



# Article Satellite Observed Spatial and Temporal Variabilities of Particulate Organic Carbon in the East China Sea

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Abstract: In this study, we investigate spatial and temporal variabilities of particulate organic carbon (POC) in the East China Sea (ECS) and explore the dominant influencing factors for its three subregions—coastal, continental shelf and open sea—by analyzing satellite derived POC from 2001 to 2011 after calibration against in situ samplings. The analysis reveals that the largest POC occurs in spring at the coastal region with a value of 297.5 mg m $^{-3}$ , and the smallest in summer at the open sea region with a value of 108.9 mg m<sup>-3</sup>. POC in the coastal region is dominated by biological activity related to river discharge of nutrients and organic matter, and is regulated by sediment discharge variation due to the Three Gorge Project and chemical fertilizer application along the Changjiang River watershed; the open sea region is dominated by water exchange with the Kuroshio current, which results in the highest sea surface temperature and the lowest chlorophyll and POC among the three subregions; POC in the continental shelf region is driven by the seasonal competition between the influence of the coastal ocean and the Kuroshio current through biological activity and water exchange. A method to estimate the organic matter reserve in the ECS was developed based on satellite data and in situ samplings. Organic carbon storage was estimated at  $4.08 \times 10^{13}$  g, which could be used as a baseline for future estimates. An improved estimation could be found with additional in situ data and with the use of a more sophisticated algorithm for satellite POC analysis.

Keywords: MODIS; POC; Chl-a; SST; organic carbon storage; East China Sea

# 1. Introduction

Marine organic carbon exists in the ocean in two main forms, dissolved organic carbon (DOC) and particulate organic carbon (POC), which account for about 90% and 10% of the total organic carbon, respectively [1,2]. Although POC occupies a smaller proportion, it is the main form of "biological pump", which buries and reserves carbon into the deep ocean and plays an important role in the global carbon cycle of marine systems [3–6].

Previous analyses of major ocean survey data in the 1980s (VERTEX) and 1990s (JGOFS) have demonstrated that the biochemical composition of POC is dynamic and informative [7,8]. Since then, increasingly detailed studies of POC components have been carried out, including exploration of POC formation and variation mechanisms, horizontal and vertical flux and source and sink estimations.

As one of the largest marginal regions with the highest primary productivity, the East China Sea (ECS) is known for strong spatial and temporal variabilities in POC [9,10]. POC generated by biological productivity in the nearshore region is significantly higher than the continental shelf and open sea regions, and is supported by nutrients supplied by coastal upwelling and terrestrial runoff [11,12]. In the continental shelf region, although the flux of Kuroshio subsurface water into ECS is larger than riverine flux into the inshore region,



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nutrient supply for biological productivity is limited by the deep water depth and strong stratification [13,14].

Available studies demonstrated the strong temporal variability of POC in ECS. Ref. [15] found that in fall, POC concentrations appear parallel to the coastline and decrease from land to open sea. In winter, this pattern can be affected by the intrusion of the Taiwan Warm Current (TWC) and stronger vertical mixing [16]. ECS is also proven to be a significant repository of sedimentary organic carbon with strong cross-shelf flux. The rate of organic carbon burial on the ECS shelf is roughly estimated as  $600 \pm 240 \times 10^9$  mol yr<sup>-1</sup> [17]. A cross-shelf export flux reaching  $106 \times 10^6$  mol yr<sup>-1</sup> was calculated using a box model [18] and a sediment trap estimation of 20–67 mg m<sup>-2</sup> d<sup>-1</sup> [19]. POC flux in the middle shelf was estimated at 785 ± 438 mg m<sup>-2</sup> yr<sup>-1</sup> (about 33.4 ± 18.6 × 10<sup>9</sup> mol yr<sup>-1</sup>), using a vertical mixing model [20]. Due to the sparseness of the spatial and temporal resolutions of field data used for these analyses, there is a high degree of uncertainty around these estimates [21,22]. To estimate the flux more accurately, it is necessary to combine multiple methods with more comprehensive spatial and temporal coverages.

Traditional methods of POC investigation have focused on laboratory measurements based on cruise samplings limited by large spatial and temporal gaps. These discrepancies can be filled by satellite observations. In this paper, Moderate Resolution Imaging Spectro-radiometer (MODIS) data collected by the National Aeronautics and Space Administration (NASA) are coupled with in situ data from the ECS in autumn 2011 and used to analyze the spatiotemporal variations of POC in different regions, and to identify the influencing factors on the spatiotemporal variations. The algorithm used by MODIS [23] usually overestimates POC in coastal regions due to interference by chromophoric dissolved organic matter and other colored matter [24–26]. Prior to detailed analysis, we must calibrate the algorithm for POC estimation using a linear regression to accommodate the complex environmental conditions in the ECS.

Previous studies have evaluated the physical and hydrological influences on the ECS at a decadal scale and demonstrated that POC can be linked to longer timescale events [27,28]. This study will also investigate the interannual variability of POC using satellite data. The organic carbon storage in ECS are in the forms of DOC and POC [29,30]. Traditional analyses of organic carbon usually depend on samples from in situ cruises and stations and lack large-scale estimations for the whole ECS. In this study, we develop a method to estimate the total organic carbon in ECS by combining remotely sensed data with in situ sampling. Our results can provide a good reference for the study of long-term and large-scale variations of POC and carbon cycle at the marginal sea.

# 2. Materials and Methods

## 2.1. Study Area

The ECS is located between  $23^{\circ}00'$ N– $33^{\circ}00'$ N and  $117^{\circ}00'$ E– $131^{\circ}00'$ E, and is bordered by Jeju Island to the north, Tokara strait and Okinawa Island to the east and the Island of Taiwan to the south (Figure 1). It is one of the widest shelf seas in the world, covering an area about  $7.7 \times 10^5$  km<sup>2</sup> (Zhang, 2010). According to bathymetry and current characteristics, the study region can be divided into three subregions: the coastal region (CR) with water depth < 50 m, covering an area of  $2.11 \times 10^5$  km<sup>2</sup>; the continental shelf region (CSR) with water depth between 50 m and 200 m, covering an area of  $3.42 \times 10^5$  km<sup>2</sup>; and the open sea region (OSR) with depth > 200 m, covering an area of  $2.45 \times 10^5$  km<sup>2</sup>.

The main circulation patterns in the ECS are composed of the nearshore and open sea current systems, with the open sea current system dominated by the Kuroshio (Figure 2). The Kuroshio enters the ECS at the east coast of Taiwan and travels to 35°N along the Japanese coast, extending from 120°E to 160°E, before flowing outward into the North Pacific [31]. The Kuroshio is narrow and fast, with high temperature, high salinity and high transparency waters, which significantly influence the ocean and atmosphere of the marginal seas in China [32,33]. Moreover, the Kuroshio is a key contributor to the heat,

nutrient and matter exchange between the ECS and the western North Pacific, and therefore affects POC in ECS [17,34–36].



**Figure 1.** Study area and locations of POC sampling stations in ECS. The study area is divided into three regions by the dashed lines, including the coastal region (CR, <50 m water depth area); the continental shelf region (CSR, 50–200 m water depth area); and the open sea region (OSR, >200 m water depth area). Blue dots represent in situ observational stations in 2011 and red square represent stations of published data.



**Figure 2.** A schematic map of the most influential currents around East China Sea in summer and winter. Arrows with solid lines represent currents that flow in the same direction during both seasons; Arrows with dashed lines indicate the winter currents that flow in the opposite directions during the summer. Abbreviation of the currents: the Bohai Sea Coastal Current (BSCC), the Yellow Sea Warm Current (YSWC), the Yellow Sea Coastal Current (YSCC), the Taiwan Warm Current (TWC), the Korea Coastal Current (KCC) and the East China Sea Coastal Current (ECSCC). This figure is based on the research of Bian et al. Reprinted/adapted with permission from Ref. [36]. 2013. AGU.

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# 2.2. Data

Daily POC, sea surface temperature (SST) and Chlorophyll-*a* (Chl-*a*) level 3 data with a horizontal resolution of 4 km collected using MODIS from 2001 to 2011 were obtained from the NASA database website (http://oceandata.sci.gsfc.nasa.gov/ (accessed on 18 December 2013)). The MODIS sensor can provide full images of the Earth every 1 to 2 days with high radiometric sensitivity. Images are organized into different processing levels, archived and made available at no charge. The MODIS POC calculation uses an algorithm based on an empirical relationship between optical measurements and in situ measurements of POC in the eastern South Pacific and eastern Atlantic Oceans [23]. This is expressed as:

$$POC_{sat} = A_i \left[ \frac{R_{rs}(\lambda_B)}{R_{rs}(555)} \right]^{B_i}$$
(1)

where  $A_i$  and  $B_i$  are regression coefficients;  $R_{rs}$  is sea surface remote sensing reflectance;  $R_{rs}(\lambda_B)/R_{rs}(555)$  represents the blue-to-green band ratio of reflectance with  $\lambda_B$  chosen from wavelengths of 443 nm, 490 nm or 510 nm. Statistics found that  $R_{rs}(443)/R_{rs}(555)$  and  $R_{rs}(490)/R_{rs}(555)$  are well correlated with open ocean POC characteristics [23]. Although the algorithm works well at a global scale, it usually results in overestimation of POC concentration in coastal waters with complex optical properties and multiple POC sources [23,24]. To correct satellite-based POC estimation, different empirical equations have been applied for different regions [25,26].

To calibrate MODIS POC estimates in our study area, we matched MODIS POC data with in situ samplings by locating satellite pixels with the closest proximity to sampling stations on the day of sampling. The sampling stations cover all three sea regions and include 58 stations from the research cruise by the scientific research vessel "Kexue 3" from 10 October to 30 October 2011 and 73 stations from previous cruises in published articles (Figure 1, [16,20,37–40]). Kexue 3 samples were filtered within 24 h using Whatman GF/F filters (pore size =  $0.7 \mu$ m) and stored in a -20 °C freezer until analysis. They were exposed to HCl vapor for 48 h to remove inorganic carbon, then dried in the oven at 60 °C. An elemental analyzer (Elementa, Germany) was used to measure and calculate the POC concentrations.

Ref. [27] has demonstrated the reliability of MODIS-derived POC estimates in areas adjacent to ECS with a focus on the Yellow–Bohai Sea. To determine more accurate estimates of POC concentrations in the studied regions, we used a linear regression relating measured POC to MODIS-derived POC (*POC*<sub>sat</sub>):

$$POC = POC_{sat} \times 0.89 - 34.3 \tag{2}$$

The correlation coefficient between in situ measured POC and satellite-derived POC increases from 0.69 before calibration to 0.74 after calibration. The root-mean-square error (RMSE) decreases from 102.73 mg m<sup>-3</sup> before calibration to 80.06 mg m<sup>-3</sup> after calibration. POC calculations in the following sessions are based on these calibrated POC estimates. This method was also applied for the calibration of Chl-*a* in the studied regions [41].

$$Chl = \begin{cases} 1.4732 \times (Chl_{sat} + 0.3115)^{0.3} - 1.0382, \ Chl_{sat} < 2.336\\ Chl_{sat} \times 0.428, \ Chl_{sat} \ge 2.336 \end{cases}$$
(3)

where *Chl<sub>sat</sub>* represents Chl-a before calibration. The MODIS standard algorithm for SST has high accuracy in the ECS, so no calibration was deemed necessary.

To estimate total organic carbon storage in ECS, we collected POC and DOC observations from available studies with details in Section 3.4.

# 3. Results and Discussion

# 3.1. Spatiotemporal Distribution

Monthly averaged POC in ECS demonstrated strong seasonal variability over the whole ECS (Figure 3). In spring (March to May), the seasonally and spatially averaged POC concentration was 231.9 mg m<sup>-3</sup>, which is 45% larger than the averaged concentration of 160.1 mg m<sup>-3</sup> in winter (December to February), 76% larger than the concentration of 132.1 mg m<sup>-3</sup> in fall (September to November) and 93% larger than the smallest averaged concentration of 119.9 mg m<sup>-3</sup> in summer (June to August).



Figure 3. Monthly averaged POC horizontal distribution in the ECS from 2001–2011.

The averaged POC also showed strong spatial variability, as shown in Figure 3. Concentration decreased from coastal region to open sea region, with year-round low POC concentrations mostly appearing in the open sea region near the Okinawa Trough under the influence of the Kuroshio Current. High POC concentration ( $>600 \text{ mg m}^{-3}$ ) appeared around the coastal region, with the largest temporal variability due to the combined effects of primary productivity, terrestrial runoff and physical processes. High POC was observed in spring, which was consistent with observational studies suggesting that POC concentrations are dominated by biological activity due to high nutrients supply by terrestrial input and upwelling [27]. POC decreased in summer, despite high river discharge from sources including the Changjiang Estuary transporting higher quantities of POC from terrestrial runoff into the coastal region [42]. The large volume of freshwater induced stronger stratification, preventing nutrients and oxygen exchange between upper and deeper oceans [43]. A combination of insufficient nutrient supply to phytoplankton growth and continuous consumption by zooplankton and bacteria led to the reduction of POC in the upper ocean layers and caused the formation of a hypoxic zone in deeper layers [35]. However, some high POC areas can still be found at the northeastern Changjiang Estuary, potentially caused by the strong terrestrial input and increased sediment resuspension by southwestern monsoons [44]. In winter, the sub-peak in POC in the northeastern Changjiang Estuary was due to resuspension by strong northeastern monsoons lasting from late September to early April [45]. This was accompanied by a sub-peak in biological productivity [46], although this secondary effect was relatively weaker than the initial effect caused by the sediment resuspension by northeastern monsoons.

#### 3.2. Relationship between POC and Chl-a/SST

Correlation analyses for Chl-*a* vs. POC and SST vs. POC were processed for all three subregions (Figure 4). The first analysis revealed that POC is positively correlated with Chl-*a* with the correlation coefficients increasing from 0.52 in the coastal region to 0.90 in open sea region.



**Figure 4.** Plots a–c represent the monthly averaged Chl-*a* vs. POC in all three selected regions of the ECS; Plots d–f represent the monthly averaged SST vs. POC. The  $r^2$  value represents the correlation coefficient and all data comparisons have passed the significance test (p < 0.05).

Chl-*a* is the main pigment used for photosynthesis by phytoplankton, and is a significant indicator of marine phytoplankton biomass, reflecting the carbon fixation capacity for primary producers in seawater. Therefore, POC and Chl-*a* can be positively correlated with each other, with the increase in Chl-*a* accompanied by an increase in POC [47,48].

Our correlation analysis demonstrated that Chl-*a* and POC have a stronger correlation in regions with simpler POC sources, as represented by the strongest correlation of  $r^2 = 0.90$  in the open sea where biological productivity is the most important POC source. Under extensive influence of nutrient-poor Kuroshio water [45,49,50], the open sea area was oligotrophic with low productivity and concentration variation of Chl-*a* and POC

remained low and stable. In the coastal region, the complex POC sources include primary productivity, terrestrial input, sediment resuspension and water exchange, all of which cause the POC to vary widely and be less correlated with Chl-*a*.

A negative correlation between POC and SST was identified in all three ECS regions, with the absolute values of  $r^2$  increasing from 0.46 in the coastal region to 0.78 in the open sea region (Figure 4d–f). The strong correlation in the open sea region was because SST dictates biological activities including the reproduction, predation and excretion of phytoplankton, which affects regional POC concentrations. For example, zooplankton and bacteria would be enhanced under appropriate seawater temperature, increasing the predation and excretion of phytoplankton and favoring the production of POC [51,52]. SST can also be correlated with POC through physical processes and can be used as an indicator of POC anomaly. A good example is that the cold-water wake induced by a typhoon event is regarded as a sign of bottom sediment entrainment and can result in an abnormal increase of POC concentrations [53,54].

# 3.3. Interannual Variabilities of POC in Different Regions of ECS

Long term variations in POC and its correlation factors, SST and Chl-*a*, were discussed in three subregions of the ECS based on satellite data from 2001 to 2011 (Figure 5). POC concentrations in all three regions showed a decreasing trend from 2001 to 2011. However, the trends in SST and Chl-*a* were not consistent for different regions, which indicates different influencing factors for POC variations.



**Figure 5.** Time series of monthly averaged POC (**a**–**c**), Chl-*a* concentrations (**d**–**f**) and SST (**g**–**i**) in three different regions of the ECS. Bold values on the right *y*-axis represent the average values from 2001 to 2011. Trend lines are calculated by linear regression.

## 3.3.1. Coastal Region

In the coastal region, POC concentration decreased by 16.3% from 2001 to 2011, while Chl-*a* and SST both increased. The increase of Chl-*a* (by 25.5% from 2001 to 2011) conflicted with our analysis in Section 3.2, and indicated a positive correlation between POC and

Chl-*a*. The inconsistent trends could be attributed to the following reasons: (1) accompanied by the development of the national economy, application of chemical fertilizers, including Nitrogen (N) and Phosphate (P) fertilizers, in the Changjiang River region increased gradually from 10.6 million tons in 2001 to 19.3 million tons in 2011 [55]. This has significantly augmented river nutrient loading; (2) The increase in P fertilizer (6.6%) application was larger than the increase in N fertilizer (5.2%). The coastal region of the ECS is P-limited [56,57], so the larger increase in P raised the N/P ratio and decreased P limitation, hence favoring phytoplankton growth and increasing Chl-*a*. In return, the enhanced phytoplankton biomass increased nutrient consumption and aggravated the imbalanced nutrient ratio in seawater [58,59]. The increase of SST also contributed to an increase in primary production by enhancing biological activities [60].

While primary production contributes to POC, it is not the only POC source in the coastal region. Terrestrial runoff, mainly from the Changjiang Estuary, is another important POC source that could potentially change POC. The construction of the Three Gorge Dam (TGD) has not only changed seasonal distribution of the Changjiang diluted water flux into the ECS [61,62], but also has decreased sediment discharge from 276 million tons in 2001 to 72 million tons in 2011 [63,64]. In addition to the sediment discharge decrease, a decrease in POC concentration was observed in the coastal region, with the variation trend similar to sediment discharge but much larger than river flux (Figure 6).



**Figure 6.** Annual water flux (vertical bars) and sediment discharge (red broken line) from the Changjiang River and POC concentration in the ECS (blue broken line), from 2001 to 2011, respectively. Data was obtained from River Sediment Bulletin of China, 2001–2011, from Datong hydrological station. Trendlines were calculated by linear regression.

When comparing the initial 6 years (2001–2006) with the final 6 years (2006–2011), we found that sediment discharge and POC concentration decreased by 36.8% and 21.6%, respectively, while water flux slightly decreased by 4.6%. Therefore, the change in POC was dominated by sediment discharge instead of primary production or other variables directly related to river flux. POC decreased less than sediment discharge (Figure 6) due to the increasing effect of primary production on POC as previously mentioned. Moreover, the reduced sediment discharge increased seawater transparency in the coastal region, which further favored primary production and increased Chl-*a*. As a result, long term POC decreased while Chl-*a* increased, which contradicts the positively correlated relationship between POC and Chl-*a*. This result indicates that (1) coastal POC variation is

strongly influenced by sediment discharge, (2) oceanic biological productivity may not be the dominant source of POC, and (3) the sediment discharge regulated by TGD is a more important influence on POC concentration in the coastal region than biological productivity.

# 3.3.2. Open Sea Region

Unlike the production of POC by both riverine and oceanic sources in the coastal region, POC in the open sea region was dominated by the Kuroshio Current waters. This region had lower POC concentrations and smaller fluctuations, and the corresponding Chl-*a* variation presented similar variations (Figure 5). Annual mean SST in this region showed a larger increase of 0.17 °C from 2001 to 2011, which may be a result of the intrusion of higher temperature water masses and heat exchange with the Kuroshio Current [65,66].

# 3.3.3. Continental Shelf Region

Seawater in the continental shelf region has multiple sources, including the Changjiang diluted water, Kuroshio Current, and water exchange with the Yellow Sea [67,68]. Therefore, POC is affected by a combination of biological productivity, terrestrial runoff and Kuroshio Current exchange. Long time series showed that in the continental shelf region, POC decreased by 0.91% each year while Chl-*a* and SST increased each year by 0.58% and 0.73%, respectively (Figure 5). As discussed above, the TGD effects could extend to the continental shelf region, especially in summer and autumn, with high sediment flux from the Changjiang diluted water greatly influencing its POC/Chl-*a* concentrations [42,43]. The weight of different influencing factors varies seasonally. To determine the dominant influencing factors in different seasons, we carried out a correlation analysis between POC in the continental shelf region with POC, Chl-*a* and SST in all sub-regions of the ECS (Table 1).

Season	Region	r <sup>2</sup> (POC)	r <sup>2</sup> (Chl- <i>a</i> )	r <sup>2</sup> (SST)
Spring	Coastal	0.34	0.17	0.17
	Continental	/	0.34	0.18
	Open sea	0.67	0.05	0.30
Summer	Coastal	0.51	0.56	0.72
	Continental	/	0.81	0.52
	Open sea	0.07	0.05	0.08
Fall	Coastal	0.69	0.01	0.08
	Continental	/	0.30	0.51
	Open sea	0.88	0.81	0.45
Winter	Coastal	0.77	0.20	0.53
	Continental	/	0.27	0.57
	Open sea	0.73	0.06	0.42

**Table 1.** Correlation between POC in continental shelf region with POC, Chl-*a* and SST in the studied regions (p < 0.05). Bold numbers represent values with significant correlation.

In spring, most of the terrestrial nutrient input does not reach the continental shelf region due to strong consumption in the coastal region. Therefore, POC in the continental shelf region was less affected by the riverine water exchange than the coastal area. Meanwhile, the Kuroshio Current was slow [69], which caused a peak in matter exchange between the Kuroshio and continental shelf water [70]. Therefore, spring POC variation in the continental shelf region was greatly influenced by POC from the Kuroshio Current, with a correlation coefficient of 0.67.

During summer, the larger river discharge from the Changjiang estuary transported abundant nutrients and organic matter to the continental shelf region, boosting POC concentration due to biological productivity and water exchange. The importance of water exchange was evidenced by the large correlation coefficients between continental shelf POC with coastal POC (0.51) and Chl-a (0.56). The importance of biological activities was

evidenced by the large correlation coefficient between POC and Chl-*a* in the continental shelf region (0.81). Biological activities are affected by temperature, so correlation between continental shelf POC and continental shelf/coastal SST was also strong (0.52/0.72). This analysis is consistent with previous research, which found that both coastal and continental shelf Chl-*a* and sea temperature dominate continental shelf POC concentrations [13,68].

In fall, the Kuroshio Current is affected by monsoons, so its axis bends closer to the continental shelf region [71,72]. Northeast monsoons together with the strong Changjiang diluted water broke continental shelf stratification which caused the increase in primary productivity. Therefore, POC transport from the coastal and open sea regions both influenced the continental shelf region, with an emphasis on transport from the open sea region, demonstrated by an  $r^2$  of 0.88.

In winter, the Changjiang diluted water flux decreased, while the influence by the open sea region remained consistent, with a correlation coefficient for continental shelf POC and Kuroshio POC at 0.73. However, the correlation between coastal POC and continental shelf POC remained strong at 0.77 under the influence of physical processes. During winter, the strong northeast monsoon and coastal currents caused a strong exchange between coastal water and continental shelf water [73]. Therefore, POC import from coastal water, the Kuroshio, and intensive mixing and entrainment activities all contributed to POC variation in winter [34,74].

This analysis demonstrated that POC variations in the continental shelf region of the ECS are affected by multiple environmental factors in different regions, and the variations are not constant year-round. Therefore, it is necessary to conduct further research and quantitative analysis to detect the specific biological, physical and chemical effects and intrinsic mechanisms that influence POC variations.

## 3.4. Estimation of Organic Carbon Storage in ECS

Since satellite data can only reflect parameter surface variability and distribution, we developed a method to estimate the total organic carbon storage in ECS by combining satellite-derived surface POC, in situ observed surface POC, in situ observed POC for different layers and seasonal POC and DOC observations from available cruises.

We first estimated depth-averaged POC in ECS ( $C_{\text{satellite-column}}POC$ ) using satelliteobserved surface POC for the whole ECS ( $C_{\text{satellite-surface}}POC$ ) and the ratio between depthaveraged POC based on in situ observations at different layers ( $C_{\text{measured-column}}POC$ ) and in situ surface observations ( $C_{\text{measured-surface}}POC$ ) in the form of:

$$\frac{C_{\text{satellite-column}}POC}{C_{\text{satellite-surface}}POC} = \frac{C_{\text{measured-column}}POC}{C_{\text{measured-surface}}POC}$$
(4)

The calculation of  $C_{\text{measured-surface}}POC$  and  $C_{\text{measured-column}}POC$  were based on historical observations shown in Table 2. We estimated POC on the surface and average over the whole water column as 174.40 mg m<sup>-3</sup> and 146.00 mg m<sup>-3</sup>, respectively. We then generated ratios between DOC and POC in different seasons with vertical integration and arithmetic mean based on POC and DOC in situ samplings from available cruises (Table 2). These ratios were coupled with satellite data to estimate the organic carbon storage in ECS.

Season/Depth	POC Range	POC Average	Reference	DOC-Range	DOC-Average	References
spring						
surface	49.15-2817.29	276.98		720-1290	890	
10 m	39.60-2736.93	304.44		/	/	
30 m	46.70-666.73	172.76	[38]	/	/	[75]
bottom	25.37-2654.07	291.82		600-1010	800	
water column average	24.33-2817.29	230.76		750–990	840	
summer						
surface	22-240	132.28		660-3050	1270	
10 m	14.5-554	170.04		760-2120	1160	
30 m	0.6-312	148.28	<b>F</b> (1)	670-1880	1090	[20]
50 m	/	/	[16]	730-1390	990	[39]
bottom	1.4-853	220.04		570-2040	970	
water column average	0.6-853	130		500-3050	1080	
autumn						
surface	39-682	132.03		590-6100	1090	
30 m	20.75-191	76.54		590-2170	940	
50 m	21.20-140.17	63.61		620-1120	870	
75 m	11.75-131.17	53.82	In situ data,	540-980	760	[76]
bottom	7.25-766	125.27	2011	440-12,030	1130	
water column average	7.25–766	97.37		440–12,030	990	
winter						
surface	36.39-1555.96	156.32		444-2491	1017	
10 m	40.27-306.96	102.61		621-1763	1066	
30 m	15.09-205.65	93.07		514-1865	950	[70]
50 m	2.49-156.98	61.65	[77]	623-1650	956	[78]
75 m	/	/	[//]	623-1373	912	
bottom	5.29-1658.96	201.88		440-1763	986	
water column average	2.49-1658.96	125.88		440–2491	967	

Table 2. Seasonal measured POC and DOC data collected from different cruises in ECS (Unit: mg m	n_3	').
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Annual average  $C_{\text{satellite-column}}POC$  calculated by equation 4 is 118.85 mg m<sup>-3</sup> (Table 3). In spring, POC accounts for the highest ratio of organic carbon (21.5%), while average organic carbon in the other seasons is less than in spring, at 13.1% (Table 4). Therefore, the calculated total organic carbon concentration reaches 907.25 mg m<sup>-3</sup>. With a total water volume of  $4.5 \times 10^{13}$  m<sup>3</sup> for ECS [79], we made preliminary calculations of the annual total organic carbon in ECS, estimated at  $4.08 \times 10^{13}$  g yr<sup>-1</sup>. This result is close to the estimation by Chen et al. [17],  $11.28 \times 10^{13}$  g yr<sup>-1</sup>, based on mass balance calculations. In conclusion, this method uses satellite data, which can cover the whole research area with consistent and continuous temporal coverage, to estimate organic carbon content. More in situ data and an improved algorithm for satellite POC analysis will enhance the accuracy of these estimations.

Year	C <sub>satellite-surface</sub> POC	C <sub>satellite-column</sub> POC
2001	158.90	133.48
2002	164.81	138.44
2003	152.43	128.04
2004	132.34	111.16
2005	133.98	112.54
2006	139.02	116.77
2007	127.60	107.18
2008	137.02	115.09
2009	145.90	122.55
2010	131.83	110.73
2011	132.60	111.38
Average	141.49	118.85

**Table 3.** Annual satellite data of POC in ECS (Unit:  $mg m^{-3}$ ).

Table 4. Seasonal POC and DOC average integral measured data (Unit:  $mg m^{-3}$ ).

Seasons	DOC	РОС	POC% in Total Organic Carbon
Spring	840	230	21.5%
Summer	1080	130	10.7%
Fall	990	97	8.9%
Winter	967	126	11.5%
Average	969	146	13.1%

# 4. Summary

In this paper, we applied a linear regression to calibrate MODIS derived POC concentrations in ECS and used calibrated POC estimates to investigate spatial and temporal variations of POC in three subregions of ECS. POC in the coastal region (with depth < 50 m) is mainly affected by water and sediment discharge from the Changjiang Estuary, which shows seasonal variability regulated by river discharge and the Three Gorge Project and demonstrates a decreasing trend at interannual scale regulated by the Three Gorge Project and chemical fertilizer application. In the continental shelf region (depth 50–200 m), variation of POC is controlled by multiple factors, dominated by the Changjiang diluted water in summer, Kuroshio Current water in spring, and a combination of both influences in fall. Although effects of the Changjiang diluted water in the coastal ocean weaken in winter, the coastal ocean still affects the continental shelf POC through northeast monsoon and induced currents. In the open sea region, POC concentration usually remains low and stable. In addition, the organic carbon stock in the entire water column has been evaluated with the ratio of measured data to satellite data. Preliminary estimation reveals that organic carbon reserve in the ECS is  $\sim 4.08 \times 10^{13}$  g per year, a value that provides a new, comparative idea of the carbon reserve estimation for future study.

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**Data Availability Statement:** Publicly available datasets were analyzed in this study. This data can be found here: http://oceandata.sci.gsfc.nasa.gov/ (accessed on 18 December 2013).

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