Reviewer #1: Dr. Marvin Lorenz

General comments:

(G1) *The manuscript examines the impact of the spatial and temporal resolution of atmospheric forcing on extreme sea levels in estuaries. The study focuses on storm Xaver and the Scheldt estuary in the southern North Sea on the Belgian coast. The authors model the atmospheric conditions during the storm at resolutions from 2 to 30 km and provide the hydrodynamic model with forcing data at temporal resolutions from every 15 minutes to 6 hours. The highest temporal and spatial resolutions provide the best results, although peak sea levels are underestimated in all simulations. The manuscript is generally well written. While the results are not surprising, this is one of the first studies to systematically investigate these impacts of resolution for extreme sea levels in an estuary, although limited to one event and one estuary. I think the manuscript will be a very useful reference in the future, and despite its exemplary nature by studying only one system and one storm, I think general conclusions can be drawn from this study. However, I think the manuscript has potential for improvement since it does not dive into the dynamical aspects that are better resolved by the higher resolution of the meteorological data, leading to the improved results. Therefore, I have several comments and suggestions that I think would improve the manuscript.*

Response: Thank you for your positive evaluation of our work and for recognizing its possible contribution to the field. We appreciate your constructive feedback and thoughtful suggestions, which have been valuable in strengthening the manuscript. We have carefully addressed each of your comments and revised the paper accordingly to improve its clarity, depth, and overall impact.

(G2) *I think the main benefit of the higher spatial resolution of the atmospheric data is that local wind speed differences over water and land within the estuary are much better represented. However, this point is not really elaborated in the manuscript. I think the impact of the paper can be greatly improved if the authors could elaborate on why the peak values are higher in the high resolution case. I think the main reason could be that the momentum transfer within the estuary is larger due to the potentially higher wind speed over the water inside the estuary, thus increasing the surge within the estuary even more. However, since the surge outside the estuary is also higher for the high-resolution case, this may not be the only or even the main reason. So how and why does the resolution affect the surge height at the coast before the surge propagates along the estuary? This also raises the question of whether the momentum transfer within the estuary is even a factor in the surge increase, or whether the better representation of the surge at the coast is the main reason for the improvement of the peak sea level within the estuary? A starting point could be the evaluation of the wind speed distributions within the different simulations and the estimation of the induced additional sea level within the estuary. I recommend that the authors try to disentangle or at least discuss the origins, as this will make the results and conclusions of this paper transferable to other systems. This will greatly increase the impact of this paper. Since spatially high resolution atmospheric forcing data are generally not available, a possible solution could be a local bias correction in the momentum transfer equation of the hydrodynamic model, which somehow depends on the spatial resolution of the atmospheric data and the width of the estuary. While I do not expect the authors to test a way to correct for the resolution bias, I think it is worthwhile to discuss possibilities like this one or other in the discussion section.*

Response: We thank the reviewer for this thoughtful and constructive comment. In response, we have expanded to examine more closely the mechanisms behind the improved peak surge representation in high-resolution simulations, with particular attention to wind momentum transfer across the domain. Although it remains challenging to quantify the relative contributions of local versus remote effects, our results show that finer atmospheric resolution leads to improved surge dynamics. This improvement appears to result from a more accurate representation of wind forcing at the sea surface, which enhances surge generation both offshore and within the estuary. While our interpretation differs from the reviewer's initial hypothesis, we agree that both the open-coast dynamics and local wind effects within the estuary for the finer atmospheric data contribute to the improved model performance. This distinction is now clarified in the revised text.

To support this, we have added adapted Fig. 2 that includes now inset views highlighting the differences in wind field structure and intensity between resolutions. This visual comparison helps illustrate how higher-resolution atmospheric forcing more accurately captures localized wind maxima, particularly over the water surfaces inside the estuary.

The additional paragraph in the discussion section now reads: *The improved performance of the model in estuarine regions can be linked to enhanced representation of wind fields at higher spatial and temporal resolutions. High-resolution atmospheric forcing significantly improves the representation of wind speed both over the sea and land (Fig. 4). Notably, wind speed simulations at 5 km spatial and 15 min temporal resolution yield the best agreement with observations over land. However, when evaluating the hydrodynamic response—particularly the surge within the estuary—the best performance is achieved with 2 km spatial resolution combined with 15 min temporal forcing. This distinction suggests that, while 5 km resolution may sufficiently capture atmospheric dynamics over land, the more refined 2 km resolution provide the best representation of the surge dynamics within the estuary. Nevertheless, given that 5 km resolution delivers close performances with lower computational cost, it may be a practical alternative in some cases. A key factor may be the improved representation of the coastline and topographic feature in the atmospheric model at higher spatial resolution (Fig. 2), which plays an important role in the atmospheric dynamics over land. Another additional explanation lies in the higher wind intensity over the sea, at high spatial and temporal resolution it enhances momentum transfer from the open sea into the estuary (Fig. 2). This improved representation of wind forcing enables more accurate simulation of surge propagation and amplification within the complex estuarine geometry.*

Specific comments:

1. *Title: I would write "across an estuary-sea continuum".*

   Response: We agree with the reviewer. The title was modified to better reflect the paper content as suggested which make more sense given the fact that the paper only focuses on one estuary.

   The modified title now reads: *"Assessing the sensitivity of storm surge simulation to the atmospheric forcing resolutions across an estuary-sea continuum"*

2. *L18: Isn't this statement true for any place on Earth, since any place always has a 1% chance of experiencing such an event? Or are the authors referring to the fact that, on average, 1.3% of the population has experienced such an event annually in the past? Either way, this sentence needs to be clarified.*

   Response: We agree that the wording was unclear and could be interpreted in multiple ways. We have revised the sentence to clarify that we are referring to the historical exposure of the global population to 1-in-100-year storm surge-induced flood events during the period 1979–2014.

The sentence now reads: *Between the 1979 and 2014, an estimated 1.3% of the world's population were exposed to a 1-in-100 year flood event induced by storm surges, with economic damages reaching up to 11 trillion USD (Nicholls, 2006; Bouwer, 2011; Muis et al., 2016).*

3. *L25: heightened → increased*

   Response: The wording has been changed as suggested.

   The sentence nows reads: *The risk on these regions is further increased when storm surges coincide with significant rainfall or high river discharge, leading to exacerbated flooding (Marcos et al., 2019).*

4. *L34/35: I do not think the statement needs references, as it is a very general statement.*

   Response: The references have been removed as suggested.

   The sentence without references now reads: *However, advances in modeling techniques, powered by improved computational capabilities, innovative algorithms, and enhanced data integration and assimilation, have significantly bridged this gap.*

5. *L35-37: This statement is not relevant to the focus of this study.*

   Response: We agree with the reviewer that this sentence was not directly relevant to the main focus of the study. It has been removed from the revised manuscript.

6. *L45/46: These are not smoothed, but simply not resolved.*

   Response: The wording has been changed as suggested, see later.

7. *L46/47: An additional point that can be added here is that an atmospheric model is not the "truth" either. Already the choice of a data set introduces uncertainties, because there is no perfect data set. Some storms are simply not represented well enough in a dataset to correctly capture sea level peaks everywhere. There may also be regional biases. For the Baltic Sea, Lorenz & Gräwe (2023) have studied this in a hindcast ensemble, where the ensemble spread is already quite large for 1 in 30 year surges.*

   Response: We agree with the reviewer. The paragraph has been revised to reflect that atmospheric models are not ground truth and that the choice of dataset introduces uncertainties. It now acknowledges that no reanalysis product captures all storm events with equal accuracy, and that regional biases can affect model outputs. The suggested reference has been included, and the paragraph has been reformulate to also consider beyond estuarine systems and encompass other topographically complex regions.

   The paragraph formerly in L41-47 now reads as:

   Despite these advances, certain aspects of the land-sea continuum modeling remain poorly understood. One issue is how the spatial and temporal resolution of atmospheric forcing influences storm surge simulations in complex topographic system, such as estuaries. Although atmospheric conditions are the primary drivers of storm surge dynamics, the finer resolution of estuarine-sea models is generally not matched by the spatial resolution of the atmospheric forcing, with the latter typically operating on scales of tens of kilometers (Dinapoli et al., 2020; Chen et al., 2023). Small-scale processes such as localized wind patterns, frontal systems, and pressure gradients are not resolved in coarse-resolution atmospheric data. As a result, these unresolved processes within estuaries can introduce errors in the simulated surge dynamics, impacting factors like the timing, *peak intensity, and spatial distribution. Additionally, the atmospheric models themselves vary in quality, and no single reanalysis product reliably captures perfectly all events. This variability can introduce regional biases and uncertainties in storm surge models output, particularly in complex topographic system (Lorenz and Gräwe, 2023)*.

To further address this point, we have also added a dedicated discussion paragraph that explicitly acknowledges the limitations of using ERA5 as the external forcing for the MAR regional atmospheric model. We note that ERA5 tends to underestimate wind intensities over the North Sea, particularly during extreme events, which may contribute to the underestimation of peak surges observed in our results. Additionally, we discuss how the MAR model, although effective at downscaling, remains sensitive to inaccuracies in the ERA5 boundary conditions. This expanded discussion highlights how uncertainties in the atmospheric input can propagate into hydrodynamic surge predictions.

The additional paragraph in the discussion section now reads as:

The use of ERA5 to externally force the regional atmospheric model (MAR) likely contributes to the underestimation of surge heights observed in our results. Any underestimation of wind intensity in ERA5 over the North Sea can propagate into the MAR simulation, resulting in reduced momentum transfer to the ocean surface, causing the surge heights to be lower than observed. But this dataset is know to underestimate dynamics of at wind speeds (Molina et al., 2021). Higher resolution in the atmospheric forcing allows for a more realistic representation of these dynamics, partially addressing the underestimation and improving surge predictions, even offshore. Additionally, the MAR model, while effective at downscaling ERA5 data, may still be sensitive to the inherent inaccuracies in the wind fields and pressure patterns provided by ERA5, especially during extreme weather events. This compounded under representation of wind intensity and atmospheric pressure gradients can further contribute to the underestimation of peak surge levels, even when higher-resolution forcing is applied. Finally, MAR is 6 hourly forced by ERA5 at its lateral boundaries and a 3 hourly forcing could improve the representation of extreme events which cross the lateral boundary very quickly.

8. *L70: flood and dry out → wet and dry*

   The sentence now reads: *As a result of the large tidal variation, the Scheldt estuary features intertidal flats and marshes that periodically wet and dry.*

9. *L80: Can you add references for this sentence, e.g. Familkhalili & Talke (2016) comes to my mind.*

   Response: The sentence have been reformulated to integrate new references, among which the one suggested by the reviewer.

   The sentence now reads:

   Over time, human activities such as embankment construction, dredging, and channel deepening have reshaped the estuary's morphology and altered its hydrodynamics, contributing to increased tidal ranges and modified storm surge behavior (Familkhalili and Talke, 2016; Ralston et al., 2019).

10. *L81: flood control areas → a better wording might be "designated flood retention areas"?*

    Response: The wording has been changed as suggested.

    The sentence now reads: *Other modifications include large designated flood retention areas to improve safety and create new intertidal habitats (Schepers et al., 2018)*.

11. *L90: sea level rises → maybe better: "temporally elevated sea levels"*

    Response: The wording has been reformulated, see later.

12. *L90: drops in atmospheric pressure and wind stress -this could be interpreted as a drop in wind stress. Please reformulate.*

    Response: The wording has been reformulated, see later.

13. *L91: atmospheric pressure deficits - do you mean low pressure systems?*

    Response: Yes, we meant low pressure systems. The wording has been changed, see later.

14. *L91: main driver of storm surges - do you mean elevated sea levels by the inverse barometric effect? I wouldn't call that a storm surge.*

    Response: The reviewer interpretation is correct, we meant elevated sea levels. The wording has been changed as suggested.

    The sentences formerly in L90-91 now reads:

    These cyclones, often originating from the polar front, cause localized and short-term elevated sea levels, known as positive surges, due to drops in atmospheric pressure and increased wind stress (Bierly, 2005). Although low pressure systems are the main driver of short term elevated sea levels in deeper waters due to the inverse barometric effect, wind stress becomes increasingly significant near the coast, causing water to accumulate and resulting in surges of up to 4 m along coastal North Sea (Mathers and Woodworth, 2004; Weisse et al., 2012; Dangendorf et al., 2014).

15. *L98: typical tidal signal → mean tidal high water*

    Response: The wording has been changed as suggested.

    The sentences now reads: *This historic event was a superposition of a spring tide and a storm surge due to strong northwesterly winds over the North Sea, resulting in surge levels surpassing the mean tidal high water by more than 4 m at several locations along the eastern North Sea coast and 2.5 m at Antwerp (Flikweert et al., 2016).*

16. *Eq. (1) and (2) - I don't think these equations are needed, as this is textbook knowledge and any hydrodynamic model solves them*

    Response: We agree with the reviewer that shallow water equations represent well-established textbook knowledge, which are commonly used in hydrodynamic models. However, we have chosen to keep them in the main text for several reasons. First, the specific formulation used in this study differs from standard presentations notably, we solve the momentum equation in terms of the transport variable $H\mathbf{u}$ rather than $\mathbf{u}$, which is a distinction not previously documented in published descriptions of the model. Second, we chose to keep Equations (1) and (2) because not all the terms are activated or implemented consistently across different model setups. Including them explicitly helps clarify the particular assumptions and physical processes considered in this study. Third, given that the Appendix includes a description of the wetting and drying scheme used in this study, we believe it is helpful to keep these equations in the main text to provide clarity and support understanding of the model framework. The inclusion serves to make the model formulation more transparent, particularly for readers less familiar with the implementation details. The reviewer also suggested removing the wetting and drying description from the Appendix; our response to that suggestion is provided later.

17. *L129: Delete "Finally, the last parametrization concerns"*

    Response: The beginning of the sentence have been removed as suggested and the sentence was reformulated to facilitate the reading flow.

    The sentence now reads: *The wind stress $\boldsymbol{\tau}_s$, which depends on the wind as external forcing, with $\mathbf{u}_{10}$ being the wind speed at 10 m above the sea surface is parametrized as:*

18. *L133: MAR - Can you spell it out as this is the first time that you are using this acronym?*

    Response: The spelling have been added.

    The sentence now reads: *The wind speed is retrieved from the regional atmospheric model MAR for 'Modèle Atmosphérique Régional', described in Section 2.3.3*

19. *L161: characterize - can you find a better word than characterize? Maybe "determine"?*

    Response: We agree that "characterize" may be too vague in this context. We thank the reviewer for its proposition but we prefer to use "represent" as it, in our opinion, better reflects the intended meaning and the inherent idea that there are multiple data sources to obtain the bathymetry use in the model. The reformulation is given later.

20. *L168/169: delete everything after "is used", as this information in not needed here*

    Response: The end of the sentence have been removed as suggested.

    The paragraph formerly in L161-171 now reads: *We use multiple data sources to represent the bathymetry across our computational domain, selecting them based on the finest resolution available over the region. Starting with a coarser resolution over the NWCS, the bathymetry becomes finer as we approach the Scheldt estuary, reaching a minimum resolution of 10 m within the estuary. The data sources are presented in the upper part of Table 1. Over the NWCS, we use bathymetry data from the EMODnet (2021) dataset, which has a resolution of 115 m. Closer to the Dutch coast and into the lower Scheldt estuary, we use higher-resolution data from Rijkwaterstaat (2021) at a resolution of 100 m. As we move further towards the upper Scheldt estuary, we refine the bathymetry using data from AGENTSCHAP MDK (2021), which provides a 10 m resolution for the shallowest regions of the estuary. We then combine and convert these datasets to the same datum, to ensure consistency across the entire domain. The reference level NAP (Normaal Amsterdams Peil). In the schematized freshwater tidal river a constant bathymetry of 7 m is provided, reflecting the mean bathymetry in this part of the river. A map describing the data sources and their locations in the domain is available in Appendix A.*

21. *L213: Here and in some other places: I suggest trying to avoid the use of "((" and "))".*

    Response: The double parentheses have been replaced with single parentheses.

22. *Table 2 / validation metrics: I suggest adding the "bias" as a metric, $bias = 1/N \sum_i^N (m_i - o_i)$. I suggest this because I wonder if there is a bias in the mean sea level, possibly due to a bias in the tidal asymmetry (Fig. 4). This metric may be helpful to the reader.*

    Response: Bias has been included as an additional validation metric and is now presented in Table 2. Additionally, we have added the Normalized RMSE (NRMSE), defined as the RMSE divided by the standard deviation of the observations. In the previous version of the manuscript, this metric was referred to as the Relative RMSE (RRMSE), but NRMSE is the more commonly accepted terminology. For clarity and consistency, the correct definition and name have now been included in the table.

Table 2: Model performance metrics.

Metrics	Description	Formula
Mean Absolute Error (MAE)	Averaged absolute difference between observation and model estimate at data point	$\text{MAE} = \frac{1}{N}\sum_{i=1}^{N}\|m_i - o_i\|$
Root Mean Square Error (RMSE)	Weight of the mismatch between model and data by the variability in data and variability	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(m_i - o_i)^2}$
Standard Deviation (σ)	Dispersion of data (model or observation) around the mean	$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$
Correlation Coefficient (R)	Quantifies the strength and direction of the linear relationship between modeled and observed values	$R = \frac{\sum_{i=1}^{N}(m_i - \overline{m})(o_i - \overline{o})}{\sqrt{\sum_{i=1}^{N}(m_i - \overline{m})^2 \sum_{i=1}^{N}(o_i - \overline{o})^2}}$
Bias	*A systematic deviation from the observed value*	$bias = \frac{1}{N}\sum_{i=1}^{N} m_i - o_i$
Normalized RMSE (NRMSE)	*RMSE normalized by the standard deviation of observations; useful for comparing datasets with different scales.*	$NRMSE = \frac{RMSE}{\sigma_o}$

23. *L222: I think these are not averaged or smoothed out, but not resolved.*

    Response: The sentences have been reformulated to clarify that the small-scale processes are not resolved in the model.

    The sentences now reads: *As the spatial resolution coarsens to 10-30 km (Fig. 2.d-f), fine-scale variations are increasingly unresolved with larger grid cells losing the details of localized phenomena.*

24. *L223: observations*

    Response: Thank you for pointing this out. The sentence mentioning "observation" was removed, and the paragraph has been revised to reflect the inclusion of additional results. Specifically, 16 weather stations have been added into the atmospheric model validation. The removed sentence previously referred to the limitation of using only a single station for validation, which is no longer applicable.

    The reformulation of the paragraph now reads as: *The high-resolution atmospheric model with spatial resolutions of 2 and 5 km (Fig. 2.b-c and d-e) captures finer detail of the wind speed variability, particularly over continental regions, where the complex topography induces localized wind patterns. The best performance is performed over land with the atmospheric model at 5 km and 15 min resolution (Fig. 4). These regions benefit most from high resolution due to the influence of land features on wind flow. In contrast, wind speeds are generally higher over the open sea but tend to be more homogeneously distributed. As the spatial resolution coarsens to 10-30 km (Fig. 2.d-f), fine-scale variations are increasingly unresolved with larger grid cells losing the details of localized phenomena. This illustrate the ability of higher resolutions to resolve mesoscale features, particularly in coastal and estuarine environments.*

25. *L229: I think the validation would benefit from a few more stations. There must be weather data available for many stations across the model domain.*

    Response: We have added 16 additional weather stations to validate the atmospheric forcing. These stations are sourced from the Global Historical Climatology Network hourly (GHCNh) dataset, which compiles observations from fixed land-based stations operated by various meteorological agencies. The locations of the stations used are shown in Fig. 2.a, with blue markers indicating stations near the Scheldt and green markers for those in the North Sea region. This has been clarified in the text by adding details about it in the section 2.4.

This section now read as: *We use various error metrics to assess the quality of our model results compared to observations from the different stations (see locations in Fig. 1). Let o and m represent the observed and modeled values, respectively, for a time series consisting of N data points. The mean of the observed time series is denoted by $\overline{o}$, and the mean of the modeled time series is denoted by $\overline{m}$. The performance metrics used to evaluate the model are summarized in Table 2. Observations include several types of data: wind speed, atmospheric pressure and water elevation. Water elevation data were sourced from Rijkswaterstaat data, providing continuous 10 min observation data along the Scheldt estuary. Wind speed and atmospheric pressure observation were acquired from from two sources: the Flemish Banks Monitoring Network and located in the Belgian Continental Shelf, Meetnet Vlaamse Banken, with resolution of 10 min and from the Global Historical Climatology Network hourly (GHCNh) dataset maintained by NOAA. The GHCNh includes observations from fixed land-based stations operated by various meteorological agencies (Fig. 2). These datasets were used to validate the atmospheric forcing. In addition to the metrics listed in Table 2, we assess the performance of the hydrodynamic model to simulate the peak in the sea level by computing the mean absolute error (MAE) for the highest water elevation value during the storm surge. Sea level or water elevation is defined as the barotropic sea level, including both tide and surge components.*

26. *Fig. 2: I think this plot and this study in general would benefit greatly if you could add an inset of the Scheldt estuary showing the resolution of the atmospheric data over the estuary for each resolution. This should show that the wind speeds over the water inside the estuary are higher than in the course resolution. This should help your argumentation of the dynamical origins, see main comment above.*

    Response: Insets has been added to Fig. 2 to show the resolution of the atmospheric data over the Scheldt estuary for each resolution. The inset highlights the differences in wind speeds over water and land within the estuary at different resolutions, supporting our argument regarding the impact of spatial resolution on storm surge dynamics. An additional figure has also been added to show the difference in quality w.r.t. the spatial and temporal resolution in the atmospheric data between the Scheldt and North Sea (Fig. 4). The dynamical origins of the differences in peak water levels are discussed in the revised manuscript, particularly in the Discussion section, more about that has been explained in the answer to the second general comment.

    The new figure reads as:

27. *Fig.2: I think it might also help if you plot some contours of isobars to illustrate the position of the low pressure system.*

    Response: Contours of isobars have been added to Fig. 2 for the snapshot considered.

28. *Fig.2: can you specify the height of the wind speed? I expect it to be u10.*

    Response: The height of the wind speed has been specified in the figure caption as 10 m above the sea surface.

    The revised version of Fig. 2 can be found hereafter.

29. *Section 3.2: Can you also validate the hydrodynamic model against other tide gauges in the domain?*

    Response: 11 other tide gauges have been added to validate the hydrodynamic model. The locations of the additional tide gauges are shown in Figure 1. And the Table 4 with the validation

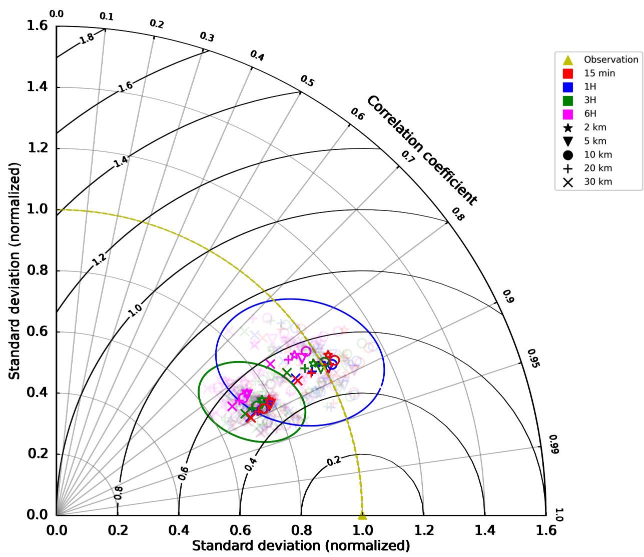

Figure 4: *Normalized Taylor diagram of the MAR simulation for wind speed, comparing different spatial resolutions, indicated by marker type, and temporal resolutions, indicated by color. Semi-transparent markers show individual validation points; bold markers represent regional centroids for weather stations in the Scheldt (blue ellipse) and the North Sea (green ellipse) regions as defined in Figure 2(a–b).*

metrics has been updated accordingly. Moreover, a Taylor diagram for the ocean model have also been added to visualize the difference in performance between the different spatial and temporal resolution between the off-shore North Sea stations and Scheldt stations. Since the domain has not been calibrated specifically for the other coastal area and to keep the diagram readable the stations in other coastal area in the domain are discarded from the Taylor Diagram analysis.

The update section 3.2 about the ocean model validation now reads: *The time series analysis obtained from the model and tide gauges show that the model accurately reproduces the tidal cycles at the different stations (Fig. 5). There is a slight overestimation of the tidal height and low tide by about 0.1 m, this overestimation is also visible when we compare the tidal constituent M2 between the observation and the model (Table 4). However, these deviations are relatively minor as compared to the tidal range of about 6 m, and overall, the stations show an good representation of the tidal dynamics. The tidal components in the model are well captured, particularly for the dominant M2 constituent. Error metrics further indicate the model's robustness (Table 4). The RMSE values in the Scheldt range from 0.221 m at Westkapelle to 0.297 m at Antwerpen Loodsgebouw, corresponding to areas with tidal amplitudes of approximately 4 m. Offshore stations show slightly higher RMSEs—up to 0.968 m at Dover, likely due to the focus of calibration on the Scheldt and coarser mesh resolution far from the estuary. Nevertheless, the model still performs adequately offshore, showing good agreement in both amplitude and phase of the M2 tidal constituent. Overall, the bias and MAE values remain close to zero, and correlation coefficients—consistently above 99% in the Scheldt and over 85% elsewhere, which demonstrate a strong linear relationship between modeled and observed water levels. This high correlation highlights the model's capability*

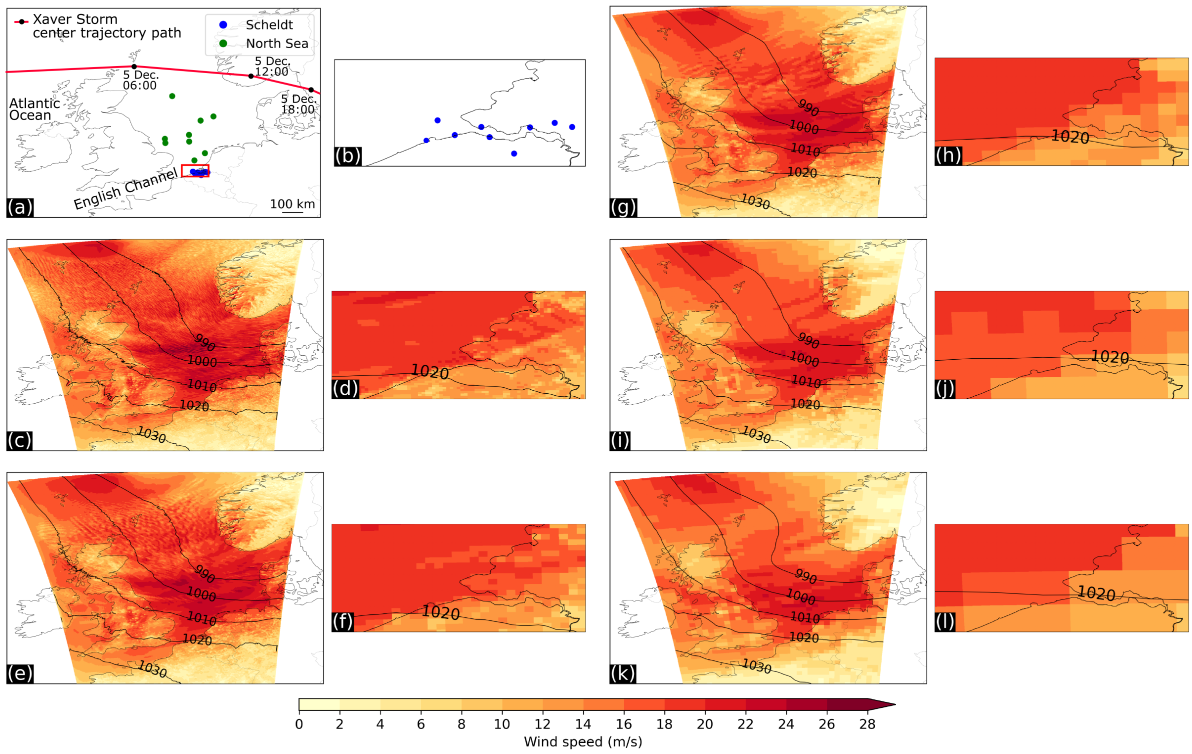

Figure 2: *(a-b) Storm Xaver's central low-pressure trajectory over the North Sea and surrounding areas, showing its path on December 5, 2013, with time stamps in UTC. The storm path is indicated by a red curve; blue and green dots represent atmospheric data validation stations for the Scheldt estuary and North Sea, respectively. Panels (c–l) display snapshots of wind velocity magnitude at 10 m above the sea surface and sea level pressure contours at 12:00 UTC on December 5, 2013, as simulated by the MAR atmospheric model at varying spatial resolutions. These resolutions range from (c-d) 2 km, (e-f) 5 km, (g-h) 10 km, (i-j) 20 km, to (k-l) 30 km, each resolution includes an inset focusing on the Scheldt estuary and adjacent coastal areas.*

in accurately capturing water elevation dynamics, particularly within the estuary, which was our primary focus.

The Taylor diagram and its result analysis for the ocean read as: *The validation across different temporal and spatial resolutions reveals two distinct clusters corresponding to the Scheldt estuary and the offshore North Sea stations (Fig. 4). To ensure clarity and maintain readability, only those validation points (i.e. stations in the Scheldt shown in Fig. 1.a) and offshore North Sea stations represented by green markers in Fig. 1.b) were included in the analysis, while other coastal stations, where no specific calibration was applied, were excluded. For both regions, the position of centroid of the model performance in the Taylor diagram improves as the temporal resolution of the atmospheric forcing becomes finer, and the best results are obtained with 15 min temporal resolution. The Scheldt cluster appears more compact and lies closer to the observational reference point, indicating that the model performs more accurately and consistently in this confined estuarine environment. Within this group, simulations at 5 km spatial resolution show the best alignment with observations, mirroring the behavior observed in the atmospheric forcing valida-*

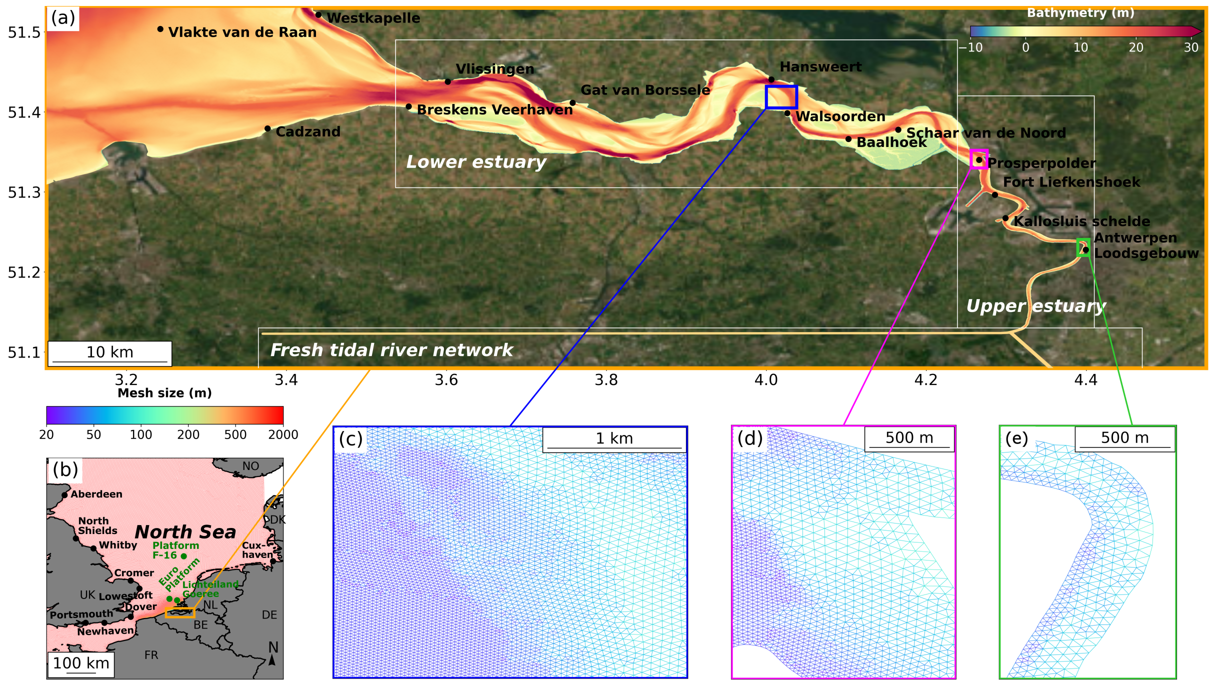

Figure 1: *Model computation domain covering the Scheldt and North Sea region. The upper panel (a) displays the bathymetry of the Scheldt estuary, with Esri World Imagery as basemap (ESRI, 2025). The white rectangles outline the tidal zones of the estuary and the fresh tidal river network is represented by artificial linear channels. Lower panels show the unstructured mesh configuration with (b) large view across the North Sea with black and green dots mark validation and (c-d) close-up views at three distinct locations on the Scheldt estuary. The dots in (a-b) mark validation points for the hydrodynamic model, colors in (b) differentiate coastal (black) and offshore (green) validation stations.*

Table 4: Error metrics and principal tidal constituent M2 amplitude and phase for various stations along the Scheldt estuary (top of table) and other locations in the domain, from November 25 to December 20, 2013.

Station	RMSE [m]	Correlation [-]	MAE [m]	Bias [cm]	$M2_{obs}$ [m]	$M2_{mod}$ [m]	$M2_{obs}$ [°]	$M2_{mod}$ [°]
Vlakte van de Raan	0.223	0.985	0.174	0.049	1.421	1.582	18.03	17.40
Cadzand	0.218	0.987	0.166	0.019	1.605	1.726	21.08	21.93
Westkapelle	0.213	0.986	0.163	0.000	1.469	1.590	25.51	24.70
Breskens Veerhaven	0.214	0.988	0.161	-0.003	1.671	1.773	29.70	29.48
Vlissingen	0.219	0.988	0.166	-0.004	1.673	1.795	31.52	32.19
Gat van Borssele	0.226	0.989	0.171	-0.078	1.756	1.895	38.13	37.80
Hansweert	0.238	0.990	0.180	-1.730	1.929	2.085	52.16	51.86
Walsoorden	0.242	0.990	0.185	-1.871	1.966	2.137	54.81	54.04
Baalhoek	0.245	0.990	0.187	-2.169	2.021	2.188	58.55	57.69
Schaar van de Noord	0.245	0.991	0.187	-2.316	2.048	2.220	60.95	60.43
Prosperpolder	0.255	0.991	0.194	-2.562	2.086	2.270	64.70	64.35
Fort Liefkenshoek	0.249	0.991	0.188	-2.868	2.154	2.295	67.21	65.86
Kallosluis Schelde	0.262	0.990	0.199	-9.805	2.191	2.339	69.13	67.29
Antwerpen Loodsgebouw	0.297	0.987	0.232	-12.059	2.218	2.361	75.65	70.91
Platform F16-A	0.158	0.949	0.118	0.019	0.502	0.560	180.27	183.49
Euro Platform	0.208	0.956	0.160	0.010	0.690	0.826	26.46	28.16
Lichteiland Goeree	0.227	0.963	0.175	0.003	0.818	0.991	40.55	41.71
Cuxhaven	0.540	0.899	0.442	-0.368	1.366	1.194	313.55	335.81
Cromer	0.684	0.844	0.569	1.708	1.513	1.479	158.56	188.84
Dover	0.968	0.866	0.803	-1.040	2.226	2.482	303.47	331.30
Lowestoft	0.403	0.813	0.323	0.581	0.665	0.676	227.88	263.35
Newhaven	0.924	0.877	0.816	-1.071	2.230	2.487	293.58	322.18
North Shields	0.635	0.880	0.537	-0.384	1.573	1.671	59.51	87.27
Portsmouth	0.663	0.859	0.594	-0.932	1.398	1.666	299.50	328.75
Whitby	0.671	0.873	0.569	-0.141	1.633	1.697	75.09	103.82

tion over the Scheldt (Fig. 4). Concerning the spatial resolution, the best results over the North Sea are obtained with the 2 km.

30. *L267: You didn't compute the bias, but the MAE. Also, I would call 20cm near zero.*

    Response: We agree with the reviewer that the MAE is near zero in the context of the mean high water levels in the region. The wording has been changed to reflect this see modifications of section 3.2 in the previous answer.

31. *Fig. 4 : I suggest adding more panels for more gauges.*

    Response: 5 more panels for more gauges have been added. We have also included the residual part derived through harmonic analysis. The residuals are calculated by subtracting the predicted tidal signal from the observed sea surface elevation using the package UTide.

    The new version of Figure 5 can be found hereafter.

32. *Tab. 4: I suggest adding the bias as a metric.*

    Response: We followed the reviewer's suggestion and added the results of the bias to the table. Bias values have been added to the table and are now discussed in the text. Bias remain low throughout most of the domain, indicating accurate model performance (Table 4). It increases in the upstream estuary, particularly near Antwerpen and reflects more complex tidal dynamics in that region, but overall correlation remains high, demonstrating the model's robustness.

33. *L285/286: I think this statement depends strongly on the characteristics of the surge (long or short,*

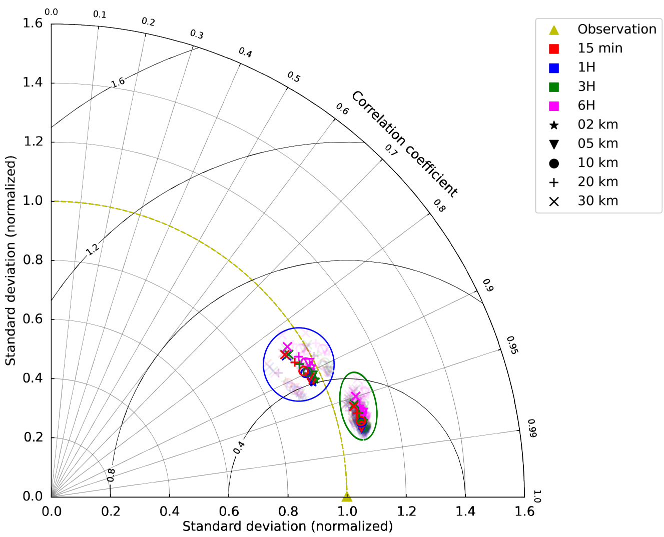

Figure 4: *Normalized Taylor diagram of sea surface elevation simulated by SLIM when forced by different spatial resolutions, indicated by marker type, and temporal resolutions, indicated by color. Semi-transparent markers show individual validation points; bold markers represent regional centroids for stations near the Scheldt estuary (blue ellipse) and the off-shore North Sea (green ellipse) regions as defined in Figure 1(a–b).*

one or more peaks etc.) and the size of the estuary. I just want to say that this general conclusion should not be drawn that quickly, although I agree with the statement.

Response: A sentences has been added to nuance the conclusion and clarify that the findings are context-dependent.

The additional statement reads as:

However, this effect likely depends on factors such as the characteristics of the surge, its duration or peak number, and the size and shape of the estuary. For Xaver Storm, the storm propagation speed highly impacted the surge characteristics (Wei et al., 2019). The results presented here apply to the Scheldt, a narrow and confined estuary. In contrast, larger systems with broader channels and multiple branches may respond less sensitively to high temporal resolution due to their wider cross-sections, longer response times, and different balances between tidal and river discharge influences.

34. *L299: I do not think that 5cm differences are "substantial" compared to a peak of 4m.*

    Response: We agree with the reviewer. The wording has been revised to better reflect the relative scale of the differences and avoid exaggeration. See later for the reformulation.

35. *L301: "with coarser temporal resolution (Figs. 8a,c and e)". - This is more evident in Fig. 7 for the spatial resolution!*

    Response: Thank for noticing this, the paragraph has been revised to clarify that the coarser temporal resolution show also a similar pattern in Fig. 7.

    The paragraph now reads: *The regions experiencing significant deviations in peak water levels expand as the temporal resolution of the atmospheric forcing becomes coarser. The deviation*

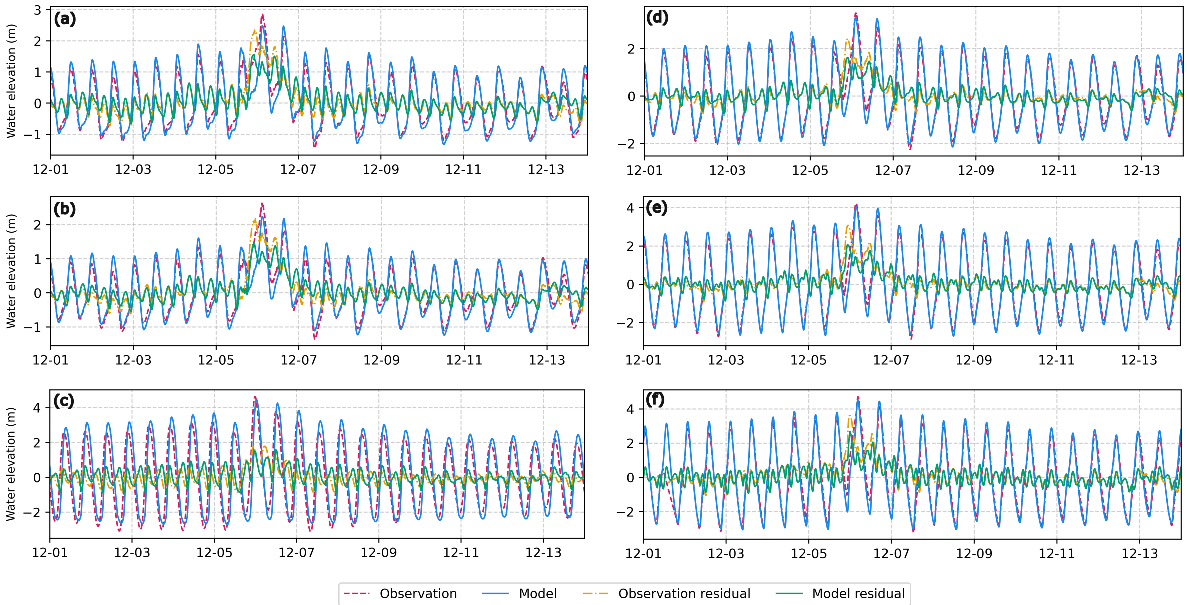

Figure 5: *Time series of sea surface elevation from December 1st to December 15th, 2013, at six locations, on the offshore and coastal North Sea stations (a) Lichteiland Goeree, (b) Euro Platform, (c) Dover; and Scheldt estuary stations: (d) Vlakte van de Raan, (e) Hansweert, and (f) Antwerpen Loodsgebouw. Results are shown as simulated by SLIM using MAR atmospheric forcing with 2 km spatial and 15 min temporal resolution (blue), compared against observed sea surface elevation (red). Detided (residual) elevations are also shown for both observations (orange) and model outputs (green).*

in peak water levels, at a fixed spatial resolution, exhibits variations of approximately ±10 cm between the simulation forced at 15 min and the other temporal resolution (Figs. 8). This pattern is particularly noticeable in the Scheldt estuary, where the close-up views (Figs. 8 b,d and f) highlight larger area with higher peak differences. A similar trend is observed for spatial resolution in Figs. 7, where coarser atmospheric forcing results in broader regions with elevated discrepancies. The area experiencing large deviations in peak water levels expands further in the North Sea, where the spatial extent of areas with large deviations in peak water levels also increases with coarser temporal resolution (Figs. 8 a, c and e). Additionally, a distinct shift in the sign of the deviation is observed when looking at the effect of temporal resolution, dividing the North Sea and the English Channel. Compared to simulations at coarser resolutions, the simulation using the reference atmospheric forcing resolution of 2 km yields higher peak water levels (positive deviation) on the Scheldt estuary and North Sea and lower peak water levels (negative deviation) on the Channel.

36. *Fig. 7: Why are the deviations in (e) and (g) in the open North Sea that large?*

    Response: Thank you for the observation. The deviations in peak surge over the open North Sea appear to be linked to differences in the quality of wind representation at varying spatial resolutions. Even offshore, higher-resolution configurations tend to better capture wind speed, which can improve the surge representation at high resolution. One explanation might be from the source of quality of the dataset used to force the MAR model.

We now address this point in the results section; the paragraph analyzing the figure has been updated accordingly. Note that the original Fig. 7 is now Fig. 9 in the revised version due to the addition of new validation figures.: *The deviation in peak water levels with a fixed temporal resolution of the atmospheric forcing increases as the spatial atmospheric forcing resolution becomes coarser across the domain (Figs. 9). This deviation peak is defined as the difference between the maximum water elevation of two simulations. The peak deviation between the simulations forced with 2 km and 5 km atmospheric resolutions (Figs. 9.a) shows value of ± 10 cm. As the resolution coarsens to 10 km, 20 km, and 30 km (Figs. 9.b-d), the deviations expand both in magnitude and spatial extent. Deviations remain modest between the 2 km and 5 km simulations, mostly under 10 cm (Fig. 9.a), but exceed 10 cm over the center area of the lower estuary as the resolution further decreases (Figs. 9.b-d), with maximum deviations approaching 40 cm in the center of the Scheldt lower estuary when comparing with simulation using 30 km resolution. The Scheldt estuary exhibits the largest deviations, with the center of the lower estuary and coastal region showing the most sensitivity to resolution changes. While the open North Sea shows smaller deviations, differences remain noticeable, especially when comparing high-resolution and coarse-resolution simulations.*

Also we elaborate on the source of these deviations. The paragraph reads as: *The benefit of better representing the atmospheric data in storm surge modeling is not specific to estuaries and can also include larger region. For example, in the Western Baltic Sea, Lorenz and Gräwe (2023) showed that the coarse resolution of atmospheric models such as ERA5 is also insufficient to resolve wind speeds correctly, leading to underestimated peak sea levels. The determination of appropriate spatial resolution for atmospheric forcing is ultimately dependent on the specific processes and scales being modeled. For coastal storm surge dynamics, which typically unfold over several hours and tens of kilometers, atmospheric forcing at such spatial scales may suffice (Agulles et al., 2024; Meyer and Gaslikova, 2023; Muller et al., 2014; Ridder et al., 2018). However, our results indicate that these standard resolutions may be inadequate for modeling storm surges in complex topographic and smaller scale regions such as estuaries. In those settings, finer-scale forcing is required to capture the local dynamics that drive the surge intensity. Furthermore, as demonstrated in our study, even some offshore areas benefit from higher-resolution atmospheric data, which yield more realistic representation of wind and hence improved surge model results.*

37. *Fig. 7: Delete "two simulations with varying spatial resolutions."*

    Response: Thank you for this suggestion. The figure caption has been revised accordingly.

38. *Discussion: A paragraph discussing the general underestimation of peak sea levels would be useful to the reader*

    Response: Thank you for your suggestion. We have added a dedicated paragraph in the discussion to address the general underestimation of peak sea levels observed in our simulations. In this paragraph, we discuss how the use of ERA5 to externally force the regional atmospheric model (MAR) likely contributes to this underestimation, due to known biases in ERA5 wind intensity—particularly over the North Sea. We also explain how these biases can propagate through the downscaling process, affecting the accuracy of momentum transfer and ultimately the modeled surge heights, even when higher-resolution atmospheric forcing is applied.

    The new paragraph reads as: *The use of ERA5 to externally force the regional atmospheric model (MAR) likely contributes to the underestimation of surge heights observed in our results. Any* *underestimation of wind intensity in ERA5 over the North Sea can propagate into the MAR simulation, resulting in reduced momentum transfer to the ocean surface, causing the surge heights to be lower than observed. But this dataset is known to underestimate dynamics of at wind speeds (Molina et al., 2021). Higher resolution in the atmospheric forcing allows for a more realistic representation of these dynamics, partially addressing the underestimation and improving surge predictions, even offshore. Additionally, the MAR model, while effective at downscaling ERA5 data, may still be sensitive to the inherent inaccuracies in the wind fields and pressure patterns provided by ERA5, especially during extreme weather events. This compounded under representation of wind intensity and atmospheric pressure gradients can further contribute to the underestimation of peak surge levels, even when higher-resolution forcing is applied. Finally, MAR is 6 hourly forced by ERA5 at its lateral boundaries and a 3 hourly forcing could improve the representation of extreme events which cross the lateral boundary very quickly.*

39. *L338-339: It is not only in estuarine environments that this resolution may be insufficient. I think this statement can be made for some environments larger than estuaries. In general, wind speeds can be underestimated if local topography in coastal areas is not well resolved in the atmospheric model. For the Western Baltic Sea, Lorenz & Gräwe (2023) find that the coarse resolution of atmospheric models such as ERA5 is also insufficient to resolve wind speeds correctly, leading to underestimated peak sea levels.*

    Response: The thank the reviewer for this suggestion. The section has been revised to clarify that the need for high-resolution atmospheric forcing is not limited to estuarine environments but also applies to other regions with complex coastal topography. To reflect this broader applicability, we have incorporated the suggested reference (Lorenz and Gräwe, 2023), which highlights similar findings for the Western Baltic Sea. This revision strengthens the generalization of our conclusions and reinforces the importance of resolving local wind patterns in a variety of coastal settings.

    The section formerly in L329-344 now reads: *The magnitude of the modeled storm surges is highly sensitive to the resolution of atmospheric forcing, a finding that aligns with previous studies (Weaver et al., 2016; Agulles et al., 2024). While Agulles et al. (2024) emphasized the role of temporal resolution, particularly at larger spatial scales, our results indicate that spatial resolution has a stronger influence when modeling estuarine environments at finer scales. This contrasts with Agulles et al.'s findings, where temporal resolution played a more significant role than spatial resolution at scales of 1.5–25 km and temporal resolutions ranging from hourly to daily. This divergence in results may be because of the difference in scales of interest, Agulles et al. (2024) focused primarily on larger-scale coastal dynamics using atmospheric data at broader spatial and temporal scales, on the continental scale along the European coastline and on several decades, while our study concentrated on the finer-scale dynamics of estuarine regions and smaller temporal scale. Similar conclusions on the importance of spatial resolution were drawn by Weaver et al. (2016), who showed that increasing the spatial resolution of meteorological forcing improved the simulation of storm surge during a cold front event in the Indian River Lagoon, Florida. This highlights that the relative importance of spatial versus temporal resolution can vary depending on the scale and characteristics of the system under study. Furthermore, our use of a different atmospheric data source from them may have contributed to these contrasting results. While Agulles et al. (2024) found optimal results using the ERA5 Reanalysis Dataset at an hourly resolution with a 31 km spatial scale, our study suggests that such spatial resolutions lead to the under performance of the surge model in complex environment such as estuaries, where finer spatial scales yield more accurate storm surge modeling.*

The benefit of better representing the atmospheric data in storm surge modeling is not specific to estuaries and can also include larger region. For example, in the Western Baltic Sea, Lorenz and Gräwe (2023) showed that the coarse resolution of atmospheric models such as ERA5 is also insufficient to resolve wind speeds correctly, leading to underestimated peak sea levels. The determination of appropriate spatial resolution for atmospheric forcing is ultimately dependent on the specific processes and scales being modeled. For coastal storm surge dynamics, which typically unfold over several hours and tens of kilometers, atmospheric forcing at such spatial scales may suffice (Agulles et al., 2024; Meyer and Gaslikova, 2023; Muller et al., 2014; Ridder et al., 2018). However, our results indicate that these standard resolutions may be inadequate for modeling storm surges in complex topographic and smaller scale regions such as estuaries. In those settings, finer-scale forcing is required to capture the local dynamics that drive the surge intensity. Furthermore, as demonstrated in our study, even some offshore areas benefit from higher-resolution atmospheric data, which yield more realistic representation of wind and hence improved surge model results.

40. *L343/344: This statement needs arguments from the results of this study, see my main comment*

    Response: We have added a paragraph to discuss the origin of the better performance of the 2 km resolution in the Scheldt estuary. The paragraph reads as:

    The improved performance of the model in estuarine regions can be linked to enhanced representation of wind fields at higher spatial and temporal resolutions. High-resolution atmospheric forcing significantly improves the representation of wind speed both over the sea and land (Fig. 4). Notably, wind speed simulations at 5 km spatial and 15 min temporal resolution yield the best agreement with observations over land. However, when evaluating the hydrodynamic response—particularly the surge within the estuary—the best performance is achieved with 2 km spatial resolution combined with 15 min temporal forcing. This distinction suggests that, while 5 km resolution may sufficiently capture atmospheric dynamics over land, the more refined 2 km resolution provide the best representation of the surge dynamics within the estuary. Nevertheless, given that 5 km resolution delivers close performances with lower computational cost, it may be a practical alternative in some cases. A key factor may be the improved representation of the coastline and topographic feature in the atmospheric model at higher spatial resolution (Fig. 2), which plays an important role in the atmospheric dynamics over land. Another additional explanation lies in the higher wind intensity over the sea, at high spatial and temporal resolution it enhances momentum transfer from the open sea into the estuary (Fig. 2). This improved representation of wind forcing enables more accurate simulation of surge propagation and amplification within the complex estuarine geometry.

41. *L345: necessitates → requires*

    Response: The wording has been changed as suggested. See the modification later.

42. *L349: this raises the question of how much further refinement is both feasible and beneficial - a bias correction could be a computationally cheaper option. I think this point can be added to the discussion, see my second main point*

    Response: We appreciate this suggestion and have expanded the discussion section discuss the potential role of bias correction as an alternative approach, see later.

43. *L357: intensive → expensive*

Response: The wording has been changed as suggested.

The paragraph formerly on L345-365 now reads: *Improving storm surge modeling through higher-resolution model requires to balance the benefits of increased accuracy and the associated computational and practical costs. This demand concerns both computing the high-resolution atmospheric model and the hydrodynamic model. Our findings demonstrate that higher temporal resolution of the atmospheric forcing (15 min), when paired with the finest spatial resolution of the atmospheric forcing (2 km) provides the best results for the peak surge simulated by the hydrodynamic model (Fig. 7). However, this raises the question of how much further refinement is both feasible and beneficial. First, for the temporal resolution of the atmospheric forcing: could higher resolution than 15 min could further refine the model result in the estuary? The surge takes around two hours to travel along the estuary, with peak water levels hitting Vlakte de Raan at 15:40 and Antwerp at 17:50 on December 6th. This 2 hours propagation time is eight times longer than our finest temporal resolution of the atmospheric forcing. Further increasing the temporal resolution may not significantly improve model accuracy and could even degrade performance. While finer resolution captures more atmospheric variability, it can also introduce numerical noise or amplify uncertainties, particularly when the timescale of atmospheric fluctuations becomes shorter than the estuary's hydrodynamic response time. In our case, the 2 km spatial and 15 min temporal resolution of the atmospheric forcing yields the best performance for simulating the peak surge, but it does not always produce the most accurate atmospheric fields. Pushing the resolution further may begin to resolve non-existent processes and introduce noise, ultimately reducing the reliability of the model outputs. Second, refining spatial resolution of the atmospheric model poses its own challenges, as it comes with substantial computational costs and is constrained by the hydrostatic assumption of the atmospheric model, which restricts the ability to achieve spatial resolutions finer than about 2 km. Refining beyond this threshold would require non-hydrostatic atmospheric models, which are computationally expensive (Dudhia, 2014). Moreover, these costs scale non-linearly with resolution and halving the grid size leads to at least a fourfold increase in computational time, due to both a higher number of grid points and reduced time steps for numerical stability. A possible cheaper solution to improve the atmospheric data could be a local bias correction of the wind speed which would have an impact on the hydrodynamic result. Finally, spatial resolution of the computational mesh also significantly impacts model outcomes. In this study, the coarsest mesh element was designed to align with the finest atmospheric spatial resolution of 2 km. If more detailed atmospheric forcing becomes available, a correspondingly finer computational mesh would be required. Improving the mesh resolution lead to better performances of the the hydrodynamic result (Saint-Amand et al., 2023). However, solving the hydrodynamics model on a finer mesh is much more computationally expensive and may lead to diminishing returns in model accuracy if not properly supported by equally detailed bathymetric data and calibrated physical parameters. Future research should therefore focus on identifying an optimal trade-off between model accuracy and the practical limitations of computational resources. Balancing these factors to improve storm surge modeling while ensuring its feasibility for real-world applications.*

44. *L388: I would split the discussion and the conclusion into two sections, as only this paragraph is a conclusion*

    Response: The discussion and conclusion have been split into two separate sections to improve clarity and structure.

45. *Appendix C: I think this detailed description of the drying and wetting is not necessary as the*

detailed implementation of the drying and flooding is not important for understanding this study. Therefore, I would suggest removing Appendix C from the manuscript and only mention wetting and drying in the methods section as it is already done and cite the reference where it is described in more detail.

Response: The wetting and drying scheme used in our model has not yet been published. We agree that its full description falls outside the main scope of this paper, however we consider that it is important to document the approach for the sake of transparency and reproducibility. This justifies the inclusion of the detailed description in Appendix C.

The method section has been revised to clarify this and the last sentence now reads: *The WD scheme applied in this study is not yet documented in published literature; therefore, a detailed description is included in Appendix C.*

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