The increased risk of flooding in Hampton Roads: On the roles of sea level rise, storm surges, hurricanes and the Gulf Stream

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Abstract The impact of sea level rise on increased tidal flooding and storm surges in the Hampton Roads region is demonstrated, using ~90 years of water level measurements in Norfolk, VA. Impacts from offshore storms and variations in the Gulf Stream (GS) are discussed as well, in view of recent studies that show that weakening in the flow of the GS (daily, interannually or decadal) is often related to elevated water levels along the U.S. east coast. Two types of impacts from hurricanes on flooding in Hampton Roads are demonstrated here. One type is when a hurricane like Isabel (2003) makes a landfall and passes near the Chesapeake Bay, causing a large, but short-term (hours to a day) storm surge. The second type is when an Atlantic hurricane like Joaquin (2015) does not make a landfall, but instead stays offshore for a relatively long time, disrupting the flow of the GS and leading to a longer period (several days or more) of higher water levels and tidal flooding. Analysis of the statistics of tropical storms and hurricanes since the 1970s shows an increase in the number of days when intense hurricanes (category 3-5) are found near the South Atlantic Bight. The observed Florida Current transport since the 1980s often shows lower transports and elevated water levels when tropical storms and hurricanes pass near the GS. Better understanding of the remote influence of the GS and offshore storms will improve future prediction of flooding and help mitigation and adaptation efforts.

1. Introduction

The National Water Level Observation Network (NWLON) operated by NOAA (https://tidesandcurrents.noaa.gov/nwlon.html) provides an essential source of data to study both, long-term sea level rise (SLR) and short-term water level variations and storm surges. These tide gauges data show that the rate of local SLR along some stretches of the U.S. east coast (around the Chesapeake Bay and the Mid-Atlantic coast in particular) is much faster than the global sea level rise; this is mostly due to land subsidence (Boon, 2012; Mitchell et al., 2013; Ezer and Atkinson, 2015; Karegar et al., 2017), with a potential recent acceleration in sea level rise due to climatic slowdown of ocean circulation (Boon, 2012, Sallenger et al., 2012; Ezer and Corlett, 2012). Norfolk, VA, on the southern side of the Chesapeake Bay (see Fig. 1 for its location), is a city that is already battling an acceleration in flooding frequency and intensity (Ezer and Atkinson, 2014, 2015; Sweet and Park, 2014), so this study will focus on this city as an example that can apply to other coastal cities and communities in the Hampton Roads area. Local SLR in Norfolk from ~90 years of tide gauge records is about 4.5 mm/y, but the SLR over the last 30 years is about 6 mm/y (Ezer and Atkinson, 2015) and probably even faster now; the local SLR rate of the past 30 years is about twice as large as the global SLR obtained from satellite altimeter data (Ezer, 2013). SLR can also escalate the damage from hurricanes, tropical storm and nor'easters. When high sea level today is added to storm surges, weaker storms today would cause as much flooding as much stronger past storms that happened when sea level was lower; this effect will be demonstrated here. There are some indications that warmer ocean waters may be related to an increase in the potential destructiveness of Atlantic hurricanes and tropical storms over the past 30 years (Emanuel, 2005). However, with strong interannual and decadal variability, finding a persistent trend in storm activities over the past century or predicting future changes in hurricane activities over the next century are challenging (Knotson and Tuleya, 2004; Vecchi and Knutson, 2008; Vecchi et al., 2008; Bender et al., 2010). Despite the difficulty of predicting the changes in the frequency and intensity of future storms, assessing the impact of SLR on storm surge is quite straight forward- if a storm with the same intensity and track that hit Norfolk 90 years ago would come today, water level of a storm surge is expected to be ~40 cm higher and many more streets would be flooded. In addition to the impact of storm surges, Atlantic storms can also have an indirect impact on the coast by modifying ocean currents and stirring more mixing. If such storms affect the Gulf Stream, coastal sea level could be affected as well (Ezer and Atkinson, 2014, 2017; Ezer et al., 2017), and this indirect impact will be further investigated here.

The connection between the flow of the Gulf Stream (GS) and sea level along the U.S. east coast has been recognized early on from observations (Blaha 1984) and models (Ezer, 2001). Somewhat surprisingly, however, is the fact that this connection may be detected on a wide range of scales. On long-term decadal variability scales for example, a potential climate-related slowdown of the Atlantic Meridional Overturning Circulation, AMOC, (Sallenger et al. 2012; McCarthy et al. 2012; Ezer et al. 2013; Ezer, 2013, 2015; Smeed et al. 2013; Srokosz and Bryden 2015), may relate to accelerated sea level rise and increased risk of flooding along the U.S. East Coast (Boon 2012; Ezer and Corlett 2012; Sallenger et al. 2012; Mitchell et al., 2013; Yin and Goddard 2013; Goddard et al. 2015; Ezer and Atkinson 2014, 2015; Sweet and Park, 2014). On short-term scales, there is now more evidence from data and models that even daily variations in the Gulf Stream can cause variations in coastal sea level (Park and Sweet, 2015; Ezer, 2016; Ezer and Atkinson, 2017; Ezer et al., 2017; Wdowinski et al., 2016), including unexpected "clear-day" flooding (i.e., unusual tidal flooding with no apparent storm or local weather events). These variations in the GS can be due to natural variability and instability (Baringer and Larsen, 2001; Meinen et al., 2010) or variations in the wind pattern (Zhao and Johns, 2014), including impacts from tropical storms and hurricanes passing near the GS (Oey et al., 2007; Kourafalou et al., 2016; Ezer and Atkinson, 2017). Note that on short term scales an important mechanism transferring large-scale oceanic signals into the shelf may involve the generation of coastal-trapped waves (Huthnance, 2004; Ezer, 2016).

The mechanism that connects the GS and coastal sea level is as follows. The GS separates between a lower sea level on its inshore side (blue in Fig. 1) and a higher sea level on its offshore side (red in Fig. 1). This sea level difference (~1 to 1.5 m) is proportional to the GS flow speed (i.e., the Geostrophic balance), so even a small and common daily change of say 10% in the GS flow may result in ~10 cm sea level change; in comparison, this amount of global SLR would occur over ~30 years.

Therefore, a weakening in the GS flow is expected to raise coastal sea level and lower offshore sea level (the offshore impact has less important implications, but can be detected from satellite altimeter data; Ezer et al., 2013).

In this paper, the latest research on various mechanisms that can cause flooding are summarized, using several data sets including tide gauge data, observations of the Florida Current (the upstream portion of the Gulf Stream, see Fig. 1) and a data set of historical hurricanes and tropical storms.

2. Data Sources

Hourly sea level records from tide gauge stations are available from NOAA (https://tidesandcurrents.noaa.gov/); here the focus is on the Sewells Point station in Norfolk, VA (see star in Fig. 1), that has the longest record in Hampton Roads. As a reference water level, the Mean Higher High Water (MHHW) from the datum centered on 1992 is used. The definitions of minor (often called "nuisance"), moderate and major flood levels relative to MHHW are consistent with NOAA's reports and recent studies of flooding (Ezer and Atkinson 2014; Sweet and Park 2014).

The daily Florida Current transport from cable measurements across the Florida Strait at 27°N (Baringer and Larsen 2001; Meinen et al. 2010) is obtained from the NOAA/Atlantic Oceanographic and Meteorological Laboratory web site (www.aoml.noaa.gov/phod/floridacurrent/); see the location in Fig. 1. The data include the periods 1982-1998 and 2000-2016 with a gap of two years.

The Atlantic hurricane and tropical storm data set HURDAT2 (Landsea et al., 2004; Landsea and Franklin, 2013) is available from NOAA's National Hurricane Center (http://www.nhc.noaa.gov/). It provides the track data every 6 hours for storms 1851-2016, but only data since the satellite age from the 1970s are used here.

Surface currents during hurricanes are obtained from NOAA's coupled operational Hurricane Weather Research and Forecasting (HWRF) model (Yablonsky et al., 2015; Tallapragada, 2016). The atmospheric model is coupled with the Princeton Ocean Model (POM), which has horizontal resolution of 7-9 km and 23 vertical terrain-following layers with higher resolution near the surface; the model domain covers the western North Atlantic Ocean (10°N-47.5°N, 30°W-100°W). A recent study (Ezer et al., 2017) used this model to evaluate the impact of hurricane Matthew (2015).

The mean sea surface height in Fig. 1 is obtained from the AVISO satellite altimetry data set that combines several available satellites; the data is now distributed by the Copernicus system (http://marine.copernicus.eu/). For comparisons between tide gauge and altimeter sea level data in the region, see Ezer (2013).

3. Results

3.1 The impact of Sea Level Rise on Flooding in Hampton Roads.

Fig. 2 shows the maximum water level (relative to MHHW) that has been reached in Sewells Point (Norfolk, VA) during the major storms that affected the region since recording started in 1927 (the highest recorded storm surge was during the hurricane of 1933). To illustrate how much sea level rise would affect storm surges over the years, an average rate of 4.5 mm/y is shown relative to 1930. For example, if the 1933's hurricane happened today, water level would reach ~2 m, with unprecedented level of flooding and damage. Note the cluster of storms of the past two decades compared with the infrequent past storm surges, which may be partly due to decadal variations in storms, but most likely be the result of SLR, as smaller storms plus SLR have the same impact as larger past storms. The frequency of minor flooding is also greatly affected by SLR. For example, if a storm surge of say 0.6m caused some minor flooding in the 1930s, an equivalent flooding would occur today with just ~0.2m water level over MHHW, so that even a slightly higher than normal tide would be enough (without any storm). This is illustrated by the dramatic increase in the hours of minor flooding in Norfolk (Fig. 3). Other cities have similar acceleration in flooding hours (Ezer and Atkinson, 2014; Sweet and Park, 2014). Note that 7 of the top 9 most flooded years happened since 1998. In addition to the clear impact of SLR and storms, there are interannual and decadal variations associated with more stormy years during El-Nino and years with low North Atlantic Oscillation (NAO) index or a weak AMOC (Ezer and Atkinson, 2014; Goddard et al., 2015). The main reason for the large increase in flood hours is that past floods occurred mostly for short periods of a few hours to a day or so during the passage of strong storms, while today we often see longer flooding periods that occur for several tidal cycles, sometimes even without any storm in sight (but possibly due to a weakening GS or an offshore storm- see discussion later).

3.2 Examples of the Impact of Hurricanes on Flooding in Hampton Roads.

There are three ways in which storms (tropical storms, hurricanes, or winter nor'easters) can cause flooding in Norfolk (and in other coastal cities): 1. Storm surges due to the direct impact of the low atmospheric pressure, winds and waves; in this case, the storm piles up water against the coast or pushes water into the Chesapeake Bay and the Elizabeth River. 2. Indirect impacts from offshore storms that do not make landfall and do not pass near Norfolk; in this case, examples are storms that impact ocean currents like the GS (see discussion later). 3. Street flooding due to intense precipitation associated with the storm. Note that in many cases several of these mechanisms can apply simultaneously.

An example of case 1 was hurricane Isabel (2003), which resulted in the second higher water level ever recorded in Norfolk (Fig. 2). This hurricane made landfall near Cape Hatteras, NC, and moved northwest south of the Chesapeake Bay (Fig. 1), wind gusts of ~30 m/s near Norfolk (Fig. 4b) caused a large storm surge that lasted a few hours (Fig. 4a); fortunately, the storm passed during the Neap tide period, so the addition of the high tide was minimal. An example of case 2 is hurricane Joaquin (2015), which looped in the South Atlantic Bight and stayed offshore for a long time without ever making a landfall (Fig. 1). However, the storm winds disturbed the flow of the GS (winds west of the storm blowing southward against the GS flow), as seen in the low transport of the Florida Current (blue line; days 270 and 280 in Fig. 5b). Because of the GS-coastal sea level relation discussed before (Ezer, 2016; Ezer and Atkinson, 2017; Ezer et al., 2017), sea level rose (red line in Fig. 5b) when GS transport dropped, causing a couple of weeks with flooding in Norfolk almost every high tide (Fig. 5a). An example of case 3 is the impact of hurricane Matthew (October 2016; see its track in Fig. 1) on flooding in the Virginia Beach area- when elevated water levels were combined with enormous amount of rain, streets could not drain and stayed flooded for a long period of time (in other regions along the South Carolina coast direct storm surge was a major factor in the flooding). The disturbance that Matthew caused to the flow of the GS can be seen in Fig. 6, from an operational atmosphere-ocean forecast model. When the eye of the storm was near the coast of south Florida, the storm broke the path of the flow, separating the Florida Current exiting the Gulf of Mexico from the downstream GS. For more details on the impact of hurricane Matthew see the recent study of Ezer et al. (2017). In the next section analysis of many other storms will be analyzed to detect those that may have affected the GS.

3.3 The impact of Tropical Storms and Hurricanes on the Florida Current.

Anecdotal examples of hurricanes affecting the GS (and its upstream portion, the Florida Current) have been discussed above, so here a more quantitative approach is taken by analyzing the HURDAT2 data set of Atlantic hurricanes and tropical storms. The data set starts from the middle 1800s using ship observations and later satellite and other data (Landsea et al., 2004), but here only data from the satellite era are considered. All the 6-hourly records of storms during 1970-2016 that are located inside the region 60°W-85°W and 20°N-40°N (i.e., near the South Atlantic Bight, SAB) were counted and summed (Fig. 7). This is the region that hurricane winds may be able to influence the GS. Instead of counting individual storms, the monthly sum can include multiple counts of the same storm, so that storms that last longer have more weight than short-lived storms. The results appear to show that there is an increase in the counts of the most intense hurricanes of category 3-5 in this region. For example, before 1993 no month had more than 10 counts of category 3-5 hurricanes, but after 1993 there were 11 such cases (10 monthly counts of 6-hourly data mean that there were at least 60 hours during one month when hurricanes of category 3-5 were located in the region- this could be one storm or multiple storms). Further statistical analysis of Atlantic hurricanes as done before (Landsea et al., 2004; Vecchi and Knudson, 2008; Vecchi et al., 2008, and others) is beyond the scope of this study, which will focus on potential influence of the storms on the GS.

The daily transport of the Florida Current (FC) has been measured by a cable across the Florida Straits since 1982 (with a large gap October 1998-June 2000 and a few smaller gaps; see Meinen et al. 2010). To evaluate if unusual transports are observed during the passage of storms, a subset of the cable data is created for only those days when storms are found in the region (as in Fig. 7). Two properties are evaluated for these "stormy" days, the FC transport (Fig. 8a) and the FC transport change (Fig. 8b). Previous studies show that variations in coastal sea level are correlated with both, the GS/FC transport and with transport change (Ezer et al., 2013; Ezer and Atkinson, 2014, 2017). During "stormy" days the FC transport can change significantly, by as much as 5-8 Sv/day (see storms with significant impact in Fig. 8b). For example, when hurricane Matthew (2016) moved along the coast (Fig. 1) the FC transport declined from ~35Sv to ~20Sv (Ezer et al., 2017), as seen in Fig. 8a and the maximum daily decline was ~5 Sv, as seen in Fig. 8b.

The track of a hurricane relative to the location of the GS/FC can make a significant difference in the impact. For example, hurricanes that caused a large daily transport decline (Fig. 8b) like Barry (1983), Karl (1998) and Wilma (2005) moved fast exactly over the FC not far from the Florida Strait (see their track in Fig. 1). However, their influence on water level in Norfolk was minimal compared with hurricanes like Sandy (2012) or Matthew (2016), which moved slowly along the GS path (Fig. 1) with enough time to influence the GS and coastal sea level.

To look at the total impact of storms on the FC transport in a more quantitative way, the histogram of the FC transport for all the days without storms (Fig. 9a) is compared with the histogram during storms (Fig. 9b). While the daily transport distribution looks Gaussian and symmetric around the mean during days with no storms, it is clearly asymmetrical with a lower mean flow and skewed probability toward low transports during storms. Note that Fig. 9a ("without storms") means without tropical storms and hurricanes, but may include other extra-tropical or winter storms that are absent from the HURDAT data set. This result confirms anecdotal observations (Ezer and Atkinson, 2014, 2017; Ezer et al., 2017) that storms can disturb the flow of the GS and thus in most cases increase the likelihood of weaker than normal GS- this weakening further contributes to higher than normal coastal sea level (in addition to the wind-driven storm surge). Ezer at al. (2017) showed, using various different data, including satellite altimeter and high-frequency radar data, that after an intense mixing of the GS water by a nearby storm it may take a few days for the current to recover, and during those days anomalously high water can be observed along the U.S. east coast.

4. Summary and conclusions

The impact of the fast rate of local sea level rise in the mid-Atlantic region (Boon 2012; Sallenger et al. 2012; Ezer and Corlett 2012; Ezer 2013) has already been felt in the acceleration of flooding in low-lying cities like Norfolk, VA, and other coastal communities along the U.S. East Coast (Mitchell et al. 2013; Ezer and Atkinson 2014, 2015, 2017; Sweet and Park 2014). Both, minor tidal flooding and major storm surge flooding has significantly increased in recent decades, as demonstrated here for Norfolk.

This report discusses the different mechanisms that contribute to the increased flooding. Some mechanisms are quite straightforward, for example, it is easy to understand how sea level rise or increases in storms frequency or intensity would result in more flooding and a greater risk of damages to flooded properties. However, other mechanisms are more complicated, for example, floods associated with non-local factors such as offshore variations in the Gulf Stream (other remote influences such as westward-propagating planetary waves and climatic variations in the North Atlantic Ocean were discussed in other studies). This study follows on the footsteps of recent studies that showed a connection between short-term weakening in the Florida Current/Gulf Stream transport and elevated coastal sea level (Ezer, 2016; Ezer and Atkinson, 2014, 2015, 2017; Ezer et al., 2017; Wdowinski et al., 2016), but here the analysis includes for the first time an attempt to evaluate the impact on the GS from all the hurricanes and tropical storms that passed the region over the past few decades. There is some indication that the most intense hurricanes (category 3-5) can be found more often near the South Atlantic Bight region, which is consistent with some other studies that suggest that warmer waters would cause an increase in the destructiveness of Atlantic hurricanes (Emanuel, 2005; Holland and Bruyère, 2014). The consequence is that due to warmer Atlantic waters, hurricanes may be able to sustain their intensity longer if they stay offshore (e.g., hurricanes Joaquin, Matthew and other recent storms), and thus may have larger impact on the GS. It was found that hurricanes that moved across the GS path or stayed in its vicinity long enough are indeed those that have the largest impact on the GS. This indirect impact of offshore storms, that sometimes do not even make landfall, can result in several days of elevated water levels and tidal flooding, until the GS recovers and returns to its normal variability (Ezer et al., 2017). When combined with storm-induced rain, these elevated water levels prevent proper draining of flooded streets and lengthening the impact, as was the case of hurricane Matthew (2016). This remote impact from storms and hurricanes is more long-lasting than cases of storm surges near the landfall area that can result in higher water levels but shorter-term impact of only a few hours, as was the case of hurricane Isabel (2003).

Analysis of the Florida Current transport since the 1980s suggests that the impact of tropical storms and hurricanes on the GS is not only detectable in a few isolated cases, but it has a significant signature in the long-term statistics of the flow variability. Since remote/indirect forcing of coastal sea level variability is not easily accounted for in storm surge models, studies of this type can help to better understand the mechanisms involved and improve water level prediction.

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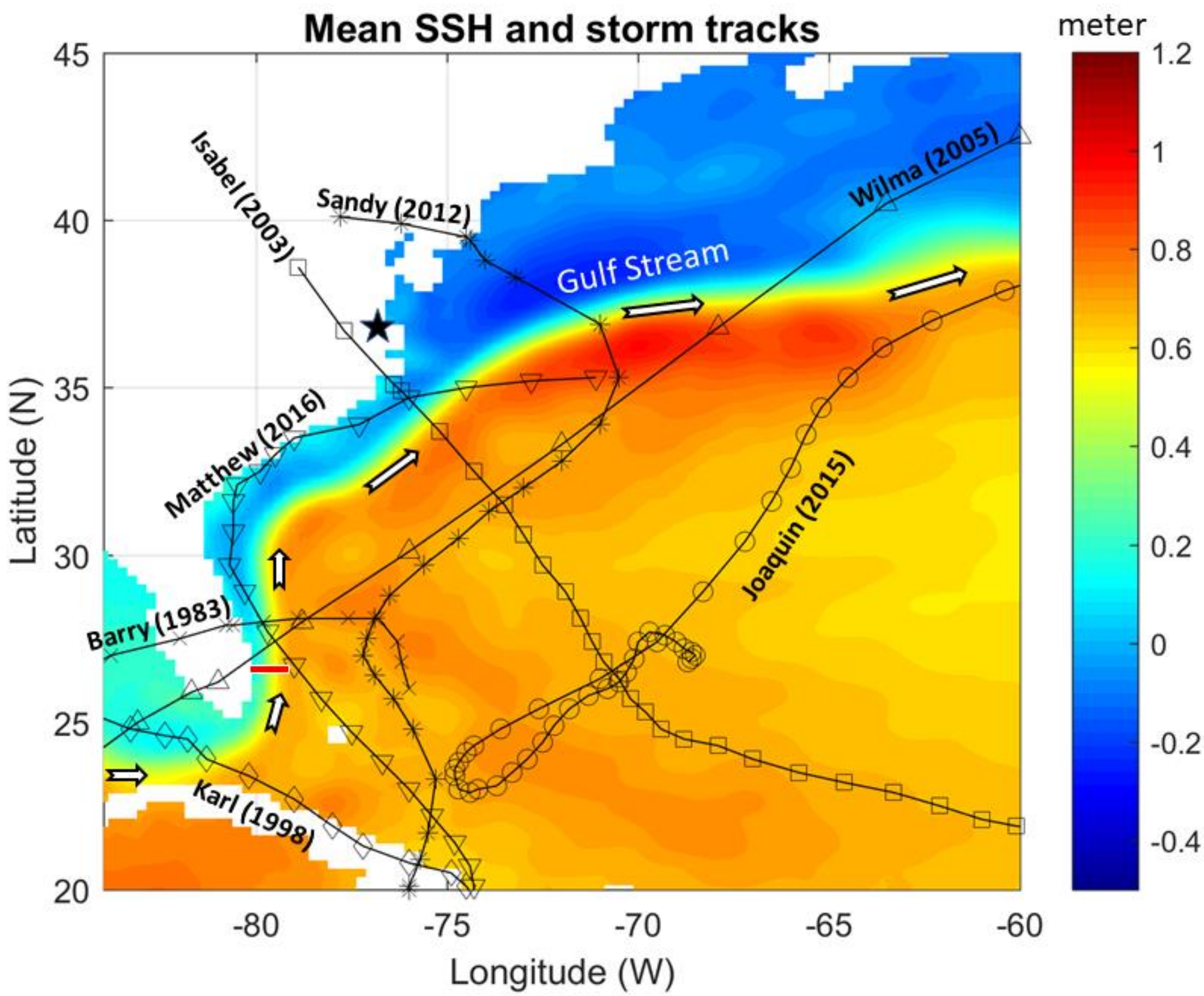


Fig. 1. Mean Sea Surface Height (SSH) from AVISO satellite altimeters are shown in color (in meters) and the location of the Gulf Stream is indicated by white arrows. The location of the Florida Current measurement across the Florida Strait is indicated by a red line and the location of Norfolk, VA, is indicated by a black star. The tracks of several storms, discussed in the paper, are shown with markers representing the location of the eye of the storm every 6 hours.

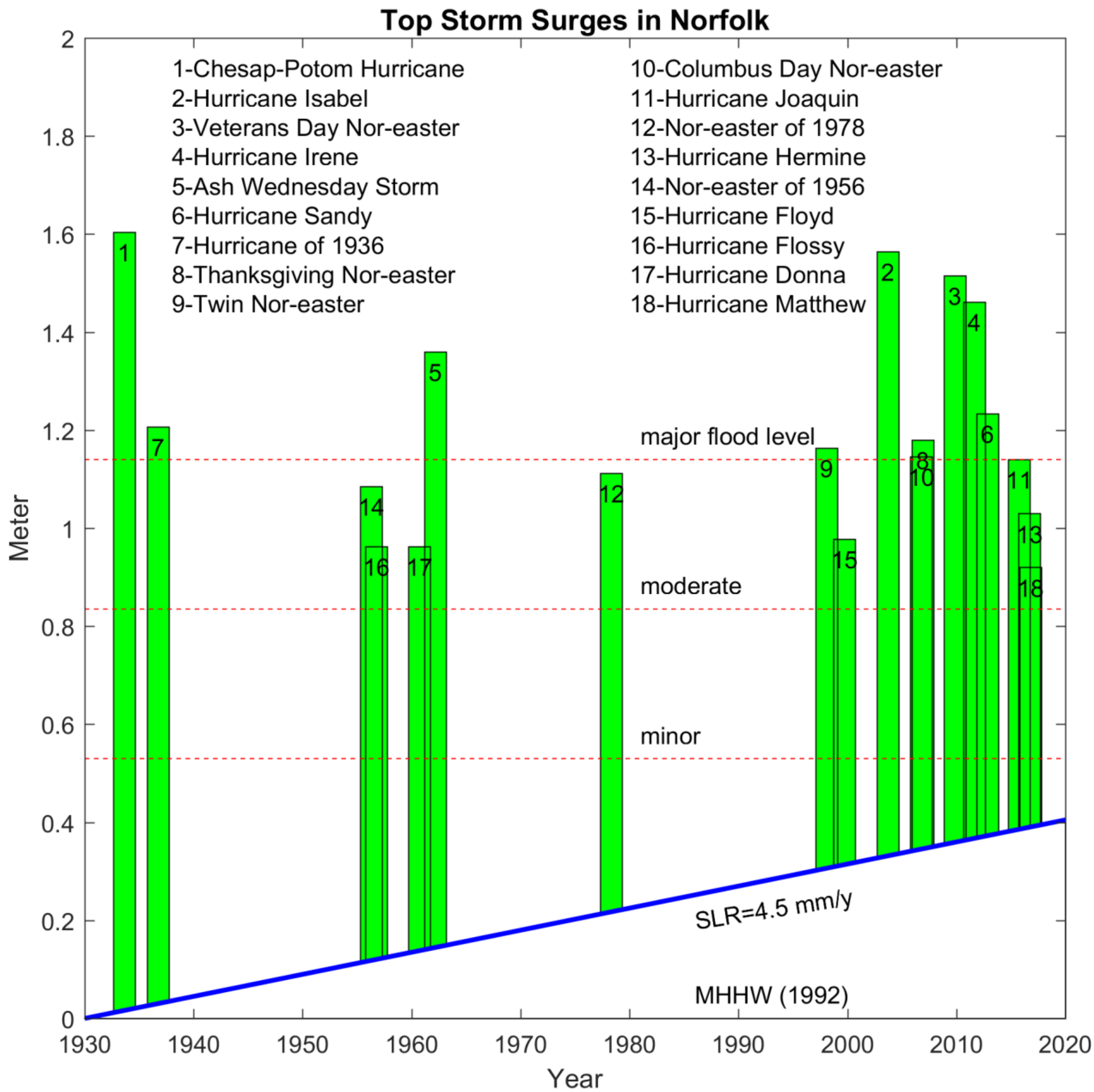
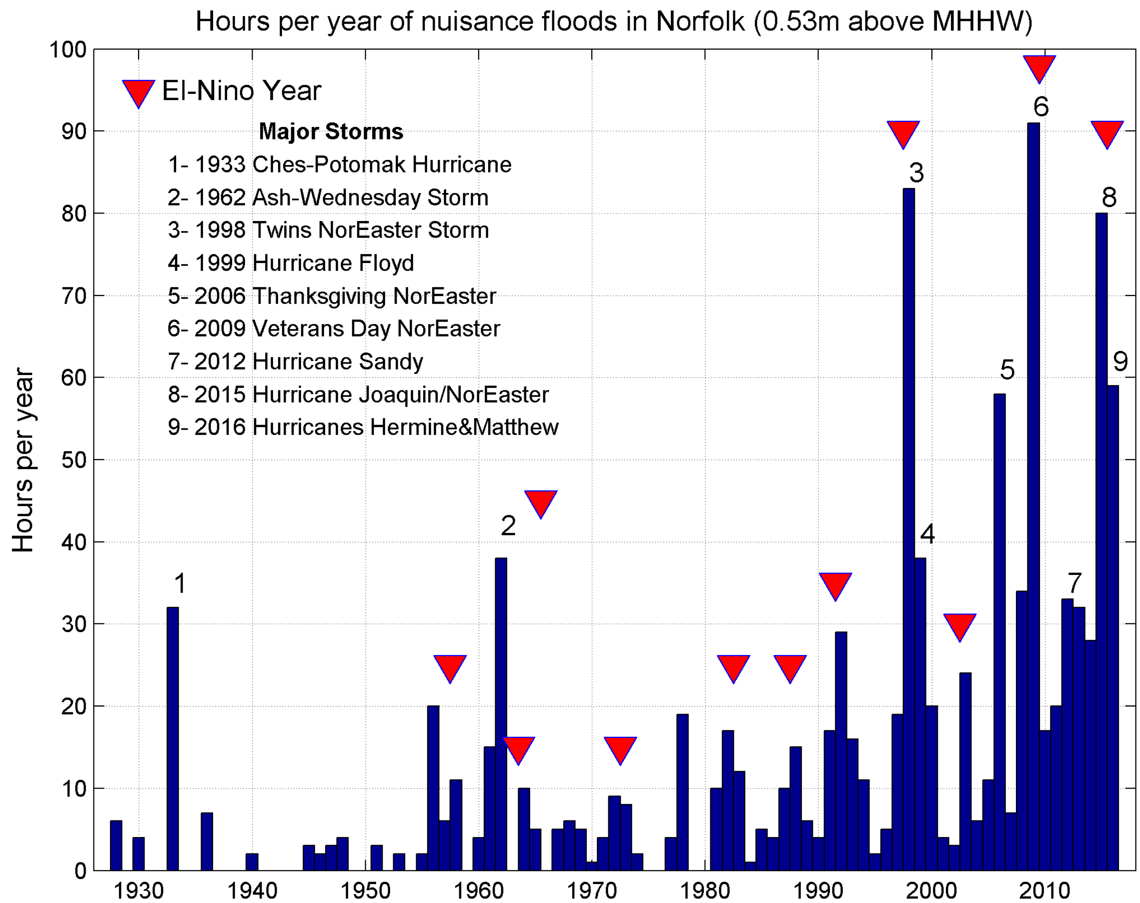


Fig. 2. The maximum water level at Sewells Point (Norfolk, VA) relative to the Mean Higher High Water (MHHW; 1992 datum) for the major storms passing the region. The impact of sea level rise (SLR) relative to 1930 is demonstrated using the average rate of that period. Also shown in horizontal dash lines are the estimated levels of minor (0.53m), moderate (0.835m) and major (1.14m) flood levels in Norfolk.



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358 **Fig. 3.** The number of hours per year that water level in Norfolk is at least 0.53 m above MHHW; this

359 level corresponds to minor street flooding (also known as nuisance flooding). Major storms in the most

360 flooded years are listed, as well as indication (red triangles) of years with El-Nino.

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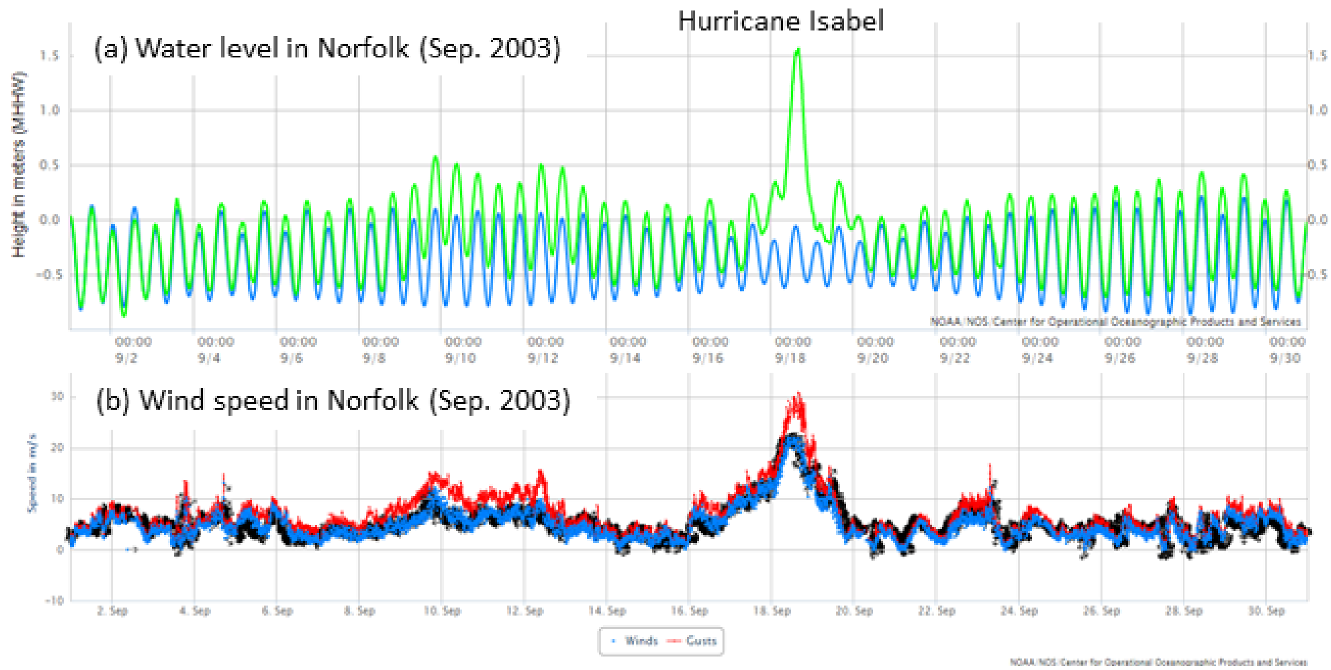


Fig. 4. Example of (a) water level and (b) wind in Sewells Point (Norfolk, VA) during hurricane Isabel in September, 2003 (see Fig. 1 for the track). Blue and green lines in (a) are for tidal prediction and observed water level (in meter relative to MHHW), respectively; blue and red lines in (b) are for mean wind and gusts (in m/s), respectively.

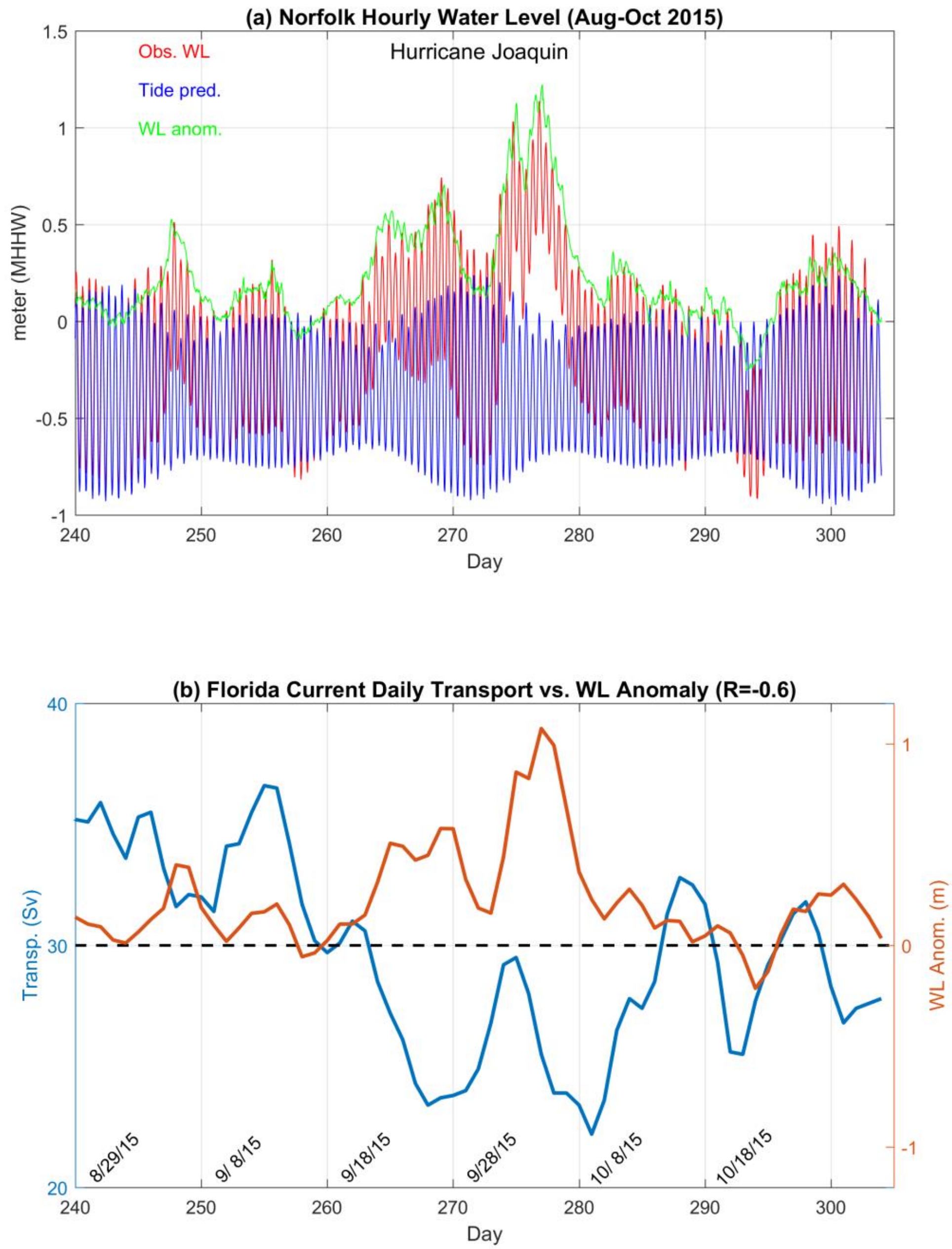


Fig. 5. (a) Hourly observed water level (red) tidal prediction (blue) and residual anomaly (green) in Norfolk from late August to late October 2015, when hurricane Joaquin was offshore the Atlantic coast (see Fig. 1 for the track). (b) Daily Florida Current transport (blue in Sv, $1Sv=10^6$ m^3/s) and water level anomaly (red in meter).

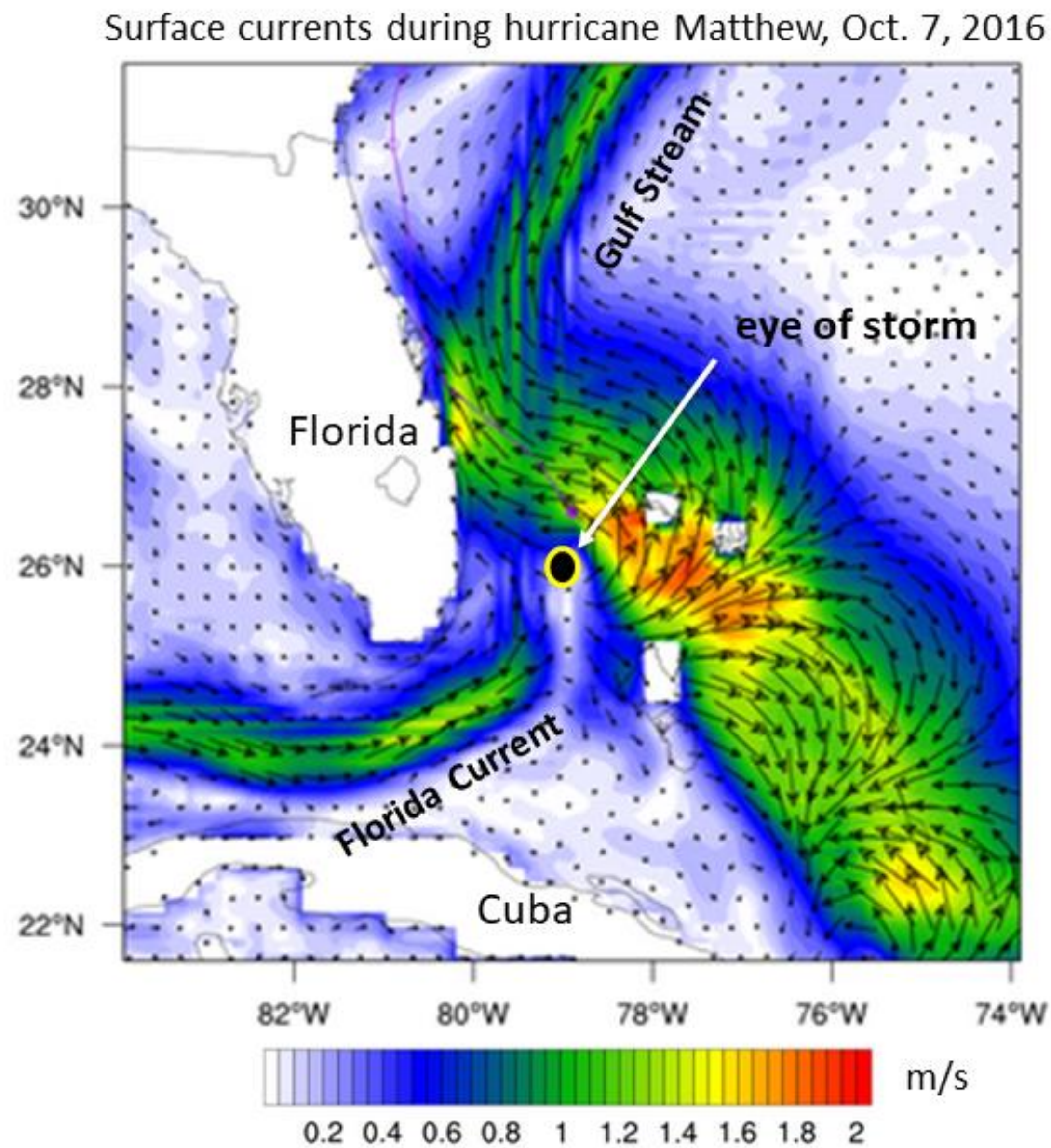


Fig. 6. Example of surface currents on October 7, 2016, when hurricane Matthew was near the south Florida coast (the eye of the storm is indicated by a circle). The simulations are from NOAA's HWRF operational coupled ocean-atmosphere forecast system. See Fig. 1 for the complete track of the storm.

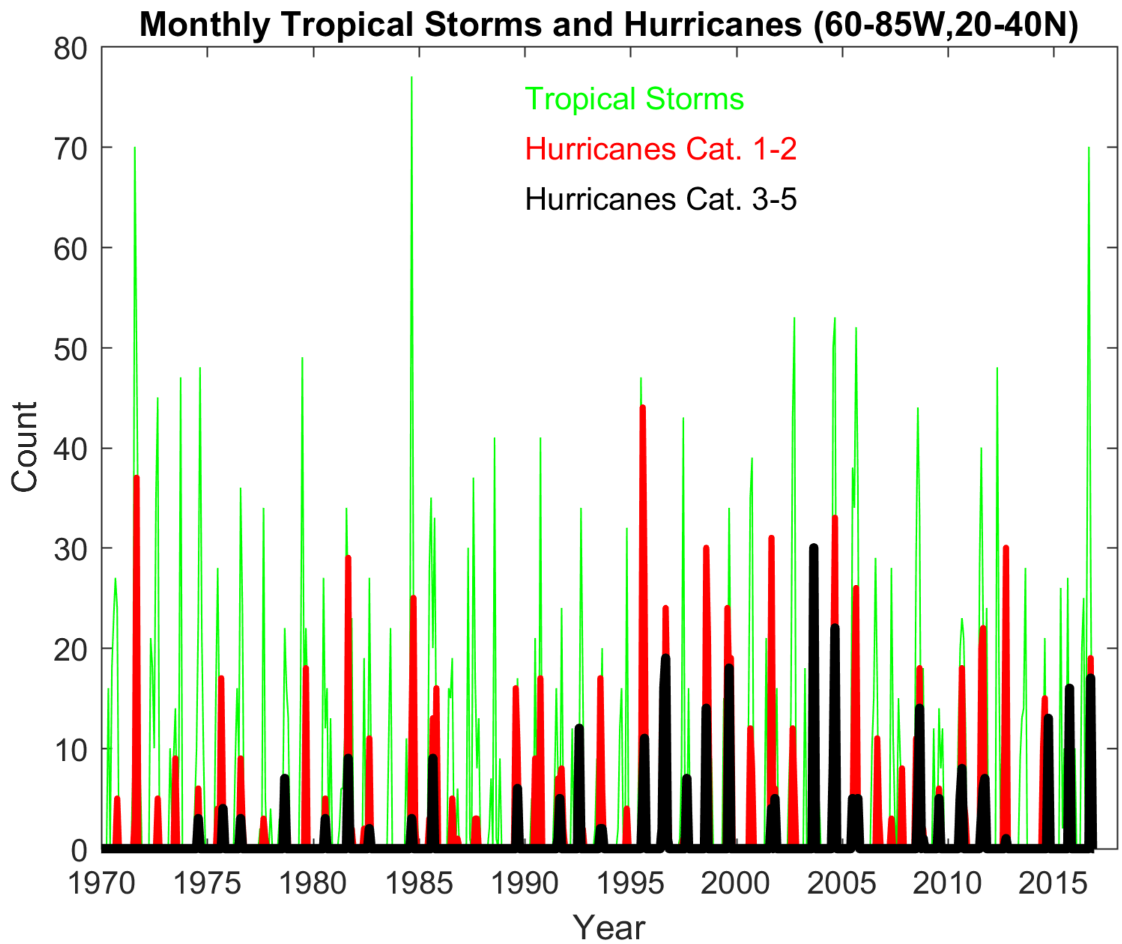


Fig. 7. Statistics of tropical storms and hurricanes near the SAB during 1970-2016. For each of three categories and for each month, all 6-hourly records of storms found in the region 60°W-85°W and 20°N-40°N were counted. The categories are: tropical storms (maximum wind Wmax < 33 m/s), hurricanes category 1-2 (33 m/s < Wmax < 50) and hurricanes category 3-5 (50 m/s < Wmax).

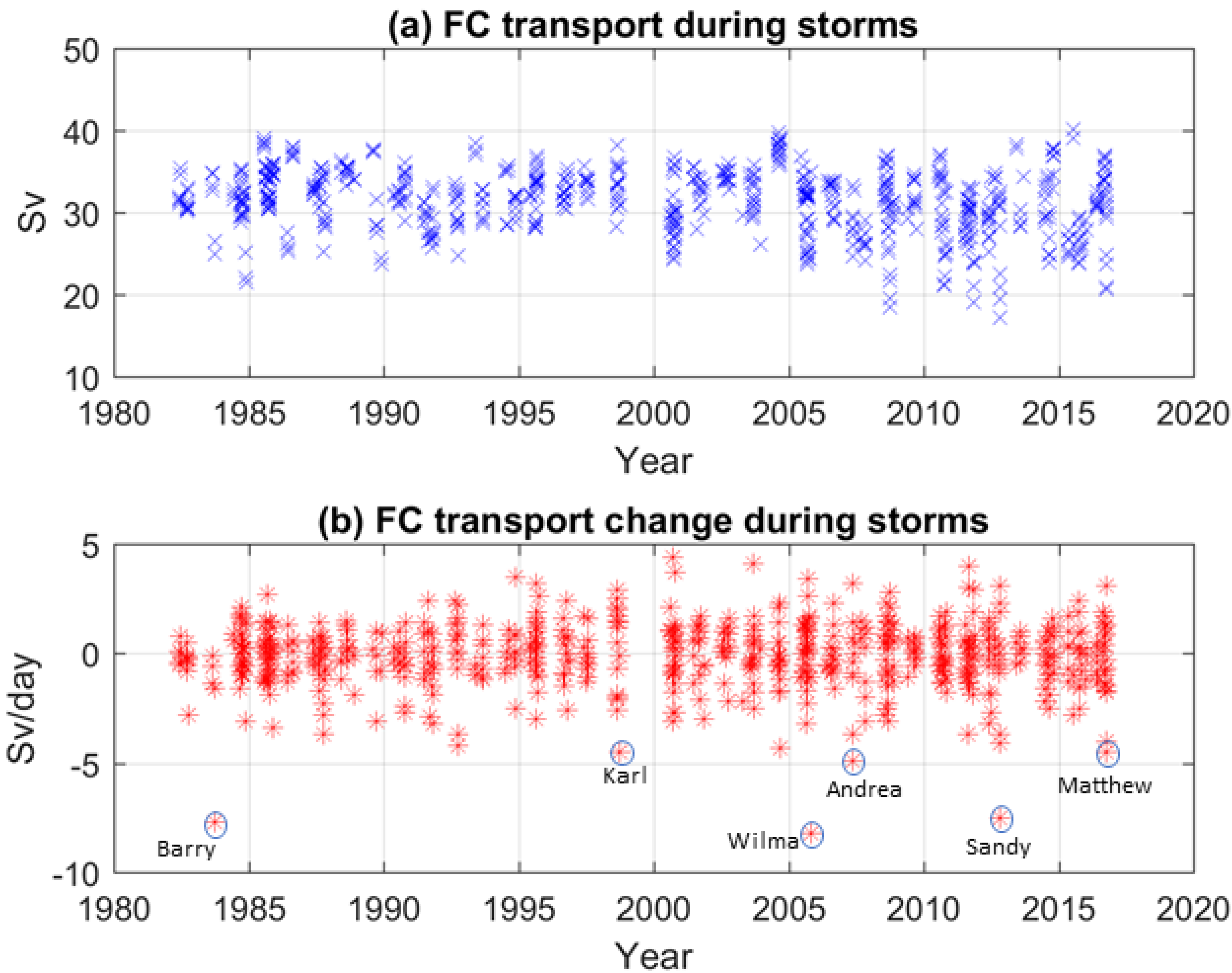
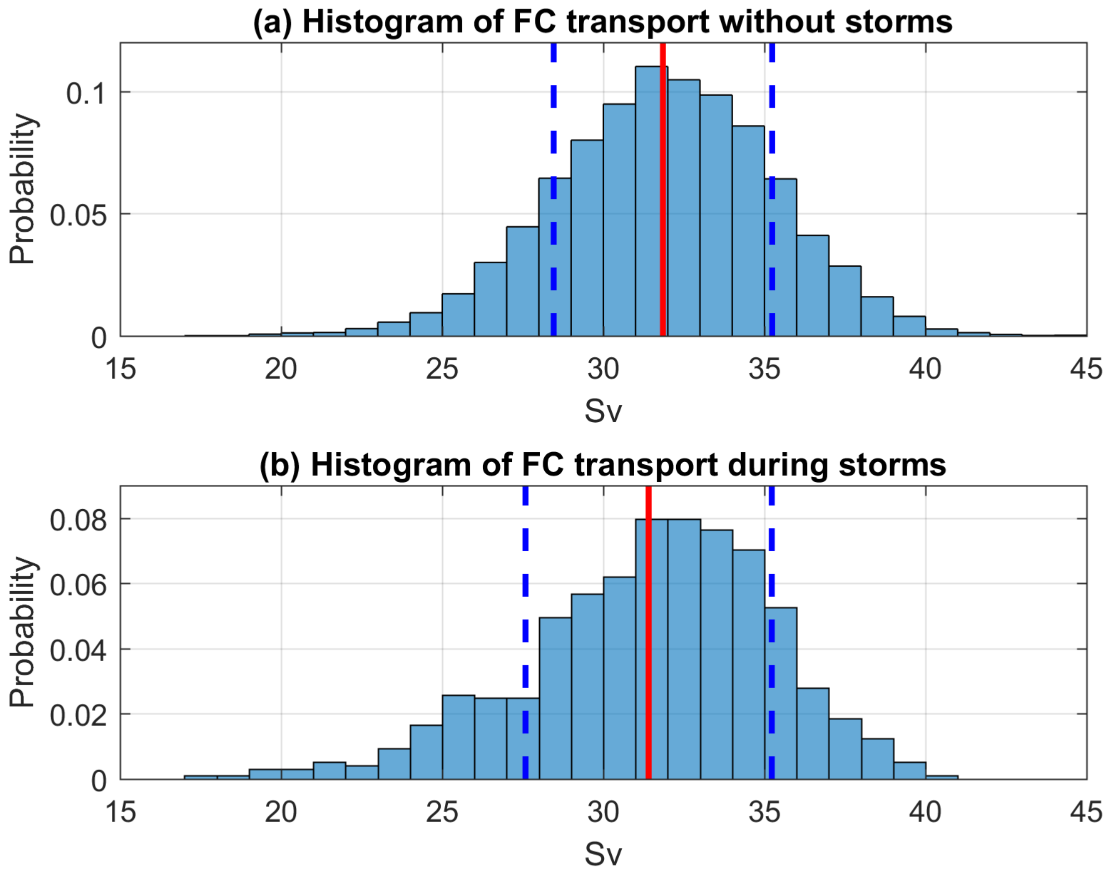


Fig. 8. (a) Florida Current (FC) transport (blue in Sverdrup) and (b) transport change (red in Sv/day) during the time that a tropical storm or hurricane was recorded in the same region as in Fig. 7. Each marker represents a day in which a storm was found in the region; some of the storms that caused the most decline in the FC transport are indicated in (b) and discussed in the text.



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393 **Fig. 9.** Histogram of FC transport 1982-2016 for (a) all the days without hurricanes or storms and (b) 394 days with recorded hurricanes or storms in the same region as in Fig. 7. Red and blue vertical lines 395 represent the mean and the standard deviation, respectively.

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