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The importance of non-tidal water-level variability for reconstructing Holocene relative sea level

Andrew C. Kemp [a, *], Timothy A. Shaw [b], Christopher G. Piecuch [c]

[a] Department of Earth and Ocean Science, Tufts University, Medford, MA, 02155, USA
[b] Earth Observatory of Singapore, Nanyang Technological University, 639798, Singapore
[c] Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543, USA

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A B S T R A C T

Salt-marsh sediment is an important geological archive for reconstructing Holocene relative sea level. The vertical uncertainty of these reconstructions is usually quantified as proportional to tidal range, resulting in a presumed primacy of microtidal regions for generating precise records. We analyzed hourly water-level predictions and measurements over 1983–2001 from 43 tide gauges on the U.S. Atlantic coast to quantify the (1) relationship between elevation (relative to tidal datums) and duration of inundation; and (2) relative importance of astronomical tides and non-tidal (meteorological, hydrologic, and oceanographic) processes. Non-tidal processes are more likely to exert a proportionally large influence on water levels in regions with small astronomical tides, and less likely to do so where tides are large. In some microtidal regions (e.g., Chesapeake Bay), the precision of RSL reconstructions is likely overestimated, while in regions with large tidal range (e.g., Gulf of Maine) it may be underestimated. Adopting an inundation frequency rather than predicted astronomical datum for the upper limit of salt-marsh distribution may reduce this bias. Relative sea-level reconstructions often assume constant tidal range through time, but in some microtidal regions this assumption should be expanded to explicitly describe additional stationarity of non-tidal contributions.

1. Introduction

At middle to high latitudes, sediment that accumulated in salt marshes is a key geological archive for reconstructing Holocene relative sea level (RSL; Engelhart and Horton, 2012; Gehrels, 1999). These reconstructions are employed across several disciplines (for example) to provide context for modern rates of RSL change (Kopp et al., 2016), quantify glacio-isostatic adjustment (Piecuch et al., 2018), and evaluate the vulnerability of coastal ecosystems to future RSL rise (Schieder and Kirwan, 2019). Salt marshes, or more specifically the plants and micro-organisms (e.g., foraminifera; Edwards and Wright, 2015) that live on them, are sea-level proxies because they have observable and quantifiable relationships to tidal elevation (Woodroffe and Barlow, 2015). Recognition of these proxies in dated stratigraphies enables RSL to be reconstructed through reasoning by analogy, where vertical uncertainty is, to the first order, proportional to tidal range (Edwards et al., 2004; Engelhart and Horton, 2012; Williams et al., 2021). However, the relationship between salt-marsh plants or micro-organisms and tidal elevation is one of correlation rather than causation (Gehrels, 2000). Vertical zonation of intertidal species and communities arises from the interaction of environmental variables, which are themselves controlled principally by the balance between submergence and subaerial exposure. Therefore, application of sea-level proxies is underpinned by an implicit assumption that elevation is a robust approximation of the gradient in flooding regime and subsequently the ecologically-significant environmental variables.

In the United States, most tidal datums are derived from water-level measurements made by tide gauges over the National Tidal Datum Epoch (NTDE; currently 1983–2001), or the correlation of shorter-duration measurements with those from a control station (Gill and Schultz, 2001). In addition to astronomical tides, these measurements capture the effects of meteorological, hydrologic, and oceanographic conditions (mechanical and numerical filters remove the influence of high-frequency waves). RSL reconstructions from one site typically assume that the relationship among tidal datums (i.e., tidal range) was unchanged through time,

* Corresponding author.
E-mail address: andrew.kemp@tufts.edu (A.C. Kemp).

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although some studies apply modeled corrections for time-dependent variability of astronomical tides (Hall et al., 2013; Hill et al., 2011). Reconstructions spanning more than one region further assume that the relationship between tidal elevation and inundation is spatially invariant.

We use hourly water-level predictions and measurements from tide gauges along the U.S. Atlantic coast to evaluate the role and importance of non-tidal water-level variability for reconstructing RSL. The U.S. Atlantic coast is used as a case study because it has a wealth of accessible water-level data spanning locations with tidal ranges from <0.3 m to >5.5 m, and a high concentration of sites where RSL has (or could be) reconstructed from buried salt-marsh sediment (Engelhart and Horton, 2012; Gehrels et al., 2020). First, we examine if and where highest astronomical tide (HAT) is a reliable estimate for the upper limit of salt marshes. Secondly, we consider the influence of non-tidal processes in controlling water-level variability, with particular emphasis on how they can distort or bias RSL reconstructions in microtidal regions. Overestimation of precision coupled with potential temporal variability in non-tidal drivers of water levels, challenges the prevailing wisdom that all microtidal settings are ideal for reconstructing RSL.

2. Data and methods

The National Oceanic and Atmospheric Administration (NOAA) operates a network of tide gauges along the U.S. coast. Tidal datums are tabulated for ~1200 tide gauges in states on the Atlantic coast (Florida includes sites on the Gulf of Mexico), a subset of which have long-term water-level measurements. We downloaded all available hourly water-level measurements (relative to the station-specific mean lower low water datum; MLLW) for the NTDE from NOAA (https://tidesandcurrents.noaa.gov/stations.html?type = Water + Levels; last accessed February 9th 2022). We also downloaded the corresponding water-level predictions. Measured water levels are the outcome of all processes, while predictions include only astronomical forcing and the mean seasonal cycle (termed *tidal* for simplicity). The difference between measured and predicted water levels therefore estimates the contribution from non-tidal and non-seasonal processes (termed *non-tidal* for simplicity). Forty-three tide gauges on the Atlantic coast had values for HAT and measurements for >75% of the hours in the NTDE. We analyzed only these stations to balance the number and geographic distribution of sites against the possibility that missing measurements could bias our analyses. From these hourly data we calculated the elevation of inundation percentiles and the duration of water levels above standardized elevations and tidal datums using the VulnToolkit package (Hill and Anisfeld, 2021) for R. This analysis was performed for measured and predicted water levels. We estimate the relative importance of tidal and non-tidal processes in causing water-level variability by dividing the standard deviation of predicted (i.e., tidal) water levels by the standard deviation of measured (i.e., tidal plus non-tidal) water levels. A value of 1 indicates that observed water-level variability is exclusively from tides, while a value < 1 indicates that non-tidal processes contribute to variability. We term this quantity the *tidal ratio*.

3. Results

Great diurnal tidal range (termed *tidal range* for simplicity) is the difference in elevation between measured MLLW and mean higher high water (MHHW). Tidal range at the 43 analyzed stations varied from 0.30 m (Vaca Key, FL) to 5.9 m (Eastport, ME; Fig. 1). Tidal ranges <0.5 m occur in Chesapeake Bay, Pamlico and Albermarle Sounds, and parts of the Florida Keys. These microtidal regions are anticipated to generate the most precise RSL reconstructions using salt marsh (mangrove in the case of the Florida Keys) sediment (Cronin et al., 2019; Kemp et al., 2017; Toscano and Macintyre, 2003). Tidal ranges >3 m occur in the Gulf of Maine, where salt marshes are expected to generate RSL reconstructions with correspondingly large vertical uncertainties (Gehrels, 1999, 2000; Kelley et al., 1995). Tidal ratio varies from 1 at Bar Harbor, ME to 0.64 at Annapolis, MD; there are six sites where the tidal ratio is < 0.8 and they are all in Chesapeake Bay (Fig. 1B).

HAT is the single highest tide predicted for the NTDE and in the absence of non-astronomical drivers of water-level changes would correspond to an inundation only marginally >0%. Where the tidal ratio is > 0.9 (including sites with tidal range of 0.3–5.9 m), the mean duration of flooding above HAT is 0.2% (Fig. 2B). At seven sites (all in Chesapeake Bay with tidal radios <0.85), HAT was exceeded for >2% of the NTDE (Fig. 2B). The maximum duration of water levels above HAT (5%) occurred at Solomon's Island, MD. This result indicates that non-tidal forcing can result in water levels regularly exceeding HAT. While this behavior only occurs where tidal range is < 1.0 m, it is not a feature of all regions with small tidal range (e.g., tidal range at Vaca Key is 0.3 m, but water levels above HAT are 0.5% and the tidal ratio is 0.91; Fig. 2B). At the five stations in the Gulf of Maine where tidal range is 3.1–5.8 m (tidal ratio of ~1; Fig. 1B), the mean duration of measured water levels above HAT was 0.0002% of the NTDE (Fig. 2).

Flooding regimes are characterized by the proportion of time during the NTDE that particular elevations were submerged. To facilitate comparison of sites with different tidal ranges, we express elevation as a standardized water level index (SWLI), where a value of 0 corresponds to local MLLW and a value of 1 represents local MHHW (Fig. 3). In the upper part of the tidal frame, there are noticeable geographic patterns in flooding regime. At 1.0 SWLI (local MHHW), inundation across all sites is 8 ± 4% (mean ± one standard deviation), but where the tidal ratio is < 0.8 the mean exceedance of MHHW was 13.5% (up to 15.3% at Annapolis) and these sites occur exclusively in Chesapeake Bay. In contrast, at 21 stations where the tidal ratio >0.95, the mean exceedance of MHHW was 5.7%. Across all sites, the mean 1% flood elevation occurs at 1.24 ± 0.15 SWLI, but where tidal ratio is < 0.8 it is 1.52 SWLI, and it is 1.14 SWLI where tidal ratio is > 0.95.

4. Discussion

4.1. Inundation curves in regions with large, non-tidal variability

Measured water-level variability captures tidal contributions that are overprinted by non-tidal (i.e., meteorological, hydrological, and oceanographic) processes. Low tidal ratios occur where the magnitude of non-tidal variability is comparable to tidal variability (Fig. 1). If non-tidal fluctuations are 25%, 50%, and 100% as large as tidal variations, then tidal ratios are 0.97, 0.89, and 0.71, respectively. Low tidal ratios in Chesapeake Bay arise from relatively large non-tidal variability (Fig. 1D) being superimposed on a small tidal range (Fig. 1C). At Annapolis for example, predicted water levels have a standard deviation of 0.14 m, and exceed MHHW for 7% of the NTDE (Fig. 3B). In contrast, measured water levels had a standard deviation of 0.22 m and exceeded MHHW for 15.3% of the NTDE. This results in a tidal ratio of 0.64 (Fig. 1B) and non-tidal water-level variability with a standard deviation of 0.18 m (Fig. 1D). The uniquely low tidal ratios observed in Chesapeake Bay likely arise from the combined and interacting effects of winds, bathymetry, and geomorphology (Davies et al., 2021; Salas-Monreal and Valle-Levinson, 2008; Wang, 1979; Zhong et al., 2008) rather than systematic misprediction of astronomical tides. Similar effects likely occur in Albemarle and Pamlico Sounds (Luettich et al., 2002; Roelofs and Bumpus, 1953). At the USCG Cape

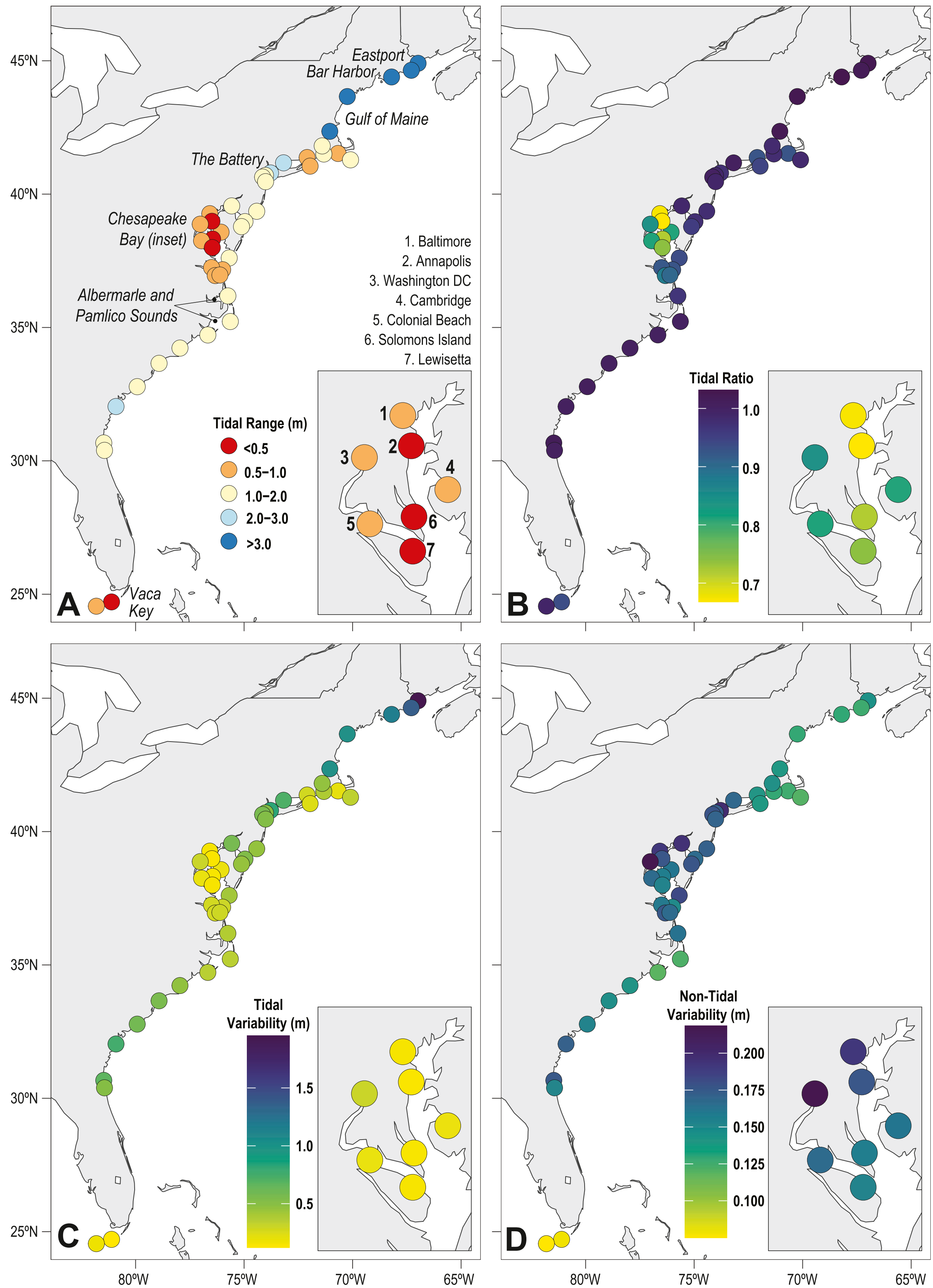

Fig. 1. **(A)** Great diurnal tidal range (difference between mean lower low water and mean higher high water) reported by NOAA for 43 tide gauges on the U.S. Atlantic coast where >75% of hourly water-level measurements and a prediction of highest astronomical tide are available. Locations discussed in the text are highlighted. **(B)** Tidal ratio (std [predicted]/std [measured]) used to estimate the relative contribution of tidal and non-tidal processes to measured water-level variability at **(C)** Standard deviation of tidal (i.e., predicted). water-level variability **(D)** Standard deviation of non-tidal (i.e., difference between measured and predicted). water-level variability.

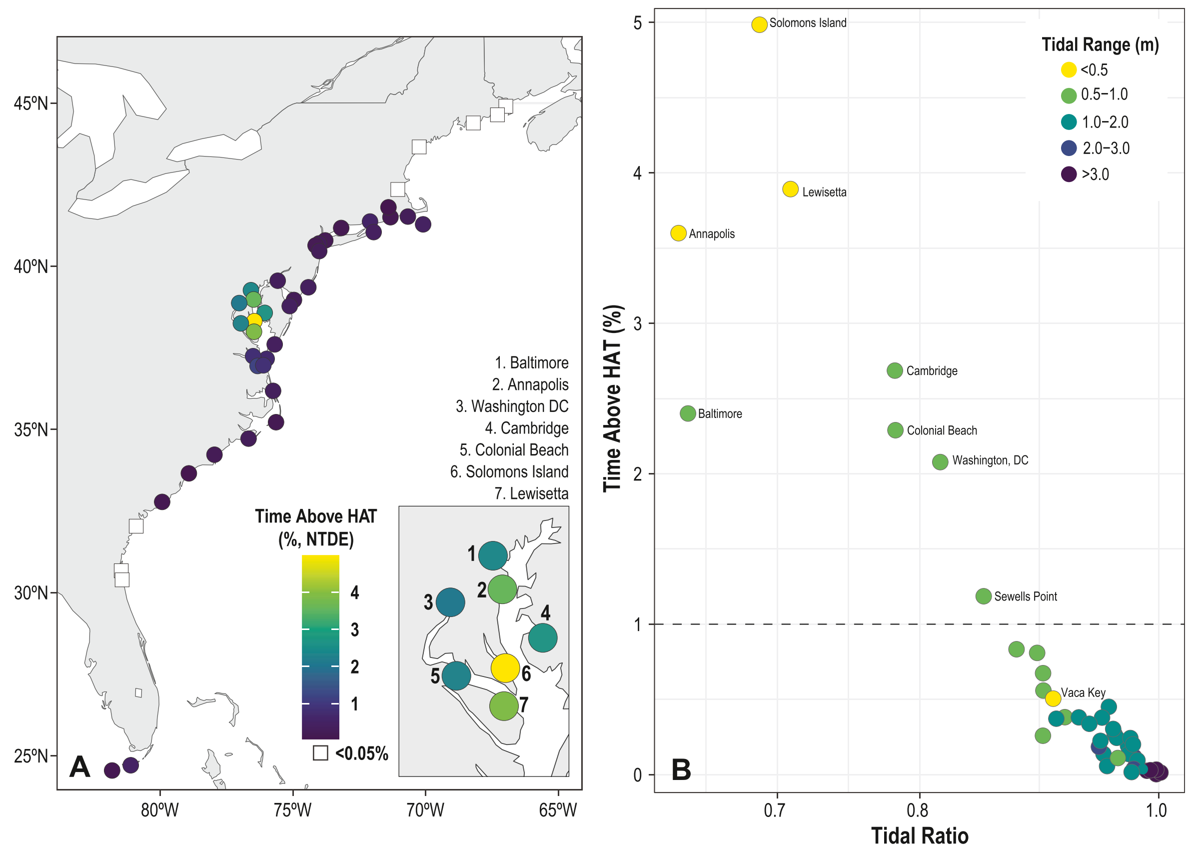

Fig. 2. Occurrence of water levels exceeding highest astronomical tide (HAT) during the National Tidal Datum Epoch (NTDE, 1983–2001). **(A)** Percentage of the tidal epoch (shading of circles) where water levels above HAT were measured by tide gauges. Open squares represent stations where water levels above HAT occurred <0.05% of the time. Locations discussed in the text are highlighted. **(B)** Relationship between duration of water levels above HAT and the tidal ratio, symbol shading corresponds to great diurnal tidal range.

Hatteras tide gauge, MHHW is above HAT and the VDatum tool (Hess et al., 2005) considers parts of Pamlico and Albermarle Sounds to be non-tidal because astronomical tides are so small compared to non-tidal water-level variations. Absence of tide gauges with long-term hourly measurements at sites behind the Outer Banks precluded including this region in our analysis.

Importantly, small tidal range is not a sufficient condition for low tidal ratio. At Vaca Key, tidal range is similarly small (0.30 m), such that predicted water levels have a standard deviation of 0.12 m (Fig. 1). However, non-tidal variability is small, and measured water levels had a standard deviation of 0.13 m. Consequently, the tidal ratio there is 0.91, and there is little difference between flooding duration above MHHW in predicted (14.1%) and measured (14.6%) water levels (Fig. 3C). At The Battery (New York City), the standard deviation of non-tidal water-level variability (0.17 m) is similar to Annapolis (0.18 m). However, since this value is modest compared to tidal variation (0.51 m), non-tidal fluctuations at The Battery do not appreciably affect the inundation curve (Fig. 3C), and the tidal ratio is high (0.96). Thus, at sites with small tidal range, non-tidal fluctuations can influence inundation frequency, but only when tidal and non-tidal variations have comparable magnitudes. Sites with larger tidal range can absorb non-tidal variability because it remains modest in scale compared to the tides (e.g., Williams et al., 2016).

4.2. Implications for generating sea-level index points from high-salt marsh sediment

On the Atlantic coast of North America sea-level index points are generated by recognizing plant macrofossils or assemblages of microorganisms preserved in buried sediment that are diagnostic of deposition in a discrete sub-environment (Engelhart and Horton, 2012; Vacchi et al., 2018). Typically, high salt-marsh sediment is preferred for reconstructing RSL because it forms in a relatively narrow elevational range, offers good preservation of proxies, and provides abundant material for radiocarbon dating. It is often assumed to form between mean high water (MHW; a measured datum) and HAT (a predicted datum). This approach requires that the inundation regime associated with each tidal datum (particularly those thought to mark the upper limit of salt marshes) is (i) spatially and (ii) temporally invariant. However, the frequency and duration of water levels exceeding HAT is spatially variable. In some microtidal regions (such as Chesapeake Bay) non-tidal factors systematically elevate water levels relative to this predicted datum (Fig. 2), with the effect that a key assumption underlying RSL reconstruction is invalidated.

Since the relationship between HAT and inundation is spatially variable, an alternative measure for the upper limit of salt-marsh formation must be found. Ideally, the limits of salt-marsh distribution (or more specifically the elevational range of the proxy being employed to reconstruct RSL) would be established empirically for each study site and region. However, when compiling and standardizing existing data (e.g., Engelhart and Horton, 2012; Khan et al., 2019) empirical observations for all proxies are rarely available at the desired spatial scale and a generic, albeit imperfect, solution is sought. Empirical inundation percentiles may be used in this capacity, if a particular percentile is ecologically plausible. One of the most robust and widely used approaches to identifying

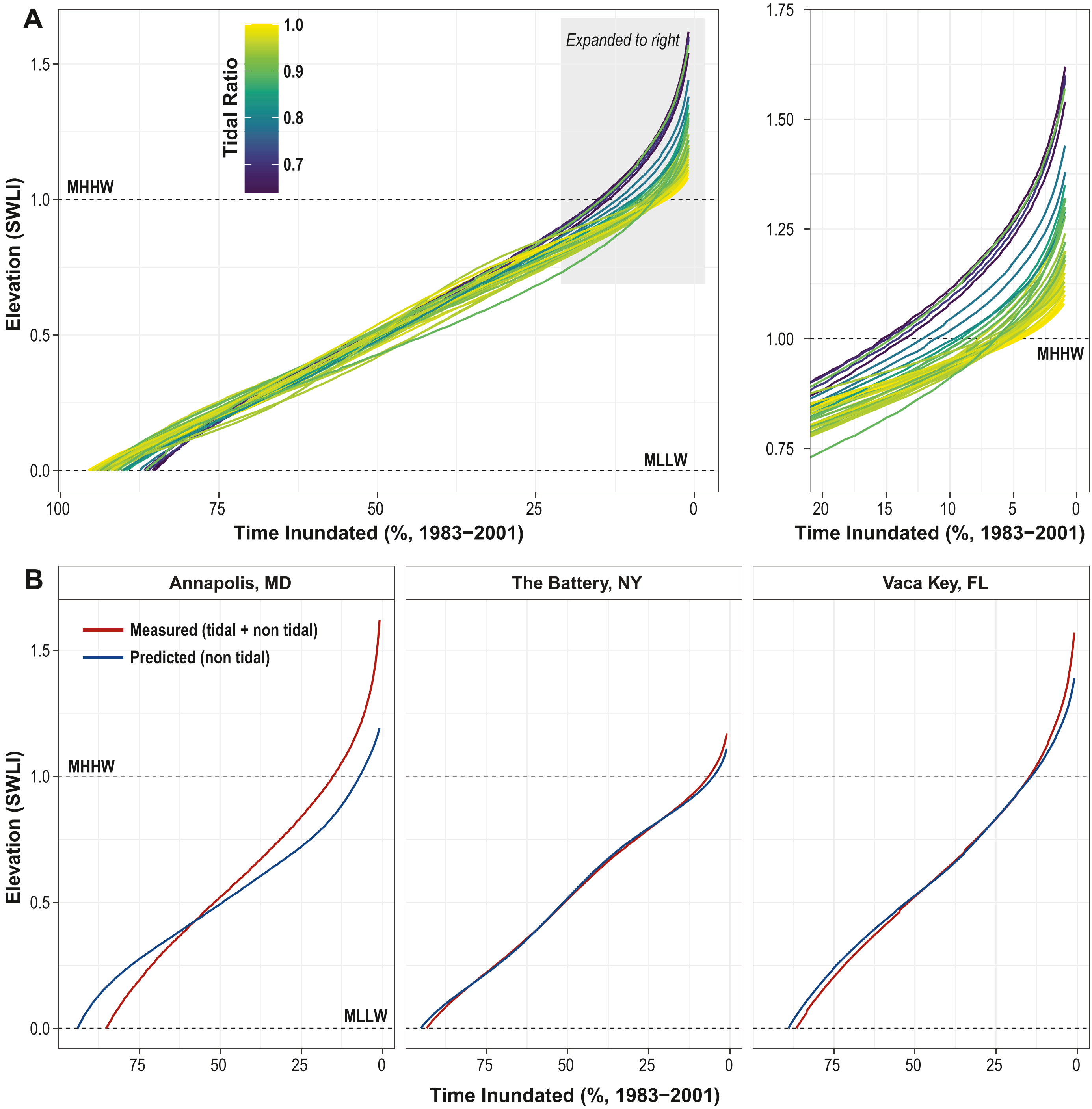

Fig. 3. **(A)** Inundation curves calculated for 43 tide gauges from hourly-tide gauge measurements (minimum 75% complete over the National Tidal Datum Epoch with a reported value for highest astronomical tide). Elevation is expressed as a standardized water level index (SWLI) to facilitate direct comparisons among sites with different tidal ranges. A value of 0 corresponds to local mean lower low water (MLLW) and a value of 1 represents local mean higher high water (MHHW). Right hand panel is a detailed view of the uppermost part of the tidal frame. Line shading corresponds to the tidal ratio, where a value of 1 indicates that water-level variability is solely from tides and values < 1 indicate that measured variability includes a contribution from non-tidal processes. **(B)** Inundation curves calculated using measured (tidal and non-tidal) and predicted (tidal only) water levels at three example stations.

sediment that accumulated in a high salt-marsh environment is the presence of characteristic assemblages of foraminifera (e.g., Edwards and Wright, 2015). Therefore the inundation level equivalent to (and likely controlling) the highest occurrence of foraminifera observed on modern salt marshes is an appropriate ecological datum in the context of reconstructing RSL (Wright et al., 2011). Anisfeld et al. (2017) examined two salt marshes in Connecticut to precisely locate the highest occurrence of foraminifera relative to local water levels that were measured by automated loggers. This analysis estimated that the highest occurrence of foraminifera occurred at elevations experiencing inundation of 0.7–3.2% over the ten years prior to sample collection. Ten years is a reasonable approximation of the time represented by the 1-cm thick surface sediment samples that are used to describe modern foraminiferal assemblages. We note that RSL rise since the end of the NTDE in 2001 complicates efforts to establish the relationship between recently-collected modern foraminifera and tidal datums. To corroborate the result of Anisfeld et al. (2017), we analyzed measured water levels in the decade preceding sampling of modern foraminifera by Wright et al. (2011). We chose this study because it took particular care to precisely locate the highest occurrence of foraminifera. At Pattagansett, CT and Elizabeth River, NC the highest occurrence of foraminifera corresponded to inundation frequencies of 0.7% and 1.0% respectively. Therefore, we adopt a 1% inundation level (over the NTDE) as the upper limit for salt-marsh formation to illustrate the effect of using a measured, ecologically-significant datum rather than HAT when generating sea-level index points. While our analysis uses the distribution of foraminifera as an example, alternative limits (including other inundation percentiles) could be also be defined for other proxies (e.g., plants, diatoms, testate amoebae, stable carbon isotopes) and these would be most robust when established empirically from systematic modern observations.

Existing compilations of sea-level index points from the U.S. Atlantic coast treated high salt-marsh sediment as forming between MHW and HAT (Engelhart and Horton, 2012), which is consistent with efforts to reconstruct Holocene RSL elsewhere (e.g., Khan et al., 2019; Vacchi et al., 2018). Consequently, the vertical uncertainty for high salt-marsh sea-level index points is proportional to tidal range and varies from $\pm$0.08 m (at Solomons Island) to $\pm$0.64 m (at Eastport). Across all sites, the mean difference between the 1% inundation elevation and HAT is 5% of tidal range, where the positive value indicates that HAT is higher than the 1% inundation elevation. If high salt-marsh sea-level index points were instead treated as forming between MHW and the 1% inundation level, the reconstruction uncertainty is reduced on average by 13.2% (i.e., RSL reconstructions are made more precise; Fig. 4A). In this context, approximating the upper limit of salt marshes as HAT results in a more conservative estimate of vertical uncertainty in RSL reconstructions than if the 1% inundation level was used instead. However, there is spatial variability in the relationship between HAT and the 1% inundation level.

Where the tidal ratio is > 0.85 adopting the 1% inundation level as the upper limit of salt-marsh formation would increase the precision of RSL reconstructions (Fig. 4B). In contrast, adopting the 1% inundation level at locations with tidal ratios <0.85 (namely Chesapeake Bay), results in a mean increase in vertical uncertainty of 44% (range 7–89%; Fig. 4B). In these regions the precision of sea-level index points developed from high salt-marsh sediment may currently be systematically and significantly over estimated. Furthermore, since the 1% inundation level is above HAT, its adoption as the upper limit of salt-marsh formation would also lower RSL reconstructions at these sites. We propose that efforts to reconstruct Holocene RSL by creating sea-level index points from salt-marsh sediment adopt a percentage inundation level as the upper limit for salt-marsh formation. This step would improve comparability of RSL reconstructions among regions and is likely to provide a more robust means to quantify vertical uncertainty than continued use of predicted datums that do not capture the influence of non-tidal factors causing systematic water-level variability in some regions (often those characterized by small tidal ranges).

Near-continuous RSL reconstructions spanning the late Holocene are developed from stratigraphically-ordered samples in a single core (usually of high salt-marsh sediment), where sample age is estimated from an age-depth model (e.g., Gehrels et al., 2020; Gerlach et al., 2017). In these reconstructions depositional elevation is often treated as a continuous variable through application of transfer functions (Kemp and Telford, 2015). Although this approach does not rely on a specific tidal datum to represent the upper limit of salt-marsh formation, there is a prevailing wisdom that the vertical uncertainty is typically 10–15% of tidal range (Barlow et al., 2013). However, in regions with very small tidal range, uncertainty is often proportionally larger and can reach ~50% of tidal range (Kemp et al., 2017; Williams et al., 2021). Since these errors represent a ~1σ range, microtidal regions may not produce near-continuous RSL reconstructions with the anticipated reduction in vertical uncertainty. The proportionally large errors for transfer functions in microtidal locations occur for two reasons. Firstly, non-tidal drivers can elevate water levels (Fig. 3B) resulting in communities of foraminifera living at unusually high elevations. For example, if elevation is standardized so that MTL = 0 SWLI and MHHW = 1 SWLI, the highest occurrence of foraminifera in regional datasets of salt-marsh foraminifera from Connecticut and southern New Jersey (tidal ranges approximately 1–2 m) is at ~1.3 SWLI (Kemp et al., 2013, 2015). In North Carolina (tidal range <0.5 m and as small as 0.13 m) the highest occurrence of foraminifera occurs at >6 SWLI (Kemp et al., 2009). Secondly, the largest source of uncertainty in transfer functions is modeling the relationship between taxa and elevation from the modern dataset. This is challenging where the environmental gradient is compressed because it weakens vertical zonation by enabling secondary factors (such as dampening of water levels across expansive marshes and variability among sites of non-tidal drivers that could arise for example from geomorphology and site aspect) to obscure the relationship between foraminifera and elevation (Kemp et al., 2009; Williams et al., 2021).

4.3. Time-variable tidal ratios

Analysis of water-level measurements demonstrates that regions experiencing proportionally large non-tidal water-level variability (low tidal ratios) have inundation curves that differ from those in regions where tidal variability is dominant (tidal ratios approaching 1; Fig. 3). Today, low tidal ratios occur only in regions with small tidal range (Chesapeake Bay and likely Albemarle and Pamlico Sounds), although not all microtidal systems are characterized by low tidal ratios (e.g., the Florida Keys; Fig. 2). Since tidal ratios in the current NTDE are observed to vary among sites, space-for-time substitution dictates that they could also vary through time (Haigh et al., 2020; Talke and Jay, 2020). Indeed, on historical time scales, analysis of water-level measurements over different windows shows that water-level extremes during storm surges (a non-tidal process) can change through time (e.g., Talke et al., 2014; Wahl and Chambers, 2015). On the longer (centennial to multi-millennial) timescales, changes in non-tidal variability are potentially larger. Stationary tidal range is a common assumption (explicit or otherwise) in RSL reconstructions (Gehrels et al., 1996), but in most instances changes in tidal range through time are evaluated as a consequence of astronomical tides and the role of non-tidal factors in controlling water levels is overlooked (see review in Griffiths and Hill, 2015). A further complication is that historic changes in tidal range (e.g., from coastal engineering at Wilmington, NC; Li et al., 2021) can render inundation values and tidal datums measured over the NTDE unrepresentative of those that occurred during the late Holocene. Efforts to apply corrections for tidal-range change typically focus on modeling how astronomical tides evolved through the Holocene in response to bathymetric changes (Gehrels, 1999; Gehrels et al., 1995; Hall et al., 2013; Hill et al., 2011). The assumption of stationary tidal range should be expanded (particularly in microtidal settings) to stationarity of inundation curves and recognize that, by extension, this requires assumed stationarity of non-tidal drivers. This expanded assumption is likely harder to justify, or to correct for using modeling (Haigh et al., 2020; Talke and Jay, 2020). The potential

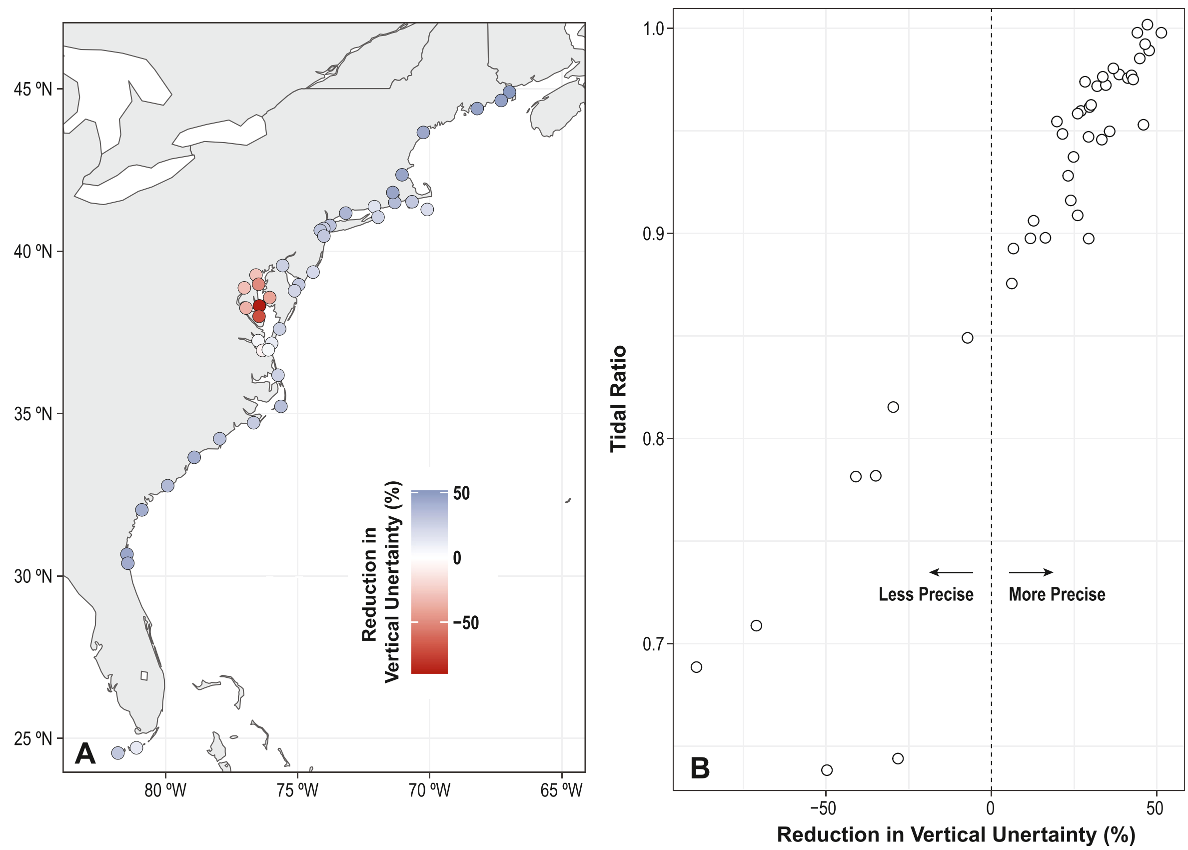

Fig. 4. Effect of adopting the 1% inundation elevation rather than highest astronomical tide (HAT) as the upper limit for salt-marsh formation. **(A)** Change in vertical precision of sea-level index points developed using high salt-marsh sediment. Negative values indicate reduced vertical precision (greater uncertainty), while positive values indicate that reconstruction precision increased (reduced uncertainty). Estimates are for a theoretical sea-level index points developed from salt marshes where water-level variability is the same as that measured at the 43 tide gauges. **(B)** At locations with small tidal ratios using the 1% inundation level rather than HAT results in greater uncertainty. Therefore, existing sea-level index points may systematically overestimate precision.

advantage of decreased vertical uncertainties for RSL reconstructions from microtidal regions must therefore be tempered by recognizing that those reconstructions are likely underpinned by assumptions about past meteorological, hydrologic, and oceanographic conditions that are difficult to test and substantiate. In contrast, where tidal range exceeds ~1 m, tidal ratios are uniformly large indicating that time-evolving contributions from non-tidal processes are less likely to materially bias Holocene RSL reconstructions.

5. Conclusions

Sediment that accumulated in high salt-marsh environments is commonly targeted to reconstruct Holocene RSL, often with an assumption that regions with small tidal range produce the most precise records. We analyzed hourly predicted and measured water levels from tide gauges on the U.S. Atlantic coast to evaluate how water-level variability arising from meteorological, hydrologic, and oceanographic processes may affect RSL reconstructions. Where non-tidal variability is relatively large in comparison to tidal variability, the relationship between elevation and inundation is distorted compared to sites with relatively modest non-tidal variability. This distortion characterizes some (e.g., Chesapeake Bay), but not all, microtidal regions with two principal implications for reconstructing RSL. Firstly, adopting HAT as an upper limit for salt-marsh formation can systematically underestimate vertical uncertainty. We propose adopting a percentile of inundation (e.g., 1%) to improve the accuracy and comparability of RSL reconstructions. Secondly, assumptions about stationary tidal range through time should more explicitly recognize stationarity of inundation regimes. Microtidal regions are more susceptible to invalidating this assumption because of time-evolving contributions to water-level variability from non-tidal processes.

Author statement

Andrew C. Kemp: Conceptualization, Methodology, Formal analysis, writing, Visualization. **Timothy A Shaw**: Conceptualization, writing, Visualization. **Christopher G Piecuch**: Methodology, Formal analysis, writing, Visualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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