Author Response

This document includes a list of key changes made to the manuscript, a point-by-point response to the two reviews, and a marked-up manuscript version.

Key manuscript changes:

- Added an analysis of mean foundation depth of primary benchmarks for comparison with our original analysis of deepest known benchmarks. We find that primary benchmark foundation depths are indistinguishable from the dataset as a whole.
- Added further analysis of data presented in Jankowski et al. (2017), suggesting that shallow subsidence occurs dominantly in the uppermost 5 m of wetland stratigraphy.
- Added data on the foundation depths of tide gauge benchmarks in the Netherlands, which support our assertion that the issues discussed in this manuscript are likely global in scope.
- Expanded our discussion to include benchmarks mounted on concrete structures with unknown foundation depths; we suggest that these structures are likely anchored at some depth below the surface and thus continue to support the main argument of our paper: that tide gauges with benchmarks anchored at depth do not record all shallow subsidence.
- Clarified that tide gauges remain critical for measuring many processes (e.g. tides, storm surge) and that we are merely discussing a specific (yet important) context where tide-gauge data may not be the best option.
- Expanded discussion of the limitations of various instruments and methods of measuring RSLR and further describe data analysis techniques that could be used to overcome some of these shortcomings.
- Clarified the novelty of work presented here and improved description of how it fits into the recent literature.

Response to the manuscript review by Philip Woodworth
Reviewer comments are in bold text; author responses are in normal text

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This paper makes use of a data set of benchmark (BM) depths at tide gauges and GPS stations in Louisiana, which enables the authors to come to conclusions regarding the ability of tide gauges to make accurate measurements of relative sea level rise in this and similar deltas. They make some recommendations on how such measurements might be done better.

We greatly appreciate this review by Dr. Philip Woodworth and his expertise in tide gauge data analysis. We also value the input from the NOAA colleagues. We have closely followed the recommendations provided in this review and believe that our manuscript is considerably improved as a result.

This is short paper which is mostly written well with decent figures. I am sure that the topics addressed have been discussed by these and other authors previously. Also they do not produce any actual new results on relative sea level trends in the area. Nevertheless the BM data set does result in a nice couple of plots which enable them to make their main point well. So I would have no objection to seeing this paper published eventually, although I do have some comments on their arguments and on the way some of the text is written.

To our knowledge, our study is actually the first systematic investigation of the foundation depths of tide gauge benchmarks and GNSS stations and the resulting implications for measurement of relative sea-level rise (RSLR). Our purpose is not to reinvent the wheel by reanalyzing time series. Instead, we draw attention to a limitation of tide-gauge data and present an alternative approach to measuring RSLR in low-elevation coastal zones.

One comment is a technical issue to do with the way that NOAA works. The authors say correctly that there are typically half a dozen BMs at each tide gauge site. Many of these are deep ones and Table 1 lists the depths of the deepest in each case. If the datum of the tide gauges is defined relative to one of these deep marks, then I can understand the arguments of the authors that relative sea level rise could be underestimated.

However, sometimes there are also surface (or near surface) marks which can appear as 'zero depth (N/A setting)' in Table S1 of the paper. Now, the NOAA web site (https://tidesandcurrents.noaa.gov/datum_options.html#STND) states explicitly that: "Station datum is referenced to the primary bench mark at the station for the definition of the tide gauge station datum".

Excellent point. We have added the clarification that NOAA tide gauges are typically leveled using a benchmark designated as the primary benchmark; secondary benchmarks are used to assess the stability of the primary benchmark. See lines 95-97.

Please note that no benchmarks listed in Table S1 are anchored at depth = 0. The shallowest benchmark is anchored at 0.9 m. A few benchmarks have unknown foundation depths (which are listed in Table S1 as "unknown"), but this should not be interpreted to be foundation depth = 0. This clarification has been added to the manuscript in lines 187-188. Several other tide gauges listed in Table S1 have no published benchmarks; in this case, the benchmark setting type and foundation depth are left blank. This is now clarified in the header of Table S1.

So, if the designated primary mark is a surface mark, the Station Datum at the gauge will have been defined by the land surface and their arguments will not apply.

In principle, we agree with this assessment: a tide gauge leveled to a primary benchmark that is anchored at the ground surface records RSLR with respect to the ground surface. However, we argue that few, if any, benchmarks in coastal Louisiana are actually anchored at ground level. See below for details. In Table S1, we have added a column listing the depth of primary benchmark foundations, wherever known.

Now, the only important site in the delta with a decent long record is Grand Isle. That has data from 1947 and its benchmark sheet (available from the NOAA web site) shows that the primary mark is BM10 which is a "survey disk on the sea wall" (again shown as zero depth and N/A setting in Table S1). This is a surface mark so the arguments of the authors do not apply here.

This is an important point and we have added detailed clarification in the manuscript. Table S1 includes two Grand Isle tide gauges. The older gauge recorded data from 1947-1980; the newer gauge has been operational since 1979. Although the two datasets are typically combined, the tide gauges have different station numbers assigned by NOAA and the older gauge is not associated with any currently-published benchmarks. The newer gauge has 5 benchmarks, and, as noted by the reviewer, the primary one is set on a seawall. Note that Table S1 indicates that this primary benchmark has an unknown foundation depth rather than listing it as foundation depth = 0.

Although the primary Grand Isle benchmark is indeed mounted on a concrete seawall, we disagree that it is a surface mark with foundation depth = 0. Just as a benchmark mounted on a steel rod driven to depth responds to changes in elevation with respect to the base of the rod, a benchmark mounted on a concrete structure responds to elevation changes with respect to the foundation of the concrete structure. Although we were unable to acquire construction details for the seawall, it is highly unlikely that the seawall is simply resting on the ground surface. We expect that the seawall foundation extends at least several meters into the subsurface in order to provide stability and protection to the adjacent Grand Isle Coast Guard station. If this is indeed the case, the primary Grand Isle benchmark should NOT be considered a surface mark. That said, we agree that it is conceivable that the foundation depth of the primary benchmark at Grand Isle is considerably shallower than that of the deepest benchmark (19.8 m). We have added this important point in the text (see lines 235-248), recognizing that this may reduce the underestimation of the rate of RSLR at this tide gauge.

This important comment prompted us to carry out some further analysis of data presented in Jankowski et al. (2017), suggesting that shallow subsidence occurs dominantly in the uppermost 5 m of the wetland stratigraphy in this region. Using data from 274 monitoring stations across coastal Louisiana, Jankowski et al. (2017) calculated a mean shallow subsidence rate of 6.8 ± 7.9 mm yr^{-1}. Limiting this analysis to stations where the instrument is anchored in Pleistocene strata and the overlying (Holocene) strata are <5 m thick, we find a mean shallow subsidence rate of 6.4 ± 5.4 mm yr^{-1}. The similarity in these two calculated shallow subsidence rates suggests that even tide gauges with associated benchmarks anchored only a few meters deep do not fully capture the shallow subsidence signal. We have included discussion of this additional analysis in lines 249-257 of the manuscript.

I looked at the information on the NOAA web site for all 31 NOAA stations given in Table 1 of the paper (i.e. the 35 stations listed minus 4 USACE stations). The NOAA web site information is essentially the same as in Table S1. Of the 31, 6 have primary marks which are surface (or very near surface) marks: Caminada Pass, East Bay, Grand Isle, Lafitte, Martello Castle and Weeks Bay. If the authors agree with this then I think their text should mention it.

We have added a column to Table S1 that lists the depth of the primary benchmark foundation, when known. The primary benchmarks for six tide gauges (Caminada Pass, East Bay, Freshwater Canal Locks, Grand Isle, Lafitte, and Martello Castle) are all set into some type of concrete structure rather than attached to steel rods that are driven to depth. Similar to the argument outlined above for the seawall at Grand Isle, we reason that most, if not all, of the concrete structures hosting benchmarks in coastal Louisiana likely have some type of foundation that extends below the ground surface. If this is the case, the primary benchmarks for the six tide gauges listed above should not be considered surface marks, although their foundations may be considerably shallower than the deepest benchmarks.

The benchmark datasheets available on the NOAA website provide only basic descriptions of the concrete structures on which these primary benchmarks are mounted: concrete retaining wall (Caminada Pass), concrete platform (East Bay), cement structure (Freshwater Canal Locks), concrete seawall (Grand Isle), concrete foundation for a small pumping station (Lafitte), and rough poured concrete (Martello Castle).

Note that the primary benchmark for the Weeks Bay tide gauge is attached to a steel rod driven to an unspecified depth, as is the primary benchmark at Cypremort Point. We assume that these rods are similar in length to those used for other NOAA benchmarks (~10-35 m) and thus these benchmarks should not be considered surface marks.

Just in case, I checked my interpretation about the way NOAA works with the COOPS Technical Director (Dr. Peter Stone) and Chief Scientist (Dr. Greg Dusek). They replied: "We control the water level observation primarily off of one primary bench mark (PBM) and then ensure the stability of that mark by using the remaining 9 or so marks. On occasions when we see substantial and/or continual differential movement between the PBM and the other marks, we adjust the PBM to a different mark determined to be
stable relative to the remaining marks."

We appreciate the input from Dr. Peter Stone and Dr. Greg Dusek. We have added this clarification to the manuscript: Tide gauges are typically leveled using a benchmark designated as the primary benchmark; secondary benchmarks are used to assess the stability of the primary benchmark (NOAA, 2013). See lines 95-97 in the manuscript.

So that confirms what is on the NOAA web site, and confirms that my comments about the six mentioned above, and Grand Isle in particular, are correct. They do not fit into the main argument of the paper, so there should be some extra wording to handle that. As for the other 25 stations in Table 1 for which the primary mark is a deep one, then I agree with their comments, but only in principle, and only at a time way into the future when these stations will have acquired records long enough for trend estimation.

For our original analysis, we chose to use the benchmark with the deepest known foundation in order to maximize the size of our dataset: 35 tide gauges have at least one benchmark with known foundation depth, but primary benchmark depths are known for only 23 tide gauges. Based on the reviewer's thoughtful comments, we have added an analysis of primary benchmark foundation depths. For benchmarks with known foundations depths (i.e. those mounted on steel rods driven to refusal), we find that primary and deepest known benchmarks are anchored an average of 21.4 ± 3.9 m and 21.5 ± 7.4 m below the surface, respectively. Note that for 8 of 23 tide gauges (35%), the primary benchmark is also the benchmark with the deepest known foundation. The mean foundation depth for all benchmarks is 21.0 ± 5.4 m. Thus, we see that primary benchmark foundation depths are indistinguishable from the dataset as a whole. We have added this new analysis in lines 190-196 in the manuscript.

As discussed above, benchmarks anchored on concrete structures are unlikely to have a foundation depth of zero. Instead, we suggest that the concrete structures that host benchmarks are likely anchored at some depth below the surface and thus the associated tide gauges continue to support the main argument of our paper: that tide gauges with benchmarks anchored at depth do not record all shallow subsidence. We do recognize, however, that these structures with unknown exact foundation depths, may be anchored at shallower depth than steel rods. See expanded discussion of this issue in lines 183-188 and 235-248 of the manuscript.

Stone and Dusek remarked: "The large number of tide gauges used in the analysis is very perplexing. The NOAA gauges [mentioned in Table 1] (which were installed by CO-OPS) were installed for wide ranges of time. Two of the gauges (Shell Beach and Grand Isle) were installed for decades and we have calculated relative sea level change rates. The others have only been installed for a few months or years and do not have enough data to calculate statistically significant RSLR [relative sea level rise]."

It is true that many of the tide gauges used in our analysis of benchmark depths were active for only a couple of years and do not have enough data to calculate a meaningful rate of RSLR. However, the purpose of this study is to investigate the foundation depths of published benchmarks, not to re-calculate rates of RSLR. Even though a significant proportion of the tide gauges may never become suitable for RSLR studies, they allow us to greatly expand the dataset on benchmark foundation characteristics. All of the foundation depths discussed in the paper come from currently-published benchmarks, even if the associated tide gauges are no longer active. See lines 222-224.

Now, Grand Isle I have already mentioned. In fact, Shell Beach has a deep primary mark, so I accept that the argument of the authors applies for that. But as Shell Beach has data (in the PSMSL) only for 2008-2017, it is hardly yet a long record. So I think some care should be taken in

the text between explaining what could happen IN PRINCIPLE regarding tide gauges with deep primary marks, and what is the real situation at the moment in the delta.

This is a good point. We have added clarification that many of the tide gauges listed in Table 1 are not useful for RSLR analyses due to their short records. However, some of the tide gauges that currently have short records could become important in the future as their records become longer (e.g. Shell Beach). Additionally, our analysis shows that benchmarks with deep subsurface foundations are the norm in coastal Louisiana and thus any rates of RSLR calculated using tide-gauge data likely do not include shallow subsidence. See lines 224-231.

This takes me to two mentions of the PSMSL in the paper. At line 50 the authors state that there are 5 PSMSL stations in Lousiana but do not give their names. They are Eugene Is (data 1939-1974), Grand Isle (1947-2017), South Pass (1980-1999), Shell Beach (2008-2017) and New Canal Station (2006-2017). As mentioned above, Grand Isle is the only important one for sea level trends. The PSMSL defines RLR datum at Grand Isle (and other NOAA sites) using the Station Datum information in each case that NOAA provides. Therefore, I think there should be a mention somewhere in the paper to the effect that the sea level rate at Grand Isle provided by the PSMSL record is not likely under-estimated as the text presently implies.

We have added the names of the five tide gauges and the years for which they have produced relative sea-level data (see lines 74-75). Our results continue to suggest that the Grand Isle tide gauge is likely underestimating the rate of RSLR. See detailed discussion above.

The other mention of the PSMSL is in the paragraph at lines 250-261. It again mentions only 5 PSMSL stations in the area. Why? The PSMSL cannot be expected to databank the density of stations that the authors need, so to somehow conflate the PSMSL with that requirement seems strange to me. In fact, what the PSMSL would be happy with in an area this size is a single tide gauge station with GPS and good BM control. Anyway, the authors show potentially they have many more than 5 so what is their problem? Also the paragraph says that of the 5 'only a few' have RSET nearby. If one takes 'a few' as meaning 3 or similar then one could read this sentence as saying that most PSMSL stations have RSET, which I think is opposite to what the authors want to say! So this paragraph needs rewording and I can't see why the PSMSL is being dragged into it at all.

We agree that conflating PSMSL with our proposed network is not appropriate. We have deleted the mention of PSMSL in this paragraph and reworded the text accordingly.

Conclusions - so I see the problems that the authors raise about deep BMs, in principle. However, I do not buy the suggestion that, instead of tide gauges, a better job could be done using RSET-MH data which seems to me to be a very rough and ready method, combined with GPS for deep submergence, combined with altimetry. RSET, GPS and altimetry data all have their own nuances and problems, and in particular altimetry until fairly recently has had problems getting very close to the coast. Tide gauges could do the job you want if you have at least one surface mark at each site, and if there is ongoing monitoring of the relative heights between surface and deep BMs. That

would solve your problem; a conversation with NOAA is required about constructing a history of the evolution of relative heights between benchmarks at each site.

We have added to the section in the manuscript acknowledging the limitations of various instruments and methods of measuring RSLR and describe data analysis techniques that could be used to overcome some of these shortcomings (see lines 330-346). As discussed above, however, we believe that most, if not all, benchmarks in coastal Louisiana are anchored at depth, including those anchored on concrete structures. There is no evidence for any true surface benchmarks in the area.

Stone and Dusek commented to me also that "The authors' did not address the mounting of the water level sensors on different structures they were comparing and how those structures can be affected by settling. Some of the stations used in their comparisons are probably installed on piers where the pilings may only be sunk a few feet. Others, like the water level stations at Shell Beach and Calcasieu Pass, LA are mounted on massive steel structures driven into consolidated sediments (which we refer to as SPIPs). The type of installation can be relevant to consider when attempting to accurately assess sensor movement relative to bench marks on land, and presumably in the cases of the SPIPs, our leveling data could indicate if deep rod marks and the shallower rod or concrete marks show variable long-term trends relative to the water level observations."

As we understand, this is exactly why tide gauges are leveled using benchmarks in the first place: to correct for any drift in the instrument that could be caused by a variety of processes, including the settling of the support structure. It seems that this issue is accounted for in well-executed monitoring programs, and thus is not something that our study needs to consider.

So, while accepting the general main point of the authors, I think the main thing is to have access to histories of all the relevant surveying information at a site. A last comment about the Conclusions is an obvious one, that the correct scientific approach is to make use of data from all techniques and see eventually how they compare, not just suggest rejecting tide gauges (which NOAA pay for, given that they are anyway needed for monitoring transient events such as storm surges) by adopting an 'alternative approach'.

This is an excellent point. We now note that best scientific practices will make use of all available data and compare the results of various measurement techniques. Furthermore, tide gauges remain critical for measuring many processes, including tides (the original and still-primary purpose of tide gauges) and event-scale phenomena such as storm surge, and are invaluable in this regard. See lines 311-315.

The Conclusions also makes some comments about deltas elsewhere around the world and lists some in Table 3. How many have deep BMs like in Louisiana? I suspect most do not, but at best have surface marks in which these arguments will not apply. It would be interesting to know.

We believe that benchmarks in other low-elevation coastal zones are likely constructed in a broadly similar fashion to those in coastal Louisiana: either attached to rods driven to refusal or mounted on existing structures with non-negligible foundation depths. For example, from conversations with Dutch colleagues, we understand that tide-gauge benchmarks in The Netherlands are ~5-25 m deep and generally anchored in the Pleistocene basement except in areas very near the coast where the Pleistocene sediment thickness is greatest (See Table 4). In other words, conditions in The Netherlands are roughly comparable to those in the Chenier Plain of coastal Louisiana (and likely other “thin” LECZs): they do not capture the shallow subsidence component, but since benchmarks are generally anchored in a relatively stable substrate they are easier to interpret than many of the tide gauges in the Mississippi Delta (and likely other “thick” LECZs) where benchmarks are essentially “floating” in the Holocene succession. Although we are fortunate to have acquired precise benchmark data from The Netherlands, we have found that information on benchmarks in other LECZs is very difficult to come by. A global analysis of benchmark construction would be a valuable but massive undertaking and is beyond the scope of the present manuscript.

So for the reasons above I think some rewriting of the text is required.

Detailed comments:

line 17 and elsewhere - GPS is better denoted at GNSS (Global Navigation Satellite System) these days.

Thank you for this recommendation. We have changed GPS to GNSS throughout the manuscript.

line 35 - a reference to long tide gauge records in N Europe and N America could be Woodworth et al. (Surveys in Geophysics, 2011). The longest US record was claimed for many years to be Key West (Maul and Martin, GRL, 1993) but I guess now one should also mention Boston (Talke, JGR, 2018).

We have added mention of the Key West, Boston, and San Francisco tide gauges and references to Maul and Martin (1993), Woodworth et al. (2011), and Talke et al. (2018). See lines 56-58.

line 49 - the PSMSL should be referenced by its web site and journal (http://www.psmsl.org and Holgate et al., J Coastal Res, 2013)

We have added these references. See lines 72-73.

line 50 - give the names of the five (see above)

We have added the names of the five tide gauges and the years for which they have relative sea-level data. See lines 74-75.

line 89 - these references should also include the IOC Manuals, see http://www.psmsl.org/train_and_info/training/manuals/

Good suggestion, we have added a link to the IOC training manuals. See lines 124-125.

line 125 - a reference is needed for where you got the Pleistocene surface information from.

We have added a reference to Heinrich et al. (2015). See line 165.

line 169 - ’because all tide gauge benchmarks’. This is not true, see above.

We have clarified that all tide gauge benchmarks with KNOWN foundation information are anchored at depth. See lines 226-227.

line 172 - I would be grateful if you did not use the word ’eustatic’ which means different things to different people (there is a recommendation about this in one of the IPCC reports). I suggest this is reworded: ... deep subsidence plus the component of RSLR associated with changes in real ocean level. (or something like that). And drop ’as well .... effects’.

Thank you for this suggestion. We now say, “…deep subsidence plus the component of RSLR associated with changes in real (geocentric) ocean level…”. See lines 229-230.

line 186 - I would reword: ... includes subsidence of that part of ... sediments deeper than the BM depth.

Good suggestion. We now say, “…deep subsidence also includes subsidence of the part of the Holocene sediment column that underlies the benchmark foundation.” See lines 265-267.

line 207 - reword to avoid eustatic: .. adding the historic rate of real (geocentric) sea-level rise ..

We have made this change throughout the manuscript.

There is a reference to Ericson et al. (2006) in the context of not using tide-gauge data. But the sea level rise value in that paper was just the global average taken from the IPCC (1.5 mm/yr) which hardly seems to me to be superior to using local tide gauges where available. I realise why Ericson et al. had to do that in their paper but it is not to be recommended in your case.

Thank you for pointing out this limitation of the Ericson et al. (2006) method of assessing delta vulnerability. We have added a note in the manuscript that this approach is hindered by relying on measurements of global rather than local sea-level rise (see lines 301-302). We have chosen to keep the reference to Ericson et al. (2006), however, because we feel it is an important example to include in our discussion of previous studies of delta vulnerability that did not use tide-gauge data.

line 223 - a reference is needed for the InSAR mention, preferably for its use in deltas.

We have added references to Dixon et al. (2006), Jones et al. (2016), and Da Lio et al. (2018). See lines 341-342.

230-233 - SWOT is only one of several efforts to improve coastal altimetry. A general reference, in which there is mention of SWOT, would be: Vignudelli, S., Kostianoy, A., Cipollini, P and Benveniste, J. (eds). 2011. Coastal altimetry. Berlin: Springer Publishing. 578pp.

Good to know. We have added the note that SWOT is one of several efforts currently in the works and we now cite Vignudelli et al. (2011). See lines 332-336.

237 - 'commonly too noisy'. From what I have read of the method I'm not surprised!

A single RSET-MH produces noisy shallow subsidence data because several spatially and temporally variable processes affect wetland surface elevation (e.g. tidal stage, wind direction and strength, belowground biomass). Despite this limitation, robust measurements of shallow subsidence can be produced by an RSET-MH dataset that includes measurements from numerous RSET-MHs. See discussion of this issue in lines 347-374.

References - need doi's adding

DOIs are not required for submission to Ocean Science, so we have left them off for now. If required by the journal, we would be happy to add them later.

453 - there should be an accent over the 'i' in Miguez

Corrected, thank you.

Figure 1 - What are the short and long vertical lines beneath the tide gauge in each panel supposed to be showing. I'd remove them. The point is that the datum of a tide gauge is determined by levelling to the BM nearby, so I would have the horizontal red line for the tide gauge at the same level as the BM and a dotted line between them. I think this figure may have been adapted from Figure 1 of Webb et al. (2013) which in their case has a short vertical band which I think is supposed to be indicating a float gauge (of which there are fewer around), and a longer vertical band which I think has the same function as the vertical red line for the BM in the present case. Anyhow, please lose the vertical lines under the tide gauges in this case.

In Figure 1, each tide gauge is now represented by a narrow red rectangle and is connected to the benchmark with a dashed line.

Figure 2 and 3 - could the lat/lon ticks and annotation face outside the map to be clearer?

These changes have been made.

Figure 3 - could the colour scale on the right be labelled Pleistocene Depth and the insert headed FD above PS or similar? As mentioned above, a reference is needed in the caption for the Pleistocene depth information. The black lines for the shoreline are hard to see. There is no point

mentioning ENG1 and 2 if they don't appear on the plot. But perhaps say (ENG1 andd ENG2, see Table 2).

In Figure 3, labels have been added to the color bar and to the inset box. In the caption, we have clarified that the Pleistocene depth information is from Heinrich et al. (2015). As also suggested, we now say "ENG1 and ENG2, see Table 2". We found that a thicker black line indicating the shoreline becomes distracting, so we have left the shoreline as-is.

Figure 4 - nice plot.

Good to hear, thank you.

Figure 6 - put mm/yr after mean, standard deviation

We have made this change.

Tables 1 and 2 - head the column 'Maximum benchmark foundation depth (m)'

We have made this change to Table 1. We did not make this change to Table 2 because the table refers to GNSS stations, which are not associated with benchmarks. The foundation depths listed in Table 2 indicate the depth of the rod or structure on which the GNSS station is mounted.

Figure S1 - I don't see the point of this figure. It has no more information than Figure 6. Doesn't do any harm I guess.

We have removed Figure S1 to avoid redundancy.

I hope these comments are useful. I have no objection to my identity being revealed. I am very grateful to Peter Stone and Greg Dusek for information which helped me complete this review.

Thanks again to all three for these very thorough and thoughtful comments.

Response to the manuscript review by an anonymous referee
Reviewer comments are in bold text; author responses are in normal text

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General comments:

This study seems closely related to the work published in GSA Today (Nienhuis et al. 2017) in which the authors were involved. But it is not clearly stated how both relate together. Nienhuis et al. is quoted towards the end of the manuscript, just before the conclusions. The findings on the underestimation due to shallow subsidence are already present in Nienhuis et al. Hence, should this manuscript be considered as supplemental information to the GSA Today one? I think it is important that the authors clarify how both studies relate together from the beginning (introduction). In addition, the introduction and the conclusion ("we present", "we propose") suggest the approach is novel. However, later on we find expressions and references which suggest it is not. Overall the authors need to make an effort to unambiguously set their study in the scientific context.

First, we would like to thank the anonymous referee for the thoughtful feedback regarding our manuscript. We have taken the referee's suggestions into account and feel that it has enabled us to make significant improvements.

The reviewer is correct in noting that there is a brief mention in the Nienhuis et al. (2017) paper that benchmarks in coastal Louisiana are typically anchored at depth and thus the associated tide gauges do not capture shallow subsidence. However, Nienhuis et al. do not go into any detail about how this information was acquired or methods to remedy this issue. Instead, the paper is relatively narrowly focused on presenting a subsidence map for coastal Louisiana and it is not concerned with the methodology of measuring present-day RSLR in LECZs in a more general sense. In the present manuscript, we present and analyze benchmark depth data, discuss limitations of a variety of techniques for measuring RSLR, and suggest an alternative method of measuring RSLR in LECZs. While the scope of the Nienhuis et al. paper is strictly limited to coastal Louisiana, here we use coastal Louisiana as a case study for an issue that is likely global in scope. Thus, we hope to reach a much wider audience than the target audience for the Nienhuis et al. paper. Therefore, while the reviewer is correct that there are distinct elements that connect the two studies, these two manuscripts are otherwise separate and stand alone. We have clarified this connection in lines 117-120 of the manuscript.

As for the novelty of our manuscript, the practice of using RSET-MHs to measure shallow subsidence is not new and we cite two studies using state-of-the-art RSET-MH methods: Webb et al. (2013) and Cahoon (2015). What is novel is the method of combining RSET-MH data with data from GNSS stations and satellite altimetry in order to produce robust measurements of RSLR. This method was first introduced by Jankowski et al. (2017), but for a different purpose (to evaluate the ability of coastal wetlands to keep pace with RSLR). Here we explore this new approach in much more detail and with the explicit objective to reach the large, multidisciplinary community concerned with obtaining better measurements of present-day rates of RSLR. We now clarify these points in lines 117-120 and 138-140 of the manuscript.

In my opinion, the manuscript suffers from a perspective bias "against" tide gauges. That is, the authors show that both the tide gauges and GPS antennas are similarly anchored deep below the surface (at almost equivalent depths). Thus, none of them can actually capture the shallow

subsidence. The combination of satellite altimetry and GPS data or the use of tide gauges suffer from the same drawback. Consequently, the statement that the novel approach eliminates the need for tide gauge data (repeated several times in the manuscript) is not objectively supported, because the same criticism applies to GPS antennas, and hence to the combination of satellite altimetry and GPS data. From my understanding, tide gauges + RSET-MH can work as well as satellite altimetry + GPS + RSET-MH. The authors need to think about it, and provide arguments to support their claim in a more convincing way, or reconsider the presentation of their findings (which are anyway interesting, in my opinion).

This is an excellent point. We have adjusted our wording throughout the manuscript to clarify that tide gauges are critical for many applications and that we are merely discussing a specific (yet important) context where tide-gauge data may not be the best option. In the abstract and conclusions (see lines 43 and 392), we now say that our proposed method of measuring RSLR in LECZs eliminates the need for tide-gauge data "in this context". Tide gauges remain critical for measuring many processes, especially tides (the original and still-primary purpose of tide gauges) and event-scale phenomena such as storm surge, and they are invaluable in this regard. We also note that best scientific practices will make use of all available data and compare the results of various measurement techniques. See lines 311-315.

Indeed, many of the issues affecting tide gauges also affect GNSS stations. Both types of instruments are generally anchored at depth and thus do not capture shallow subsidence. In principle, both GNSS stations and tide gauges could be used to measure deep subsidence and these data could then be combined with measurements of shallow subsidence (plus geocentric sea-level rise, in the case of GNSS data) to calculate RSLR. However, the tide gauges must have sufficiently long time series (at least 30 years) and known foundation depths to be useful in this context. In coastal Louisiana, the number of tide gauges that meet these criteria (n = 5) are fewer in number than GNSS stations with known foundation depths (n = 10). Additionally, GNSS data are less susceptible to short-term environmental conditions (i.e. wind speed and direction, tides, atmospheric pressure changes) than are tide gauge data. Thus, GNSS is the preferred method for measuring deep subsidence. This additional information is now included in lines 316-321 and 327-329 of the manuscript.

The manuscript (introduction) suggests an assessment of their findings in LECZs worldwide, but the authors do not provide evidence that the findings apply beyond their case study zone, except for some general considerations (sediment thick in different coastal areas of world from the literature). The authors should be aware that different countries (agencies) have different practices in building infrastructures (tide gauges or GPS antenna monumentations). The US case study is likely not representative of the wide range of practices elsewhere. They should consider reducing the scope of the claims, and develop a cautious discussion in extending the findings in LECZ worlwide. The title may be revisited too.

We have acquired information on benchmarks in The Netherlands and now include them in the manuscript for comparison. From conversations with Dutch colleagues, we understand that tide-gauge benchmarks in The Netherlands are ~5-25 m deep and generally anchored in the Pleistocene basement except in areas where the Holocene sediment thickness is greatest (see newly-added Table 4). In other words, conditions in The Netherlands are roughly comparable to those in the Chenier Plain of coastal Louisiana (and likely other "thin" LECZs): they do not capture the shallow subsidence component, but because benchmarks are generally anchored in a relatively stable substrate they are easier to interpret than many of the tide gauges in the Mississippi Delta (and likely other "thick" LECZs) where benchmarks are essentially "floating" in the Holocene succession. This additional information is included in lines 279-

287. We expect that benchmarks in other LECZs are likely constructed in a broadly similar fashion to those in coastal Louisiana and The Netherlands: either attached to rods driven to refusal or mounted on existing structures with non-negligible foundation depths. Although we are fortunate to have acquired relatively precise benchmark data from The Netherlands, we have found that information on benchmarks in other LECZs is very difficult to come by. A global analysis of benchmark construction would be a valuable but massive undertaking and is beyond the scope of the present manuscript.

In line with the above comment, I would suggest a search in the literature about GPS station monumnetations to support the worldwide extension. I vaguely remember a talk a decade ago or so about GPS antenna monumentations within an IGS meeting or an IAG scientific assembly. The concern of the study was the ability of the different types of GPS antenna monumentations to estimate actual ground / crustal motions. I think it might be worth searching for the details of this study or later studies on this subject.

Concerted efforts are currently underway to address the complexities regarding GNSS monumentation. At a newly-constructed subsidence superstation located in the lower Mississippi Delta, for example, three GNSS instruments were anchored at different depths in order to build a depth-integrated profile of subsidence (Allison et al., 2016). Novel approaches like these are expected to greatly improve our understanding of subsidence in LECZs in the future. This information is now mentioned in lines 322-326.

In addition, we now refer to the information available on hundreds of individual GNSS stations through the International GNSS Service (http://www.igs.org/network) and the National Geodetic Survey (https://www.ngs.noaa.gov/CORS/). See lines 127-129 in the manuscript. Site photos indicate that most GNSS stations are indeed mounted on existing buildings. Although the foundation depth of these buildings likely varies and tracking down foundation information for each building would require an enormous effort, it is likely that most (if not all) are anchored at some depth beneath the surface. Put differently, it is unlikely that these buildings are simply floating on the ground surface.

In addition to the above comment, the choice of the deepest benchmark in section 4 needs to be supported, especially regarding the leveling analysis and practice to maintain the tide gauge datum, which can differ from one country (agency) to another (agency). Furthermore, I think this methodological choice should not be presented / discussed in the "Results" section but in the methods section.

Excellent point. For our original analysis, we chose to use the benchmark with the deepest known foundation in order to maximize the size of our dataset: 35 tide gauges have at least one benchmark with known foundation depth, but primary benchmark depths are known for only 23 tide gauges. For comparison, we have added an analysis of primary benchmark foundation depths. For benchmarks with known foundations depths (i.e. those mounted on steel rods driven to refusal), we find that primary and deepest known benchmarks are anchored an average of 21.4 ± 3.9 m and 21.5 ± 7.4 m below the surface, respectively. Note that for 8 of 23 tide gauges (35%), the primary benchmark is also the benchmark with the deepest known foundation. The mean foundation depth for all benchmarks is 21.0 ± 5.4 m. Thus, we see that primary benchmark foundation depths are indistinguishable from the dataset as a whole. We have improved the explanation of our methods (and agree that it fits better in the Methods section than in the Results) and added a description of this new analysis in lines 167-170 and 190-196 in the manuscript.

In addition, we have acquired information on benchmarks in the Netherlands (see above for an in-depth discussion). Dutch benchmarks are constructed in a similar fashion as those in coastal Louisiana (i.e.

mounted on steel rods, sheet piling, or concrete) and are also anchored at depth. Foundation depths range from 5 to 25 m. This information is now included in the manuscript in lines 279-287 and in Table 4.

The manuscript is overall well written with good illustrations (Figures). In my opinion, it needs to consider the above comments. My suggestion is therefore a major revision.

Specific comments & Technical corrections:

p.2, L17-18: The expression is confusing. That is, if the station is >14 m, it includes the surface, and thus can capture any land motion. Consider rephrasing, why not using the same form as with the tide gauges? (Simply remove ">").

We compiled GNSS station foundation information from Dokka et al. (2006) and Karegar et al. (2015). In these papers, minimum (rather than exact) foundation depths are given for two of the GNSS stations. They are reported as >20 m (site BVHS) and >15 m (site HOUM) and we adopt this notation in our manuscript (see Table 2). We have now highlighted these sites more clearly in Figure 4. We use these minimum foundation depths for the BVHS and HOUM stations when calculating the mean foundation depth for all GNSS stations and then indicate that this mean value is in fact a minimum value. In line 208 (see also lines 39 and 377), we report that GNSS stations are anchored an average of >14.3 m below the land surface (i.e. the average foundation depth is no shallower than 14.3 m) and thus do not include processes occurring in the shallow subsurface.

p.2. L22: the need for tide gauge data is often multi-application. The authors should be careful with this claim, and state the context of it (eliminates the need for this specific application and LECZ situation). In addition, see major comment above, that is, the same concerns apply to the GPS monumnetation, hence both tide gauges and GPS show the same drawback.

Please see above for an in-depth discussion of this issue. We have adjusted our wording throughout the manuscript to clarify that we are focused on a specific context where tide-gauge data may not be the best option. Tide gauges remain critical for measuring many processes and are invaluable in this regard. See lines 311-315.

p.2, L34: a reference to support this claim is missing. It could be Holgate et al. (2013) which describes a data bank or similar; it could be an (the) article(s) that rescued the historical data of the stations listed in brackets.

We now refer to five of the longest tide gauge records and cite three papers that presented the historical data: Key West, USA (Maul and Martin, 1993); Brest, France; Świnoujście, Poland; New York, USA; and San Francisco, USA (Woodworth et al., 2011); Boston, USA (Talke et al., 2018). See lines 55-58.

p.2. L37: Watson et al. is a good paper but it is not relevant in the context of this sentence. (Its global sea-level rise estimate is based on satellite altimetry data). Maybe the reference can be used somewhere else.

We have removed the reference to Watson et al. (2015) from this sentence.

p.3 L50. Consider adding the reference for the PSMSL (Holgate et al. 2013 in J. Coastal Res).

Good suggestion, we have added a reference to Holgate et al. (2013) as well as the PSMSL web address (http://www.psmsl.org). See lines 72-73.

p.3. L53. What signals encompass "natural variability" here?

In lines 78-81, we have clarified that the natural variability includes phenomena such as storms, El Niño-Southern Oscillation cycles, changes in the orbital declination of the moon, shifts in ocean currents, and atmospheric pressure variability (Pugh, 1987; Douglas, 1991; Shennan and Woodworth, 1992).

p.4, L93. A reference is needed to support this claim. I vaguely remember a talk several years (decade?) ago at an IGS or IAG meeting about GPS antenna monumentations (structure, depth. . .) with some statistics. The concern of the study was the ability of GPS antennas to estimate actual ground / crustal motions. I think it can be worth searching the literature, especially since L97 states the issue of the nature of GPS station foundations as an objective of the study.

Please see above for an in-depth discussion of this topic. Efforts are currently underway to address the complexities regarding GNSS monumentation. In addition, we now refer to the information available on hundreds of individual GNSS stations through the International GNSS Service and the National Geodetic Survey.

p.4. L100. Confusing (see general comments above). The expression suggests the approach is novel, especially because in the previous sentence it is stated what is not the purpose of the study. However, there are two references at the end of the sentence. Is this study a refinement? Consider rephrasing and clarifying.

Please see above for an in-depth discussion of this issue. In this manuscript, we present a novel method to measure RSLR in LECZs. We now clarify that the reader should see Webb et al. (2013) and Cahoon (2015) for descriptions of the RSET-MH method (see lines 138-140), which can be used to measure one component of RLSR (shallow subsidence).

p.5, L144-145. This choice needs to be supported, especially regarding the leveling analysis and practice to maintain the tide gauge datum, which can differ from one country (agency) to another (agency).

Please see above for an in-depth discussion of this topic. In our original analysis, we chose to use the benchmark with the deepest known foundation in order to maximize the size of our dataset. For comparison, we have added an analysis of primary benchmark foundation depths. We find that primary benchmark depths are indistinguishable from the dataset as a whole. We have improved the explanation of our methods and added a description of this new analysis in lines 167-170 and 190-196 in the manuscript.

For a better global context, we now include information on benchmarks in the Netherlands, which are constructed in a similar fashion as those in coastal Louisiana and are also anchored at depth. Discussion of this information is now included in the manuscript in lines 279-282.

p.6, L172 (L205 too). What is behind the term 'eustatic'?

The term "eustatic" has been removed from the manuscript and replaced with clearer terminology. We now refer to this phenomenon as "real (geocentric) sea-level rise".

p.14. I cannot see whether there are squares and circles co-located. Consider using a different colour too, it may help.

The color scheme in Figure 2 has been changed to improve readability. Tide gauges and GNSS stations are now shown as dark blue circles and light orange squares, respectively.

Measuring rates of present-day relative sea-level rise in low-elevation coastal zones: A critical evaluation

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1. ABSTRACT

Although tide gauges are the primary source of data used to calculate multi-decadal to century-scale rates of relative sea-level change, we question the ~~reliability~~ usefulness of tide-gauge data in rapidly subsiding low-elevation coastal zones (LECZs). Tide gauges measure relative sea-level rise (RSLR) with respect to the base of associated benchmarks. Focusing on coastal Louisiana, the largest LECZ in the United States, we find that these benchmarks (*n* = 35) are anchored an average of 21.5 m below the land surface. Because at least 60% of subsidence occurs in the top 5 ~~10~~ m of the sediment column in this area, tide gauges in coastal Louisiana do not capture the primary contributor to RSLR. Similarly, ~~g~~Global ~~n~~Navigation ~~s~~Satellite ~~s~~System (~~GPS~~ GNSS) stations (*n* = 10) are anchored an average of >14.3 m below the land surface and therefore also do not capture shallow subsidence. As a result, tide gauges and GNSS~~GPS~~ stations in coastal Louisiana, and likely in LECZs worldwide, systematically underestimate rates of RSLR as experienced at the land surface. We present an alternative approach that explicitly measures RSLR in LECZs with respect to the land surface and eliminates the need for tide-gauge data in this context. Shallow subsidence is measured by rod surface-elevation table–marker horizons (RSET-MHs) and added to measurements of deep subsidence from ~~GPS~~ GNSS data, plus sea-level rise from satellite altimetry. We show that for a LECZ the size of coastal Louisiana (25,000-30,000 km^2), about 40 RSET-MH instruments suffice to collect useful data. Rates of RSLR obtained from this approach are substantially higher than rates as inferred from tide-gauge data. We therefore conclude that LECZs may be at higher risk of flooding, and within a shorter time horizon, than previously assumed.

2. INTRODUCTION

In the current era of accelerated sea-level rise, accurate measurements of relative sea-level change are critical to predict the conditions that coastal areas will face in coming decades and beyond. Such measurements traditionally come from tide gauges, which provide the longest available instrumental records of relative sea-level rise (RSLR). Some of the oldest tide gauges have records spanning 150-200+ years [~~(~~e.g. Key West, USA (Maul and Martin, 1993); Brest, France; Świnoujście, Poland; ~~;~~ New York, USA; and San Francisco, USA (Woodworth et al., 2011); and Boston, USA (Talke et al., 2018)~~)~~]. Tide-gauge data have played a central role in calculations of global sea-level rise (e.g. Gornitz et al., 1982) and they continue to do so today (e.g. Church and White, 2011; Church et al., 2013; Hay et al., 2015~~; Watson et al., 2015~~).

Tide-gauge data are also heavily relied upon to evaluate the vulnerability of low-elevation coastal zones (LECZs) (e.g. Syvitski et al., 2009; Nicholls and Cazenave, 2010; Kopp et al., 2014; Pfeffer and Allemand, 2016). LECZs include large deltas and coastal plains that often have accumulated thick packages (tens of meters or more) of highly compressible Holocene strata and are the home to some of the world's largest population centers (e.g. Tokyo, Shanghai, Bangkok, Manila) that are increasingly at risk due to RSLR. At the regional level, tide-gauge data have been used to study a variety of spatially variable processes. For example, in coastal Louisiana, the largest LECZ in the United States, tide-gauge data have been used to measure land subsidence (Swanson and Thurlow, 1973), the acceleration of RSLR (Nummedal, 1983), multi-decadal rates of subsidence and RSLR (Penland and Ramsey, 1990), and the impact of fluid extraction on RSLR (Kolker et al., 2011).

The Permanent Service for Mean Sea Level (PSMSL; http://www.psmsl.org; Holgate et al., 2013) maintains records for nearly 2000 tide gauges globally, including five ~~located~~ in coastal Louisiana: Eugene Island (data from 1939-1974), Grand Isle (1947-present), South Pass (1980-1999), Shell Beach (2008-present) and New Canal Station (2006-present). In many parts of the world, however, tide gauges with long, continuous records are few and far between. As a result, many studies of RSLR rely on tide-gauge records that are too short (longer than 50 years is preferable but at least 30 years is necessary to filter out natural variability ~~including~~due to phenomena such as storms, El Niño-Southern Oscillation cycles, changes in the orbital declination of the moon, shifts in ocean currents, and atmospheric pressure variability; Pugh, 1987; Douglas, 1991; Shennan and Woodworth, 1992), are from inappropriate locations (e.g. outside of the area being studied), or both. For example, of the 32 tide gauges used by Syvitski et al. (2009), 21 were located outside the delta of interest, 11 had records of <30 years, and 8 had both shortcomings. Furthermore, subsidence rates are highly spatially variable, often increasing or decreasing 2- to 4-fold within short distances (a few km or less) as a result of subsurface fluid withdrawal and differential compaction, among other factors (e.g. Teatini et al., 2005; Törnqvist et al., 2008; Minderhoud et al., 2017; Koster et al., 2018; also see the review by Higgins, 2016). As a result, tide gauges provide limited information on subsidence rates beyond the instrument's immediate surroundings. Even if a tide gauge has a sufficiently long record and is appropriately located, it is critical to determine what processes the tide gauge is measuring, and what it is not measuring. In LECZs, this is commonly not straightforward.

Tide gauges measure RSLR with respect to a nearby set of benchmarks. Leveling campaigns are conducted regularly (for example, at least once every six months for NOAA tide gauges; NOAA, 2013) to account for any changes in the elevation of the tide gauge with respect to these reference points. Tide gauges are typically leveled using a benchmark designated as the primary benchmark; secondary benchmarks are used to assess the stability of the primary benchmark (NOAA, 2013).

Figure 1 shows a schematic of tide gauges and associated benchmarks in three contrasting environments. Along rocky coastlines, benchmarks are typically anchored directly onto bedrock that is exposed at the surface (Fig. 1a). A tide gauge in such a setting therefore measures RSLR with respect to the land surface. In contrast, benchmarks in LECZs are typically anchored at depth. In thin LECZs, which are defined herein as those with unconsolidated sediment packages <20 m thick, benchmark foundations typically penetrate the surficial layer of unconsolidated (usually Holocene) sediment and are anchored in the underlying consolidated (usually Pleistocene) strata (Fig. 1b). In thick LECZs, defined as possessing unconsolidated sediment packages that are >20 m thick, benchmark foundations are generally not sufficiently deep to reach the consolidated strata and are anchored within the unconsolidated sediment (Fig. 1c).

Regardless of the environment, all tide gauges measure changes in water surface elevation with respect to the foundation depth of their associated benchmarks. As a result, tide gauges with benchmarks anchored at depth do not account for processes occurring in the shallow subsurface, above the benchmark foundation. For the purposes of this study, we define the subsidence that occurs above a benchmark's foundation as "shallow subsidence". Subsidence below a benchmark's foundation is termed "deep subsidence". In coastal Louisiana, at least 60% of subsidence occurs in the shallowest 5-10 meters (Cahoon et al., 1995; Jankowski et al., 2017). Tide gauges with benchmarks anchored at depth do not record this key component of RSLR. This issue was recognized~~first mentioned~~ by Jankowski et al. (2017) and Nienhuis et al. (2017), but ~~that~~neither study ~~did not~~ elaborated on this problem. Here, we present a~~go into~~ detailed assessment of~~ about how the~~ benchmark information associated with tide gauges, followed by a discussion of its implications as well as~~was acquired and~~ methods to remedy this issue.

In order to better understand the contribution of vertical ground motion to RSLR, tide-gauge data are often used in conjunction with ~~global positioning systemg~~Global ~~n~~Navigation ~~s~~Satellite ~~s~~System (~~GPS)~~GNSS) data (e.g. Mazzotti et al., 2009; Wöppelmann et al., 2009; Wöppelmann and Marcos, 2016; see also the Intergovernmental Oceanographic Commission manuals on sea-level measurement and interpretation, available at http://www.psmsl.org/train_and_info/training/manuals/). In LECZs, ~~GPS~~ GNSS stations are typically mounted on existing buildings or attached to rods that are driven to refusal (i.e. the depth at which friction prevents deeper penetration; see International GNSS Service station information at http://www.igs.org/network and National Geodetic Survey station information at https://www.ngs.noaa.gov/CORS/) and record the deep subsidence that occurs beneath their foundations. Similar to tide gauges, ~~GPS~~ GNSS stations are nearly always anchored at depth and thus face many of the same concerns: they do not record shallow subsidence that occurs in the strata above the depth of their foundations.

Accurate measurements of RSLR are vital to predict the sustainability of world deltas and for communities in LECZs to adapt to their changing coastlines. In this study, we investigate the nature of tide gauge benchmarks and ~~GPS~~ GNSS station foundations in coastal Louisiana and assess the implications for measurements of RSLR and subsidence in LECZs worldwide. Re-analysis of time series from tide gauges and GNSS ~~GPS~~ stations is not the purpose of our study. Instead, we present an alternative approach to measuring RSLR in LECZs where shallow subsidence is determined using the rod surface-elevation table–marker horizon method [~~(~~RSET-MH; see Webb et al. (~~,~~2013) and~~;~~ Cahoon~~,~~ (2015) for detailed descriptions of this method]~~)~~ and deep subsidence is determined using GNSS ~~GPS~~ data. ~~This method was briefly mentioned by Jankowski et al. (2017), but here we explore it in detail.~~ Using the Mississippi Delta (a thick LECZ) and the Chenier Plain (a thin LECZ) in coastal Louisiana as the primary study areas, we determine benchmark foundation depths and the type of strata in which the foundations are anchored. This allows us to determine which subsidence processes are measured by tide gauges and GNSS ~~GPS~~ stations and to evaluate their usefulness as recorders of RSLR. We then place our findings in the context of LECZs worldwide. Our results suggest that tide gauges (and existing analyses of tide-gauge data) in these environments may underestimate rates of RSLR as observed at the land surface, and as a result, many LECZs may be at higher risk of submergence than previously recognized.

3. DATA AND METHODS

Relative sea level and subsidence data are abundant in the Mississippi Delta and Chenier Plain, making coastal Louisiana an excellent target to assess methods of measuring RSLR. Records for at least 131 operational or previously operational tide gauges in this region are maintained by the National Oceanic and Atmospheric Administration (NOAA; https://tidesandcurrents.noaa.gov), the U.S. Army Corps of Engineers (USACE; http://www.rivergages.com and USACE 2015), and the U.S. Geological Survey (USGS; http://nwis.waterdata.usgs.gov). Although 37 of these tide gauges have records spanning more than 30 years, many of their records are incomplete and have large data gaps. Many other tide gauges in coastal Louisiana have ~~extremely~~ short records; nearly half have time series <10 years~~,~~ and a quarter are <2 years long (see Table S1 for information on all 131 tide gauges).

By means of exhaustive record combing of NOAA, USACE, and USGS archives, benchmark foundation depths were determined for tide gauges located in the Holocene landscape of the Mississippi Delta and Chenier Plain. Foundation depths were then compared to the local elevation of the Pleistocene surface (with respect to the North American Vertical Datum of 1988, NAVD 88; Heinrich et al., 2015). Because the land surface elevations at the tide gauge locations are close to sea level, the elevation of the Pleistocene surface is essentially equivalent to its depth beneath the land surface.

When a tide gauge is associated with multiple benchmarks, the benchmark with the deepest known foundation was used for this analysis in order to maximize the size of our dataset. For comparison, the analysis was repeated using primary benchmarks only.

A similar approach was taken to determine foundation depths of GNSS ~~GPS~~ stations. GNSS ~~GPS~~ station information was compiled from Dokka et al. (2006) and Karegar et al. (2015). Of the 45 GNSS ~~GPS~~ stations used for analysis by one or both studies, 17 are located in the Holocene landscape of coastal Louisiana. GNSS ~~GPS~~ station foundation depths were compared to the local depth of the Pleistocene surface, similar to what was done for the tide gauges.

4. RESULTS

The 131 tide gauges in coastal Louisiana were examined for benchmark information (Table S1, Fig. 2). Benchmark foundation depths are available for only 35 tide gauges (Table 1), including 31 maintained by NOAA and 4 maintained by USACE (see Table S1 for information on all 131 tide gauges). Each of these NOAA tide gauges is associated with 3 to 11 benchmarks (mean = 6 benchmarks), 77% of which have known foundation depths. The total number of associated benchmarks is unknown for the USACE tide gauges. Benchmarks with known foundation depths are typically mounted on steel rods driven to refusal. Benchmarks with unknown foundation depths are typically mounted on concrete structures of a variety of types (e.g. building foundations, bridge abutments, and seawalls). These concrete structures are likely to have foundations that extend into the subsurface, but specific construction details are unknown. ~~N~~It is important to note that an unknown foundation depth should not be ~~confused with~~interpreted as a foundation depth of zero. The remaining 96 tide gauges (73% of the total) have no available benchmark foundation information.

For tide gauges with available benchmark information, benchmark foundation depths range from 0.9 to 35.1 m, with a mean of 21.0 ± 5.4 m ~~21.5 ± 7.4 m~~ and a median of 20.7~~3.2~~ m. Deepest known benchmarks are anchored an average of 21.5 ± 7.4 m below the ground surface, with a median depth of 23.2 m. Comparing this mean to the mean foundation depth of primary benchmarks (21.4 ± 3.9 m, *n* = 23), we find that there is no meaningful difference. Note that for 8 of 23 tide gauges (35%), the primary benchmark is also the benchmark with the deepest known foundation. The mean foundation depth for the shallowest known benchmarks is 17.3 ± 7.0 m.

When a tide gauge is associated with multiple benchmarks, the benchmark with the deepest known foundation was used for this analysis. ~~When a tide gauge is associated with multiple benchmarks, the benchmark with the deepest known foundation was used for this analysis.~~ Figure 3 shows the location of tide gauges in coastal Louisiana (circles) and the foundation depth of their associated benchmarks relative to the local depth to the Pleistocene surface. The depth to the Pleistocene surface from the land surface at tide gauge locations ranges from 5 to 142 m, with a mean of 47 ± 34 m and a median of 44 m (Fig. 4). Thus, benchmark foundations are anchored an average of 25.5 m above the Pleistocene surface. Only 11 of the 35 tide gauges (31%) have benchmarks anchored in Pleistocene strata; the remaining 24 tide gauges (69%) have benchmarks anchored in Holocene strata.

Of the 17 GNSS ~~GPS~~ stations in coastal Louisiana, 10 (59%) have known foundation depths (Table 2, Fig. 3). Information for all 17 GNSS ~~GPS~~ stations in coastal Louisiana is available in Table S2. Foundation depths of the 10 GNSS ~~GPS~~ stations range from 1 to 36.5 m, with a mean of >14.3 ± 11.9 m and a median of 14.9 m (Table 2). Note that for two GNSS ~~GPS~~ stations only minimum foundation depths are available; these minimum values are used in the analysis in order to produce conservative results. At GNSS ~~GPS~~ station locations, the depth to the Pleistocene surface ranges from 10 to 78 m, with a mean of 38.5 ± 20.4 m and a median of 34.5 m (Fig. 4). Thus, GNSS ~~GPS~~ station foundations are anchored an average of 24.2 m above the Pleistocene surface. Only one of the 10 GNSS ~~GPS~~ stations (10%) is anchored in Pleistocene strata, whereas the remaining 9 GNSS ~~GPS~~ stations (90%) are anchored in Holocene strata. Figure 3 shows the location of GNSS ~~GPS~~ stations in coastal Louisiana (squares) and their foundation depth relative to the local depth to the Pleistocene surface.

5. DISCUSSION

5.1. Implications for the interpretation of tide gauge and ~~GPS~~ GNSS records

In coastal Louisiana, foundation information for tide gauge benchmarks and GNSS ~~GPS~~ stations is often not available, essentially precluding the interpretation of resulting time series in

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terms of rates of RSLR. Although many of the tide gauges listed in Table 1 are not useful for RSLR analyses due to their short records, all of the benchmarks used for the present~~is~~ analysis are currently published and considered stable.~~However~~ Furthermore, some of the tide gauges that currently have short ~~records~~time series could become important in the future as their records become longer (e.g. Shell Beach). B~~, b~~ecause all tide gauge benchmarks with ~~available~~ known foundation information are anchored at depth rather than at ground level, and most (91%) are anchored well below the land surface (>10 m), their interpretation is far from straightforward. Tide gauges with benchmarks anchored at depth measure deep subsidence plus the ~~eustatic~~ component of RSLR ~~as well as other oceanographic effects~~associated with changes in real (geocentric) ocean level, but do not capture shallow subsidence, often a dominant element of total subsidence in this region. Similarly, all GNSS ~~GPS~~ stations are anchored at depth (60% are anchored >10 m deep) and also do not record shallow subsidence. Thus, tide gauges and GNSS ~~GPS~~ stations in coastal Louisiana systematically underestimate the rates of local RSLR and subsidence, respectively.

Many tide gauges in coastal Louisiana have benchmarks that are mounted on existing concrete structures. The primary benchmark for the Grand Isle tide gauge, for example, is mounted on a seawall. Similar to tide gauges that measure RSLR with respect to a benchmark mounted on a steel rod driven to depth, the Grand Isle tide gauge produces a time series of RSLR ~~responds to changes in elevation with respect to the base of the rod, a benchmark mounted on a concrete structure responds to elevation changes~~ with respect to the foundation of the concrete structure into which its primary benchmark is mounted. Although we were unable to acquire construction details for the seawall at Grand Isle, it is highly unlikely that ~~the seawall~~it is simply resting on the ~~ground~~land surface. We expect that the seawall foundation extends at least several meters into the subsurface in order to provide stability and protection to the adjacent Grand Isle Coast Guard station. Five other tide gauges also have primary benchmarks anchored on concrete structures: Caminada Pass, East Bay, Freshwater Canal Locks, Lafitte, and Martello Castle. Although all of these primary benchmarks are likely anchored at some depth below the surface, it is conceivable that their foundations are ~~considerably~~ shallower than that of the deepest benchmarks (e.g. 19.8 m at Grand Isle). This may reduce the underestimation of the rate of RSLR measured by ~~each~~these tide gauges.

~~However~~On the other hand, ~~further analysis of~~the RSET-MH data presented by~~in~~ Jankowski et al. (2017) suggest~~s~~ that shallow subsidence occurs dominantly in the uppermost 5 m in coastal Louisiana~~of wetland stratigraphy~~. ~~If this is the case, tide gauges with benchmarks anchored as little as 5 m below the surface would not capture shallow subsidence and thus underestimate RSLR.~~ Using data from 274 monitoring stations~~ across coastal Louisiana~~, ~~Jankowski et al. (2017)~~Jankowski et al. (2017) calculated a mean shallow subsidence rate of 6.8 ± 7.9 mm yr^{-1}. Limiting this analysis to stations where the instrument is anchored in Pleistocene strata and the overlying (Holocene) strata are <5 m thick, we find a mean shallow subsidence rate of 6.4 ± 5.4 mm yr^{-1} (n = 55). The similarity ~~in~~between these two numbers ~~calculated~~

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~~shallow subsidence rates~~ suggests that ~~minimal~~ shallow subsidence is concentrated in the uppermost~~occurs at depths greater than~~ 5 m in this region. The implication would be that~~If this is the case,~~ tide gauges with benchmarks anchored as little as 5 m below the surface would still not capture shallow subsidence and thus underestimate the rate of RSLR.

If a tide gauge benchmark is anchored in Pleistocene deposits, deep subsidence consists solely of subsidence within the Pleistocene and underlying strata (Fig. 1b). This scenario is common in LECZs with a relatively thin Holocene sediment package, such as the Chenier Plain. In the Chenier Plain, the Pleistocene surface subsides at a rate of ~1 mm yr^{-1}, yet the wetland surface is subsiding notably faster, at a rate of 7.5 mm yr^{-1} on average (Jankowski et al., 2017). The remaining 6.5 mm yr^{-1} of shallow subsidence occurs above the depth of local benchmark foundations and is typically not captured by tide gauges in this region.

In the case of a benchmark that is anchored in Holocene strata, deep subsidence also includes subsidence of the ~~underlying~~ part of the Holocene sediment column~~s~~ that ~~are deeper than~~underlies the benchmark foundation. This scenario (Fig. 1c) is common in LECZs with thick sediment packages such as the Mississippi Delta, and further complicates the interpretation of tide-gauge data. Compaction of deeper Holocene strata may result in an increase in the measured rate of RSLR when compared to tide gauges with benchmarks anchored in Pleistocene strata. However, tide gauges with benchmarks anchored in Holocene strata still record rates of RSLR that are considerably lower than what is seen at the land surface in the Mississippi Delta (13 ± 9 mm yr^{-1}; Jankowski et al., 2017). For example, Kolker et al. (2011) and Karegar et al. (2015) calculated modern RSLR rates from tide-gauge data in the Mississippi Delta of ~3 mm yr^{-1} (after adding the long-term rate of RSLR measured at Pensacola, Florida) and at least ~7 mm yr^{-1}, respectively.

Around the world, many LECZs have sediment packages that exceed 20 m in thickness, and some are as thick as 100 m or more (Table 3). Benchmarks in these areas are likely constructed in a broadly similar fashion to those in coastal Louisiana: either attached to rods driven to refusal or mounted on existing structures with non-negligible foundation depths. Tide-gauge benchmarks in The Netherlands, for example, are anchored ~~∼~~5-25 m deep (R. Hoogland, personal communication, 2018) and generally reach the Pleistocene basement except in areas ~~very near the coast~~ where the ~~Pleist~~Holocene sediment thickness is greatest (Table 4). Thus, conditions in The Netherlands are roughly comparable to those in the Chenier Plain of coastal Louisiana (and likely other "thin" LECZs): tide gauges do not capture the shallow subsidence component of RSLR, but because benchmarks are generally anchored in a relatively stable substrate they are easier to interpret than many of the tide gauges in the Mississippi Delta (and likely other "thick" LECZs) where benchmarks are essentially "floating" in the Holocene succession.

In ~~such settings~~LECZs globally, tide gauges likely underestimate the local rate of RSLR. A lack of reliable RSLR data will be increasingly problematic in several large deltas that are home to major population centers (e.g. Ganges-Brahmaputra, Song Hong, Yangtze, Mekong, Nile) and are experiencing rapid subsidence (Alam, 1996; Mathers and Zalasiewicz, 1999; Shi et al., 2008; Erban et al., 2014; Gebremichael et al., 2018). In these areas and in LECZs globally, people and infrastructure may therefore be even more vulnerable to flooding than previously recognized (e.g. Syvitski et al., 2009; Tessler et al., 2015).

Two studies that considered delta vulnerability on a global scale (Ericson et al., 2006; Tessler et al., 2015) are noteworthy because they did not depend on tide-gauge data. These studies determined RSLR by adding the historic ~~eustatic~~ rate of real (geocentric) sea-level rise to natural and anthropogenic subsidence data (Ericson et al., 2006) or by combining sea-level rise from satellite altimetry with subsidence estimates associated with fluid extraction (Tessler et al., 2015). While these approaches bypass the problems with tide gauges discussed above, they are also inherently limited by the need to characterize individual deltas by single metrics, by relying on measurements of global rather than local sea-level rise, and/or by not considering all major subsidence processes (notably shallow compaction). In the next section, we build on the recent study by Jankowski et al. (2017) to offer an alternative approach to measure RSLR in LECZs.

5.2. An alternative method for measuring present-day rates of relative sea-level rise

In order to accurately measure present-day RSLR in LECZs, we propose an alternative approach that combines measurements of shallow subsidence from RSET-MHs with measurements of deep subsidence and the oceanic component of sea-level rise from GNSS ~~GPS~~ and satellite altimetry data, respectively (Fig. 5). This approach results in RSLR measurements expressed with respect to the land surface and eliminates the need for tide-gauge data. ~~Note~~ Nevertheless, we stress that best scientific practices will make use of all available data and compare the results of various measurement techniques. Furthermore, tide gauges remain critical for measuring many other processes, ~~especially~~including tides (the original and still-primary purpose of tide gauges) and event-scale phenomena such as storm surge, and ~~a~~remain invaluable in this regard.

In principle, both GNSS stations and tide gauges could be used to measure deep subsidence and these data could then be combined with measurements of shallow subsidence (plus geocentric sea-level rise, in the case of GNSS data) to calculate RSLR. However, ~~the~~ tide gauges must have sufficiently long time series (at least 30 years) and known foundation depths to be useful in this context. In coastal Louisiana, the number of tide gauges that meet these criteria (*n* = 5) are ~~far~~ fewer than the number of GNSS stations with known foundation depths (*n* = 10). Additionally, concerted efforts are currently underway to address the complexities regarding GNSS monumentation. At a newly- constructed subsidence superstation located in the lower Mississippi Delta, for example, three GNSS instruments ~~we~~are anchored at different depths in order to ~~build~~obtain a depth-integrated subsidence profile ~~of subsidence~~ (Allison et al., 2016). Although this type of analysis is new, it ~~will~~can greatly improve our understanding of subsidence in LECZs in the future. Furthermore, GNSS data are less susceptible to short-term environmental conditions (i.e. wind speed and direction, tides, atmospheric pressure changes) than are tide gauge data. Thus, GNSS is the preferred method for measuring deep subsidence.

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Although RSET-MHs, GNSS, and satellite altimetry all have unique limitations, technology is rapidly improving and ~~minimiz~~reducing these shortcomings. Until recently, for example, satellite altimetry was ineffective in coastal areas (Cipollini et al., 2017). However, the launch of the Surface Water and Ocean Topography (SWOT; https://swot.jpl.nasa.gov/home.htm) mission in 2021 is one of several efforts that are expected to significantly improve the quality of sea-surface records in the coastal zone and could therefore become an important element of the approach advocated here (Vignudelli et al., 2011). One remaining limitation of ~~this~~ our proposed method of measuring RSLR is that RSET-MHs are only useful in wetland environments such as marshes (e.g. Day et al., 2011) and mangroves (e.g. Lovelock et al., 2015). However, space-based geodetic methods such as interferometric synthetic-aperture radar (InSAR) are effective at measuring subsidence rates (the sum of shallow and deep subsidence rates) in heavily human-modified delta environments (e.g. ~~cities~~urban areas, agricultural land; Dixon et al., 2006; Jones et al., 2016; Da Lio et al., 2018), and thus can be complementary to RSET-MH datasets in this context. Ideally, RSET-MHs are installed with similar foundation depths as nearby GNSS ~~GPS~~ stations in order to confirm that the two instruments are neither duplicating nor missing subsidence intervals. In coastal Louisiana, however, 33% of GNSS ~~GPS~~ stations have no known foundation information, and this lack of information is likely a common phenomenon worldwide. ~~Finally, the launch of the Surface Water and Ocean Topography (SWOT; https://swot.jpl.nasa.gov/home.htm) mission in 2021 is one of several efforts that is are expected to significantly improve the quality of sea-surface records in the coastal zone and could therefore become an important element of the approach advocated here (Vignudelli et al., 2011).~~

Currently, coastal Louisiana has nearly 350 RSET-MHs operated by the USGS as part of the Coastwide Reference Monitoring System (CRMS; https://lacoast.gov/crms2), which provide shallow subsidence data at high spatial resolution. Although data from a single RSET-MH are commonly too noisy to produce a reliable trend (Jankowski et al., 2017), partly because most RSET-MHs were installed within the last decade and thus have time series that are mostly <10 years long, such a high density of RSET-MHs is not necessary to produce adequate estimates of shallow subsidence rates for a wider region. Using a Monte Carlo approach, we took random samples from subsets of the full RSET-MH dataset for coastal Louisiana (n = 274) to determine the smallest sample size that would still produce reasonable outcomes with an acceptable error. While determining the acceptable error is inherently somewhat arbitrary, the results show that in coastal Louisiana a minimum of 40 RSET-MHs would be needed in order to produce a mean shallow subsidence rate with a sufficiently narrow 95% confidence interval (4.54–9.18 mm yr^{-1}; ~~Figs.~~Fig.ure 6~~ and S1~~). In terms of density and given the size of coastal Louisiana (25,000-30,000 km^2), we estimate that two RSET-MHs per 1000 km^2 would suffice. Although this density is slightly higher than strictly needed in coastal Louisiana, it is conceivable that higher densities may be necessary in smaller LECZs.

In addition, averaging data from at least 40 RSET-MHs will encompass the high spatial variability commonly seen in shallow subsidence. In coastal Louisiana, spatial correlation in subsidence rates is largely limited to distances <5 km, and no correlation exists beyond 25 km (Nienhuis et al., 2017). As a result, the relevance of a single measurement of shallow subsidence is limited to the area immediately around the instrument. Around the world, tide gauges are generally spaced tens if not hundreds of kilometers apart. Even if tide gauges had benchmarks anchored at the land surface and were able to measure shallow subsidence~~ and record the rate of RSLR with respect to the land surface~~, there simply are not enough tide gauges with records that are sufficiently long for RSLR analysis to capture the large spatial variability in shallow subsidence. ~~Today, tide gauges around the world are generally spaced tens if not hundreds of km apart (for example, the five PSMSL stations in Louisiana are spaced, on average, 95 km apart), and only a few are associated with RSET-MHs. Although this lack of data prevents comprehensive measurement of subsidence in most LECZs today~~~~As a result, i~~In LECZs worldwide, our ability to predict local rates of RSLR will improve as more RSET-MHs are added to a growing global network. We therefore echo Webb et al. (2013) who first proposed this type of global RSET-MH network, arguing that the instruments are low-cost and produce highly valuable measurements of shallow subsidence.

6. CONCLUSIONS

In the Mississippi Delta and Chenier Plain of coastal Louisiana, tide gauge benchmarks and GNSS ~~GPS~~ stations are anchored an average of 21.5 ± 7.4 m and >14.3 ± 11.9 m below the land surface, respectively. By comparison, the local depth to the Pleistocene surface averages 47 ± 34 m at tide gauge locations and 38.5 ± 20.4 m at GNSS ~~GPS~~ stations. Instruments located in the Chenier Plain, a thin LECZ with Holocene strata typically only 5-10 m thick, are generally anchored in consolidated Pleistocene strata. In the Mississippi Delta, a ~~thick~~ LECZ where the Holocene sediment package is an order of magnitude thicker, tide gauge benchmarks and GNSS ~~GPS~~ stations are typically anchored within unconsolidated Holocene strata and therefore produce time series that are very difficult to interpret. Instruments anchored at depth do not capture shallow subsidence, a major component of total subsidence in this area. As a result, tide gauges and GNSS ~~GPS~~ stations in coastal Louisiana, and likely in LECZs worldwide, underestimate rates of RSLR and subsidence with respect to the land surface by a variable but unknown amount.

In order to accurately measure present-day RSLR in LECZs, we propose an alternative method which combines measurements of shallow subsidence from RSET-MHs with measurements of deep subsidence and the oceanic component of sea-level rise from GNSS ~~GPS~~ stations and satellite altimetry, respectively. This approach produces rates of RSLR that are explicitly tied to the land surface and eliminates the need for tide-gauge data in this context. We find that for an area the size of coastal Louisiana, a minimum density of two RSET-MHs per 1000 km^2 is necessary in order to obtain robust shallow subsidence data. We support the call for a global network of RSET-MHs as first put forward by Webb et al. (2013) and recently echoed by Osland et al. (2017). Data from such a global network will help refine existing plans for coastal adaptation that presently may be inadequate to deal with potentially higher-than-anticipated rates of RSLR.

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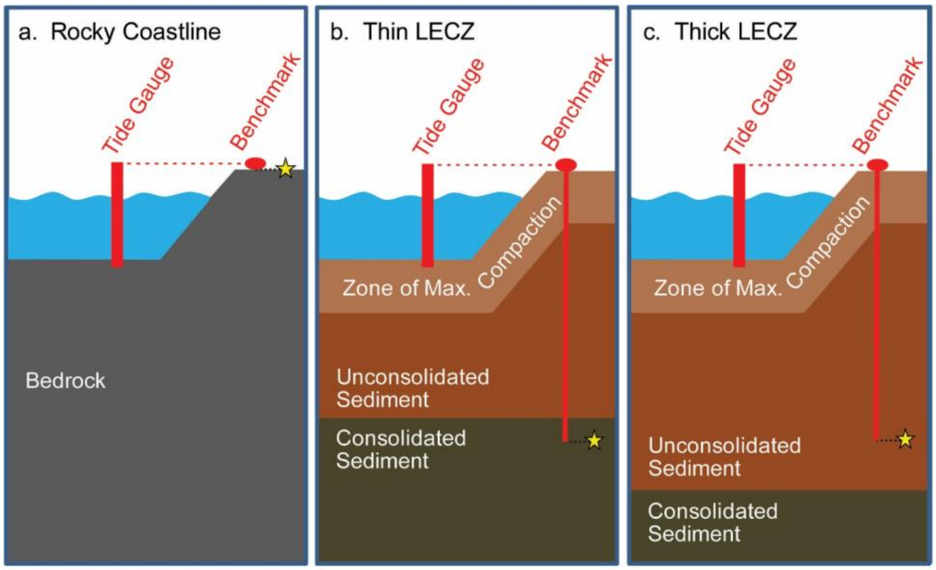
FIGURES



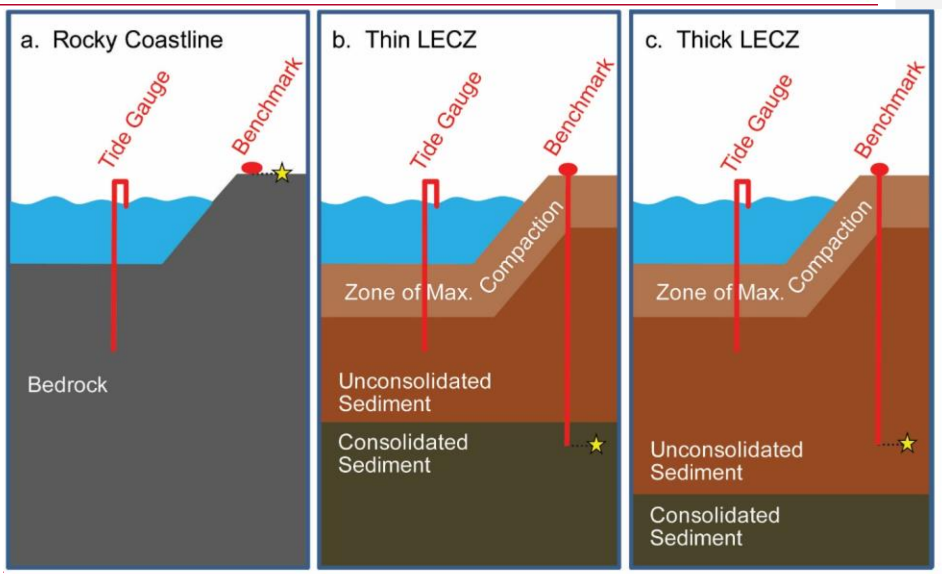


Figure 1: Schematic of a tide gauge and associated benchmark on a rocky coastline (a), a thin LECZ (b), and a thick LECZ (c). In all three environments, the tide gauge measures RSLR with respect to the base of the benchmark foundation, which is indicated by a star in each panel.

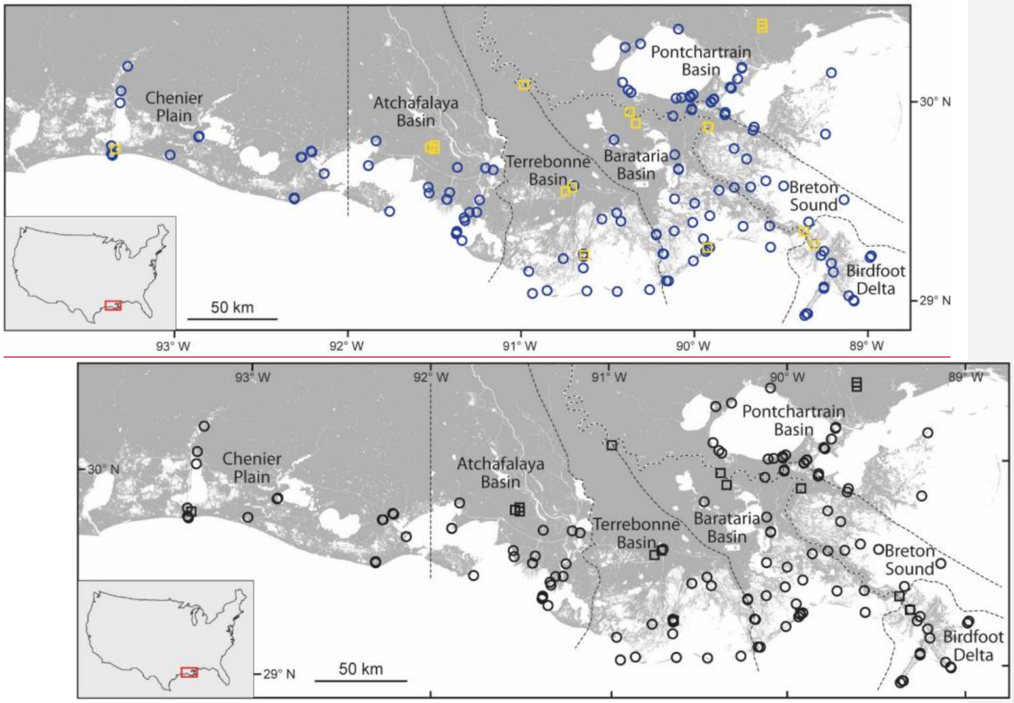
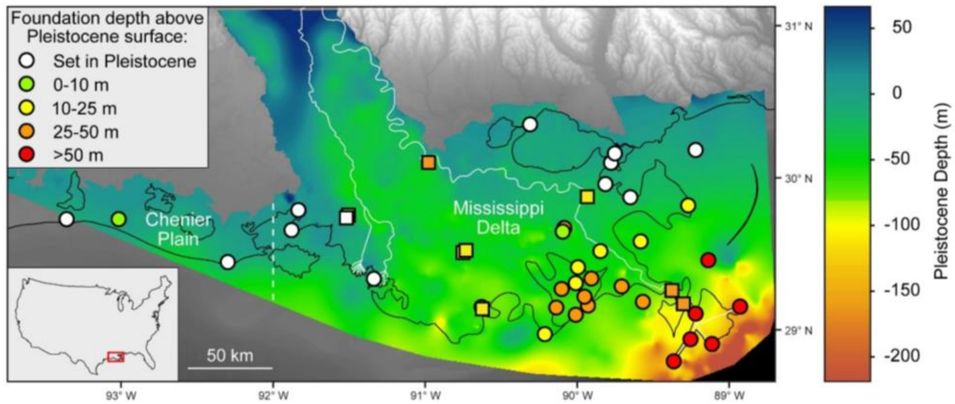


Figure 2: Location of tide gauges (circles, *n* = 131) and ~~GPS~~ GNSS stations (squares, *n* = 17) in the Holocene landscape of coastal Louisiana. Dashed lines delineate geographic areas discussed in the text.



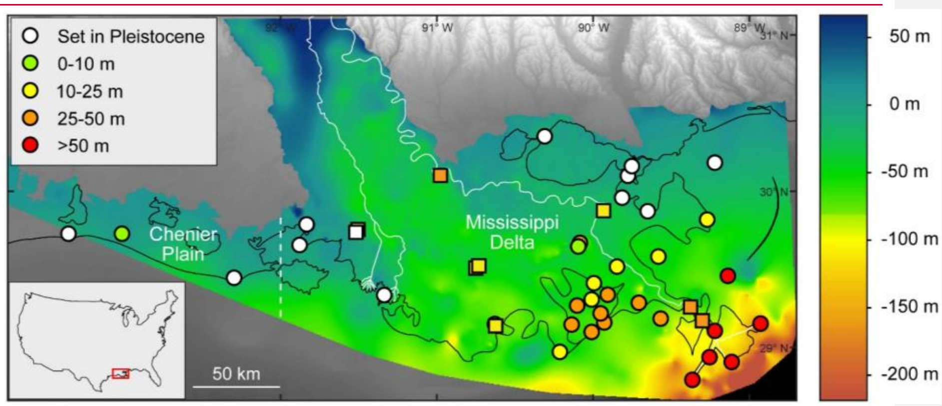
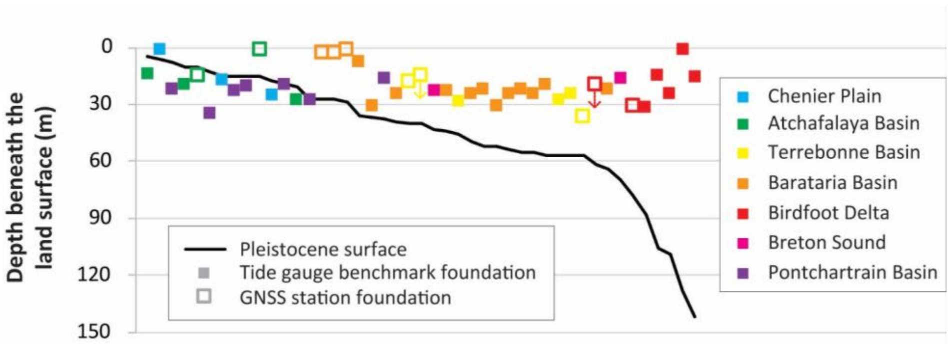


Figure 3: Elevation of the Pleistocene surface in coastal Louisiana (with respect to NAVD 88), which approximates the depth of the Pleistocene surface beneath the land surface given land surface elevations close to mean sea level. Circles and squares indicate tide gauge and ~~GPS~~ GNSS station locations, respectively, and are color coded according to foundation height above the Pleistocene surface. Note that two ~~GPS~~ GNSS stations (ENG1 and ENG2, see Table 2) have the same coordinates (and the same foundation depth) and plot on top of one another. The dashed white line, located at longitude 92° W, divides the Mississippi Delta from the Chenier Plain. Solid white lines show the Mississippi and Atchafalaya Rivers. Black lines indicate shorelines. ~~Base map~~Pleistocene depth information is from Heinrich et al. (2015).



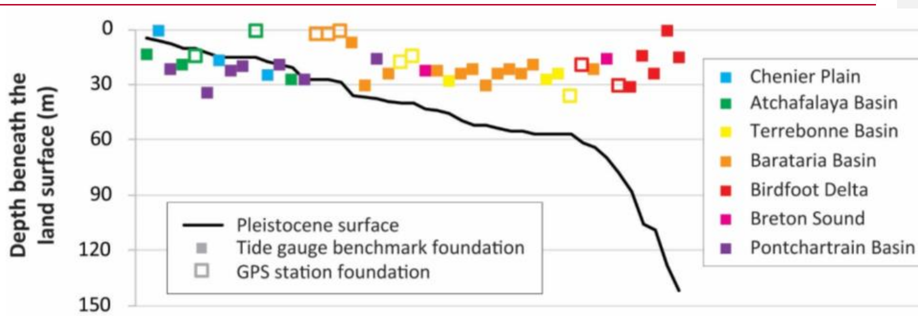
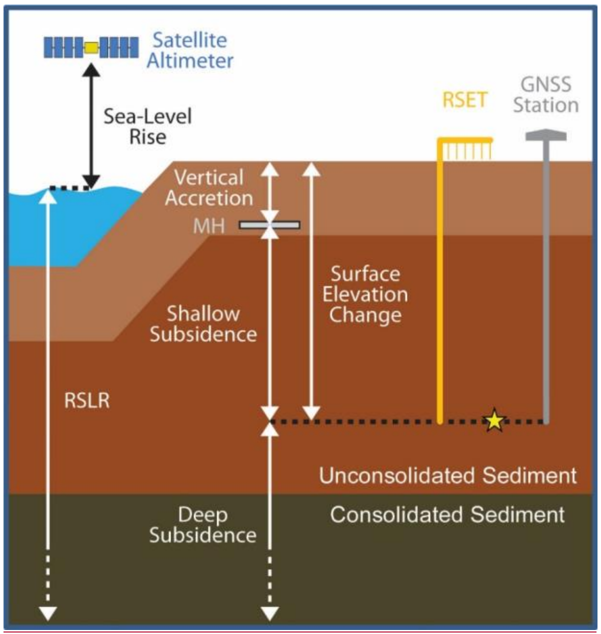


Figure 4: Schematic dip-oriented cross section comparing the depth of tide gauge benchmarks and ~~GPS~~ GNSS station foundations to the local depth to the Pleistocene surface. Sites are arranged by increasing depth of the Pleistocene surface. Note that two GNSS stations have minimum foundation depths (see Table 2), ~~which are~~ indicated here by small, downward-pointing arrows. See Figure~~.~~ 2 for the location of geographic areas.


Satellite Altimeter
Sea-Level Rise
RSET
GNSS Station
Vertical Accretion
MH
Surface Elevation Change
Shallow Subsidence
RSLR
Unconsolidated Sediment
Consolidated Sediment
Deep Subsidence

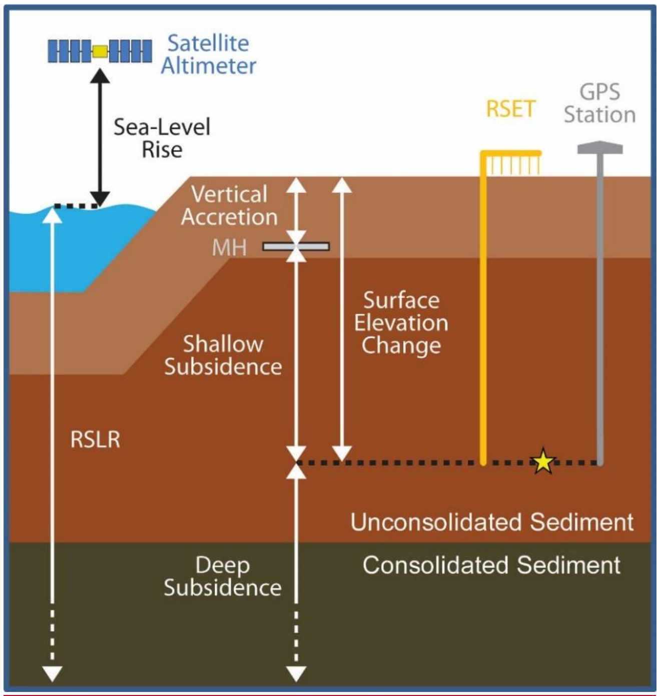
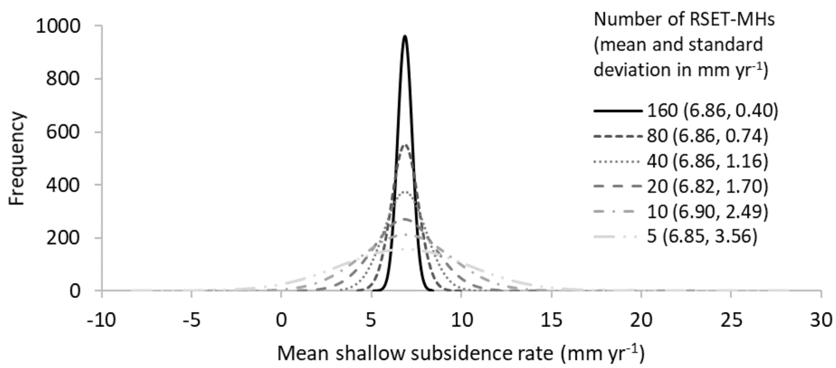


Figure 5. Schematic of combined instrumentation that includes a RSET-MH, which measures shallow subsidence, and a ~~GPS~~ GNSS station, which measures deep subsidence. To measure shallow subsidence using a RSET-MH, surface elevation change is subtracted from vertical accretion (Cahoon, 2015). Surface elevation change is the change in height from a horizontal arm at a fixed elevation to the wetland surface, measured using vertical pins. Vertical accretion is the thickness of ~~material~~sediment that accumulates above a feldspar marker horizon. If constructed with similar foundation depths (as shown by the star), the RSET-MH and ~~GPS~~ GNSS station collect data that are complementary and can be added together and combined with satellite altimetry data to calculate the rate of RSLR.



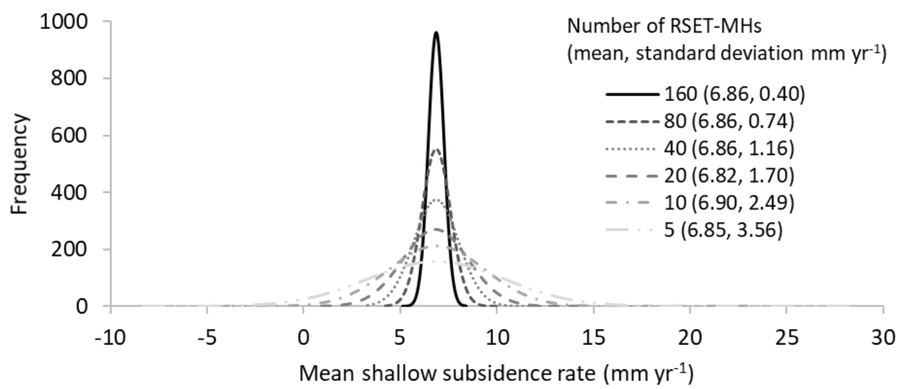


Figure 6. Probability density functions of the mean shallow subsidence rate for a given number of RSET-MHs, calculated using a Monte Carlo simulation and 10,000 randomizations per analysis. ~~More detailed results for each of the six cases are presented in Fig. S1.~~

TABLES

Table 1: Tide gauges in the Holocene landscape of coastal Louisiana with known foundation information (*n* = 35).

Tide gauge name	Agency	Latitude	Longitude	~~Benchmark~~ Maximum benchmark foundation depth (m)	Depth to Pleistocene surface (m)	Benchmark foundation height above Pleistocene surface (m)
Amerada Pass	NOAA	29.4500	-91.3383	27.4	21	Set in Pleistocene
Barataria Waterway	USACE	29.6694	-90.1106	7.4	36	29
Bay Gardene	NOAA	29.5983	-89.6183	23.2	43	20
Bay Rambo	NOAA	29.3617	-90.1400	24.4	54	30
Bayou Petit Caillou	USACE	29.2543	-90.6635	24.4	57	33
Bayou St. Denis	NOAA	29.4967	-90.0250	23.2	44	21

Billet Bay	NOAA	29.3717	-89.7517	21.9	52	30
Breton Island	NOAA	29.4933	-89.1733	16.8	70	53
Calcasieu Pass	NOAA	29.7683	-93.3433	25	18	Set in Pleistocene
Caminada Pass	NOAA	29.2100	-90.0400	21.9	55	33
Chef Menteur Pass	NOAA	30.0650	-89.8000	35.1	13	Set in Pleistocene
Comfort Island	NOAA	29.8233	-89.2700	16.8	38	21
Cypremort Point	NOAA	29.7133	-91.8800	19.4	10	Set in Pleistocene
East Bay	NOAA	29.0533	-89.3050	14.6	106	91
East Timbalier Island	NOAA	29.0767	-90.2850	28.8	46	17
Freshwater Canal Locks	NOAA	29.5517	-92.3050	17.1	15	Set in Pleistocene
Grand Isle	NOAA	29.2633	-89.9567	19.8	57	37
Grand Pass	NOAA	30.1267	-89.2217	23.2	15	Set in Pleistocene
Greens Ditch	NOAA	30.1117	-89.7600	21.9	8	Set in Pleistocene
Hackberry Bay	NOAA	29.4017	-90.0383	30.5	52	22
Lafitte	NOAA	29.6667	-90.1117	30.5	37	7
Lake Judge Perez	NOAA	29.5583	-89.8833	24.4	39	15
Leeville	NOAA	29.2483	-90.2117	28	57	29
Martello Castle	NOAA	29.9450	-89.8350	19.51	19	Set in Pleistocene
Mendicant Island	NOAA	29.3183	-89.9800	24.4	55	31
Mermentau River	USACE	29.7704	-93.0135	1.5	6	5
North Pass	NOAA	29.2050	-89.0367	15.2	142	127
Pass Manchac	NOAA	30.2967	-90.3117	20.7	15	Set in Pleistocene
Pelican Island	NOAA	29.2667	-89.5983	21.9	64	42
Pilottown	NOAA	29.1783	-89.2583	32	88	56
Port Eads	USACE	29.0147	-89.1658	0.9	128	127
Shell Beach	NOAA	29.8683	-89.6733	27.4	27	Set in Pleistocene
Southwest Pass	NOAA	28.9250	-89.4183	24.4	109	85
St. Mary's Point	NOAA	29.4317	-89.9383	24.4	50	26
Weeks Bay	NOAA	29.8367	-91.8367	14.3	5	Set in Pleistocene

Table 2: ~~GPS~~ GNSS stations in the Holocene landscape of coastal Louisiana with known foundation information (*n* = 10).

~~GPS~~ GNSS station code	Latitude	Longitude	Foundation depth (m)	Depth to Pleistocene surface (m)	Foundation height above Pleistocene surface (m)	Data source
AWES	30.10	-90.98	1	29	28	Karegar et al. (2015)
BVHS	29.34	-89.41	>20	62	<42	Dokka et al. (2006); Karegar et al. (2015)
ENG1	29.88	-89.94	~3	27	~24	Karegar et al. (2015)
ENG2	29.88	-89.94	~3	27	~24	Dokka et al. (2006)
FRAN	29.80	-91.53	14.7	10	Set in Pleistocene	Dokka et al. (2006)

FSHS	29.81	-91.50	1	15	14	Karegar et al. (2015)
HOMA	29.57	-90.76	18.3	40	22	Dokka et al. (2006)
HOUM	29.59	-90.72	>15	40	<25	Dokka et al. (2006); Karegar et al. (2015)
LMCN	29.25	-90.66	36.5	57	21	Dokka et al. (2006); Karegar et al. (2015)
VENI	29.28	-89.36	30.5	78	48	Dokka et al. (2006)

Table 3. Holocene sediment thicknesses of LECZs around the world, measured close to the shoreline where ~~sediments~~coastal strata tend to be the thickest.

Low-elevation coastal zone	Maximum thickness (m)	LECZ type	Reference
Chenier Plain, Miranda, New Zealand	3-5	thin	Woodroffe et al. (1983)
Chenier Plain, SW Louisiana, USA	5-10	thin	Heinrich et al. (2015)
Venice Lagoon, Italy	10-15	thin	Zecchin et al. (2009)
Chao Phraya Delta, Thailand	10-15	thin	Tanabe et al. (2003a)
Vistula Delta, Poland	10-20	thin	Mojski (1995)
Rhine-Meuse Delta, The Netherlands	20-25	thick	Hijma et al. (2009)
Huanghe Delta (modern), China	20-25	thick	Xue (1993); Yi et al. (2003)
Po Delta, Italy	20-25	thick	Amorosi et al. (2017)
Tokyo Lowland, Japan	20-60	thick	Tanabe et al. (2015)
Mekong Delta, Vietnam	25-40	thick	Ta et al. (2002); Tanabe et al. (2003b)
Nobi Plain, Japan	30-40	thick	Hori et al. (2011)
Shatt al-Arab Delta, Iraq	30-40	thick	Larsen (1975)
Nile Delta, Egypt	30-50	thick	Stanley and Warne (1993)
Song Hong Delta, Vietnam	35-40	thick	Funabiki et al. (2007)
Fly Delta, Papua New Guinea	35-45	thick	Harris et al. (1993)
Ganges-Brahmaputra Delta, Bangladesh	50-100	thick	Goodbred and Kuehl (2000)
Mississippi Delta, SE Louisiana, USA	50-100	thick	Heinrich et al. (2015)
Yangtze Delta, China	60-90	thick	Li et al. (2000)
Indus Delta, Pakistan	110-120	thick	Clift et al. (2010)

Table 4. Benchmark foundation depths and local depth to the Pleistocene surface for tide gauges in The Netherlands. Benchmark depths from R. Hoogland (personal communication, 2018). Pleistocene surface depths are from ~~Deltares~~Vos et al. (2011).

Tide gauge name	Agency	Latitude	Longitude	Benchmark foundation depth (m)	Depth to Pleistocene surface (m)	Benchmark foundation height above Pleistocene surface (m)
Vlissingen	Rijkswaterstaat	51.4422	3.5961	17.6	4-6	Set in Pleistocene
Hoek van Holland	Rijkswaterstaat	51.9775	4.1200	14	20-22	6-8
IJmuiden	Rijkswaterstaat	52.4622	4.5547	13	18-20	5-7
Den Helder	Rijkswaterstaat	52.9644	4.7450	5-25	2-4	Set in Pleistocene

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Harlingen	Rijkswaterstaat	53.1756	5.4094	5-25	4-6	Likely set in Pleistocene
Delfzijl	Rijkswaterstaat	53.3264	6.9331	20	6-8	Set in Pleistocene

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