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Sea Level Rise in Virginia – Causes, Effects and Response

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ABSTRACT

Sea level rise (SLR) along Virginia's coasts and around the Chesapeake Bay as measured by tide gauges is analyzed and discussed. It is shown that the SLR rates vary between one location to another and in most locations the rates increase over time (i.e., SLR is accelerating). The latest science of SLR is reviewed and the causes of the high SLR rates in Virginia are discussed. The impacts of land subsidence and ocean currents (changes in the Gulf Stream in particular) on sea level are especially notable and important for predicting future SLR in Virginia. The consequences of SLR on increased duration and severity of floods are demonstrated and potential responses are discussed.

1. INTRODUCTION

One of the environmental consequences of climate change that have been the most visible in Virginia is sea level rise (SLR). While sea level along the coasts of Virginia is slowly rising, the impacts of waves and storm surges increase as waters are pushed farther into previously unaffected coastal areas and low-lying streets. Both natural features such as marshes and barrier islands and also the built features such as docks, shipyards, tunnels, homes and hotels constructed along the shoreline are all affected. People living on the coast do not always recognize sea level rise itself, but they clearly see that there is more frequent flooding and that areas that were not flooded in the past are now becoming new flood-prone areas (Atkinson et al. 2013; Mitchell et al. 2013; Ezer and Atkinson 2014; Sweet and Park 2014).

The relative SLR rate (i.e., local water level relative to land) on Virginia's coasts is one of the highest of all U.S. coasts and the rate appears to be accelerating (Boon 2012; Ezer and Corlett 2012; Ezer 2013; Sallenger et al. 2012; Kopp 2013). SLR rates from tide gauges in Virginia over the past 10-30 years are ~4-6 mm/year, which are higher than the global mean SLR rate of ~1.7 mm/year over the past century as seen from tide gauges and even higher than the ~3.2 mm/year over the past 20 years as seen from satellite altimeter data (Church and White 2011; Ezer 2013). Note that SLR of 3 mm/yr is equivalent to about 1 foot/century. Relative SLR is primarily the result of three processes: 1. global SLR due to warming ocean temperatures and melting land ice, 2. local land subsidence (sinking) and 3. ocean dynamics. The impact of land subsidence and ocean dynamics is especially evident in Virginia. The Virginia coast is experiencing subsidence due to human activities such as groundwater extraction and historic geological processes (Boon et al. 2010; Eggleston and Pope 2013). Changes in the flow of offshore currents and the Gulf Stream in particular can result in water level anomalies and flooding (Sweet et al. 2009; Ezer and Atkinson 2014). Since much of Virginia's coastal areas are flat, small amounts of SLR can have dramatic impacts- increased flooding and coastal erosion, and altering marshes. Dealing with these issues requires knowledge on future SLR to design and plan accordingly.

2. CURRENT TRENDS IN SEA LEVEL RISE

Water level measurements from 13 locations around the Chesapeake Bay and the Virginia coast were analyzed (Fig. 1)- 8 stations with long records (~40-110 years) and 5 stations with shorter records (10-20 years). Water levels along the U.S. coast are measured by tide gauges maintained by the National Oceanic and Atmospheric Administration (NOAA) (Zervas 2009). Hourly data are obtained from the NOAA website (www.tidesandcurrents.noaa.gov); these data are used for calculations of potential flooding and storm surge impacts (Atkinson et al. 2013; Ezer and Atkinson 2014; Sweet and Park 2014). Monthly mean data for stations around the globe are archived by the Permanent Service for Mean Sea Level (PSMSL; www.psmsl.org; Woodworth and Player 2003). The PSMSL monthly data were used for the stations with long records, while the NOAA data were used for the stations with short records (Fig. 1); monthly means were calculated from hourly data before calculating SLR rates. Note that the statistical accuracy of calculating SLR rates from linear regression (fitting the data with a straight line, the slope of which represents the mean rate) depends on record length. For example, a record of 60 years would yield an error in SLR of less than ±0.5 mm/yr (at 95% confidence level), while a record of 30 years would have an error of less than ±1.5 mm/yr (Zervas 2009; Boon et al. 2010). However, there are only 2 tide gauge stations in Virginia with observations of over 60 years (86 years at Sewells Point in Norfolk and 62 years at Kiptopeake on the eastern shore). Therefore, long records from Maryland and short records from Virginia are analyzed as well.

The analysis of the long records is shown in Fig. 2 and that for the shorter records is shown in Fig. 3. Also shown (smooth black line in Fig. 2) are inter-annual variations after removing high-frequency variations using Empirical Mode Decomposition (EMD; Huang et al. 1998; Ezer and Corlett 2012). SLR rates are calculated for the past 30 years, and the 30 years before that, to see if the rates are constant or changing.

The results reveal several interesting findings:

1. Everywhere in the region sea level is rising faster than the global rates. However, SLR rates are not constant- they vary in time (due to climatic changes in the ocean) and in place (due to local and regional land subsidence, see discussion later). SLR is largest in the lower Chesapeake Bay (CBBT and Norfolk), and a little lower in the northern Bay (Baltimore, MD, and Washington, DC) and in the eastern shore peninsula (Kiptopeke and Wachapreague).
2. Sea level is persistently accelerating. The average SLR from 30-60 years ago (2.45 mm/y for 1953-1983; Fig. 2) has increased to a higher rate over the past 30 years (4.73 mm/y for 1983-2013; Fig. 2) and seems even faster in recent years (5.4 mm/y for 1996-2014; Fig. 3). The latter calculations for the short records are less accurate, but they are consistent with the same

increasing trend of the longer measurements. The findings here support previous studies that identified the Mid-Atlantic region as a “hotspot” for accelerated sea level rise (Boon 2012; Ezer and Corlett 2012; Sallenger et al. 2012; Ezer 2013), but provides more details for Virginia’s coasts than previous studies which focused only on long records.

3. There are coherent inter-annual variations (smooth black lines in Fig. 2) that can cause a prolong periods (months to several years) of anomalously high water; such periods are seen for example around 1975 and 2009. These two periods have similar weakening GS (Ezer 2015), increased flooding (Sweet 2009; Mitchell et al. 2013; Sweet and Park 2014; Ezer and Atkinson 2014) and increased coastal erosion (Theuerkauf et al. 2014). The relation between these water level anomalies and changes in ocean currents will be discussion later.

3. CAUSES OF LOCAL SEA LEVEL RISE

Most discussions of SLR are about the average rise of the global sea level measured by satellites and tide stations (Church and White 2011); the global SLR is mostly attributed to increase in the volume of the ocean due to land-ice melting and thermal expansion due to warming of ocean waters. However, the rate of local SLR can vary significantly from place to place (Ezer 2013). The rate of local SLR can also change more rapidly over time than global SLR does due to decadal, multi-decadal and other long-term changes in ocean circulation (Ezer 2015). Below, we will thus discuss two aspects that have particularly large impact on local sea level in Virginia.

3.1 Land subsidence

Local SLR is the change in sea level relative to the coast. Thus, if the land is sinking (i.e., land subsidence) or rising, the relative sea level can rise faster or slower than the global SLR rate. It turns out that much of the Virginia coast is sinking; there are two main reasons for this subsidence, Glacial Isostatic Adjustment (GIA) and underground water extraction, and they are explained below. Note however, that measuring the exact rate of subsidence at every point is difficult; even the modern Global Positioning System (GPS) that accurately measures land movement has only very few stations in Virginia with relatively short records of only a decade or so (Eggleston and Pope 2013).

The first factor affecting subsidence in Virginia is GIA, which is caused by the earth responding to the disappearance of the Laurentide ice sheet a few tens of thousands years ago. The earth crust is rising in the northern regions of New York and Quebec while sinking occurs in the regions south of New York, including Virginia (Sella et al. 2007). GIA is estimated to cause a subsidence of about 0.6-1.8 mm/yr (1 mm/yr ~ 0.3 feet per century) (Engelhart et al. 2009; Engelhart and Horton 2012). Note however, that subsidence due to GIA is a very slow process over thousands of years, so it cannot contribute to the recent acceleration in SLR seen in tide gauge data. The Chesapeake Bay Impact Crater (Powars and Bruce 1999) affected the geology of the region as well, but is thought to contribute little to the regional subsidence rates (summarized in Eggleston and Pope 2013).

The second factor affecting subsidence in Virginia is groundwater withdrawal, which is a more local effect than GIA. A recent USGS report provided important new information on the subsidence rates related to groundwater withdrawals near two Virginia cities (Eggleston and

Pope 2013): Franklin and WestPoint (Fig. 4). Highest subsidence rates at those locations were 3.8 and 4.8 for West Point and Franklin respectively. The extent of this effect extends throughout the lower Bay region with rates of 2.0 to 2.8 in the heavily populated Virginia Beach and Norfolk areas. So ground water pumping can cause a subsidence rate between 2.0 and 4.8 mm/yr and contribute to the higher SLR rates seen in Fig. 2 and Fig. 3. Updating the subsidence maps using new data from GPS and other sources is needed and is an ongoing process.

3.2 Ocean dynamics

One of the least understood contributions to SLR is the impact of offshore ocean currents, which can result in spatial variations of SLR along the coast (Ezer 2013) and temporal variations in SLR rates that make predictions more challenging. In particular, recent research focused on the causes for a "hotspot" of accelerated sea level rise along the U.S. East Coast north of Cape Hatteras, North Carolina (Boon 2012; Ezer and Corlett 2012; Sallenger et al. 2012; Kopp 2013; Ezer 2013; Ezer et al. 2013). These studies suggest that the acceleration in SLR may be a dynamic response to climate-related slowdown in ocean circulation, and in particular, weakening of the Atlantic Meridional Overturning Circulation (AMOC; McCarthy et al. 2012; Smeed et al. 2014). The Gulf Stream (GS) is a crucial part of AMOC (as well as wind-driven and density-driven components, see McCarthy et al. 2012, for details), and recent studies show that when the GS weakens sea level rises along the U.S. East coast (Ezer et al. 2013; Ezer 2013, 2015). The idea that the GS can impact sea level along the U.S. East Coast is not new (Montgomery 1938; Blaha 1984; Maul et al 1985), but the process is still not fully understood despite recent observations and models that captured the GS-SLR connections. The basic mechanism is as follows. Sea level is tilted across the GS (i.e., sea level is ~1-1.5 m lower on the onshore side of the GS than the offshore side) and this tilt depends on the speed of the current (this is called "geostropic" balance), therefore changes in the path and strength of the GS can cause variations in sea level and they evidently do so (Ezer 2001, 2013, 2015; Sweet et al. 2009; Ezer et al. 2013). Climatic changes in large-scale wind patterns may also contribute to coastal sea level anomalies observed along the U.S. East Coast (Woodworth et al. 2014), either directly, or by influencing the Gulf Stream flow. These studies found that inter-annual variations in sea level (such as those seen in Fig. 2) are correlated with changes in the GS flow.

Anomalously higher water levels and increased flooding often happens during periods when the GS is weakening (Sweet et al. 2009; Ezer et al. 2013; Ezer and Atkinson 2014). The impact of the GS on sea level can be seen not only on inter-annual and longer time scales, but also on daily, weekly and monthly basis, as seen in Fig. 5. The observed hourly water level in Norfolk (Fig. 5a) is apparently influenced by the GS flow, which is measured (Meinen et al. 2010) by a cable across the Florida Straits (Fig. 5b). For example, at the first half of March, 2014, there were two periods (days 65 and 75 in Fig. 5) when water level anomaly was ~0.5 m (~1.5 ft) above the tidal prediction and at the same time the GS transport declined by ~10% (-3 Sv compared to mean flow of ~30 Sv; Sv is 1 million cubic meter per second). How to use this information on changing ocean currents to improve prediction of coastal sea level is a great challenge. Currently, storm surge computer models used by scientists at NOAA and other institutions, are mainly driven by local wind, so they neglect the impact on sea level from offshore changes in ocean currents.

3.3 Summary of estimated contributions to SLR (positive=increase SLR)

SLR Process	Rate mm/y	Reference and notes
Subsidence – GIA	0.6-1.8 mm/yr	USGS; Engelhart & Horton (2012); Miller et al. (2013)
Subsidence – Ground water pumping	2-4.8 mm/yr (location dependent)	USGS; Eggleston & Pope (2013)
Subsidence – Impact crater	Probably small/unknown	USGS; Powars and Bruce (1999); Boon et al. (2010)
Ocean circulation	±5-10 mm/yr (includes decadal variations)	Ezer (2013); Ezer et al. (2013)
Global scale thermal expansion and land ice melt	1.7-3.2 mm/yr (larger recent rates)	Church and White (2011); Ezer (2013); many others.

4. IMPACT OF SEA LEVEL RISE

The impact of sea level rise can already be felt in many low-lying Virginia communities (Mitchell et al. 2013; Atkinson et al. 2013) and in particular, on the streets of Norfolk (Fig. 6). The frequency and duration of minor tidal flooding has increased dramatically in recent decades along many U.S. coasts (Ezer and Atkinson 2014; Sweet and Park 2014). This is sometimes called "nuisance" flooding, which is not catastrophic, but causes some streets to be covered with water, blocking traffic and preventing residence from reaching work, hospitals, etc.; in Norfolk for example, this level is about 30-50 cm, or about 1 foot or more above Mean Higher High Water (MHHW). For example, before 1980 Norfolk experienced in average only ~30 hours of minor flooding per year and a year with flooding of more than 50 hours occurred only once every 10 years (black bars in Fig. 6). However, since the 1990s, annual flooding of 100-200 hours happens almost every year. In the past, a hurricane or strong nor'easter storm was needed to cause flooding, while today with the additional sea level rise a threshold is reached such that even a small weather event or a regular Spring Tide (during full or new moon) can cause flooding. Big storms, such as Sandy in 2012, will cause today much more damage than past storms that happened when sea level was lower.

Projections of future flooding are estimated here from past statistics by using randomly sampled past water level anomalies from the hourly data plus prescribed SLR rates. Two different scenarios are shown in Fig. 6, a very conservative SLR rate of 4 mm/y (lower than today's rate in Norfolk) in gray and a larger SLR rate of 8 mm/y in white (assuming an increase in SLR rate over today's rate). The projections demonstrate very dramatic impact of future SLR on the frequency of nuisance floods. By 2050 the annual hours of minor floods will increase from ~200 hours in 2013 to ~500 hours for the low SLR scenario and up to ~1300 hours for the high SLR case (~4 full days of floods per month). This means for example, that many roads along the water will not be passable for long periods of time so people living in some neighborhoods will have to find alternative roads and parking slots away from those streets. The impact of major storms on inundation (not shown) will also increase dramatically.

Various initiatives, from local-, city- and state-level, have been taken already as a response to increased flooding in Virginia in general and in the streets of Norfolk in particular. For example, Old Dominion University (ODU) established in 2010 the Climate Change and Sea Level Rise Initiative (http://www.odu.edu//research/initiatives/ccslri/), which involves education, research and outreach activities in climate studies and the developments of mitigation and adaptation strategies. Virginia Sea Grant, ODU and the Hampton Roads Planning District Commission (HRPDC) plan and host quarterly meetings of the Flood Adaptation Forum, which bring together professionals in adaptation including local municipal government staff, scientific experts, private sector engineers, state and federal agency staff and other stakeholders. The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project (http://www.centerforsealevelrise.org/) was formed to create a plan for coordination across federal, state and local government agencies. Residents in flood-prone streets in the Hampton Roads region can receive flood warning from a local network and from a new Sea Level Rise App for smart phones (developed by the Norfolk-based, environmental non-profit group Wetlands Watch). Houses and roads in flood-prone streets in Norfolk have already been raised, and flood gates and walls protect the business district of downtown Norfolk, but other areas need protection, so various means for mitigation and adaptations are under consideration.

5. SUMMARY

Sea level will likely continue to rise for decades to come, and local rates in Virginia may continue to rise even faster than the global SLR. Studies need to better understand and quantify the contribution from land subsidence and ocean dynamics using combination of measurements, theory and models. Because of the flat topography of the Virginia coasts and the large population living around the Chesapeake Bay and along the Atlantic coast, the impacts of future sea level rise need to be addressed. The SLR into the far future, say 100 years from now, is predicted by global scales climate models (see for example the reports from the Intergovernmental Panel on Climate Change, IPCC) and has quite large uncertainties. However, local SLR in Virginia for the relatively short term, say 10-30 years, can be estimated from the statistics of the past based on tide gauge stations (Boon 2012; Ezer and Corlett 2012). Since future SLR is predicted to be at least as fast as the current rates (and likely faster), a rough estimate of about 1.5-2.5 ft/century for our region is not unreasonable, based on the data analyzed here. If the Gulf Stream slow down continues the rates may be considerably higher.

ACKNOWLEGEMENTS

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Figure Captions

Fig. 1. Map of the Chesapeake Bay region and location of tide gauge stations. Long and short records are indicated and analyzed separately in figures 2 and 3, respectively.

Fig. 2. Monthly sea level in the Chesapeake Bay for stations with long records (from 40 years in Chesapeake Bay Bridge Tunnel, CBBT, to 110 years in Baltimore). Inter-annual variations are shown by black heavy lines and linear trends by dash lines. SLR rates in mm/yr are shown for two 30-year periods.

Fig. 3. Monthly sea level and trends as in Fig. 3, but for tide gauge stations in Virginia with relatively short records. The SLR rates in mm/y are listed under the station names.

Fig. 4. Land subsidence in Virginia (negative values represent land sinking in mm/year) from 1940 to 1971. The fastest sinking sites are centered near West Point and Franklin townships, where large paper mills extract underground water from wells. The bull-eye feature in Kiptopeke is near the center of the Impact Crater (source: U.S. Geological Survey).

Fig. 5. Examples of the influence of the Gulf Stream on water level in Norfolk. (a) Tide prediction (gray) and observed (black) water level; water level of ~0.3m above Mean Higher High Water (MHHW) are prone to flooding. (b) Observed flow of the Florida Current (upstream part of the GS) from cable measurements (www.aoml.noaa.gov/phod/floridacurrent/). Transport is in Sverdrup units (1Sv= million cubic meter per second). (c) Water level anomaly (solid) and changes in the GS flow (dash; in Sv/day) are anti-correlated. An example of water level anomaly that resulted in street flooding in mid March is indicated.

Fig. 6. Hours per year that minor flooding starts in the streets of the historic Hague district of Norfolk, VA, when water level is ~1 ft (30 cm) above MHHW. Black bars are based on past observations of the tide gauge at Sewells Point; gray and white bars are estimated projections until 2050 for future SLR rates of 4 and 8 mm/y, respectively.

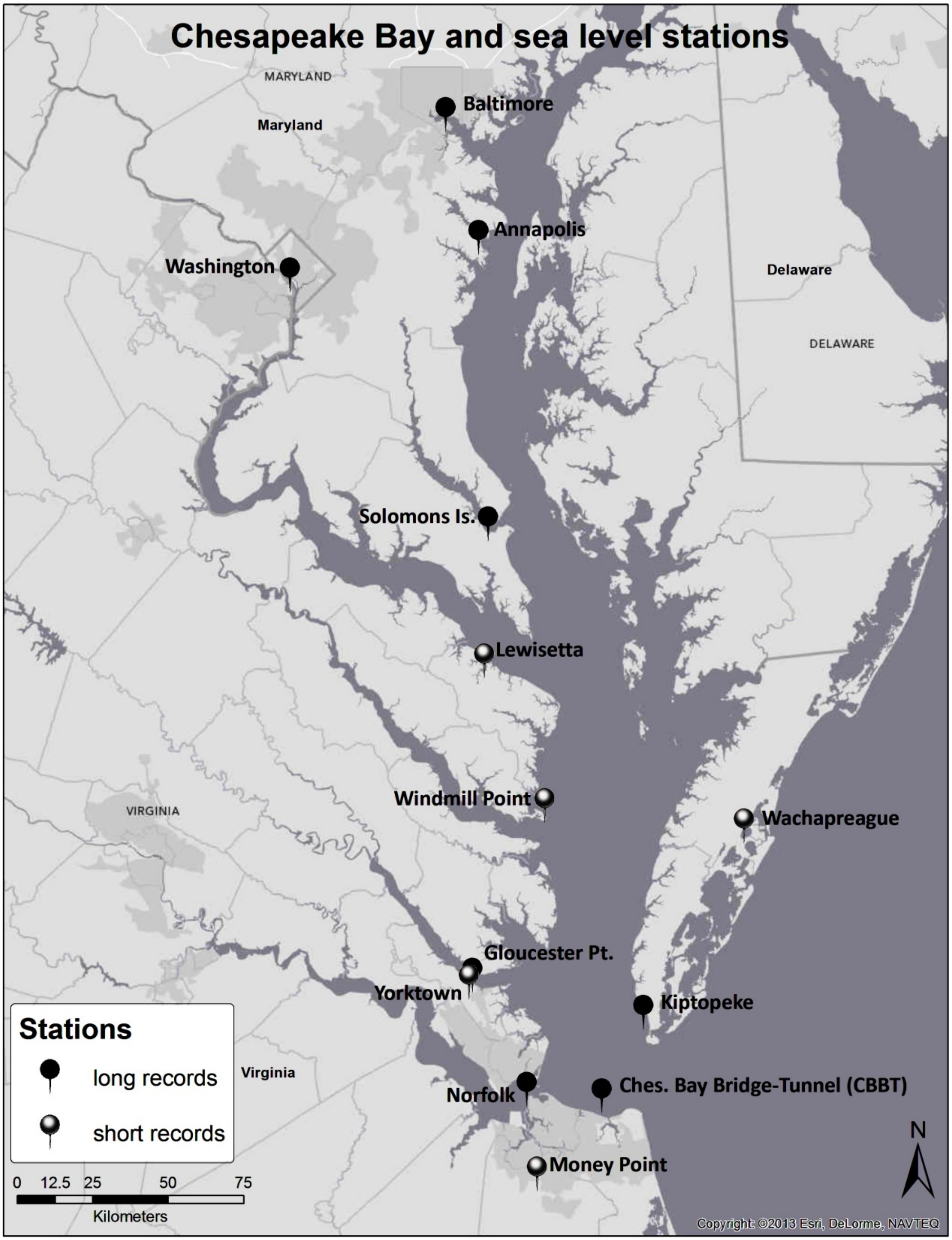

Chesapeake Bay and sea level stations
MARYLAND
Maryland
Baltimore
Annapolis
Washington
Delaware
DELAWARE
Solomons Is.
Lewisetta
VIRGINIA
Windmill Point
Wachapreague
Gloucester Pt.
Yorktown
Kiptopeke
Stations
long records
short records
Virginia
Norfolk
Ches. Bay Bridge-Tunnel (CBBT)
Money Point
N
0 12.5 25 50 75
Kilometers
Copyright: ©2013 Esri, DeLorme, NAVTEQ

Fig. 1

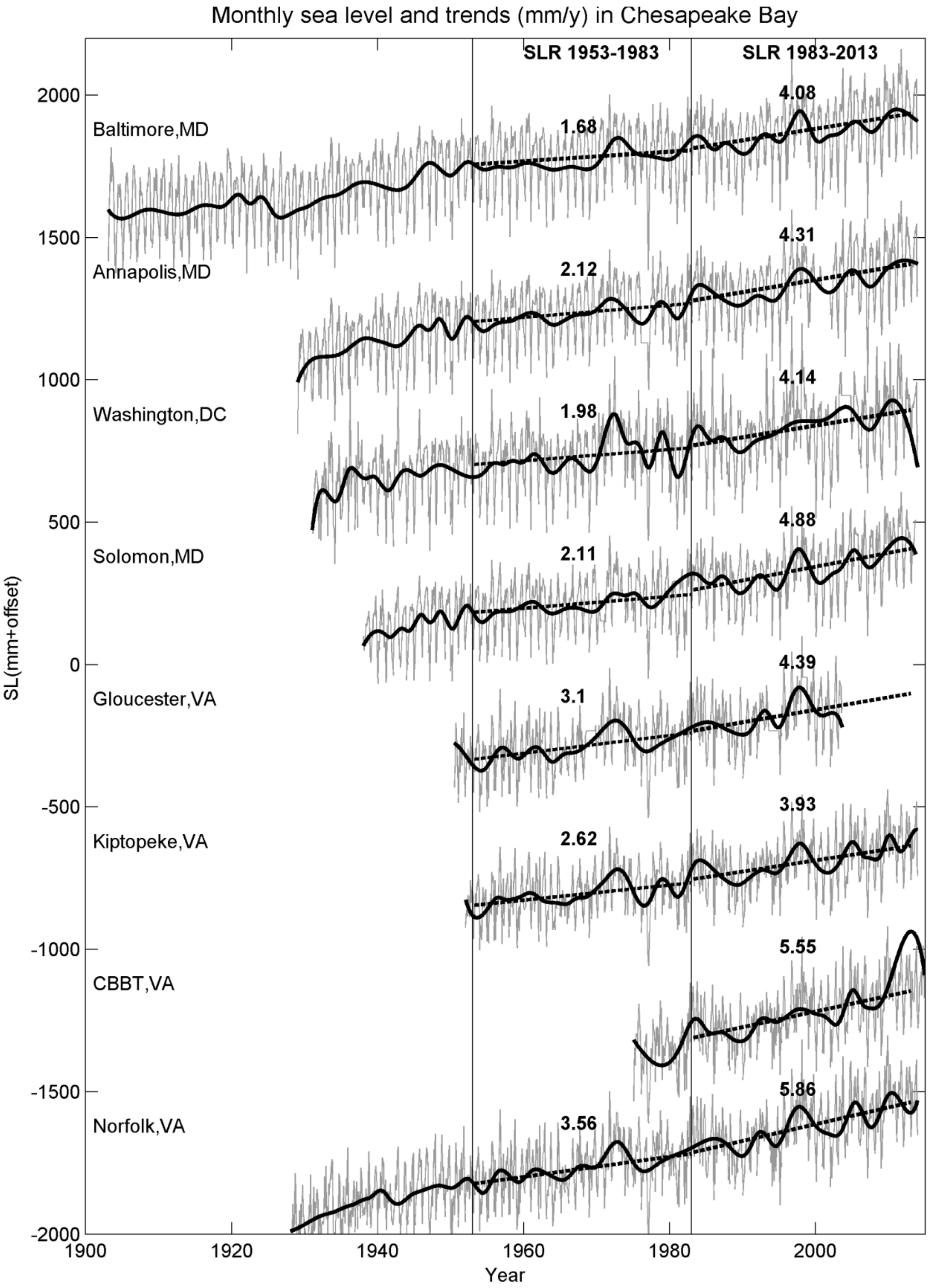

Monthly sea level and trends (mm/y) in Chesapeake Bay
SLR 1953-1983
SLR 1983-2013
Baltimore,MD
1.68
4.08
Annapolis,MD
2.12
4.31
Washington,DC
1.98
4.14
Solomon,MD
2.11
4.88
Gloucester,VA
3.1
4.39
Kiptopeke,VA
2.62
3.93
CBBT,VA
5.55
Norfolk,VA
3.56
5.86
SL(mm+offset)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
1900
1920
1940
1960
1980
2000
Year

Fig. 2

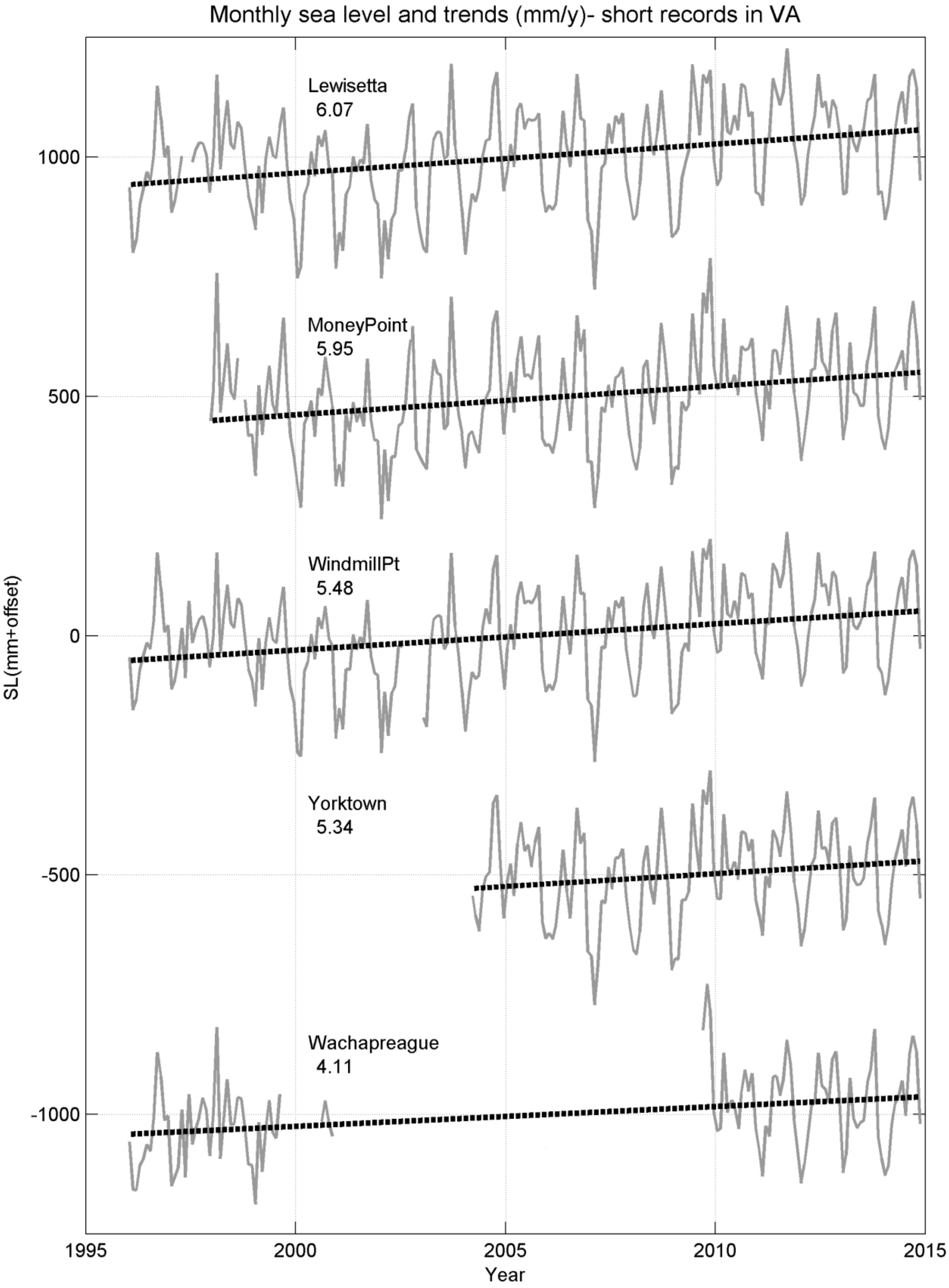

Monthly sea level and trends (mm/y)- short records in VA
Lewisetta
6.07
MoneyPoint
5.95
WindmillPt
5.48
Yorktown
5.34
Wachapreague
4.11
SL(mm+offset)
1000
500
0
-500
-1000
1995
2000
2005
2010
2015
Year

Fig. 3

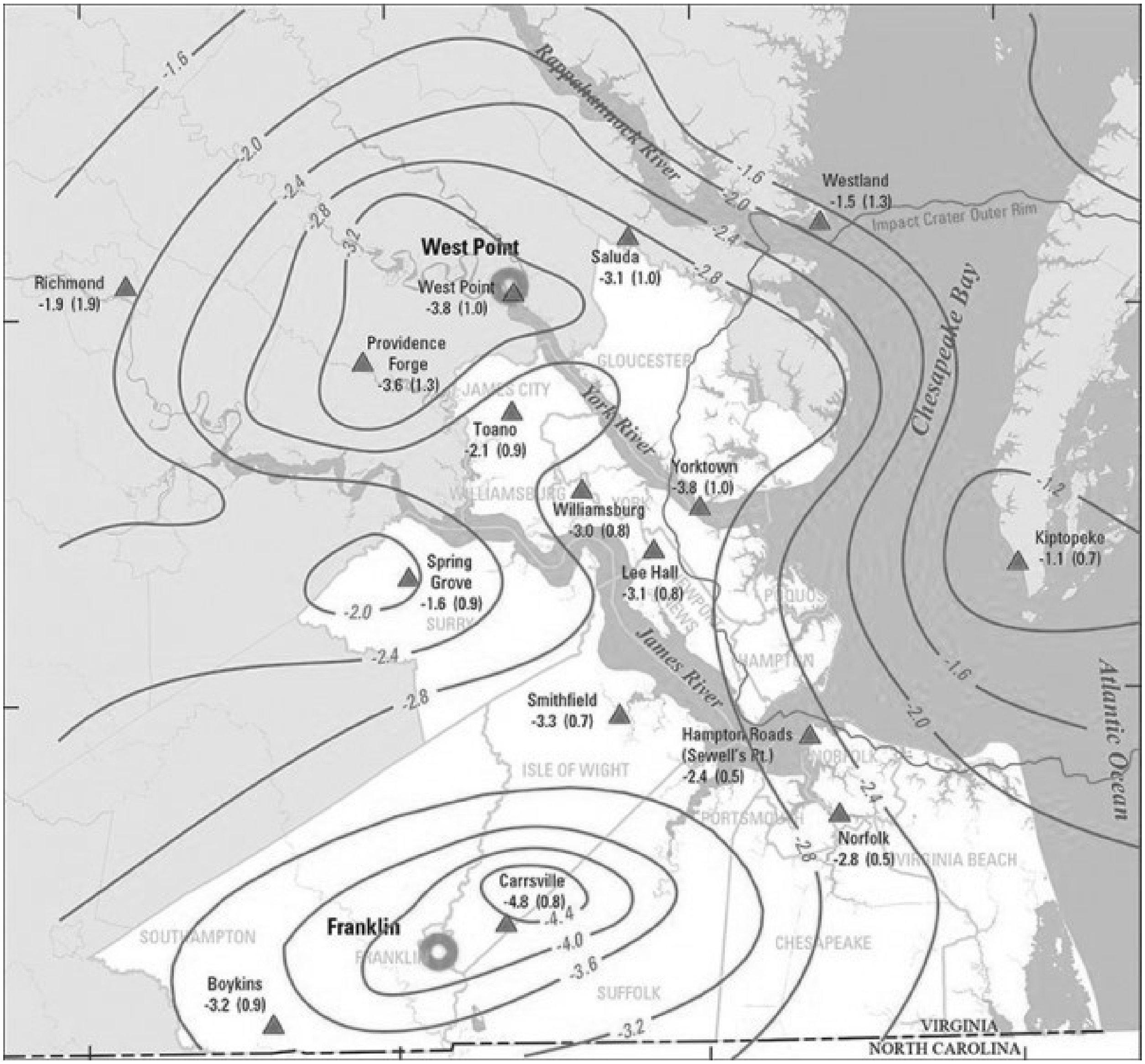
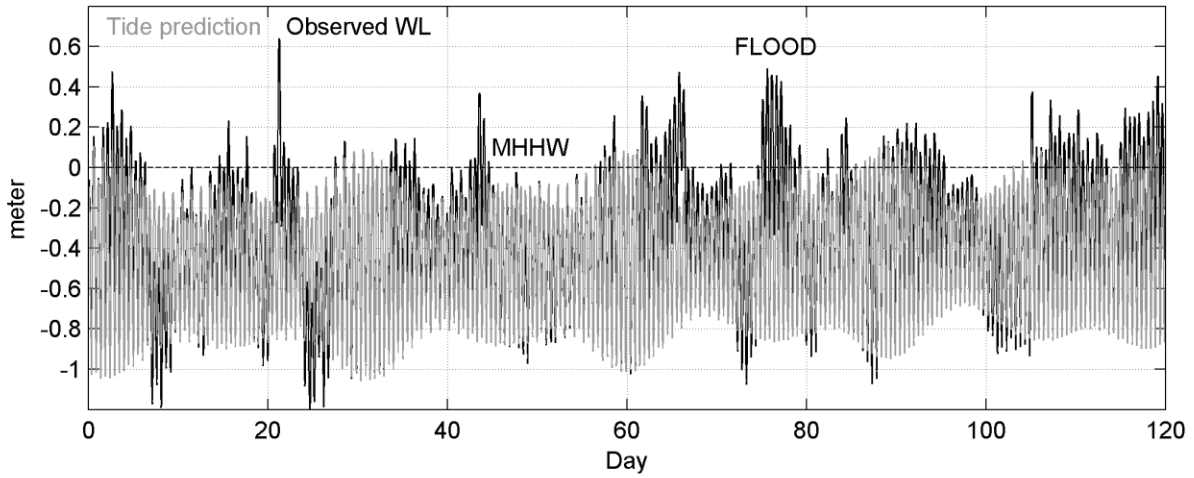
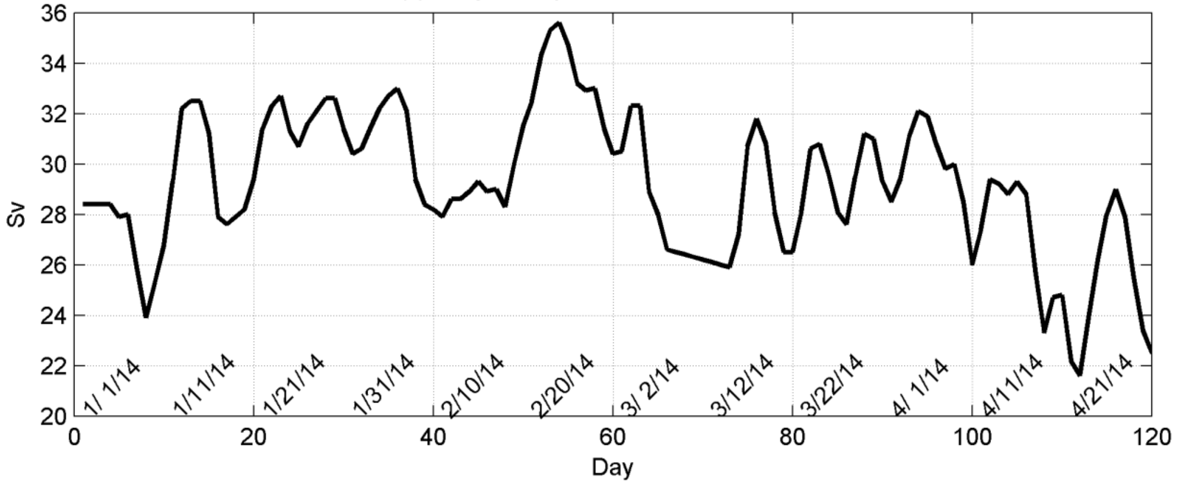

Rappahannock River
York River
James River
Chesapeake Bay
Atlantic Ocean
Impact Crater Outer Rim
West Point
Franklin
Westland
-1.5 (1.3)
Saluda
-3.1 (1.0)
Richmond
-1.9 (1.9)
West Point
-3.8 (1.0)
Providence
Forge
-3.6 (1.3)
Toano
-2.1 (0.9)
Yorktown
-3.8 (1.0)
Williamsburg
-3.0 (0.8)
Lee Hall
-3.1 (0.8)
Kiptopeke
-1.1 (0.7)
Spring
Grove
-1.6 (0.9)
Smithfield
-3.3 (0.7)
Hampton Roads
(Sewell's Pt.)
-2.4 (0.5)
Norfolk
-2.8 (0.5)
Carrsville
-4.8 (0.8)
Boykins
-3.2 (0.9)
GLOUCESTER
JAMES CITY
WILLIAMSBURG
YORK
NEWPORT NEWS
POQUOSON
HAMPTON
SURRY
ISLE OF WIGHT
NORFOLK
PORTSMOUTH
VIRGINIA BEACH
SOUTHAMPTON
FRANKLIN
SUFFOLK
CHESAPEAKE
VIRGINIA
NORTH CAROLINA
-1.2
-1.6
-2.0
-2.4
-2.8
-3.2
-3.6
-4.0
-4.4

Fig. 4

(a) Hourly Water Level in Norfolk (Jan-Apr, 2014)



(b) Daily Transport of the Florida Current



(c) FC Change vs. WL Anom. (R=-0.42, Conf>99%)

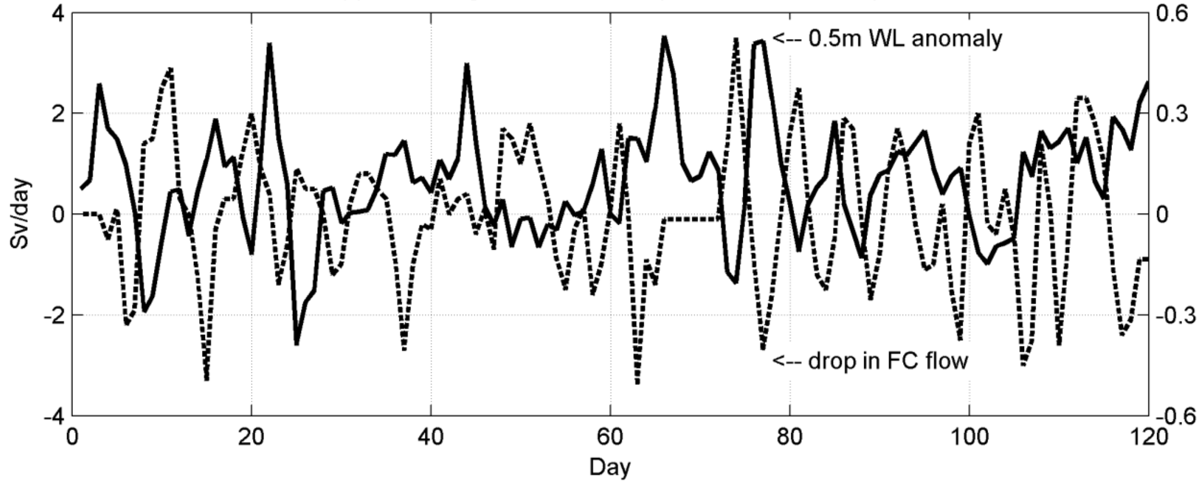


Fig. 5

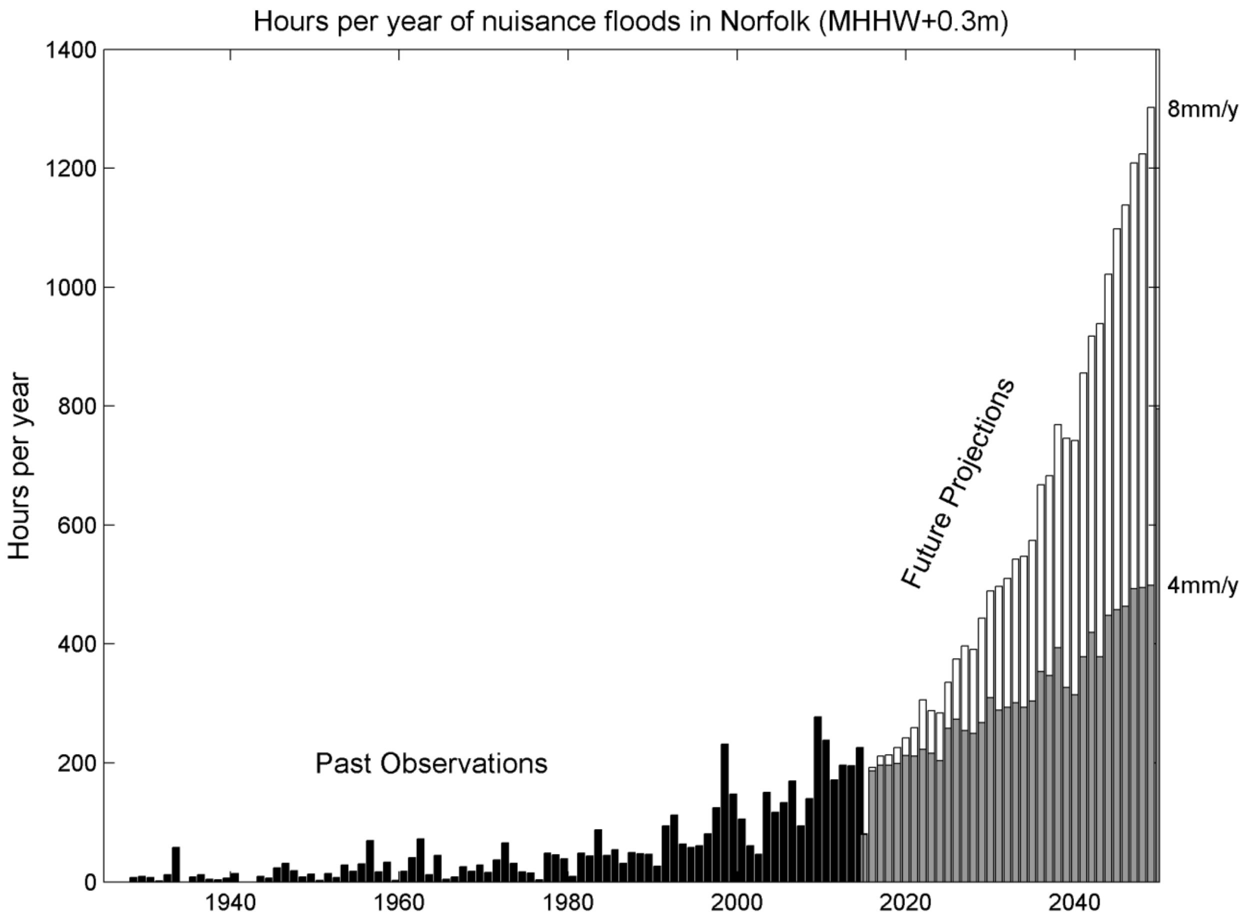

Hours per year of nuisance floods in Norfolk (MHHW+0.3m)
Hours per year
1400
1200
1000
800
600
400
200
0
1940
1960
1980
2000
2020
2040
Past Observations
Future Projections
8mm/y
4mm/y

Fig. 6