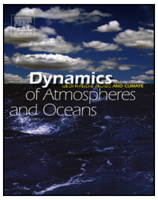
Dynamics of Atmospheres and Oceans 80 (2017) 124–138

Contents lists available at ScienceDirect

Dynamics of Atmospheres and Oceans

journal homepage: www.elsevier.com/locate/dynatmoce



Observations and operational model simulations reveal the impact of Hurricane Matthew (2016) on the Gulf Stream and coastal sea level

Tal Ezer*, Larry P. Atkinson, Robert Tuleya

Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, Norfolk, VA, 23508, USA

ARTICLE INFO

Article history:
Received 2 March 2017
Received in revised form 18 July 2017
Accepted 25 October 2017

Keywords:
Coastal currents
Sea level
Hurricanes
Flooding
Gulf stream
Florida current

ABSTRACT

In October 7–9, 2016, Hurricane Matthew moved along the southeastern coast of the U.S., causing major flooding and significant damage, even to locations farther north well away from the storm's winds. Various observations, such as tide gauge data, cable measurements of the Florida Current (FC) transport, satellite altimeter data and high-frequency radar data, were analyzed to evaluate the impact of the storm. The data show a dramatic decline in the FC flow and increased coastal sea level along the U.S. coast. Weakening of the Gulf Stream (GS) downstream from the storm's area contributed to high coastal sea levels farther north. Analyses of simulations of an operational hurricane-ocean coupled model reveal the disruption that the hurricane caused to the GS flow, including a decline in transport of ~20 Sv ($1\,\text{Sv} = 10^6\,\text{m}^3\,\text{s}^{-1}$). In comparison, the observed FC reached a maximum transport of ~40 Sv before the storm on September 10 and a minimum of ~20 Sv after the storm on October 12. The hurricane impacts both the geostrophic part of the GS and the wind-driven currents, generating inertial oscillations with velocities of up to $\pm 1\,\text{m}\,\text{s}^{-1}$. Analysis of the observed FC transport since 1982 indicated that the magnitude of the current weakening in October 2016 was quite rare (outside 3 standard deviations from the mean). Such a large FC weakening in the past occurred more often in October and November, but is extremely rare in June-August. Similar impacts on the FC from past tropical storms and hurricanes suggest that storms may contribute to seasonal and interannual variations in the FC. The results also demonstrated the extended range of coastal impacts that remote storms can cause through their influence on ocean currents.

1. Introduction

Hurricane Matthew developed in the Caribbean in late September 2016, and quickly intensified from category 1–5 (maximum wind of 260 km h^{-1}), before weakening to category 3–4 when moving northward across Cuba and Haiti and causing significant damage and loss of life. During October 7–9 the hurricane moved along the coasts of Florida, Georgia, South Carolina and North Carolina, before looping east and dissipating. The southeastern States suffered several billions of dollars of damages, mostly due to large amount of rain and storm surge flooding (see the National Hurricane Center, http://www.nhc.noaa.gov/, and various weather news reports such as

---

* Corresponding author.
E-mail address: tezer@odu.edu (T. Ezer).

https://doi.org/10.1016/j.dynatmoce.2017.10.006

https://weather.com/storms/hurricane/news/hurricane-matthew-bahamas-florida-georgia-carolinas-forecast). Tide gauge data along the storm passage show that storm surges reached water levels of ∼1–1.5 m in Fernandina, FL, Pulasky, GA, Charleston, SC, and Wilmington, NC (all levels are relative to Mean Higher High Water, MHHW). However, somewhat surprising was that water levels farther away from the storm were also raised significantly, for example to ∼1 m (MHHW) in Norfolk, VA, and 0.3–0.5 m in other locations in the Chesapeake Bay and the Atlantic coast (as far as the New Jersey coast, as shown later). Significant flood damage to houses in Virginia Beach may be attributed to street flooding due to extreme rainfall that could not drain because sea levels were high at the same time. Interestingly enough, a similar phenomenon of high water levels in Norfolk happened a year earlier (September–October 2015) when hurricane Joaquin was located well offshore- details of the sea level during this storm was reported in a recent study (Ezer and Atkinson, 2017). This latter study also demonstrated some predictability skill in using the Florida Current measurements to infer high water levels in Norfolk.

One possible hypothesis for how a remote storm can influence coastal sea level along the U.S. East Coast is through the impact of the storm on the Gulf Stream (GS). Weakening in a western boundary current transport will decrease the seaward sea level slope across the current (i.e., the GS) and increase coastal sea level on the onshore side of the current; this idea was suggested decades ago (Blaha, 1984) and confirmed by recent observations (Ezer et al., 2013, Ezer and Atkinson, 2014, 2017; Ezer, 2015, 2016) and numerical models (Ezer, 2001, 2016; Goddard et al., 2015). On long time-scales, studies suggest that recent sea level acceleration on the U.S. East Coast may be partly driven by climate-related slowdown of the Atlantic Meridional Overturning Circulation (AMOC) (McCarthy et al., 2012; Smeed et al., 2013) and a weakening Gulf Stream (Boon, 2012; Ezer and Corlett, 2012; Sallenger et al., 2012; Ezer et al., 2013). However, these long-term variations in the GS are relatively small and involve also basin-scale decadal and longer variations that are not directly related to coastal sea level. On the other hand, large short-term fluctuations in the GS transport (order of ∼5–10 SV within few days) are quite common, and there is growing evidence that these variations can be detected within days in coastal sea level records. The short-term variations can cause unexpected tidal flooding even when there is no storm nearby (Ezer and Atkinson, 2014; Park and Sweet, 2015; Wdowinski et al., 2016). The mechanism of this observed short-term sea level-GS correlation (with very short lag of hours to few days) was recently explored by numerical simulations (Ezer, 2016). The simulations demonstrated how variations in the FC transport with periods of 2–10 days can create a fast moving barotropic signal downstream along the GS path that then ignites coastal trapped waves that result in coherent sea level variations along long stretches of the U.S. East coast. It should be noted that while the focus of our study is on the portion of coastal sea level variability that is contributed by ocean dynamics, impact from variations in wind and atmospheric pressure (through the inverted barometer effect, IB) are of course, very significant. IB variability on interannual and multidecadal time scales may contribute as much as 10–30% of the sea level signal (Piecuch and Ponte, 2015) and wind plays a major role on these scales as well (Piecuch et al., 2016; Woodworth et al., 2016). IB and wind could play even larger roles in short time scales associated with tropical storms and hurricanes.

The impact of storms and hurricanes on the ocean is often focused on the heat loss and the cooling effect of surface temperatures (Bender and Ginis, 2000; Shay et al., 2000; Li et al., 2002; Oey et al., 2006, 2007; Yablonsky et al., 2015), while less attention is given to the impact on ocean currents. Some modeling studies demonstrate that hurricanes can significantly alter even strong ocean currents: for example, Hurricane Wilma (2005) caused intensification of the Loop Current (Oey et al., 2006), while Hurricane Bill (2009) created a large temporary reduction of the GS transport north of Cape Hatteras associated with deepening of the mixed layer and reduction of stratification (Kourafalou et al., 2016); the latter study found similar impacts from several other hurricanes. Winter storms moving over the warm GS can also have significant impact on both air-sea heat fluxes and GS currents (Li et al., 2002). Note that while the focus here is on the interaction of Atlantic Ocean hurricanes with the Gulf Stream, similar interactions between Pacific Ocean Typhoons and the Kuroshio have also been studied (Wu et al., 2008; Liu and Wei, 2015), so influence from storms on western boundary currents and ocean circulation may be an important issue for further research.

In this study, several direct and remote sensing data sources, as well as simulations from an operational hurricane-ocean coupled model, are analyzed to reveal the impact of Hurricane Matthew (2016) on ocean currents and coastal sea level. In particular, the goal is to focus not only on the direct impact of wind-driven storm surges which are quite well studied, but also study potential indirect mechanisms where strong ocean currents are altered by the storm and then can influence coastal sea level.

2. Data and models

Hourly water level records from tide gauge data along the U.S. coast were obtained from NOAA (http://opendap.co-ops.nos.noaa.gov/dods/). These records have been used for various studies of sea level rise (Boon, 2012; Ezer and Corlett, 2012; Ezer, 2013). When calculating non-tidal daily values of WL anomalies from the hourly data, errors are estimated to be around ±5–10 cm (i.e., values are expected to be within mean ± error 95% of the time), and the higher values were used during storms. The daily Florida Current (FC) transport has been available since March 1982 (with a major gap in data from October 1998 to June 2000) using the cable measurements across the Florida Strait at ∼27°N (Baringer and Larsen 2001; Meinen et al., 2010). The FC cable data are available on the Atlantic Oceanographic and Meteorological Laboratory web page (www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the DOC—NOAA Climate Program Office-Climate Observation Division. NOAA reports in this web site indicate quite unchanged error bars in the daily value, about ±1.6 Sv. The FC transport experienced seasonal and interannual variability, as well as modulations due