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Limits and perspectives to assessing morphological resilience in the Wadden Sea

Check for updates

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The world heritage site Wadden Sea on the Northwestern European continental shelf is the world's largest coherent channel-shoal environment. It hosts numerous unique ecosystems and serves as natural coastal protection for the mainland. As one of the world's most frequently monitored coasts, its morphological evolution under relative sea level rise (SLR, includes vertical land movement) was studied intensely and can be considered as benchmark for the adaptation of other tidal flat and marsh areas[1–7].

Recent studies focused on the accretion of intertidal flats under SLR because their submergence poses severe negative consequences for coastal protection[8] and biodiversity[9]. These morphometric analyses reported a general steepening tendency, characterized by deepening tidal channels in combination with accreting tidal flats[10,11]. Miao et al.[12] (M25 in the following) suggest that these previously reported accretion rates were overestimated due to an inconsistent number of small-scale features in long-term topographic datasets, e.g., creeks and gullies, resolved only in more recent topography. While bias arising from combining modern high-resolution topography with interpolated conventional datasets is a valid concern, the evidence provided in M25 and limitations of the underlying topography dataset cannot support far-reaching conclusions such as diminishing resilience. In this work, we discuss the conceptual challenges of defining coastal morphological resilience und critically examine M25's methods. Our supplement describes the uncertainty of topography datasets (S1), pitfalls in morphometric analysis (S2), presents implications of the harmonization proposed by M25 on an integrated morphometric analysis (S3), and proposes ways forward (S4).

Coastal morphological resilience of tidal flats in times of sea level rise

Coastal resilience is the ability of socioeconomic and natural systems to cope with disturbances induced by external factors such as SLR, extreme events, or human activity by adapting and maintaining essential functions[13,14]. As an extension of this concept, morphological resilience can be defined by the capacity of a system to adapt under changing conditions while maintaining its distinct characteristics. The vertical growth of tidal flats (accretion) relative to SLR represents only one component in this framework: If accretion falls below SLR, progressive submergence occurs, whereas exceedance promotes aggradation (e.g., marsh expansion). Other components influencing coastal resilience are, e.g., steepness, tidal prism, or sediment availability, all of which are linked and evolve nonlinearly.

How the Wadden Sea will respond to SLR remains uncertain. As morphological time-scales span multiple decades or longer[15], the short observational record in the Wadden Sea (i.e., 27-years) can only be indicative for large-scale changes. It is debatable whether existing observations are sufficient in both quantity and quality to confidently assess the present state (see S1), let alone to discuss a transition toward another morphological regime.

Morphological resilience further depends on the rate of SLR: As SLR acceleration is already evident, consistent time-scales are increasingly relevant. However, M25 reused local trends[16] derived from 1993-2011 (one nodal cycle) to assess 1998–2022 (~ 1.4 nodal cycles) and applied spatial interpolation. To assess resilience, SLR analysis should be reconducted using more gauges to capture local phenomena, e.g., imposed by the asymmetric changes in tidal high and low water[17,18].

The effect of low-pass filters on small scale features

M25 suggest to improve comparability within the multi-decadal topographic datasets by filtering solely recent high-resolution topographies to align them with the less-detailed surveys of the past (Fig. 1 or suppl. Fig. 3 in M25). In other words, exclusively newer topographies with many small-scale features were smoothed to replicate the lower level of detail from older data. Small-scale features thereby removed include primarily minor channels with dimensions close to the resolution of the topography dataset (10 m). The key assumption herein is that older topographies were randomly sampled and interpolated in the past. However, efforts to maintain creeks and gullies were conducted, e.g., by surveying frequently or with directional interpolation techniques. Therefore, applying filters to high-resolution topography may not lead to equivalent older low-resolution data.

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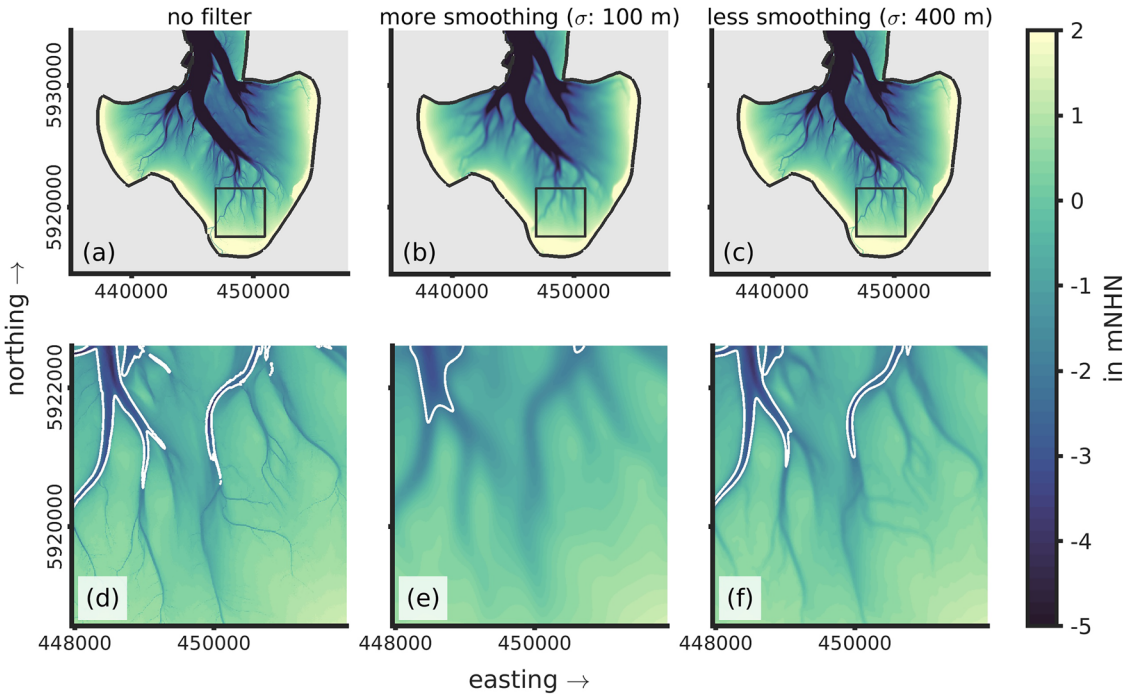


Fig. 1 | The effect of different Gaussian filters in Jade Bay. The original topography of the year 2020 (left column) illustrates full small-scale features on a 10 m grid (**a**, **d**), while a filter threshold of $\sigma = 100$ (middle column, **b**, **e** and $\sigma = 400$ (right column, **c**, **f**) artificially reduces the number of channels by spatial smoothing. The white −2 mNHN (NHN, German chart datum) isobath (**d**–**f** only) is used for reference of changes in lateral intertidal extent. EPSG: 25832, see Fig. 1 in M25 for additional spatial reference.

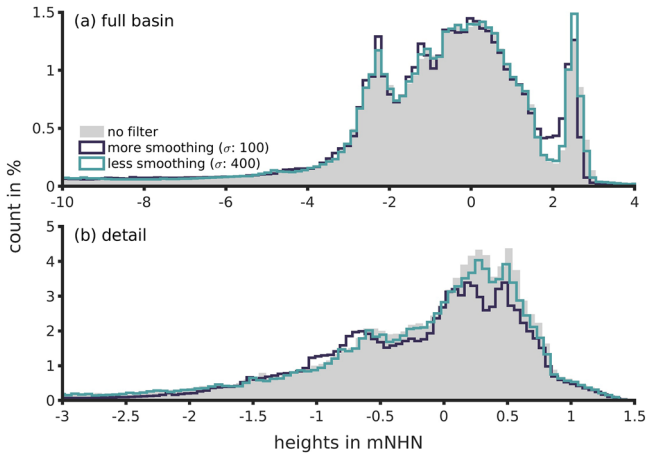


Fig. 2 | Elevation distribution of a topography in 2020. a represents data from Fig. 1a-c and **b** the detail from Fig. 1d-f. Note that all samples below −10 mNHN were discarded to focus on changes outside of the distribution's tail.

Another drawback of filtering is the substantial loss in information (Fig. 1e-f) and, more importantly, a departure from the most accurate observational data available (i.e., the most modern). M25 suggest using a Gaussian filter (spatial smoothing) to harmonize the frequency spectrum of topography data over time. Filter intensity is controlled by a threshold (σ) which represents a standard deviation of elevation samples in the frequency domain. The threshold defines a compromise between noise reduction and detail preservation: A lower sigma leads to more smoothing, as it results in a narrower filter window excluding more high-frequency components (see M25 for details).

Figure 1 illustrates how spatial smoothing increases the number of low-elevation samples in the intertidal zone for different filter thresholds. Although the method is visibly effective in removing small-scale features, it also adds more low-lying elevations (previously creeks and gullies) to the intertidal zone; an expected outcome given the method is designed to remove sharp local gradients (Fig. 1e-f). Consequently, a filter decreases mean intertidal elevations by design and the decrease magnitude corresponds to filter threshold (in-depth analysis in S2-S3). Again, this observation questions whether the suggested normalization produces truly comparable datasets since smoothing not only removes small-scale features but strongly affects the elevation's distribution (Fig. 2). A simple visual inspection of the filter effect on the original dataset (Fig. 1d-f, Fig. 2) supports this chain of arguments as the result is not a realistic estimate of a high-resolution topography with less small-scale structures.

It is unclear why the authors discarded a more straightforward option of volume-conserving grid downsampling with standard aggregation methods to achieve a scale alignment while preserving key characteristics.

Conclusion

The assessment of coastal morphological resilience requires long-term datasets with high resolution, extensive observations, and robust statistical methods. As the latest contribution on the morphological evolution of the Wadden Sea, M25[12] emphasized the need for critical evaluation and normalization of multi-decadal topographic datasets in resilience assessments. In both their conclusions and accompanying media coverage, they highlight diminishing morphological resilience in the Wadden Sea. Although discussions about inconsistencies in scientific datasets is welcome, practical implications must always be interpreted in a broader context of measurement uncertainty (see S1), statistical significance (see S2), and system knowledge (see S3).

We argue that the prevailing uncertainty of available topographic datasets (see S1), the short temporal coverage, and the lack of local SLR estimates still prohibit the assessment morphological resilience. In other words, M25's interpretations about declining resilience are still selective because robust conclusions are not supported by the observations and their statistical assessment, yet. We demonstrated that the impact of the suggested filter method in M25 has visibly distorting and implausible effects on the

data. However, the impact was still surprisingly low when applying filtered data in a state-of-the-art integrated analysis (see S3). We presented evidence that the method of M25 introduces a systematic decrease in mean intertidal elevation corresponding to filter intensity which is why varying filter threshold to normalize the frequency domain over time has potential to impose artificial bias on trend estimates.

Concluding, M25's classification into shallowing, quasi-stable, or deepening based on uncertain estimates neglects the inherent complexity of natural tidal flat morphodynamics and ultimately coastal resilience (see S1). The observation that multiple of their accretion estimates actually replicate trends from previous studies[11,19] furthermore indicates less conceptual advancement than the title suggests. Statistical concerns (see S2) and a lack of reproducibility (see S3) come as an additional caveat. We emphasize that morphometric assessments at coasts can only be indicative for the foreseeable future as highlighted in previous studies[10,11,19]. Still, M25 remains relevant as a call for continuing high-resolution datasets and potential advancements in the assessment (see S4).

Data availability

All digital elevation data were published in the TrilaWatt and EasyGSH-DB initiatives[20,21] as described in literature[11,22]. The filtered digital elevation models from Fig. 1 (b-c) are based on the above-mentioned data and can be easily reproduced using the provided filter thresholds.

Code availability

Figures were created using MATLAB r2023b. Method and code for the integrated quantile regression assessment of topography data were published previously by Pineda Leiva et al.[11] and the Gaussian filters were implemented according to the method of Miao et al.[12]. For the latter, we used the Python packages Numpy, Pandas, SciPy, Statsmodels, Matplotlib, RasterIO, and GeoPandas (last access 15th December 2025).

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Author contributions

Robert Lepper (R.L.) conceptualized and drafted this work. Diego Pineda Leiva (D.P.L.) conducted data analyses and R.L. visualized the results. D.P.L., Marvin Lorenz (M.L.), Jannek Gundlach (G.L.), and Marthe Wassink (M.W.) participated in initial interpretation of Miao et al. and assisted in revising the manuscript together with Edwin Elias (E.E.), Jessica Kelln (J.K.), Christian Winter (C.W.), DS van Maren (DS.M), Zheng-Bing Wang (ZB.W), and Frank Kösters (F.K.). All authors approved the final version and all authors share equal responsibility for the overall integrity of the study. DS.M, F.K., ZB.W. and C.W. acquired funding and supervised this work.

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Competing interests
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