<u>Response to reviewer 2, review 1 from 15.05.2024</u>

We would like to thank the reviewer for their helpful recommendations. We very much appreciate the time and effort they took to carefully read the manuscript and to formulate detailed and constructive suggestions on how to improve it.

In the following, you find our responses to the individual recommendations (in bold):

1. **The shoreline concept and definition appear to be used ambiguously, requiring further clarification and objectivity. For instance, the terms 'shoreline' and 'coastline' seems to be used interchangeably, and comparisons between morphology-based, imagery-based, or elevation-based shorelines are not directly applicable (see [https://doi.org/10.2112/03-0071.1] [https://doi.org/1016/j.earscirev.2016.01.002] for reviews). How does this ambiguity relate to the reported bias? Additionally, can it justify the differences between tools, as mentioned by the authors, where 'the presented CASSIE-derived shoreline changes are only reliable over longer time periods, with CASSIE-derived shorelines being on average 39.2 m further seaward than the shorelines from CoastSat'? It seems that some differences arise because the authors are not measuring the same indicators.**

<u>Response</u>
We agree that the interchangeable use of the terms "coastline", "shoreline" (and also "land-water interface") is an issue in the existing literature. Inspired by Boak and Turner (2005), we were using these terms with the following meanings:

- Coastline: A stretch along the coast, including both land and water surfaces.
- Land-water interface: The dynamic boundary between land and water
- Shoreline: A proxy for the ideal, instantaneous land-water interface which can be an idealised line like in this study, but could also be a pattern of inundated and dry areas

CASSIE and CoastSat are two different tools to extract shorelines from optical images. While the data and the target parameter are the same in both tools (delineate the border between sand and water in Landsat images), the implemented algorithms are quite different. In short, CASSIE uses Otsu thresholding of the NDWI histogram of the image to create a binary image, from which polygons are extracted. The intersection of these polygons with pre-defined transects is the resulting shoreline proxy. CoastSat on the other hand first classifies the images (the classes are ‘sand’, ‘water’, ‘white-water’ and ‘other land features’) with a neural network classifier, before computing the Otsu threshold from an MNDWI image, and applying a marching squares algorithm to derive the contour along the found threshold. The bias we found between satellite-derived shorelines from CASSIE and from CoastSat is therefore most likely to be rooted in the differences between the respective algorithms.

When comparing satellite-derived shorelines and shorelines defined as the intersection between land elevation and a horizontal plane at sea level, we are indeed comparing two different proxies for the shoreline position. However, both realisations capture the same morphological phenomenon.

For clarification, we've added the following paragraph in the introduction under the sub-heading "Shoreline positions":

The terms "coastline", "shoreline" and "land-water interface" are not used uniformly in the existing literature. Inspired by e.g. Boak and Turner (2005), we use these terms here as follows. A coastline describes the stretch along the coast, including both land and water surfaces. The land-water interface is the dynamic boundary between land and water. The shoreline is a proxy for the ideal, instantaneous land-water interface. In this study, we use two different techniques to observe shoreline positions and their temporal evolution. These are the detection of shorelines from optical satellite images, and the derivation of shorelines by intersecting land elevation data with a plane at sea surface height. Both realisations of the shoreline position refer to the same geological feature. Their comparability depends on the respective observation uncertainties, the careful handling of different reference systems and the application of tidal corrections.

2. **What is the influence of wave-runup on satellite derived the results? For wave dominated coasts this factor should be accounted for.**

<u>Response</u>
We would like to thank the reviewer to point out that waves can have an effect on satellite-derived shorelines, which we have not considered before. We therefore did additional computations with ERA5 hourly data of significant wave height and peak wave period, interpolated to the time of image acquisition, following the formulas by Stockdon et al. (2006), and computed the horizontal shift for each transect and each point in time. We found a median horizontal correction due to wave run-up of 15 m, which can be considered significant. However, applying this correction to the cross-shore timeseries of satellite-derived shorelines from CASSIE slightly increased the median standard deviation from 82.2 m to 85.5 m. There is no significant change in trends (median difference is 0.3 m/year). As the correction for wave run-up increases the noise of the timeseries (instead of reducing it as expected), we conclude that accounting for it would not improve the results.

We think the reason for this increase in noise could be that wave run-up is the highest possible water level that exists only during very short periods of time that are not necessarily the times of image acquisition. We therefore also tried to correct only for wave set-up in order to account for the change in mean sea level close to the coast due to waves. The horizontal shift due to wave set-up ranges between 0.6 m and 6.9 m, with no detectable changes in standard deviation or trends. We conclude that the correction for wave set-up is too small to be able to improve the results.

We added a section to the appendix (section A5) explaining all used formulas for wave run-up and wave set-up as well as the resulting corrections and their impact on the cross-shore timeseries.

3. **Authors should explain and justify why “the horizontal shift can become unrealistically large, especially for small beach slopes.”**

<u>Response</u>
We've added some numbers to the respective paragraph to illustrate the magnitudes that extremely small beach slopes and the resulting corrections can take due to the numerical instability (division by very small numbers) that we consider not realistic. We are aware that it is hard to define quantitatively what is realistic or not. The choice of an arbitrary threshold is admittedly not a very elegant solution but one that seems us appropriate when using approximations for the beach slope and the resulting horizontal shift.

The horizontal shift Δx resulting from the approximation formula (2) using the local beach slope can reach the physical limits of the beach if the local beach slope becomes very small. Some of the calculated beach slopes get as small as $8 \cdot 10^{15}$ ($\tan \beta$) or even 0, leading to corrections up to 3.8 km or even infinity. We therefore apply an arbitrary threshold of ± 100 m for the maximum tidal correction.

4. **In the manuscript the study area is introduced without any prior justification. The choice of Terschelling should be justified.**

<u>Response</u>
Thank you for pointing this out, this part got lost in the editing process. We've re-added the following sentences to the study area description:

As a study area we chose the barrier island of Terschelling, that lies in a row of barrier islands separating the North Sea from the Wadden Sea at the Northern Dutch and German coast (Fig. 1a). We selected this study area because of its suitability for validating our method; it houses two tide gauges and a GNSS station, is covered by yearly LiDAR and bathymetry observations and its orientation is not parallel to the ground tracks of the satellite altimeters. This configuration allows us compare the respective local and remote-sensing observations, and to include the influence of vertical land motion. Additionally, Terschelling has a sandy beach, the type of beach that most available tools to extract satellite-derived shorelines are tailored to.

5. **Oceanographic setting: authors state the “Short-term sea level variations at Terschelling are dominated by diurnal tides with a tidal range of 1.2 m–2.8 m during neap tide and spring tide, respectively.”, but information on storm surge magnitude is also relevant. Concerning wave climate, period and direction characteristics are also needed.**

<u>Response</u>
We've added more information on the oceanographic setting (with old parts in grey):

Short-term sea level variations at Terschelling are dominated by diurnal tides with a tidal range of 1.2 m-2.8 m during neap tide and spring tide, respectively. The average wave height is 1.5 m with a mean period of 8 seconds coming from west to north-east direction.

During storms, the wave heights can increase to 5-6 m, with an increased period of 10-15 seconds (Quataert et al., 2020).

6. **In my view, the title could be enhanced to better align with the paper's content. The remote sensing observations are not compared but integrated instead. Therefore, I propose revising the title to something like "Changing Sea Level, Changing Shorelines: Integration of Remote Sensing Observations at the Terschelling Barrier Island" for improved clarity.**

Response
The paper contains several data comparisons (tide gauge vs altimetry, satellite-derived shorelines from CASSIE vs CoastSat, satellite-derived shorelines from CASSIE with different processing parameters, CASSIE-derived shorelines vs Jarkus shorelines) and one data combination (land elevation + sea level to compute "Jarkus shorelines" from the intersection). We agree that the term "integration" can better reflect the range of comparisons and combinations, and changed the title of the manuscript accordingly.

7. **A clear identification of major bottlenecks in the approach is missing.**

Response
We've added the following sub-section 'Limitations' as part of the discussion.

Limitations
This works presented an evaluation of different datasets used for coastal monitoring and their combined processing, at the cost of not going in depth into the details of the single techniques.

For deriving an altimetry timeseries, we restricted ourselves to the use of one single dataset. This is an along-track product retracked with ALES, an algorithm specifically designed for coastal areas, provided by the OpenADB (see section 2.1). This OpenADB ALES product has been used successfully before in studies combining altimetry and tide gauges (e.g. Mangini et al., 2022; Oelsmann et al., 2021). Our comparison to the local tide gauges and the use for computing the Jarkus shorelines in comparison to the other solutions showed that altimetry can be used to study shoreline changes. However, in order to get the full picture of uncertainties in altimetry datasets, it could be useful to additionally include other products, such as the ESA CCI gridded product (Copernicus Climate Change Service, 2018).

When correcting the tide gauge observations in order to make them comparable to altimetry, we applied only a correction for atmospheric pressure changes, neglecting sea level changes due to wind. Wind and atmospheric pressure are in sea level studies often accounted for by using the Dynamic Atmospheric Correction (DAC) by Carrère and Lyard (2003). However, when we integrated the DAC dataset in our calculation we found two spikes that are not exhibited in the altimetry dataset, and therefore decided not to use it. The comparison between altimetry and tide gauges could therefore be improved by finding a way to account for sea level changes due to wind in the tide gauge observations.

Another correction applied to the tide gauges for the comparison with altimetry was the vertical land motion (VLM). Here we used only data from a GNSS station as a proxy for VLM. However, this approach may neglect other ongoing processes such as sediment compaction below the base of the GNSS station (Karegar et al., 2020). Additionally, we showed that identifying significant discontinuities in the GNSS timeseries due to antenna changes is not a straightforward task, leading to a relatively wide range of possible VLM rates between -0.18 mm yr−1 and 1.15 mm yr−1 (section2.3). The picture of all VLM processes ongoing at Terschelling could be further improved by including InSAR (Interferometric SAR) data and GIA (Glacial Isostatic Adjustment) models.

The computation of shorelines as the intersection between land elevation data and a horizontal plane at sea level height ("Jarkus shoreline") was limited to the JARKUS transects with spacings of about 250 m. This could potentially be improved by using a gridded digital elevation model, if available in the required horizontal resolution and vertical accuracy, and applying image classification methods as was done for example by Liu et al. (2007) and Yousef et al. (2013). Additionally, the computation using the function from the JAT toolbox is limited by the JARKUS cross-shore resolution of 5 m, therefore the uncertainty for a single shoreline position can be up to ± 2.5 m. This could be improved by implementing a linear regression technique as presented by Stockdonf et al. (2002).

Due to the complex morphology at the eastern and western tip of Terschelling (see pictures in figure A6), deriving satellite-derived shorelines from Landsat turned out to be a challenging task. As a result, the cross-shore timeseries based on shorelines from CASSIE in these areas exhibited discontinuities with magnitudes of several hundred meters. Ideas to improve cross-shore timeseries of satellite-derived shorelines comprise post-processing steps such as outlier removal, or experimenting with different shoreline extraction algorithms, as well as using higher resolution optical sensors.

For all timeseries of cross-shore changes, we've subjectively selected a subset of transects used in the curved coastline sections of the eastern and western tip of the island. Therefore all given trends averaged over certain parts of the coastline might change with a different choice of transects. Another arbitrary processing decision whose influence we didn't investigate further was the rejection of horizontal tidal corrections for satellite-derived shorelines that exceed ± 100 m.

8. **If space- and time-variable beach slope is available then information on satellite derived shoreline is generally not needed. That information is mainly needed for validation purposes.**

Response

We agree that satellite-derived shorelines are in this case not required to determine the influence of sea level rise and morphodynamics on the shoreline position, but serve here only as validation. However, the main purpose of the paper is not to determine the impact of sea level rise on shoreline positions at Terschelling, but to prepare synthesis methods of remote sensing datasets that can be applied to other coastlines of the world, and to show that the Bruun Rule is not the only way forward. As satellite-derived shorelines can play an important role in areas where highly accurate land elevation data in high spatial and temporal resolution is not available, we wanted to illustrate the processing chain from using tools like CASSIE or CoastSat to the final cross-shore timeseries and especially their uncertainties.

9. **A figure of a representative cross-shore profile would be very useful in order to allow the reader to perceive the main morphological features, such as the presence of bars, beach face and berm characteristics, the existence of a dune.**

Response
Figure 8 of the manuscript shows three example profiles from each of the three sections exhibiting landward and seaward movements. The main intention of this figure was to illustrate the effect of the tidal correction, but it shows also some of the morphological features at Terschelling. We've updated the figure with texts and colours to clarify the situation. Additionally, we've added a panel of pictures in the appendix to give an impression of the study site, and made references to this in the main text.

10. **Closure depth should also be reported.**

Response
We added an estimate for the closure depth from a previous study to the study area description (section 1.3):

The long-term closure depth is reported to lie between 4 m and 10 m, with a tendency for smaller values in the west and larger values to the east of Terschelling (Marsh et al., 1999).

11. **Concerning the response to sea level rise is not clear if authors used or not the Brunn Rule (as it mentioned in the introduction but no other reference is made).**

Response
The second paragraph of the introduction introduces the drivers of shoreline change and quantifying their individual contributions. As the Bruun Rule is widely used to quantify the effect of morphodynamics and sea level rise on the shoreline, it seemed appropriate to give a short overview of its shortcomings and its widespread use in the current literature. In the third paragraph however we explain that we approach this task by using observations instead of models.

We've modified the beginning of the third paragraph as follows (old parts in grey) to make clear that the Bruun Rule is not used here:

Nowadays, there are several decades of remote sensing data available for coastal monitoring (Laignel et al., 2023). Instead of using the Bruun Rule, we suggest an *alternative approach using observations for sea level and vertical land motion in combination with estimates of shoreline changes to quantify the geometrical relation between sea level and shoreline changes.*

12. **Referring to Brunel and Sabatier (2009), the authors assert that protected 'pocket beaches' are more susceptible to inundation from sea-level rise compared to open beaches, which are more affected by increased wave energy. However, this assertion may depend on the time scales considered. In sandy beaches with equilibrium morphological profiles, the ratio between shoreline retreat and sea-level rise is substantially higher than in pocket and platform beaches. For further insights on this topic, authors are encouraged to consult relevant references.**

Response

We agree that the example of pocket beaches studies by Brunel and Sabatier (2009) does not represent the full range of coastal settings. We therefore replaced this example with a short summary of site-specific factors that can influence the results (with old parts in grey):

The coast of Terschelling offers contrasting conditions, such as retreating and advancing areas, or a straight central coastline and more complex configurations especially at the Western tip of the island. However, the impact of sea level rise on the shoreline position depends on a variety of local factors, such as the type of sediment and the volume of the available sediment budget, the shape, orientation and exposure of the coastline, the hydrodynamic conditions such as tidal range, relative sea level changes, wave energy, currents and possibly also climate modes such as the NAO, the presence of rivers, vegetation or morphological features like dunes or sandbars, episodic extreme events like storm surges, and finally human impacts (e.g. Toimil et al., 2020; Ranasinghe, 2016; Le Cozannet et al., 2014; Almar et al., 2023; Vousdoukas et al., 2023). Our conclusions for Terschelling that morphodynamics were responsible for the larger part of the shoreline changes between 1992 and 2022 can therefore not be transferred to other study sites and other time periods. Nevertheless, the methodology to determine the geometrical influence of sea level change and morphodynamics using land elevation data, altimetry and satellite-derived shorelines can in principal be applied to all sandy coasts, under the condition that the observed shoreline and sea level changes exceed the uncertainty ranges.

Minor comments:

1. Line 4 – Knowing “about the individual contributions of sea level change, vertical land motion and morphodynamics “ is not only essential to “necessary to make informed choices when applying coastal defence measure” but also for selecting other adaptation options.

Response

We've changed the respective sentence as follows (old parts in grey):

Therefore, knowledge about the individual contributions of sea level change, vertical land motion and morphodynamics on shoreline changes is necessary to make informed choices for climate change adaptation, such as applying coastal defence measures.

2. In figure 2, should “information” replace “output data “?

Response

In our understanding, "information" is a more generic category that entails sub-categories such as "output data". We would like to keep the more specific term "output data", also to make the distinction between input from other sources and output after applying the methods from this paper more clear.

3. The number of significative figures in “g” is exaggerated.

Response

Thank you for pointing this out. Indeed our inner geodesist might have gotten a little overexcited here. We reduced the number of digits after the comma to the common g = 9.81 m/s^2.

4. Long-shore should be replaced by longshore.

Response

We've replace the word "long-shore" with the word "longshore".

5. The phrase “the tide gauge observations have to be corrected for vertical land motion” does not apply if we are interested in relative sea level – which is the case when considering sea level influence on coastal change. This is because the focus is on the changes in sea level relative to the land surface rather than absolute sea level measurements.

Response

We agree that the study of shoreline changes requires relative sea level observations that are not corrected for VLM. These thoughts are partly reflected in the different solutions of Jarkus shorelines, where we used (among others) both, corrected and uncorrected tide gauge data in order to see there differences (which were small, see section 4.2). Furthermore, for the comparison with cross-shore changes from CASSIE, we use solution created with uncorrected tide gauge data (see section 3.5).

The cited sentence comes from the section "2.2 Sea level heights from tide gauges", which explains how we make tide gauge observations comparable to altimetry observations, in order to validate the latter. To avoid comparing relative sea level with absolute sea level, we bring these two together by correcting for vertical land motion.

6. Separating data from methods can complicate the text's coherence and flow.

Response
We generally agree that having the data description and the methods together in one section can help the reader's understanding. In this case we chose to separate data and methods, as we were using several different datasets that had already undergone some processing. We therefore decided to use the "data" section to describe pre-processing steps that we implemented but are not novel, as well as processing that was done by someone else, and use the "methods" section to describe our own processing.

We've added the following half-sentence to the introduction to point this structure out to the reader (old parts in grey):

After describing the datasets and the required post-processing steps in section 2, we start by evaluating the ability of offshore altimetry observations to capture sea level variations at the coast by comparing altimetric sea level anomalies to sea surface heights from tide gauges (Sect. 3.1).

References

Boak, Elizabeth H., and Ian L. Turner. “Shoreline Definition and Detection: A Review.” *Journal of Coastal Research* 2005, no. 214 (July 2005): 688–703. https://doi.org/10.2112/03-0071.1.

Stockdon, Hilary F., Rob A. Holman, Peter A. Howd, and Asbury H. Sallenger. “Empirical Parameterization of Setup, Swash, and Runup.” *Coastal Engineering* 53, no. 7 (May 1, 2006): 573–88. https://doi.org/10.1016/j.coastaleng.2005.12.005.

Almeida, Luis Pedro, Israel Efraim de Oliveira, Rodrigo Lyra, Rudimar Luís Scaranto Dazzi, Vinícius Gabriel Martins, and Antonio Henrique da Fontoura Klein. “Coastal Analyst System from Space Imagery Engine (CASSIE): Shoreline Management Module.” *Environmental Modelling & Software* 140 (June 1, 2021): 105033. https://doi.org/10.1016/j.envsoft.2021.105033.