Compound flooding in a subtropical estuary caused by Hurricane Irma 2017

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Key points

- Compound flooding occurred during Hurricane Irma around Jacksonville, Florida
- Maximum surge occurred extemporaneously to maximum winds and fluvial discharge
- Compound flooding occurred when the ocean obstructed the fluvial seaward discharge

Abstract

Hurricane Irma affected the Florida peninsula in September 2017. The east coast of the peninsula was hit particularly hard: the city of Jacksonville flooded around the St. Johns River estuary with non-tidal water levels that exceeded 1.5 m and precipitation that surpassed 20 cm in 24 hours. This study used observations such as water and wind velocities, river discharge, and conductivity data to determine whether compounding forcings influenced flood levels. Results show that flooding was initiated by a pulse from the ocean and then exacerbated by high river discharge. The 1-2 punch from the ocean and then the river caused record flooding, with impacts that lasted through the rest of September. Peak water levels occurred while hurricane winds were receding, and river discharge was increasing. Compound flood models should consider the phase lag between driving processes, as the individual peaks may not occur simultaneously, yet exacerbate flooding.

Plain Language Summary

Hurricane Irma affected the Florida peninsula in September 2017. The east coast of the peninsula was hit particularly hard: the city of Jacksonville flooded around the St. Johns River estuary with non-tidal water levels that exceeded 1.5 m and precipitation that exceeded 20 cm in 24 hours. This study used oceanic and atmospheric observations to determine whether compounding forcings influenced flood levels. Results show that flooding started by a pulse from the ocean and then exacerbated by high river flows. The 1-2 punch from the ocean and then the river caused record flooding, with impacts that lasted through the rest of September. Peak non-tidal water levels occurred while hurricane winds were receding, and river flow was increasing. Storm-related flooding models should consider the timing between ocean and river flooding, as the individual peaks may not occur simultaneously, yet still cause flooding.

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1. Introduction

Flooding becomes ‘compounded’ when two or more physical processes combine to exacerbate its impacts (Zscheischler et al., 2018; Ward et al., 2018). Hurricanes are accompanied by wind- and barometric pressure driven storm surge, and by heavy precipitation. Thus, the threat of compound flooding during hurricanes can become imminent (Wahl et al., 2015; Nasr et al., 2021). Furthermore, specific storm conditions and landfall characteristics that determine the timing of precipitation, river discharge, and storm surge peaks can lead to different mechanisms driving compound flooding (Gori et al., 2020, Valle-Levinson et al., 2020). Thus, the interaction of different flood drivers should be considered when evaluating flood risk so to avoid underestimation of peak flood levels (Kumbier et al., 2018).

Damage from Hurricane Irma was the fifth costliest in the United States, amounting to approximately 50 billion dollars across Florida, Georgia, and South Carolina (NOAA, 2018). Record flooding occurred in northeastern Florida, representing one of the worst flooding events in Jacksonville (NOAA, 2018). While much of this flooding has been attributed to record-breaking river discharge, extreme water levels may have been exacerbated by the combination of ocean and riverine processes.

Hurricanes have been identified as one of the primary drivers of compound flooding (e.g., Orton et al., 2018, Wu et al., 2018) due to the generation of anomalously high waves, storm surge, and rainfall. While understanding the joint probability of the magnitude of the physical drivers is important for understanding impacts, these studies often assume the drivers occur synchronously. Case studies have however established that the timing of storm surge, tide, and rainfall are crucial to understanding the magnitude of extreme water levels causing flooding (Harrison et al., 2021, Gori et al., 2020; Valle-Levinson et al., 2020). For example, in the Cape Fear Estuary, maximum rainfall intensity and the phase lag between surge + astronomical tide and peak rainfall were the two main predictors of compound flooding severity among a large set of hurricane-related predictors (Gori et al., 2021). Thus, the timing and magnitude of driving processes is likely important for estimating compound flooding impacts.

The objective of this study was to determine the contributions to flooding from ocean surge and from river surge in a subtropical estuary during Hurricane Irma. Such contribution was evaluated with measurements of water level, current velocities and salinity, which allowed disentanglement of the competing ocean and riverine processes. Ocean-driven surge initiated water levels above flooding levels. However, the highest surge was generated as ocean waters receded, while constricting the fluvial drainage to the ocean. Peak water levels near the estuary mouth occurred during an increasing ocean-driven surge near high tide. Peak water levels at upriver stations also occurred near a high tide but were more strongly influenced by river discharge than by oceanic inflow. Understanding the components that contribute to flooding in past extreme weather events can be beneficial for improved flooding predictions. This research shows that the peak interactions of the forcings and their timing are crucial for flooding occurrence.

1.1. Study area

The Lower St. Johns River is the longest estuary in Florida and runs northward from Lake George to the mouth at the Atlantic Ocean in Jacksonville (Fig. 1a-c). The river is relatively flat with a bed slope of 0.12 cm/km (Toth, 1993). The deepest section is located at the mouth of the estuarine area, for ship activity near Jacksonville's seaport (Henrie and Valle-Levinson, 2014). Water levels in the study area are typically affected by ocean-driven processes and local winds. The lower St. Johns River is forced by the ocean through the inlet at Mayport with a semidiurnal tidal amplitude of ~0.69 m (Henrie and Valle-Levinson, 2014), and 90.5% of the tidal variability explained by the tidal harmonic M_2 (Sucsy and Morris, 2001). Local winds impacting the St. Johns River estuary have an average monthly speed from 2.4 to 4.4 m/s and seasonal variability in their N-S directionality marked by northerly winds from September to January and southerly for the rest of the year (Henrie and Valle-Levinson, 2014). The mean discharge from a nine-year record (1996 to 2005) at the Acosta station (USGS-ID: 02246500) is 241.5 m^3/s (Sucsy et al., 2012). The annual average rainfall is about 131 cm/yr, with June through September being the rainy season (Bergman, 1992). Tropical storms from July to October contribute mainly to the largest net precipitation of 150 mm (Henrie and Valle-Levinson, 2014). Maximum rainfalls and discharges in the St. Johns River estuary may be associated to the North Atlantic hurricane season, which causes extreme wind and precipitation conditions as observed during Hurricane Irma.

Hurricane Irma started as a tropical wave near Northwest Africa on August 27th, 2017. The storm system became a tropical depression on August 30th and then a hurricane on August 31st, when it made landfall on Barbuda as a category 5 storm. On September 10th, the hurricane made landfall in southwestern Florida on Marco Island as a category 3 storm with maximum sustained winds of 185 km/h. On the next morning of September 11th, Irma traveled northward over land in Florida and transformed from a category 2 storm to a tropical storm. By the afternoon of September 11th, the storm moved along the west coast of northern Florida and onto Georgia by the evening of September 11th, The storm eventually ended in Missouri on September 13th. More details on the hurricane's trajectory are given by a NOAA report by Cangialosi et al. (2018). Water levels surpassed every station's National Weather Service moderate flooding threshold along the St. Johns River (see Fig. 1d) during the passage of Irma.

2. Methodology

Observations related to river and ocean processes were analyzed to determine the drivers of high-water levels along the St. Johns River (Fig. 1b-c). Observed and predicted water level, atmospheric pressure, water velocity, and wind velocity were downloaded from the National Oceanic and Atmospheric Administration (NOAA) (tidesandcurrents.noaa.gov/map/index.html). River discharge, water temperature, and conductivity data were downloaded from the United States Geological Survey (http://maps.waterdata.usgs.gov/mapper/index.html), and precipitation data came from the Florida Climate Center (https://water.weather.gov/precip/). Station names, numbers, and data availability are listed in Table 1, while station locations are provided in Figure 1d. Salinity was calculated with water temperature and conductivity data from the USGS stations using the TEOS-10 Matlab toolbox (www.teos-10.org). Storm surge at each station was calculated by subtracting predicted water levels from observed water levels. While primarily composed of wind and pressure-driven forcing, the surge is also influenced by river discharge, precipitation, nonlinear interaction with the tide, and oceanic planetary waves or thermal expansion produced by seasonal changes and climate change (Haigh et al., 2016). We distinguish between storm surge generated by riverine and ocean processes by calling them river-driven surge or ocean-driven surge.

This study analyzes data 6 days before and after the peak water level, from September 5, 2017, to September 17, 2017. The peak of the hurricane within the vicinity of the study site was determined by the time of the lowest barometric pressure (988 hPa) at the Mayport Bar Pilots Dock NOAA station (see Fig. 1b). Flood levels could be described spatially by examining stations along the St Johns River (Fig. 1c). Time of recovery for water level, flow, and salinity fields were determined to document the duration of record high-water levels.

3. Results

3.1. Conditions during Hurricane Irma

Hurricane Irma caused an atmospheric pressure drop from ~1014 mb on September 10, 2017 to ~988 mb at 12:30:00 UTC on September 11(So et al., 2019), a difference of 26 hPa (or mb, see Fig. 2a). The time of lowest pressure was used as a reference time for the passing of Hurricane Irma through the study area, indicated as a vertical black line in Figure 1a and Figure 2. When Irma was over North Florida, the strongest winds appeared in the Jacksonville area to the northeast of its eye (So et al., 2019; NOAA, 2018). The Jacksonville International Airport recorded sustained 2-minute, 10-meter winds of 26 m/s at 10:53 UTC on September 11th, with gusts of 39 m/s (NOAA, 2018). Similarly, the Mayport Bar Pilots Dock NOAA station recorded wind velocities ranging from 20 to 25 m/s (Fig. 2b) and gusts peaking at approximately 40 m/s during the hurricane (So et al., 2019). Because of the counterclockwise rotation of hurricane winds, air motion was westward (onshore towards Jacksonville) until the end of September 11th, when the winds shifted eastward (offshore).

The Florida Climate Center reported three days of precipitation from September 9th to September 11th, according to the Jacksonville International Airport and Jacksonville Beach stations. The Jacksonville International Airport recorded 23.4 cm of total rainfall from Hurricane Irma (NOAA, 2018), while a >50 km in a radius around Jacksonville received over 25 cm of precipitation on September 11 (Fig. 1a). The precipitation close to Jacksonville was the highest on the Florida Peninsula during the hurricane and led to the highest discharge on record in the St. John's River, >4000 m^3/s.

Along-river water levels began increasing on September 9th and peaked between September 11th and 12th depending on the along-river location. Water level near the estuary's mouth (e.g., Mayport and Acosta) peaked earliest, on September 11th, two hours after high tides, while landward stations peaked later (see triangles on Fig. 1d). The water levels did not return to predicted levels until approximately October 10th (not shown). Similar to peak water level, storm surge at the St. John's River began increasing on September 8th-9th and peaked around midday on September 11th (Fig. 2d). The storm surge reached 1.95 m, 1.85 m, 1.83 m, and 1.59 m at Mayport, Dames Point Bridge, Acosta Bridge, and Racy Point, respectively. Storm surge at landward stations peaked later than storm surge at seaward stations.

3.2. Evidence for compounding processes

Salinity values varied tidally at expected ranges for a tidal estuary until September 7th (Fig. 2e). From September 8th to September 11th, salinity values increased, reaching maximum values of 34.58 g/kg, 32.12 g/kg, 30.47 g/kg, and 27.08 g/kg at Dames Point Bridge, Jacksonville University, Acosta Bridge, and BL Marco LK stations, respectively. The salinity peaks were at least 15 g/kg over their pre-hurricane values observed on September 5th 2017. Dames Point station reached a maximum, 34.58 g/kg, close to the dry-season maximum in the same year, which was 36.36 g/kg (not shown). The stations closest to the ocean increased first. Salinity levels then dropped lower than typical for a sustained period after the eye of the hurricane passed Jacksonville, midday on September 11th. Salinity at Dames Point Bridge, which is the measurement station closest to the ocean, returned to pre-hurricane levels, ~15 g/kg, in October (not shown), earlier than at the rest of the stations. The wind-induced volume inflow (Fig. 2b) resulted in the negative discharge in Figure 2c marked by the green rectangle. The negative discharge indicated an ocean-related surge that reached a peak of ~ -1500 m^3/s.

At the same time, seaward along-river water velocities (ebb periods) increased landward until the eye of the hurricane (Fig. 2f). The greatest along-river velocity throughout the whole record showed in Figure 2f was related to a landward pulse with a speed of 1.4 m/s at Acosta Bridge on September 11th, immediately followed by a seaward pulse on September 12th. River discharge switched to positive, meaning volume outflow, soon after the time of onshore wind peak ~ -21 m/s (blue rectangle in Figure 2). The discharge reached maximum values of > 4000 m^3/s; ~20 times the average river outflow of 241 m^3/s (Sucsy et al., 2012). It took more than 4 days for the river to return to relatively ‘normal' discharges of ~ 500 m^3/s.

4. **Discussion**

4.1. Surge drivers in the St. John's Estuary During Hurricane Irma

This study highlights that river discharge was a sizable contributor to the storm surge magnitude measured in the St. Johns River during Hurricane Irma. Storm surge can be defined as a rise in water level above the predicted tide. Methods for estimating the magnitude of the storm surge subtract the predicted tide from the observational record, as done in this study. The magnitude of storm surge along the open coast is often dominated by a combination of wind setup and low barometric pressure via the inverse barometer effect. Yet, during Hurricane Irma, atmospheric forcing, alone, was insufficient to account for peak surge levels at the Mayport station (So et al., 2019). In their analytical approximation, So et al (2019) reported a peak of ~1.5 m, which was 0.45 m lower than the surge level observed, accounting for approximately 77% of the total surge level (see magenta dotted line in Fig. 2d). So et al. (2019) attributed the underestimated magnitude to coastline orientation and neglect of atmospheric pressure.

This observational analysis found that the highest onshore wind (-23.7 m/s) was not coincident with the maximum surge recorded for the water level stations at Mayport, Dames, Acosta, and Racy (Figure 3 a, b, c, and d respectively). The maximum surge at each station was observed with a lag of around 25 min. except in Racy where the maximum was observed around 2.5 hours after the maximum at Mayport. Maximum surge, observed at each station occurred as the onshore wind magnitude decreased and the discharge increased. The surge at Racy station (Figure 3d), the farthest from the mouth, occurred after the hurricane eye passage and when wind switched seaward. In fact, storm surge increased to the peak as winds were decreasing (Fig. 3). The initial rise in storm surge within the St. Johns River estuary can be attributed to the ocean. As onshore winds increased, ocean water was transported upriver, and the storm surge began to increase in magnitude (Fig. 3). The inflow of the ocean was also evident in multiple observations including the salinity, the along-river velocities, and the river discharge (Fig.2). The impact of the ocean's pulse was so influential that there was no tidal outflow for two consecutive tidal cycles (Fig. 2d), except at Mile Point station which is the closest, ~7 km, to the estuary's entrance. The weakening of the ocean's dominance could be seen by the rapid decrease in the salinity and the switching from negative river discharge to positive river discharge (Fig. 2c and e). This switching time from negative discharge, indicative of the river flowing landward, to positive discharge, indicative of the river flowing seaward, corresponded with the highest wind recorded. The strongest winds appeared before the eye of the hurricane passed over the area. Discharge and along-estuary velocity in the seaward direction rapidly increased, which coincided with a decrease in onshore winds (Fig. 2).

The storm surge maximum of 1.95 m was reached at 10:30:00 UTC on September 11th shortly after river discharge had switched from negative to positive. This also coincided with a rapid decrease in salinity values and a decrease in the zonal wind velocity. Thus, surge level was highest when the estuary was in transition from ocean-dominated processes to river dominated processes. At this time, the onshore wind velocity was -19.3 m/s and the discharge was 649 m^3/s. Surge decreased to below 1 m once the wind was close to switching directions. During the storm surge (blue rectangle in Fig. 2), fluvial flooding was an additional factor that contributed ~26% of the total flooding based on the theoretical atmospherically driven surge calculated by So et al. (2019). Other studies (e.g., Serafin et al., 2019) found the river signal contributing to the magnitude of storm surge along the Quillayute River, Washington. Thus, the fluvial contribution to a storm surge is a factor to be considered in future storm-related flooding predictions and maps.

4.2. Irma's 1-2 Punch: Disentangling Flood Drivers

The record flooding from Hurricane Irma observed in Jacksonville, Florida was caused by a combination of factors: record-breaking discharge from heavy precipitation, ocean-driven surge from winds, and near-high tides around the mouth of the estuary. As Irma moved northward along Florida, precipitation bands reached the St. Johns River before the highest winds arrived on September 11th. Onshore winds drove ocean waters into the St. Johns River estuary and caused the first punch to estuarine flooding at the Mayport, Dames, and Acosta stations. The second punch came from river discharge caused by Irma's heavy rainfall. The lagged response of the watershed increased discharge in the river after the major rain bands had fallen, coincident with the increasing ocean-driven surge. The 1-2 punch thus originated from a combination of both factors. The ocean-driven flood wave caused by high winds essentially trapped river discharge, allowing for it to "pile up" and preventing drainage to the ocean, which exacerbated flooding. This phenomenon is similar to what occurred two weeks prior to Hurricane Irma during Hurricane Harvey in the Houston-Galveston Bay, where high discharge was prevented from draining to the ocean due to coastal constrictions between Houston and the Galveston Bay, and a high surge pushing upriver (Valle-Levinson et al., 2020). In the case of Hurricane Harvey, there were 5 days without tidal inflow to the Galveston Bay. In the St. John's River, there was only ~1 day.

Would the flooding in Jacksonville have been as bad without the specific timing of events? The size of the watershed dictates how fast river discharge increases following a precipitation event, which influences how discharge and storm surge may combine to drive compound flooding (Dykstra and Dzwonkowski, 2021). Harrison et al., (2021) compared compound flooding in two different-sized estuaries in the UK and found that the larger, Humber, showed no dependence on the timing between the river surge and the ocean surge. Contrastingly, the small estuary, Dyfi, had a 'quick' response due to its strong dependence on the timing between ocean and river surges. In another example, Gori et al., (2020) found that rain bands occurring in advance of storm landfall are more likely to lead to river-surge compounding as was observed in the St. Johns River estuary. Thus, the phase lag between combined forcing is necessary for understanding the likelihood for compound flooding as peak flooding may not always occur during the peak of either individual process.

Finally, the estuary geometry and shape may also impact compound flooding. Lyddon et al., (2018) assessed the contribution of estuary geometry to the flooding and suggested that tidal and surge amplitude is amplified within funnel shaped estuaries. The St. Johns River geometry widens from a narrow inlet of ~ 1 km to ~ 4 km in an extent between Jacksonville and Racy Point (Henrie and Valle-Levinson, 2014). Thus, the flooding observed at the St. Johns River was enhanced by its size more than its shape.

5. Conclusion

This study explains the competition between ocean surge and river surge provided by measurements of water level, water velocity, salinity and atmospheric forcing during the impact of Hurricane Irma. Flooding from the storm started with onshore winds transporting ocean water into the estuary from September 8 to September 11. Salinity increased during these three days throughout the system, with the ocean surge. It even reached ocean-level values. Precipitation from September 9 to September 11 also contributed to flooding. Specifically, one-day precipitation on September 11 exceeded 25 cm. The ocean surge held the precipitation-related freshwater at the up-river reaches. Ocean-related surge likely contributed 74% of the total flooding, while fluvial flooding should have contributed ~26%, neglecting the atmospheric pressure contribution. After winds relaxed, the ocean-related flooding was compounded by a river surge. This river surge freshened the estuary for two days as marked by the plummeting salinity values. Predicted water levels were exceeded by almost 2 m because of the compound flooding. The 1-2 punch from ocean and then the river caused record flooding to Jacksonville during the hurricane with impacts that lasted for nearly 20 days.

Acknowledgements

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Table I. Source, station name, and station number for collected data. Name is simplified in parenthesis for analysis throughout the rest of the document.

Data Collection			
Source	Station Name	Station Number	Data Type(s)
USGS	St Johns River at **Racy** Pt Near Hastings Fl	02245290	Salinity
USGS	St Johns R **Dames** Point Bridge at Jacksonville, Fl	302309081333001	Salinity
USGS	St Johns River at **Jax U**niv at Jacksonville Fl	302112081364200	Salinity
USGS	St. Johns River at Jacksonville, Fl (nr **Acosta** Br)	02246500	Salinity, River discharge
USGS	St Johns River Bl **Marco** Lk at Jacksonville, Fl	301817081393600	Salinity
NOAA	**Mayport** (Bar Pilots Dock), FL	8720218	Winds, Water level, Barometric pressure
NOAA	**Dames** Point, FL	8720219	Water level, Current velocity
NOAA	Southbank Riverwalk, St Johns River, FL (nr **Acosta** Br)	8720226	Water level
NOAA	**Acosta** Br	jx0701	Current velocity
NOAA	**Trout River** Cut LB 64	jx0601	Current velocity
NOAA	**Fulton** Cutoff LB 34	jx0401	Current velocity
NOAA	**Mile** Point LB 20	jx0302	Current velocity
NOAA	**Racy** Pt	8720625	Water levels

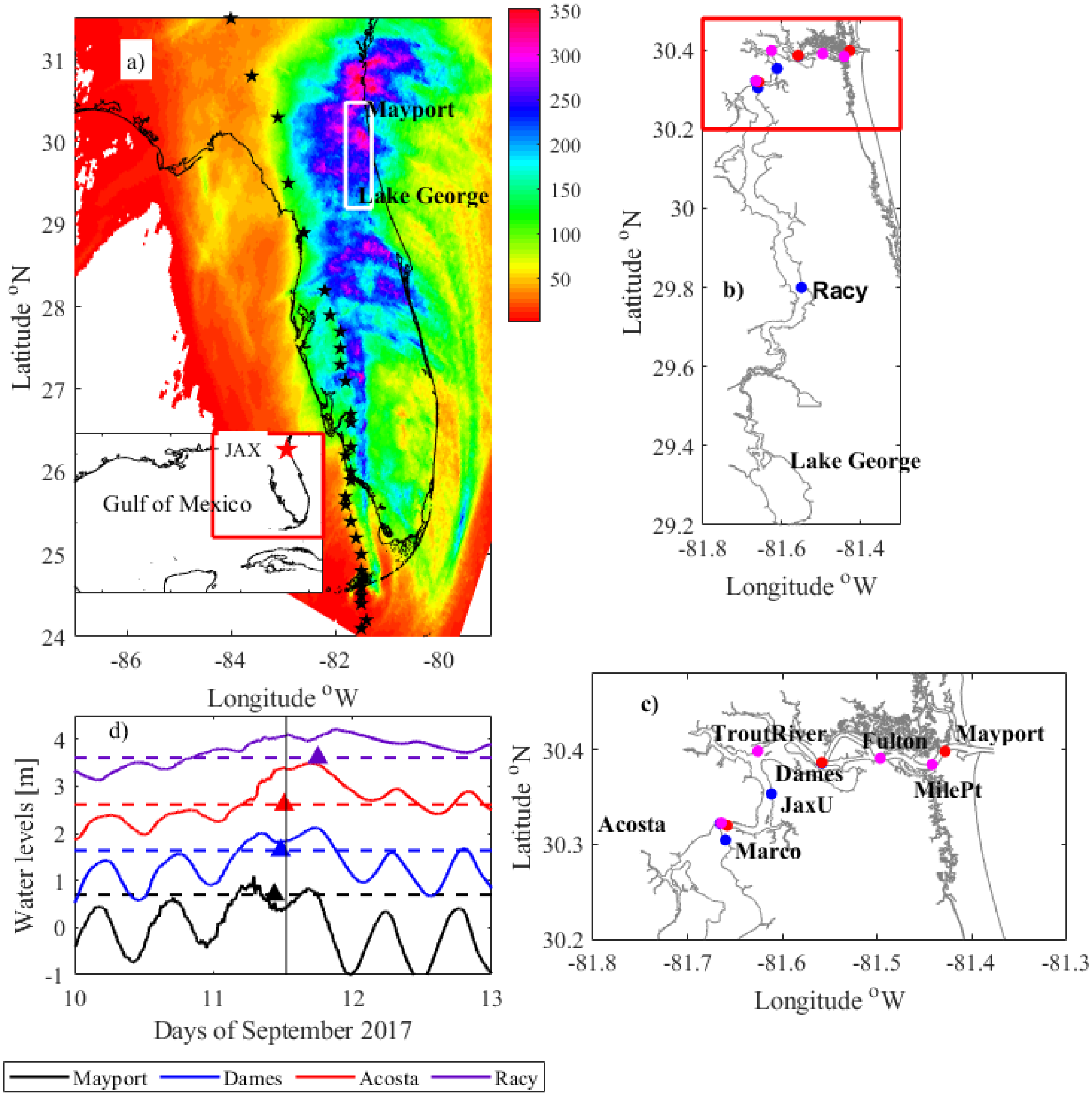

Figure 1. a-c) Study area. a) Gulf of Mexico (inset), the red rectangle encloses the Florida Peninsula displayed. In color, precipitation in mm for September 11, 2017; the black stars denote the hurricane Irma track along the peninsula. The St. Johns River estuary is enclosed within the white rectangle and displayed in b). b) Northern part of the St. Johns River from the estuary mouth to Lake George indicating the station at Racy Point (Racy) which is the station located farther upstream; the red rectangle encloses the northernmost section of the river. c) Stations located in the St. Johns River estuary. Blue-, red-, and magenta-colored circles denote stations location where salinity, water level, and current velocity were collected, respectively. Current velocity was additionally collected from Dames station. Also, water level was measured by the Racy station. Wind speed and direction, and barometric pressure were collected from station at Mayport (see Table I). d) Water levels with 1m offsets to see differences between the four stations along the St. Johns River; the horizontal dashed lines indicate moderate flood level threshold for each station.

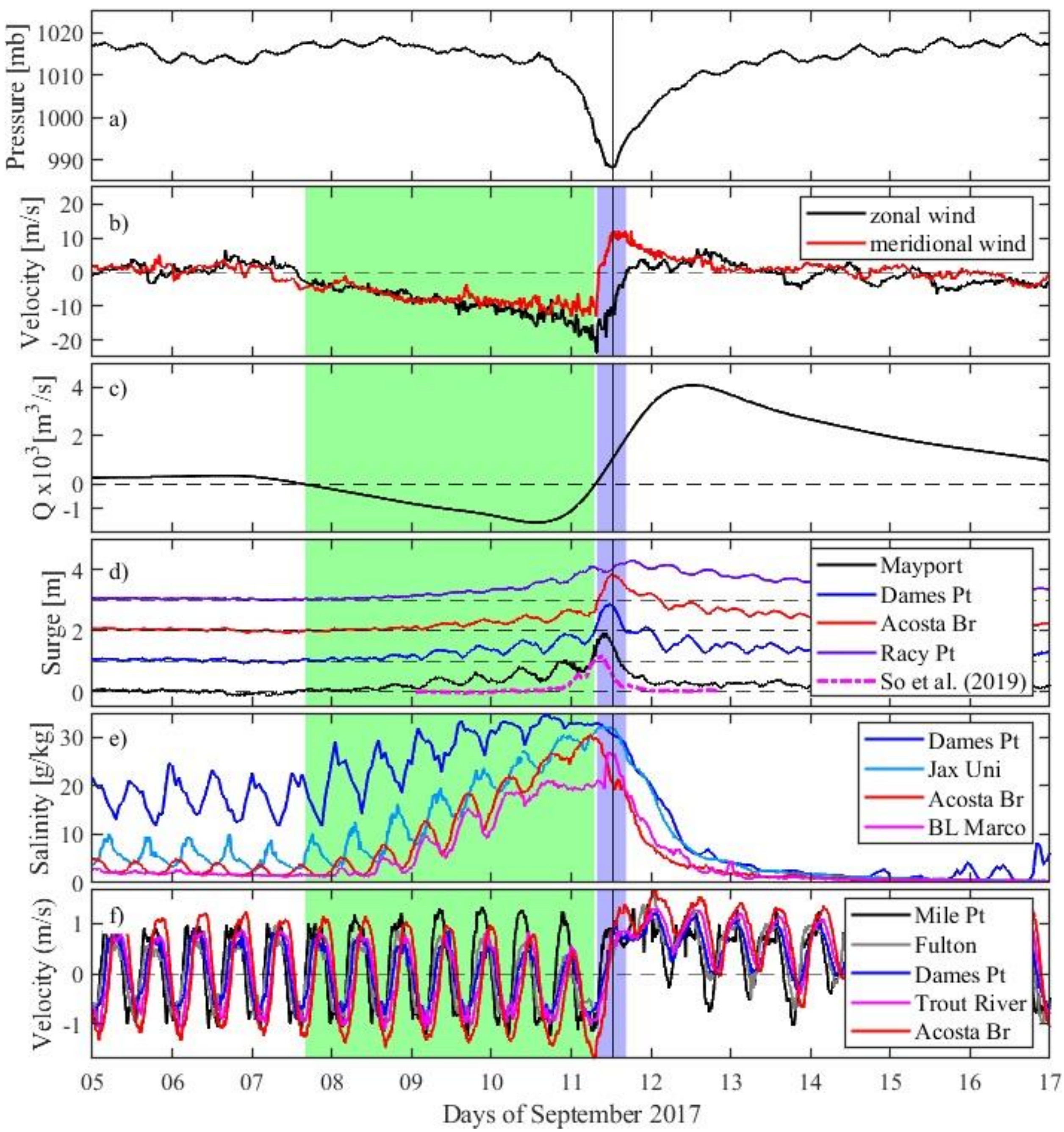

Figure 2. Meteorological and river conditions before, during, and after Hurricane Irma, from September 5th to 17th of 2017. a) Atmospheric pressure measured at Mayport; vertical black line to indicate time of lowest of pressure at 12:30:00 UTC on September 11, 2017. b) zonal and meridional wind components in black and red, respectively. c) Tidally filtered river discharge, *Q*, obtained from station located at Acosta Bridge (station 02246500). d) Storm surge at four stations along the St Johns River, e) Salinities along the main channel, f) Along-channel velocities. The green rectangle encloses the time of negative discharge registered at Acosta Br, indicating an upstream flow. The blue rectangle encloses the time from the strongest negative zonal wind (westward, onshore) until the wind switches sign to positive (eastward, offshore).

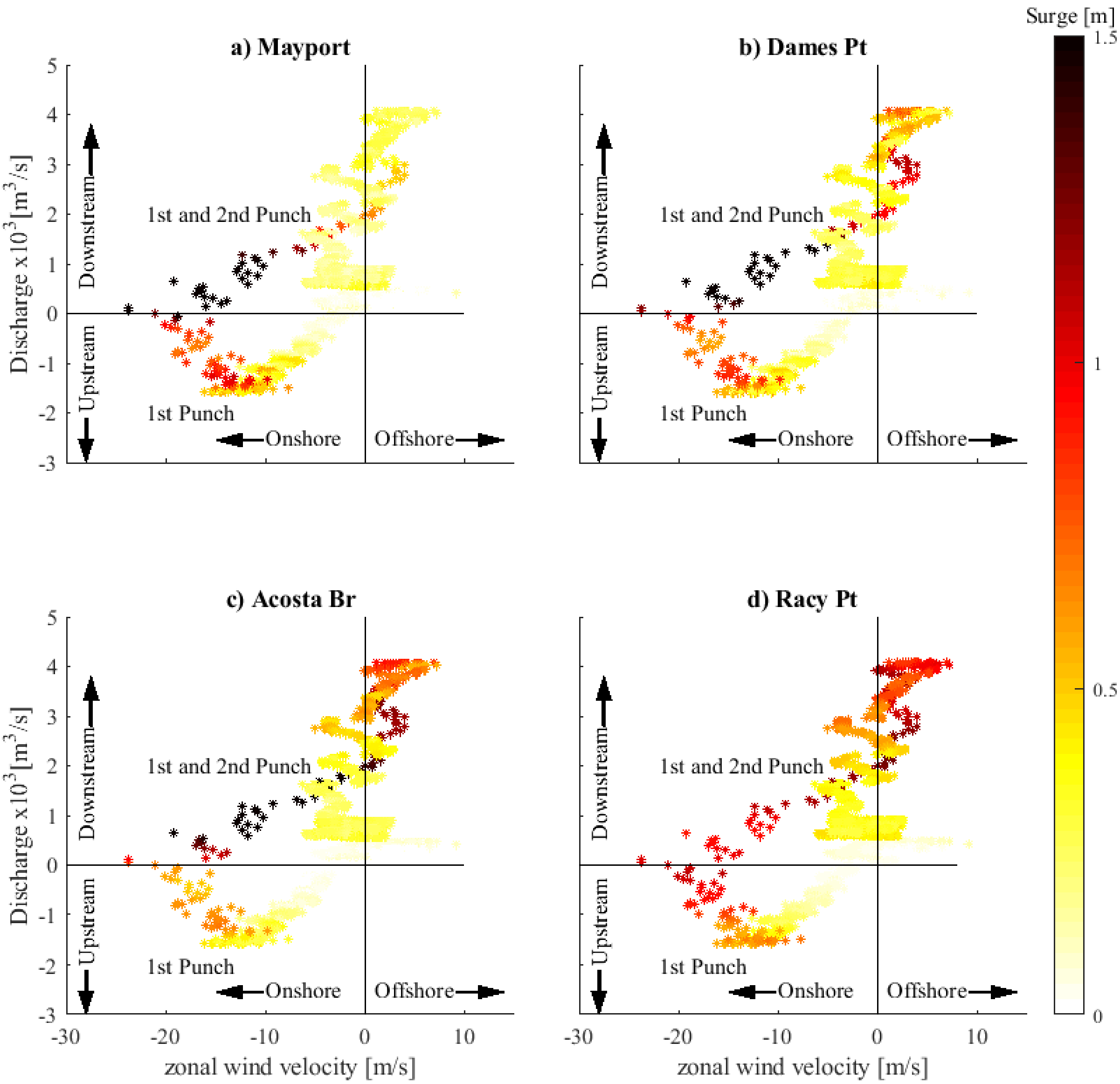

Figure 3. Scatter plot of zonal wind (x-axis) and tidally averaged river discharge (y-axis). The colored asterisks denote the surge elevation at a) Mayport, b) Dames Pt., c) Acosta Br., and d) Racy Pt., stations. Each diagram is divided in four panels. The lower left panel corresponds to onshore wind and upstream flow, the 1st punch from ocean. The upper left panel corresponds to conditions of onshore, 1st punch, and fluvial-induced downstream flow, 2nd punch.