Accelerated flooding along the U. S. East Coast: On the impact of sea level rise, tides, storms, the Gulf Stream and NAO

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Abstract.

Recent studies identified the U.S. East Coast north of Cape Hatteras as a "hotspot" for accelerated sea level rise (SLR), and the analysis presented here show that the area is also a "hotspot for accelerated flooding". The duration of minor tidal flooding (defined as 0.3 m above MHHW) has accelerated in recent years for most coastal locations from the Gulf of Maine to Florida. The average increase in annual minor flooding duration was ~20 hours from the period until 1970 to 1971-1990, and ~50 hours from 1971-1990 to 1991-2013; spatial variations in acceleration of flooding resembles the spatial variations of acceleration in sea level. The increase in minor flooding can be predicted from SLR and tidal range, but the frequency of extreme storm-surge flooding events (0.9 m above MHHW) is less predictable, and affected by the North Atlantic Oscillations (NAO). The number of extreme storm surge events since 1960 oscillates with a period of ~15-year and interannual variations in the number of storms is anti-correlated with the NAO index. With higher seas, there are also more flooding events that are unrelated to storm surges. For example, it is demonstrated that week-long flooding events in Norfolk, VA, are often related to periods of decrease in the Florida Current transport. The results indicate that previously reported connections between decadal variations in the Gulf Stream and coastal sea level may also apply to short-term variations, so flood predictions may be improved if the Gulf Stream influence is considered.

1. Introduction

High relative sea level rise (SLR) rates recorded by tide gauges along the U.S. East Coast (Fig. 1) and sea level acceleration north of Cape Hatteras, North Carolina [*Boon*, 2012; *Ezer and Corlett*, 2012; *Sallenger et al*., 2012; *Kopp*, 2013; *Ezer*, 2013; *Ezer et al*., 2013] are expected to increase coastal flooding associated with tides and storm surges. The Mid-Atlantic coastal region has been called a "hot spot of accelerated SLR", and positive acceleration has been calculated by at least 4 different statistical methods [*Boon*, 2012; *Ezer and Corlett*, 2012; *Sallenger et al*., 2012; *Kopp*, 2013]. However, how to detect statistically significant sea level acceleration is still being debated [*Haigh et al.*, 2014], and uncertainties remain about the implications of sea level acceleration for the likelihood of future flooding and coastal risk management issues [*Nicholls and Cazenave*, 2010; *Cazenave and Cozannet*, 2014]. Therefore, we will show here that acceleration in flooding extent is more clearly detectable than acceleration in SLR rates; both accelerations are correlated with each other and show similar spatial patterns along the coast. Moreover, flooding statistics, as presented in this study, are useful for practical purposes of developing flood mitigation strategies. Several low-lying populated regions along the U. S. coasts are especially vulnerable to SLR, including south Florida [*Zhang*, 2011], and the Hampton Roads region in the lower Chesapeake Bay [*Kleinosky et al., 2007; Atkinson et al*., 2013; *Boesch et al*., 2013; *Mitchell et al*., 2013]. In addition to large land subsidence around the Chesapeake Bay area due to Glacial Isostatic Adjustment, GIA [*Boon et al*., 2010; *Kopp*, 2013], SLR acceleration in the Mid-Atlantic coastal region has been found to be highly correlated with recent offshore shift and weakening in the Gulf Stream just north of Cape Hatteras, as seen in altimeter data [*Ezer et al*., 2013] and in direct observations of the Florida Current [*Ezer*, 2013]. The latter finding is consistent with dynamic sea level changes seen in ocean models [*Ezer*, 1999, 2001, *Levermann et al*., 2005; *Yin et al*., 2009; *Yin and Goddard*, 2013] and expected weakening in the Atlantic Meridional Overturning Circulation (AMOC) under warmer climate conditions [*Hakkinen and Rhines*, 2004; *Sallenger et al*., 2012; *McCarthy et al*., 2012; *Srokosz et al*., 2012; *Smeed et al*., 2013]. Although the long-term weakening of the GS is still small and difficult to detect [*Rossby et al*., 2013], variations on scales ranging from weeks to decades may result in large temporal and spatial variations of SLR rates along the U.S. East Coast [*Kopp*, 2013; *Ezer*, 2013].

The motivation for our study comes from the fact that temporal and spatial variations in sea level pose challenging questions on how to assess the flooding risk of coastal regions. For example, it is well recognized that a storm surge larger than normal may occur if a hurricane landfall coincides with high tide (e.g., when storm Sandy hit New Jersey and New York in 2012), but less understood is the possibility that a storm surge coincides with a period of relatively higher sea level due to seasonal variations or a weaker GS [*Sweet et al*., 2009]. Periods of anomalous high water can last weeks or months [*Sweet et al*., 2009], and possibly years or decades [*Ezer et al*., 2013; *Ezer*, 2013]. There are numerous studies that assess the risk of extreme events, for example, *Kemp and Horton* [2013] study the contribution of SLR and high tide timing to hurricane flooding in New York City over the past ~200 years, while *Zhang and Sheng* [2013] used observations and numerical model simulations to study the contribution of storms and tides to extreme sea level events along the eastern coast of North America. The latter study did not consider the impact of SLR, and neither study considered the impact of changes in ocean dynamics or the GS. For each tide gauge in the U.S. NOAA provides statistics of 1%, 10%, 50%, and 99% annual exceedance probability (tidesandcurrents.noaa.gov). For example, 1% exceedance probability means that the likelihood of water level reaching particular water level in any year is in average 1/100; an extreme storm surge event of this type is "the average recurrence interval" [see *Hunter*, 2010 for definitions]. But how to interpret such information or use it for risk management or mitigation planning is not always clear. Moreover, the NOAA exceedance statistics is based on the

average of past measurements, so it does not consider how the likelihood of flooding has changed in the past and how it will change in the future due to the impact of SLR. A simple statistical method to estimate the expected exceedance under future SLR has been offered by *Hunter* [2012]. However, in the study presented here we do not attempt to calculate probability statistics of sea level, as it has already been done by other studies mentioned above. Instead, we provide more practical information on the duration of (potential) flooding when water level reached a particular level and how the likelihood of floods change over time and space. Moreover, while most other studies focus on extreme storm surge events, we also provide flood statistics for minor and moderate tidal flooding events which are not catastrophic, but very important for people living near waterfronts and coasts. Such information was found to be very useful to communicate flood risks to the local population and planners in the flood-prone region around the city of Norfolk, VA [*Atkinson et al*., 2013] and along the shores of the Chesapeake Bay [*Boesch et al*., 2013; *Mitchell et al*., 2013].

Observed coastal relative sea level at a particular time (t) and location (x) is the result of several components,

$$h(x,t) = DAT(x) + GLB(t) + SUB(x,t) + LOC(x,t) + TID(x,t) + STO(x,t)\,. \quad (1)$$

Each component have different temporal (T) and spatial (X) scales: DAT is a reference datum (the current National Tidal Datum Epoch is based on averages for 1983-2001), GLB is the global SLR (T~ decades to centuries), SUB is the local land subsidence due to GIA (X~ 100-1000 km; T~1000s of years), LOC is local changes due to groundwater extraction, weather pattern, ocean dynamics, changes in gravity field due to mass redistribution and other processes not homogeneous in space (X~ 10s-100s km; T~ days to years), TID is the tidal contribution (T~ hours-days) and STO is major storm surge events (T~ months-years). For short term sea level variations, GLB, SUB and TID contributions are the most predictable and the LOC and STO the most unpredictable.

Fig. 2 shows an example of the different contributions to a high-water storm event in Norfolk, where the local SLR is ~1.5 times larger than the altimeter derived global mean sea level of the past ~20 years and ~3 times larger than the tide-gauge derived [*Church and White*, 2011] global mean SLR of the past century. In the past, GIA was responsible to the large local SLR in Norfolk [*Boon et al*., 2010], but additional acceleration in SLR in recent years may be due to weakening GS since ~2004 according to *Ezer et al*. [2013], so one needs to assess the impact on these changes in ocean currents on potential flooding. We define a storm surge event as a period when water level reached a particular level above Mean High-High Water (MHHW). For example, Fig. 3 shows that 17 extreme storm surge events occurred in Norfolk over the past 85 years, when water level reached at least 0.9 m (~3 feet) above MHHW. The impact of SLR is also demonstrated in Fig. 3- the top storm surge was caused by the Chesapeake-Potomac Hurricane of 1933 when sea level was ~0.4 m lower than today, so a storm surge with similar strength if occurring today could cause water level to reach ~2 m above MHHW. Note also that, more than half of the big storm surges occurred during the past 15 years, but only one storm occurred in a 35-year span, between 1963-1997 suggesting that SLR as well as decadal variations may affect the frequency of storm events. The changing frequency of storm events will thus be addressed in this study. However, the frequency of storm events and the maximum water level reached for each storm do not accurately represent the flooding risk and damage. For example, the most flooding in Norfolk happened during the "Veterans Day Northeaster" of 2009 because floods lasted for several tidal cycles when water continued to flow into more streets compared with much stronger hurricanes when water receded immediately after the storm passed. To capture this phenomenon, from hourly sea level data,

h(t), the total hours of flooding per year (*T*) for each station ("i") are calculated for 3 selected critical water levels (*WLc* above MHHW),

$$T_i^{year} = \sum_{year} t \quad ; \quad h(t) > WLc\,,\ WLc = 0.3,\ 0.6,\ 0.9m\ . \tag{2}$$

Note that local topography and coastal slopes may result in a non-linear relation between SLR and actual inundation [*Zhang*, 2011], so a more detailed analysis is needed to determine if a particular place will be flooded or not. However, the 3 categories of flooding defined by *WLc* roughly represent (for example in downtown Norfolk) minor tidal flooding (that is sometimes referred to as "nuisance flooding" with wet streets), moderate weather related flooding (e.g., a weather front passing during Spring tide) and extreme storm events (e.g., a hurricane or major nor'easter), respectively. Note that the calculations based on Eq. 2 are directly related to the exceedance probability and the average recurrence interval [e.g., see *Hunter*, 2010, for definitions]; the higher the critical water level *WLc*, the lower the recurrence interval is. However since exceedance probability is routinely calculated by NOAA, it is not repeated here. Instead, analyzing how flooding frequency and duration change between different locations and how they are affected by the different components in Eq. 1, as well as by large scale Atlantic Ocean variations, are the main goals of this study.

2. Sea level data

Hourly sea level records from 11 tide gauge stations were obtained from NOAA (http://opendap.co-ops.nos.noaa.gov/dods/). The locations are shown in Fig. 1 and information on each station, including tidal range and SLR, are listed in Table 1. The data cover 4 different regions along the U. S. coast, 3 stations in the Gulf of Maine, 3 stations in the Mid-Atlantic Bight, 3 stations in the South Atlantic Bight and one station (Key West) between the Florida Strait and the Gulf of Mexico (Fig. 1). Only stations with relatively long and continuous hourly records were used, with an average period of 87 years. These stations represent large variations in tidal range, from ~0.5 m (the southernmost point, Key West, FL) to ~6 m (the northernmost point, Eastport, ME). With these data, the impact of tidal range on flooding can be evaluated. The mean (relative) SLR rate varies from ~1.9 mm y^{-1} (Gulf of Maine) to ~4-5 mm y^{-1} (lower Mid-Atlantic Bight). Note that most studies of SLR use monthly data, which may cover in some stations longer records than the hourly data, so the SLR rates in Table 1 are slightly different than those reported by *Ezer* [2013], *Boon* [2012] and others. *Ezer* [2013] described the significant spatial difference in mean SLR and acceleration between stations north and south of Cape Hatteras, apparently a dynamic response related to the separation point of the Gulf Stream from the coast. However, the spatial pattern of flooding along the coast may be more complex, since in additional to the spatial pattern of SLR, variations in tidal range and in the frequency of storms also vary along the coast, as quantified recently by *Zhang and Sheng* [2013].

3. Results

3.1. Flood duration and frequency: impact of sea level rise and tides

Communities prone to flooding often prepare for flood events based on expected water level (relative to say MHHW) obtained from tide and storm surge models. For example, in a flood-prone neighborhood near downtown Norfolk, high tide is sometimes accompanied by unexplained anomalous high waters that may reach 0.3m (~1foot) above MHHW even when there is no local wind events (see more on this in section 3.3). This condition can result in minor tidal flooding that can cause what is referred to as "nuisance flooding". When an additional weather front passes the region during high tide,

water level may reach 0.6m (~2feet) above MHHW and more streets will be flooded. During a major tropical storm, nor'easter or hurricane, water level could reach over 0.9m (~3feet) above MHHW (Fig. 3) and several blocks of city streets from the water front will be completely under water. In the later case flood gates in the downtown area of the city and in highway tunnels would be closed. Therefore, the same statistics of annual flooding time that has been used to characterize floods and plan mitigation strategies in Norfolk [*Atkinson et al*., 2013] have been extended here to other locations; examples are shown in Fig. 4a-4g and the results for all the 11 locations are listed in Table 1. Note that the terms "minor", "moderate" and "major" flooding events refer here to 0.3, 0.6 and 0.9 m above MHHW, though specific locations may have different coastal slopes, height of streets above water or some protection measures (e.g., flood walls), so that the actual flood risk may be different.

The impact of tidal range on potential flooding can be seen for example in the difference between Eastport (Fig. 4a) and Portland (Fig. 4b). The two stations located in the same region, the Gulf of Maine, have similar tidal modulation (Neap/Spring tide relation) and similar SLR, but the tidal range is almost twice as large in Eastport than it is in Portland (Table 1), resulting in 2-10 times longer flood duration in Eastport than that in Portland. Note that tidal range by itself may not predict the exceedance probability very well if tidal modulation is different, as demonstrated for example by some Australian stations [*Hunter*, 2012]. The potential for minor, moderate or major floods in Eastport are dominated by the high tide, and between 1958 and 2009 the increase in flooding due to SLR is relatively small. However, in every year since 2010 major floods (top panel of Fig. 4a) are larger than in any year before 2010. This may relate to the unusual warming north of the Gulf Stream that started around 2004 and affected the lobster fishery in the Gulf of Main [*Mills et al*., 2013]. In Portland (Fig. 4b) and Boston (not shown) on the other hand, significant increase in minor and moderate flooding due to SLR is more visible, but extreme sea level ("major flooding") is rare and shows only decadal variations with no apparent gradual increase. In the Mid-Atlantic region, New York (Fig. 4c), Atlantic City and Lewes (not shown) and Norfolk (Fig. 4d), dramatic increase in minor and moderate flooding is seen, which is consistent with the high SLR and recent acceleration of SLR in this region [*Boon*, 2012; *Sallenger et al*., 2012; *Kopp*, 2013; *Ezer*, 2013; *Ezer et al*., 2013]. In Norfolk, for example (Fig. 4d), years with more than 50 hours of minor flooding were very rare until the 1980s (4 times in over 50 years) and only happened when nor'easters or hurricanes passed the region. However, over the past 20 years, minor flooding of 50-250 hours per year became commonplace. In the South Atlantic Bight, the pattern of flooding is quite different than that of the Mid-Atlantic region, since relative coastal SLR associated with land subsidence (term SUB in Eq. 1) is not as large, and SLR acceleration is smaller than that in the Mid-Atlantic coastal region [*Boon*, 2012; *Ezer*, 2013]. In Wilmington there seem to be a significant increase in minor flooding after the 1980s but it is attributed to an increase in tidal range (bottom panel of Fig. 4e) and not due to SLR alone. The tidal station is located in the Cape Fear River; the river has seen continuous sediment filling and several cycles of dredging over the years, which apparently changed the tidal dynamics. In Wilmington (Fig. 4e) and Charleston (Fig. 4f), major floods are rare and happened only during a couple of hurricanes. Key West, with its small tidal range (Fig. 4g), experienced an increase in minor flooding only over the past decade, and almost no major floods except a single year, 2005 (when hurricanes Katrina and Wilma passed nearby).

Fig. 5 summarizes the minor flooding (0.3 m above MHHW) hours at the 11 locations; the averaged annual flooding is calculated for three periods: 1. Before 1971, 2. 1971-1990, and 3. 1991-2013. While all stations show significant increase in flooding from the 1970s to the 1990s and 2000s, an apparent spatial pattern emerges from this comparison. Three locations are clearly distinct from the general pattern: the northernmost location, Eastport, has such a large tidal range that it is the only location with high minor floods (over 40 hours) even before 1971, while the southernmost point, Key

West, has very minimal floods throughout the record. Wilmington, just south of Cape Hatteras, also has an unusual pattern, with almost no flooding until 1990, but a large increase of 10 fold in recent years due to local sand fill and dredging that caused an increased tidal range, as discussed before. There is a significant increase in flooding at all locations, which is typically ~200% to 600% after the 1990s relative to the floods experienced before the 1970s. The question is- "Is there a consistent acceleration in flooding?" The acceleration in minor flooding is estimated by

$$ACC(hr/yr^2) = \frac{\frac{(T3-T2)}{(Y3-Y2)} - \frac{(T2-T1)}{(Y2-Y1)}}{(Y3-Y1)/2} \quad . \tag{3}$$

Y1, Y2 and Y3 are the years in the middle of the 3 periods, from the beginning of the record to 1970, from 1971 to 1990 and from 1991 to 2013, respectively, and T1, T2 and T3 are the average annual flooding hours for the 3 periods. All the stations show positive acceleration (Table 1), and a distinct pattern. Excluding the northernmost and southernmost stations, acceleration in flooding increases gradually as one moves south from Portland (ACC~0.01 hr yr^2) to Lewes and Norfolk (ACC~0.15 hr yr^2), and then from Wilmington (ACC~0.04 hr yr^2) to Pulaski (ACC~0.08 hr yr^2). The change in the acceleration at Cape Hatteras and the general pattern of ACC closely resembles the SLR acceleration pattern found by *Ezer* [2013]. Although acceleration in SLR is not necessarily precondition for acceleration in flooding, the similarity in the pattern of spatial variations between acceleration in SLR and flooding suggests that ocean dynamics (i.e., term LOC in Eq. 1) may play a role in causing the differences between the Mid-Atlantic Bight north of Cape Hatteras and the South Atlantic Bight south of Cape Hatteras. Fig. 6 compares the acceleration in minor flooding (ACC) with the acceleration in sea level, calculated by *Ezer* [2013]; the latter uses an Empirical Mode Decomposition (EMD) method to separate a non-linear trend from oscillating modes [see *Ezer and Corlett*, 2012, for details]. Data at Eastport was omitted in Fig. 6 due to its unusual high tide that obscures the results. Results show that accelerations in sea level and in floods are significantly correlated (R=0.77, confidence level>99%). The largest acceleration in both, sea level and flood duration is at Norfolk, VA, and Lewes, DE, the closest locations downstream from the separation point of the Gulf Stream at Cape Hatteras. The locations with the lowest flood acceleration are those farthest away from Cape Hatteras in both directions (Portland in the north and Key West in the south).

The contributions of tides and SLR to (minor) flooding are shown in Fig. 7 (excluding data from Wilmington due to varying tidal range). Before 1990, flooding period was highly correlated with the tidal range (correlation coefficient R>0.9 and statistical confidence >99.9%) and only small differences are seen between the period before 1971 and 1971-1990. After 1990 SLR seems to play an additional role, so the correlation between tidal range and flooding is somewhat smaller (R=0.77, though still significant at 99% level). The fact that all 3 lines in Fig. 6a have almost the same slope indicates that tidal contribution to flooding is quite linear and predictable. The average increase in minor flooding is ~20 hours per year between the beginning of the records to1970 and 1971-1990, but ~50 hours per year between 1971-1990 and 1991-2013.

3.2. Extreme sea level events and the impact of the North Atlantic Oscillations

Extreme storm surge events (defined here at 0.9 m over MHHW) are relatively rare and are related to hurricanes or intense storms (except where tides are very large, such as in Eastport). A storm such as Hurricane Sandy caused more floods in 2012 than a storm with similar strength 100 years ago when sea level was lower (assuming both hit at the same tidal stage) [*Kemp and Horton*, 2013].

However, predicting the frequency of big storms and the location they hit the coast may be difficult and depend on many factors, such as variations of weather and climate over the continental U.S. and conditions over the Atlantic Ocean. Fig. 3 and Fig. 4 (and the other stations not shown) indicate that extreme sea level events in the Mid-Atlantic region have some decadal-like variations rather than a gradual increase as seen in minor and moderate flooding events, suggesting a modulation by large-scale ocean-atmosphere patterns.

One of the most widely used patterns that affect decadal and multidecadal variations in the Atlantic region is the North Atlantic Oscillation (NAO) index [*Hurrell*, 1995], representing north-south dipole of pressure anomalies over the North Atlantic Ocean. The NAO is associated with changes in the intensity and location of the jet stream and storm track, as well as changes in temperature and precipitation patterns. For example, strong positive phases of the NAO tend to be associated with warmer temperatures in the eastern U. S. The NAO may also be connected to long-term variations in sea level and the transport of the GS [*Ezer et al*., 2013]. An extreme storm surge event is defined here as a year with at least one event with water level reaching at least 0.9 m above MHHW (i.e., a non-zero bar in the upper panels of Fig. 4). While it is possible that a single storm moving along the coast may cause extreme events at more than one location, they are considered here as separate events, since we attempt to characterize the total impact of storms on the coast. An index of the average number per year of extreme storm events hitting somewhere along the coast for each 5-year period is shown in Fig. 8 (green line) and compared with 5-year averages of the NAO index (blue line). Note that only stations with at least 2 extreme events were included. The small number of events do not allow calculating statistical significance, but qualitatively there seem to be interesting relations between NAO and extreme events. The average number of extreme storm surge events per year generally increased from ~0.5 before 1950 to ~3.5 in 1990; at the same time the NAO shows an upward trend as well; *Hurrell* [1985] and others described this multidecadal shift in the NAO. An increase in storminess [*Dowson et al*., 2002] and warmer temperatures along the U.S. coast associated with more positive NAO [*Mills et al*., 2013] may relate to this trend, though more research on this possibility is needed, which is beyond the scope of this study. During the time between the 1970s and 1990s the sub-polar region also experienced an increase in sea level and weakening circulation [*Hakkinen and Rhines*, 2004] which may have weakened the AMOC and the GS transports [*Ezer et al*., 2013]. An interesting result is that between 1950 and 2010 there is an oscillation in the number of extreme events with a period of about 15 years (significant peaks in extreme events in 1960-1965, 1975-1980, 1990-1995 and 2005-2010). Those variations show that minima and maxima and extreme events are anti-correlates with peaks in the NAO (7 such cases are indicated by the vertical red bars in Fig. 8), so more storms seem to be expected during a period when NAO reached a local minimum. These variations could relate to wind-driven decadal variations in the Atlantic Ocean circulation and GS transport (which was found to be anti-correlated with NAO variations; *Ezer et al*., 2013). In any case, while SLR contributes to the damage caused by extreme storm surge events, it does not seem to explain the decadal pattern of extreme flooding events, so one needs to consider also large-scale atmosphere-ocean patterns.

3.3. Minor short term flooding and the impact of the Gulf Stream

Recent studies suggest a strong connection between long-term variations in the GS and coastal sea level [*Ezer*, 2013; *Ezer et al*., 2013], whereas weakening of the GS reduces the sea level slope across the GS, resulting in lower water level east of the GS and higher water level onshore along the coast. The same studies found that variations in the GS strength, estimated from either satellite altimeter data over the Mid-Atlantic Bight [*Ezer et al*., 2013], or from direct observations of the Florida Current transport across the Florida Strait [*Ezer*, 2013], produce similar correlations with decadal variations in coastal sea

level. Connections between the GS transport at the Florida Straits and coastal sea level, from Key West to Norfolk, on seasonal time-scales, have been suggested as well [*Blaha*, 1985]. High-frequency (e.g., meso-scale or wind-driven) variations in the strength of the GS may also influence high-frequency variations in coastal sea level. For example, a NOAA report [*Sweet et al*., 2009] suggests that unusually high water level along the mid-Atlantic coast in the summer of 2009 may have been related to a period of weak Florida Current transport. Low-lying cities in the Chesapeake Bay, such as Norfolk, Virginia, noticed in recent years prolong periods of flooding during high tides when water levels exceed the official NOAA prediction by 0.3-0.5 m, even when there is no storm in the region. Wind-driven numerical models seem to underestimate these events by as much as 0.5 m. Could such events be partly responsible for the increased in frequency of minor flooding events as observed around the Chesapeake Bay [*Atkinson et al*., 2013; *Mitchell et al*., 2013; *Boesch et al*., 2013]?. As an example, Fig. 8a shows the hourly tidal prediction and observed water level in Sewells Point, Norfolk, for the first three months of 2013. During this period, there were no major storms, but at least 6 events when the observed water level was at least 20 cm above the NOAA prediction for more than one tidal cycle (causing minor street flooding in downtown Norfolk), and one event of extremely low observed water level of 40 cm below the prediction (day 50). While some of the short (~1 day) anomalies may be due to local wind, there is no atmospheric explanation for high water anomaly that lasts for weeks (e.g., days 55-75). When comparing the water level anomaly (or residual) to the daily Florida Current transport [*Baringer et al*., 2013] (Fig. 8b), it was found that the change in the transport is highly anti-correlated (R=-0.5; significance >99%) with the water level (Fig. 8c). When the FC (i.e., the GS measured at the Florida Strait) is on a weakening trend such as from February 20 to March 12, water level is considerably higher than normal (with only a short break when the FC increased slightly at day 65). *Ezer et al*. [2013] noticed that on decadal scales water level in the mid-Atlantic coast have higher correlations with *changes* in the GS (after it separated from the coast), then the correlation with the GS strength itself; a simple dynamic balance equations were presented by *Ezer et al*. to explain this relation. They also show significant correlation on monthly to decadal scales between the FC cable transport upstream of Cape Hatteras and altimeter-derived GS strength downstream of Cape Hatteras. Here it was shown that the same mechanism also works for high-frequency oscillations. The fact that there is no time lag between changes in the Florida Current at 27°N and changes in sea level more than 1000 km farther north, indicates that the entire western boundary current may have some coherent variations that are probably driven by Ekman transports associated with variations in the large-scale wind stress over the subtropical gyre [*McCarthy et al*., 2012]. A recent study, using data and models, in fact, supports the hypothesis suggested above, it shows coherent correlation between FC transport and sea level along the GS from south Florida to 40°N and coherent correlation between the FC transport and wind stress over the subtropical gyre [Fig. 4 in *Zhao and Johns*, 2014]. If oceanic anomalies in sea level propagate toward the coast by means of fast moving barotropic waves, the response at the coast would be within hours. More research is needed on this driving mechanism, which is beyond the scope of this paper. However, a practical implication of the finding is the possibility to improve water level prediction on the coast using GS data from either satellite or the Florida Current cable measurements.

4. Summary and conclusions

Recent findings show an accelerated SLR ("hotspot") along the U.S. east coast north of Cape Hatteras and significant variations of SLR rates along the coast [*Boon*, 2012; *Ezer and Corlett*, 2012; *Sallenger et al*., 2012; *Kopp*, 2013; *Ezer*, 2013]; a potential driver for those may be climate-related changes in the AMOC [*Hakkinen and Rhines*, 2004; *McCarthy et al*., 2012; *Srokosz et al*., 2012; *Smeed et al*., 2013] and its upper branch, the Gulf Stream [*Ezer et al*., 2013]. But it is not always clear how this

information can be used to assess risks and impacts on different coasts and cities vulnerable to flooding [*Nicholls and Cazenave*, 2010; *Cazenave and Cozannet*, 2014]. Therefore, we calculated here a matrix of flood statistics, based on 3 given water level above a known high tide reference level (representing "minor", "moderate" and "extreme" flood events); this analysis is more easily used for practical purposes of flood mitigation and risk assessment than standard exceedance probability statistics (though the two methods are related). The results show very clearly that the U. S. East Coast (in particular the Mid-Atlantic coastal area north of Cape Hatteras) is a "hotspot of accelerated flooding" and that acceleration in SLR is highly correlated with acceleration in minor flood durations. Minor to moderate flooding increased significantly in the 1990s. Until the 1980s, the increase in flooding was relatively moderate, and flooding was, in most cases, associated with particular storm events. However, in recent years, flooding became more common and even a small weather front or anomaly related to offshore currents change can cause flooding over several tidal cycles. The result is acceleration in flooding durations, with larger increase in flooding along the coasts of the lower Mid-Atlantic Bight, where SLR acceleration is also larger. An interesting result was that extreme storm surge events seem to be correlated with decadal and multi-decadal variations of the NAO, in additional to the general increase in flooding due to SLR. It was found that decadal oscillations (of ~15 year period) in the number of extreme storm surge events are anti-correlated with decadal variations in the NAO; the results are consistent with mechanism involved wind-driven oscillations in the Atlantic Ocean circulation and the Gulf Stream [*Ezer*, 1999, 2001; *Ezer et al*., 2013].

What are the implications of these results with respect to flood risks due to future SLR? The average recurrence interval is expected to change, so in Norfolk, for example, a flood with a 80-year return level (define by an annual exceedance probability of 1/80) today is expected to occur in average every ~40 years if sea level would rise by 0.1 m; by 2050 when sea level in Norfolk is expected to rise by ~0.5 m [*Boon*, 2012; *Ezer and Corlett*, 2012] such flood level will be expected to occur every ~6 years (based on our calculations, not shown, and statistics provided by NOAA). The increase in the impact of storm surges due to rising seas and potentially due to slowing down of the Gulf Stream will result in increase in flood durations, as demonstrated here. The main goal of this study was to provide information on flood statistics, spatial variations and the various forcing components involved, in the hope that such information will be useful for improving flood predictions and for planning mitigation and adaptation strategies in flood-prone regions such as the Hampton Roads area (where the authors reside).

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Table 1. Information about the hourly sea level data used in this study and the calculated statistics. The mean high tidal range is defined as the difference between MHHW and MLLW. The mean sea level rise (SLR) obtained from linear regression and the 95% confidence interval are estimated based on Zervas (2009). The minor flooding estimate for different periods is based on the hours per year with water level at least 0.3m over MHHW; the 2 stations in the extreme north and south were neglected in the calculations of the mean flooding of all stations (last 4 columns of the bottom row). ACC is the estimated acceleration in flooding time (see Eq. 3 in text).

Station name, location and starting hourly data (all end in 2013)				Sea level statistics					
				Tidal range (m)	SLR (mm/y)	hours/yr of WL>0.3m			ACC
	Lat (°N)	Lon (°W)	Y1	MHHW-MLLW	Mean ±95%CI	Y1-1970	1971-1990	1991-2013	hr/yr^2
1. Eastport, ME	44.90	66.98	1958	5.87	1.93±0.55	127	110	183	0.24
2. Portland, ME	43.66	70.25	1911	3.02	1.89±0.20	38	79	109	0.013
3. Boston, MA	42.35	71.05	1922	3.13	2.79±0.24	40	71	116	0.045
4. Battery, NY	40.70	74.01	1920	1.54	3.12±0.23	19	41	99	0.076
5. Atlantic City, NJ	39.36	74.42	1912	1.40	4.16±0.20	12	33	94	0.078
6. Lewes, DE	38.78	75.12	1967	1.42	3.82±0.73	31	33	89	0.150
7. Norfolk, VA	36.95	76.33	1927	0.84	4.54±0.26	19	39	128	0.136
8. Wilmington, NC	34.23	77.95	1938	1.43	2.01±0.32	2.5	6	28	0.038
9. Charleston, SC	32.78	79.93	1922	1.76	3.15±0.24	12	27	71	0.060
10. Ft. Pulaski, GA	32.03	80.90	1921	2.29	3.16±0.23	19	41	99	0.076
11. Key West, FL	24.56	81.81	1913	0.55	2.39±0.20	4	4.5	13	0.013
mean± SD			87 yrs	1.92±0.8	3.00±0.9	21±13	41±22	92±29	

Figure Captions

Figure 1. Map of the U.S. East Coast (based on Google Earth) and location of tide gauge stations.

Figure 2. Comparison of monthly sea level in Norfolk (green) with global mean sea level obtained from tide gauges (blue) and AVISO satellite altimeters (red). The different contributions to a storm surge event are illustrated. See *Ezer* [2013] for information on the global data sets.

Figure 3. Maximum measured water level (relative to MHHW, defined by the mean of the epoch period 1982-2001) at Sewells Point, Norfolk, VA, during the top 17 storm surges . The sea level rise during the observed period is indicated by the blue line. . The total amplitude of the storm surge relative to the mean water level at the time of the storm is the difference between the top of the green bar and the blue line.

Figure 4a. Potential flooding statistics for Eastport, ME, in the Gulf of Maine. From bottom to top: 1) hourly sea level data, and hours per year of water reaching 2) 0.3 m, 3) 0.6 m and 4) 0.9 m above MHHW (the values in meter are exact while the values in feet are approximated; the Imperial/U.S. Customary Units are listed since they are used in weather reports and flood risk assessment in the U.S.). Yellow, white and red lines in 1) indicate linear SLR trend, MHHW, and the 3 flood lines, respectively.

Figure 4b. Same as Fig. 4a, but for Portland, ME, in the Gulf of Maine.

Figure 4c. Same as Fig. 4a, but for Battary station, New York, NY.

Figure 4d. Same as Fig. 4a, but for Sewells Point, Norfolk, VA, in the lower Chesapeake Bay.

Figure 4e. Same as Fig. 4a, but for Wilmington, NC. The station is located in the Cape Fear River, which is connected to the South-Atlantic Bight.

Figure 4f. Same as Fig. 4a, but for Charleston, SC, in the South-Atlantic Bight.

Figure 4g. Same as Fig. 4a, but for Key West, FL.

Figure 5. Summary of the mean number of hours per year of water level of at least 0.3 m above MHHW. Green, blue and red bars are averages over 3 different periods, before 1971, 1971-1990, and after 1991-2013, respectively. The percentage increase in potential minor flooding from the first to the third period is indicated for each station.

Figure 6. Acceleration in SLR [in mm y^{-2}, from *Ezer*, 2013] versus acceleration in minor flooding (in annual flood hours of 0.3m over MHHW per year per year); see text for details of the calculations. The data from Eastport is omitted due to its unusual high tide relative to other stations (Fig. 5). The linear regression line (in green), the correlation coefficient and the confidence level of the correlation are indicated.

528 **Figure 7**. The impact of tidal range on potential minor flooding (0.3 m above MHHW). The green, blue
529 and red markers and line fit represent the same 3 periods as in Fig. 5. The linear correlation coefficients
530 and statistical confidence level are indicated.
531
532 **Figure 8**. The number of extreme storm surge events versus the North Atlantic Oscillation (NAO)
533 Index. Green line and axis on the right: index of "high-water storm events" calculated by the average
534 number of storm surges per year in for each 5-year period. A storm event is defined as a year in which
535 water level reached 0.9 m over MHHW at least once at any station (i.e., each non-zero bar in the top
536 panels of figures 4a-4e is considered as a "storm event"). Multiple storms hitting the same location on
537 the same year is counted once, but impact of same storm at 2 different locations is considered as 2
538 impacts. Blue line and axis on the left: 5-year averaged NAO index. Each marker is located at the
539 beginning of a 5-year period. The vertical red dash lines indicate times where high/low peaks in storm
540 events coincide with low/high peaks in the NAO Index.
541 **Figure 9**. (a) Example of hourly water level in Sewells Point, Norfolk, from January to March, 2013.
542 Red, blue and green lines represent observed water level, tidal prediction and residual (observed-
543 prediction), respectively. (b) Daily Florida Current (FC) transport recorded by the cable data across the
544 Florida Straits. (c) The water level residual anomaly in Norfolk (green; in cm) and the FC transport
545 change (blue; in Sv change per day times $10 = 10^5$ m^3d^{-1}); the correlation coefficient and confidence
546 level of the correlation between sea level anomaly and FC change are indicated.
547


Eastport
Portland
Boston
Gulf of Maine
New York
Lewes
Mid-Atlantic Bight
Norfolk
Cape Hatteras
Atlantic Ocean
Wilmington
Charleston
Pulaski
South-Atlantic Bight
Key West
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat

Fig.1

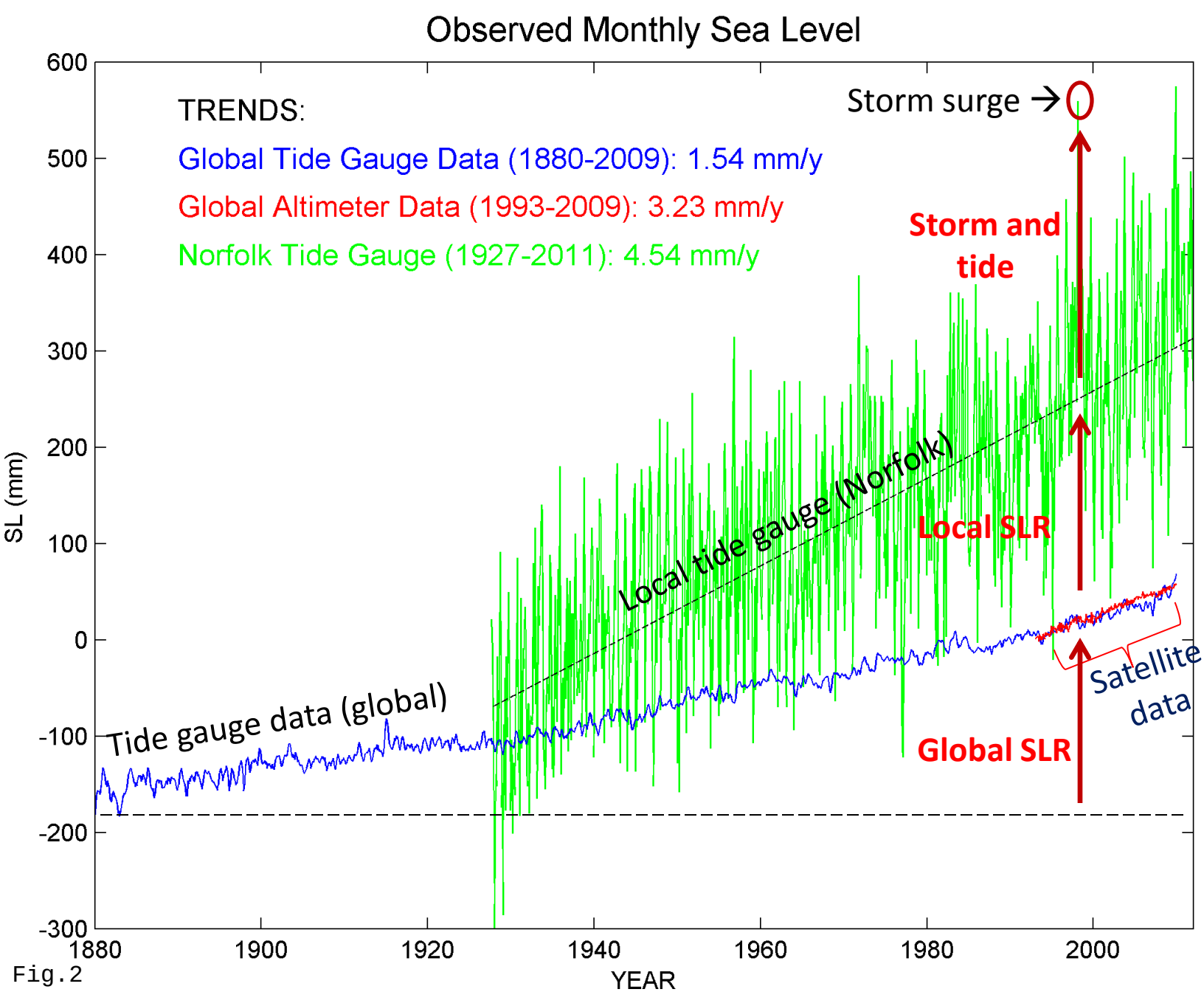
Observed Monthly Sea Level
TRENDS:
Global Tide Gauge Data (1880-2009): 1.54 mm/y
Global Altimeter Data (1993-2009): 3.23 mm/y
Norfolk Tide Gauge (1927-2011): 4.54 mm/y
Storm surge
Storm and tide
Local SLR
Global SLR
Satellite data
Local tide gauge (Norfolk)
Tide gauge data (global)
SL (mm)
YEAR
600
500
400
300
200
100
0
-100
-200
-300
1880
1900
1920
1940
1960
1980
2000

Fig.2

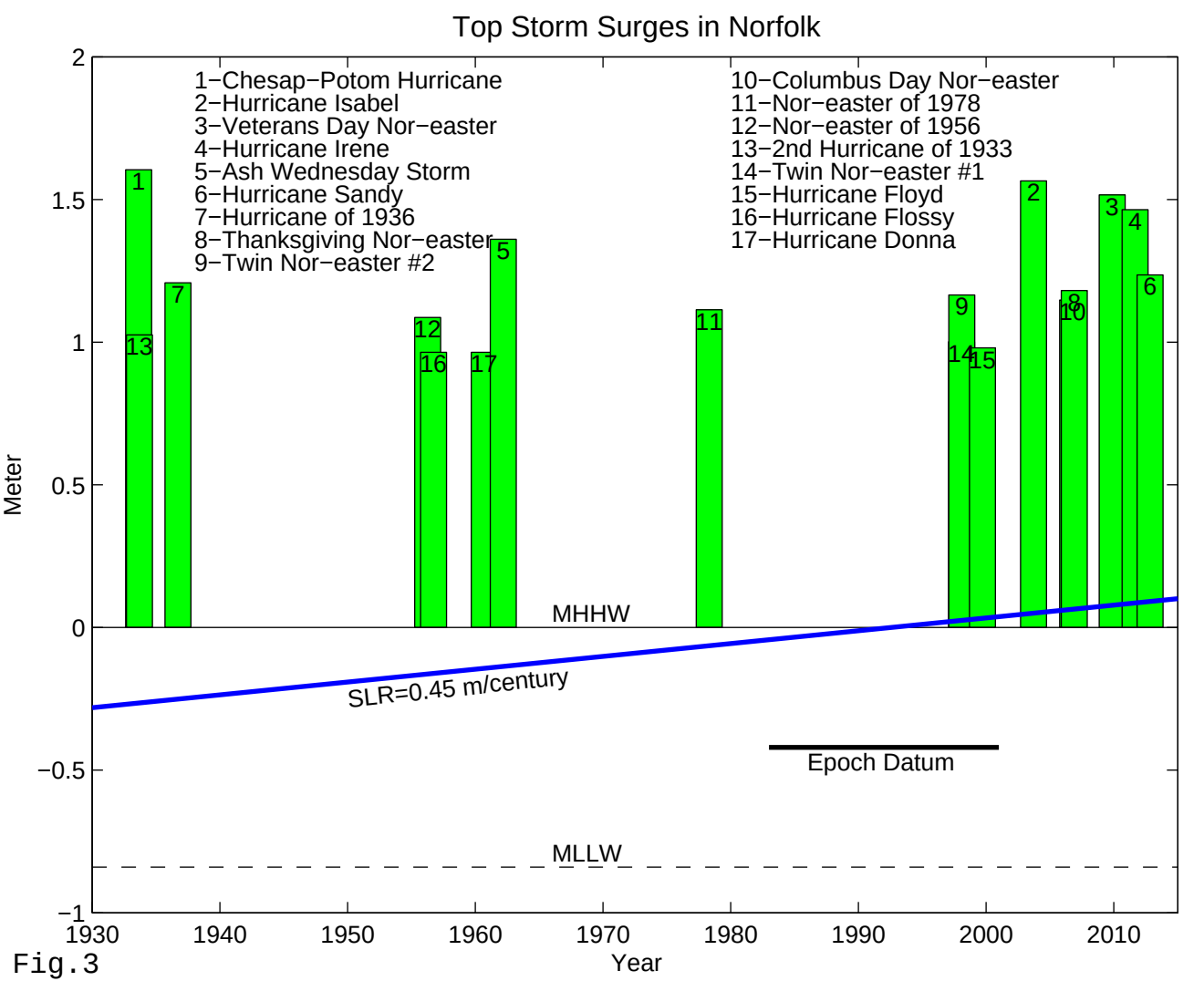
Top Storm Surges in Norfolk
1−Chesap−Potom Hurricane
2−Hurricane Isabel
3−Veterans Day Nor−easter
4−Hurricane Irene
5−Ash Wednesday Storm
6−Hurricane Sandy
7−Hurricane of 1936
8−Thanksgiving Nor−easter
9−Twin Nor−easter #2
10−Columbus Day Nor−easter
11−Nor−easter of 1978
12−Nor−easter of 1956
13−2nd Hurricane of 1933
14−Twin Nor−easter #1
15−Hurricane Floyd
16−Hurricane Flossy
17−Hurricane Donna
MHHW
SLR=0.45 m/century
Epoch Datum
MLLW
Meter
Year
2
1.5
1
0.5
0
−0.5
−1
1930
1940
1950
1960
1970
1980
1990
2000
2010

Fig.3

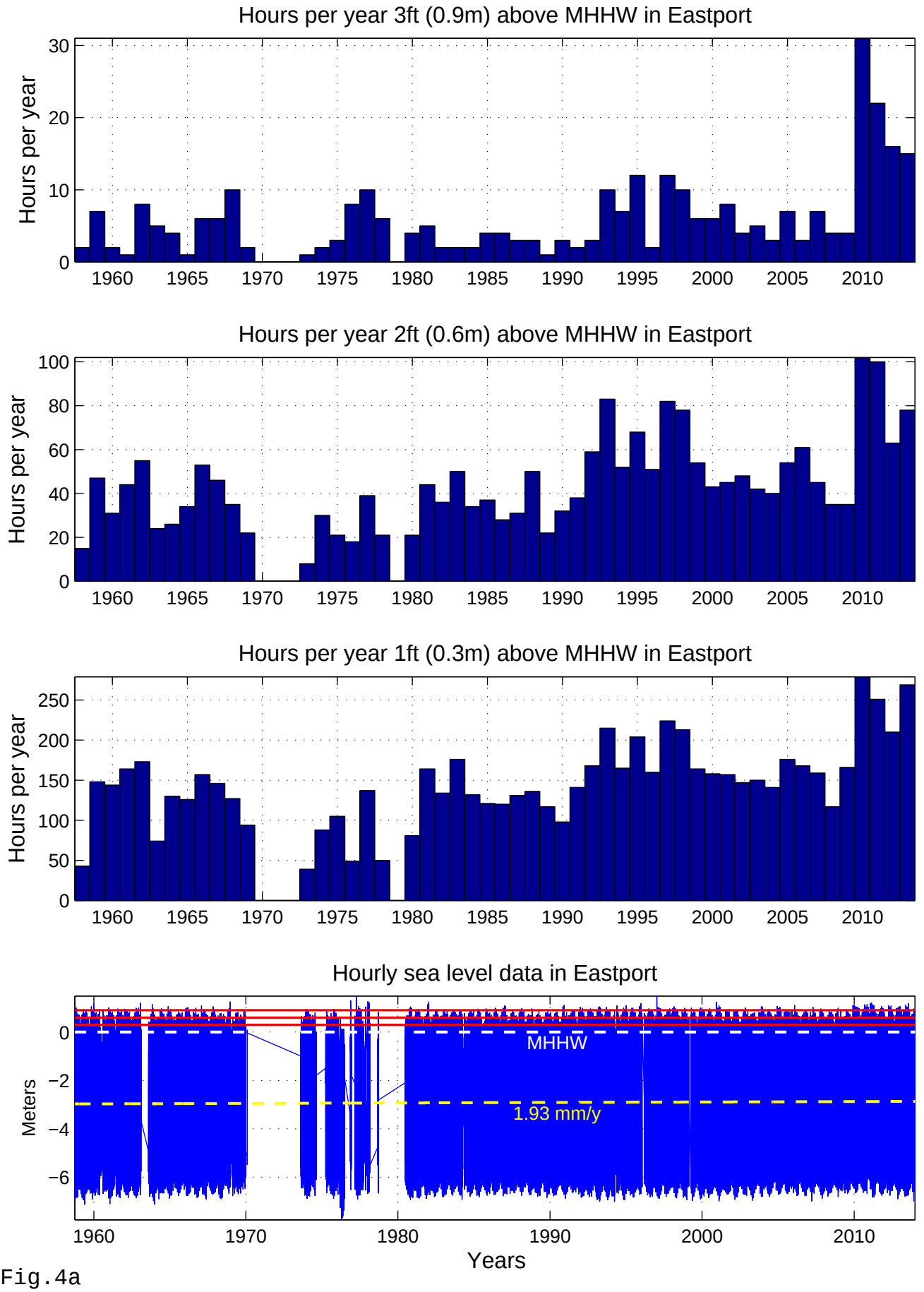
Hours per year 3ft (0.9m) above MHHW in Eastport
Hours per year
0
10
20
30
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Hours per year 2ft (0.6m) above MHHW in Eastport
Hours per year
0
20
40
60
80
100
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Hours per year 1ft (0.3m) above MHHW in Eastport
Hours per year
0
50
100
150
200
250
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Hourly sea level data in Eastport
Meters
0
−2
−4
−6
MHHW
1.93 mm/y
1960
1970
1980
1990
2000
2010
Years

Fig.4a

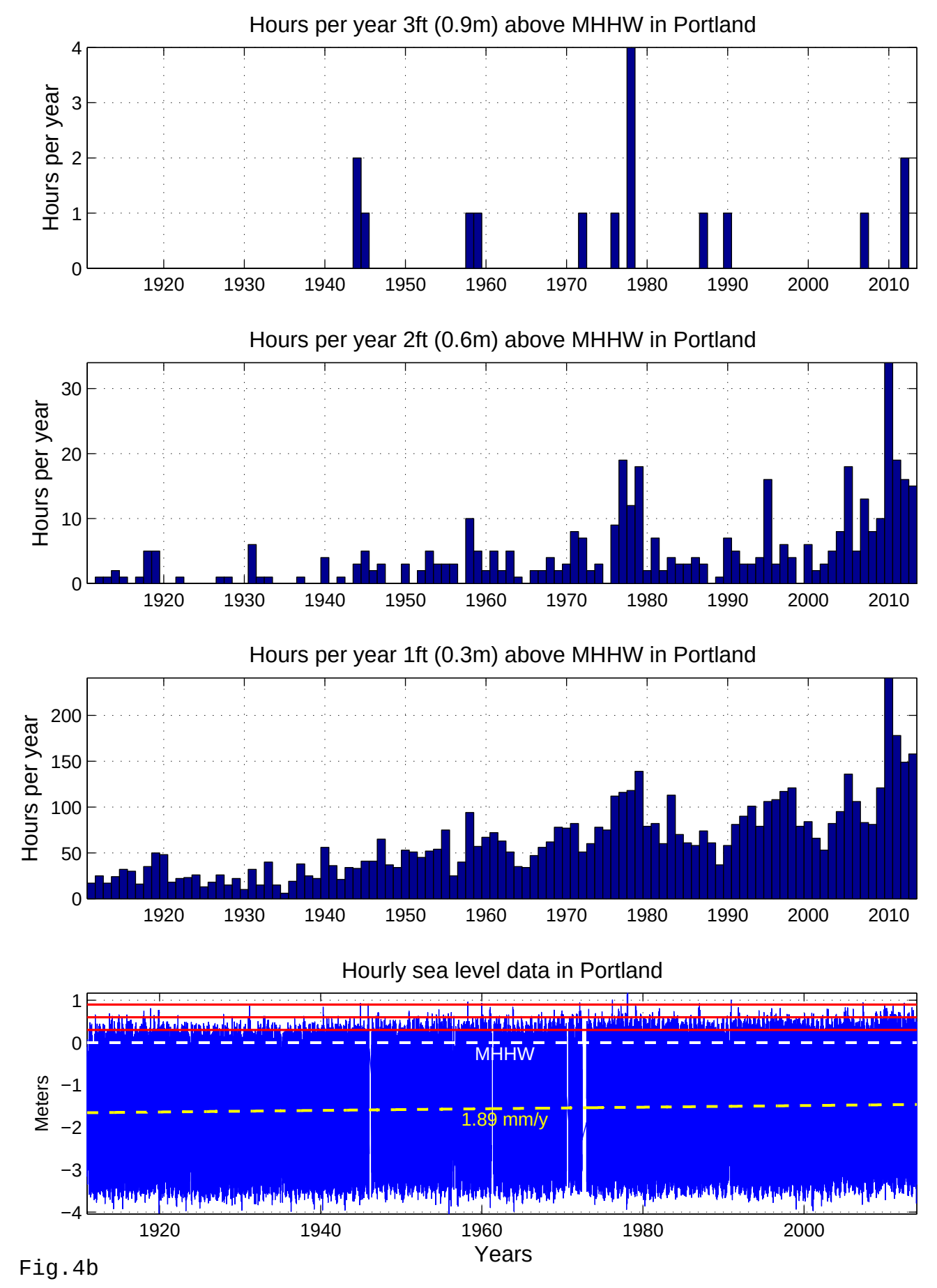
Hours per year 3ft (0.9m) above MHHW in Portland
Hours per year
0
1
2
3
4
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in Portland
Hours per year
0
10
20
30
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in Portland
Hours per year
0
50
100
150
200
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in Portland
Meters
1
0
−1
−2
−3
−4
MHHW
1.89 mm/y
1920
1940
1960
1980
2000
Years

Fig.4b

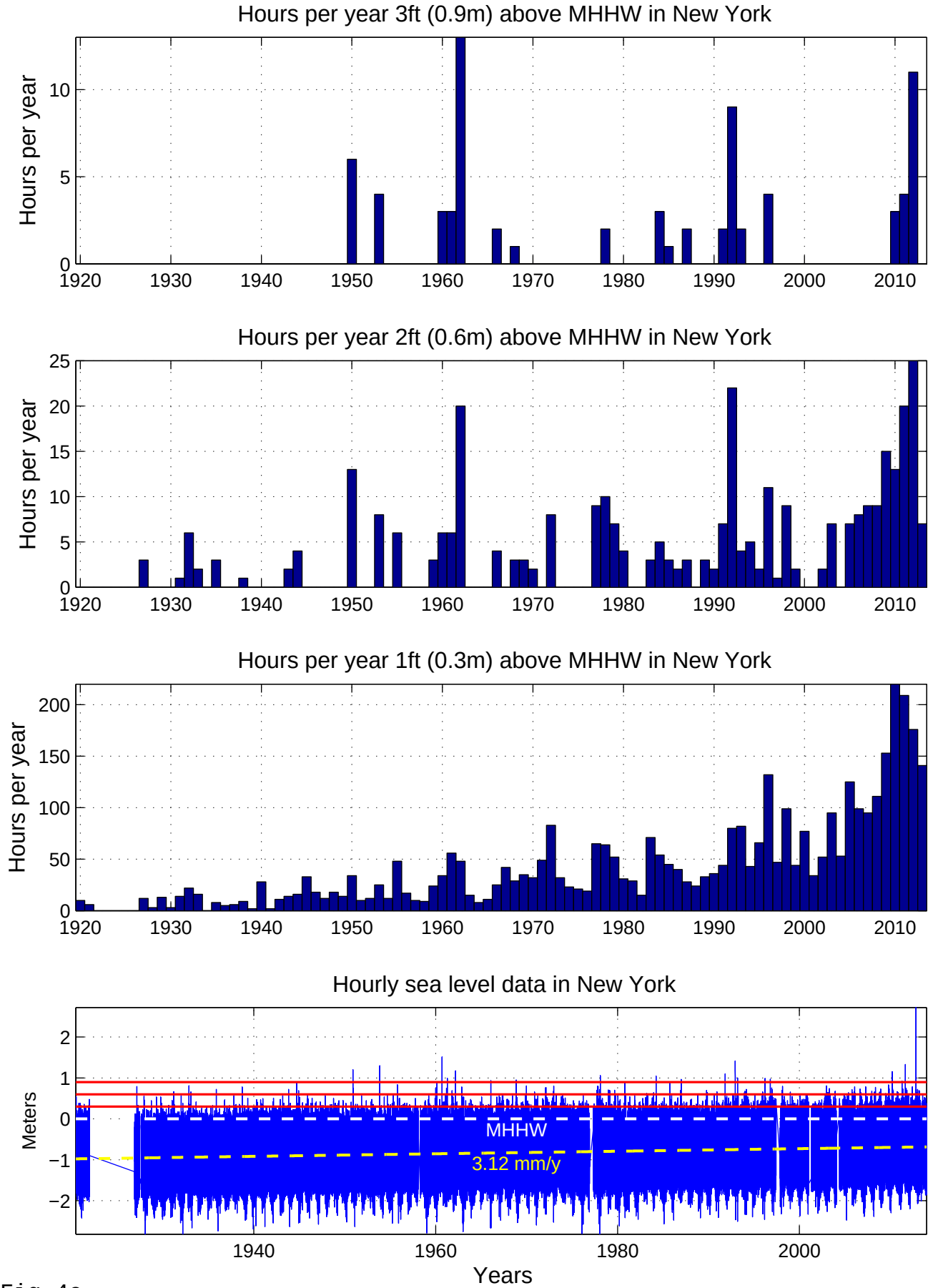
Hours per year 3ft (0.9m) above MHHW in New York
Hours per year
0
5
10
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in New York
Hours per year
0
5
10
15
20
25
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in New York
Hours per year
0
50
100
150
200
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in New York
Meters
2
1
0
−1
−2
MHHW
3.12 mm/y
1940
1960
1980
2000
Years

Fig.4c

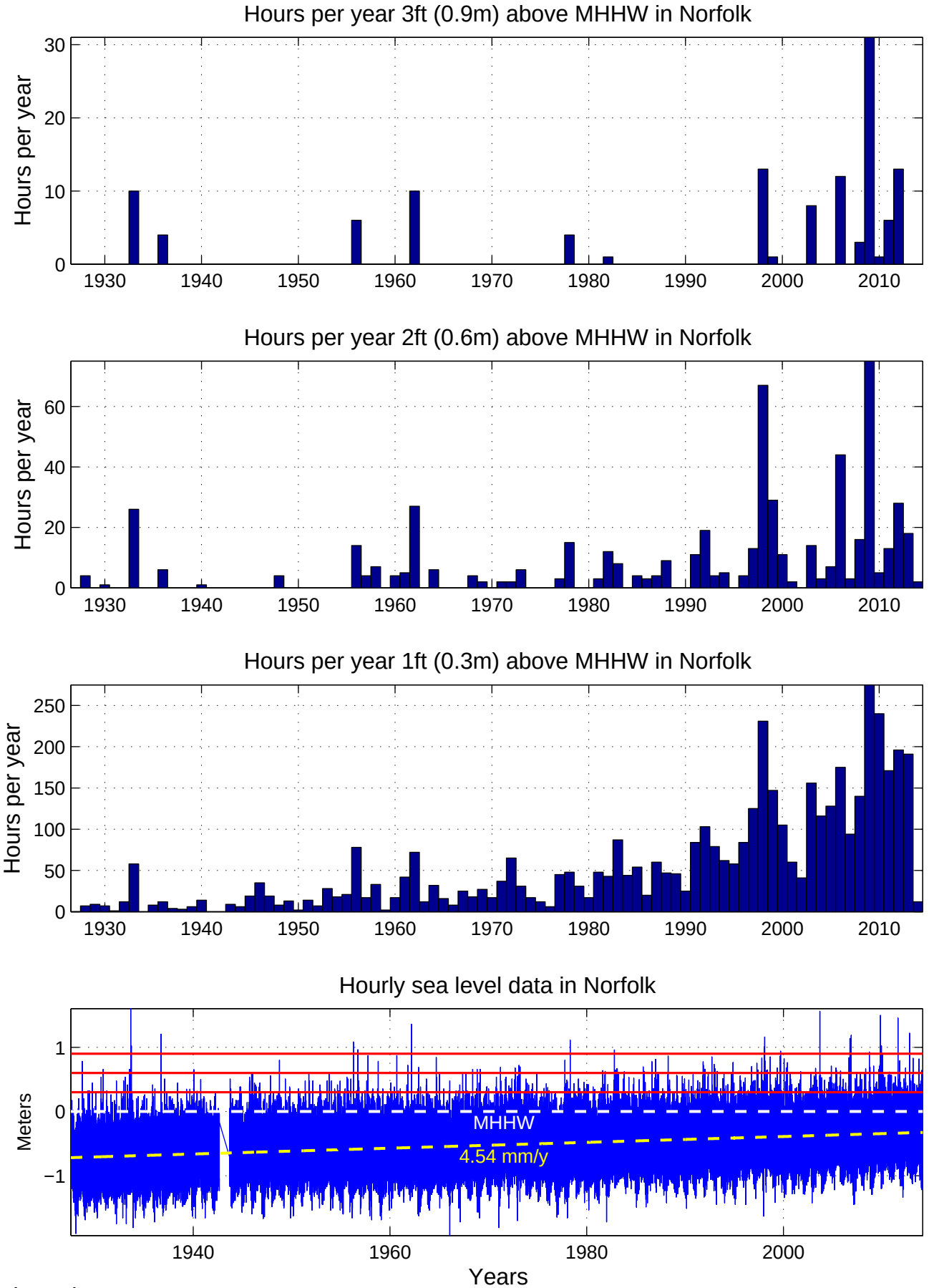
Hours per year 3ft (0.9m) above MHHW in Norfolk
Hours per year
0
10
20
30
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in Norfolk
Hours per year
0
20
40
60
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in Norfolk
Hours per year
0
50
100
150
200
250
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in Norfolk
Meters
1
0
−1
MHHW
4.54 mm/y
1940
1960
1980
2000
Years

Fig.4d

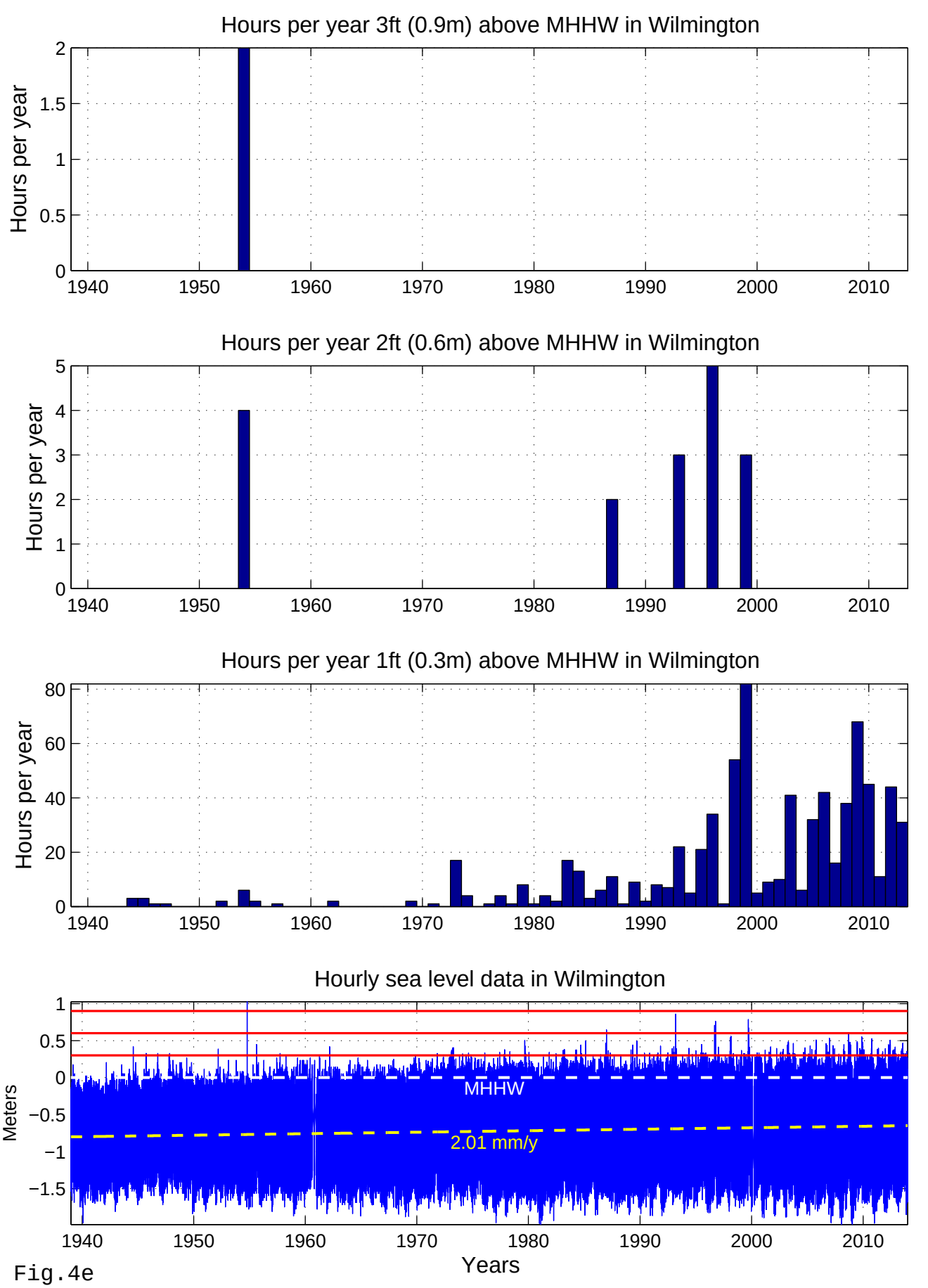
Hours per year 3ft (0.9m) above MHHW in Wilmington
Hours per year
0
0.5
1
1.5
2
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in Wilmington
Hours per year
0
1
2
3
4
5
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in Wilmington
Hours per year
0
20
40
60
80
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in Wilmington
Meters
1
0.5
0
−0.5
−1
−1.5
MHHW
2.01 mm/y
1940
1950
1960
1970
1980
1990
2000
2010
Years

Fig.4e

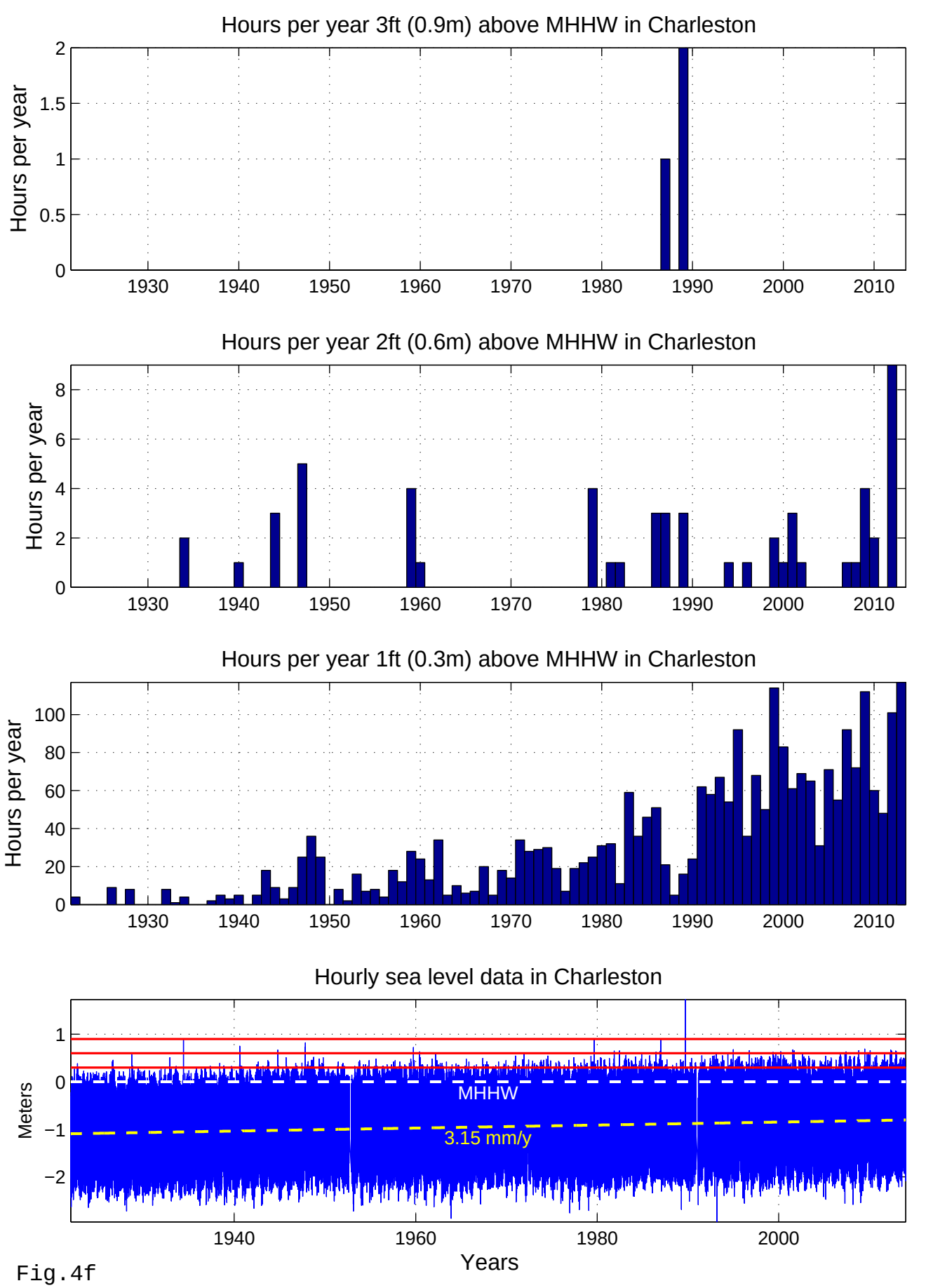
Hours per year 3ft (0.9m) above MHHW in Charleston
Hours per year
0
0.5
1
1.5
2
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in Charleston
Hours per year
0
2
4
6
8
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in Charleston
Hours per year
0
20
40
60
80
100
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in Charleston
Meters
1
0
−1
−2
MHHW
3.15 mm/y
1940
1960
1980
2000
Years

Fig.4f

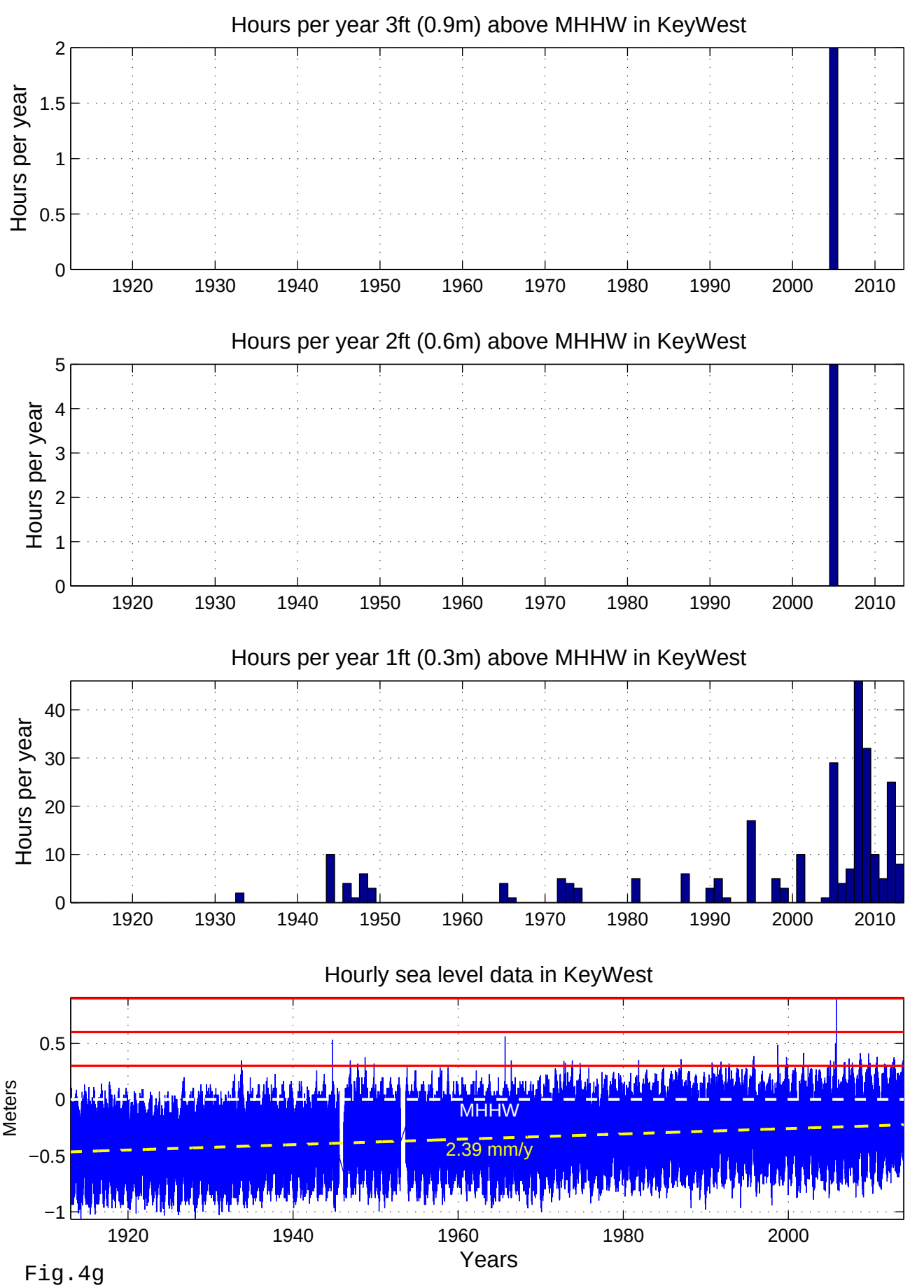
Hours per year 3ft (0.9m) above MHHW in KeyWest
Hours per year
2
1.5
1
0.5
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 2ft (0.6m) above MHHW in KeyWest
Hours per year
5
4
3
2
1
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hours per year 1ft (0.3m) above MHHW in KeyWest
Hours per year
40
30
20
10
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Hourly sea level data in KeyWest
Meters
0.5
0
−0.5
−1
MHHW
2.39 mm/y
1920
1940
1960
1980
2000
Years

Fig.4g

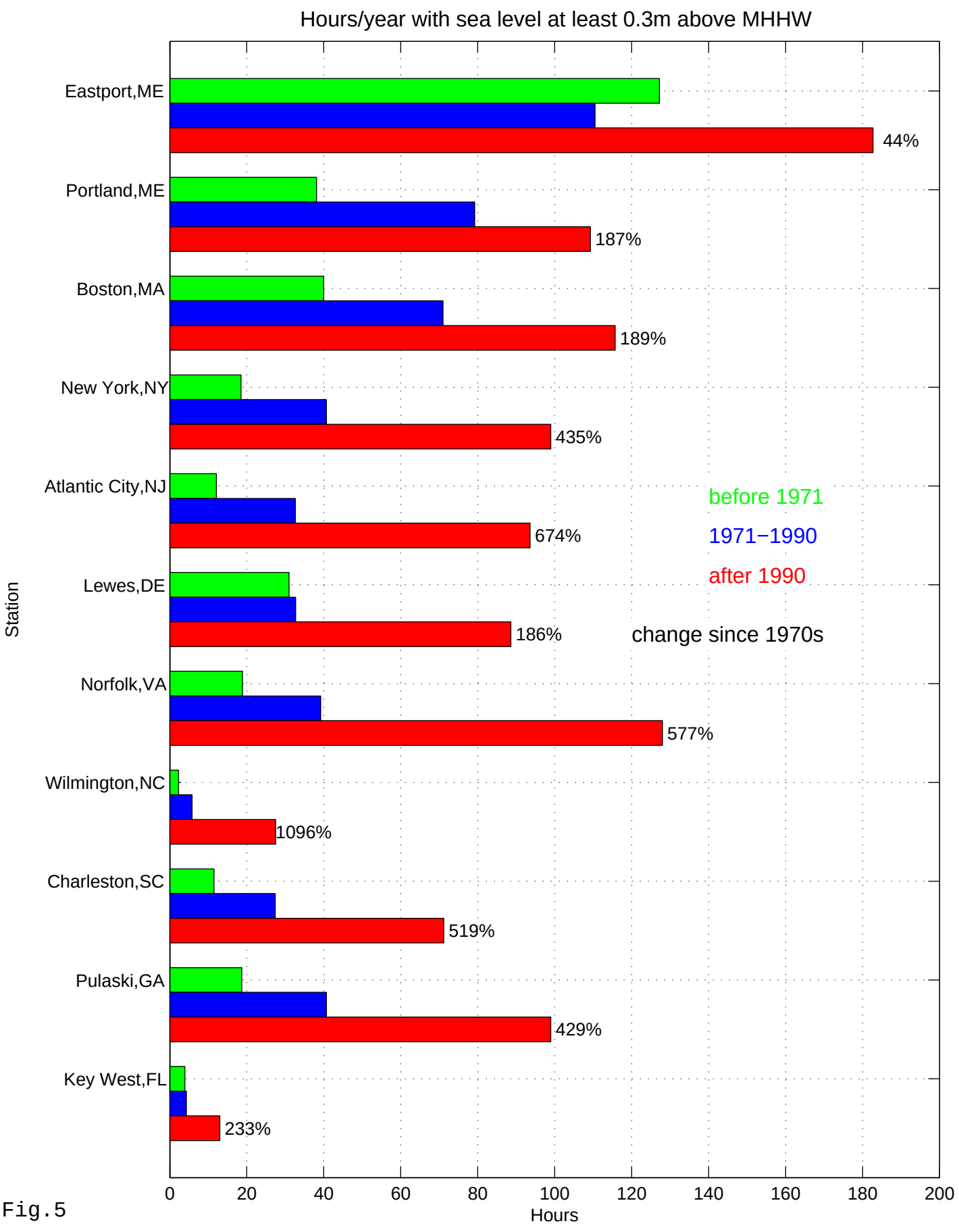
Hours/year with sea level at least 0.3m above MHHW
Eastport,ME
Portland,ME
Boston,MA
New York,NY
Atlantic City,NJ
Lewes,DE
Norfolk,VA
Wilmington,NC
Charleston,SC
Pulaski,GA
Key West,FL
44%
187%
189%
435%
674%
186%
577%
1096%
519%
429%
233%
before 1971
1971−1990
after 1990
change since 1970s
Station
0
20
40
60
80
100
120
140
160
180
200
Hours

Fig.5

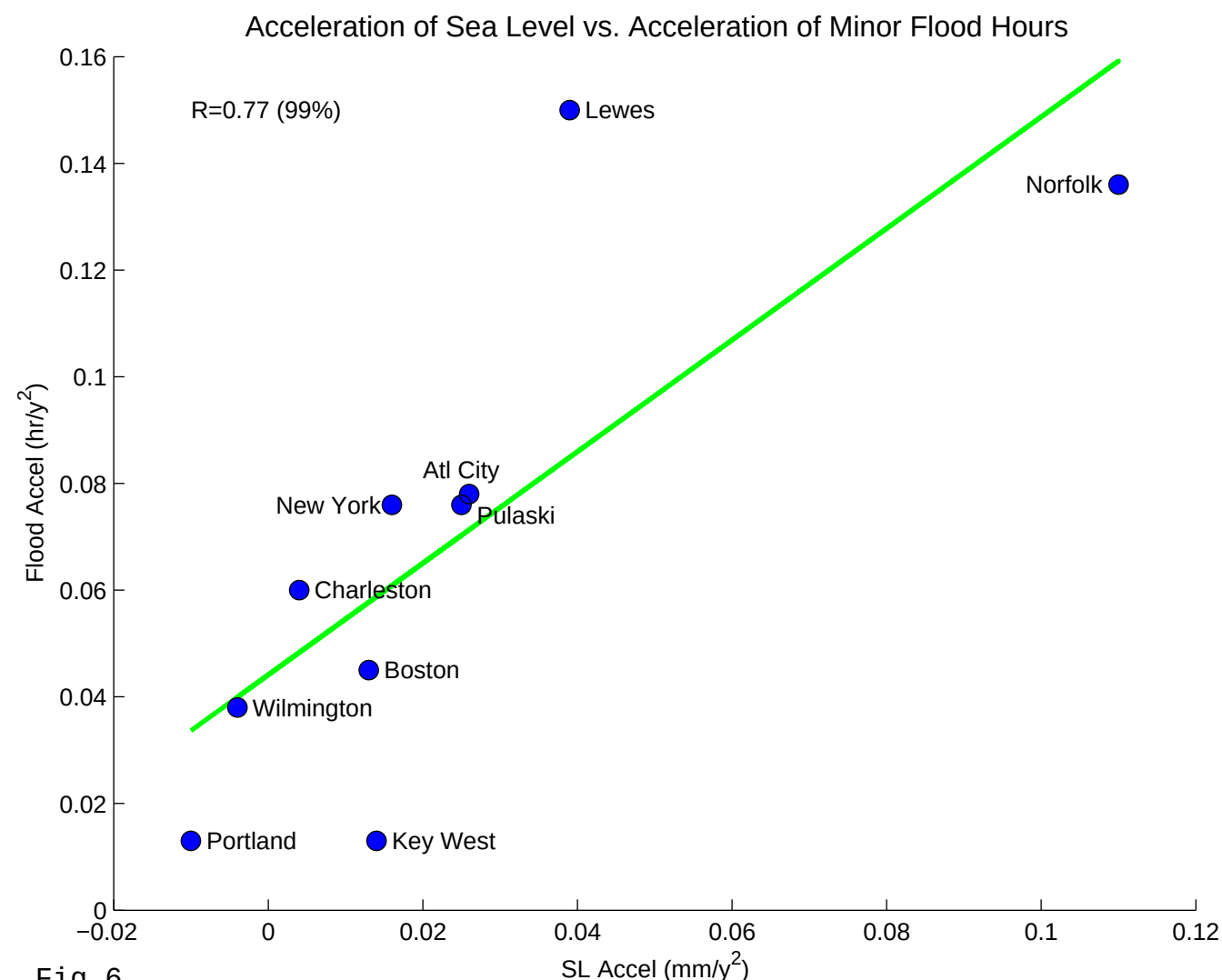
Acceleration of Sea Level vs. Acceleration of Minor Flood Hours
R=0.77 (99%)
Lewes
Norfolk
Atl City
New York
Pulaski
Charleston
Boston
Wilmington
Portland
Key West
Flood Accel (hr/y2)
SL Accel (mm/y2)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
0
0.02
0.04
0.06
0.08
0.1
0.12

Fig.6

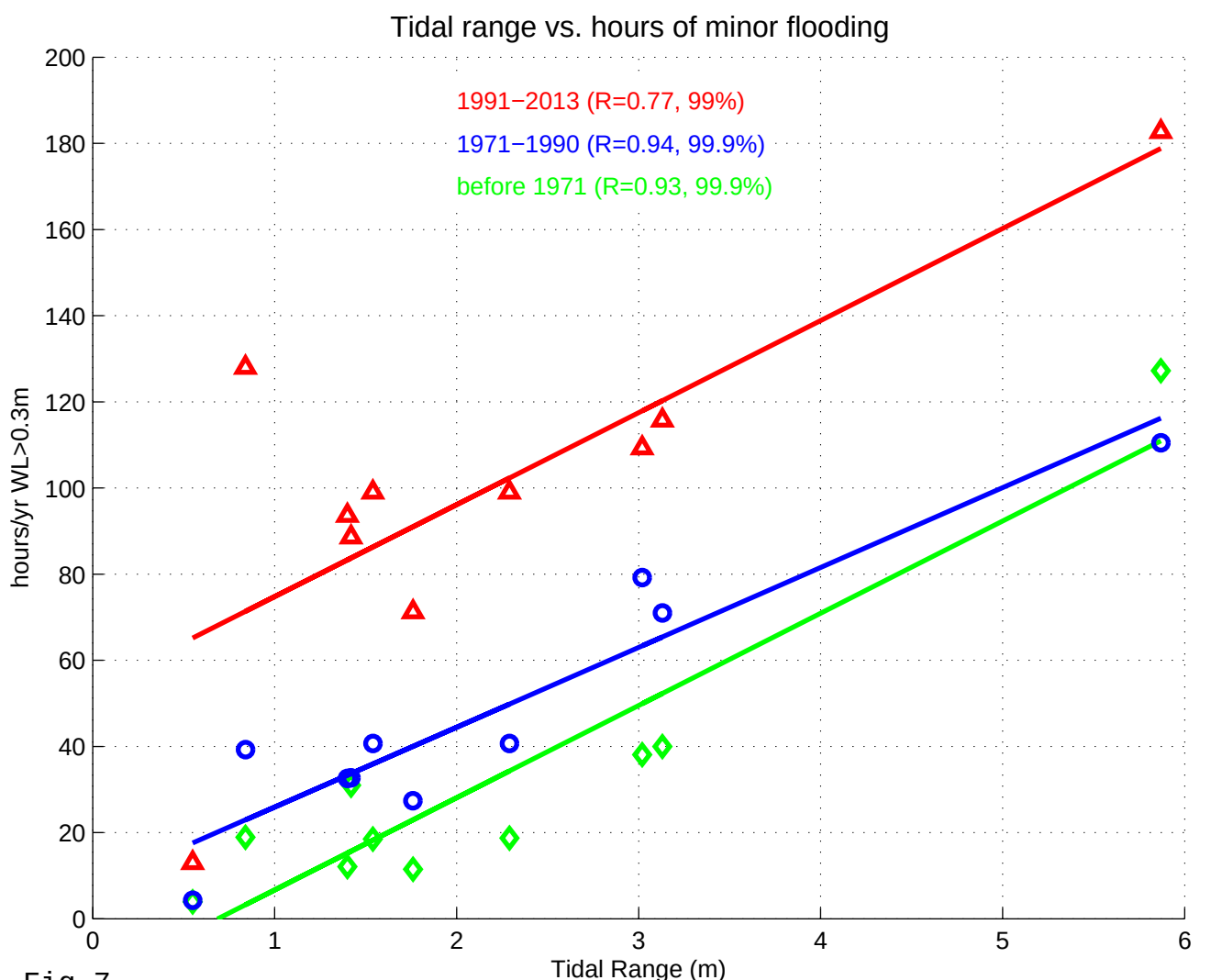
Tidal range vs. hours of minor flooding
1991−2013 (R=0.77, 99%)
1971−1990 (R=0.94, 99.9%)
before 1971 (R=0.93, 99.9%)
hours/yr WL>0.3m
Tidal Range (m)
0
20
40
60
80
100
120
140
160
180
200
0
1
2
3
4
5
6

Fig.7

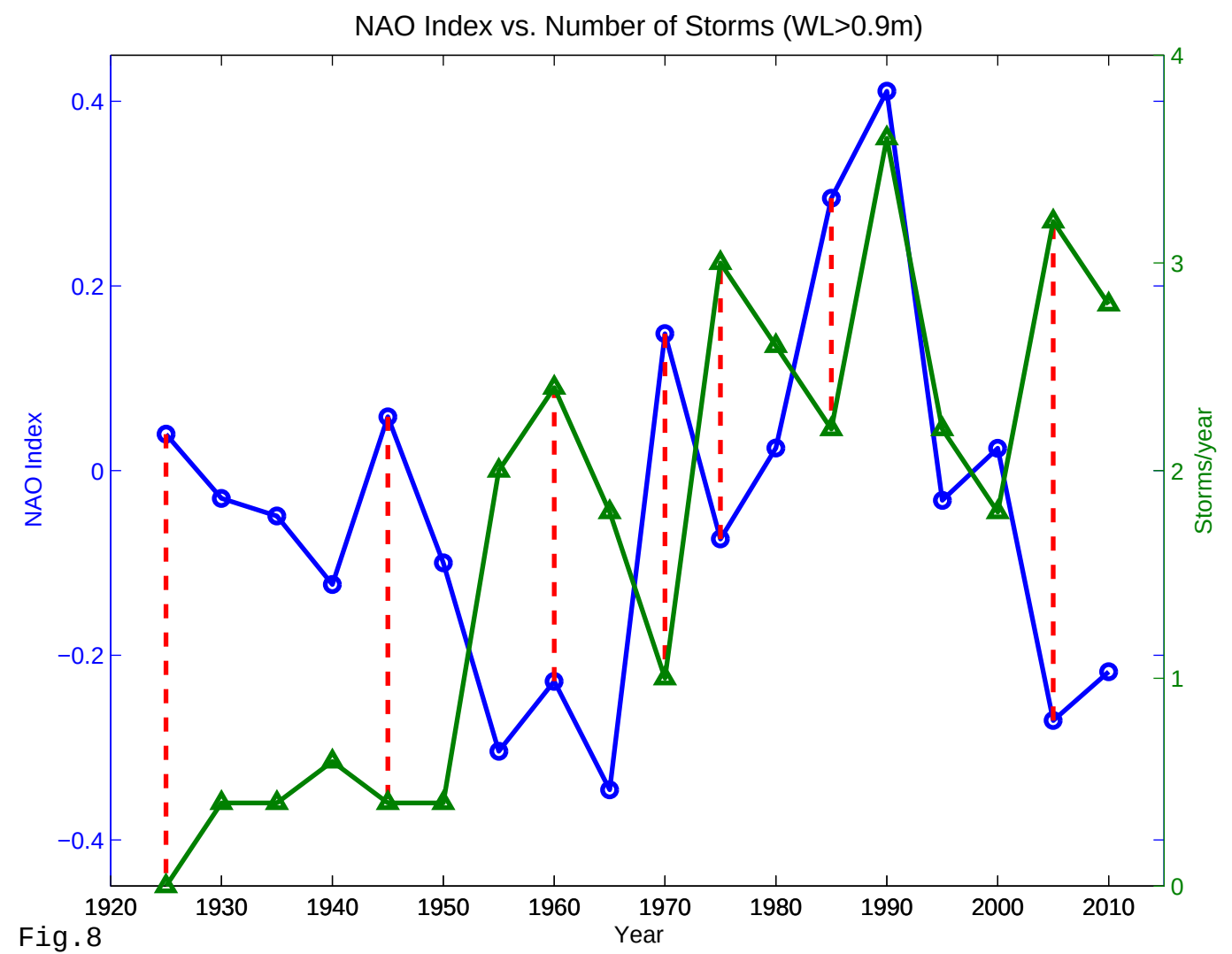
NAO Index vs. Number of Storms (WL>0.9m)
NAO Index
Storms/year
Year
0.4
0.2
0
−0.2
−0.4
4
3
2
1
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Fig.8

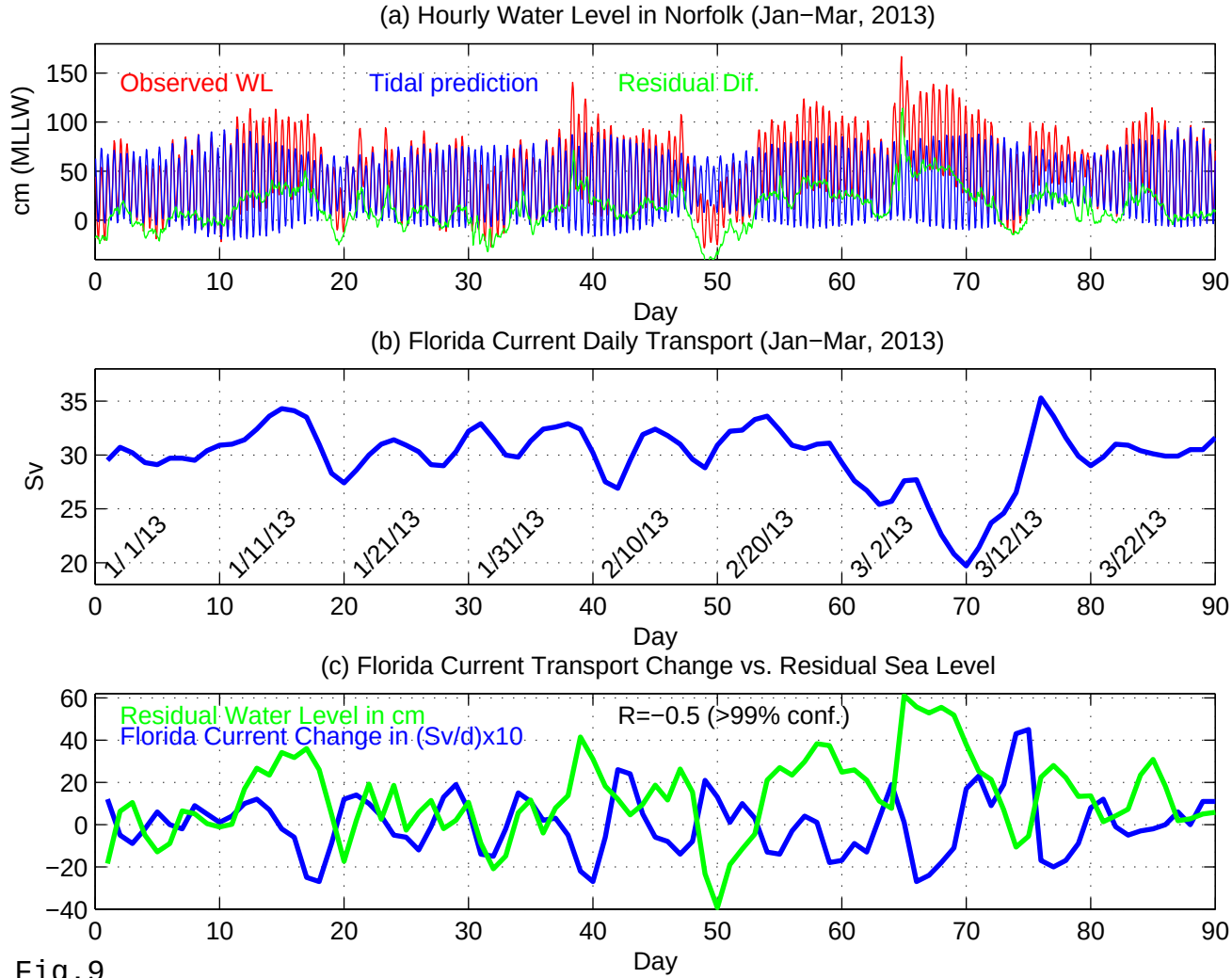
(a) Hourly Water Level in Norfolk (Jan−Mar, 2013)
Observed WL
Tidal prediction
Residual Dif.
cm (MLLW)
Day
(b) Florida Current Daily Transport (Jan−Mar, 2013)
Sv
1/ 1/13
1/11/13
1/21/13
1/31/13
2/10/13
2/20/13
3/ 2/13
3/12/13
3/22/13
Day
(c) Florida Current Transport Change vs. Residual Sea Level
Residual Water Level in cm
Florida Current Change in (Sv/d)x10
R=−0.5 (>99% conf.)
Day

Fig.9