Satellite-derived particulate organic carbon flux in the Changjiang River through different stages of the Three Gorges Dam

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\textbf{ABSTRACT}

As the largest Asian river and fourth world's largest river by water flow, the Changjiang River transports a considerable amount of terrigenous particulate organic carbon (POC) into ocean, which has experienced significant pressure from human activities. We conducted monthly sampling (from May 2015 to May 2016) at Datong, the most downstream non-tidal hydrological station along the Changjiang River. To monitor long-term POC variations, we developed a two-step POC algorithm for Landsat satellite data and calculated monthly POC flux during 2000–2016. Monthly POC flux ranged from a minimum of $1.4 \times 10^4$ t C in February 2016 to a maximum of $52.04 \times 10^4$ t C in May 2002, with a mean of $13.04 \times 10^4$ t C/month. At Datong, monthly POC flux was positively exponentially related to water flow ($N = 118$, $R = 0.69$, $p < 0.01$). In the wet season (May to October) with high water flow, a large amount of terrigenous POC was flushed into the Changjiang River. After the Three Gorges Dam (TGD), both POC concentration ($R = 0.46$, $p < 0.01$) and POC flux ($R = 0.33$, $p < 0.01$) significantly exponentially decreased during 2000–2016. After 2011 with regular operation of the TGD, POC transport at Datong showed relative stability and its seasonal difference became smaller. POC concentration from the TGD to Datong in the Changjiang mainstream (~1000 km) was also derived from Landsat data, which was spatially varied with water flow, slope gradient, and watercourse width. This study improved our understanding of the spatiotemporal variations of POC transport in the Changjiang mainstream, especially the influences of the TGD construction.

1. Introduction

Rivers play crucial roles in connecting land and ocean ecosystems, the two largest active carbon pools in global carbon cycle (Siegenthaler and Sarmiento, 1993; Wang et al., 2012). On a global scale, rivers deliver approximately $2.0 \times 10^8$ t C/yr of particulate organic carbon (POC) into marginal seas (Wang et al., 2012). After coastal transformation and oxidation consumption, the remaining riverine POC is buried in estuarine and/or coastal sediments, constituting a significant carbon sink (Bianchi and Allison, 2009; Saliot et al., 2002; Wollast, 1991). Regarding on global riverine POC flux, 23.74% was transported by Asian rivers (Seitzinger et al., 2005). Asian rivers are usually characterized by seasonally varied POC concentration, with high values in large water flow seasons (Liu et al., 2015a; Ran et al., 2013; Wang et al., 2012). With wide spatial coverage and high temporal repeatability, satellite remote sensing is ideal and necessary for retrieving dynamic riverine POC concentration.

As the largest Asian river according to annual water flow, the Changjiang River exports a great deal of terrigenous POC into the East China Sea (ECS) every year (Duan et al., 2008; Liu et al., 2014; Wang et al., 2012). Over the past several decades, moreover, sediment yield in the Changjiang watershed has been markedly influenced by extensive human activities, the construction of Three Gorges Dam (TGD) for example (Wang et al., 2009; Yang et al., 2006, 2007). In November 1997, the Changjiang River was intercepted for TGD construction. On 1 June 2003, the TGD began impoundment. Water level reached 135 m on 10 June 2003, 156 m on October 2006, and 175 m by the end of October 2010, respectively (Zhang et al., 2014). When at 175 m, water storage is...
about \(3.93 \times 10^{11} \text{ m}^3\) and catchment area is about \(1.08 \times 10^8 \text{ km}^2\) (http://news.xinhuanet.com/).

The TGD has reportedly changed material transport of the Changjiang River, leading to ecological changes in the ECS (Bai et al., 2014, 2015; Feng et al., 2014). Xu and Milliman (2009) reported that the TGD trapped about 60% of upstream input sediment during 2003–2006. After 2003, the Changjiang River has entered a phase with sediment flux at Datong hydrological station < 200 mt/yr, compared with average value of \(\sim 340\) mt/yr during 1986–2002 (Yang et al., 2006). As part of the suspended sediment, POC transport has also been reduced by the TGD (Wu et al., 2016; Zhang et al., 2014). Based on biweekly measurements in Changjiang River estuary (CRE) from 2003 to 2011, Wu et al. (2016) reported that a sharp decrease of POC flux was observed, especially in the wet season. However, long-term monitoring is still mandatory for assessing POC changes in the Changjiang River through different stages of the TGD.

With low cost and labor-consuming, satellite remote sensing is a good alternative tool to explore long-term riverine POC variations. Many remote sensing algorithms had been developed for oceanic POC closely related to phytoplankton density (Stramska, 2009; Stramski et al., 1999, 2008), but they were not applicable to riverine POC primarily sourced from watershed soil (Liu et al., 2015a; Wang et al., 2012). In addition, with usual spatial resolution of ~1 km, commonly used ocean color data is too coarse to be applied to rivers with widths of only several kilometers at most. Alternatively, long-term Landsat satellite data with a resolution of 30 m was a good choice and had been frequently used to derive turbidity (Joshi et al., 2017b), total suspended matter (TSM) (Islam et al., 2001, 2002; Lymburner et al., 2016; Wang et al., 2009), dissolved organic matter (Griffin et al., 2011; Joshi et al., 2017a; Kutser et al., 2016), etc. in riverine or coastal small waters. However, due to limited in-situ POC measurement, a 16-day revisit period for Landsat satellite, and locally dependent relationships between POC and TSM (Gao et al., 2002; Ran et al., 2013; Zhang et al., 2014), etc., few studies about monitoring riverine POC had been reported. These also lead to the importance of validation work and the limited matchup data when using Landsat data.

To monitor dynamic POC in the Changjiang River from space and determine POC variations after the TGD, we conducted one-year sampling (May 2015 to May 2016) in each month at Datong, the most downstream non-tidal hydrological station. Then, we developed a two-step POC satellite algorithm and retrieved sequenced POC concentration from both Landsat TM and ETM+ data during 2000–2016. Combining water flow, long-term sequenced POC flux was also calculated. Furthermore, we investigated seasonal POC variations at Datong through different stages of the TGD.

### 2. Study area

The Changjiang River originates from the Qinghai-Tibetan Plateau (Wu et al., 2007; Xu and Milliman, 2009). It is 6300 km long and covers a basin area of \(1.94 \times 10^6 \text{ km}^2\) before finally emptying into the ECS (Zhang et al., 2014). The part upstream of the Yichang hydrological station (downstream non-tidal hydrological station). Then, we developed a two-step POC sampling (May 2015 to May 2016) in each month at Datong, the most downstream non-tidal hydrological station. Then, we developed a two-step POC satellite algorithm and retrieved sequenced POC concentration from both Landsat TM and ETM+ data during 2000–2016. Combining water flow, long-term sequenced POC flux was also calculated. Furthermore, we investigated seasonal POC variations at Datong through different stages of the TGD.

### 3. Materials and data processing

#### 3.1. TSM, POC, and other in-situ data

**In-situ sampling** was conducted in the middle of each month from May 2015 to May 2016, using hydrographic survey vessel, China (No. 138). At each station of P1, P2, and P3 (Fig. 1b), waters at three depths (surface, middle, and bottom) were collected using a Niskin sampler (General Oceanics Inc. USA) within about 15 min. When collecting water, the sampler was fixed at 0.5 m to the water surface, half the water depth, and 0.5 m to the water bottom, respectively (Fig. 1c).

In each month, surface waters were also collected at station P4 several hours before and/or after the Datong section sampling (Fig. 1b).

Water was filtered through pre-combusted GF/F membrane (Whatman, UK, 0.7 μm pore size and 47 mm) and pre-weighted cellulose acetate membrane (Sartorius, Germany, 0.45 μm pore size and 47 mm) to obtain POC and TSM samples, respectively. All samples were stored in a refrigerator (~18°C) until laboratory measurement. POC content was determined using high temperature combustion method (680°C) by referring to the Joint Global Ocean Flux Study (JGOFS) protocols (Knapp et al., 1994). As Strickland and Parsons (1972), TSM content was determined gravimetrically, with a precision of 0.01 mg. In total, we collected 141 TSM samples and 141 POC samples (Table 1).

The published in-situ POC and TSM by Wang et al. (2012) were also used to supplement our in-situ dataset for following analysis. Wang et al. (2012) monthly collected surface, middle, and bottom waters in the central mainstream at Datong in 2009, and mixed them at a 2:1:1 volume ratio. By following JGOFS (Knapp et al., 1994), waters were also filtered through pre-combusted GF/F filters to obtain POC samples and POC content was determined using a Perkin-Elmer 2400 CHNS Analyzer (USA) with an analytical precision of ± 4%. For TSM, Wang et al. (2012) used values by oven drying method from the Ministry of Water Resources of China (MWRC).

In addition to POC and TSM, we also collected Chl-α, colored dissolved organic matter (CDOM), and suspended particle samples (Table 1). Chl-α concentration was measured using a Turner fluorometer (Knapp et al., 1994). Absorption coefficient spectra of CDOM (\(a_{CDOM}\)) and no-algal particle (\(a_p\)) from 250 to 900 nm with an interval of 1 nm were determined by the spectrophotometric method (Mueller et al., 2003). Additional details about collection, storage, and measurement of these parameters can be found in the previously published article by Bai et al. (2013). In total, we collected 141 Chl-α, 139 CDOM (two were contaminated), and 141 NAP samples (Table 1). Using \(a_{CDOM}\) and \(a_p\) between 430 and 450 nm, we further calculated CDOM spectral slope at 440 nm (\(S_{CDOM(440)}\)) and NAP spectral slope at 440 nm (\(S_n\)) (Table 1).

From September 2012 to July 2015, an YSI turbidimeter was deployed to measure TSM concentration at station P4 around 10:00 local time every day by MWRC, namely the YSI-measured TSM. Monthly water flow and TSM at Datong from 2000 to 2016 were used. Monthly water flow and mean TSM at Yichang from 2003 to 2016 were also used. These data was sourced from the MWRC (2000–2016).

#### 3.2. Water reflectance

When collecting water at Datong, radiance spectra of water surface \(L_{\text{w}}\), sky light \(L_{\text{sky}}\), and a standard reflecting plate \(L_p\) were also measured using a ASD FieldSpec Spectroradiometer (USA), which measured radiance from 350 to 2390 nm with an interval of 1 nm. \(L_{\text{w}}, L_{\text{sky}},\) and \(L_p\) were determined from above-water measurements by following the Ocean Optical Protocols proposed by NASA (Mueller et al., 2003). When measuring \(L_{\text{w}}\) and \(L_{\text{sky}}\), the probe was positioned at 90–135° to the north and 20 m in the south (Fig. 1c). Rivers upstream of Datong drain 94.3% of the total basin area and account for > 95% of water and sediment transports in the whole basin (Duan et al., 2008).
the plane of incident radiation to minimize the effects of sun glint and ship shadow. View angle to the aplanob direction was 135–150° for \( L_{ws} \), but 30–45° for \( L_{sky} \). Based on measured radiances, water reflectance (\( R_{ws}, \) sr \(^{-1} \)) was calculated using Eq. (1) (Mueller et al., 2003).

\[
R_{ws}(\lambda) = \frac{\rho(\lambda) / L_{ws}(\lambda) - r L_{sky}(\lambda)) / (\pi L_{p}(\lambda))}
\]

where, \( \rho(\lambda) \) is the reflectance of the standard reflecting plate; \( r \) is the reflectance of the air-water interface, with \( r = 0.028 \) for the turbid Changjiang River waters like those in the Pearl River Estuary (Liu et al., 2015a).

### 3.3. Landsat satellite data

In this study, both data of TM onboard the Landsat-5 satellite (Landsat-5 TM) and ETM+ onboard the Landsat-7 satellite (Landsat-7 ETM+) was used. Landsat-5 TM recorded data from March 1984 to May 2012. Landsat-7 ETM+ has continuously recorded data since July 1999. Both Landsat-5 TM and Landsat-7 ETM+ scan the earth surface around 10:30 a.m. local time. The Landsat-5 TM and Landsat-7 ETM+ had four similar visible light bands setups, with central wavelength at 485 nm, 560 nm, 660 nm, and 830 nm, respectively. The scan-line corrector of Landsat-7 ETM+ failed after 30 May 2003, resulting in about 22% per scene without being scanned (Singh and Prasad, 2014). Nonetheless, the valid data was still available (Griffin et al., 2011; Wang et al., 2007, 2009).

In total, 59 scenes of Landsat-5 TM data and 118 scenes of Landsat-7 ETM+ data during 2000–2016 were downloaded from the Geospatial Data Cloud Center (http://www.gscloud.cn/). For the Level 1T data, radiometric calibration, geometric rectification, and topographic correction had been processed. Accurate atmospheric correction of inland waters is an unresolved issue (Kutser et al., 2016). For Landsat data, the fast line-of-sight atmospheric analysis of spectral hypercubes (FLAASH) was reported valid to remove atmospheric effects and calculate water reflectance for inland waters (Bernardo et al., 2017; Joshi et al., 2017b; Kutser et al., 2005, Kutser, 2012). Therefore, we used the FLAASH.
Based on ENVI 4.8 software (ENVI, 2008). For region R in Fig. 1b, mean water reflectance of each visible band was further calculated by the following three steps (Bailey and Wendell, 2006):

1) For each band, we extracted valid values within the $10 \times 10$ pixels box (Fig. 1b). Invalid pixels of Landsat-7 ETM+ data after 30 May 2003 were ignored.
2) If valid pixels were $> 50\%$ ($> 50$ pixels), we further calculated their mean and standard deviation (SD) and deleted pixels beyond mean $\pm 1.5$SD.
3) If variation coefficient (VC; SD/mean) of the remaining pixels was $< 0.15$, mean water reflectance of the remaining pixels was available.

4. Algorithm development and validation

4.1. Water reflectance simulation using a bio-optical model

Hyperspectral water reflectance simulation of turbid inland water can be simulated using bio-optical model (Kutser et al., 2001). From May 2015 to May 2016, the in-situ surface TSM was within 26.66–96.67 mg/L. Actually, TSM range at Datong is much wider than our measurements, with monthly mean TSM of 30.5–735.4 mg/L during 2000–2016 reported by MWRC (2000–2016). To enlarge the data range and develop a robust algorithm, we simulated water reflectance using a bio-optical model. For Lambertian radiance, water reflectance at wavelength $\lambda$ ($R_{w}(\lambda)$) was expressed using Eq. (2) (Lee et al., 1998):

$$R_{w}(\lambda) = 0.518rs(\lambda)/[1 - 0.562r_{s}(\lambda)]$$

(2)

where, $r_{s}(\lambda)$ is the subsurface water reflectance. To calculate $r_{s}(\lambda)$, we chose the widely used expression proposed by Gordon et al. (1988), shown as Eq. (3).

$$r_{s}(\lambda) \approx (0.0949 + 0.0794u(\lambda))u(\lambda)$$

(3)

where, $u(x)$ is the intermediate variable; $a(\lambda)$ is the total absorption coefficient; $b_{s}(\lambda)$ is the total backscattering coefficient. Both $a(\lambda)$ and $b_{s}(\lambda)$ are determined by clean water, phytoplankton, non-algal particle (NAP), and CDOM together, so we got Eq. (4).

$$a(\lambda) = aw(\lambda) + ap(\lambda) + an(\lambda) + ag(\lambda)$$

$$b_{s}(\lambda) = bbw(\lambda) + Bbbp(\lambda) + Bbn(\lambda)$$

(4)

where, $b$ is the scattering coefficient; $B$ is the backscattering ratio ($b_{bb}$/ $b$); footnotes w, n, and $g$ refer to clean water, phytoplankton, NAP, and CDOM, respectively. In the bio-optical simulation, the used empirical equations and parameters for different constituents are shown in Table 2.

For the 54 in-situ water reflectance measurements, CDOM varied in a narrow range (Table 1), but corresponding TSM ranged from 22.00 to 76.99 mg/L. Using the conversion coefficient of Chl-$a$ to TSM of 0.12 by Oyama et al. (2009), we also got that phytoplankton contributed only 0.42 ± 0.25% to TSM. Therefore, water reflectance variation was mainly determined by the NAP content, and we set Chl-$a$, $a_{CDOM}$, and $S_{CDOM}$ as the mean in-situ values in the simulation (Table 1). For NAP, we used the empirical equations by Ruddick et al. (2006), assuming optics in turbid waters were only described by pure water and NAP (Table 2). From the validation results using in-situ data, the modeled $a_{n}$ at four visible light bands of Landsat-5 TM were satisfactory (Fig. 2a). By setting in-situ TSM concentrations as inputs, we simulated water reflectance and compared with in-situ data (Section 3.2). For the four visible light bands of Landsat-5 TM, average relative errors (ARE) were 14.4%, 17.01%, 22.26%, and 21.31%, respectively (Fig. 2b).

With the developed bio-optical model above, we set monthly mean TSM values at Datong during 2000–2016 as inputs to simulate water reflectance ($N = 204$). From reported data by the MWRC, we got that monthly mean TSM at Datong ranged from 30.5 to 735.4 mg/L during 2000–2016, with values only in six months larger than 400 mg/L (MWRC, 2000–2016).

4.2. POC satellite algorithm for Landsat data

From hyperspectral water reflectance in narrow bands, we could calculate TSM using numerical method such as linear matrix inversion (Hakvoort et al., 2002). However, this method cannot be used to retrieve TSM from Landsat data in wide bands. Although POC is not one water color constituent like Chl-$a$, CDOM and TSM, which all have working bio-optical models (Jiang et al., 2015; Lee et al., 1998), POC is usually related to TSM (Gao et al., 2002; Ludwig et al., 1996; Ni et al., 2008). Therefore, we first retrieved TSM from Landsat data, and then further calculated POC from TSM. To develop a TSM algorithm, we first computed equivalent band reflectance ($r_{equiv}$) of Landdata from the 204 simulated water reflectance spectra (Section 4.1). For a specific band with central wavelength of $\lambda$, $r_{equiv}(\lambda)$ was calculated using Eq. (5) (Liu et al., 2015a).

$$r_{equiv}(\lambda) = \left[ \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} f(\lambda) R_{w}(\lambda) \text{d}\lambda \right] / \left[ \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} f(\lambda) \text{d}\lambda \right]$$

(5)

where, $f(\lambda)$ is the spectral response function of Landsat-5 TM or Landsat-7 ETM+; $L(\lambda)$ is the solar irradiance at the top of the atmosphere; integral calculation ranges from 400 nm ($\lambda_{\text{min}}$) to 900 nm ($\lambda_{\text{max}}$); and $R_{w}(\lambda)$ is the simulated water reflectance. For both Landsat-5 TM and Landsat-7 ETM+, we found that TSM showed power relation to the equivalent reflectance ratio of $r_{equiv}(\text{band4})/r_{equiv}(\text{band1})$, shown as Eq. (6).

$$\log_{10}(\text{TSM}) = a \times \text{Ratio}^{b}$$

$$\text{Ratio} = r_{equiv}(\text{band4})/r_{equiv}(\text{band1})$$

(6)

where, both $a$ and $b$ are fitting coefficients; for Landsat-5 TM, $a = 2.1454$, $b = 0.2945$; for Landsat-7 ETM+, $a = 2.1012$, $b = 0.2935$. The Eq. (6) was applied to retrieve TSM concentration from in-situ water reflectance. For both Landsat-5 TM and Landsat-7 ETM+ data, we used 13.69% and 13.46%, respectively (Fig. 3a).

For all in-situ TSM and POC concentrations (Section 3.1), POC showed a significant linear correlation with TSM, with $R^{2} = 0.98$ and $p < 0.01$ (Fig. 3b). The linear relationship between POC and TSM reflected their consistent variations; with an increase in TSM by 100 mg/L, POC increased by 1.12 mg/L (Fig. 3b). Therefore, we calculated POC from satellite-derived TSM using Eq. (7).

$$\text{POC} = 0.0112 \times \text{TSM} + 0.1115$$

(7)

where, [TSM] is satellite-derived TSM by Eq. (6). In sum, we retrieved POC from Landsat TM and ETM+ data through a two-step algorithm by Eqs. (6) and (7).
4.3. Evaluation of the POC algorithm performance

Water reflectance variations at Datong were mainly determined by TSM, especially the NAP (Section 4.1). NAP could not only decrease water reflectance by absorbing irradiance, but also increase reflectance by scattering irradiance (Bricaud and Stramski, 1990; Mueller et al., 2003). Absorption coefficient of NAP exponentially decreased with increasing wavelength (Bricaud and Stramski, 1990). With negligible absorption, water reflectance at long wavelength depended on scattering by TSM. Therefore, red band (band 3) or near-infrared band (band 4) with long wavelengths were often used to retrieve TSM or turbidity from Landsat data (Bernardo et al., 2017; Islam et al., 2002; Joshi et al., 2017b; Lymburner et al., 2016; Saliot et al., 2002; Wang et al., 2007, 2009). For the Changjiang River, Wang et al. (2009) used the single band 4 of Landsat ETM+. At short wavelength (band 1), NAP strongly absorbed irradiance and had greatly impacts on decreasing water reflectance. Therefore, ratio of $R_{rs}(\text{band} 4)/R_{rs}(\text{band} 1)$ increased with increasing TSM concentration. To retrieve TSM in the CRE from space, He et al. (2013) also used a similar index ($R_{rs}(745 \text{ nm})/R_{rs}(490 \text{ nm})$).

By setting TSM = 30 and 120 mg/L, we calculated $R_{rs}(\text{band} 4)/R_{rs}(\text{band} 1)$ ratio with different $a_{\text{CDOM}}$ and Chl-a values. Results in Fig. 4. The formula is $y = 0.0112x + 0.1115$, with $R^2=0.88$, $p=0.01$, and RMSE = 0.15 mg/L.

Fig. 2. Validations of the bio-optical simulation. (a) Comparisons between modeled and in-situ $a_n$. (b) Comparisons between modeled and in-situ water reflectance. For Band 1, Band 2, Band 3, and Band 4, we used central wavelengths of Landsat-5 TM. Landsat-7 ETM+ had similar visible light bands setups as Landsat-5 TM (Section 3.3).

Fig. 3. Algorithms for retrieving POC and validations. (a) Comparisons between modeled TSM using in-situ water reflectance and in-situ TSM. (b) Correlation between in-situ POC and TSM at Datong. (c) and (d) are comparison results between in-situ and modeled POC calculated from in-situ water reflectance using spectral response functions of Landsat-5 TM and Landsat-7 ETM+, respectively.
showed that variations of both $a_{\text{CDOM}}$ and Chl-a had not significant impacts on $R_s(band4)/R_s(band1)$. With TSM = 30 mg/L, $a_{\text{CDOM}}$ and Chl-a could vary $R_s(band4)/R_s(band1)$ by 6.85% (Fig. 4a); with TSM = 120 mg/L, $a_{\text{CDOM}}$ and Chl-a could vary $R_s(band4)/R_s(band1)$ by only 2.01% (Fig. 4b). In addition, with complex components and aerosol types, precise atmospheric correction of inland waters was still not achievable (Bernardo et al., 2017; He et al., 2013; Kutser, 2012). In this case, band ratio algorithm also allowed removal of atmospheric correction errors to a certain extent (IOCCG, 2018; Kutser, 2012). Therefore, $R_s(band4)/R_s(band1)$ ratio was used to ratio to retrieve TSM.

Using the developed algorithms, we calculated POC concentration from in-situ water reflectance (Section 3.2). For Landsat-5 TM, relative error (RE) ranged from 0.12% to 32.62%, with ARE of 10.22% (Fig. 3c); for Landsat-7 ETM+, their ARE were 16.23% and 14.32%, respectively (Fig. 3d). Islam et al. (2002) and Wang et al. (2009) had proposed algorithms to retrieve TSM using single bands 3 and 4 of Landsat data, respectively. For comparison, we calibrated both algorithms using our in-situ data and estimated POC. Our band ratio algorithm was better; for Landsat-5 TM, their ARE were 16.23% and 14.32%, respectively (Fig. 3d); for Landsat-7 ETM+, their ARE were 16.23% and 14.33%, respectively (Fig. 3d).

The developed algorithm was also applied to Landsat-derived water reflectance to estimate POC concentration. During the sampling year (Section 3.1), only eight scenes of Landsat-7 ETM+ data were available and cloud-free at Datong. By following the match-up criteria used by NASA (Bailey and Werdell, 2006), only in-situ POC on May 12, 2015 had valid match-up. The satellite-derived POC had absolute error (AE) of 0.19 mg/L and RE of 42.22% (Fig. 4c). Using Eq. (7), YSI-measured POC was calculated from YSI-measured TSM (Section 3.1). For the YSI-measured POC, 21 match-ups were found, with ARE = 33.82% (Fig. 4c). In addition, we found that monthly mean satellite-derived POC varied consistently with monthly mean TSM from the MWRC, with Pearson’s $r = 0.41$ and $p < 0.01$ (Fig. 5a). Overall, the developed algorithms were applicable for retrieving POC in the Changjiang River from Landsat data.

5. Results

5.1. Variations in POC concentration

Fig. 6 shows the in-situ POC concentrations at different stations and depths from May 2015 to May 2016 (Section 3.1). For each station, POC at three depths were usually close, especially at the station P1 (Fig. 6). At the north station P1 (Fig. 1b), POC ranged from 0.47 to 1.34 mg/L; mean POC at the surface, middle, and bottom depths were 0.74 mg/L, 0.77 mg/L, and 0.77 mg/L, respectively (Fig. 6a). At the middle station P2 (Fig. 1b), POC ranged from 0.44 to 1.15 mg/L; mean POC at the three depths were 0.68 mg/L, 0.67 mg/L, and 0.71 mg/L, respectively (Fig. 6b). At the south station P3, POC ranged from 0.37 to 0.99 mg/L; mean POC at the three depths were 0.68 mg/L, 0.67 mg/L, and 0.67 mg/L, respectively (Fig. 6c). For a specific depth across the Datong section (Fig. 1b, c), POC in the north (P1) was slightly higher than that in the south (P3). The riverbed was covered by sediment in the north, but rock in the south, and thus sediment resuspension was more significant in the north. However, due to low flow velocity, sediment resuspension in the north was limited, especially in winter with low water flow at Datong (Fig. 6d). For all three stations across the Datong section (Fig. 1b), mean POC concentration was lowest in May 2015 and highest in April 2016 (Fig. 6d). Moreover, there was no significant relationship between in-situ POC and water flow (Fig. 6d). In general, POC concentration at Datong was spatially consistent, but time-varying (Fig. 6).

With temporally varied POC at Datong, it is necessary and achievable to monitor POC concentration and flux from long-term archived Landsat data. The developed algorithms (Section 4.2) were applied to derive mean POC concentration in region R (Fig. 1b) from Landsat reflectance data (Section 3.3). Results are shown in Fig. 5a. Landsat-derived POC concentration was significantly time-varying, with a
minimum of 0.26 mg/L on 8 February 2016 and a maximum of 8.1 mg/L on 26 September 2001 (Fig. 5a). During 2000–2016, monthly mean POC concentration ranged from 0.83 to 2.41 mg/L, with minimum in April and maximum in September. Moreover, POC concentration decreased exponentially with respect to time from 2000 to 2016, with $R = 0.46$ and $p < 0.01$ (Fig. 5a). Within each stage of TGD operation, it was also the same; from 2000 to 2010, the exponential fitting results were $R = 0.33$ and $p < 0.01$; and from 2011 to 2016, the exponential fitting results were $R = 0.37$ and $p < 0.01$.

The monthly decrease trend of POC concentration was mainly driven by its significant decrease in wet season. From satellite-derived POC, we calculated seasonal mean POC concentrations in the wet and dry seasons (Fig. 5b). Seasonal mean POC varied greatly in different years. Along with the TGD construction, seasonal variability in POC

![Time-series of satellite-derived POC.](image)

**Fig. 5.** Time-series of satellite-derived POC. (a) Satellite-derived POC concentrations during 2000–2016. Water level of the TGD reached 135 m in June 2003, 156 m in October 2006, and 175 m in October 2010, respectively. (b) Seasonal mean POC concentration. The wet season contained months from May to October, and the dry season contained all other months in the same year. (c) Seasonal mean POC concentrations in different periods. Period I included years during 2000–2005; Period II included years during 2006–2010; and Period III included years during 2011–2016.

![In-situ POC concentrations at Datong from May 2015 to May 2016.](image)

**Fig. 6.** In-situ POC concentrations at Datong from May 2015 to May 2016. Sampling locations were shown as Fig. 1. Monthly water flow at Datong was from the MWRC (2000–2016).
concentration decreased from 2000 to 2016 (Fig. 5b). After 2011, mean POC concentrations in both wet and dry seasons were very close (Fig. 5b). According to the TGD construction phase (Fig. 5a), we investigated three periods: 2000–2005 (Period I), 2006–2010 (Period II), and 2011–2016 (Period III). Differences in seasonal POC concentrations were significant in Period I, but not in Period II and III (Fig. 5c).

5.2. Variations in POC flux

With spatially consistent POC concentration at Datong section (Fig. 6), Landsat-derived surface POC concentration in region R could represent the mean POC concentration across the entire Datong section. In each month, we took the arithmetic mean of all Landsat-derived POC concentrations as the monthly mean value. By multiplying monthly mean POC concentration by water flow at Datong, we obtained the monthly POC flux, as shown in Fig. 7a.

During 2000–2016, monthly POC flux ranged from a minimum of $1.4 \times 10^4$ t in February 2016 to a maximum of $52.04 \times 10^4$ t in May 2002, with a mean of $13.04 \times 10^4$ t/month. Moreover, POC flux in 2009 was $1.35 \times 10^5$ t C/yr, only 12.94% lower than the reported value using monthly in-situ data by Wang et al. (2012). Due to POC concentration decrease in wet season (Fig. 5b), monthly POC flux also showed significant decrease from 2000 to 2016, with $R = 0.33$ and $p < 0.01$ (Fig. 7a). Monthly POC flux also seasonally varied, with high values in the wet months, and was positively exponentially related to water flow ($R = 0.69, p < 0.01$) (Fig. 7b). About 75.01% of POC transport happened in the wet season.

From monthly water flow and POC flux in Fig. 7a, we also calculated monthly climatologic POC fluxes (arithmetic means), as shown in Fig. 7c. Monthly climatologic POC flux ranged from a minimum of $4.47 \times 10^4$ t C in February to a maximum of $17.61 \times 10^4$ t C in September, with a mean of $9.55 \times 10^4$ t C/month (Fig. 7c). Monthly climatologic POC flux was also significantly related to water flow, with $R^2 = 0.91$ and $p < 0.01$ (Fig. 7c).

6. Discussions

6.1. Relationship between POC and TSM

At Datong, POC was linearly related to TSM concentration (Fig. 3b). In other form, POC content in TSM (POC(%TSM)) decreased by means of an inverse proportional function with increasing TSM, with $R^2 = 0.48$ and $p < 0.01$ (Fig. 8). At Datong, POC(%TSM) was lower than the fitted values of global rivers (Ludwig et al., 1996) and tropical rivers (Huang et al., 2012). Moreover, even the fitted curve of the Changjiang mainstream (Zhang et al., 2014) was not suitable for Datong, especially for waters with high TSM concentrations (Fig. 8).

The relationship between POC and TSM concentration was determined by POC compositions. Riverine POC is categorized as autochthonous from phytoplankton and allochthonous from soil (Saliot et al., 2002). Autochthonous POC is composed of phytoplankton and related particles with high POC(%TSM), and is an important component in rivers with relatively flat gradients (Gao et al., 2002). Allochthonous POC includes highly decomposed organic matter from soil, vegetation, and weathered material with low POC(%TSM) (Gao et al., 2002; Wang et al., 2012). At Datong, in-situ TSM was $51.11 \pm 22.13$ mg/L (Table 1). High TSM concentration inhibited phytoplankton growth because of light limitation (Ran et al., 2013). With great water discharge (Bai et al., 2013, 2014), high flow velocity was also disadvantageous to phytoplankton growth (Gao et al., 2002). In these
POC(%TSM) exponentially decreased with increasing TSM concentration. For the Changjiang mainstream, Zhang et al. (2014) reported that there was a power relation between POC(%TSM) and TSM concentration. For open oceans, POC was majorly sourced from phytoplankton and POC algorithm usually used remote sensing reflectance at Chl-a sensitive blue or green band (Stramski et al., 1999), or their ratios (Stramski, 2009; Stramski et al., 2008). The same as the Pearl River Estuary (Liu et al., 2015a), POC was majorly sourced from NAP at Datong and near-infrared band sensitive to NAP was used (Section 4.2). With similar source, moreover, relationship between POC and TSM might also be different (Gao et al., 2002; Milliman et al., 1984). Along the Pearl River, POC and TSM showed a positive linear relation at the Makou hydrological station (Gao et al., 2002), but a power function at eight river outlets (Ni et al., 2008). Jiang et al. (2015) reported that it was unlikely to develop a POC algorithm that was independent of POC sources, but the two-step process allowed for a common approach to identify appropriate algorithm. By referring to others (Jiang et al., 2015; Stramski et al., 1999), therefore, a two-step POC algorithm based on the significant correlation between POC and TSM was developed (Fig. 3b).

6.2. Impact factors on POC transport at Datong

The TGD had great impacts on POC decrease at Datong. Yang et al. (2007) reported that sediment flux across the Datong section was majorly sourced from the upstream of the TGD. Monthly TSM showed significant decrease during 2003–2016 at Yichang, only 40 km downstream of the TGD, with $R = 0.51$ and $p < 0.01$ (Fig. 9a). Moreover, there was also a significant linear correlation between monthly TSM concentration at Yichang and that at Datong, with $R^2 = 0.65$ and $p < 0.01$. It has been reported that the TGD had little impact on water discharge (Bai et al., 2014; Duan et al., 2008), but drastically altered the sediment flux (Xu and Milliman, 2009; Yang et al., 2006). Xu and Milliman (2009) reported that the TGD trapped about 60% of upstream sediment during 2003–2006. Across China, Chu et al. (2009) reported that dam/reservoir construction accounted for 56% of sediment reduction in nine major Chinese rivers entering oceans during 1959–2007. Globally, Maavara et al. (2017) reported that dam/reservoir buried allochthonous POC by only 9.83 ± 2.97 Tg C/yr in 1970, but 20.91 ± 6.46 Tg C/yr in 2000; moreover, the value would be 40.17 ± 26.93 Tg C/yr in 2030.

The TGD had also decreased the seasonal POC variations at Datong. After the TGD, TSM at Yichang was significantly decreased, especially in the wet season (Fig. 9a), which was time consistent with POC at Datong (Fig. 5b). From 2003 to 2016, both the SD of monthly POC concentration at Yichang and the SD of satellite-derived POC concentration at Datong decreased significantly and were linearly correlated ($R^2 = 0.62$, $p < 0.01$) (Fig. 9b). All these indicated the weakening effects of the TGD on seasonal variability of POC concentration at Datong. Based on biweekly sampling in the CRE from 2003 to 2011, Wu et al. (2016) also reported that the TGD had decreased the seasonal variations of terrigenous organic matter in the Changjiang River. For the Mekong River, Lu and Siew (2006) also reported that dams had significantly decreased monthly TSM in several hydrological stations.

Climate fluctuation also had impacts on POC transport at Datong. High in-situ POC in April 2016 (Fig. 6) was due to the large precipitation under a strong El Niño event in 2016 (Fig. 10). El Niño would increase precipitation over the middle and lower reaches of the Changjiang River (Yu and Zhai, 2018). Because of strong El Niño events around 2003, 2010, and 2016, water flows were significant high in summer at Datong, but not at Yichang (Fig. 10). High precipitation would flush a great deal of terrigenous POC into rivers (Ran et al., 2013). During 2000–2016, maximum monthly Ocean Niño Index (ONI) was

Fig. 8. The relationship between in-situ POC(%TSM) and TSM concentration. Ludwig et al. (1996) reported a global fitting curve based on data from 60 world-wide rivers with relatively flat terrain and small precipitation gradients in Europe, America, and tropical Africa. For tropical rivers, Huang et al. (2012) reported that there was power relation between POC(%TSM) and TSM concentration. For the Changjiang mainstream, Zhang et al. (2014) reported that POC(%TSM) exponentially decreased with increasing TSM concentration.

Fig. 9. Impacts of the TGD on POC transport at Datong. (a) Variations in monthly total water flow and mean TSM concentration at Yichang during 2003–2016. Data before 2003 was unavailable. (b) SD of satellite-derived POC concentration at Datong and that of monthly mean TSM at Yichang in different years.
significantly related to maximum monthly water discharge at Datong, with $R = 0.57$ and $p < 0.01$. The same as TSM (Feng et al., 2014), variations of POC from the Changjiang River would further change POC in the CRE and its adjacent coastal waters.

6.3. POC concentration along the Changjiang mainstream

POC concentration spatially varied along the Changjiang mainstream. Flow velocity at Datong was usually high in the wet season (Duan et al., 2008). With high flow velocity, bottom sediment would be re-suspended so as to increase POC concentration. This partly explained the usually high POC concentration at Datong in the wet season (Fig. 5a). On the contrary, suspended sediment would also deposit to bottom and decrease riverine POC. With low water flow velocity, POC was found to be low in the TGD region (Zhang et al., 2014). Based on in-situ data, Zhang et al. (2014) reported that surface POC concentration in the Changjiang mainstream (from the Fuling city to the CRE) ranged from 0.2 to 2.4 mg/L in April 2006, but from 0.2 to 1.3 mg/L in April 2008. In these cases, satellite remote sensing could improve our understanding about spatial variations of POC concentration along the Changjiang mainstream.

Fig. 11 shows the Landsat-derived POC concentration in the mainstream from the Yichang to Datong, covering a length of ~1000 km. With large slope gradient, riverbed flushing was...
significant from Yichang to Hankou (MWRC, 2000–2016). As results, POC concentration showed an increase along the short river reach downstream of Yichang and then tended to be stable on 30 May 2011, but increased gradually after Changlingli on 8 June 2011 (Fig. 11). Besides different topography, this might due to low water flow of $2.43 \times 10^{10}$ m$^3$/month at Yichang in May 2011, but $4.19 \times 10^{10}$ m$^3$/month in June 2011 (MWRC, 2000–2016). In June 2011, about $8.05 \times 10^8$ m$^3$/day of water was discharged into the Changjiang mainstream from the Dongting Lake (MWRC, 2000–2016). This considerable water flow increased riverbed erosion and continually increased the POC concentration from Changlingli to Hankou (Fig. 11).

Xu and Milliman (2009) also reported that riverbed erosion mainly took place in mainstream from Yichang to Hankou. In July 2011, water flow at Yichang was higher than that in June 2011 (MWRC, 2000–2016), resulting in the high POC concentration downstream of the Hankou (Fig. 11). On 28 July 2011, POC concentration showed no obvious changes from Hukou to Datong (Fig. 11), likely due to the diminished riverbed erosion (Xu and Milliman, 2009). Moreover, with small slope gradient and wide watercourse, suspended POC might even deposit to bottom. In summary, POC concentration in the Changjiang mainstream is dependent upon the combined effects of water flow, slope gradient and watercourse width.

7. Conclusions and outlook

At Datong, water reflectance was primarily determined by TSM concentration. Due to limited in-situ data, we simulated water reflectance based on a bio-optical model and developed a two-step POC remote sensing algorithm using the reflectance ratio of near-infrared to blue band ($r_{\text{blue}}(\text{band})/r_{\text{near-infrared}}(\text{band})$) for Landsat data. From 2000 to 2016, both POC concentration and flux at Datong were significantly seasonally varied, with high values in the wet seasons. Under the influence of the TGD, both POC concentration and flux significantly decreased by following exponential functions. After regular TGD runs, riverine particulate organic carbon in the Xiangjiang River (South China): seasonal variation in content and flux budget. Environ. Geol. 41, 826–832.


