Recent increases of rainfall and flooding from tropical cyclones (TCs) in North Carolina (USA): implications for organic matter and nutrient cycling in coastal watersheds

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Abstract Coastal North Carolina experienced 36 tropical cyclones (TCs), including three floods of historical significance in the past two decades (Hurricanes Floyd-1999, Matthew-2016 and Florence-2018). These events caused catastrophic flooding and major alterations of water quality, fisheries habitat and ecological conditions of the Albemarle-Pamlico Sound (APS), the second largest estuarine complex in the United States. Continuous rainfall records for coastal NC since 1898 reveal a period of unprecedented high precipitation storm events since the late-1990s. Six of seven of the "wettest" storm events in this > 120-year record occurred in the past two decades, identifying a period of elevated precipitation and flooding associated with recent TCs. We examined storm-related freshwater discharge, carbon (C) and nutrient, i.e., nitrogen (N) and phosphorus (P) loadings, and evaluated contributions to total annual inputs in the Neuse River Estuary (NRE), a major sub-estuary of the APS. These contributions were highly significant, accounting for > 50% of annual loads depending on antecedent conditions and storm-related flooding. Depending on the magnitude of freshwater discharge, the NRE either acted as a "processor" to partially assimilate and metabolize the loads or acted as a "pipeline" to transport the loads to the APS and coastal Atlantic Ocean. Under base-flow, terrestrial sources dominate riverine carbon. During storm events these carbon sources are enhanced through the inundation and release of carbon from wetlands. These findings show that event-scale discharge plays an important and, at times, predominant

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role in C, N and P loadings. We appear to have entered a new climatic regime characterized by more frequent extreme precipitation events, with major ramifications for hydrology, cycling of C, N and P, water quality and habitat conditions in estuarine and coastal waters.

Keywords Tropical cyclones · Flooding · Organic carbon · Nutrient cycling · Phytoplankton · Estuarine · Coastal · North carolina

Introduction

Since the mid-1990s, coastal North Carolina, USA has been struck by 36 tropical cyclones (TCs), indicative of a recent increase in such events (Paerl et al. 2018, 2019) (Fig. 1 and Table 1). This increase appears to reflect regional and global patterns, as the frequency and magnitude of events have increased over several decades (Webster et al. 2005; Holland and Webster 2007; Seneviratne et al. 2012; Wuebbles et al. 2014; NOAA National Hurricane Center-Fig. 2). North Carolina's low-lying, readily flooded coastal region is on the "front doorstep" of these increases with concomitant biogeochemical and trophic impacts (Frankson et al. 2019). The number of TCs making landfall in North Carolina is highly variable from year to year, while TC intensity and rainfall rates are projected to increase in a warming climate (Konrad and Perry 2010). This low-lying region is also impacted by sea level rise (Frankson et al. 2019), which combines with frequent TCs to make coastal North Carolina and the neighboring mid-Atlantic region highly vulnerable to flooding.

In the last two decades (1999–2019), coastal North Carolina experienced three major floods from TCs that were considered 50-year events (i.e., an annual probability of 2%): Floyd (1999), Matthew (2016), and Florence (2018) (Paerl et al. 2019). An examination of major storm events impacting the North Carolina coastline since 1898 indicated that 6 of 7 of the highest rainfall events occurred during the last two decades (Paerl et al. 2019), a trend in keeping with increased precipitation associated with TCs globally (Allan and Soden 2008; Asadieh and Krakauer 2015; Lehmann et al. 2015). These storms led to unprecedented flood damage, accompanied by large inorganic and organic C, N and P pulses in freshwater discharge impacting estuarine and coastal waters (Bianchi et al.

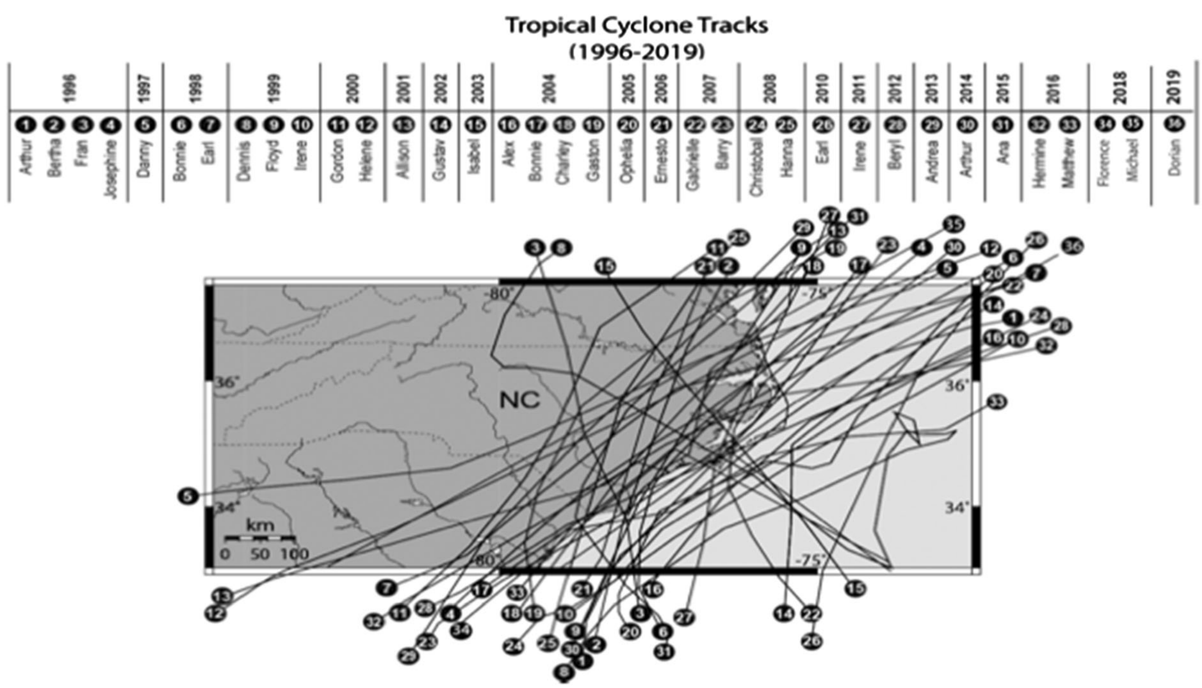

Fig. 1 Tropical cyclone dates and tracks as they impacted coastal North Carolina, USA, since the recent period of elevated storm activity which commenced in the mid-1990s. Updated from Paerl et al. (2018)

Table 1 Tropical cyclones impacting North Carolina from 1996–2019

Tropical cyclone	Date	Storm characteristics (Paerl et al. 2018)	Precipitation amount (mm)	Impact on North Carolina
Tropical Storm Arthur	20 Jun 1996	Dry and windy	100	Moderate
Hurricane Bertha	12 Jul 1996	Dry and windy	80	Moderate
Hurricane Fran	6 Sep 1996	Wet and windy	406	Major
Tropical Storm Josephine	8 Oct 1996	Wet and windy	100	Moderate
Hurricane Danny	24 Jul 1997	Dry and calm	300	Minimal
Hurricane Bonnie	27 Aug 1998	Dry and windy	371	Major
Hurricane Earl	4 Sep 1998	Dry and windy	102	Moderate
Hurricane Dennis	4 Sep 1999	Wet and windy	506	Major
Hurricane Floyd	16 Sep 1999	Wet and windy	484	Major
Hurricane Irene	18 Oct 1999	Wet and windy	255	Major
Hurricane Gordon	19 Sep 2000	Wet and windy	145	Major
Tropical Storm Helene	23 Sep 2000	Dry and windy	211	Moderate
Tropical Storm Allison	13 Jun 2001	Dry and calm	406	Moderate
Hurricane Gustav	10 Sep 2002	Dry and windy	125	Minimal
Hurricane Isabel	18 Sep 2003	Dry and windy	115	Moderate
Hurricane Alex	3 Aug 2004	Dry and calm	127	Minimal
Tropical Storm Bonnie	13 Aug 2004	Dry and calm	77	Minimal
Hurricane Charley	14 Aug 2004	Wet and calm	150	Minimal
Hurricane Gaston	30 Aug 2004	Dry and calm	155	Minimal
Hurricane Ophelia	14 Sep 2005	Dry and windy	254	Major
Hurricane Ernesto	1 Aug 2006	Wet and windy	371	Major
Tropical Storm Barry	3 Jun 2007	Dry and windy	95	Minimal
Tropical Storm Gabrielle	9 Sep 2007	Dry and calm	200	Minimal
Tropical Storm Cristobal	20 Jul 2008	Dry and calm	87	Minimal
Hurricane Hanna	29 Sep 2008	Dry and calm	97	Minimal
Hurricane Earl	3 Sep 2010	Dry and windy	115	Moderate
Hurricane Nicole	29 Sep 2010	Wet and calm	573	Major
Hurricane Irene	27 Aug 2011	Wet and windy	360	Major
Tropical Storm Beryl	30 May 2012	Dry and windy	179	Minimal
Tropical Storm Andrea	7 Jun 2013	Dry and windy	188	Minimal
Hurricane Arthur	4 Jul 2014	Dry and windy	107	Moderate
Tropical Storm Ana	7 May 2015	Wet and calm	175	Minimal
Hurricane Joaquin	3 Oct 2015	Wet and windy	200	Major
Hurricane Hermine	2 Sep 2016	Dry and windy	200	Minimal
Hurricane Matthew	8 Oct 2016	Wet and windy	610	Major
Hurricane Florence	14 Sep 2018	Wet and Windy	913	Major
Hurricane Michael	11 Oct 2018	Wet and calm	330	Moderate
Hurricane Dorian	5 Sep 2019	Wet and Calm	250	Moderate

The tropical cyclones are listed with the date of impact in North Carolina, the characteristics of the storm, rainfall amounts in North Carolina, and the impact on North Carolina

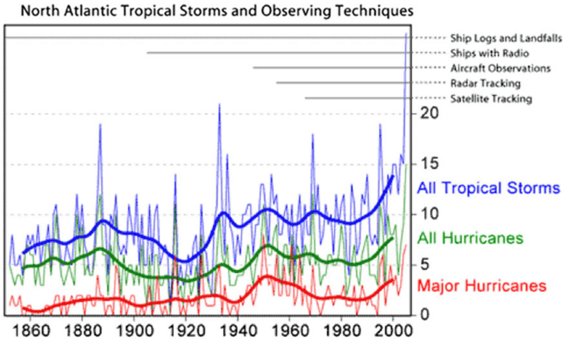

Fig. 2 History of the tropical storms, hurricanes, and major hurricanes (Category 3+) in the North Atlantic Ocean, derived from the analysis of the National Hurricane Center, Miami, FL, USA

2013; Paerl et al. 2006; Osburn et al. 2019a, b) (Fig. 3). Increasingly frequent extreme events in recent years appear to be altering hydrologic and biogeochemical dynamics of estuarine and coastal waters, leading us to pose the question: Are we witnessing increasing occurrences of "hot moments" that "occur when episodic hydrological flow-paths reactivate and/or mobilize accumulated reactants?" (McClain et al. 2003).

In this contribution, we draw on a long-term water quality monitoring program (since 1994) to characterize and quantify C, N and P inputs to the nutrient-sensitive receiving waters of the Neuse River Estuary (NRE), a major tributary of the 2nd largest estuarine complex in the United States, and the Albemarle-Pamlico Sound (APS), the US's largest lagoonal ecosystem and a major fisheries nursery. We also examined hydrologic and nutrient impacts on the base of the food web in the NRE where phytoplankton account for > 80% of primary production (Paerl et al. 1998). These events also promote hypoxia and anoxia, which are commonly observed in periodically vertically-stratified sub-estuaries of the APS (Mallin and Corbett 2006). These impacts have been detailed for the NRE in previous publications (Paerl et al. 2006, 2018).

The objectives of this study were to quantify event-scale responses to TCs compared to seasonal- to interannual patterns of C, N and P loadings as baseline conditions. We addressed two questions: (1) How does the recent increase of precipitation and freshwater discharge associated with TCs drive fundamental changes of C, N and P cycling in the NRE-APS continuum and adjacent coastal waters, and (2) What are the overall biogeochemical and ecological impacts of increased loadings?

Methods and materials

Study site: the Neuse River Estuary-Pamlico Sound estuarine continuum

North Carolina's Neuse River Estuary (NRE) is a lagoonal, micro-tidal ecosystem, representative of ~ 20 global estuarine and coastal waters (Kennish and Paerl 2010). It is the largest sub-estuary of the Albemarle-Pamlico Sound (APS) system. The APS drains approximately 50% of North Carolina's and 20% of Virginia's coastal plain regions via 5 major rivers (Bales et al. 2000; Bales 2003) (Fig. 4). The NRE receives inputs from a 14,600 km^2 watershed that has experienced urbanization of its headwaters and has intensive, rapidly expanding row-crop agriculture and swine/poultry operations toward the coast (Stow et al. 2001; Paerl et al. 2019). As for many estuarine and coastal waters, primary production and algal bloom formation in the NRE are largely N-limited for much of the year (Paerl et al. 1995, 2007; Rudek et al. 1991). High water column primary production (> 300 g C m^{-2} y^{-1}) results from excessive N loading and efficient recycling, especially in the summer (Christian et al. 1991; Boyer et al. 1993, 1994). Vertical density stratification in the main channel also promotes extensive bottom-water hypoxia (< 2.0 mg O_2 L^{-1}) in summer-fall (Buzzelli et al. 2002).

The full sequence of biotic responses to nutrient and hydrologic perturbations in estuarine and coastal waters dominated by freshwater discharge may not fully develop or can be masked by rapid flushing (Hopkinson and Vallino 1995). However, the APS is poorly flushed due its large estuarine volume relative to river inflows, the microtidal regime of the NC coastline, and weak tidal exchange through three shallow inlets along the Outer Banks. Residence times generally range from one to three months for the NRE and up to a year for Pamlico Sound (Pietrafesa et al., 1996; Paerl et al. 2009; Peierls et al. 2012) and are strongly impacted by changes in freshwater input. Changes in residence time due to floods or droughts are accompanied by changes in salinity and nutrient concentrations that drive significant changes in the

Fig. 3 US Geological Survey's Landsat 8 satellite showing colored dissolved organic matter (CDOM) in floodwater discharged to North Carolina estuarine and coastal ecosystems following Hurricane Florence in September, 2018. Upper frame shows a true color image, while lower frame has been processed to emphasize CDOM. Photo courtesy of Landsat Data Webpage (https://www.usgs.gov/land-resources/nli/landsat)

phytoplankton community (Hall et al. 2008; Paerl et al. 2018). The NRE has been the site of numerous harmful algal bloom events, ranging from toxic cyanobacterial blooms upstream (Paerl 1983; Fulton and Paerl 1988; Lung and Paerl 1988) to dinoflagellate and raphidophyte blooms downstream (Pinckney et al. 1997, 1998; Valdes-Weaver et al. 2006; Paerl et al. 2007, 2010, 2013; Hall et al. 2008).

The Neuse River Estuary Modeling and Monitoring Program (ModMon) (https://paerllab.web.unc.edu/projects/modmon/) has produced a database of observational, experimental research, and modeling results on C dynamics, nutrient-productivity relationships, and algal blooms (Luettich et al. 2000; Bowen and Hieronymus 2000; Paerl et al. 2009; Peierls et al. 2012) for the Neuse River Estuary since 1994 and for western Pamlico Sound (PS) since 2000. Other observations are provided by the North Carolina Department of Environmental Quality (NC-DEQ), which conducts monthly water-quality monitoring (including phytoplankton taxonomic composition) in the NRE. Together, these activities comprise more than 25 years of data with high spatio-temporal resolution (c.f. Paerl et al. 2018).

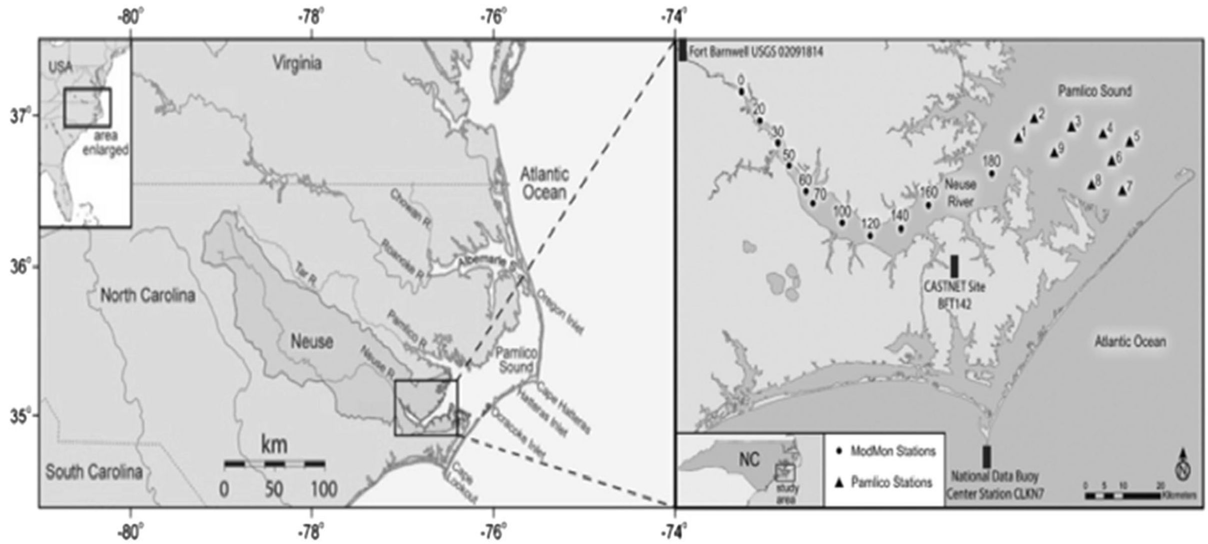

Fig. 4 Maps showing (left) the location of the Neuse River estuary, its watershed and the downstream Pamlico Sound. The right hand side shows the Neuse River and its Estuary, including the upstream Fort Barnwell USGS gaging station and the water quality sampling stations of the Neuse River Modeling and Monitoring Program, ModMon. The locations of the EPA Clean Air Status and Trends Network (CASTNET) air monitoring site BFT142 and National Data Buoy Center station CLKN7 at Cape Lookout are also shown

ModMon sampling consisted of bi-weekly visits to 11 stations along the main axis of the NRE (Fig. 3), including vertical profiles with collection of near-surface and near-bottom water (Paerl 2005; Paerl et al. 2006). In western PS, samples were collected monthly at nine stations (Fig. 4). At each station, profiles of temperature, salinity, and dissolved oxygen were made at 0.5 m depth intervals using a YSI 6600 multi-parameter water quality sonde (Yellow Springs Inc, Yellow Springs, OH). Dissolved oxygen was calibrated with water-saturated air according to the YSI User's Manual with accuracy of 2% or 0.2 mg L^{-1}. Discrete samples for nutrient concentrations, phytoplankton biomass and community composition, and inorganic and organic C species were collected from near-surface (0.2 m depth) and bottom waters (0.5 m above bottom) using a non-destructive diaphragm pump, dispensed into 4 L polyethylene bottles. Samples were maintained in the dark at in situ temperature in a large insulated container and returned to the laboratory at the UNC-CH Institute of Marine Sciences, Morehead City (IMS) within 4 h of collection for processing.

Freshwater discharge, flushing time, C and nutrient loading

Average, daily discharge from the Neuse River was measured by the US Geological Survey at Fort Barnwell (USGS 02091814) (Fig. 4). Daily material loadings of C, N and P were calculated using Weighted Regressions on Time Discharge and Season (WRTDS) (Hirsch and DeCicco 2015; Hirsch et al. 2010) using daily average river flow and material concentrations at the head of the estuary by ModMon (or NC DEQ for total N and total P) (Fig. 4). Half window widths of the tricube weight function were set to default values: 6 months for seasonality, 7 years for time, and 2 natural log units for discharge (Hirsch and DeCicco 2015). Changes in flushing time of the Neuse River Estuary that resulted from changing river flow conditions were calculated based on freshwater discharge at Fort Barnwell and salinity depth profiles measured at ModMon stations 0 to 180 using the date-specific freshwater replacement method (Alber and Sheldon 1999). See Peierls et al. (2012) for details on how the method was implemented.

Carbon and nutrient analyses

C and N measured at ModMon stations included: total dissolved nitrogen (TDN), nitrate plus nitrite (NO_3^{-} + NO_2^{-}), ammonium (NH_4^+), soluble reactive phosphate (SRP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and particulate nitrogen (PN). Dissolved inorganic nitrogen (DIN) was NO_3^- + NO_2^{-} + NH_4^+. Dissolved organic nitrogen (DON) was computed by difference as TDN—DIN. Nutrient analyses used 100 mL aliquots filtered through pre-combusted (4 h at 525 °C) 25 mm diameter Whatman GF/F filters into acid-washed and sample-rinsed 150 mL polyethylene bottles that were subsequently frozen at − 20 °C. Filtrates were analyzed for dissolved N forms and SRP with a Lachat/Zellweger Analytics QuickChem 8000 flow injection autoanalyzer using standard protocols (Lachat method numbers 31-107-04-1-C, 31-107-06-1-B, and 31-115-01-3-C, respectively) (Peierls et al. 2012). Particulate organic carbon and nitrogen were measured on seston collected on pre-combusted GF/F filters, analyzed by high-temperature combustion using a Costech ECS 4010 analyzer (Peierls and Paerl 2010). DIC and DOC were measured on a Shimadzu Total Organic Carbon Analyzer (TOC-5000A) (Crosswell et al. 2014).

Phytoplankton biomass

Chlorophyll *a* (Chl-*a*), an indicator of phytoplankton biomass, was measured on near-surface and near-bottom samples by filtering 50 mL of NRE water onto GF/F filters. Filters were frozen at − 20 °C and subsequently extracted using a tissue grinder in 90% acetone (EPA method 445.0, Arar et al. 1997). Chl-*a* in extracts were measured using the non-acidification method of Welschmeyer (1994) on a Turner Designs Trilogy fluorometer calibrated with pure Chl-*a* (Turner Designs, Sunnyvale, CA).

Results and discussion

Loads of dissolved organic carbon (DOC), total N (TN) and total P (TP) were driven by freshwater discharge at the sampling station 0 furthest upstream (Figs. 5, 6, 7, 8). Seasonal patterns were evident as periods of elevated discharge and nutrient loads: (1) a winter-spring period with elevated rainfall and runoff; (2) a summer-fall period with maxima in years experiencing TCs, contrasted with years without summer-fall TCs (e.g., 1997) when elevated nutrient and DOC loadings were not observed.

Some TCs grazed the coastline and had little effect on loads (e.g., Gordon in 2000, Charley in 2004, Ana in 2015), while storms that made landfall significantly affected loads, e.g. Fran (1996), Floyd (1999), Matthew (2016), Florence (2018). These differences can be traced to three factors: (1) the storm track, especially after landfall; (2) forward speed of the storm; (3) amount of rainfall associated with the storm; and (4) storm surges. Storms that remained offshore or grazed the coastline (e.g. Gordon, Charley) generally delivered little rainfall, with highest winds and rainfall typically occurring to the right of the storm and remaining offshore. Forward speed of TCs strongly affected rainfall, especially once landfall occurred. This was the case with Fran, Floyd, Matthew, and Florence (Figs. 5–8); slow-moving, high-rainfall events that appear to be increasing in frequency (Paerl et al. 2019).

Freshwater discharge associated with TCs strongly affected hydrologic characteristics of the NRE, including water residence times. On average, the flushing time of the NRE is about 2 months (Fig. 9), and commonly exceeds 4 months during protracted dry periods (e.g. 2007). Increased river discharge from TCs with high precipitation, however, rapidly increases the flushing rate of the estuary. Following extreme floods associated with Matthew and Florence, residence time of the NRE was only about 10 days, and for Floyd less than 5 days.

Impacts of discharge from a high-volume flushing event associated with Florence (Sept. 2018) are shown as disruptions of vertical profiles of physical–chemical properties (salinity, temperature, dissolved oxygen) that also flushed phytoplankton biomass (as Chl-*a*) from the system (Fig. 10). In contrast, events with lower discharge (e.g. TC Ernesto in 2006) led to elevated levels of DOC, TN and TP, with strong vertical stratification and significant horizontal gradients of physical–chemical properties (Fig. 11). These conditions of increased nutrient delivery favored algal growth and formation of blooms as freshwater discharge was not high enough to flush phytoplankton from the estuary. Furthermore, freshwater discharge was not sufficiently high to disrupt vertical density

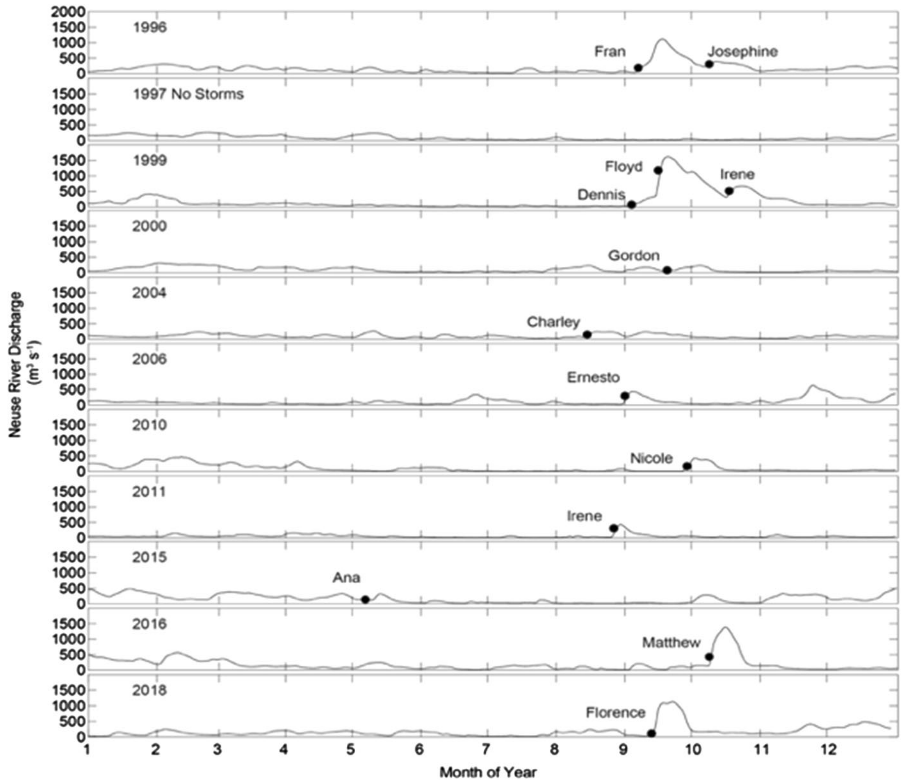

Fig. 5 Daily Neuse River freshwater discharge at the Fort Barnwell (USGS 02091814) gauging station upstream from the head of the Neuse River Estuary, as shown in Fig. 4, for selected years

stratification, and these conditions supported a bloom of the toxic dinoflagellate, *Karlodinium veneficum* (Hall et al. 2008) (Fig. 11).

In the case of a tropical depression in July 2002 that delivered substantial rainfall to coastal North Carolina, high discharge to the NRE and the nearby Pamlico River flushed phytoplankton from the system into the PS (Paerl et al. 2007). Nutrient-rich waters then supported algal growth and blooms in the PS, a much larger system than adjacent sub-estuaries with a substantially longer residence time of up to one year (Pietrafesa et al. 1996).

Significant differences in annual loadings of DOC and nutrients occurred in years with and without TCs. In years without TCs (1999, 2004, 2010), typical seasonal patterns of DOC, TN and TP loadings were observed (Figs. 5, 6, 7, 8). In years with TCs accompanied by moderate rainfall, up to half the annual loadings of DOC and nutrients were associated with storm events. In years with TCs accompanied by very high rainfall, more than half the annual loadings were associated with storm events. Given the sampling protocol, we were not able to quantify additional contributions from storm surges.

Summarizing, TCs with high rainfall have the potential to double annual loadings of DOC and nutrients to the NRE and PS. For TC Floyd (1999), approximately 80% of annual N and 60% of the annual P loads were attributed to surface runoff and subsurface groundwater (Paerl et al. 2001, 2006). With regard to organic matter, approximately 80% of annual allochthonous POC and an equivalent percentage of annual DOC inputs were attributable to floodwaters from Floyd (Paerl et al., 2001, 2006). For the Pamlico Sound alone, this single event provided 60% of the annual load (Bales 2003; Paerl et al. 2006).

Biogeochemical and ecological impacts

Hurricane Floyd struck eastern North Carolina in Sept. 1999, overwhelming the NRE with extremely high freshwater discharge, and essentially turning it into a "pipeline" that emptied into the APS (Paerl et al. 2001, 2006). This event led to very large discharge of

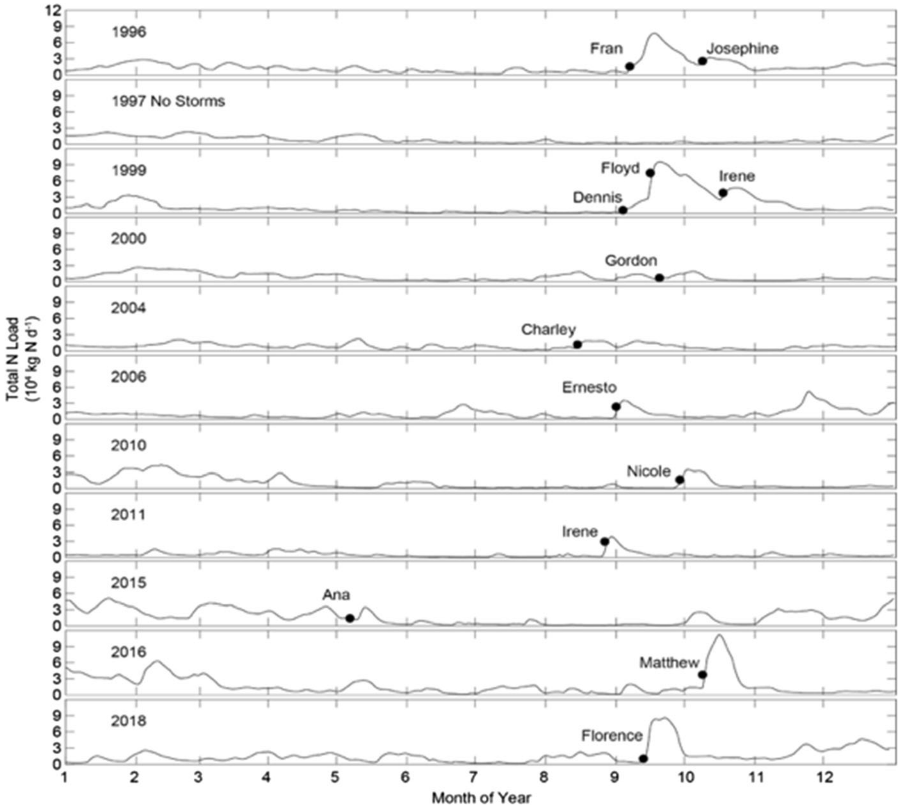

Fig. 6 Daily total nitrogen (TN) load at the head of the Neuse River Estuary

freshwater overlying denser saline water, resulting in strong, persistent vertical stratification, and extensive hypoxia in bottom waters of the APS, with massive fish and shellfish kills and an abrupt increase in fish disease (Eby and Crowder 2002; Adams et al. 2003; Paerl et al. 2006).

Prevailing hydrologic conditions in a given year strongly affect overall impacts of TCs on estuarine and coastal waters. For example, Hurricane Matthew in 2016 occurred during a "wet" year with above-average discharge from winter through spring (Fig. 12). Thus, impacts of Hurricane Matthew on annual C, N and P loadings were masked by "high-flow" conditions compared to TCs passing through the NRE and its watershed during "dry" years (Paerl et al. 2018). Moreover, precipitation from Hurricane Matthew was largely focused in the upper regions of the watersheds, and the pulse of waters associated with Matthew took 2–4 weeks to reach the NRE and Pamlico Sound proper. Nutrient loadings following Hurricane Matthew accounted for $\sim$ 50% of the annual SRP loading and $\sim$ 20% of the annual DIN load to the NRE and Pamlico Sound (Paerl et al. 2018). In the first two weeks following Matthew, 25% of annual C loading for 2016 was delivered to the estuary (Osburn et al. 2019a, b). The majority (67%) of the C load was DOC (Osburn et al. 2019a, b), similar to observations for other TCs such as Floyd (Paerl et al. 2018).

Hurricane Florence stalled off the North Carolina coast for several days from late September to early October, 2018, and upon landfall delivered > 70 cm of rainfall to eastern NC and the NRE watershed (Paerl et al. 2019). Similar to Floyd and Matthew, floodwaters from Florence led to extensive freshening of the NRE (Fig. 9). The sheer volume of freshwater discharge and high flushing rates prevented salinity stratification. Initial estimates of DOC loading suggest that the concentration doubled near peak river discharge, with Florence accounting for a 75% increase of the annual DOC load to the NRE (cf. Fig. 8).

The combined effects of Hurricanes Floyd, Matthew, and Florence on hydrologic, C, N and P loadings to the NRE and APS systems in the past 20 years were

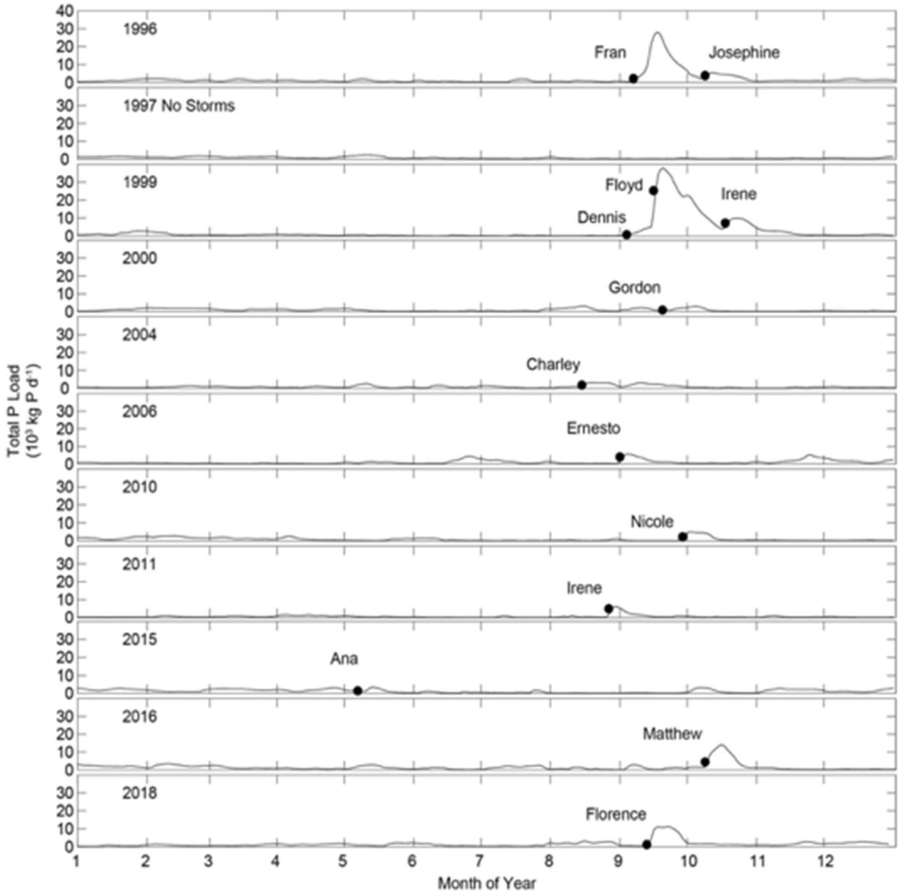

Fig. 7 Daily total phosphorus (TP) load at the head of the Neuse River Estuary

unmatched in recorded history of hurricanes and TCs for coastal North Carolina (Paerl et al. 2019). While long-term C, N and P cycling dynamics of the legacy loads delivered by these storms are still evolving, short-term biogeochemical and trophic impacts are evident. A notable example is expansion of the hypoxic zone in the estuarine continuum following Floyd that compressed finfish and shellfish habitats (Eby and Crowder 2002; Eggleston et al. 2010).

Enhanced nutrient loads associated with TCs (Figs. 5–8) stimulated phytoplankton production, but effects varied in time and space, depending on estuarine flushing rates and the magnitude of high-nutrient freshwater discharge. For example, in conditions of moderate discharge and nutrient enrichment but freshwater discharge insufficiently high to exceed phytoplankton growth rates and flush algae out of the system, stimulation of phytoplankton biomass as Chl *a* was evident in the NRE shortly after storm passage. Examples of this response included TCs Isabel (2003), Charley (2004), Ernesto (2006) and Joaquin (2015) (Fig. 13). Conversely, a delayed phytoplankton response to TCs with high rainfall and discharge, was exemplified by Floyd (1999), Matthew (2016) and Florence (2016) that essentially turned the NRE into a "pipeline" where phytoplankton growth was not stimulated until months after the event (Fig. 13). Under these conditions, a large proportion of the short-term (days to weeks) growth response of phytoplankton occurred in the larger, longer residence time downstream Pamlico Sound (Paerl et al. 2007). The NRE response can lag by a matter of weeks, depending on how quickly high river flow recedes. Examples of this scenario include Floyd (1999–2000) and Florence (2018) (Fig. 13).

Some TCs such as Ernesto (2006) generated large pulse loadings of nutrients in freshwater discharge, producing optimal conditions for development of

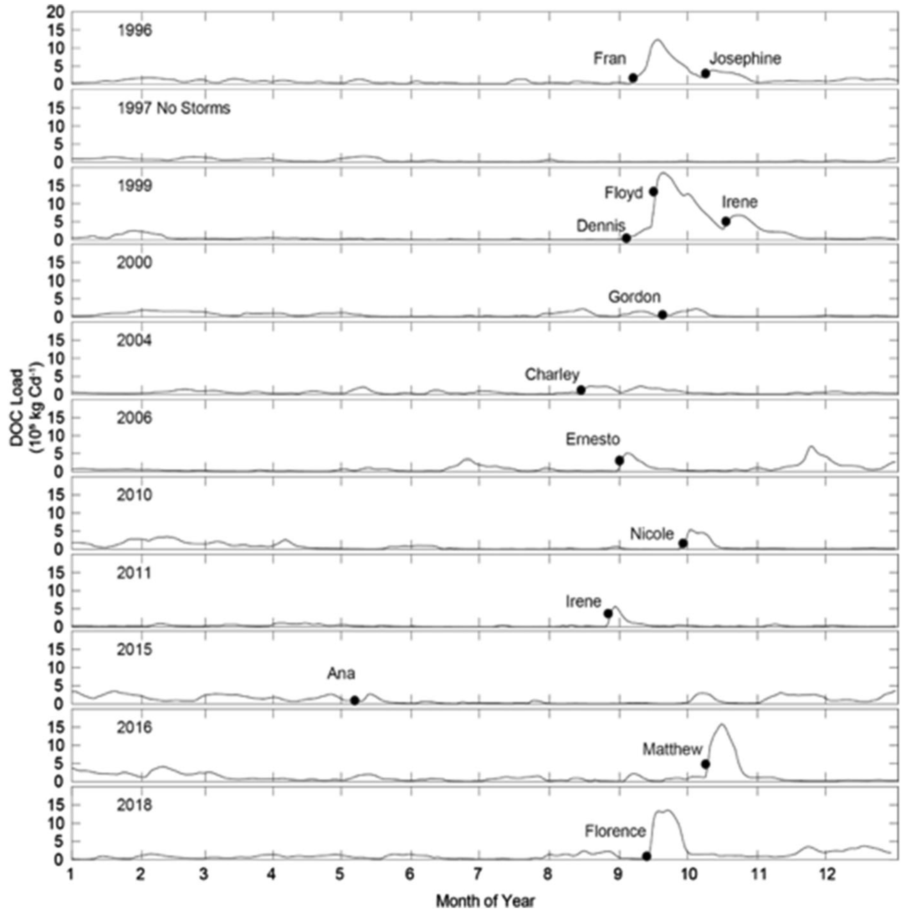

Fig. 8 Daily dissolved organic carbon (DOC) load based on concentrations measured at the head of the Neuse River Estuary

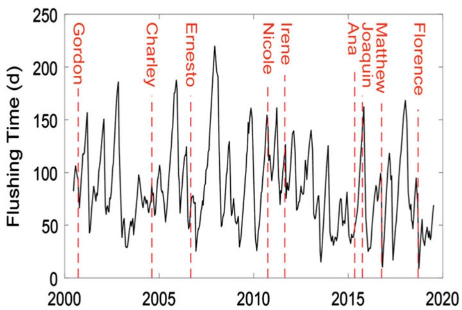

Fig. 9 Time series of flushing time of the Neuse River Estuary in relation to the timing of "wet" tropical cyclones that resulted in significant increases in river discharge. See Paerl et al. (2018) for details on the objective definition of "wet" storms

harmful algal blooms (HABs) of the toxic dinoflagellate, *Karlodinium veneficum.* These HABs occurred in the mid-estuarine region of the microtidal NRE where nutrient-rich freshwater discharge and moderate flushing provided long enough water residence time for blooms to proliferate (Hall et al. 2008) (Fig. 11). Large phytoplankton blooms also occurred in the PS with its longer residence time in response to nutrient loadings in freshwater discharge following passage of Hurricane Floyd (1999–2000) (Tester et al. 2003). Freshening of coastal ecosystems in North Carolina associated with an increased frequency of TCs and associated precipitation affects salinity gradients in the NRE-PS continuum, with periods of depressed salinity extending well downstream (Paerl et al. 2006; 2018). These conditions favor low-salinity phytoplankton groups, such as chlorophytes and cyanobacteria (Pinckney et al. 1998; Hall et al. 2013; Paerl et al. 2013, 2018). Other estuarine and coastal waters experiencing increased discharge and flooding associated with a higher frequency of major storm and rainfall events show evidence of a similar

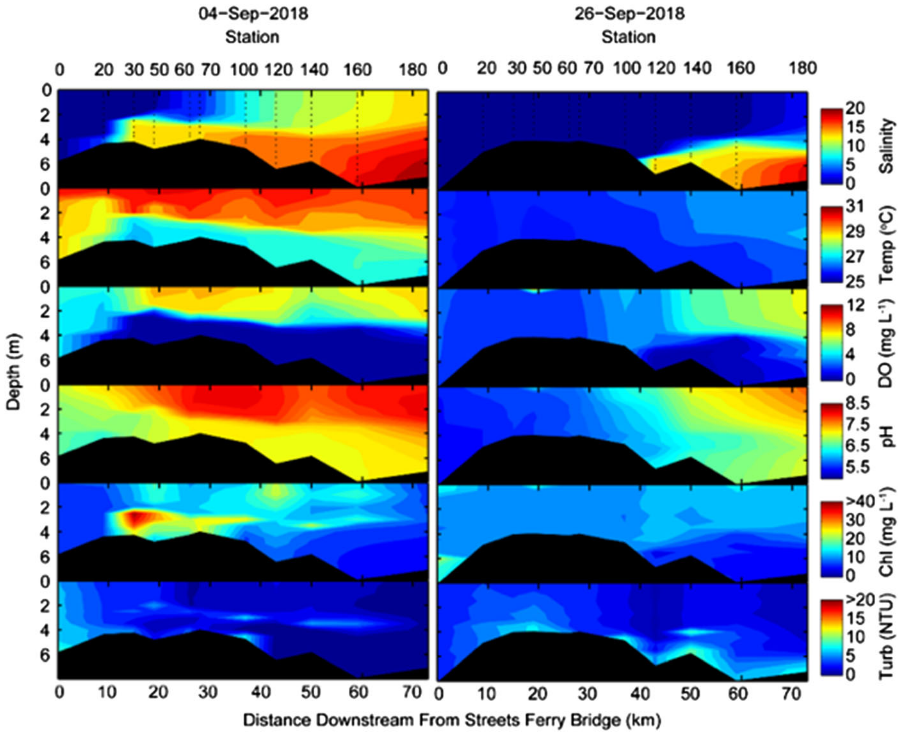

Fig. 10 Physical–chemical impacts of freshwater discharge resulting from Hurricane Florence (September, 2018) on the Neuse River Estuary, NC. Shown are water column profiles (dashed vertical lines show location of ModMon station profiles) of salinity, temperature, dissolved oxygen, pH, chlorophyll *a* (as an indicator of algal biomass) and turbidity, before (left hand side) and after (right hand side) the storm made landfall

phytoplankton bloom response. For example in the Mississippi Delta, northern Gulf of Mexico, increased rainfall and flood events in the Mississippi watershed produced large plumes of nutrient-rich freshwater that extended into coastal bayous and bays (Bargu et al. 2019). These conditions promoted the downstream expansion of harmful (toxic) cyanobacterial genera, including *Dolichospermum* and *Microcystis* (Riekenberg et al. 2015; Bargu et al. 2019). In the APS, a parallel scenario is observed in the brackish Albemarle Sound that drains several rivers in eastern North Carolina and southeastern Virginia, including the Chowan and Roanoke. The Chowan River has a history of harmful cyanobacterial blooms, or CyanoHABs (*Dolichospermum* and *Microcystis*) and is currently experiencing a bloom resurgence (https://www.albemarlercd.org/fighting-algal-blooms.html). These systems have also experienced increased storm-related freshwater and C, N and P loadings that create periods of fresher and more nutrient rich conditions that favors CyanoHAB expansion into oligohaline Albemarle Sound where *Dolichospermum*, *Microcystis* and *Cylindrospermopsis* populations have become widespread and common (Calandrino and Paerl 2011; NC DEQ 2019).

Increased DOC and DON loadings coincide with increases of freshwater discharge and nutrient loadings associated with TCs. Bioassays conducted *in-situ* on the New River Estuary, North Carolina showed that organic matter in freshwater discharge stimulated phytoplankton biomass and altered taxonomic composition, stimulating several dinoflagellate and cyanobacterial taxa (Altman and Paerl 2012). These findings suggest specific components of the DOM (i.e., DON) pool play a role in phytoplankton dynamics. Bacterial production may also be stimulated by DOM in freshwater discharge (allochthonous) or DOM produced by phytoplankton (autochthonous) (Peierls and Paerl 2010; Peierls and Paerl 2011).

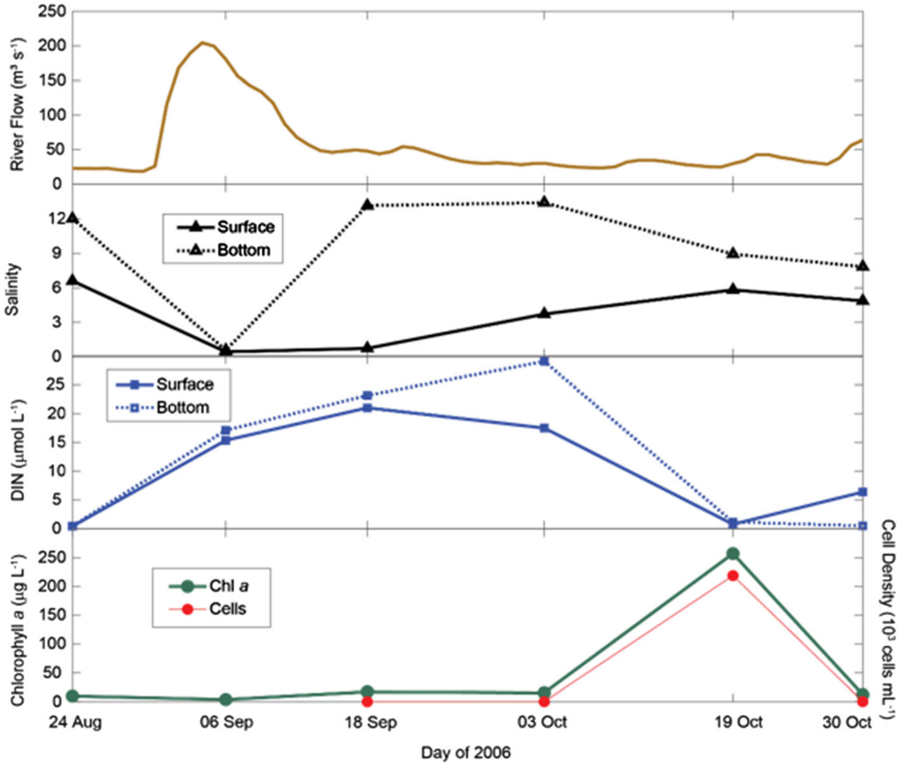

Fig. 11 A toxic dinoflagellate (*Karlodinium veneficum*) bloom associated with nutrient-enriched runoff from tropical storm Ernesto, October, 2006, which set up strong vertical and horizontal salinity gradients in the NRE

Implications for carbon cycling

As observed for nutrient loadings, the increasing intensity and frequency of TCs also affect C loading and cycling in estuarine and coastal waters. Freshwater loads of nutrients and organic matter provide the fuel for microbial consumption of oxygen, often leading to extensive hypoxia and anoxia throughout the APS (Buzzelli et al 2002; Paerl et al. 1998, 2001, 2006, 2018) (Fig. 14). Furthermore, breakdown and cycling of allochthonous organic matter mediated by heterotrophic microbes (Peierls and Paerl 2010) modulates nutrient availability, primary production of organic matter, and ultimately, trophic state. The importance of ecosystem-scale DOC loadings attributable to TCs are exemplified by Hurricane Matthew (2016) which accounted for up to 25% of the annual DOC load to the NRE and Pamlico Sound (Osburn et al. 2019a, b), representing a disproportionate impact on the annual DOC loading to the estuarine system in 2016.

The source of this additional DOC loading was largely a result of the flooding of freshwater wetlands at the head of the estuary, shifting the quality of DOM imported into the estuary from upstream, terrestrial-sources to wetlands-derived sources following the storm event (Rudolph et al. 2020; Osburn et al. 2019a, b; Table 2). Not only did this result in enhanced DOC loading from the Neuse River to the NRE, but it also enhanced DOC loading from the NRE to the downstream Pamlico Sound, as the "pulse" of wetland-derived DOC was "shunted" to the sound (Rudolph et al. 2020; Osburn et al. 2019a, b; Hounshell et al. 2019; Table 2). In the weeks to months following Hurricane Matthew, the wetland-derived organic matter flushed into Pamlico Sound and was oxidized to CO_2 thereby switching the system from a CO_2 sink to a CO_2 source and changing the role of the estuary in the processing of organic matter. (Osburn et al. 2019a, b).

Changing quality and quantity of DOC flushed into estuarine and coastal waters could have important implications for the role of ecosystems, such as APS,

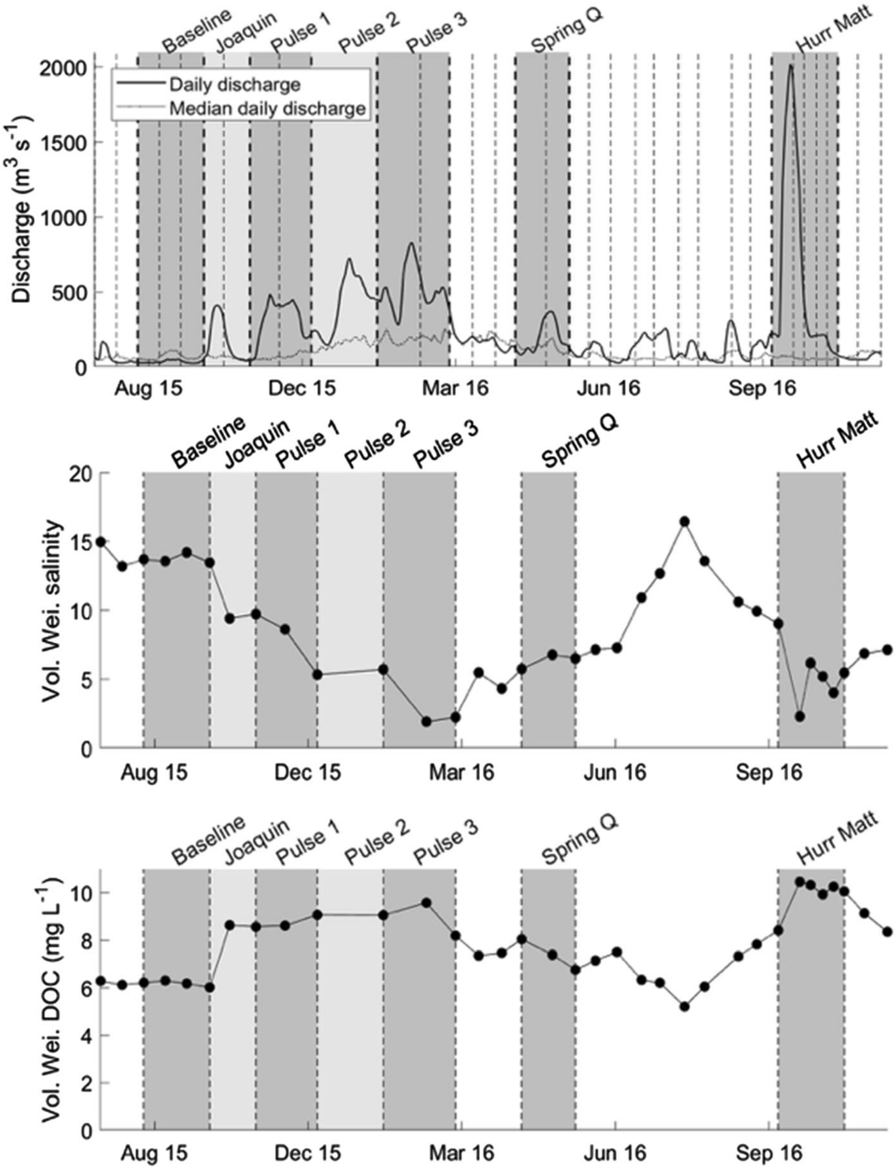

Fig. 12 River discharge, salinity and DOC for seven discrete discharge events in the Neuse River Estuary, starting with offshore storm Joaquin September, 2015 and ending with Hurricane Matthew in September, 2016. From Hounshell et al. (2019)

in the global C cycle (Bauer et al. 2013). With an increase of extreme discharge events associated with TCs, some estuaries, such as the Neuse River, may switch from 'processors' of DOC to 'pipelines' with direct export of terrestrial DOC to downstream sounds and coastal waters, such as Pamlico Sound, which themselves become important processors (Osburn et al. 2019a, b; Hounshell et al. 2019). This could result in estuaries and coastal waters experiencing extended hypoxia and acidification (Wallace et al. 2014) as well as reorganizing coastal C cycles (Najjar et al. 2018; Yan et al. 2020). Additional studies are needed to assess the direct link between wetlands-derived DOC flushed into estuarine and coastal waters following TCs with observed CO_2 fluxes, but preliminary results suggest these coastal ecosystems become important locations for the transformation of this wetland-derived DOC in the weeks and months following storm events associated with extreme precipitation (Osburn et al. 2019a, b).

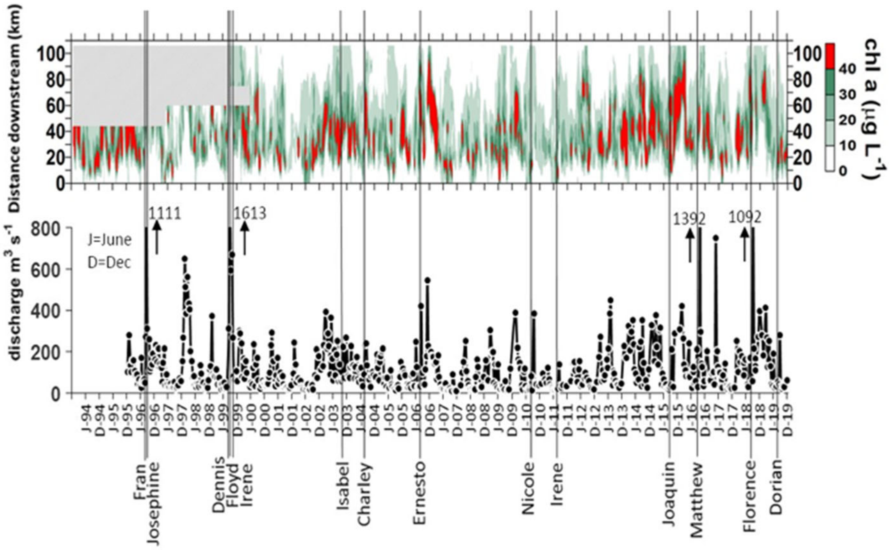

Fig. 13 Discharge ($m^3\ s^{-1}$) in relation to phytoplankton production (as Chl *a*) downstream in the Neuse River Estuary-Pamlico Sound estuarine continuum

Additionally, following TCs with comparatively less extreme precipitation, such as Hurricane Irene in 2014, Crosswell et al. (2014) observed a significant release of CO_2 from the NRE and Pamlico Sound following TC passage. Specifically, the authors reported extensive DOM enrichment associated with Hurricane Irene (2014) in the NRE and Pamlico Sound, leading to a massive pulse of CO_2-release to the atmosphere, roughly equivalent to the annual amount of CO_2 fixed by phytoplankton in these systems (Crosswell et al. 2014). Results following both Hurricane Matthew, a disproportionally high precipitation event, as well as following Hurricane Irene, demonstrate the importance of TCs on controlling riverine DOM loading and processing under a range of TC characteristics.

DOM quality of exported DOC storm loads is also likely an important factor in the response of estuaries to TCs. For example, Other studies have reported similar changes of DOM quantity and quality following hurricanes. Letourneau and Medeiros (2019) observed increases of DOC concentrations of terrestrial quality following passage of Hurricane Matthew, despite little change in freshwater discharge to Georgia estuaries. The increasing terrestrial quality of DOM associated with freshwater discharge was linked to increased microbial degradation (Letourneau and Medeiros 2019), pointing to potential linkages of TCs to DOM quality, microbial degradation, and CO_2 production. Lu and Liu (2019) observed significant enrichment of DOM in four Texas rivers draining into the northern Gulf of Mexico following major storms. The authors noted that DOM quality shifted from protein-like and lipid-like compounds at base flow conditions, to lignin, tannin and condensed aromatic structure during high freshwater discharge. Similarly, in the Newport River Estuary, near the APS, increases in aromatic DOC were correlated to higher microbial mineralization rates of aromatic C (Osburn et al. 2019b). Thus, terrestrial DOM flushed into estuarine systems during high-flow conditions has been traced to mobilization of organic matter from the watersheds and wetlands due to flooding, consistent with findings in the NRE and Pamlico Sound (Rudolph et al. 2020).

Results of previous studies and evidence presented here show that increased TCs exert a disproportionate impact on C, N and P loadings to estuarine and coastal waters, with qualitative and quantitative effects on primary producers and associated microheterotrophs (Paerl et al. 2006, 2018; Peierls et al. 2003, 2011).

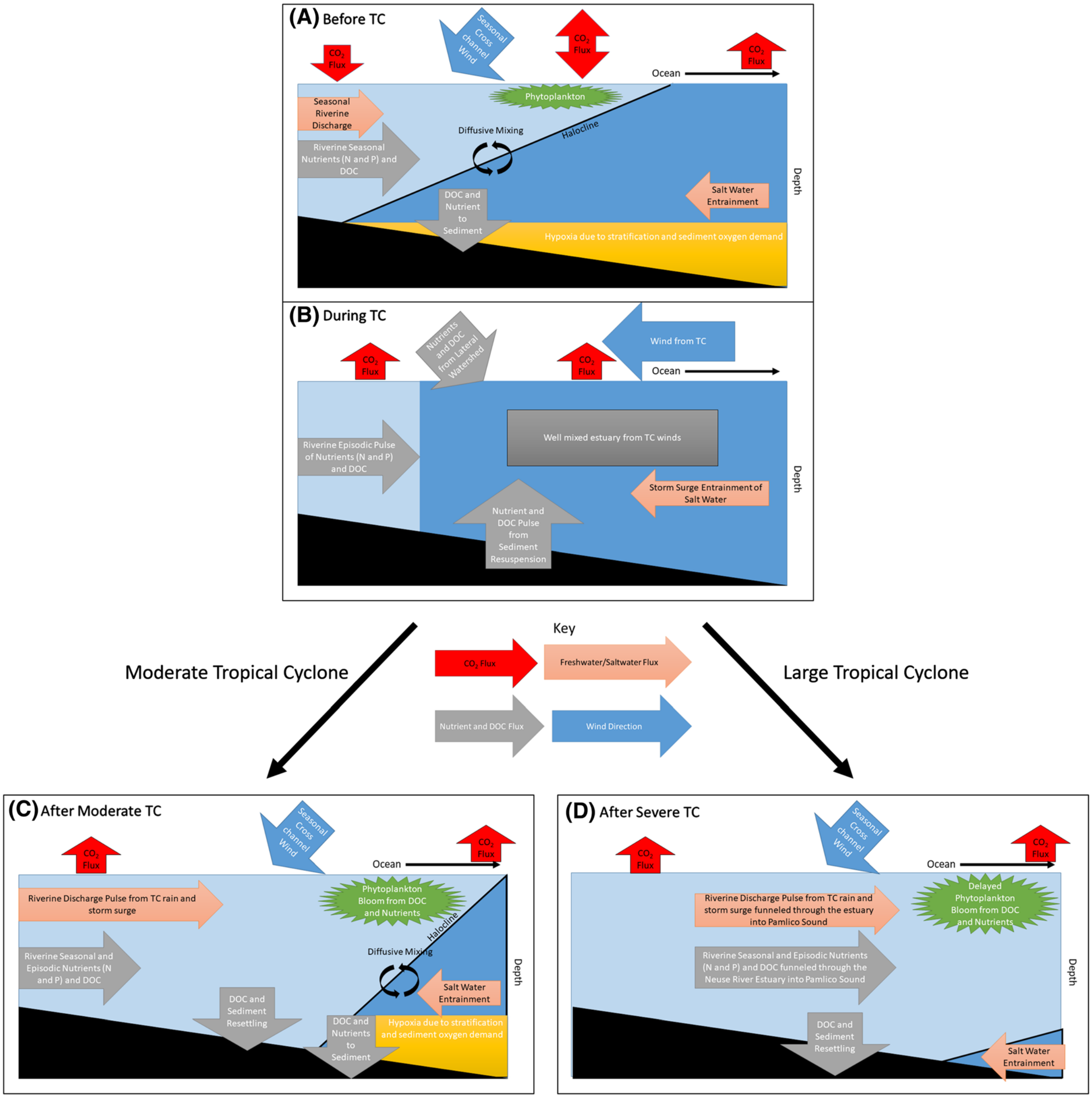

Fig. 14 Conceptual figure, showing the interactive effects of TC-related freshwater discharge, DOC and nutrient loading and wind mixing on physical structure of the water column, phytoplankton and associated microbial activities and biogeochemical responses, including hypoxia and air–water CO_2 exchange in a lagoonal estuary like the Neuse River Estuary. Illustrated are the before, during and after TC scenarios. During moderate storms, the DOC and DON from the storms lead to a down estuary bloom. During severe storms, the DOC and DON from the storms is flushed out of the estuary into Pamlico Sound

Short- and long-term biogeochemical impacts, including coastal C, N and P cycling, oxygen dynamics, habitat alteration, and trophodynamics deserve careful scrutiny as we have entered a “new normal” with increased TCs and associated extremes of precipitation and freshwater discharge (Seneviratne et al. 2012; Wetz and Yoskowitz 2013; Asadieh and Krakauer 2015; Paerl et al. 2019).

Table 2 DOC mass loading from Neuse River and freshwater wetlands into the NRE-PS, in response to Hurricane Matthew

Location	Total DOC mass (Gg C)	NRE DOC (%)	PS DOC (%)
Fort Barnwell, NC			
1 d[a]	0.436	9.2	3.1
7 d[a]	3.042	64.1	22.0
Wetlands			
Max[b]	2.260	47.7	16.3
Mean[c]	0.965	20.4	7.0
NRE			
Max[d]	4.741	–	34.2
PS			
Max[e]	13.849	–	–

Mean [DOC] value from high discharge (7.429 mg C L^{-1}). Maximum [DOC] from freshwater wetlands in autumn (14.4 mg C L^{-1}). Mean [DOC] from freshwater wetlands in autumn (6.15 mg C L^{-1}). Maximum [DOC] stock change from NRE. Maximum [DOC] stock change from PS. From Rudolph et al. 2020

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