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Storm surge projections and implications for water management in South Florida

**Joseph Park · Jayantha Obeysekera ·
Michelle Irizarry · Jenifer Barnes ·
Paul Trimble · Winifred Park-Said**

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Abstract Water resource management in South Florida faces nearly intractable problems, in part due to weather and climate variability. Rising sea level and coastal storm surge are two phenomena with significant impacts on natural systems, fresh water supplies and flood drainage capability. However, decision support information regarding management of water resources in response to storm surge is not well developed. In an effort to address this need we analyze long term tidal records from Key West, Pensacola and Mayport Florida to extract surge distributions, to which we apply a nonlinear eustatic sea level rise model to project storm surge return levels and periods. Examination of climate connections reveals a statistically significant dependence between surge distributions and the Atlantic Multidecadal Oscillation (AMO). Based on a recent probabilistic model for AMO phase changes, we develop AMO-dependent surge distributions. These AMO-dependent surge projections are used to examine the flood control response of a coastal water management structure as an example of how climate dependent water resource forcings can be used in the formulation of decision support tools.

1 Introduction

South Florida is home to over seven million people and its population is projected to increase to over ten million by 2025 and possibly 12–15 million by 2050. Servicing the water demand requires a significant utility infrastructure, and the South Florida water management system is recognized as one of the most complex, spatially

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J. Park (✉) · J. Obeysekera · M. Irizarry · J. Barnes · P. Trimble · W. Park-Said
Hydrologic and Environmental Systems Modeling, South Florida Water Management District,
3301 Gun Club Rd., West Palm Beach, FL, USA
e-mail: jpark@sfwmd.gov

distributed, environmentally sensitive and heavily managed in the world (SFWMD 2009). Primary water management objectives are to sustain limited surface storage and aquifer levels for adequate water supply, to protect the extensive natural environment, while simultaneously providing flood control in response to the sub-tropical climate which imposes large episodic rain stresses. Balancing these competing goals is not easy. Indeed, Rittel and Webber (1973) classified such policy and societal planning problems as 'wicked': they often result in conflicting decisions and an optimal solution is unlikely. Add uncertain and non-stationary climate forcings to the mix, and the prospect facing water managers concerned with resource protection is indeed daunting. Nonetheless, the growing body of knowledge relating climate forcings to natural resource utilization offers new insights and opportunities to face these challenges.

Recent projections of global climate change and sea level rise, and their regional implications, suggest a significant potential for negative impacts on flood control and water supply functions, as well as on existing and future ecosystem restoration projects in South Florida (SFWMD 2009). An issue of special concern is the occurrence of extreme sea levels, usually associated with synoptic scale meteorologic events such as extratropical frontal storms, tropical storms and hurricanes. Indeed, as noted in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC): "Societal impacts of sea level change primarily occur via the extreme levels rather than as a direct consequence of mean sea level changes" (Bindoff et al. 2007). Such impacts are recognized in the actuarial sciences, where potential economic losses have been quantified (FASS 2010; Anthoff et al. 2010), and there has been recent progress assessing local coastal inundation based on sea level rise projections (Mousavi et al. 2010). However, appropriate decision-support information for coastal infrastructure and water management governance are lacking.

The Biscayne aquifer is the primary source of fresh water for coastal communities in the southern end of the Florida peninsula. This formation is relatively thin (several meters in the center of the peninsula to less than 100 m along the coast) and extends to the land surface. This aquifer is oceanic in origin consisting of various carbonate depositions from ancient shallow seas, for example oolites and limestone, both of which are highly porous and provide large hydraulic conductivities. This geology in conjunction with low land surface elevations ensures that the aquifer-ocean hydraulic system is strongly coupled. From an aquifer perspective, oceanic saltwater intrusion is a continual process driven by the hydraulic head (elevation difference) between the sea and the aquifer (Parker et al. 1955). Therefore elevation of the sea surface whether in the long term or even over short periods, threatens the viability of fresh water resources.

The high hydraulic conductivity and unconfined upper layer of the aquifer (it extends to the land surface) also means that canal-aquifer coupling is strong. Therefore, some measure of control over aquifer water levels can be attempted through control of canal water levels. Accordingly, canal networks in South Florida are maintained at predetermined water levels to not only reduce saltwater intrusion (requiring high water levels to offset the hydraulic gradient of ocean water) but also to provide flood protection (requiring low water levels to accept rainfall runoff). Clearly these are conflicting goals. As population increases and demands for both fresh water and flood protection increase, there will be more intense competition to meet water management objectives for the prevention of salt water intrusion while also providing flood protection for the region.

Canal levels in South Florida are maintained by a series of gravity driven submerged weirs with controllable flow gates. The instantaneous flow capacity of such a control structure is determined by the difference between the upstream (headwater) and downstream (tailwater) water level elevation. From a flood protection point of view, regional water control structures located near the coast are vulnerable as rising sea levels raise tailwater elevations to a point which limits the capacity to discharge flood waters.

Considering the above implications of sea level impacts to water resources in South Florida, it is clear that sea level rise and surge projections, strategies, and decision support for both the short and long term should be developed. Long term strategies addressing multi-decadal or centennial time scales will have to consider the wide dispersion of sea level rise (SLR) estimates amongst future climate scenarios (Bindoff et al. 2007). These long term uncertainties are not the focus of this paper. Rather we characterize coastal surge behaviors and establish links between regional climate projections and surge statistics to project climate-dependent surge levels which can seriously impact flood control and fresh water resources in South Florida. We are motivated by the need for planning and design data for coastal infrastructure improvements and operational management policies in response to climate change over the next several decades, and thereby establish a statistical methodology by which future water level exceedances can be estimated on secular and multidecadal timescales. Such methods are not only applicable to water management; they can be applied to any decision-making context wherein storm surge impacts are important.

1.1 Climate and storm surge

Analysis of coastal storm surge is hampered by the fact that surge events are episodic and relatively poorly sampled. Nonetheless, progress has been made towards elucidating some important characteristics of surge behavior. A primary conclusion is that with regional exceptions, extreme coastal water levels are increasing at rates consistent with that of mean sea level rise (Haigh et al. 2010; Park et al. 2010; Araujo and Pugh 2008; Woodworth and Blackman 2004). This suggests that there is not an emergent process driving an increase in surge levels independent from secular SLR.

Concerning climate forcing, many researchers have reported links between surge variability and climate indices (Haigh et al. 2010; Park et al. 2010; Woodworth et al. 2009; Woodworth and Blackman 2004; Bromirski et al. 2003; Woodworth and Blackman 2002; Seymour 1996). In particular, recent analysis by Park et al. (2010) found positive trends between both surge levels and duration with respect to the Atlantic Multidecadal Oscillation (AMO) (Kerr 2000) at Key West and Pensacola, Florida.

That there is a dependence between Florida surge levels and the AMO suggests that information regarding the current or forecast state of the AMO might be leveraged to refine predictions of surge levels. Such information does not currently exist in terms of model forecasting, however, Enfield and Cid-Serrano (2006) have developed a probabilistic framework to assess AMO phase changes. This opens the possibility that water managers may be able to incorporate climate-dependent scenarios in the development of management strategies aimed at extreme event mitigation. For example, water policy might consider flood drainage system draw downs in anticipation of extreme storm events, or raising of coastal aquifer levels to counter saltwater intrusion. Indeed, the development of such decision-support information is a crucial step for moving the science of climate change into realized climate response. In this regard one would do well to consider the question posed by Enfield and Cid-Serrano (2006) “As scientists, how do we convert these relationships into decision support products useful to water managers, insurance actuaries, and others, whose principal interest lies in knowing when future climate regime shifts will likely occur that affect long-horizon decisions?”

A goal of this paper is to quantify probabilistic surge return levels and periods based on historical tide gauge data at Key West, Pensacola and Mayport. We also show that the AMO phase has an impact on the surge return levels at Key West and Pensacola. We then turn to the projection of surge levels based on SLR scenarios currently required by the U.S. Army Corps of Engineers in the design of coastal projects (USACE 2009). Based on evidence that extreme coastal water levels are increasing at rates consistent with that of mean sea level rise, the SLR scenarios are used as location parameters to probability distributions of observed storm surges allowing estimation of future surge return statistics. Next, the dependence of storm surge on the AMO is coupled with the probabilistic AMO transition framework suggested by Enfield and Cid-Serrano (2006) in order to project surge return levels as a function of pre-existing and forecast AMO conditions. Lastly, the projected surge values are examined in the context of design information for South Florida water management adaptation and coastal aquifer management strategies.

2 Coastal storm surge data

Storm surge can be defined as the residual unsmoothed water level after astronomical tidal components have been removed from the observed water levels (Zhang et al. 2000; Woodworth and Blackman 2002), this is commonly referred to as non-tide residual (NTR). The NTR will have contributions from all processes not modeled in the astronomical components, for example, sub-tidal or infragravity waves, internal waves which couple to the littoral zone, coastal upwelling and downwelling (Liu and Weisberg 2007), sea level rise components and meteorological forcings. Given an observational record of sufficient length, sea level rise can be removed from the NTR. The meteorological component is the one associated with storm surge and typically has amplitude much greater than other coastal processes. Thus we consider the NTR (surge) to be defined by observed data with the SLR and astronomical tidal components removed.

The tidal data and astronomical predictions used to compute the NTRs were obtained from hourly NOAA (2009a) tide gauge records at Key West (1913–2008), Pensacola (1923–2008) and Mayport (1928–2008) Florida. The reference geodetic datum of the gauge records is the North American Vertical Datum (NAVD88). The hourly data were detrended according to sea level rise trends computed at each station by NOAA (2009b). We then compute hourly NTR by subtracting the prediction from the observed data, and finally compute monthly block-maxima (the maximum NTR from non-overlapping time windows of duration 1 month) from the hourly NTR. Figure 1 plots the NTR monthly block-maxima of the three stations. The Key West NTRs are roughly one-half the magnitude of the values at Pensacola or Mayport. This is largely due to the generally deep bathymetry surrounding

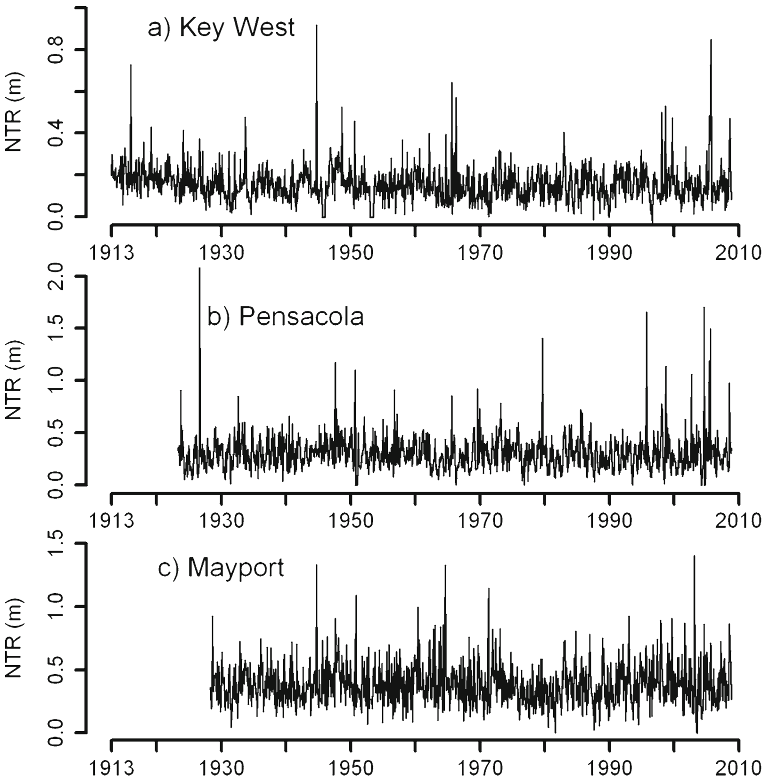


Fig. 1 NTR monthly block-maxima at Key West, Pensacola and Mayport Florida

Key West which limits surge development, while at Pensacola and Mayport the extensively shallow and wide continental shelf facilitates larger wave setup and surges (Harris 1963).

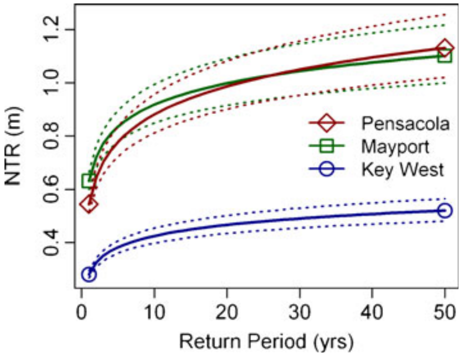
3 Historical storm surge return levels

NTR levels can be associated with expected return periods by equating the probability of exceedance of the NTR with the inverse of a return period, that is, the return level is the quantile of the fitted probability distribution corresponding to the upper tail probability 1/(T N_T), where T is the return period and N_T the number of data points per period. In the present analysis we use a return period of 1 year and monthly block-maxima so that $N_T = 12$. The distribution model we employ is the generalized extreme value (GEV) (Coles 2001) which has a distribution function

$$F(x) = \exp\left\{-\left[1+\varepsilon\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\varepsilon}\right\} \tag{1}$$

where ε, σ and μ are the shape, scale and location parameters respectively. Maximum likelihood fits of the GEV were performed on the NTR data of Fig. 1 with the R (R

Fig. 2 NTR return levels estimated from GEV fits to the NTR data in Fig. 1. 95% confidence intervals are shown with the *dotted lines*



Development Core Team 2008) *evd* package (Stephenson 2009). The corresponding NTR return level are shown in Fig. 2. These distributions estimate the expected frequency of occurrence of NTR levels, and, as expected from inspection of the data in Fig. 1 return levels at Pensacola and Mayport are roughly twice those of Key West. Curves of this type based on observed data are conventionally considered as design criteria in the development of coastal infrastructure. In a world of stationary sea level statistics, this could be a viable approach, however, in light of the inherent non-stationarity of SLR statistics and extremes, consideration should be given to statistics based on SLR projections which address changing climate.

3.1 Climate dependence

As discussed in the Introduction, recent analysis has identified a link between NTR levels at Key West and Pensacola and the AMO index (Park et al. 2010; NOAA 2009c); both NTR levels and event durations have statistically significant linear dependence on the AMO index. The expected AMO dependence at Mayport was not found, likely a result of estuarine influences from the St. Johns river confluence at the Mayport tidal station. Following the work in Park et al. (2010), we have partitioned the NTR data at Key West and Pensacola into two AMO regimes referred to as Warm (values of the index greater than 0.1) and Cool (values less than –0.1). With GEV distributions fit to these two subsets the resulting return levels are depicted in

Fig. 3 NTR return levels at Key West and Pensacola as a function of two AMO index regimes: Warm (index > 0.1) and Cool (index < -0.1). *Dotted lines* are 95% confidence levels

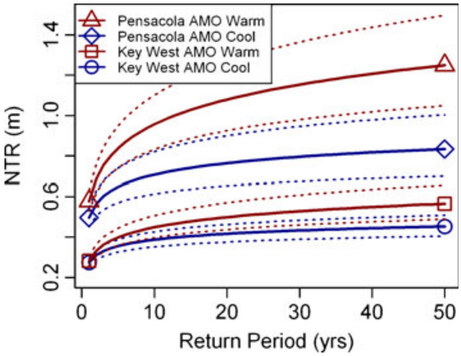


Fig. 3. Here we see a statistically significant decomposition of the Pensacola return levels as a function of the AMO index at the 95% confidence level, while the Key West estimates have a slight overlap but still suggest AMO dependent NTR behavior. The implication is that warm AMO conditions are associated with increased NTR levels as a function of return period. This is hypothesized to represent a link between the AMO and size of the Atlantic Warm Pool (Enfield and Cid-Serrano 2010), facilitating increased tropical storm activity (Wang et al. 2008; Goldenberg et al. 2001) resulting in a greater likelihood of extreme coastal water levels.

4 Surge projections

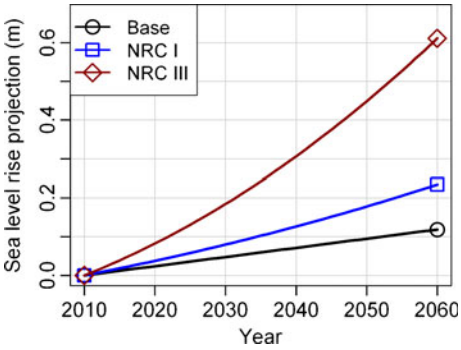
As discussed earlier, there is ample evidence that secular trends in coastal surge are driven primarily by the change in mean SLR. It is then plausible to transfer projections of SLR onto the NTR distributions for estimates of future NTR behavior. While this is straightforward, a joint probability formalism with probabilistic convolution is required to account for transference of the SLR uncertainty to the projected NTR statistics (Liu et al. 2010; Hunter 2009). Here we do not attempt to account for the uncertainty in the SLR projections, although extensions to the work reported in this paper are currently in progress to address this issue.

The SLR projections used here were proposed and adopted by the U.S. Army Corps of Engineers (USACE) for the design of civil infrastructure impacted by SLR (USACE 2009). This method starts with a local SLR trend based on observed data to account for isostatic adjustments, and adds a nonlinear time-dependent term to represent eustatic SLR contributions. The nonlinear term is modified from a National Research Council report (NRC 1987) which assumed three scenarios corresponding to 0.5, 1.0 and 1.5 m of eustatic SLR over the period 1987–2100. These scenarios are referred to as NRC I, NRC II and NRC III curves respectively, although in the USACE document the coefficients are adjusted to account for more recent global SLR estimates and the scenarios are referred to as ‘modified’ NRC curves. Guidance from the USACE method requires consideration of a baseline (historical trend extrapolation) and modified NRC curves I and III. To estimate the local historic SLR, including the isostatic term, an average of the mean SLR trend (NOAA 2009b) at five South Florida tidal stations (Miami Beach, Vaca Key, Key West, Fort Myers, St. Petersburg) results in a value of 2.37 mm/yr. Application of the USACE method to this base rate with modified NRC curves I and III forms the basis of our SLR projections. These projections are shown for the period 2010–2060 in Fig. 4. Note that the modified NRC I and III projections implicitly include the base extrapolation from historical data, thereby incorporating estimates for the rate of total (steric, isostatic and eustatic) SLR.

A surge projection is estimated by applying a SLR scenario (NRC I or NRC III) as a time-dependent location parameter to an NTR GEV fit to historic data (return levels of the GEV’s are shown in Fig. 2). The projected GEV distribution of the NTR at time t can then be modeled as

$$F\left(NTR, t\right) = \exp\left\{-\left[1 + \varepsilon\left(\frac{NTR - (\mu + R(t))}{\sigma}\right)\right]^{-1/\varepsilon}\right\} \tag{2}$$

Fig. 4 Sea level rise projections for South Florida based on a historic baseline trend of 2.37 mm/year, and two eustatic scenarios from the USACE method



where $R(t)$ is the SLR projection at time t. It should be noted that these projections implicitly include a SLR component with $R(t)$, but not an astronomical component as it was removed by definition of the NTR. A geodetic referenced total water level projection would require addition of predicted astronomical tide to the NTR projection.

Projected NTR return levels at Key West with the modified NRC I scenario are shown in Fig. 5, and with NRC III values in Fig. 6. The horizontal axis corresponds to the future time t of Eq. 2 in years, and the vertical axis to the NTR return period in years.

Both of these scenarios suggest significant changes in NTR behavior over the coming decades. Considering the NRC I scenario depicted in Fig. 5, at a future time of 5 years the NTR return level of 0.5 m has a return period of approximately 30 years, while at a future time of 25 years, the 0.5 m NTR level has a return period of roughly 8 years. The NRC III scenario at Key West suggests a more aggressive situation with 0.5 m NTR levels predicted every couple of years at a future time of 20 years.

Fig. 5 Projected NTR return levels at Key West based on a time-dependent SLR specified by the modified NRC I curve

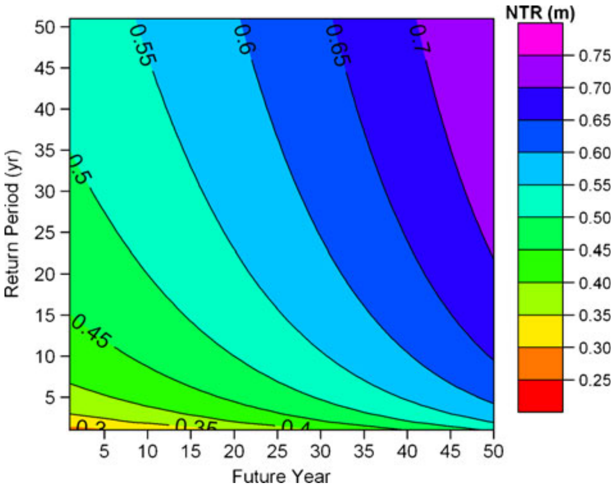
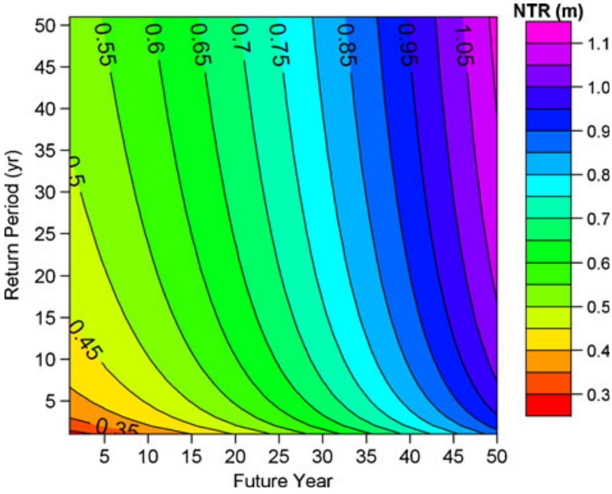


Fig. 6 Projected NTR return levels at Key West based on a time-dependent SLR specified by the modified NRC III curve



Such an acceleration of surge levels warrants closer scrutiny. A comparison of projected NTR return levels under NRC I and NRC III scenarios at 50 years with historical return levels (Table 1) shows that if historic conditions prevail, such that eustatic SLR components remain linear, then expected NTR return levels at a 50 year return period at Key West are within about (0.52–0.38) = 0.14 m of values with 5 year return period. At Pensacola and Mayport the difference is roughly 0.3 m. However, under conditions projected by NRC I or III scenarios there is a significant increase in expected NTR levels at all return periods. For example, at Key West under NRC I conditions the NTR return levels at a 5 year return period is 0.62 m, which is larger than the return level under historic conditions at a 50 year return period (0.52 m). This predicts that under NRC I conditions within a 5 year period an NTR event will exceed that of a one in 50 year event under historic conditions. At Pensacola and Mayport the NRC I projection at a 10 year return period roughly equates to that of the historic levels at a 50 year return period.

Effectively, these projections suggest that a given expected surge return level is being ‘condensed’ in time such that the interval between surge occurrences can rapidly decrease. Considering that both Key West and Pensacola are low elevation areas, such an increase in NTR levels has potential to create significant negative impacts.

Table 1 Comparison of historical NTR return levels (m) with projections at 50 years in the future (2060) based on NRC I and III SLR scenarios

Return period (years)	Key West			Pensacola			Mayport		
	Historic	NRC I	NRC III	Historic	NRC I	NRC III	Historic	NRC I	NRC III
5	0.38	0.62	0.99	0.78	1.01	1.39	0.83	1.07	1.45
10	0.43	0.66	1.04	0.88	1.11	1.49	0.92	1.15	1.53
20	0.47	0.70	1.08	0.99	1.22	1.60	1.00	1.23	1.61
30	0.49	0.72	1.10	1.05	1.28	1.66	1.04	1.28	1.65
40	0.51	0.74	1.12	1.10	1.33	1.71	1.08	1.31	1.69
50	0.52	0.76	1.13	1.13	1.37	1.74	1.10	1.34	1.71

4.1 AMO dependence

As discussed earlier, there is a body of evidence establishing links between climate processes and coastal surge levels. Relevant to Florida, Park et al. (2010) found a dependence between the AMO index and NTR levels and durations at Key West and Pensacola. Enfield and Cid-Serrano (2006) developed a probabilistic interpretation of AMO phase-change that can provide a basis for projection of AMO-dependent climate responses towards the goal of informing risk-based decision support. Here we attempt such a synthesis by combining AMO phase-transition statistics with AMO-dependent GEV distributions of NTR at Key West.

Enfield and Cid-Serrano (2006) analyzed an AMO index developed from instrumental and tree-ring reconstruction records spanning a 424 year period. Based on a resampling scheme they fit a gamma distribution to phase changes of the reconstruction and developed a probabilistic projection for AMO phase changes. Figure 7 plots projections from Eq. 1 of Enfield and Cid-Serrano (2006) estimating probabilities for AMO phase changes based on the number of years since the last transition and the number of years into the future for which a probabilistic assessment of phase change is desired. For example, if it has been 5 years since the last AMO regime change, then at 15 years in the future the probability of an AMO regime change during the 15 year period is approximately 60%.

With a method to estimate future AMO phase shifts, our attention turns to joining AMO-dependent NTR statistics with AMO phase change projections. With the assumption that we will model only one AMO transition, and that the AMO states are restricted to a binary regime of either warm or cool (as defined earlier), we can denote the probability of changing from the current phase to the other within the forecast time period as p, and the probability of remaining in the same phase as $1 - p$. Assuming independence between AMO regime changes, the distribution function for NTR levels as a function of forecast period t can be specified as

$$F\,(NTR, t) = p\,[F_N\,(NTR, t)] + (1 - p)\,[F_C\,(NTR, t)] \tag{3}$$

where F_C corresponds to the projected NTR GEV distribution function of the *current* AMO phase and F_N the *next* regime.

As an example of AMO-dependent NTR projections we evaluate return levels computed from GEV distributions for Key West and Pensacola at future times of 15 and 25 years (calendar years 2025 and 2035) for the modified NRC III SLR

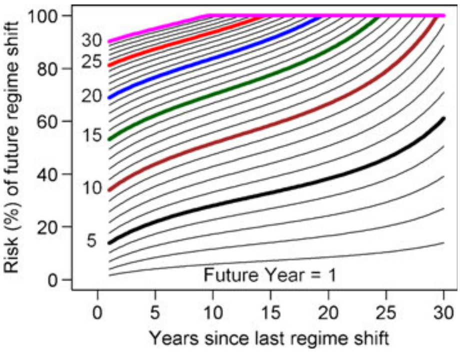


Fig. 7 Probabilistic assessments for an AMO phase shift based on the number of years from the last shift and the number of years into the future. Computed from Eq. 1 of Enfield and Cid-Serrano (2006)

projections. Values of p are estimated from the projections of Enfield and Cid-Serrano (2006) with previous AMO regime shifts at 5 and 20 years past. Figure 8 plots the resulting AMO-dependent NTR projections for Key West where the NTR distributions are denoted by the pair: [Initial AMO regime, Years since last AMO shift]. For example, the curve labeled "Cool 20" in panel a) has the initial (current) distribution F_C assigned to the Key West AMO cool regime GEV projected at 15 years in the future (2025) based on modified NRC III SLR, while the AMO transition probability p was selected for the previous AMO shift having occurred 20 years in the past. Also shown in Fig. 8 are the NTR return levels fit to the observed data (Fig. 2) and return levels for the modified NRC III SLR projections without regard for AMO dependence (vertical sections of Fig. 6 at years 2025 in panel a, and 2035 in panel b).

Aside from the expected increase in NTR return levels due to the modified NRC III sea level projections, several things are apparent in Fig. 8. First, for the projections of 15 years (2025) in panel a), there is not a great deal of dependence on the AMO conditions. While the results suggest that transitioning from a currently cool AMO regime into a warm one can produce expected NTR events with higher amplitudes than a transition from currently warm to cool, the amplitude of the change is small, roughly 0.1 m. However, when considering a 25 year projection (panel b), the AMO-dependence becomes clearer, again showing that a transition from cool to warm conditions portends higher NTR event levels. The change in AMO-dependence between the 15 and 25 year projections can partially be explained by the differences

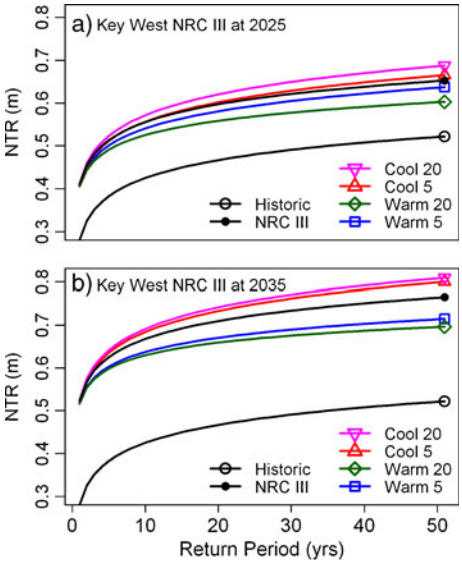


Fig. 8 Key West NTR return level projections based on synthesis of AMO warm and cool NTR distributions according to Eq. 3 based on modified NRC III SLR projections. The AMO phase change probability is computed for a future time of 15 or 25 years (2025 or 2035). Curves are denoted according to the initial AMO phase of warm or cool, and the previous AMO shift at either 5 or 20 years ago. Return levels are also shown for the historic data, and for the modified NRC III projection without AMO dependence. **a** AMO-dependent projections at 15 years (2025), **b** AMO-dependent projections at 25 years (2035)

in AMO transition probabilities. For the 25 year future projection, AMO transition probabilities are above 80% regardless of the time since the last transition, and near 100% when the previous transition was more than 10 years past (Fig. 7). In such cases we expect the AMO-dependence exhibited in Fig. 3 to contribute to a large degree, whereas for cases when the AMO transition probabilities are smaller, as with the 15 year projection, the AMO-dependence will be mitigated.

Another conclusion supported by Fig. 8 is that at Key West the length of time since the last AMO transition is less important than the current and future state of the AMO. Generally, when the current state is AMO cool, and there will be a transition into AMO warm, one can expect higher amplitude NTR events.

It must be mentioned that we have assumed only a single AMO transition will occur. When dealing with 25 year forecasts, especially when the previous AMO transition has occurred more than a few years in the past, it is entirely possible, as demonstrated in reconstructed records (Gray et al. 2004) that multiple AMO transitions can occur. Thus with the methods presented here, caution is needed for projections of AMO transition periods (time since last change to future year) that exceed two or three decades.

NTR return level projections at Pensacola are presented in Fig. 9. Panel a plots the 15 year (2025) forecast, while the 25 year (2035) projections are shown in panel b. Qualitatively, these results show behavior similar to Key West in that one can expect higher NTR levels when transitioning from AMO cool to warm conditions. However, the AMO-dependence is stronger with a roughly 0.4 to 0.5 m difference in NTR

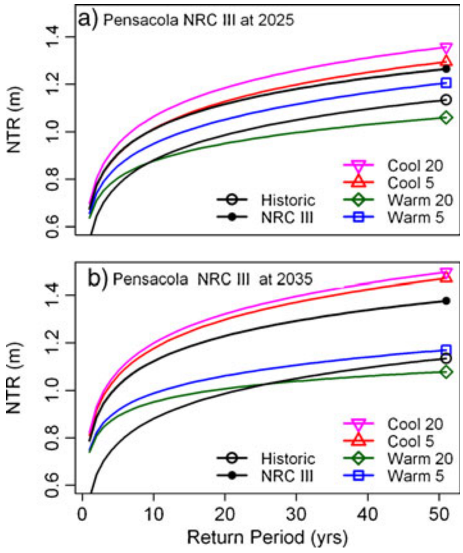


Fig. 9 Pensacola NTR return level projections based on synthesis of AMO warm and cool NTR distributions according to Eq. 3 based on modified NRC III SLR projections. The AMO phase change probability is computed for a future time of 15 or 25 years (2025 or 2035). Curves are denoted according to the initial AMO phase of warm or cool, and the previous AMO shift at either 5 or 20 years ago. Return levels are also shown for the historic data, and for the modified NRC III projection without AMO dependence. **a** AMO-dependent projections at 15 years (2025), **b** AMO-dependent projections at 25 years (2035)

return level as a function of return period. Remarkably, these projections indicate that if the current AMO phase is warm, projected NTR levels in 2035 could be at or below levels computed from a historical distribution. Of course, the alternative scenario suggests that when transitioning into an AMO warm phase during the next quarter century that NTR return levels could be up to 0.5 m above historical expectations.

5 Water management implications

5.1 Coastal flood drainage

One of the main forcings to South Florida water management is rainfall. Statewide, Florida has a mean annual rainfall of 137 cm (54 in.); however, the panhandle and southeast coast are the wettest regions with annual rainfall reaching or exceeding 165 cm (65 in.). Local variability is large and intense rain events common. When imposed on the heavily urbanized southeast coast this forcing presents significant water management challenges for drainage and flood control.

As described previously, coastal runoff (water not absorbed by the surficial aquifer) is ultimately drained to the ocean through a series of canals and gravity driven weirs. These drainage structures have a flow capacity determined by the instantaneous water level difference upstream (canal) and downstream (ocean or intracoastal tidal region) of the weir. Given the naturally low surface elevations of South Florida, margins for flow capacity reduction in response to increasing sea levels, whether short or long term, are small and diminishing. For example, analysis of the design headwater/tailwater differences at SFWMD drainage structures has identified several coastal drainage structures in danger of losing flow capacity in response to a 15 cm (6 in.) sea level rise; Fig. 10 illustrates the structures. Many of these structures were designed and installed three to five decades ago, and have already lost some flow capacity as a result of SLR.

In addition to the long term reduction in flow capacity, there are short term effects from tidal variation that impede coastal structure discharge. For example, structure S29 is a coastal gated spillway with four control gates located in the city of North Miami Beach. In order to limit flooding, this structure attempts to maintain upstream (canal) water levels between 0.31 and 0.46 m (1.0–1.5 ft), however, when the downstream tidal level approaches or exceeds the upstream level, the control gates are automatically closed to prevent saltwater intrusion into the canal. Figure 11 depicts an event starting on September 1, 2008, 10:00 GMT where the structure was required to discharge, but was unable to do so continuously since the downstream tidal levels mandated gate closure with each tidal cycle. The superposition of either SLR or surge will further reduce structure flow capacity.

One adaptation strategy is to install hydraulic pump stations at coastal structures in an attempt to compensate for lost capacity. In fact, this is currently being considered at S29 and several other impacted structures. Let us consider a design exercise aimed at sizing a pump station for S29 to maintain upstream headwater levels at current conditions in response to projected NTR scenarios. The approach is to increase the downstream water levels for the discharge event shown in Fig. 11 based on projections of NTR return levels and SLR. The structure flow rating curve

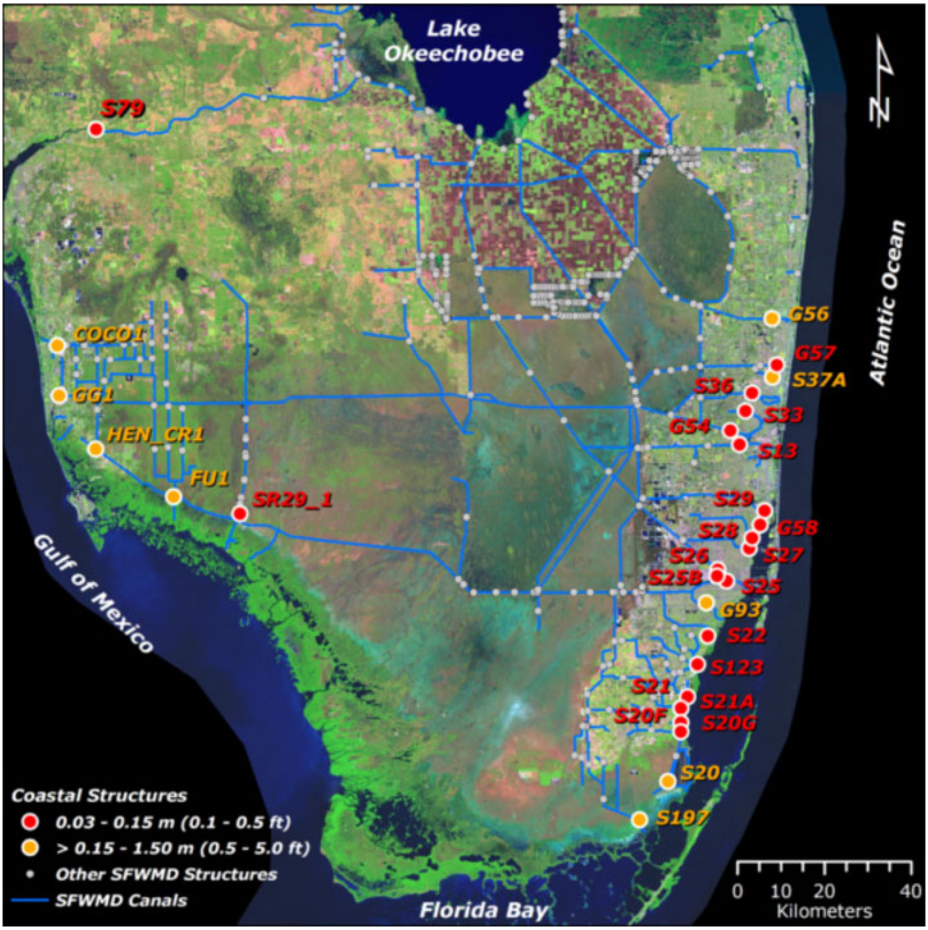


Fig. 10 Coastal drainage structures that may lose flow capacity in response to a 15 cm (6 in.) increase in mean sea level

is then used to compute the flow capacity based on the new downstream water level while keeping the upstream water level the same. The difference between the projected flow, and the flow based on historic data (Fig. 11b) provides an estimate for pump capacity needed to maintain the upstream water level (Fig. 11a) due to the lost discharge capacity.

To properly apply an NTR projection at the S29 structure one should ideally have NTR statistics from data within a few kilometers of the structure. Unfortunately, Key West is the nearest tidal station with long term records and is the only option available at this time. Modifications to the Key West surge levels could be made based on coastal wave models specific to North Miami Beach, however, that is beyond the scope of the present analysis.

We consider a future date of 2035 with NTR projected from NRC I and NRC III scenarios based on a current AMO warm phase with the previous phase change assumed to have occurred 20 years ago. The last assumption has been shown to be

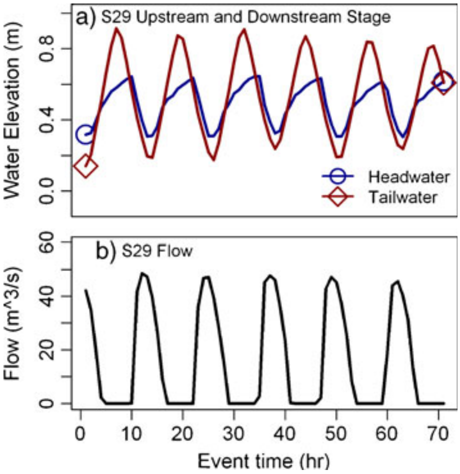


Fig. 11 **a** Upstream (headwater) and downstream (tailwater) levels at coastal water control structure S29 during a flood control release on September 1, 2008. **b** Structure flow clearly demonstrating that the downstream tidal water levels control the structure discharge

rather insensitive to the projections, so that 20 years is a reasonable approximation to the length of time since the last AMO transition, which is generally considered to have occurred in 1995. As a design criteria we use the projected NTR return level corresponding to the 50 year return period. Under these conditions the modified NRC I projected NTR is 0.55 m, and the NRC III projection 0.69 m.

Since storm surges have a limited timespan, we model a surge event as a sinewave of one-half period. That is, the surge event can be expressed as $S(t) = NTR \sin(\pi t / T_S)$ with values of t from 0 to T_S, where NTR is the projected surge return level (which include the eustatic SLR component) and T_S is set to a length of 35 h (since the mean value of surge duration at Key West is approximately 30 h). Figure 12 shows the results of two projections applied to the S29 data (Fig. 11). The upper panel of Fig. 12 plots the modified downstream water levels based on a superposition of the historic values (of September 1, 2008) and the projected surge events $S(t)$, where the surge event was initiated at time index of 15 h. Outside of the surge event (15–50 h) the historic levels have been adjusted according the modified NRC I or III SLR projection at year 2035.

Panel b of Fig. 12 shows estimated flow deficits as a result of increased tidal water levels under modified NRC III projected conditions; the bottom plot shows the estimated deficits for modified NRC I projections. Two conclusions arise from these results. First, the projected surge event overwhelms the structure gravity flow capacity by increasing downstream tidal levels beyond the point where gravity driven flow is possible. A pump to compensate for this event would require a significant flow capacity. However, since the pump will be able to operate continuously, not as a function of downstream tidal levels, it should be possible to use a lower capacity pump for comparable upstream water level reductions. Second, the sensitivity of flow capacity reduction to small changes in SLR is striking. Inspection of Fig. 12 outside the surge event (prior to hour 15, after hour 50) reveals a small difference in downstream water level increase; specifically, 0.10 m (4 in.) for the NRC I projection and 0.24 m (9.5 in.) for NRC III, but with large differences in the flow required to maintain the upstream water levels. It appears that a threshold has been surpassed

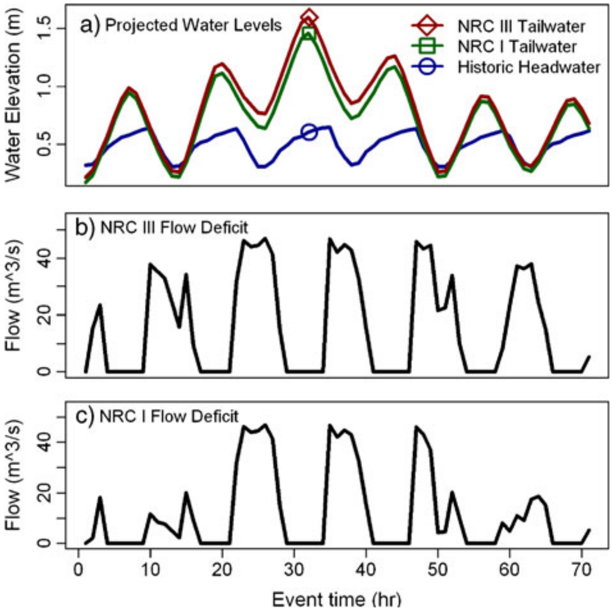


Fig. 12 **a** Projected downstream tidal water levels at water control structure S29 based on NRC I and NRC III NTR projections applied to data from September 1, 2008. The surge event is initiated at time 15 and has duration of 35 h. **b** flow deficits in relation to flows of September 1, 2008 required to maintain the same upstream water levels for NRC III downstream tidal levels, **c** same as in **b** but for the NRC I NTR projection

in the nonlinear flow response of the structure such that a downstream tidal level increase between 4 and 9 in. is sufficient to nearly incapacitate this structure.

5.2 Saltwater intrusion and storm surge flooding

Most coastal communities in South Florida depend on wellfields that tap freshwater from shallow aquifers which are some of the most permeable in the world. Accelerated saltwater intrusion due to projected sea level rise of the magnitudes shown in Fig. 4 has the potential to contaminate many of these coastal wellfields. The lateral movement of the saltwater interface due to the increase in mean sea level is a long term phenomenon, however, the larger storm surges projected in this study may have a secondary, but more immediate impact. The flooding of flat, coastal regions and the resulting wave run-up during extreme storms may cover large depressions in the interior and result in rapid vertical infiltration of saltwater down into the freshwater aquifers.

Mechanics of saltwater migration through surface infiltration or open pits is highly complex and non-linear due to the unsteady nature of the stratification (denser sea water over less dense fresh water) and the significant spatial and geologic inhomogeneities. Efforts are underway to develop models that include density-dependent flow to understand and predict saline infiltration, dynamics of the saltwater front, and determine which utility wellfields are at risk of contamination. Future efforts to couple these intrusion models with surge statistics and inundation models are needed to gain a better understanding of how higher storms surges will impact water resources in South Florida.

6 Conclusions

Many challenges face water managers in Florida. Climatic change, however, may be one of the most important in terms of resource adaptability and sustainability. Recent advances in the understanding of climate variability, modeling capabilities, and the identification of links to processes such as the hydrological cycle provide opportunities to develop and refine decision support tools for ecosystem and natural resource management. The incorporation of climate outlooks into water resource management in South Florida has been in use for some time (SFWMD 2010), however, oceanic forcings on the aquifer and hydraulic drainage systems have yet to be considered for decision support. In coastal areas, sea level rise and storm surge are geophysical forcings capable of producing deleterious consequences to water resource management, both from the potable water supply and flood control perspectives. Results presented in this paper are intended to synthesize recently published climate links between the AMO and Florida surge levels with climate variability analysis of the AMO to facilitate projection of surge statistics with the goal of forming decision support tools for planning and adaptation strategies.

Traditional design analysis for coastal infrastructure relies on estimation of NTR return levels and periods based on extreme value distributions fit to historical NTR data. Following this approach we found NTRs of roughly 0.5 m at Key West, and 1.1 m for Pensacola and Mayport at a 50 year return period. Based on evidence that increasing NTR levels are coherent with long term SLR we assessed projections of NTR return levels by incorporating USACE SLR scenarios into the time-dependent location parameter of the NTR distributions. Results of these projections indicate a significant condensation of surge return periods at all stations. The one-in-fifty year surge event can become a one-in-five year event depending on the SLR scenario and station.

Reliance on only time-dependent statistics may miss important links to climate variability that naturally affect surge and flood behavior. Accordingly, assessment of NTRs in relation to the AMO index found statistically significant decompositions of NTR return levels at Key West and Pensacola. By coupling these AMO-dependent distributions with SLR scenarios and a probabilistic AMO phase change formulation, we projected NTR return levels with respect to SLR and the AMO index. As one would expect from examination of the AMO-dependent NTR distributions, within the assumption of a single AMO phase change in the forecast period, a transition from currently cool to future warm AMO conditions portends a potentially significant increase in NTR levels during the forecast period, with the converse applying if current conditions conform to AMO warm. Interestingly, projected NTR dependence on the length of time since the previous AMO transition appears to be weaker than dependence on the regime (warm or cool) itself.

Concerning design projections, the importance of considering climate dependent links such as the AMO-NTR dependence is clear. The natural variability in NTR introduced by the AMO has the potential to significantly increase, or decrease projected NTR levels within timescales of several decades. An application of NTR projections to a flood control example at structure S29 maintained by the South Florida Water Management District illustrates the current and near-term importance of SLR and surge effects on public infrastructure. This suggests that development and refinement of climate based decision support tools should address decadal timescales as well as longer term variability.

The method presented here for the synthesis of historic data, SLR projections, and climate-dependent transition probabilities into projections of coastal storm surge has relevance to many coastal interests, not just water management concerns. Areas of improvement for the approach include the ability to transfer the uncertainties in the SLR projections to the NTR projections, a joint-probability framework has been suggested (Liu et al. 2010; Hunter 2009). Another concern is that the NTR projections do not account for emerging changes in the behavior of tropical storms as a function of climatic change. Recent work by Bender et al. (2010) strengthens evidence indicating a decrease in the total number of North Atlantic hurricanes, but an increase in the number of strong (Saffir-Simpson scale 3–5) storms in the latter part of the twenty-first century. As modeling and predictability of storm surge forcings mature, it would be desirable to incorporate climate-dependent changes into the projected storm surge statistics. Finally, and perhaps most importantly, there is a need to couple surge projections with regionally specific hydrodynamic coastal inundation models (Mousavi et al. 2010; FASS 2010).

From the perspective of a public service organization tasked with preservation and protection of precious water resources and the public welfare, a broader and deeper emphasis on research aimed at developing and providing decision support and policy information regarding climate variability and forcing is acutely needed.

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