide basic data for the study of long time series global ocean POC flux, we developed a monthly dataset of POC flux in the bottom of global ocean euphotic layer from 2003 to 2018. First, the performance of several classic POC flux estimation models was evaluated by using the *in-situ* POC flux and NPP products in this paper. Then, the best estimation method was selected to calculated global ocean POC flux combined with the MODIS products data and the NPP product data.

2 Metadata of the Dataset

The metadata of the MODIS-based monthly dataset of POC Flux in the bottom of the global ocean euphotic layer (2003–2018)[14] is summarized in Table 1. It includes the dataset full name, short name, authors, year of the dataset, temporal resolution, spatial resolution, data format, data size, data files, data publisher, and data sharing policy, etc.

3 Methods

3.1 Data Sources

The source data includes the remote sensing data and the *in-situ* POC flux data. The remote sensing data includes MODIS products such as SST, Chl and Zeu, as well as the NPP products produced based on three model of VGPM[16], CbPM[17] and SAbPM[18]. All the products are global ocean monthly data from January 2003 to December 2018 with a spatial resolution of 9 km. The *in-situ* POC flux data include the data measured in the Hawaii site (HOT), the Bermuda site (BATS), the Beaufort Sea and the East China Sea[19–21]. A total of 285 POC flux *in-situ* data were collected at different water depths from 2003 to 2016. After data preprocessing and satellite synchronization matching, a total of 230 *in-situ* POC flux data were used as testing dataset, accounting for 80.7% of all *in-situ* data.

Table 1 Metadata Summary of the MODIS-based monthly dataset of POC Flux in the bottom of the global ocean euphotic layer (2003–2018)

Items	Description
Dataset full name	MODIS-based monthly dataset of POC Flux in the bottom of the global ocean euphotic layer (2003–2018)
Dataset short name	GlobalMarinePOC
Authors	Xie, F. T. ABH-7123-2020, Aerospace Information Research Institute, Chinese Academy of Sciences, xieft@radi.ac.cn Zhou, X. L-7359-2016, Aerospace Information Research Institute, Chinese Academy of Sciences, zhouxiang@radi.ac.cn Tao, Z. L-4530-2016, Aerospace Information Research Institute, Chinese Academy of Sciences, taozui@radi.ac.cn Lv, T. T. R-8978-2016, Aerospace Information Research Institute, Chinese Academy of Sciences, lvtt@radi.ac.cn Wang, J. ABH-9051-2020, Aerospace Information Research Institute, Chinese Academy of Sciences, wangjin01@radi.ac.cn Li, R. X. ABH-7136-2020, Aerospace Information Research Institute, Chinese Academy of Sciences, liruoxi19@mails.ucas.ac.cn
Geographical region	Global ocean Year 2003–2018 Temporal resolution Month
Spatial resolution	9 km Data format .hdf Data size 4.48 GB
Data files	Consists of 192 files (compressed into 16 files)
Foundations	Ministry of Science and Technology of P. R. China (2018YFE0124200); Chinese Academy of Sciences (2020)
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing & Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data* & *Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the 'ten per cent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[15]
Communication and searchable system	DOI, DCI, CSCD, WDS/ISC, GEOSS, China GEOSS, Crossref

3.2 Algorithm Principle

POC flux is the product of e-ratio and NPP, so both the accuracy of the e-ratio estimation model and NPP data will affect the estimation results of POC flux. The accuracy of seven classic e-ratio estimation models in Table 2 was first evaluated by using the *in-situ* POC flux and three different NPP products. Since the *in-situ* POC flux were collected from different water depths, and the data calculated by the models is the POC flux in the bottom of the ocean euphotic layer, they cannot be compared directly. We first used the classic POC flux vertical migration formula[22] to convert all POC flux data to the data of 150 m water depth (most of the *in-situ* data were collected at this depth), then compared them and used the logarithmic deviation (Bias), the logarithmic root mean square error (RMSD), coefficient of determination (R^2) and the average relative error (r.e) to evaluate the results[23].

The vertical migration of POC flux is shown in Equation (1), where POC(z) and POC(z_0) are the POC flux at water depth z and z_0, respectively.

$$\mathrm{POC(z)} = \mathrm{POC(z_0)} \times \left(\frac{\mathrm{z}}{\mathrm{z_0}}\right)^{-0.858} \tag{1}$$

Table 2 lists seven classic e-ratio estimation models, in which $\mathrm{Chl_{tot}}$ is the integral of Chl in ocean euphotic layer.

Table 2 Seven classic POC output ratio (e-ratio) estimation models

Author	Model Expression
Baines (1994)	$e-\text{ratio}=10^{-0.67+0.30\times\log10(\text{Chl}_{tot}/\text{Zeu})}$
Laws (2000)	$e-\text{ratio}=0.62-(0.02\times\text{SST})$
Dunne (2005a)	$\text{e}-\text{ratio}=\max(0.04,\min(0.72,-0.0081\times\text{SST}+0.0668\times\ln(\text{Chl}/\text{Zeu})+0.426))$
Dunne (2005b)	$\text{e}-\text{ratio}=\max(0.04,\min(0.72,-0.0101\times\text{SST}+0.0582\times\ln(\text{NPP}/\text{Zeu})+0.419))$
Henson (2011)	$\text{e}-\text{ratio}=0.23\times\text{e}^{(-0.08\times\text{SST})}$
Laws (2011a)	$\text{e}-\text{ratio}=((0.5857-0.0165\times\text{SST})\times\text{NPP})/(51.7+\text{NPP})$
Laws (2011b)	$\text{e}-\text{ratio}=0.04756\times(0.78-(0.43\times\text{SST})/30)\times\text{NPP}^{0.307}$

After evaluation, we found that the POC flux calculated using the e-ratio model of Dunne (2005a)[11] and the NPP data of SAbPM model has the highest accuracy and stability. On this basis, global ocean e-ratio data was calculated by using MODIS' SST, Chl and Zeu products, and then combined with the NPP data published by Tao *et al*.[24], POC flux in the bottom of global ocean euphotic layer was calculated according to Equation (2).

$$\text{POC flux}=\text{e}-\text{ratio}\times\text{NPP} \tag{2}$$

3.3 Technical Route

The technical route of developing the dataset is shown in Figure 1. First, e-ratio of global ocean was calculated by using the MODIS products from 2003 to 2018 according to Dunne (2005a)'s estimation model in Table 2, and then multiplied by the NPP data to obtain the estimation global ocean POC flux. For comparative analysis, both the estimation POC flux and the *in-situ* POC flux were converted to the data of 150 m water depth according to Equation (1), and used the accuracy indicators in section 3.2 to evaluate the accuracy and stability of the estimated POC flux. Finally, the optimal method for estimating POC flux was selected, that is, the combination of the e-ratio estimated by Dunne (2005a)'s model and the NPP data retrieved by the SAbPM model. Using the MODIS products and NPP products from January 2003 to December 2018 as inputs, the MODIS-based monthly dataset of POC flux in the bottom of global ocean euphotic layer was developed.

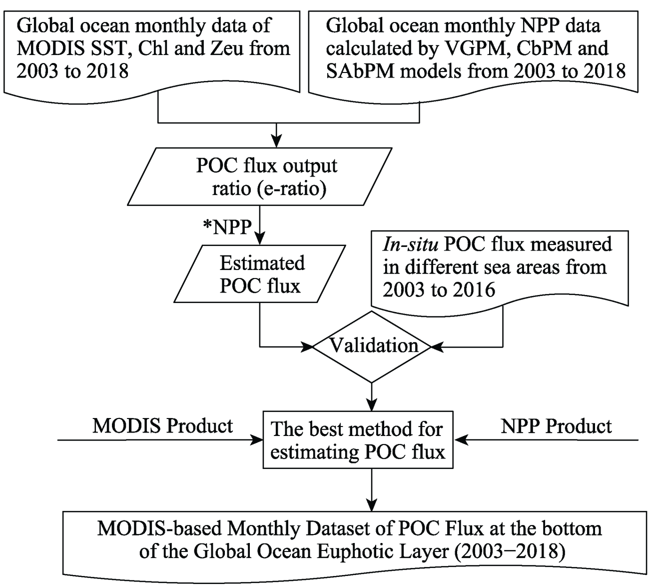

Figure 1 The technical route of developing the dataset

4 Results and Validation

4.1 Data Products

The monthly average data with the spatial resolution of 9 km contains a total of 192 data files from January 2003 to December 2018. Each data file includes

POC_flux and pe_ratio two parameters, the former is POC flux and the latter is e-ratio. The unit of POC flux is mgC·m^{-2}·day^{-1}, and e-ratio has no unit. The data is stored in '.hdf' format, with a total data size of 13.3 GB. The data is compressed into '.zip' format according to different year, that is, a total of 16 compresses files with the data size of 4.48 GB.

4.2 Data Results

From Figure 2, we can see that the global ocean POC flux has different distribution characteristics in different regions. The POC flux in most sea areas is less than 100 mgC·m^{-2}·day^{-1} between 30°N and 30°S, while in high latitude sea areas, the maximum POC flux may exceed 600 mgC·m^{-2}·day^{-1}. In addition, the POC flux in Continental Margins is much higher than the POC flux in Deep Ocean, where Continental Margins refers to the sea areas with a water depth less than 2,000 m, while the water depth of Deep Ocean is greater than 2,000 m. In order to highlight the spatial distribution of POC flux, we have calculated the annual average data of the global ocean POC flux from 2003 to 2018, and analyzed the proportion of POC flux in different latitudes and sea areas to the total global ocean POC flux. The results are shown in Table 3.

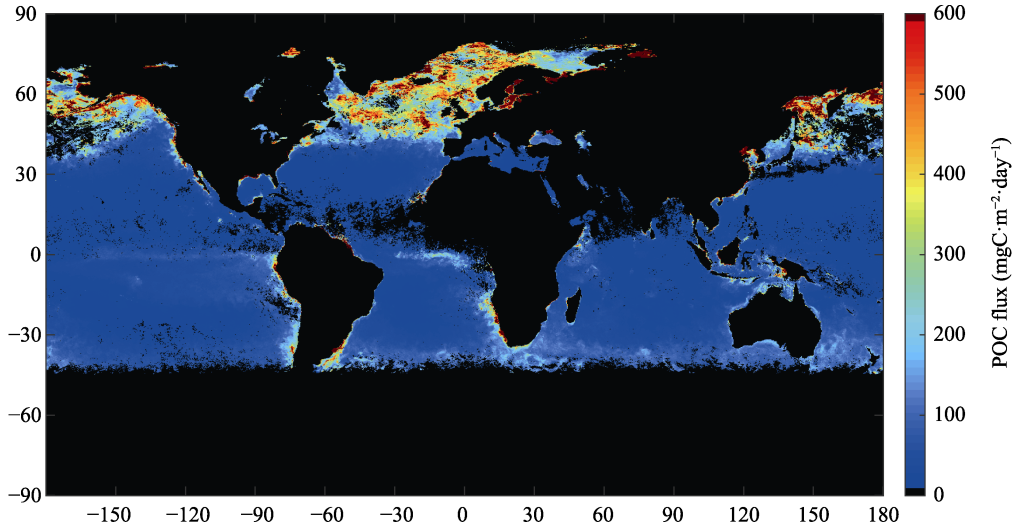

Figure 2 Map of monthly average POC flux in the bottom of global ocean euphotic layer (June 2015)

Table 3 The proportion of POC flux statistics in different latitudes and sea areas

Sea Areas	POC flux
0–30°	28.70%
30–60°	61.00%
60–90°	10.30%
Continental Margins	29.50%
Deep Ocean	70.50%

From Table 3, we found that the annually average amount of POC flux is 11 PgC·m^{-2}·yr^{-1}, where the POC flux in the low latitude (0–30°) sea areas accounts for 28.7% of the total, and the POC flux in the mid latitude (30–60°) sea areas accounts for 61%. It is caused by the difference of e-ratio, the e-ratio of low latitude sea areas is generally low, only about 10%, while the average e-ratio of mid latitude sea areas is more than 30%, and the e-ratio of some continental shelf sea areas is even higher than 50%. In the high latitude (60–90°) sea areas, due to the small ocean area and the freezing period in the north and south poles, the POC flux only accounts for 10.3% of the total. In addition, the POC flux in Deep Ocean accounts for 70.5% of the total, and the POC flux in Continental Margins accounts for 29.5%. Although the area of Continental Margins is about 4.8×10^7 km^2, which is only 1/7 of the global ocean area, the POC flux in Continental Margins accounts for about 1/3 of the global ocean due to the higher e-ratio. It is a non-negligible part of the global ocean carbon cycle and worthwhile for us to conduct more research.

From Figure 3, we found that the POC flux in the bottom of global ocean euphotic layer shows a decreasing trend. We analyzed the changes of POC flux in time scale in the sea areas at latitudes of 0–30°, 30–60° and 60–90°, respectively, and found that in low latitude and mid latitude sea areas, the annually average POC flux decreased year by year, and the rate of descent is faster in low latitude sea areas. In high latitude sea areas, the annually average POC flux is increasing year by year. Global warming led to the area of open waters in the Polar Regions increasing continuously, which explains the continuous increase of POC flux.

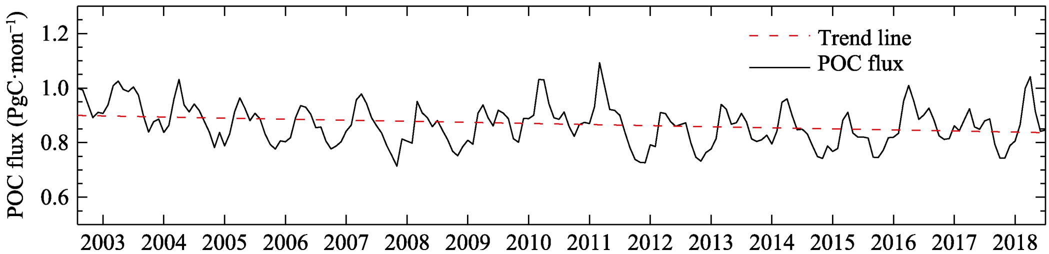

Figure 3 Monthly average POC flux of global ocean from 2003 to 2018

4.3 Data Validation

Compared with the POC flux data calculated by using other e-ratio models and NPP products, the global ocean POC flux estimated by using Dunne (2005a)'s e-ratio model and the NPP product of SAbPM model has the highest accuracy and stability. Among the accuracy indicators, Bias is only –0.01, RMSD is 0.17, R^2 is 0.50 and r.e is 30%. The detailed comparison results of the estimated POC flux with the *in-situ* POC flux can be found in Xie *et al*. (2019)[25]. In addition, the annually average POC flux of global ocean is about 11 PgC·m^{-2}·yr^{-1}. Taking into account the average relative error of the estimation results and the lack of data in polar regions, the annually average POC flux of global ocean calculated in this dataset is about 8.5–14.3 PgC·m^{-2}·yr^{-1}. It is close to the estimation results of most researchers[12, 26–27], which proves that the POC flux dataset developed in this paper is accurate and reliable.

The *in-situ* POC fluxes of HOT and BATS are long time series data from 2003 to 2016, and their temporal changes can be used to clarify the trend of global ocean POC flux. Figure 4 is the scatter plots of the *in-situ* POC flux data in these two sites. From the trend lines and the coefficients of equations in the figure, it can be seen that from 2003 to 2016, the POC flux shows a decreasing trend year by year. It is consistent with the changing trend of the POC flux estimated in this paper, proving that POC flux in this dataset can clearly reflect the change of global ocean POC flux.

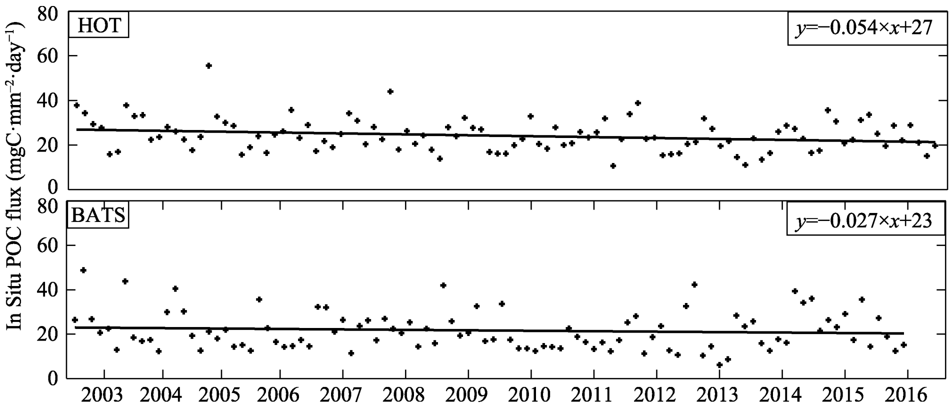

Figure 4 Monthly data of *in-situ* POC flux in HOT and BATS and their changing trend from 2003 to 2016

5 Discussion and Conclusion

BCP is related to the regulation of CO_2 content in the atmosphere, the carbon cycle and carbon balance in the ocean, and POC flux is a key indicator to evaluate the efficiency of BCP. Therefore, the issue on spatial and temporal variations of POC flux is a hot topic that many researchers pay attention to. Based on Dunne (2005a)'s e-ratio estimation model and NPP products provided by Tao *et al.* (2019), this paper developed MODIS-based monthly dataset of POC flux in the bottom of global ocean euphotic layer (2003–2018).

The *in-situ* POC fluxes used in this paper to validate the estimation results are the measured data of long time series observation sites in the equatorial Pacific Ocean (HOT and BATS), as well as some observation data in the East China Sea and the Beaufort Sea. The observation areas cover the low, mid and high latitude sea areas, and the values of *in-situ* data cover the range of high and low values, both of which prove that these i*n-situ* POC flux data are enough to represent the global ocean POC flux. Compared with these *in-situ* POC flux data, the POC flux calculated by using Dunne (2005a)'s e-ratio model and NPP data based on SAbPM model has the highest accuracy and the best stability. In addition, we analyzed the variation of global ocean monthly POC flux from 2003 to 2018, and found that it shows a decreasing trend year by year, which is consistent with the changing trend of the *in-situ* POC flux.

In summary, the MODIS-based monthly dataset of POC flux in the bottom of global ocean euphotic layer (2003–2018) developed in this study provides basic data of a time series of global ocean POC flux, which sould be effectively used to in studying the spatial distribution and temporal variation of global ocean POC flux.

Author Contributions

Zhou, X. and Tao, Z. made the overall design for the development of the dataset. Xie, F. T. and Tao, Z. collected and processed MODIS data, POC flux *in-situ* data and NPP products. Xie, F. T. finished data analysis and validation, all the authors jointly wrote and revised the data paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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