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Key Points:

- 2015/2016 El Niño event induced a positive precipitation anomaly that increased FDOM_H export during dry seasons from a subtropical watershed
- The wetter El Niño dry season was followed by lower FDOM_H export during the subsequent wet season
- Watershed processes buffered FDOM_H export relative to the El Niño-induced increase of precipitation/discharge

Supporting Information:

- Supporting Information S1

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El Niño-Driven Dry Season Flushing Enhances Dissolved Organic Matter Export From a Subtropical Watershed

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Abstract The 2015/2016 super El Niño event resulted in a positive precipitation anomaly during dry seasons in the Jiulong River watershed, southeast China. Four years (2014–2017) of high frequency, in situ humic-like fluorescent DOM (FDOM_H) data in the Jiulong Estuary were coupled with extrapolation to a freshwater end-member FDOM_H concentration and river discharge data to estimate riverine FDOM_H export. The wetter El Niño dry season was followed by lower FDOM_H export during the subsequent wet season. Furthermore, in the dry season after El Niño reached its strongest phase, a 90–187% increase in FDOM_H export occurred. If widespread, this pattern suggests El Niño events may enhance export of FDOM_H from south China rivers in dry seasons resulting in seasonal and annual shunting of the terrestrial DOM export, modulating coastal carbon cycling. This study highlights the need to incorporate climate-driven regulation patterns on DOM transport across the land-ocean interface.

1. Introduction

El Niño Southern Oscillation (ENSO) is one of the most significant climate perturbations on Earth. ENSO causes large-scale anomalous atmospheric circulation patterns and hydroclimate extremes (e.g., floods and droughts) around the world (Chen et al., 2017), dramatically changing terrestrial and oceanic carbon cycles (Bastos et al., 2018; Tian et al., 1998). The 2015/2016 super El Niño event, the strongest and longest-lasting event (i.e., 19 months) ever recorded, induced a widespread precipitation anomaly around the Pacific Ocean. Contrary to unprecedented high temperature and drought conditions in Southeast Asia and Australia (Pepler, 2016; Thirumalai et al., 2017), a strong positive precipitation anomaly occurred in southeast China and coastal areas of the temperate United States during the El Niño (Lim et al., 2017; Ma et al., 2018). In particular, a series of unusual rainstorm events occurred during the normal dry seasons, resulting in a seasonal to annual shift in hydrological patterns in affected watersheds.

Export of terrestrial dissolved organic matter (DOM) to coastal waters represents an important link between terrestrial and oceanic carbon pools (Battin et al., 2009; Bauer & Bianchi, 2011). Different from normal wet season rainstorm events (Fellman et al., 2009; Yang et al., 2013), the El Niño-driven “wet” dry season may induce a seasonal shunting of watershed DOM export and other perturbations (e.g., nutrients and suspended sediments) on coastal ecosystems. Due to their long-term duration, El Niño impacts exert much longer perturbations than episodic rainstorm events on riverine DOM export from watersheds (Medeiros et al., 2015). This implies that El Niño-regulated DOM export has a notable climate-driven regulation pattern on seasonal to annual time scales, unlike the weather-driven patterns occurring on much shorter time scales (Raymond et al., 2016). Due to lack of monitoring programs that cover entire El Niño life cycles, there is an important knowledge gap limiting our understanding of how these climate events regulate carbon cycle between the land-ocean interface.

Long-term perturbation of El Niño events on watersheds makes it crucial to deploy effective monitoring tools that provide reliable, continuous, and high-frequency DOM measurements, such as in situ optical fluorescent DOM (FDOM) sensors (Saraceno et al., 2009; Wymore et al., 2018). The excitation-emission wavelength of current commercial FDOM sensors represents humic-like FDOM (FDOM_H) components,

which are considered a good proxy for the terrestrial DOM fraction (Coble, 1996; Guo et al., 2014; Yang et al., 2019). In many aquatic systems, FDOM is highly correlated with DOC (Guo et al., 2011; Webb et al., 2018), suggesting that FDOM sensors provide an effective tool for monitoring watershed DOM dynamics and export (Shultz et al., 2018; Wymore et al., 2018).

Here we present 4 years (2014–2017) of FDOM_H sensor data, demonstrating that the 2015/2016 El Niño-driven precipitation anomaly initiated an extraordinary dry season flushing of DOM from a subtropical river of southeast China. Confinement of this DOM flux within the winter monsoon-driven coastal currents suggests that the seasonal shunting of peak watershed DOM fluxes to coastal areas in El Niño years possibly changes CO₂ flux patterns between land-atmosphere and ocean-atmosphere interfaces. This study highlights the need to include spatiotemporal shunting of DOM export patterns by unusually “wet” dry seasons into models of DOM transport across the land-ocean interface.

2. Materials and Methods

2.1. Study Area

The Jiulong River, a medium-sized subtropical river in Fujian Province, China, has a length of 258 km and a drainage area of 14,741 km². Watershed land cover is dominated by forests (69.4%) (Yang et al., 2012). Mean population density is >200 persons per km², with intensive human activities (e.g., sewage discharge, agriculture, and animal husbandry) affecting water quality (Yu et al., 2015). Over 100 hydropower stations are distributed within the watershed, thus increasing the water residence time especially during the low flow period (Gao et al., 2018). The annual mean temperature and precipitation are 19.9–21.1°C and 1,400–1,800 mm, respectively. The hydrological cycle in Jiulong River watershed consists of a pre-dry season (January–March), wet season (April–September) that includes monsoon rain (April–June) and typhoon rain (July–September) periods, and post-dry season (October–December). The East Asian monsoon generally contributes ~75% of precipitation during the wet season (Huang, 2008). There are two major tributaries (north and west) to the Jiulong River that converge at the head of the Estuary, with a multi-year average runoff of 814 mm year^{−1} discharging into the Taiwan Strait. Tides in the estuary are semidiurnal with a mean tidal range of 2.7–4.0 m (Guo et al., 2011).

2.2. Buoy Deployment and Data Processing

A buoy equipped with multi-parameter sensors (YSI, Yellow Springs, OH), including an EXO FDOM_H Sensor Ti 599104-01 (Ex/Em = 365 ± 5/480 ± 40 nm) with automatic temperature compensation, was deployed at a depth of 0.8 m in the middle reach of Jiulong River Estuary (Figure S1a in the supporting information). This location avoided the estuarine turbidity maximum zone in the upper estuary. A central wiper and copper tape were installed on the sonde to inhibit biofouling. All sensor data (temperature, salinity, turbidity, and FDOM_H) were collected at a 30 min interval. Fluorescence intensity of the FDOM_H sensor was standardized to quinine sulfate units (QSUs) using a two-point calibration during monthly maintenance.

As an optical monitoring tool, the FDOM sensor performance was susceptible to inner filter effects (IFE) caused by high DOC and turbidity concentrations (Downing et al., 2012). As a result, correction procedures are often necessary for obtaining reliable data (see details in the supporting information). After correction, 92.7% of FDOM_H data were available for analysis during the study period (1 January 2014 to 31 December 2017). We were not able to correct 1.6% of the data due to high turbidity during the flood tide period and equipment malfunction or maintenance accounted for the remaining 5.7% of the missing data record.

2.3. Estimate of River End-Member FDOM_H and Flux Calculation

FDOM_H for the river end-member was estimated using the classical effective concentration method (Officer, 1979; Figures S2a–S2c). As all FDOM_H data within each tide cycle showed strong conservative mixing behavior in medium and high salinity waters ($R^2: 0.95 \pm 0.06$) (Figure S3), a simple regression line was established for each flood/ebb tide and extrapolated to zero salinity to obtain the effective FDOM_H (C_0 , QSU). The actual river end-member FDOM_H was lower than this effective FDOM_H due to contributions from estuarine addition (e.g., particle desorption and sediment resuspension) in low-salinity waters (Guo et al., 2011). However, effective FDOM_H reflects the variation tendency of the river end-member FDOM_H as the seasonal bias from estuarine addition was small (~2%), with slightly higher additions only

during the drought season (~5%). This small bias did not influence the statistical significance of $FDOM_H$ between different seasons (see sections 4.2 and 4.3). Daily $FDOM_H$ was the average of estimated $FDOM_H$ for each tide cycle. For missing/uncorrectable sensor data that occurred at steady-flow conditions, the daily $FDOM_H$ of the river end-member was estimated by a mathematical smoothing method. For missing/uncorrectable sensor data that occurred during storm event periods, missing peak values were set as two times that of the smoothed data based on a previous storm event study (Yang et al., 2013).

The daily $FDOM_H$ flux was determined as

$$F_{DOM} = C_{0d} \times Q_d, \quad (1)$$

where F_{DOM} represents the export $FDOM_H$ flux eventually discharged into the sea (Officer, 1979), which included a relatively stable estuarine addition flux throughout the different seasons (Guo et al., 2011), and C_{0d} and Q_d are daily effective $FDOM_H$ (QSU) and daily discharge ($m^3 day^{-1}$, from hydrological stations on North and West River tributaries; Figure S1a). As one QSU is equal to the fluorescence intensity of $1 \mu g L^{-1}$ (i.e., $10^3 \mu g QS$ equivalent m^{-3}) quinine sulfate (QS) at 350 nm excitation and 450 nm emission wavelengths, the units of daily $FDOM_H$ flux were $\mu g QS$ equiv day^{-1} (Yamashita & Tanoue, 2008).

To identify the $FDOM_H$ flux contributed by rainstorm events, baseflow was first calculated by an automatic segmentation procedure (Smoothed Minima method) (Nathan & McMahon, 1990). A storm event was designated as a flow peak that exceeded two times the yearly average discharge, and which started and ended when discharge was more than 1.2 times the previous baseflow (Gao et al., 2018). The antecedent precipitation index (API) was calculated as

$$API = \sum K^i P_i, \quad (2)$$

where K is a constant ($K = 0.85$) and P_i is precipitation for 1, 2, 3, ..., i days ($i = 14$) prior to the flood event ($API < 15$: dry; $15 < API < 30$: medium; $API > 30$: wet).

3. Results

The hydrological cycle in Jiulong River watershed showed large annual and seasonal variations between 2014 and 2017. Total annual precipitation was 1,518, 1,754, 2,314, and 1,350 mm (Figure 1b), with significantly ($p < 0.05$) higher precipitation in the 2016 El Niño year. The number of rainstorm events (11) in 2016 was also higher than the other years (6, 9, and 6 for 2014, 2015, and 2017; Table S1). At the seasonal scale, precipitation during the wet season across all 4 years showed no significant difference ($p > 0.05$; Figure 1c). However, precipitation amounts for both pre-dry and post-dry seasons of 2016 (604 and 408 mm) and post-dry season of 2015 (235 mm) were all significantly higher than other dry seasons (73–199 mm; $p < 0.05$). Notably, abnormal rainfall events in the pre-dry season of 2016 (Figure 1c) delivered as much precipitation as its wet season, creating a large anomaly to the normal precipitation pattern.

Daily discharge of the Jiulong River from 2014 to 2017 fluctuated between 0.4 and $27.0 mm day^{-1}$, with average annual discharge of 2.1, 2.3, 4.3, and $2.3 mm day^{-1}$, respectively (Figure 1b). Consistent with the higher precipitation and frequent rainstorm events in 2016 (Table S1), discharge in 2016 was also higher than the other 3 years ($p < 0.05$). At the seasonal scale, discharge in both wet and dry seasons of 2016 was higher than the respective wet and dry seasons of the other 3 years ($p < 0.05$; Figure 1d). Notably, discharge in the two dry seasons of 2016 showed no difference from the other wet seasons ($p > 0.05$; Figure 1d). The atypical six storm events during the 2016 dry seasons had high average (3.6 – $7.6 mm day^{-1}$) and peak (9.5 – $24.8 mm day^{-1}$) discharges. In contrast, storm events in dry seasons of the other years were only observed in late 2015 and early 2017 and had much lower average (2.5 – $3.8 mm day^{-1}$) and peak (5.2 – $10.1 mm day^{-1}$) discharges.

Daily $FDOM_H$ of the freshwater end-member ranged from 5.2 to 45.3 QSU (Figure 1b), with an average of 19.7 ± 5.4 QSU from 2014 to 2017. Annual average $FDOM_H$ in 2016 (14.7 ± 4.7 QSU) was lower than the other 3 years (2014: 21.4 ± 3.6 ; 2015: 21.5 ± 5.4 ; and 2017: 21.2 ± 4.7 QSU) ($p < 0.05$). At the seasonal scale, $FDOM_H$ in the dry seasons of 2014/2015 and post-dry season of 2017 was significantly higher ($p < 0.05$) than the other dry seasons (Figure 1e). $FDOM_H$ consistently decreased from the 2015 pre-dry season to their lowest average values in the 2016 pre-dry season, followed by a general increase through 2017. At the

Figure 1. El Niño 3.4 index, meteorological, hydrological, and freshwater (river) end-member FDOM_H data in Jiulong River watershed during the study period. (a) Niño 3.4 index is a 3-month running mean of sea surface temperature anomalies; (b) time series of daily precipitation, river discharge, and freshwater end-member FDOM_H. Daily precipitation data were the average of eight weather stations distributed throughout the watershed (<http://www.weather.com.cn/>). (c–f) Seasonal variation of total precipitation, total discharge, daily average FDOM_H, and total FDOM_H flux in the four hydrologic seasons. Different letters indicate significant difference at $p < 0.05$.

storm-event scale, FDOM_H showed two contrasting responses to discharge fluctuations. (Type I) peak FDOM_H occurred before or was coincident with peak discharge (Figures 2 and S4), while (Type II) peak FDOM_H occurred later than peak discharge (Figures 2 and S5). Notably, the antecedent precipitation index (*API*) of Type I events (16.9 ± 9.0 mm), an assessment of catchment moisture status prior to a storm event (Table S1), was significantly lower than for Type II events (20.5 ± 14.1 mm) ($p < 0.05$).

Annual FDOM_H export fluxes from the Jiulong River watershed were 2.42×10^{14} , 2.59×10^{14} , 3.54×10^{14} , and 2.64×10^{14} μg QS equiv year⁻¹ from 2014 to 2017, respectively (Table S2). The FDOM_H flux in 2016 was 136–146% higher than the other 3 years ($p < 0.05$). The percentage contribution of FDOM_H fluxes by storm events accounted for as high as 69% in 2016 (Table S2). At the seasonal scale, FDOM_H fluxes in wet seasons were higher than dry seasons ($p < 0.05$; Figure 1f). Further, fluxes in the 2016 dry seasons were higher than in other dry seasons ($p < 0.05$; Figure 1f). The percentage of flux contributions by storm events during dry seasons from late 2015 to early 2017 were 45%, 75%, 70%, and 24%, respectively (Table S2). FDOM_H fluxes in other dry seasons were contributed only by baseflow.

4. Discussion

4.1. Hydrologic Response to 2015/2016 El Niño Event

The 2015/2016 super El Niño event created abnormal precipitation events across many global regions (e.g., Southeast China and Western United States) (Chen et al., 2018; Lim et al., 2018; Ma et al., 2018). In the Jiulong River watershed, a total of 10 rainfall events occurred during the dry seasons from late 2015 to early 2017 (Table S1). In particular, extremely high precipitation occurred during the pre-dry season of 2016 after the peak of this extreme climatic event (December 2015). High precipitation also occurred

Figure 2. Assessment of two types of storm events for the study period (2014–2017) based on the lag time between peak FDOM_{H} and peak discharge (after correction for the time difference between peak discharge and minimum sensor salinity within each storm event). Negative or zero lag times indicate peak FDOM_{H} occurs before or is coincident with peak discharge (Type I). Positive lag time implies peak FDOM_{H} occurs later than peak discharge (Type II). The lag times of all events were evaluated by linear regression tests.

during the post-dry season of 2016 after the positive sea surface temperature anomalies over the basin-wide Indian Ocean in summer of 2016 (Chen et al., 2018). This indicates a 1–2 month lag time in the precipitation response to the 2015/2016 El Niño event ($p < 0.05$; Figure S6).

Delay in the regional climate response to super El Niño events was previously reported (Ma et al., 2018). El Niño events may cause a large-scale anomaly for the western North Pacific anticyclone (WNPAC) (Yuan & Yang, 2012). The WNPAC enhances precipitation in southeastern China through modulating the western North Pacific subtropical high and further regulating atmospheric moisture transport (Chen et al., 2014). Given the time required for atmospheric moisture transport, the precipitation lag period in Jiulong River watershed maybe expected. Indeed, El Niño-related WNPAC could persist from an El Niño winter to the subsequent summer, even if the El Niño has already dissipated (Chen et al., 2018). Thus, we posit that the above-normal rainfall anomaly in dry seasons from late 2015 to early 2017 was directly related to the 2015/2016 El Niño event (Figure 1c).

Discharge patterns of Jiulong River generally followed the variation of precipitation in the watershed (Figures 1c and 1d), consistent with the general regulation mode of river runoff by watershed rainfall (Gao et al., 2018; Yang et al., 2013). Although the precipitation amount in the 2016 pre-dry and wet seasons

showed no difference ($p > 0.05$), the runoff in the wet season was significantly higher than the pre-dry season ($p < 0.05$) (Figure 1d). Soil moisture status in the watershed increased after the El Niño-induced increase of rainfall during the 2015/2016 dry seasons. As a result, the runoff-to-rainfall coefficient in the 2016 wet season increased; that is, a greater fraction of rainfall becomes runoff as opposed to recharging soil water storage (Norbiato et al., 2009). Likewise, the rainfall amount in the 2016 post-dry season was lower than in the pre-dry season ($p < 0.05$), but the post-dry season runoff maintained a similar level ($p > 0.05$) (Figures 1c and 1d).

Figure 3. Relationship of FDOM_H concentration and baseflow discharge (mean $\pm$ std dev). Baseflow is defined as the time between storm events.

4.2. Response of FDOM_H Dynamics and Fluxes to El Niño Event During Dry Seasons

Consistent with the distinct changes in dry season hydrology, FDOM_{H} dynamics during baseflow periods of dry seasons also changed. The highest FDOM_{H} concentrations (24 ± 3.3 QSU) occurred in the non-El Niño 2014/2015 dry seasons and 2017 post-dry season, that is, the lowest baseflow periods during the 2014–2017 study (Figure 3). These FDOM_{H} values remained the highest and were higher than other seasons ($p < 0.05$) even

after subtracting the additional signal ($\sim 5\%$) from low-salinity estuary waters during drought seasons (Guo et al., 2011). Similarly high FDOM_H followed an extreme drought period during the 2008/2009 dry seasons in this watershed (Guo et al., 2011; Hong et al., 2012). During drought periods, the reduction of river flow, exacerbated by reservoir impoundment, increased water residence time and enhanced in situ production of FDOM_H in this eutrophic river (Hong et al., 2012). FDOM_H derived from agricultural and urban pollution sources also accumulates in the fluvial system during drought periods (Wilson & Xenopoulos, 2009). Although multiple sources contributed to increased FDOM_H concentration, total FDOM_H export flux reached its lowest levels due to the large reduction of discharge (Table S2).

As baseflow discharge during dry seasons increased, FDOM_H decreased (Figure 3, $p < 0.05$) and reached its lowest values in the 2016 pre-dry season ($11.6 \text{ QSU} \pm 2\%$). This indicates that a dilution effect regulates FDOM_H dynamics under El Niño-induced high baseflow conditions. Similar to other storm-event studies in many global watersheds (Fellman et al., 2009; Yang et al., 2013), two extraordinary Type I storm events flushed large amounts of FDOM_H from the watershed (Figure 2). Low antecedent soil moisture (API index: 3.7 and 21.8 mm) and the occurrence of the FDOM_H peak earlier than peak discharge (Figure S4) indicate that FDOM_H was flushed mainly from readily mobilized pools stored in the watershed through surficial flow paths during the early phase of the event (Mann et al., 2012). The FDOM_H source in surficial flow paths could originate from litter leaching and/or anthropogenic sources (Yang et al., 2012). Rapid decrease of FDOM_H during and after peak discharge suggest that the contribution from soil interflow (i.e., leachable FDOM_H in the soil profile) was small during Type I storm events (Yang et al., 2013). Following this flushing process, FDOM_H in baseflow was diluted as further DOM contributions were limited (Bao et al., 2019). As a result, although FDOM_H flux in this “wetter” dry season was 93% and 161% higher than in the normal pre-dry seasons of 2014 and 2015, its increased magnitude was only 40–48% of the corresponding increase in discharge (192% and 400%, respectively). This demonstrates a dilution-induced buffering effect for watershed DOM export under perturbation by the El Niño-induced precipitation anomaly. This is clearly illustrated by the lower rate of increase for cumulative FDOM_H flux compared with cumulative discharge flux (Figure S7) (i.e., deviation below the 1:1 line) after storm events in January 2016. There was a similar, but much weaker, tendency in early 2017 when the El Niño event had nearly dissipated (Figure S7).

The cumulative discharge flux for the 2016 post-dry season was as high as the pre-dry season of 2016, but its FDOM_H export flux was significantly higher than the latter ($p < 0.05$). This suggests a different FDOM_H regulating mechanism for this “wetter” dry season. Precipitation before this post-dry season (1,906 mm) was even higher than the annual precipitation in normal years (1,400–1,800 mm). The high antecedent soil moisture (Table S1) suggests strong FDOM_H leaching from the soil profile via increased contributions from soil interflow (Bao et al., 2019; Yang et al., 2013). As this hydrologic flow path has an appreciable lag time relative to surficial runoff, there is a delay in the FDOM_H peak relative to the discharge peak for three Type II storm events (Figure S5). The increased contribution of soil-derived humic DOM resulted in the baseflow FDOM_H in this pos-dry season being higher than in the pre-dry season ($p < 0.05$) (Figures 1e and 3). High soil moisture status also made the baseflow of the 2016 post-dry season significantly higher than the pre-dry season ($p < 0.05$). As a result, the flux contributed by baseflow in this season was significantly increased. Together with the contribution by storm events (Table S2), FDOM_H flux in the 2016 post-dry season was the highest among all dry seasons (Figure 1f).

4.3. Coupling FDOM_H Dynamics in Monsoon Season With Hydrology of Preceding Dry Season

In monsoon seasons (early stage of wet season), variations in FDOM_H levels and flux showed contrasting patterns between normal and El Niño years. The average FDOM_H in 2015 was clearly above the FDOM_H -baseflow curve of the dry season (Figure 3). The rate of increase in FDOM_H flux was higher than the rate of increase for the discharge flux in 2015 (Figure S7). However, average FDOM_H in the 2016 El Niño year was among the lowest of all monsoon periods and close to the dry season curve (Figure 3). As a result, the rate of increase in FDOM_H flux was lower than the rate of increase for the discharge flux in 2016 (Figure S7).

There were large differences between the API index and the first storm-event type during the monsoon seasons of El Niño and non-El Niño years (Table S1 and Figure 2). This suggests that the hydrologic conditions associated with the pre-dry season may closely regulate FDOM_H dynamics of the subsequent monsoon

season. The low API index (16.7 mm) of a Type I storm event (Event 7) in the 2015 monsoon period suggests that there was effective flushing of FDOM_H stored in the watershed during the extreme dry season drought of 2015. A similar “first-flush effect” for nitrogen and phosphorus has been observed in the Jiulong River watershed and other watersheds (Chen et al., 2015; Ribarova et al., 2008). A dominance of surficial flow paths and the beginning of agricultural activities during this period could provide major sources of FDOM_H (Eckard et al., 2017). In contrast, the variation of FDOM_H and discharge flux rates in 2016 indicates a watershed buffering effect for DOM due to dilution that continued to dominate FDOM_H dynamics after the El Niño-induced “wetter” pre-dry season. Thus, FDOM_H dynamics in the Jiulong River watershed during monsoon seasons demonstrate a close coupling with the hydrology of the preceding dry seasons: enhanced flushing pattern in normal hydrological years versus a buffering effect pattern in El Niño years (Figure 3).

4.4. Significance of El Niño Events on Carbon Cycle Between Land and Ocean

The 2015/2016 super El Niño event triggered a seasonal shunting of FDOM_H export from the Jiulong River watershed. The general pattern of FDOM_H storage in dry seasons followed by wet season flushing in normal hydrological years (i.e., 2014 and 2015) was replaced by an advanced flushing by dry season storm events in the El Niño year. This resulted in a pulse of FDOM_H export in the pre-dry season of 2016. FDOM_H export fluxes were 90–187% higher than that of the 2014 and 2015 pre-dry seasons after El Niño reached its strongest phase. Similar to other river and estuarine systems (Bauer & Bianchi, 2011; Saraceno et al., 2009; Wymore et al., 2018), there was a significant correlation between FDOM_H and DOC in the Jiulong River Estuary (Figure S8; Guo et al., 2011). Thus, it is expected that the export pattern of DOC from Jiulong River resembles that of FDOM_H .

On the larger regional scale, a significant increase of discharge during the El Niño dry period was widespread throughout rivers of south and central China (Table S3). For the two largest rivers in China, the Yangtze and Pearl Rivers (Lin, 2007), which have an average discharge 69 and 28 times higher than the Jiulong River (Milliman & Farnsworth, 2011), discharge during the dry seasons of the El Niño year (2016) was 41–55% and 206–247% higher than in 2014 and 2015. The increase in discharge was much higher for medium and smaller rivers (26–864%), with an average increase of 238% (Table S3). For illustration purposes, we assumed that the watershed buffering effect for these medium and smaller rivers was similar to the Jiulong River (i.e., increase of DOM flux was ~40% of discharge increase) and the large Yangtze and Pearl Rivers had no appreciable buffering effect (Bao et al., 2015). Based on this assumption, the El Niño-induced increase of DOM export to Chinese coastal waters during the post-dry season of 2015 and pre-dry season of 2016 would reach 23–30% and 82–93% higher than the same periods of non-El Niño years, respectively.

Driven by the dominant northeast winter Asian monsoon in dry seasons, El Niño-flushed terrestrial DOM is transported southward along the coasts by the Chinese Coastal Current (Figure S1b). FDOM_H (determined at 365/460 nm) usually represents relatively biologically recalcitrant dissolved organic matter (RDOM) in fluvial systems, and photobleaching/photodegradation destruction of RDOM in the winter dry season is lower than the summer wet season. Thus, the El Niño-enhanced fluvial DOM fluxes may be transported greater distances, thereby enhancing marine carbon cycling and processing as far south as the coast of Viet Nam (Zheng et al., 2006). In contrast, large storm events during wet seasons can often inject a portion of the DOM flux into the open ocean. Given that much of the terrestrial-derived DOM will be eventually degraded to CO_2 (Bianchi et al., 2013; Osburn et al., 2019), El Niño-enhanced transfer of terrestrially derived carbon to the ocean can result in losses of stored carbon from soils to the atmosphere, thereby having a strong impact on coastal carbon cycling dynamics.

On the global scale, it can be expected that the 2015/2016 super El Niño event would similarly enhance DOM export from land to ocean in the western and eastern United States due to increased rainfall and subsequent runoff/leaching (Lim et al., 2018; Yoon & Raymond, 2012). In contrast, a decrease of DOM fluxes may have occurred in parts of southeast Asia (Thirumalai et al., 2017) and the Amazon basin (Bastos et al., 2018) due to extreme drought events. Thus, the 2015/2016 El Niño event could contribute to latitudinal adjustments in terrestrial DOM export. As extreme El Niño events are projected to occur more frequently in a warming world (Thirumalai et al., 2017) and extreme events are not predictable, deployment of long-term FDOM

and water quality monitoring programs is necessary across several global river and estuarine systems to provide critical information to improve assessments of DOM dynamics in response to climatic perturbations (Carstea et al., 2020).

5. Conclusions

Results from our 4-year, high-frequency FDOM_H sensor revealed that a super El Niño event induced seasonal shunting of DOM transport between the land-sea interface. As the dry seasons became much wetter in response to the extreme 2015/2016 El Niño event, there was extraordinary dry season DOM flushing from our watershed in south-central China, influencing carbon biogeochemistry of widespread coastal ecosystems. The wetter El Niño dry season was followed by lower FDOM_H export during the subsequent wet season. These results highlight the need to include annual and seasonal scale DOM export dynamics, as regulated by ENSO events, into models of DOM transport across the land-ocean interface. In situ protein-like fluorescence sensors, which represent biologically labile DOM components, should also be considered in addition to FDOM_H sensors, to provide a powerful tool to assess short-term (e.g., storm events), medium-term (e.g., El Niño or drought events), and long-term perturbations (e.g., climate change) to DOM biogeochemistry in terrestrial and marine ecosystems.

Conflicts of Interest

The authors declared that they have no conflicts of interest to this work.

Data Availability Statement

Daily precipitation and FDOM_H data are available at 4TU.Research Data (<http://doi.org/10.4121/uuid:1b233566-0330-4a23-aade-0b61c3460881>).

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