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Modeling the transport of freshwater and dissolved organic carbon in the Neuse River Estuary, NC, USA following Hurricane Irene (2011)

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A B S T R A C T

Numerical models are useful tools that aid in understanding complex flows and the distribution of suspended material over large geographic areas and during extreme weather events. Here we describe the use of a three-dimensional numerical model (Delft3D) to simulate freshwater and dissolved organic carbon (DOC) transport over a 3-week period, following intense precipitation that led to high river discharge into the brackish Neuse River Estuary (NRE), NC, from Hurricane Irene (Aug. 2011). The model was calibrated and validated using field measurements of water level elevations, vertical salinity profiles, and surface DOC concentrations in the estuary. DOC was simulated as a conservative tracer over the study period. Model results indicate differences in the intensity of the freshwater and DOC-laden plumes as they propagated along estuary due to a one week time lag between the maximum discharge of 540 $m^3\ s^{-1}$ and maximum DOC concentration of 29.85 mg L^{-1} entering the NRE from the river. In the upper estuary, the surface DOC concentration increased by 18 mg L^{-1} above the pre-storm value of 7 mg L^{-1}; the maximum concentration occurred 10 days after the passage of the storm. In the lower estuary, the outer edge of the DOC plume reached Pamlico Sound after 3 weeks with a surface DOC concentration that was 3 mg L^{-1} above the pre-storm value. Results also indicate cross-channel salinity differences up to 10 ppt and DOC concentration differences up to 15 mg L^{-1} in the upper NRE to due to wind-driven motion of the estuary. The methods described here could be applied to other coastal plain estuarine systems to simulate and characterize flow rates and DOC transport during and succeeding storm events where field measurements are often limited.

1. Introduction

Organic matter is the largest reactive reservoir of reduced carbon on Earth (Bianchi, 2011) and exists in the aquatic environment as both particulate and dissolved material. The major source of allochthonous organic matter to the coastal ocean is organic rich soils and plant material within watersheds (Thurman, 1985). The riverine transport of this terrestrially derived organic matter makes up a significant portion of the global carbon cycle as rivers annually transport an estimated 200–530 Tg (teragrams) of total organic carbon (TOC) to the coastal ocean. The delivery of TOC to the coastal ocean is partitioned as 138–288 Tg C yr^{-1} of particulate organic carbon (POC) and 214–360 Tg C yr^{-1} of dissolved organic carbon (DOC) (McKee, 2003 and references therein). During periods of high river discharge or in rivers with high sediment loads, the ratio of POC to DOC can be equal, however in large rivers the concentration of DOC often dominates and the amount of POC is commonly only half that of DOC (Thurman, 1985). Dissolved organic matter (DOM) is the largest ocean reservoir of reduced carbon (Benner et al., 1992) with seawater DOC containing nearly as much carbon as the atmospheric CO_2 pool (Hedges, 1992 and references therein).

The transport of large concentrations of terrestrially derived DOM by rivers can significantly influence the overall quality and ecological processes of coastal waters. For example, DOM can serve as a food source to marine invertebrates (Yahel et al., 2003; Baines et al., 2005) and bacteria (Tranvik, 1992) and control water column light availability (Markager and Vincent, 2000; Kostoglidis et al., 2005; Foden et al., 2008). In addition, colored dissolved organic matter (CDOM), the light absorbing fraction of DOM, is known to interfere with remote sensing estimates of chlorophyll *a* in coastal waters (Carder et al., 1989). The photoreactive nature of DOM can lead to the formation of CO_2 and CO (Miller and Zepp, 1995), thereby creating a possibly significant water to atmospheric flux of

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carbon (Cai, 2011). Additionally, DOM has been found to be associated with the transport of toxic substances (Ravichandran, 2004) and the production of harmful disinfection byproducts (Kitis et al., 2002; Wang et al., 2007; Chow et al., 2011). Although DOM plays a significant role in many coastal environments, there remains an important need to gain a better understanding of the coupling processes and transport and fate of terrestrially derived DOM in coastal waters.

The Albemarle-Pamlico Estuarine System (APES) of eastern North Carolina (Fig. 1), the second largest estuarine system and largest lagoonal estuary in the United States, is an important asset that provides many ecological services that are vital to the state's economy. The APES drains an approximately 73,400 km^2 watershed with the majority of freshwater discharge coming from four rivers (Chowan, Roanoke, Tar and Neuse) primarily draining the Piedmont and Coastal-Plain regions of North Carolina (Miller et al., 2011a). The APES is bounded to the east by the Outer Banks barrier island system, resulting in a limited exchange of APES water with the Atlantic Ocean through three major tidal inlets. Pamlico Sound is the largest major water body occupying ~5335 km^2 of the APES surface area and supports important commercial and recreational fishing industries. The Tar and Neuse River watersheds connected to Pamlico Sound drain approximately 25,640 km^2 (Giese et al., 1979). The Neuse River drains the largest and most populated watershed directly draining to Pamlico Sound, flowing ~320 km through the Piedmont and Coastal-Plain provinces of North Carolina and draining approximately 16,000 km^2 dominated by agriculture and forest (Stow et al., 2001; Whitall et al., 2003). The Neuse River broadens at New Bern, NC to form the headwaters of the Neuse River Estuary (NRE). The NRE (Fig. 2) is a shallow drowned river valley with an average depth of 4.6 m (Matson et al., 1983) that flows ~70 km before discharging into the southwest region of Pamlico Sound. Due to the few narrow inlets

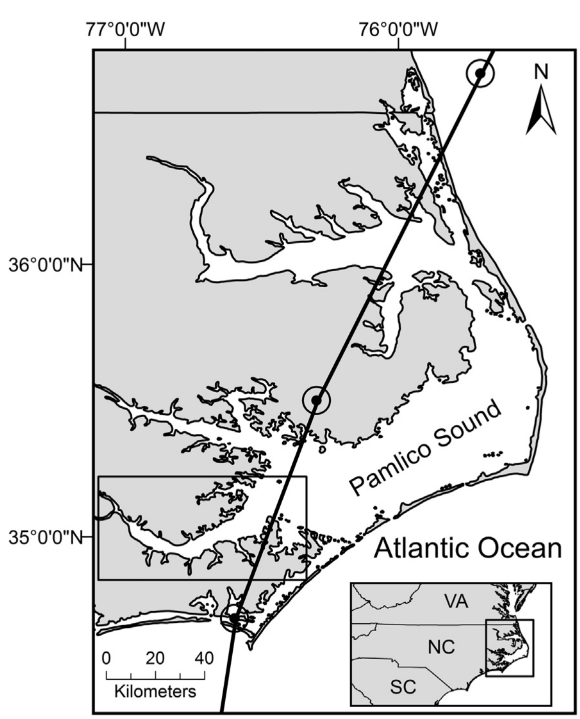

Fig. 1. Map of the Albemarle-Pamlico Estuarine System (APES) showing the track of Hurricane Irene (black line) through eastern North Carolina (inset). The circles indicate the storm's location at 1200 UTC Aug. 27, 1800 UTC Aug. 27 and 0000 UTC Aug. 28 from south to north, respectively. The black box denotes the Neuse River Estuary (NRE), shown in detail in Fig. 2.

of the APES, the resulting small (≤10 cm amplitude (Wells and Kim, 1989, 1991; Benninger and Wells, 1993)) astronomical tides play a limited role on the hydrodynamics within the NRE (Luettich et al., 2000, 2002). With a limited tidal influence, water and material transport within the system is mainly forced by winds (Wells and Kim, 1989, 1991; Luettich et al., 2000) and river discharge (Wells and Kim, 1989, 1991).

Potential negative impacts from the transport, distribution and fate of terrestrially derived material within the system may be increased by the 1–2 month residence time of the NRE (Knowles, 1975; Robbins and Bales, 1995) and 11-month residence time of Pamlico Sound (Giese et al., 1979). For example, persistent phytoplankton blooms (Paerl et al., 1995; Pinckney et al., 1997), fish kills (Paerl et al., 1998), and bottom water hypoxia-anoxia (Paerl et al., 1998) within the NRE, associated with eutrophication driven by nutrients and materials derived from within the NRE watershed (Paerl et al., 1995), has led to long-term monitoring of water quality parameters (excluding DOM) within the NRE.

Material transported from terrestrial to aquatic environments often increases in concentration following precipitation events or rapid snowmelt (Hinton et al., 1997; Boyer et al., 1997, 2000; Buffam et al., 2001; Inamdar et al., 2004, 2006; Raymond and Saiers, 2010). Rain events mobilize and transport both particulate and dissolved material (e.g., nutrients, sediment, organic matter) from North Carolina's coastal watersheds and deliver this material to the streams and rivers that drain to the APES. It is well documented that rain events can significantly influence the water quality and organic matter loading to the NRE (e.g., Paerl et al., 1998, 2001; Bales, 2003; Burkholder et al., 2004; Paerl et al., 2006; Wetz and Paerl, 2008). Much of this understanding was derived from studies that examined the mobilization and transport of organic material within the Neuse River and NRE following a series of tropical systems (Hurricanes Dennis, Floyd, and Irene) that impacted coastal North Carolina in 1999. The unprecedented floodwaters resulting from these tropical systems exported large amounts of organic material (Bales, 2003) such that these storms may have had a long-term effect on DOC concentrations within the NRE (Christian et al., 2004). Following the storms, DOC concentrations at the mouth of the NRE roughly doubled the pre-storm concentrations of 6.0–8.4 mg L^{-1} (Paerl et al., 2001). Similarly, Paerl et al. (1998) report that greater than 14 × 10^6 kg of organic carbon were transported to the NRE following Hurricane Fran in September 1996, leading to fish kills throughout the study area. These previous studies demonstrate the coupling between rainfall events, increased loadings of terrestrially derived material and system response of the NRE and APES.

Because of the potential increase in the frequency of intense Atlantic tropical cyclones (Bender et al., 2010) and the projected increase in heavy rainfall associated with tropical cyclones (Seneviratne et al., 2012), it is vitally important that we gain a better understanding of how storms currently impact the transport of organic matter to coastal waters such as the APES. Hurricane Irene, which directly affected eastern North Carolina in August 2011, provided an opportunity to further investigate the impact of tropical systems on the hydrodynamics and transport of organic matter within the NRE. Hurricane Irene made landfall near Cape Lookout, NC on Aug. 27, 2011 as a category 1 hurricane with maximum winds of 39 m s^{-1}. Maximum sustained winds and maximum gusts (Fig. 3) near the middle NRE at Cherry Point (Fig. 2) were measured at 23 m s^{-1} and 31 m s^{-1}, respectively (Avila and Cangialosi, 2011). Within the Neuse River Basin (NRB), the highest accumulated (Aug. 21–28) amount of rainfall, 38 cm, was measured at New Bern (Avila and Cangialosi, 2011). During the same time period, the accumulated rainfall at Grifton, NC, located ~50 km upstream from New Bern, was 34 cm with the majority