Geoscientific Model Development | Ms. Ref. No.: GMD-2023-151

Development and performance of a high-resolution surface wave and storm surge forecast model (COASTLINES-LO): Application to a large lake

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Response to Reviewers Comments

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8 Feb, 2024

Editor Comment:

I thank the referees for their comments. Based on these, I encourage Laura Swatridge and co-authors to respond to these comments and to prepare a revised manuscript for submission.

With good wishes,

Andy Wickert

> **Response:** We thank the Editors and the anonymous reviewers for taking the time to read and provide comments and suggestions on how to improve the manuscript. All reviewer feedback has been addressed, by updating figures, clarifying details in the text, and improving the discussion of the results.
>
> This document provides a point-by-point description of modifications that were made to the manuscript based on the reviewer's feedback. These details are provided using indented blue text underneath each comment.

Reviewer 1:

> Response: As indicated by the Editor, the comments from Reviewer 1 were "unhelpful and self-serving". We therefore politely ignore these comments and respond in detail to the constructive comments from Reviewer 2 and Reviewer 3 below.

Reviewer 2.

Review of 'Development and performance of a high-resolution surface wave and storm surge forecast model (COASTLINES-LO): Application to a large lake' by L.L. Swatridge et al. submitted to the journal Geoscientific Model Development.

This is the coupled wave-current model's application to the Great Lakes, specifically Lake Ontario, and the parameters focusing on is the significant wave height and water level. The authors have done a lot of efforts in the numerical model development and the forecasting system, which is tested under both normal and storm conditions. The model performance has been validated by comparing with another popular forecasting system in the Great Lakes (i.e., Great Lakes Forecasting System, GLCFS) and NDBC (National Data Buoy Center) and ECCC (Environment and Climate Change Canada) observations. The authors conclude that their coupled 2D Deltft3D-SWAN model has a comparable ability with the GLCFS 3D FVCOM model, while it is more computationally efficient. Based on the reviewer judgement, the manuscript is interesting and nice, while it needs major revisions before being proceeding further. The following are my specific comments.

Response: Thank you for the detailed review and suggestions on ways we can improve the manuscript. Your feedback is very much appreciated.

In 2 Method – 2.1. Modeling Approach. At Page 5 in Lines 135 – 138. 'The Delft3D simulations uses a curvilinear grid with a horizontal resolution gradually ranging from 250 – 450 m …… 350 – 600 m for the wave model'. Why do authors do not use the same grid for both the storm surge model and the wave model?

Response: The wave model grid resolution was relaxed to reduce the computational requirements needed to run a simulation. When using the original grid (same as the circulation model), the computational time was increased to above 6 hours, as the number of computational cells is almost doubled in the higher resolution grid (333216 for circulation; 169400 for wave). To further justify this decision, the text has been updated as:

Line 135: "The Delft3D simulation uses a curvilinear grid with a horizontal resolution gradually ranging from 250-450 m. The wave grid has a coarser resolution, ranging from 350-600 m, thus reducing the computational time required to complete a wave simulation while still achieving higher resolution in nearshore areas."

At Page 5 in Line 140, please add a space between '0.07' and 'm'.

Response: Corrected

At Page 5 in Lines 144-146, 'Simulations use a time step of 120 s to satisfy ……'. Is the 120 s time step for the storm surge or wave model setting? What is the time step for another model?

Response: Text updated to add more details regarding time steps, as follows:

"Hydrodynamic simulations use a time step of 120 s to satisfy the Courant–Friedrichs–Lewy stability criterion, and the wave model uses a stationary computational approach"

At Page 6 in Fig. 1, please add the title of the colorbar, maybe 'Bathymetry (m)'?

Response: Figure updated with label on the legend.

At Page 6 in Lines 160-163: ‘No lateral open boundary ……’. As far as the reviewer understand, the Niagara River is a river with larger river discharges. By not including it, the coastal circulation and wave dynamics maybe influenced. Could the authors show the influence or the difference by including the Niagara River (and the St. Lawrence River) for storm surge and wave simulations?

> Response: While the Niagara and St. Lawrence rivers are the major inflows/outflows to the lake, we have concluded that including this influence in the model is not necessary, and outside of the scope of a real-time forecast model. Based on previous modelling studies in Lake Ontario (i.e. Prakash et al. 2007; McCombs et al. 2014), the influence of river flows only extends to approximately 10 km of the river inlet, thus for the large scale simulations in the current work, which focuses on lake-wide water levels and waves, this can be ignored, and is now justified in the text as:
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> Line 161: “No lateral boundary conditions are applied to account for the influence of the riverine flows (Niagara and St. Lawrence Rivers), as previous works have found the hydrodynamic influence of river flows is limited to within 10 km of the river inlet, and therefore have a negligible impact on large-scale circulation and water levels over event-based timescales (Prakash et al., 2007; McCombs et al. 2014a).”
>
> The other major impact of the river flows is their influence on mean water levels in the lake. In the real-time system, this is included by updating water levels in the lake in the post processing stage based on observed data.
>
> Line 186: “Seasonal changes in water levels due to inflows, outflows, and evaporation are not included, but are accounted for in post-processing.”.

At Page 7 in Fig. 2, what do MDF and MDW stand for?

> Response: Figure updated to say ‘Model Definition Files’ instead of MDF and MDW, to make workflow diagram more easily understood for readers

At Page 8 in Lines 201-203: ‘Hourly surface waves and winds are measured in Lake Ontario at one US Natioal Data Buoy Center (NDBC) buoy and ECCC buoys ……’. Based on Table 1, it shows 3 NDBC + 1 ECCC buoys. Please double check and be consistent between the descriptions and table.

> Response: Thank you, table 1 was updated with the correct information, and checked to ensure this is consistent with the text.

At Page 9 in Table 1, why do the water levels stations add no information on the location depths?

> Response: Depth information for water level gauges is not available, likely as these stations are located around the perimeter of the lake in relatively shallow depths. We agree that this data gap in Table 1 is confusing, so to correct this, table 1 has been separated into two tables (one for wave

buoys, one for water level gauges) and referenced in the text accordingly. Additionally, the text describing the water level gauges has been updated:

Line 199: Near real-time observations of water surface elevation (η) data are available at 9 water level gauges around the perimeter of Lake Ontario.

In the Method section, the reviewer considers that it is better adding the mathematical expressions for the statistics definition. For example, the (normalized) root mean square error, correlation coefficient, relative error etc.

Response: Expressions for each error metric have been added in the text, and referenced accordingly

There are some mismatches between the texts and the Figure at Page 10. I suggest delete Fig. 3i in Line 228, change the Fig. 3c to Fig. 3e in Line 231. By doing so, the contents and the figure can be consistent with each other.

Response: Thank you, text has been corrected as suggested.

At Page 10 in Line 229, please add 'the' between 'overpredict' and 'maximum'.

Response: Corrected

At Page 11 in Lines 245-246, based on the Fig. 1, I think station 'East Lake Ontario' in the east of the lake not northeast.

Response: Yes, that's true. The text has been updated as:
"Stations in the eastern end of the lake (Prince Edward Point, East Lake Ontario)…"

At Page 11 in Lines 245-247, 'Stations in the northeast region of the lake …… generally experienced the largest waves, due to the prominent northeasterly direction of storms over the lake resulting in a larger fetch at these locations.' Could you show me the wind map and time series?

Response: References have been added to support the statement describing the dominant wind patterns over Lake Ontario (ie. Lacke et al. 2007; McCombs et al. 2014a). In addition, the reviewer can refer to Figure S2 in the supplementary material for an example of a wind field/time series validation of wind speeds over Lake Ontario for the first selected storm event.

Lacke, M. C., Knox, J. A., Frye, J. D., Stewart, A. E., Durkee, J. D., Fuhrmann, C. M., & Dillingham, S. M. (2007). A climatology of cold-season non convective wind events in the Great Lakes region. Journal of Climate, 20(24), 6012-6022. https://doi.org/10.1175/2007JCLI1750.1

At Page 12 in Fig. 4, why the simulations have a data gap in about Feb. 2022?

Response: Thank you, good catch. The model was offline for a period between February 9 – 27, 2022 as a result of a service change in the HRDPS meteorological system. The modelling system had to be updated to account for the new delivery format for the atmospheric inputs. This explanation has been added into the Figure 4 caption as follows:

"Note that the model was offline and unavailable between February 9 – 27 (2022) due to a change of is delivery format for the meteorological inputs."

At Page 13 in Section 3.2. Storm event forecasts. The authors select the November 11, 2021, storm event to check the model performance. Why the authors choose this event to study? In addition, it would be better to choose more storm events to examine the model performance under storm conditions, e.g., more than 2.

Response: This event was selected as this is the largest event with available observed data at all wave buoys, thus allowing for the most complete validation possible. The second event selected had limited available wave data but was the strongest event over the operational period. Both events had distinct wind fields, thus representing model results over a wide range of conditions. The text has been updated as:

Line 270: "The performance of the model was evaluated over an event on November 11, 2021, which generated the largest waves and storm surge over the 20-month operational period with available observed water level and wave data."

In the scope of this paper, the authors feel analysis of these events is sufficient to validate model performance. However, it is also noted that in the long time series comparison of results, many storm events are included and simulated with good agreement.

We do agree that further investigation into storm events would be valuable and suggest this as a recommendation.

Line 455: "Additional investigation of real-time model performance during storm events, when the lake is stratified, is recommended for further model validation."

At Page 13 in Lines 271-272, 'A setdown of about 0.10 m was recorded at the Burlington station, which was underpredicted by the model by up to 0.05 m'. The under-prediction for this station is large (e.g., 50%), could they explain the reason for this bias and can it be improved? The reviewer is not sure that why the 50% error here, but it is 0-20% error in Figure 6c for the same station and event?

Response: Yes, the relative error at this station that was computed remains below 20% over the storm duration, despite a maximum observed and modelled set down of 10 and 5 cm. . This is because the calculation of relative error in Figure 6 is in reference to the mean water level in the lake at the beginning of the event, not to the zero datum. We agree this is unclear and creates misleading error statistics in Figure 6, but this decision was made to allow for consistency in storm surge values for consecutive forecasts. To clarify this, the relative error mathematical expression has been added, as referenced above to show how this is calculated (Eq. 4). In addition, the text has been updated:

Line 223: "For each forecast, the relative error (RE; eq. 4), between observed and simulated maximum storm surge relative to the mean water level at water level gauge locations, and between observed and modelled maximum wave heights at buoy locations was computed."

Figures 5, 7, 9, 10 needs improvements since there are so many solid lines in one figure, which make the reviewer hard to identify it.

Response: We agree that these figures show too many lines, making them difficult to understand. To improve the plots, the number of overlapping forecasts in Figures 5 and 7 has been decreased, from 16 forecast to 9, and the x-limits of the figure have been reduced so the forecasts of the storm event are larger and easier to see.

Figure 9 has been updated in a similar way, now only showing 8 forecasts over a shorter time period.

In Figure 10, all forecast lines were kept, as each one corresponds to a point on the scatter plots on the right, and therefore we feel it is important to show all the information. To improve the clarity of this plot, the colormap has been updated to improve the contrast between the different forecasts, and the limits of the plot have been shortened.

At Page 12 in Figure 4, the authors show the comparison of the Hs between the simulation and observations. How about the peak wave period (Tp)?

Response: Plots showing period results are now included in Figure S2 in the supplementary material, and referenced in the text as:

Line 250: "Results showing forecasted wave period compared to observations are shown in Fig S2 in the supplementary material."

Figures 6, 8, 10: Usually, the RE and RMSE could be improved as the length time for prediction decreases, why not all points follow this trend? For example, could the authors explain Page 19 Lines 360-361 'However, after the 18 h forecast there was a slight increase in RE from less than 1 % to about 5 % (Fig. 10b)'?

Response: We agree that that would be the expected trend, based on how atmospheric predictions tend to increase in accuracy with reduced lead time. However, there are other factors contributing to uncertainties in the results, such as model resolution, initial conditions, and background hydrodynamic processes that are not included/resolved in the model.

We note that the change from 1% error to 5% error observed in Figure 10b only corresponds to about 5 cm difference between forecasted water levels. The increased RE may be due to error in the magnitude and direction of the wind fields. This could also be an issue with the model setup, as calibrated parameters (i.e. friction, viscosity) can influence results. These were tuned to try to achieve optimal performance for a range of conditions, however it is not feasible to be able to account for all possible storm conditions. As this is a real-time model, additional calibration/adjustments could not be made to improve results for specific events, and the response of the lake to the unique conditions for each storm event is different.

Some discussion on this was added: Line 391: "Cases where the error increases (Fig 10b) or remains constant (Fig. 8), may result from sources of uncertainty in model calibration and/or neglecting additional hydrodynamic processes in the model setup (e.g., 3-dimensional circulation, density stratification).

At Page 15 in Lines 300-302, 'Measured waves during …… due to the shift in wind direction during the storm'. Could the authors more specifically point out the wind direction shift from which to which?

Response: The text has been updated to give a more detailed description of wind direction over the event:

"Measured waves during this event reached up to 2.10 m, with the buoys in the western region of the lake (Fig. 7c, d) experiencing peak wave heights about 12 h earlier than the buoys in the eastern region of the lake (Fig. 7a, b). This is explained by the shift in wind direction over the storm duration, with winds originally from the southeast, rotating clockwise, then blowing dominantly from the west along the axis of the lake (Fig. S2 in the supplementary material) ."

At Page 17 in Figure 8, what do these arrows stand for in panels a and b?

Response: The figure caption has been updated with additional details explaining the plot, as follows:

"Contour plots showing maps of modelled waves with vectors indicating wave direction at the peak of the storm event from two forecasts, starting a) November 11, 00:00 UTC and b) November 12, 00:00 UTC with observed data plotted at the observation locations in black circles. Note that every 10th vector is plotted for clarity.|"

At Page 19 in Line 347, 'select stations' maybe changed to 'selected stations'?

Response: Corrected

At Page 23 in Line 455, pleas add 'to' after 'In order'.

Response: Corrected

The authors emphasis that the Delft3D-SWAN (COASTLINES-LO) is highly computational efficient and can be easily applied to other lake systems. The reviewer would suggest they add a Table to compare the computational information between their system and GLCFS (e.g., computational nodes, elements, time step, total time, computational cores, parameter information etc.)

Response: A table summarizing the key differences between the modelling systems has been added to the supplementary material, and references in the text as follow:

Line 399: " Differences between predictions from these models can be explained according to the setup of each system, including different hydrodynamic models, grid resolutions, and atmospheric forcing inputs, which are summarized in table S2 in the supplementary material."

Reviewer 3:

I am happy to provide feedback on this manuscript. The manuscript presents a script written in Python/Matlab that performs pre-processing, running, and post-processing of a depth-averaged Delft3D+SWAN model to forecast water levels and waves in Lake Ontario for 48 hours. The manuscript is well-written and easy to understand. This study has the potential to make a valuable contribution to water management in Lake Ontario. However, the scientific/operational contributions of the proposed modeling framework and better discussion would benefit from improvement. Therefore, I recommend a "moderate revision" of this manuscript before it is published.

Please find below some specific comments:

The term "automated prediction" is used ambiguously in the abstract and several parts of the manuscript. It is recommended to provide a detailed explanation or use a different term altogether.

Response: The term "automated" in the abstract has been removed, and rephrased as "A real-time forecast model of surface hydrodynamics in Lake Ontario (Coastlines-LO) was developed to automatically predict storm surge and surface waves…"

We feel the use of the phrase throughout the manuscript accurately describes how the prediction system continuously runs without the need for any human inputs. Section 2.2 has been updated to make it more clear that all workflows are automated:

Line 170: "For pre-processing, initiation of the modelling system is scheduled to occur when a new HRDPS forecast becomes available"

The reason for the low computational demand of the proposed modeling framework is due to the lower spatial resolution used in the Delft3D/SWAN grid, as well as the depth average configuration which turns the 3D model into a 2D model. Additionally, the GLCFS is currently operational on NOAA's computational system, which means that its computational cost is affordable. Therefore, it is important to clearly state the operational and scientific contributions of the proposed modeling framework.

Response: Yes, to run this system on a local desktop computer, the resolution was limited and certain processes had to be neglected. Despite this, results compare well with the operational system developed by NOAA, which while operational, we doubt can be run on a desktop PC and easily adapted to a different waterbody or to simulate different state variables (e.g., surface water quality). We have highlighted the novelty of our workflow finding in the discussion and conclusion sections.

Please provide the source for the measurements and observations mentioned in Figure 1.

Response: A reference to table 1 has been added in the caption for Figure 1, to provide information about the observation points. The bathymetry source has also been added in the caption, and we refer the reviewer to Line 142 for a detailed description of the bathymetric dataset.

Could you confirm if the Python/Matlab scripts are currently being used for operations? Also, are these scripts available to the public?

Response: Yes, the model is currently operational, and the results are updated in real time on the project webpage: (https://coastlines.engineering.queensu.ca/lake-ontario/).

All model scripts, and input files, as well as results referenced in the manuscript are archived on Zenoda and made available for viewing through the link: (https://doi.org/10.5281/zenodo.10407863, Swatridge, 2023), as described in section 6. Code and Data Availability Statement.

It is suggested to also include metrics such as RMSE and RE (%) in Figure 11, and to add a table to clearly indicate the differences between the proposed model and GLCFS.

Response: A table summarizing the key differences between the modelling systems has been added to the supplementary material, (Table S2) and references in the text.

Summary error statistics from the comparison of the two models has been added in table S3 in the supplementary material and is referred to in section 4.2.

It is recommended to include the different viewpoints and angles in the proposed modeling framework.

Response: Through the development of this modelling system, a balance between computational efficiency and accuracy had to be achieved to allow the model to run in the required timeframe. We recommend in future work to expand the analysis to include an investigation on the effects of adding an ice model (there is presently not an ice model in DELFT3D), or different wind field inputs, and applying the modelling system to other large water bodies with open boundaries where connected to the ocean.