Reviewer 1:

This manuscript presents a global analysis of tidal characteristics from a recently expanded global database of tide gauges. Due to the relevance of coastal tides for a wide-range of communities, particularly with the new SWOT satellite, I think this is a timely and important contribution. Furthermore, I believe that this manuscript has the potential to be a key reference for these communities for a long time to come. The following points are mostly minor, but I think the authors should carefully revise the manuscript to ensure it has the potential impact that it can have in line with the suggestions below. I suggest minor revisions.

Main Critique:

The text reads somewhere between a review paper, a foundational textbook, and a journal paper on tides from tide gauges (with some very interesting results in trends and time at high tide). The unfortunate aspect of doing all three is that it leaves more to be desired from each one.

For example, the section on data and methodology reads less like a summary of data and methodology and more like a section which introduces the basics of tidal analysis and gauge datasets. In fact, there are many missing details regarding the methodology (see later comments) which are needed to ensure replication. My suggestion is to choose one or the other, either strip back the very general and light overview in favor of a comprehensive methodology, or put the methods in the appendix and keep the general introduction to tides. The latter would make it easier to present both a foundational description of the basics of tides, and the characteristics they have globally.

Instead of adding this to an appendix, we feel this makes more sense to keep here. We have added to the introduction and have added a justification here as to why we have discussed this. Additionally, we have added references to other methods as well that are not covered to lines 131-137:

“It is important to note that several additional methods exist for tidal analysis. These include the response method (Munk and Cartwright 1960; Monahan et al., 2025), the wavelet-based approach (Lobo et al., 2024), and the species concordance method (George and Simon 1984), as well as methods that modify the harmonic analysis approach (Matte et al 2013, Pan et al 2023). Within this manuscript, we rely solely on the harmonic method, due to it being the most widely used method for tidal analysis and the method employed in the TICON-4 dataset. However, a future study could assess the differences in tidal analysis approaches and the impacts this could have on tidal statistics or tidal predictions.”

Beyond the methods, I suggest the authors make clear exactly what role this paper is to have: a review of things we can, and have, learned from global tide gauges along-side some new insights.

To address this we have re-written the last paragraph of the introduction and the first paragraph of the Conclusion, with the aim to address the main objectives of this manuscript. The last paragraph of the Introduction is now (lines 55-60):

"*This manuscript is intended to provide a synthesis of tidal characteristics from updated in-situ tide-gauge observations, by revisiting established tidal datums with new insights into tidal behaviour. By providing these insights, we aim to offer a coherent reference for tidal dynamics that demonstrates their importance along the coast. This synthesis is intended to support a wide variety of cross-disciplinary applications for both local and scientific communities. The up-to-date synthesis of the best available data and knowledge additionally supports both future modelling and analysis and to help identify knowledge and data gaps."*

We have also added the first paragraph to the Conclusion (lines 463-467):

"*This manuscript provides a global analysis of tidal characteristics based on tide gauge observations. We revisited established methods such as tidal range and form factors, which, thanks to the extended efforts of GESLA-4, have been applied to additional regions along global coasts. Additionally, we have provided updated perspectives on tidal changes across the coasts as well as for the first time, a global assessment of the duration of high-water periods. The latter statistic provides a new perspective on the potential of compound flooding across the ocean, and can be particularly useful for coastal management efforts.***"**

The remaining points are organized according to the section they come from.

Section 4:

This section presents a useful overview of various tidal characteristics and the way we quantify them. While the details are well covered, for non-tidal readers this is a deluge of information baked into notation and jargon that does not become more intuitive with the global figures. An easy fix could be to include supplementary figures which visualize what these quantities amount to for representative problems. The authors already do this in Figure B1, but I think even more value would come from some of the more advanced characteristics. Figure 1 of Phil's Differences between Mean Tide Level and Mean Sea Level paper is a fantastic example of how this might be done.

We agree that such a figure will facilitate understanding of some of the more advanced tidal statistics and the general context, and have added one to the appendix that integrates many of the presented characteristics. The figure should allow for a good intuitive understanding of the ideas behind the characteristics. We feel that the cited literature contains sufficient supplementary information to allow the interested reader to densify the background knowledge. Also, we created a Table, Table B1, to describe the terms used in this manuscript. We have added references to

this in lines 149 - 150: *"(summary of these datums are presented in Table B1 and visualized in Figure B1)."*

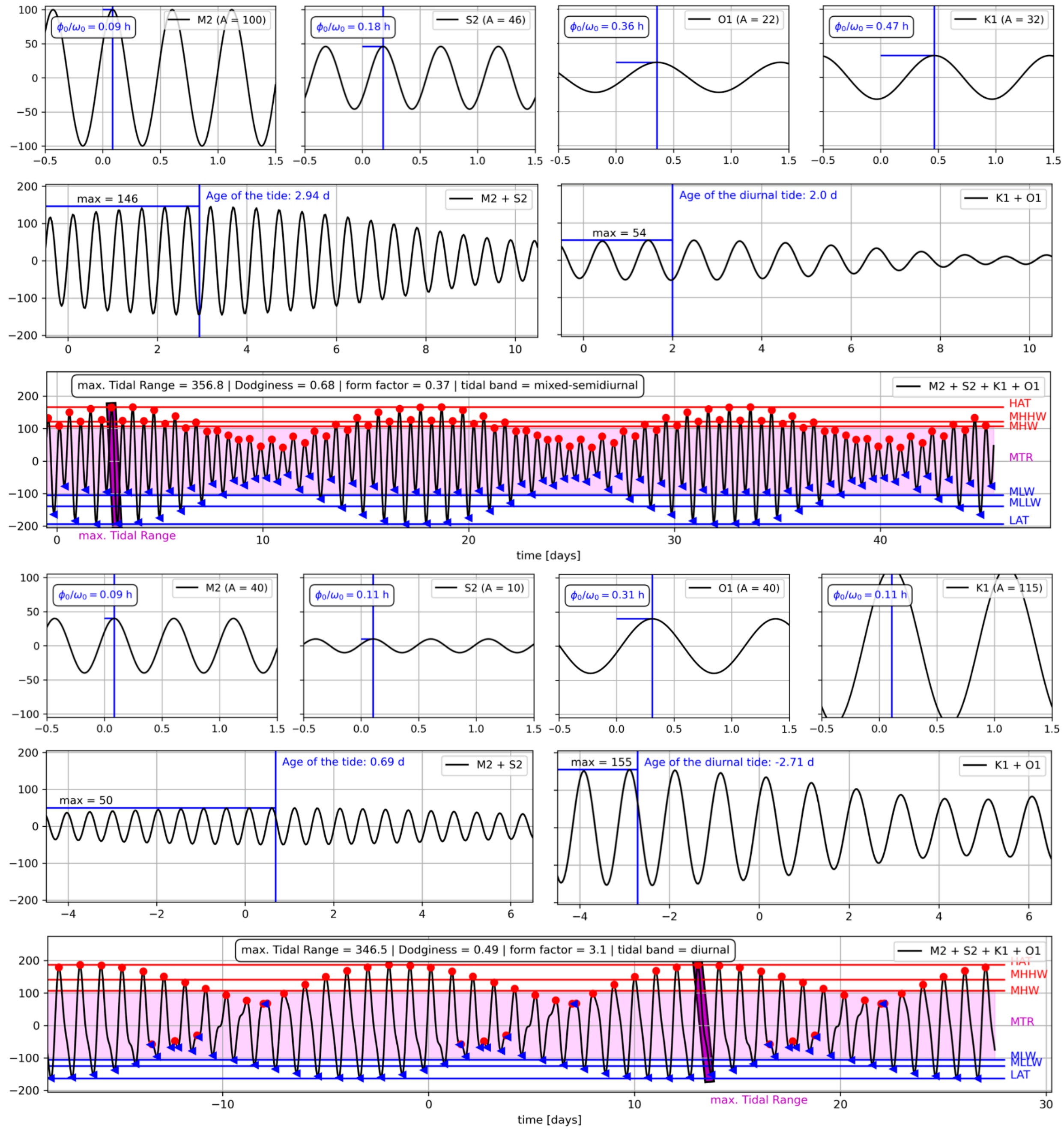


Fig. Bx: Top: Sea surface height time series for four major tides (M2, S2, K1, O1) with the local phase shift ϕ_0 indicated. The amplitude ratio between M2 and S2 (100 : 46), as well as the ratio between K1 and O1 (32 : 22), approximates the respective ratios in the TGP. Second Row: Resulting semidiurnal (M2 + S2) and diurnal (K1 + O1) time series indicating the age of the tide, i.e., the maximum constructive interference after t=0, where diurnal and semidiurnal forcing are maximum. Third row: Tidal time series as a *consequence of all 4 tides with maxima (red) and minima (blue) indicated. Additionally, the tidal datums and some tidal characteristics introduced in the text, e.g., the maximum tidal range and the mean tidal range (purple), are indicated. The lower half of the figure shows the same information for a diurnal tidal regime, dominated by K1, exhibiting a negative age of the diurnal tide.*

Table B1: A summary of the statistics presented in this manuscript. Additional information on these characteristics can be found in (Doodson and Warburg, 1941; Pugh and Woodworth, 2014).

Tidal Characteristic	Brief Description
Form factor	Ratio of the amplitude tidal constituents used to classify tide type; diurnal, semi-diurnal or mixed. Formula is $F = \frac{K_1+O_1}{M_2+S_2}$.
HAT	The Highest Astronomical Tide, the highest tide caused by astronomical forcing.
LAT	The Lowest Astronomical Tide, the lowest tide caused by astronomical forcing.
Maximum Tidal range	The maximum of the estimated tidal ranges.
MHW	Mean High Water, the average height of all high tides is estimated.
MHHW	Mean Higher High Water, the average height of the highest tide recorded each day.
Great Diurnal Range	The height difference between the highest and lowest tides of the day, the maximum daily change caused by tides.
Dodginess	Parameter used to describe the extent to which the amplitude of the local tide varies over a lunar cycle. Defined in Equation 2
Age of Tide	The lag between the new or full moon and the maximum spring tidal ranges. Defined in Equation 3.
Age of Diurnal	The interval in hours between the maximum declination of the Moon and the time of high water of the following spring tide. Defined in Equation 4
HWFC	High Water Full and Change or "vulgar establishment", the relationship between the moon phase and the resultant high tide, i.e. how long after the moon is overhead a high tide occurs.

Tidal Durations:

I think this is extremely useful and interesting to the flood community, but I wish there was a bit more discussion of the why. E.g. it seems relatively obvious a diurnal tide would spend a bit longer at a peak than a semi-diurnal one. What superposition of constituents creates especially long peaks? Are there any interesting mechanisms at play? This doesn't require a massive rejig of the figures, but at least an effort at explaining to readers where these discrepancies come from, perhaps through a simple synthetic example in the appendix from two representative sites.

We have added some additional discussion and an equation that describes how the duration of a tidal high-water stand depends on the amplitude of the diurnal and semidiurnal tide, and their relative phasing. This is described in Lines 349 onwards, with a reference for further discussion, theory, and simplified illustrations to Talke (2025).

"*A simple trigonometric identity explains that the duration of a tide near its peak (t_d) depends on the inundation depths, the amplitude of the tide above the mean water level (A), and the effective period of the sine wave that best represents each high water stand (see Talke 2025 for a derivation):*

$t_d = \frac{T}{\pi} cos^{-1}(1 - \frac{s}{A})$.

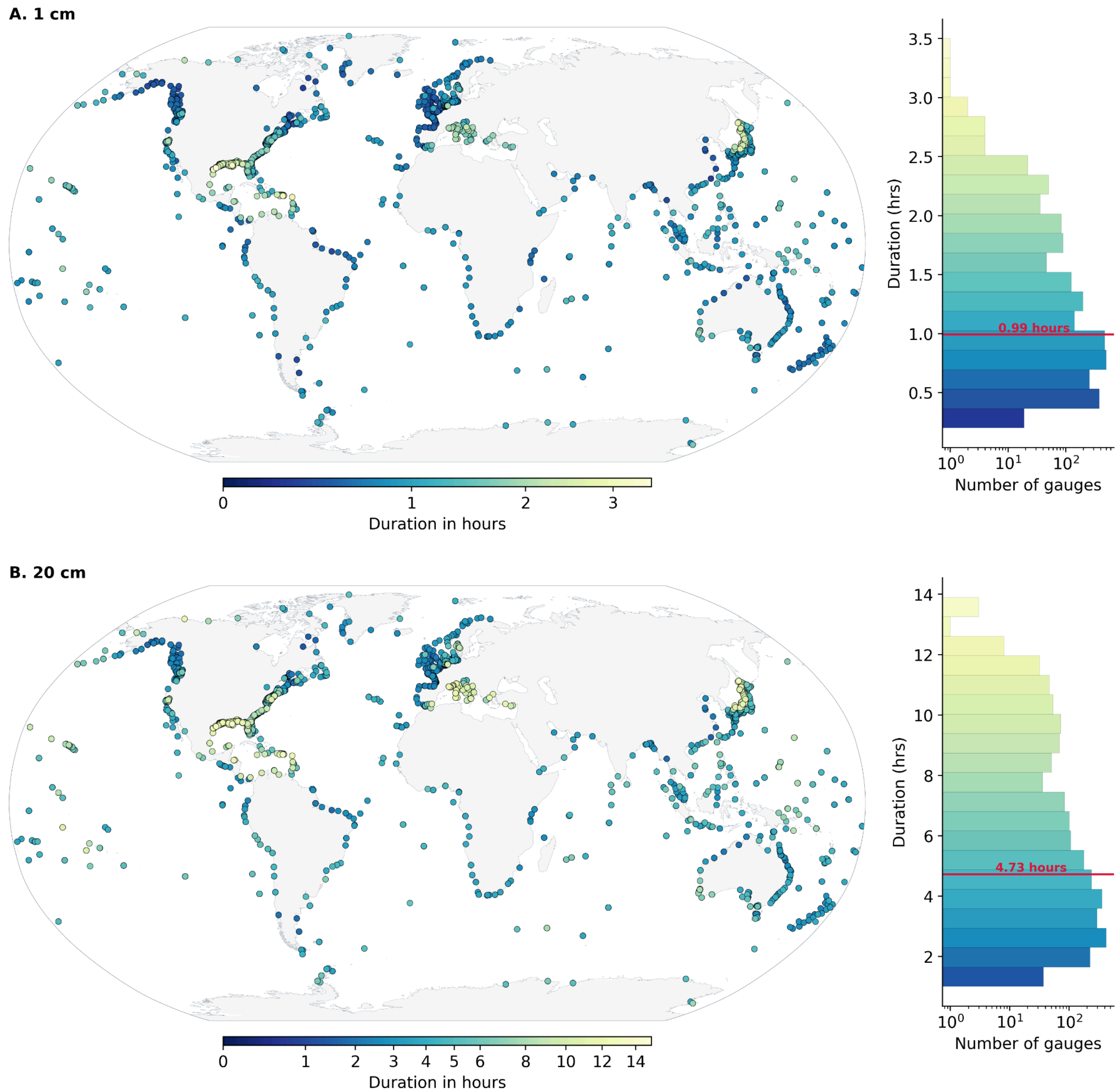
*For most locations, the amplitude of the high water stand (A) is driven primarily by the sum of the diurnal and semidiurnal band wave, with a correction for their relative phase (Talke, 2025); as tide amplitudes and relative phases vary over the synodic and tropical spring-neap cycles, the ratio $\frac{s}{A}$(and thus duration) will correspondingly shift. Additionally, and perhaps surprisingly, the period T that best describes an individual high-water stand is typically neither semi-diurnal (12-13 hours) nor diurnal (24-25 hours), unless one band clearly dominates. Instead, as shown both empirically and theoretically by Talke (2025), the period T used in Equation 5 is a composite of both tidal bands, but usually biased towards the semidiurnal frequency. For example, the superposition of a 0.64m semidiurnal wave (12.4 hour period) with a 0.46m diurnal wave (24.8 hour period, relative phase = 0) will result in a composite wave with a period of 15 hours (Talke, 2025). The duration of some high-water stands (<10%) are not easily fit by a sinusoidal wave, particularly if amplitudes are small and the timing of diurnal and semidiurnal waves are significantly out of phase; moreover, the influence of quarter-diurnal constituents and other bands in shallow water remains to be elucidated (Talke, 2025). The variability of high-water stands between spring and neap tides and due to seasonal and longer-time scale variability remains to be elucidated, as does the duration of low-water time periods. Nonetheless, as shown here, significant global variability in the typical duration of a spring-high water period exists, driven by fundamental differences in the relative phases and amplitudes of the diurnal and semidiurnal constituent bands***."**

"Globally, the coastal tides evaluated stay within 1 cm of their peak from 0.2 to 3.5 hours, with a mean of 1.0 hours. The time spent within 20 cm of the peak varies from 1 to 14 hours, with a mean of 4.7 hours." Please consider presenting distributions on Figure 7 in the form of a histogram with the mean plotted on it. Given this is a strictly positive statistic, and likely heavy tailed, is it appropriate to present a mean only?

To address this we have added a histogram to the Figure 7. We have adjusted the caption to:

"For A and B, respectively, a histogram is presented to represent the distribution of durations across all tide gauges, with the red line indicating the mean duration."

and added to lines 336-338: *"The distribution of these durations within the selected thresholds is shown in Figure 7, which demonstrates that despite these mean values* *(demonstrated in a line within the histogram), there is a strong variation in the duration hours spread globally.”*



It is obvious that this is relevant for inundation, but I think even a back of the napkin calculation of how would greatly increase the impact of these results. My suggestions would be to consider a place with considerable sunny day flooding like the East coast of the US where there are well documented future estimates of sunny day flooding frequency that would be straightforward to translate to time at high water. Discrepancies in the shape around the high-water would therefore lead to large discrepancies in the durations of future floods.

We agree this is an interesting test and a very nice potential follow-up study to highlight how sea level rise can increase tidal flooding in the future, globally. However, adding sea-level rise projections at each location and accounting for the effects of vertical land motion does not fit the objectives of this paper. Moreover, many of the GESLA-4 records are not reduced to a geocentric datum, potentially complicating analysis of flood-time over specific datums. We prefer to remain focused on the observed tidal characteristics before tackling such topics to avoid over complicating. Focusing primarily on tidal characteristics also aligns with the earlier comment by this reviewer to be more focused on what the manuscript addresses. We note that the Talke (2025) paper on tidal duration already analyzes US sea-level rise and the time-scale to transition from tidal flood durations of zero to two hours, and refer readers to that. We add a reference to that in line 376-379:

"The effects of relative sea-level rise on future tidal flood duration for the USA are explored by Talke (2025), with results suggesting that the time-scale to transition from a zero to two-hour high-tide flood varies from 1 to nearly 100 years. Future research can build on the results shown here to evaluate how tide-induced flooding events could change as a result of local sea level changes.".

The authors also allude to tide-surge interaction here "Additionally, tidal properties interact with storm surge to produce a composite wave; generally speaking, the longer the high-water stand, the longer the ensuing high-water period during a storm may be, given equal meteorological forcing." A brief discussion of how longer or shorter high-water stands interact with the surge component would be interesting. For example the sqrt(gH) dependence, and 1/H dependence of wind stress would yield very different interaction characteristics.

We have added the following brief discussion to Lines 367 of the original manuscript following the above discussion.

"*The superposition of a tide and surge wave can result in a composite sine wave, similar to what happens when a diurnal and semidiurnal wave are added, provided their peaks are not significantly phase shifted, and the surge can be approximated near its peak by a sine wave (see e.g Familkhalili, Talke & Jay, 2020). Under these conditions, Equation 5 can approximate the duration of the storm-tide above a threshold, and provide insights into the processes driving flood duration. As with tidal bands, theory and empirical analysis suggest that the resulting storm-tide amplitude A depends on the individual amplitudes and relative phases of the tide and storm surge (Talke, 2025). Additionally, the period T of the storm tide wave used in equation 5 is a composite of the two frequencies, but biased towards the smaller period wave (see Talke, 2025). Additional nonlinearities related to phase speed and frictional nonlinearities may additionally affect this analysis, and more work is warranted to empirically assess storm-tide durations.***"**

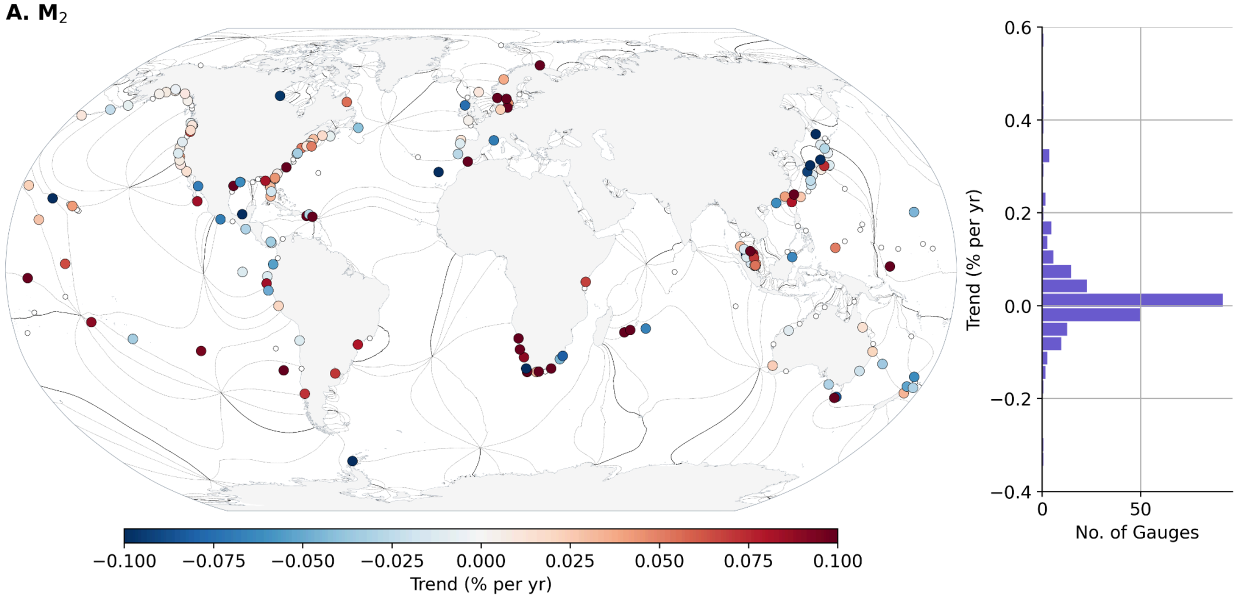
Tidal Trends:

There is not enough information about how uncertainties are estimated for the trends, or the estimator employed for the harmonic analysis, or indeed the final estimated uncertainties. One cannot evaluate the veracity of the statistical significance if this information is not included. See Innocenti et al. 2022, Monahan et al 2025 etc. for relevant discussion on uncertainty estimation in tidal estimators. Further, all estimates need to be reported with uncertainties. It also needs to be made clear whether the subsequent description of globally observed trends are computed exclusively from the statistically significant trends, or all of the trends. Given this, the revised manuscript should also report the confidence in this by incorporating the uncertainty. Figure 8 should also be modified to reflect the uncertainties, cross-hatching, opacity, size, etc. would all be welcome to reflect the confidence in the individual estimates to the readers.

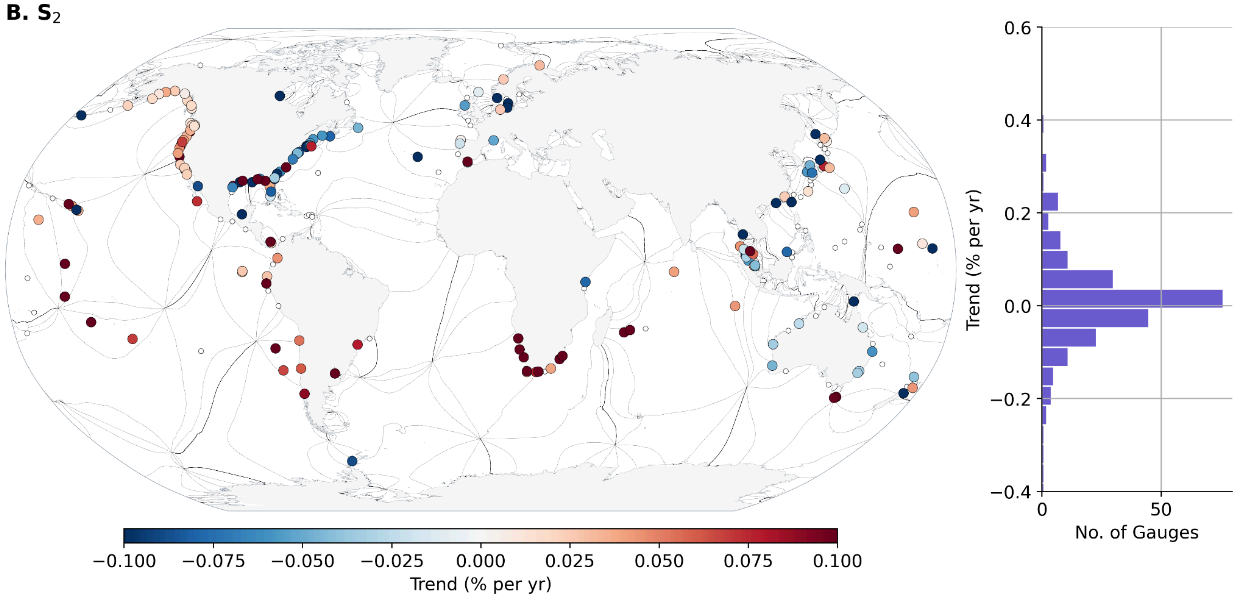
We have added the discussion below and use uncertainties to mask out estimations from Figure 8 where the uncertainty is larger than the estimation. Additionally, we add a histogram as requested by a later comment. White smallers circles are where we have a trend that does not exceed its uncertainty. Data and uncertainty is now included in the trend data included in the SEANOE link in the data availability section. We have added to lines 397 - 404:

"*Yearly amplitude trends were estimated by fitting an ordinary least squares linear regression to the annual amplitude values, after excluding values outside one standard deviation from the median. To account for any potential temporal autocorrelation in the tide gauges, we utilized Newey-West Heteroscedasticity and autocorrelation-consistent standard errors. The trend was quantified as the mean annual change in the fitted values. The uncertainty was estimated as the mean width of the 95% observation confidence interval from the adjusted regression predictions. In the provided dataset, available at: the trend and the uncertainty for each constituent are provided. However, in Figure 8, the trends are only shown when the trend exceeds the uncertainty value, with the gauge marked with a small white dot when this is not the case.***"**

A. M$_2$



B. S$_2$



Previously in the manuscript it is also stated that there are numerous duplicate records in the database. Are these accounted for in the processing? If you state that 52 and 53% of the trends are significant without removing duplicates, the true geographically balanced estimate may differ.

Yes, this is one reason why we selected one data source directly, the UHSLC-RQ, to maintain highest possible quality gauges but also to reduce duplicates. To clarify this to readers we have added to line 406: *"The use of one data source also prevents any duplicated tide gauges being used, which could bias any mean or median statistics presented below."*

Given the massive variability in trends, does it make sense to report global average statistics? Again, histograms on the plots would be useful in confirming whether a mean is appropriate to report here. Additionally, if you state qualitatively that there are regionally coherent trends, this needs to be quantitatively supported in the text:

“For the S2 tide, clear region-specific changes in the tides can be observed, particularly positive trends on the west coast of America” of _____ +/- ____ mm/year. This doesn’t need to be done everywhere, but it is worth citing the main areas as these trends will likely spur future work.

The histogram has been added to Figure 8. We have already added quantitative statements of uncertainty to some of the text, and have added a few more. Below is the changes made:

“For the M2 tide, the trends are positive in 58% of the tide gauges, with mean absolute trend of 0.19 +/- 0.11 mm/year and ranging from -1.47 mm/year to 1.80 mm/year. For the S2 tide, the trends are positive in 54% of tide gauges, with mean trending being 0.10 +/- 0.05 mm/year, ranging between -1.17 mm/yr to 0.98 mm/yr.”

“For the S_2 tide, clear region-specific changes in the tides can be observed, particularly positive trends on the west coast of America of 0.07 +/- 0.02 mm/yr, with negative trends of on average -0.08 +/- 0.03 mm/yr are observed on the eastern coast, which agrees with…”

“Our analysis shows that tide gauges in Southern Africa exhibit the largest variations in tidal amplitudes across both the M_2 and S_2 tides (Figure 8) of 0.39 +/- 0.25 mm/yr and 0.30 +/- 0.16 mm/yr respectively, particularly for long-term gauges located in harbours or estuaries (the Knysna tide gauge, located in an estuary in South Africa, exhibits the largest calculated M2 trend, 1.80 +/- 0.2 mm/yr), … “

I am sympathetic to the need to do batch processing of gauge estimated trends for a paper like this; however, the potential for systematic errors to crop up in the gauge estimates cannot be ignored. The manuscript as written mentions these errors but does not meaningfully engage with them. If the trends reported are intended to be released and used by the public, some attempt needs to be made to reconcile this. For this work, one need not identify all such gauges, but using this manuscript as a means of flagging this potential issue will be valuable to future tidal researches in order to prevent inaccurate trends from being presented. Given the authors focus on tide gauges, and that this manuscript is in some sense an overview of the use of these data in tidal research, it would seem useful to summarize some of the primary ways that errors manifest in these data and how they differ from say altimetry or bottom pressure sensors, etc.

We have mentioned in the manuscript and discussed in the previous comment how to interact with the uncertainties of these estimations in lines 397 - 404 and we account for them in Figure 8. Below we have given a discussion on the errors that can arise in the measurements of tide gauges that can influence the estimations.

We have expanded on the following statement previously within our manuscript: *"Such anomalous trends can result from a variety of factors, ranging from changes in tide gauge measurements, undocumented errors, or the influence of river processes on measurements (Woodworth, 2010)." -> "Anomalous amplitude trends can result from a variety of factors, ranging from malfunctioning instrumentation to measurements nominally correct but somehow affected by localized tidal effects unrepresentative of the surrounding sea (Woodworth, 2010). Measurement errors, such as elevations corrupted by biofouling or silt buildup, can build up slowly enough to impact amplitudes and/or phases over months or even years (depending on gauge maintenance), and they can thus affect estimated trends. Similarly, environmental changes such as the daily heating and cooling of the gauge can affect some constituents if not properly accounted for (e.g., acoustic gauges are known to be sensitive to environmental temperatures affecting sound speed; Hunter, 2003); these kinds of errors tend to turn up when instrumentation changes and can thus induce small errors over long periods.*

Other anomalous tidal trends reflect correct physical measurements but of a localized nature. A prime and common example is a change in tide following harbor renovations or following nearby dredging for navigational purposes. In fact, one of the largest amplitude trends in North America (of 1.6 mm/y) occurs at Wilmington, North Carolina (cf., Flick et al., 2003) and is likely the result of dredging in the Cape Fear River (Familkhalili & Talke, 2016). Such river effects are not easily eliminated from our data, since so many tide gauges have historically been located in or very near rivers because of their obvious importance to navigation. Tide gauges impacted by tectonic or other vertical land motions can be especially problematic for determining sea-level trends, but they usually have little impact on tidal trends. More common and more problematic, however, is any horizontal relocation of the gauge, even over short distances. For example, Ray & Talke (2019) discuss the tide gauge at Portsmouth, New Hampshire, which has a favorably long time series (beginning in 1926) but is spoiled by repeated relocations at different spots around Seavey Island (in the Piscataque River between Maine and New Hampshire), subsequently moved in 2003 farther downstream; these repeated relocations, some of them unreported, hamper any attempt at trend estimation.

These challenges in deriving tidal trends, which as shown here are of very small magnitudes, are not limited to tide gauges, as efforts to derive such trends from satellite altimetry are also susceptible to a large number of different errors, some of them very difficult to mitigate (see Ray and Schindelegger 2025 for more information)."

Hunter, J. R. (2003), On the Temperature Correction of the Aquatrak Acoustic Tide Gauge, J. Atmos Oceanic Tech., 20, 1230-1235.

Flick et al.: https://doi.org/10.1061/(ASCE)0733-950X(2003)129:4(155)

River Tides

It is unclear why this section has been included in the manuscript as written. River tides are both interesting and important in many regions as the authors rightly point out. However, the authors do not present any results beyond an abbreviated summary of the interesting characteristics of tidal rivers. Simply summarizing these mechanisms is not novel, nor particularly useful for the manuscript if not backed up by some observations of this in the tide-gauge data globally. I suggest the authors either add a figure which explicitly looks at river characteristics, including the mechanisms they discuss using NS_Tide, CWT_Multi, or even response based approaches (e.g. RTide) or they remove the section entirely and remark that this warrants future work. Certainly, an entire manuscript could be dedicated to global tidal river characteristics from gauges.

We have significantly reduced this section and highlight the importance of such a study in the future. Lines 450 onwards, have been replaced by:

"7 A note on river tides

Tides in rivers, deltas, and estuaries are greatly influenced by river flow, geometry, and shallow water effects (e.g., Le Provost, 1991; Kästner et al., 2019; Hoitink and Jay, 2016). The complex nonlinear interactions between tides, river flow, and shallow-water topography mean that using the harmonic method may be insufficient to provide in-depth characterisations of tidal characteristics within rivers. Multiple methods have been developed to characterize river-tide interactions, such as the response-based RTide approach (Monahan et al., 2025), a modified harmonic analysis approach that includes r non-stationary effects (NS_Tide; Matte et al., 2013) and the continuous wavelet transform method (CWT_multi; Lobo et al 2024). However, a global dataset of river tide gauges is currently unavailable within GESLA-4, though river and deltaic systems within some countries (such as The United States, The Netherlands, and Germany) are reasonably well-covered. An effort to characterize river tides globally, similar to this effort, would clearly be of high value to the community, especially considering the importances of these system to communities (Hart-Davis et al., 2026; Beemster et al., 2026). Our synthesis motivates such an effort, but is beyond the scope of this current work."

Conclusion

Further to my main criticism, throughout the manuscript I found myself questioning what the intent of the manuscript is. At some points it appears to be trying to be something like an abbreviated textbook where various global tidal characteristics and mechanisms are discussed. At other points, such as for trends and the times at high-water it seems to present interesting scientific results. The conclusion did not reconcile this dilemma.

We have re-written paragraphs in the Introduction and Conclusion to address this as discussed earlier in the response.

If this is intended to be a review paper on what we can understand about tides from tide gauges I think this is great, but the authors should consider speaking about the open challenges in tidal research from these data. This goes well beyond purely observational dataset gaps which are emphasized in the present conclusion. What more is there to be done with tide gauges beyond what was presented here?

We have added to lines 469:

"*Beyond ocean tides, the maintenance of these tide gauge records is critical for detecting and understanding changes in sea level, both in the context of sea level rise as well as for extremes such as flooding events (Haigh et al 2022).***"**

And lines 475:

"*Additionally, it is clear from the available observations that a knowledge gap exists in the characterization of river tides. This is largely due to the lack of a harmonized dataset of river measurements, such as GESLA-4, and to the challenge of presenting non-stationary tidal statistics in such a global analysis. Conducting such an analysis on river tide characteristics would certainly be a highly valuable resource for the community."*

Pedantic points:

When introducing equation 3 (age of semidiurnal tide), include the full description of the symbols used in the equation before "alternatively". Can be confusing if readers don't see an explanation for S_S2, S_M2. (you do this correctly in Equation 4).

Amended.

"It is probably true to say that this diurnal age parameter is made much less use of now in scientific studies than the semidiurnal age of the tide." Either remove statements like this or qualify them: e.g. Due to ____ the diurnal age of the tide is less relevant.

We have decided to omit this.

"A complementary tidal statistic to this analysis is whether the superposition of semidiurnal and diurnal constituents tends to produce especially large high waters or is more biased toward low outliers; readers are referred to the discussion by Byun et al. (2023) for more information on this" Why not include this? Most of the other statistics are not novel so why refer readers away for this one especially given its relevance for flooding?

We referred to this research aimed at mentioning complementary studies focusing on flooding statistics. To again address the main concerns of this reviewer by refining the scope, we have decided to remove this text from the manuscript.

It would be helpful to have a table in the appendix which contains each of the tidal characteristics and their definition so that readers can easily see them in one place.

We have added the figure B1 amd Table B1 above as a response to the reviewer to summarize this.

Final thoughts:

I think this paper has potential to be an excellent summary of what we can learn about tides from global tide-gauge measurements – and that it will be very successful. In all, I think these revisions are actually fairly minor and mainly just require more information on methods, reporting of uncertainties, and a rejigging of the text to make the goals of the paper more clear.

-TM

Innocenti et al 2022: Analytical and residual bootstrap methods for parameter uncertainty assessment in tidal analysis with temporally correlated noise

Monahan et al 2025: Tidal Corrections From and for SWOT Using a Spatially Coherent Variational Bayesian Harmonic Analysis