Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL082014

Key Points:
- Hurricane Matthew delivered 25% of the annual carbon loading to North Carolina coastal waters in 2016
- Wetland-derived terrestrial organic matter persisted in coastal waters for several months following Hurricane Matthew
- Degradation of terrestrial organic matter in coastal waters supported vertical CO_2 fluxes months after the storm

Supporting Information:
- Supporting Information S1

Correspondence to:
C. L. Osburn,
closburn@ncsu.edu

Citation:
Osburn, C. L., Rudolph, J. C., Paerl, H. W., Hounshell, A. G., & Van Dam, B. R. (2019). Lingering carbon cycle effects of Hurricane Matthew in North Carolina's coastal waters. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2019GL082014

Received 14 JAN 2019
Accepted 12 FEB 2019
Accepted article online 14 FEB 2019

Lingering Carbon Cycle Effects of Hurricane Matthew in North Carolina's Coastal Waters

Christopher L. Osburn[1], Jacob C. Rudolph[1], Hans W. Paerl[2], Alexandria G. Hounshell[2], and Bryce R. Van Dam[2,3]

[1]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, USA, [2]Institute of Marine Sciences, University of North Carolina-Chapel Hill, Morehead City, NC, USA, [3]Now at Department of Biological Sciences and Southeast Environmental Research Center, Florida International University, Miami, FL, USA

Abstract In 2016, Hurricane Matthew accounted for 25% of the annual riverine C loading to the Neuse River Estuary-Pamlico Sound, in eastern North Carolina. Unlike inland watersheds, dissolved organic carbon (DOC) was the dominant component of C flux from this coastal watershed and stable carbon isotope and chromophoric dissolved organic matter evidence indicated the estuary and sound were dominated by wetland-derived terrigenous organic matter sources for several months following the storm. Persistence of wetland-derived DOC enabled its degradation to carbon dioxide (CO_2), which was supported by sea-to-air CO_2 fluxes measured in the sound weeks after the storm. Under future increasingly extreme weather events such as Hurricane Matthew, and most recently Hurricane Florence (September 2018), degradation of terrestrial DOC in floodwaters could increase flux of CO_2 from estuaries and coastal waters to the atmosphere.

Plain Language Summary Recent hurricanes along the Southeastern and Gulf coasts of the United States have received much attention, because these extreme events have led to immense societal and economic impacts. Wetlands in coastal watersheds store large amounts of organic matter and upon flooding during extreme weather events are poised to release this material into adjacent rivers and estuaries where its decomposition can generate carbon dioxide. Alteration of carbon balances in these events can shift impacted coastal ecosystems from states of carbon sinks to carbon sources for periods of weeks to months. Understanding the balance between these states is important to our understanding of how, and how long, regional carbon cycling is impacted after such extreme weather events. A biweekly record of dissolved and particulate organic matter quantity and quality from a coastal watershed in North Carolina in the 3 months following Hurricane Matthew in 2016 illustrated a major input of wetland carbon to coastal waters caused by this storm and its substantial lingering effect on coastal carbon cycling.

1. Introduction

Extreme weather events (EWEs)—such as the record rainfall and massive flooding recently experienced along the southeast and Gulf coasts of the United States from Hurricanes Matthew in 2016; Harvey, Irma, and Jose in 2017; and Florence in 2018—are becoming more frequent and occurring with greater intensity (Bender et al., 2010; Lehmann et al., 2015; Trenberth, 2011). National and international foci on impacts of extreme events on carbon (C) cycling outline a need to assess impacts on and feedback effects between these symptoms of climate change and C cycling (Fleming et al., 2018; Intergovernmental Panel on Climate Change, 2007). However, limited information exists on the long-term carbon cycling implications of extreme events.

While events such as tropical storms are ephemeral, lasting perhaps a few days to a week, their effects on coastal environments can possibly last for multiple years to decades, especially in an era of increased tropical cyclone activity (Paerl et al., 2006, 2018). Few studies of carbon biogeochemistry in estuaries and coastal waters have been conducted following major EWEs, largely because of flooding and infrastructure damage that renders rivers and coastal waters unnavigable, making sampling sites inaccessible or unsafe to access. The few studies that have been conducted on quality as well as the quantity of dissolved or particulate organic carbon (DOC and POC, respectively) in coastal waters following extreme events indicate rapid change in quality toward terrigenous sources (Bianchi et al., 2013; Majidzadeh et al., 2017; Osburn et al., 2012).

Recently, Paerl et al. (2018) summarized biogeochemical and ecosystem impacts of tropical storms over the past 20 years on the Neuse River Estuary (NRE) and the Pamlico Sound (PS), part of the second largest estuarine system in the United States and its largest lagoonal estuary. Stocks of dissolved and particulate organic matter increased dramatically as a result of these episodic extreme events, representing approximately 20% of the annual loads of DOC and POC. Following tropical storms, Paerl et al. (2018) and Crosswell et al. (2014) also noted a shift in air-water CO_2 exchange from that of a carbon sink to a carbon source. Within the context of the Flood Pulse and Pulse Shunt concepts (Junk & Wantzen, 2004; Raymond et al., 2016), Paerl et al. (2018) speculated that wetlands may be important sources of the organic carbon pulses released from a watershed resulting from heavy precipitation associated with tropical storms and shunted into downstream coastal waters. However, other than increased concentrations of DOC and POC in the NRE-PS as the flood pulse transited downstream, data were lacking to confirm a wetland source.

Non-tidal wetlands play a prominent role in river export of organic matter from catchments. Wetlands typically contain higher amounts of photochemically- and biologically-labile organic matter compared to upland sources, and the degree of hydrological connectivity between a river and its adjacent wetlands modulates this export (Lambert et al., 2015). Export of chromophoric dissolved organic matter (CDOM) is likewise enhanced by connection of rivers to wetlands (Spencer et al., 2013); upon transport to coastal waters, some of this material is rapidly converted to CO_2 (Bianchi et al., 2013). Following EWEs, DOC cycling may be particularly important, given the generally positive relationship between DOC and discharge. Thus, event-scale phenomena play important yet poorly defined roles in the coastal carbon cycle (Najjar et al., 2018).

Here we present evidence suggesting that wetlands were primary sources of DOC and POC export to North Carolina coastal waters after extreme precipitation associated with Hurricane Matthew in 2016. We demonstrate that, following Hurricane Matthew, the export of significant quantities of potentially reactive DOC into coastal waters persisted for weeks to months afterward, causing lingering impacts on estuarine C cycling. Results from this study indicate that event-scale phenomena such as hurricanes result in coastal waters as significant CO_2 sources to the atmosphere, and thus may function as positive feedbacks in the global C cycle.

2. Sampling and Methods

The NRE-PS comprise part of the USA's second largest estuarine complex and largest lagoonal estuary (Table S1 in the supporting information). The Neuse River's watershed is approximately 16,150 km^2 and it is the major tributary to the lower PS, an area approximately 7,700 km^2. Astronomical tides are <10 cm, and circulation in the combined NRE-PS system is controlled by river flow (Neuse and Trent Rivers) and winds (Luettich et al., 2002). The residence time of river water in the NRE-PS varies from roughly 1 week to >1 year, long enough for internal processing of terrigenous materials transported from the watershed into these coastal waters (Paerl et al., 2001, 2006). Meteorological observations of daily average wind speed (m/s) were obtained from National Oceanic and Atmospheric Administration's National Centers for Environmental Information (https://www.ncdc.noaa.gov/).

Duration of the flood pulse was 20 days (8 to 28 October 2016), and at 1.41×10^9 m^3, was 25% of the annual discharge for 2016. Peak discharge (1,399 m^3/s) at Ft. Barnwell (U.S. Geological Survey site 02091814), above head of tides, was reached on 15 October 2016, about 7 days after passage of Matthew. River flow returned to prestorm levels (approximately 150 m^3/s) roughly 12 days later (Weaver et al., 2016).

Surface water samples were collected from a bridge over the Neuse River at Ft. Barnwell and from a network of estuarine stations throughout the NRE-PS (Table S2 and Figure S1). Samples for dissolved inorganic carbon (DIC) were immediately filtered through 0.2-μm polyethersulfone filters into glass vials, capped with Teflon-lined septa and stored without headspace at 4 °C until analysis. Water samples for DOC and POC were collected in precleaned, brown high-density polyethylene (HDPE) bottles and filtered through precombusted 0.7-μm glass fiber filters (Whatman, Inc.) within 24 hr of collection. The filtrate was stored at 4 °C until measurement of optical properties. CDOM absorption was measured from 200 to 800 nm on a Varian Cary 300 UV spectrophotometer against an ultrapure Milli-Q water blank. Afterward, samples were acidified to pH ~2 with 85% H_3PO_4 and stored at 4 °C until analysis of DOC concentration and stable carbon isotope ratio of DOC (δ^{13}C, units of per mille; Osburn & St-Jean, 2007). Material retained on the filters was dried overnight in an oven at 60 °C, vapor acidified, re-dried, then packed into tin capsules for elemental analysis of POC concentration ([POC]), elemental C:N ratios, and δ^{13}C values of POC. DIC concentration

Table 1
Estimates of C fluxes to North Carolina coastal waters from Hurricane Matthew With Comparison to 2009, a Year in Which No Hurricanes Impacted the Region

	g C per event or annual			
Pool	Matthew	Annual in 2016	Percent of annual in 2016	Annual in 2009
DOC	1.28×10^{10}	5.14×10^{10}	25	2.88×10^{10}
POC	1.47×10^{9}	4.04×10^{9}	36	3.72×10^{9}
DIC	4.50×10^{9}	2.27×10^{10}	22	1.77×10^{10}
Total	1.92×10^{10}	7.82×10^{10}	25	5.03×10^{10}
DOC:POC	9	13	—	8

Note. DOC = dissolved organic carbon; POC = particulate organic carbon; DIC = dissolved inorganic carbon.

([DIC]) and δ^{13}C-DIC values were measured on an OI Analytical TOC analyzer (Doctor et al., 2008). In situ measurements of temperature, salinity, and pH, collected during sampling, were used in conjunction with meteorological observations and [DIC] to compute pCO_2 and CO_2 fluxes using the CO2calc software (Robbins et al., 2010; Table S3).

Stocks of DOC and POC (Gg C for each) in the estuary and sound were computed as the [DOC] or [POC] in grams of carbon per cubic meter multiplied by the volume of the estuary (9.96×10^8 m^3) or the sound (4.17×10^9 m^3). These stock estimates neglect changes in volume to either water body resulting from increased water levels during flooding and thus are driven by changes in concentration. Results were compared to 20-year mean averages of [DOC] or [POC] for the NRE-PS measured during the NRE Modeling and Monitoring (ModMon) sampling program (Paerl et al., 2018). Significant differences reported herein were based on two-sample *t* tests ($P < 0.01$). Fluxes of DOC and POC were computed using the flow-weighted mean method (Littlewood, 1992) with corrections for flow between Ft. Barnwell and the estuary (Figure S2).

3. Results and Discussion

Flooding in the Neuse River basin occurred shortly after the accumulated precipitation of about 400 mm, which fell within 48 hr of Hurricane Matthew's passage over eastern NC (Figure S1). River levels at Fort Barnwell, NC, exceeded flood stage for 6 days (Figure S2). In the 40-km stretch between Ft. Barnwell and station NR0 in the estuary, a number of semiconnected to disconnected riparian wetlands are situated adjacent to the Neuse River's main channel. During the period of high discharge after the storm, wetlands adjacent to the channel began to flood, leading to visible connectivity with main and side channels of the river after the storm from 8 October to 8 November 2016 (Figure S3; Rudolph, 2018). As a result, pulses of wetland-derived DOC were delivered to the river, then shunted into the estuary and sound.

Hurricane Matthew resulted in increased carbon stocks, which lingered in the estuary and sound for at least 2 months following the storm. In addition to higher river flow, [DOC] increased dramatically in the estuary and sound when compared to 20-year mean values supplied by the ModMon database (Table S4). Little change in [POC] occurred, while [DIC] decreased. Thus, the major effect of the storm was to increase DOC stocks in the estuary by 64% (12.3 Gg C from 7.5 Gg C), while POC stocks showed no significant change. In the sound, DOC stocks increased by 66% (35.8 vs. 21.9 Gg), while POC stocks showed a slight, but significant, increase from 4.9 to 5.1 Gg C. The riverine DOC flux, just above head of tides, was 1.49×10^9 g C/day 2 weeks after passage of Hurricane Matthew. That flux decreased to about 8.27×10^7 g C/day about 20 days after the storm. Daily riverine DOC fluxes to the NRE-PS increased by nearly a factor of 20 after Hurricane Matthew, much larger than the fivefold increase after Hurricane Irene in 2011 (Crosswell et al., 2014). Riverine POC flux was 1.77×10^8 g C/day 2 weeks after Hurricane Matthew, decreasing to 2.62×10^6 g C/day after ~3 weeks.

The magnitude of total C flux after Matthew was indeed substantial in 2016. The riverine DOC and POC fluxes from Matthew were 25% and 36% of the corresponding annual fluxes in 2016, respectively (Table 1), consistent with other EWEs in the region over the past 20 years (Paerl et al., 2018). Despite the large flux of POC, the lack of a significant change in POC stock in the estuary suggests much of this material was deposited rapidly in the upper estuary (Giffin & Corbett, 2003). [DIC] in the NRE-PS was diluted by Matthew's floodwaters (Table S4), yet riverine DIC fluxes were relatively large, and Matthew delivered about 22% of the annual DIC load (Table 1). Overall, the hurricane generated floodwaters that exported 19 Gg C, 66% of which was DOC, with much smaller fractions of DIC and POC, 26% and 8%, respectively. Thus, unlike inland watersheds, DOC rather than POC remained the dominant form of C exported from a coastal watershed after an extreme event (Dhillon & Inamdar, 2013).

Compared to 2009, a year without a major tropical cyclone affecting the region, the effects of Matthew on C flux were striking (Table 1). Matthew's DOC flux in 2016 was nearly half the annual DOC flux in 2009.

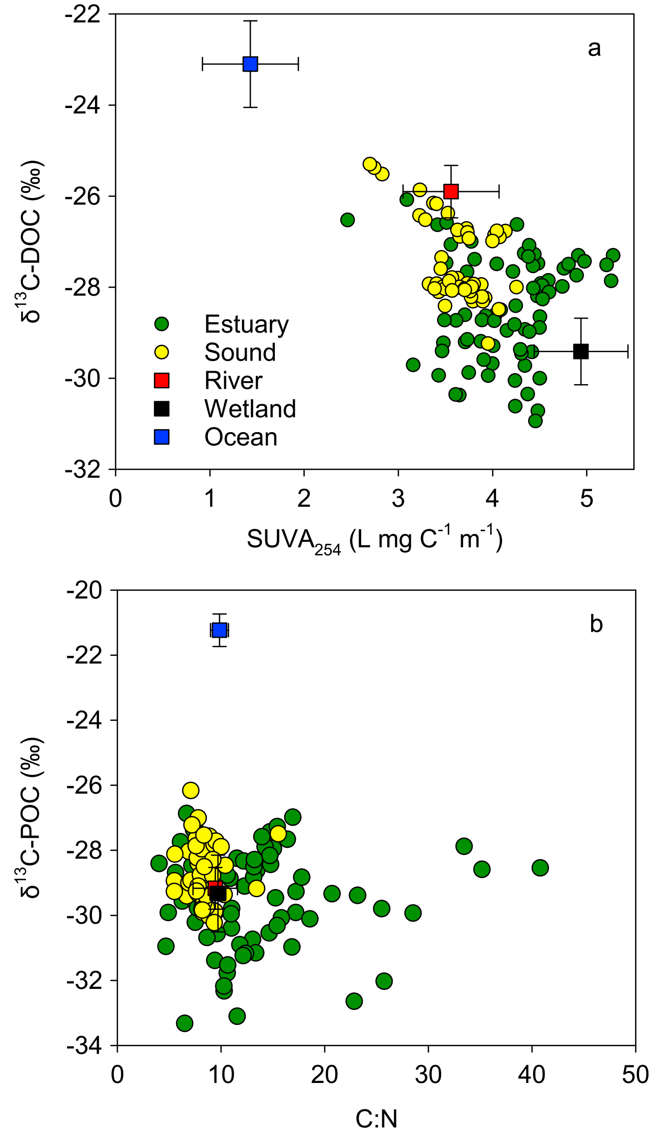

Figure 1. (a) Biplot of SUVA$_{254}$ and δ^{13}C-DOC values for the Neuse River Estuary and Pamlico Sound following Hurricane Matthew in 2016. Mean (±1 standard deviation) of reference values of the river, its fringing wetlands, and the adjacent coastal Atlantic Ocean also are shown, as well as values for the NRE-PS during baseflow prior to Hurricane Florence in 2018 (see text). (b) Biplot of δ^{13}C-POC and atomic C:N ratios.

Matthew's POC flux was 39% of the annual POC flux in 2009, similar to 2016. In 2009, the DOC:POC ratio was 8, compared to a DOC:POC ratio of 13 in 2016. Thus, a clear effect of Matthew was a greater export of DOC than of POC from the watershed to receiving waters, possibly due to deposition of POC in the upper estuary.

The major effect of this event, however, was the persistence of terrigenous DOC in the estuary and sound in the weeks following Hurricane Matthew (Figure 1a). First, the stable carbon isotope (δ^{13}C) values of DOC for the NRE-PS were −26‰ to −31‰ after the storm, implying that terrigenous OM sources were dominant (likely C3 land plants). SUVA$_{254}$ values, which serve as an index of aromatic organic C, ranged from 3.4–4.8 L·mg C^{-1}·m^{-1}, consistent with watersheds containing abundant wetlands (Spencer et al., 2013). By contrast, δ^{13}C and SUVA$_{254}$ values for samples collected from the inner shelf of the coastal Atlantic Ocean (34°41′N, 76°40 W), which communicates with PS through several narrow inlets, were −23.1 ± 0.5‰ and 1.4 ± 0.5 L·mg C^{-1}·m^{-1}, respectively (Atar, 2017). These values are characteristic of planktonic primary production, thus representing a coastal ocean end-member of plankton-dominated OM mixing with terrigenous OM in the sound. Based on the dissimilarity between the δ^{13}C and SUVA$_{254}$ values in the estuary and sound after the storm and those for coastal ocean water, a significant planktonic influence on DOC in the NRE-PS was unlikely (Paerl et al., 2018). Second, the influence of wetlands on terrigenous DOC in the estuary and sound following Matthew was exemplified by the range of wetland δ^{13}C and SUVA$_{254}$ values (−29.4 ± 0.7‰ and 4.9 ± 0.5 L·mg C^{-1}·m^{-1}, respectively) in contrast with values for the Neuse River above head of tides at Ft. Barnwell during the same period (−25.9 ± 0.6‰ and 3.6 ± 0.5 L·mg C^{-1}·m^{-1}). The lower δ^{13}C values and higher SUVA$_{254}$ values of the wetlands bracketed the majority of NRE-PS values, which strongly suggested the importance of wetland DOC to these coastal waters, similar to many upland watersheds with forested wetlands (Lambert et al., 2015; Majidzadeh et al., 2017).

Further evidence of the distinctive wetland-sourced DOC that persisted for months after Matthew comes in comparison to recent observations of the NRE-PS just prior to Hurricane Florence in September 2018. The Neuse River experienced high river flow (>150 m^3/s) for several weeks prior to Florence, resulting in mean values of SUVA$_{254}$ and δ^{13}C-DOC for the NR proper that were not significantly different than the mean values following Matthew (P > 0.05). Prior to Florence, mean SUVA$_{254}$ values were 4.2 ± 0.5 L·mg C^{-1}·m^{-1} in the NRE and 3.3 ± 0.1 L·mg C^{-1}·m^{-1} in the PS, while mean δ^{13}C-DOC values were −27.7 ± 0.8‰ in the NRE and −24.6 ± 0.7‰ in the PS. The high river flow in the weeks prior to Florence presumably flooded the riparian wetlands adjacent to the river, which explained the DOC quality in the NRE prior to Florence resembling post-Matthew values (Figure 1a). In contrast, the lower SUVA$_{254}$ and enriched δ^{13}C-DOC values in the sound prior to Florence indicated an absence of wetland-derived DOC.

Thus, we posit that as the river became hydrologically connected to adjacent wetlands, mobilization of wetland-derived DOC into the main channel clearly augmented, if not dominated, any upland sources of DOC. In the Yadkin-Pee Dee coastal watershed in South Carolina, flow-separation analysis indicated the drainage of wetlands via subsurface pathways after storm runoff from Matthew had declined and thus extended the shunt of terrigenous, wetland-derived DOC to coastal waters, similar to what our observations imply (Majidzadeh et al., 2017). These results, coupled with the long residence time of enclosed coastal waters such as sounds, explain the surprisingly long retention of terrigenous material flushed from the

10.1029/2019GL082014

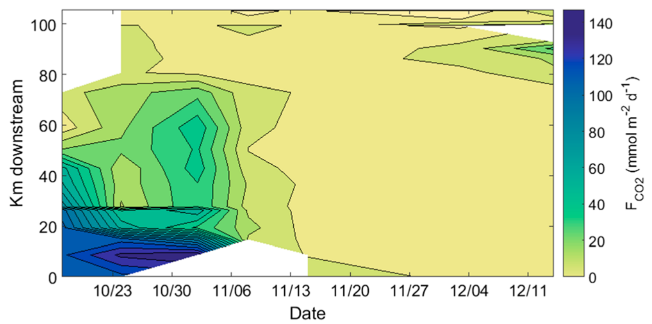

Figure 2. Spatiotemporal distribution of sea-to-air CO_2 fluxes from surface waters of the Neuse River Estuary and Pamlico Sound. Values are plotted as kilometer downstream from the head-of-tides sampling station on the estuary. White areas indicate no data.

watershed into the NRE-PS, which persisted in this coastal system well into November and early December roughly 2 months following passage of Hurricane Matthew over the region (Table 1).

In contrast to the very clear effects of storm-driven pulses of wetland DOC in NRE-PS waters, POC quality assessed using C:N and $\delta^{13}C$ values indicated a mix of terrigenous and planktonic sources (Figure 1b). River and wetland $\delta^{13}C$ values and C:N values overlapped. Generally, $\delta^{13}C$ values were -29 ± 1‰ while C:N values were <12. Mean $\delta^{13}C$-POC and C:N values for coastal Atlantic Ocean water were -21.2 ± 0.5‰ and 9.8 ± 0.9 (Atar, 2017), respectively, clearly outside the range of observations in this study, yet consistent for largely planktonic sources of organic matter (Bianchi & Bauer, 2011). Carbon isotope values for estuarine phytoplankton can range between −35‰ and −20‰, influenced strongly by inorganic C sources used during primary production (Bouillon et al., 2011); $\delta^{13}C$-DIC values in the NRE-PS ranged between −3‰ and −16‰ (Figure S4) and could explain the depleted $\delta^{13}C$-POC values for samples in the estuary and sound. These samples also had C:N values between 6 and 10, close to median ranges for the NRE-PS (Peierls & Paerl, 2010). While the breadth of these values overlap between strict terrigenous or marine (planktonic) sources, POC in the sound appeared to be influenced more by planktonic sources, based on C:N values generally <10, especially well after the storm (Figure S5). Nutrient-driven primary production in the NRE-PS is dramatically enhanced by hurricanes, which may partially explain the observed POC and $\delta^{13}C$ values (Paerl et al., 2006, 2018). These C:N and $\delta^{13}C$ values could also be explained in part by the resuspension of estuarine sediment, as has been suggested for previous EWEs (Crosswell et al., 2014).

After passage of the storm, the region experienced roughly 6 weeks of clear, sunny days. Primary production rates were enhanced under these conditions, increasing from 12 ± 19 to 31 ± 17 mg C·m^{-3}·hr^{-1} between 17 October 2016 and 8 November 2016. This likely supported the switch in POC from terrigenous sources during high flow to planktonic sources in the nutrient-fueled weeks following the storm (Paerl et al., 2018). Rates of primary production, even at their maximum in NRE and PS, also were not high enough to produce the stock increase of DOC computed for these coastal waters (see above), especially given the high flow and high turbidity common in flood waters (Paerl et al., 2018).

Ultimately, the lingering presence of wetland-derived, terrigenous DOC in the NRE-PS following Matthew helped sustain a positive sea-to-air flux of CO_2. Weather conditions in the NRE-PS after Hurricane Matthew were clear but breezy (Figure S6), which can enhance air-water CO_2 exchange (Crosswell et al., 2012; Van Dam et al., 2018). Indeed, we observed sustained and mostly positive CO_2 emissions across the NRE-PS after Hurricane Matthew (range: −4 to 131 mmol C·m^{-2}·day^{-1}), which extended well in to December (Figure 2). This finding compared favorably to a non-steady state box model of the NRE after Matthew, which showed that the estuary acted as a DOC sink for 2 weeks following the storm (Hounshell et al., 2019). At this time, $SUVA_{254}$ values remained >3.0 L·mg C^{-1}·m^{-1} and $\delta^{13}C$-DOC values remained <−26‰ (Figure 1), indicating that DOC remained dominated by terrigenous, probably wetland-derived, carbon. Fluxes of CO_2 were somewhat lower in the PS than in the NRE (mean = 5 mmol C·m^{-2}·day^{-1} vs. 24 mmol C·m^{-2}·day^{-1} for the estuary). However, because of the relatively large size of the PS, areally aggregated fluxes for the entire NRE-PS were dominated by emissions from the PS (Table S5). CO_2 emissions from the PS are likely affected by inputs from the adjacent Tar-Pamlico River system; thus values in Table S5 are listed for both the NRE, as well as the NRE + PS. We believe the most appropriate value falls between these estimates. Overall, CO_2 emissions from the NRE-PS were about an order of magnitude less than lateral C fluxes, which were dominated by DOC, a result consistent with prior events (Table 1; Crosswell et al., 2017).

Recent work on the NRE following Hurricane Joaquin showed a similar magnitude of CO_2 release from surface waters, attributed to riverine CO_2 inputs, and microbial degradation of terrestrial DOC to DIC (Van Dam et al., 2018). Results of this study also indicated a clear role for microbial and/or photochemical processing of terrestrial DOC as a key lingering effect in the NRE-PS (Osburn et al., 2012; Paerl et al., 2018). After the 2011 Mississippi River flood, microbial genomic information indicated that soil microorganisms capable

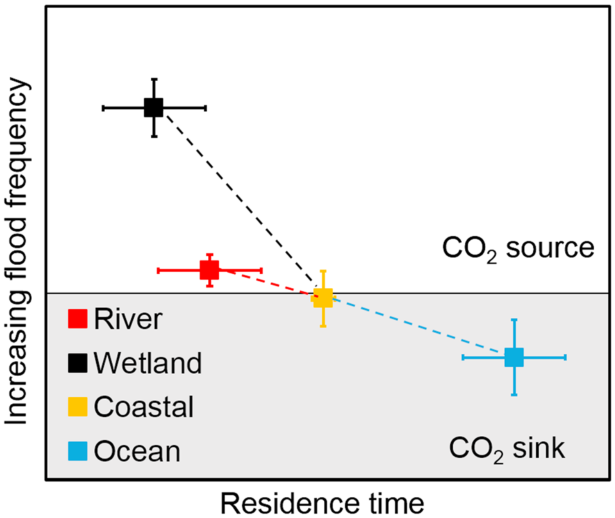

Figure 3. Conceptual model based on Figures 1a and 2 illustrating the increasing contribution of wetlands to terrigenous DOC exported and degraded to CO_2 in coastal waters as a result of extreme weather events. Dotted lines represent mixing of end-member sources in coastal waters.

of degrading terrigenous DOM were present in the plume waters of the north Gulf of Mexico and contributed to net release of CO_2 to the atmosphere (Bianchi et al., 2013). Therefore, we hypothesize that similar mechanisms were at play in the NRE-PS, in which flood waters carried with them not just wetland-sourced organic matter but also the microbial populations capable of metabolizing that material.

Because exchange with the coastal ocean is restricted to a few narrow tidal inlets, residence time in the PS is relatively long (~1 year), enabling substantial degradation of organic matter (Lin et al., 2007). After Matthew, the relatively clear, sunny weather in late October into November occurred when water temperatures in the NRE-PS remained between 10 and 20 °C, a range over which bacterial production tends to increase and was maximized following pulses of floodwater following Hurricane Isabel in 2003 (Peierls & Paerl, 2010). We suspect that the lingering effect of these EWEs is the sustained mineralization of terrestrial DOC to CO_2 following these pulses, which played a key role in sustaining the large observed CO_2 emissions.

We synthesized the observations in Figures 1a and 2 to present a conceptual model of DOC sources and CO_2 cycling in coastal waters based on wetland flooding caused by EWEs (Figure 3). Events having precipitation sufficient to mobilize DOC stored in forested swamps and wetlands cause a change in DOC quality in coastal waters with long enough residence times to enable sunlight and/or heterotrophic microorganisms to oxidize DOC to CO_2. This production of CO_2 initiates or sustains a regime change of coastal waters from CO_2 sinks to CO_2 sources. Lateral fluxes of wetland-derived terrigenous DOC not degraded in estuaries and sounds may be further degraded in adjacent coastal waters. Lagoonal systems such as the NRE-PS comprise about 24% of estuaries globally (Dürr et al., 2011). These environments, as well as large river plume regions, where long residence times will enable photochemical and microbial conversion of terrigenous DOC back into CO_2, will be key observational sites and serve as sentinels for changes to coastal carbon cycling as global climate change proceeds.

4. Conclusions

Results from a 500-year flooding event showed that terrigenous, wetland-derived DOC flushed into receiving waters can have persistent effects on carbon cycling processes, which linger for months afterward. Record-breaking rainfall patterns are predicted due to the warming of the atmosphere and an increase in its ability to store moisture (Lehmann et al., 2015; Walsh et al., 2016). While much attention is justifiably focused on the effects of storm surge and associated flooding, landward effects of flooding in coastal watersheds can produce large pulses of DOC from the landscape. These DOC pulses are subsequently shunted downstream to estuaries and coastal waters to await their complicated fate (Raymond et al., 2016). This work suggests that reactive organic matter exported from watersheds to coastal waters after EWEs is at least partially degraded to CO_2 and could sustain the large CO_2 emissions that were observed, perhaps a key poststorm feature in estuarine and coastal ecosystems (Avery et al., 2004; Bianchi et al., 2013; Osburn et al., 2012). Conditions leading up to a EWE may also be important, enabling a coastal watershed to be poised to release large amounts of C into downstream waters or, in the case of subsequent storms, perhaps stripping a watershed of leachable C. Under either scenario, it will be important to include meteorological, soil, and wetland biogeochemical information to better understand subtleties in the characteristics of carbon released from watersheds during extreme events and transformed in coastal waters.

Acknowledgments
We thank Roxane Bowden, Stephen Richardson, Betsy Abare, Jeremy Braddy, Karen Rossignol, and Randy Sloup for technical assistance. The UNC-Chapel Hill/North Carolina Department of Environmental Quality ModMon Program is thanked for logistical support. This work was funded by National Science Foundation grants OCE 1705972 and OCE 1706009, the North Carolina Sea Grant Program, the UNC Water Resources Research Institute, and the National Fish and Wildlife Foundation Project 8020.16.053916. Data used for this paper can be found at the NSF Biological and Chemical Oceanographic Data Management Office (BCO-DMO; https://www.bco-dmo.org/project/734599).

References

Atar, J. N. (2017). Contrasting estuarine and coastal organic matter dynamics from varying climatic regions (Master's thesis). Retrieved from NCSU repository. (http://www.lib.ncsu.edu/resolver/1840.20/34424). Raleigh, NC: North Carolina State University.

Avery, G. B., Kieber, R. J., Willey, J. D., Shank, G. C., & Whitehead, R. F. (2004). Impact of hurricanes on the flux of rainwater and Cape Fear River water dissolved organic carbon to Long Bay, southeastern United States. *Global Biogeochemical Cycles*, *18*, GB3085. https://doi.org/10.1029/2004GB002229

Bender, M. A., Knutson, T. R., Tuleya, R. E., Sirutis, J. J., Vecchi, G. A., Garner, S. T., & Held, I. M. (2010). Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science*, *327*(5964), 454–458. https://doi.org/10.1126/science.1180568

Bianchi, T. S., & Bauer, J. E. (2011). Particulate organic carbon cycling and transformation. In E. Wolanski & D. S. McLusky (Eds.), *Treatise on Estuarine and Coastal Science* (Vol 5, pp. 69–117). Waltham: Academic Press. https://doi.org/10.1016/B978-0-12-374711-2.00503-9

Bianchi, T. S., Garcia-Tigreros, F., Yvon-Lewis, S. A., Shields, M., Mills, H. J., Butman, D., et al. (2013). Enhanced transfer of terrestrially derived carbon to the atmosphere in a flooding event. *Geophysical Research Letters*, *40*, 116–122. https://doi.org/10.1029/2012GL054145

Bouillon, S., R. M. Connolly, and D. P. Gillikin (2011), Use of stable isotopes to understand food webs and ecosystem functioning in estuaries. In E. Wolanski & D. McLusky (Eds.), *Treatise on estuarine and coastal science* (Vol. 7, pp. 143–173). Waltham: Academic Press.

Crosswell, J. R., Anderson, I. C., Stanhope, J. W., Van Dam, B., Brush, M. J., Ensign, S., et al. (2017). Carbon budget of a shallow, lagoonal estuary: Transformations and source-sink dynamics along the river-estuary-ocean continuum. *Limnology and Oceanography*, *62*(S1), S29–S45. https://doi.org/10.1002/lno.10631

Crosswell, J. R., Wetz, M. S., Hales, B., & Paerl, H. W. (2012). Air-water CO_2 fluxes in the microtidal Neuse River Estuary, North Carolina. *Journal of Geophysical Research*, *117*, C08017. https://doi.org/10.1029/2012JC007925

Crosswell, J. R., Wetz, M. S., Hales, B., & Paerl, H. W. (2014). Extensive CO_2 emissions from shallow coastal waters during passage of Hurricane Irene (August 2011) over the mid-Atlantic Coast of the U.S.A. *Limnology and Oceanography*, *59*(5), 1651–1665. https://doi.org/10.4319/lo.2014.59.5.1651

Dhillon, G. S., & Inamdar, S. (2013). Extreme storms and changes in particulate and dissolved organic carbon in runoff: Entering uncharted waters? *Geophysical Research Letters*, *40*, 1322–1327. https://doi.org/10.1002/grl.50306

Doctor, D. H., Kendall, C., Sebestyen, S. D., Shanley, J. B., Ohte, N., & Boyer, E. W. (2008). Carbon isotope fractionation of dissolved inorganic carbon (DIC) due to outgassing of carbon dioxide from a headwater stream. *Hydrological Processes*, *22*(14), 2410–2423. https://doi.org/10.1002/hyp.6833

Dürr, H. H., Laruelle, G. G., van Kempen, C. M., Slomp, C. P., Meybeck, M., & Middelkoop, H. (2011). Worldwide typology of nearshore coastal systems: Defining the estuarine filter of river inputs to the oceans. *Estuaries and Coasts*, *34*(3), 441–458. https://doi.org/10.1007/s12237-011-9381-y

Fleming, E., Payne, J. L., Sweet, W. V., Craghan, M., Haines, J., Hart, J. A. F., et al. (2018). *Chapter 8: Coastal effects. Impacts, risks, and adaptation in the United States: The Fourth National Climate Assessment, Volume II*. Washington, DC: U.S. Global Change Research Program.

Giffin, D., & Corbett, D. R. (2003). Evaluation of sediment dynamics in coastal systems via short-lived radioisotopes. *Journal of Marine Systems*, *42*(3–4), 83–96. https://doi.org/10.1016/S0924-7963(03)00068-X

Hounshell, A. G., Rudolph, J. C., Van Dam, B. R., Hall, N. S., Osburn, C. L., & Paerl, H. W. (2019). Extreme weather events modulate processing and export of dissolved organic carbon in the Neuse River Estuary, NC. *Estuarine, Coastal and Shelf Science*, *219*, 189–200. https://doi.org/10.1016/j.ecss.2019.01.020

Intergovernmental Panel on Climate Change (2007). *Climate Change (2007). The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al. (Eds.)] (996 pp.). Cambridge, UK and New York: Cambridge University Press.

Junk, W. J., & Wantzen, K. M. (2004). The flood pulse concept: New aspects, approaches, and applications. An Update. In R. Welcomme, & T. Petr (Eds.), *Proceedings of the 2nd Large River Symposium (LARS), Pnom Penh, Cambodia Food and Agriculture Organization & Mekong River Commission* (pp. 117–149). Bangkok: FAO Regional Office for Asia and the Pacific.

Lambert, T., Darchambeau, F., Bouillon, S., Alhou, B., Mbega, J.-D., Teodoru, C. R., et al. (2015). Landscape control on the spatial and temporal variability of Chromophoric dissolved organic matter and dissolved organic carbon in large African rivers. *Ecosystems*, *18*(7), 1224–1239. https://doi.org/10.1007/s10021-015-9894-5

Lehmann, J., Coumou, D., & Frieler, K. (2015). Increased record-breaking precipitation events under global warming. *Climatic Change*, *132*(4), 501–515. https://doi.org/10.1007/s10584-015-1434-y

Lin, J., Xie, L., Pietrafesa, L. J., Ramus, J. S., & Paerl, H. W. (2007). Water quality gradients across Albemarle-Pamlico estuarine system: Seasonal variations and model applications. *Journal of Coastal Research*, *23*(1), 213–229.

Littlewood, I. G. (1992). Estimating contaminant loads in rivers: A review, (IH Report no. 117). Retrieved from https://nora.nerc.ac.uk/7353/1/IH_117.pdf

Luettich, R. A., Carr, S. D., Reynolds-Fleming, J. V., Fulcher, C. W., & McNinch, J. E. (2002). Semi-diurnal seiching in a shallow, micro-tidal lagoonal estuary. *Continental Shelf Research*, *22*(11-13), 1669–1681. https://doi.org/10.1016/S0278-4343(02)00031-6

Majidzadeh, H., Uzun, H., Ruecker, A., Miller, D., Vernon, J., Zhang, H., Bao, S., et al. (2017). Extreme flooding mobilized dissolved organic matter from coastal forested wetlands. *Biogeochemistry*, *136*(3), 293–309. https://doi.org/10.1007/s10533-017-0394-x

Najjar, R. G., Herrmann, M., Alexander, R., Boyer, E. W., Burdige, D. J., Butman, D., Cai, W. J., et al. (2018). Carbon budget of tidal wetlands, estuaries, and shelf waters of eastern North America. *Global Biogeochemical Cycles*, *32*, 389–416. https://doi.org/10.1002/2017GB005790

Osburn, C. L., Handsel, L. T., Mikan, M. P., Paerl, H. W., & Montgomery, M. T. (2012). Fluorescence tracking of dissolved and particulate organic matter quality in a river-dominated estuary. *Environmental Science & Technology*, *46*(16), 8628–8636. https://doi.org/10.1021/es3007723

Osburn, C. L., & St-Jean, G. (2007). The use of wet chemical oxidation with high-amplification isotope ratio mass spectrometry (WCO-IRMS) to measure stable isotope values of dissolved organic carbon in seawater. *Limnology and Oceanography: Methods*, *5*(10), 296–308. https://doi.org/10.4319/lom.2007.5.296

Paerl, H. W., Bales, J. D., Ausley, L. W., Buzzelli, C. P., Crowder, L. B., Eby, L. A., et al. (2001). Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(10), 5655–5660. https://doi.org/10.1073/pnas.101097398

Paerl, H. W., Crosswell, J. R., van Dam, B., Hall, N. S., Rossignol, K. L., Osburn, C. L., et al. (2018). Two decades of tropical cyclone impacts on North Carolina's estuarine carbon, nutrient and phytoplankton dynamics: Implications for biogeochemical cycling and water quality in a stormier world. *Biogeochemistry*, *141*(3), 307–332. https://doi.org/10.1007/s10533-018-0438-x

Paerl, H. W., Valdes, L. M., Peierls, B. L., Adolf, J. E., & Harding, L. W. (2006). Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. *Limnology and Oceanography*, *51*(1part2), 448–462. https://doi.org/10.4319/lo.2006.51.1_part_2.0448

Peierls, B. L., & Paerl, H. W. (2010). Temperature, organic matter, and the control of bacterioplankton in the Neuse River and Pamlico Sound estuarine system. *Aquatic Microbial Ecology*, *60*(2), 139–149. https://doi.org/10.3354/ame1415

Raymond, P. A., Saiers, J. E., & Sobczak, W. V. (2016). Hydrological and biogeochemical controls on watershed dissolved organic matter transport: Pulse- shunt concept. *Ecology*, *97*(1), 5–16. https://doi.org/10.1890/14-1684.1

Robbins, L. L., M. E. Hansen, J. A. Kleypas, & S. C. Meylan (2010). CO2calc: A user-friendly seawater carbon calculator for Windows, Mac OS X, and iOS (iPhone).

Rudolph, J. (2018). Hurricane Matthew's effect on wetland organic matter sources to North Carolina coastal waters, (Master's thesis). Retrieved from NCSU Repository. (http://www.lib.ncsu.edu/resolver/1840.20/35722). Raleigh, NC: North Carolina State University.

Spencer, R. G. M., Aiken, G. R., Dornblaser, M. M., Butler, K. D., Holmes, R. M., Fiske, G., et al. (2013). Chromophoric dissolved organic matter export from U.S. rivers. *Geophysical Research Letters*, *40*, 1575–1579. https://doi.org/10.1002/grl.50357

Trenberth, K. (2011). Changes in precipitation with climage change. *Climate Research*, *47*(1), 123–138. https://doi.org/10.2307/24872346.

Van Dam, B. R., Crosswell, J. R., & Paerl, H. W. (2018). Flood-driven CO2 emissions from adjacent North Carolina estuaries during Hurricane Joaquin (2015). *Marine Chemistry*, *207*, 1–12. https://doi.org/10.1016/J.MARCHEM.2018.10.001

Walsh, K. J. E., McBride, J. L., Klotzbach, P. J., Balachandran, S., Camargo, S. J., Holland, G., et al. (2016). Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(1), 65–89. https://doi.org/10.1002/wcc.371

Weaver, J. C., Feaster, T. D., & Robbins, J. C. (2016). Preliminary peak stage and streamflow data at selected streamgaging stations in North Carolina and South Carolina for flooding following Hurricane Matthew, October 2016, (Open File Report). Retrieved from https://pubs.er.usgs.gov/publication/ofr20161205