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Global-to-local scale storm surge modelling on tropical cyclone affected coasts

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Abstract
The physics of extreme high-water during coastal storms covers a wide range of scales, from tides and storms propagating over long distances to the shape of local bays, reefs and islands all contributing to what is potentially extreme high-water. Traditionally, modelling of storm-surges is mostly performed at a regional scale, sometimes extended with nested more detailed models to account for local effects. With the development of more and more accurate global tide and surge models this division may shift. In this study we show the recent advances of the Global Tide Surge Model, since our previous report [9] of version 1, including Self-Attraction and Loading (SAL) representation, dissipation of internal waves, grid refinements near the coast and bathymetry at the South Pole.

An open question is now, how to incorporate local effects with a global model. One option is to mimic the traditional approach and use the global model as a template for a regional model. Another option is to bypass the regional model and directly nest a detailed model in the global one. We will show an example of the first in this paper. An example of the second is planned as a collaborative initiative between Deltares and Risk Frontiers. An important question is what level is needed at the various scales needed to obtain accurate results. We will present both cases at the conference.

Keywords: storm surge, cyclones, sensitivity analysis, risk assessment.

1. Introduction

Tropical cyclones threaten a large part of the world's coastline and a substantial fraction of their casualties is caused by coastal inundation. Storm surge magnitude is often underestimated by coastal communities as the notion of exposure is mostly based on cyclone intensity. In reality, storm surge is also influenced by the shape of the coast, the coastal bathymetry and the position of the cyclone track. The complexity of storm-surge dynamics makes the potential benefits of modelling very large but also very challenging because both global-scale and local-scale processes need to be equally well resolved.

GTSM is a Global Tide and Storm Surge Model developed in Delft3D-FM. GLObal Storm Surge Information System (GLOSSIS) is an operational system that runs the GTSM four times per day using meteorological wind and pressure field forecasts from the National Centers for Environmental Prediction's Global Forecasting System (NCEP/GFS) as forcing. Both are developed by Deltares and together they provide high-quality forecasts on water level and storm surge at the global scale, and can be used to provide high-quality boundary conditions for finer-scale, regional models and to study the global effects of climate change. Additionally, they can be used as a predictive tool for the risk of storm surge to coastal areas in real time, which is lacking for many communities on a global scale. Using the new flexible mesh (FM) technology, the mesh resolution of the GTSM can be refined at the coast for local-scale applications without the need for consecutive nesting.

In this paper, the advances to both the GTSM and GLOSSIS since the presentation at Coast and Ports 2015 [8] are discussed. The importance of observational data for storm surge modelling on tropical-cyclone affected coasts is also explored through a collaborative initiative between Deltares and Risk Frontiers. To do this, the performance of the GTSM in a data-poor setting (Mozambique, East Africa) is compared to performance when applied in a data-rich setting (Queensland, East Australia).

2. Global Tide and Storm surge Model

A first implementation of the global storm surge model performed (GTSMv1) well in deep water [8]. Ongoing research on improvements of the model in shallow and coastal regions has led to improved results (GTSMv2).

2.1 Improvements to GTSM

2.1.1 Self-Attraction and Loading (SAL)

The processes of tidal forcing together with the elastic deformation of the seabed are termed SAL [9]. Initially, SAL has been approximated by reducing the gravitational constant by uniform scaling factor of 0.1. This was an oversimplified parameterization as the SAL effects cannot be uniform at every place on Earth. During calibration, the bathymetry had been adapted to compensate for phase errors arising from the approximate SAL representation [8].

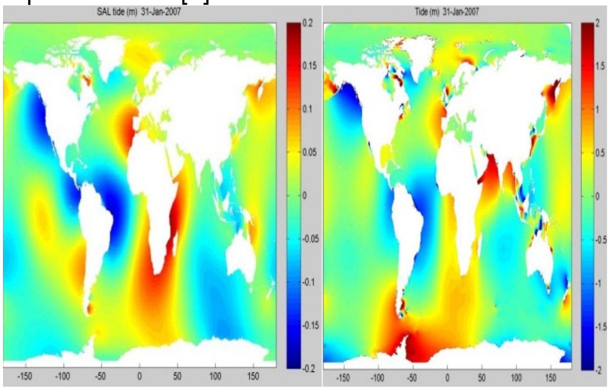

Figure 1: Model output for the same time step for (left) the SAL tide and (right) the tide computed without SAL. SAL tide scale is set to 10% of the tide's scale. Patterns are similar, but the beta approximation is clearly not valid for all regions and is overly simplistic.

Regional models generally do not include the SAL body force internally, but instead rely on open boundary forcing. Therefore it is important that GTSM includes SAL. For those reasons, the full SAL equations as published by Kuhlman [1] have been implemented in the latest version of GTSM. This has improved the root mean square error (RMSE) both at the coast and in deep water on average by ~35%, contributing to the overall improvement shown in Table 1. Furthermore, these equations are run in parallel, which means they provide no additional overhead to the computational effort. After recalibration and validation of the model the new implementation will be applied with GLOSSIS.

2.1.2 Dissipation of internal waves

The barotropic tidal dissipation is primarily a consequence of two processes: the nonlinear transfer of energy to turbulence in the bottom boundary layer and the linear transfer of energy to internal waves (baroclinic conversion). In the deep ocean, tidal current velocities are very small and the main energy dissipation mechanism is the energy transfer to internal waves.

A new parameterization for dissipation through the generation of internal waves over steep bathymetry has been implemented (see equation 1), which dissipates energy only in the direction of the steep bathymetry gradient and not along isobaths as was previously implemented.

$$\tau_{IT} = C\rho N\kappa^{-1}\left(\nabla h \cdot u\right)\nabla h \qquad (1)$$

This formulation includes a user-defined parameter which allows for calibration. This anisotropic parameterization better describes the nature of the dissipation mechanism in reality and results in more realistic total dissipation values and distribution globally.

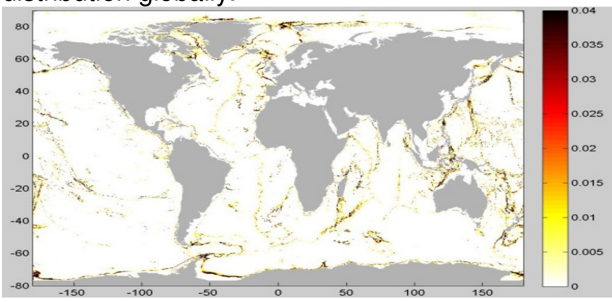

Figure 2 Distribution of barotropic energy dissipation through the generation of internal waves for one month, using the new parameterization (W/m2). As expected, the dissipation is concentrated around ocean ridges, continental shelves and island chains in deep water.

2.1.3 Grid refinement

A methodology to automatically introduce higher resolution for areas of steep bathymetry in the ocean (e.g. shelf breaks and mid-ocean ridges and trenches) has recently been developed (Figure 3). Capturing bathymetry gradients accurately at these areas is crucial in order to allow for dissipation through the generation of internal waves, as mentioned above.

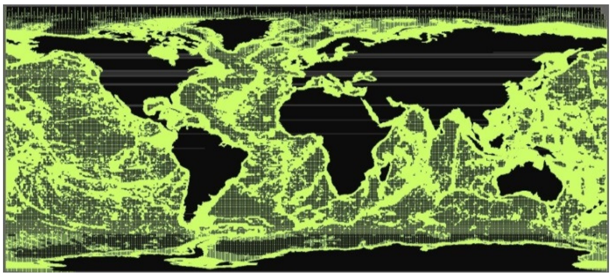

Figure 3: Bathymetry gradient based grid refinement

2.1.4 Bathymetry at the South Pole

Several global tide models have shown that tides propagate under the floating ice-sheets around the south-pole. The bathymetry of GTSM is based on GEBCO2014 [10], in which the ice-covered Weddell Sea and Ross Sea areas are considered above sea level (=land). Therefore below-ice tidal propagation cannot be modelled in these locations. It is expected that errors from this extended throughout the Southern Ocean and potentially to lower latitudes (Figure 4). Furthermore, local (ice-induced) dissipation was not modelled, and instead ice boundaries were fully reflective.

In GTSMv2 the bathymetry below the ice shelf has been updated, which has led to considerable improvement of the model (Figure 5). Originally we used the data in ETOPO bedrock, but this is bed level relative to geoid without considering the ice thickness. Therefore, ice thickness has now been removed and only the water column thickness is used as the bathymetry data in these areas.

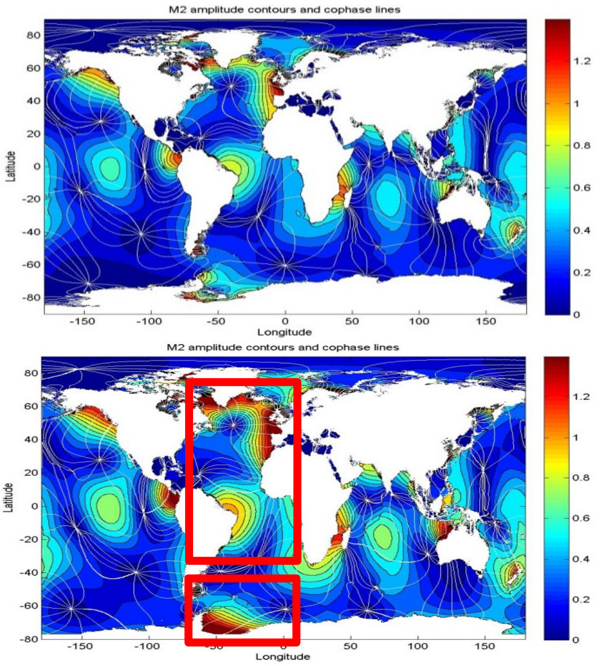

Figure 4: M2 Co-tidal chart for FES2012 benchmark in global tidal models (top) and GTSM (bottom) show a clear misrepresentation close to the ice-covered seas and an over prediction in the Atlantic ocean.

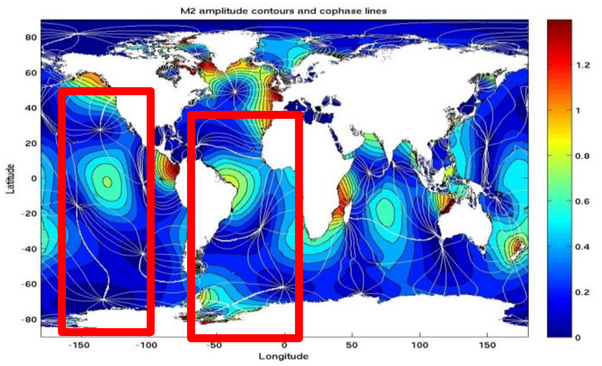

Figure 5: M2 Co-tidal chart for GTSM model including bathymetry below the permanent ice shelves shows clear improvements, especially for the Atlantic and Pacific Oceans due to improved bathymetries for the Weddell and Ross Seas, respectively.

Table 1: Calibration results for tide on deep water [cm] for both the calibrated GTSMv1 and the yet uncalibrated GTSMv2

Region	**RMSE GTSMv1 before / after calibration**		**RMSE GTSMv2 before calibration**
Arctic	5.1	3.2	5.4
North Atlantic	9.4	7.4	8.5
South Atlantic	12.1	8.4	6.6
North Pacific	8.1	6.2	8.2
South Pacific	11.2	7.3	8.9
Indian Ocean	11.7	8.2	8.6
South Ocean	12.4	10.2	7.1
Total	**10.2**	**7.4**	**7.7**

With these improvements we achieve accuracies of around ~8 cm in the deep ocean and ~19 cm for coastal stations, before any spatial calibration of either friction coefficient(s) or bathymetry (Table 1).

2.1.5 Parallelisation

The GTSM model can now be run in parallel, since the SAL routine has been made applicable for parallel runs. A one week forecast of GTSMv2 run on 8 cores takes approximately 30 minutes of computation time (or 3 minutes / day), while GTSMv1 takes just under 15 minutes. The increase in computation time is due to the increase in cells (from ~0.8 million to ~1.9 million) and the addition of the online full SAL routine. With these computation times it remains feasible to use GTSMv2 in an operational forecasting system.

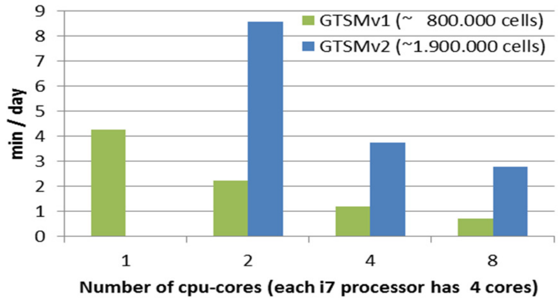

Figure 6: GTSMv2 and v1 computation times on a cluster; wall-clock in minutes per simulation day

2.2 Future work with GTSM

2.2.1 Grid refinement around islands

As a result of the aforementioned grid refinement process, grids surrounding islands undergo a fast transition from low to high resolution. This should be smoothed for a better representation, which is important to calculate energy dissipation and transfer. While this smoothing will only have a local effect, our aim is for relatively accurate surge values at the coast globally. The proposed smoothing would prevent isolated fine cells, and instead would refine cells more in clusters. With a string of islands, this would result in an intact chain of cell refinement. A trade-off has to be made between computational effort and (local) accuracy.

This development is in-line with the movement towards higher coastal (and potentially overall) resolution of the grid in future releases.

2.2.2 Improved bottom friction formulation

Distinguish bottom friction formulation between deep water (Chezy) and shallow water (Manning). Potentially also vary the formulation based on different seabed characteristics (e.g. sand and reef).

2.2.3 Inclusion of more physical processes

Inclusion of other physical processes like the baroclinic pressure gradient, seasonality of ice, and seasonality of brunt vaisala frequency.

2.2.4 Validation and calibration
Extend the validation against 281 tidal time-series [8] with altimetry data from the JASON-3 satellite (see section 3.1.2). The initial calibration was performed on a coarse version of the model, due to restrictions in run time. To be able to make optimal use of the parallelisation of GTSM, we are developing parallel processing of the OpenDA algorithm used for calibration. This would allow us to run the calibration on the full model, which would be a big improvement.

3. Global Operational Forecasting System

The system, as described in [8], has been running in operational mode since 2015. It has received some major improvements since that time, and has been tested for a number of storm events.

3.1 Improvements to GLOSSIS

3.1.1 Model update
GTSMv2 as described in this paper has been implemented in GLOSSIS. Additional to the wind and pressure field forcing from NCEP/GFS, the model can now also be run using wind and pressure fields from ECMWF's TIGGE archive. The GLOSSIS system also generates FES2012 [8] at all output points, allowing for an on-the-fly comparison with the GTSM tidal predictions.

3.1.2 Live remote-sensing data
The volume and quality of near real-time remote sensing data is steadily increasing, thanks in part to ESA's Sentinel program, which provides global datasets. GLOSSIS has been extended with real-time radar altimeter water level and surge measurements from the JASON-3 and Sentinel-3 satellites, as well as scatterometer measurements from the ASCAT satellite. This data can be used for a qualitative comparison with the GTSM model. Work on more elaborate forms of comparison and on assimilation of this data is in progress.

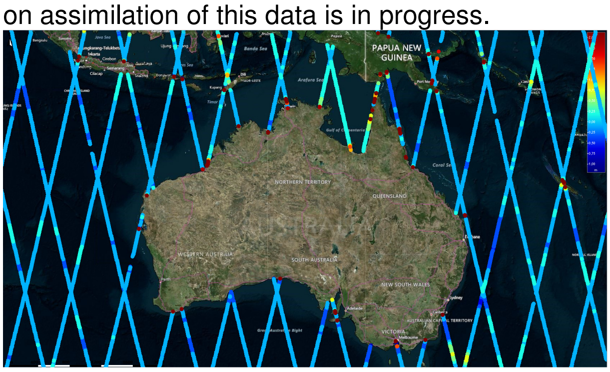

Figure 7: Real-time Sentinel-3 altimeter measurements

3.1.3 Automated alert levels
Alert levels based on the global re-analysis of GTSM [8] have been implemented for all DIVA stations. These levels represent the maximum water level achieved during storm events with return periods of 2 (yellow), 10 (orange) and 50 years (red). An alert is triggered in GLOSSIS when levels are exceeded in the 10 day forecast, indicating a potential significant storm event.

3.1.4 Archiving and dissemination
Since the fall of 2016, GLOSSIS forecasts are archived in the Open Archive [3]. This allows for a further analysis on forecast skill once the archive contains sufficient events. The archive stores the data in NetCDF files, which can also be used for dissemination of the forecasts with the use of a THREDDS server. This way boundary conditions for external regional models can be provided.

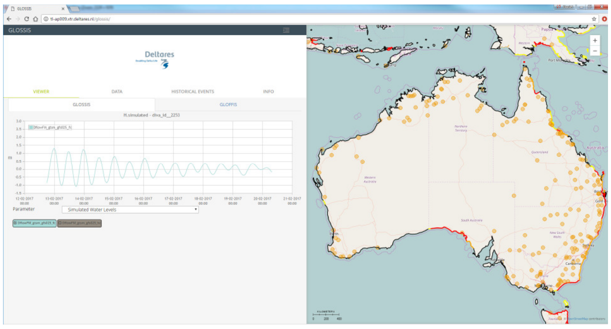

Figure 8: GLOSSIS results disseminated in a webviewer

A web-viewer has been developed through which the GLOSSIS forecasts are made available, together with the forecasts from GLOFFIS, a global forecasting system focusing on fluvial flooding [6].

3.2 Future work with GLOSSIS

3.2.1 Data assimilation
At present the GLOSSIS system ingests real-time water level measurements from the IOC network as well as from a number of radar altimeter satellites. This data is already used for on-the-fly model verification, but initiatives are underway to allow for assimilation of the data as well. This work will focus on updating of the model state using Kalman filtering techniques. This requires a more rigorous quality control of the data, which is also in progress.

3.2.2 Wave modelling
For many of the world's coastlines, wave conditions and associated run-up and overtopping, contribute significantly to flooding. Therefore GLOSSIS will be extended with a global wave model based on Wave Watch III. The resulting wave forecasts will be disseminated in a similar manner, and could be used as boundary conditions for regional and local models.

3.2.3 Dissemination of model results
The archive and web-viewer as described in section 3.1.4 currently still have restricted access, but will be made more accessible in the future.

3.2.4 Re-analysis GTSMv2
The evaluation of GLOSSIS forecasts for events in 2016 (see section 4) revealed inconsistencies

between the alert levels computed in [8] and the forecast water levels computed in GLOSSIS. The ERA interim data used in [8] underestimates cyclones, leading to an underestimation of the return period levels. On the other hand, the tides, particularly spring tides, are overestimated in GTSM, causing the (too low) alert levels to be exceeded too often.

Therefore, the re-analysis [8] will be repeated for with the upcoming new ERA Interim dataset, which has a higher resolution and resolves the high wind speeds achieved in hurricane events better. Furthermore, the re-analysis will be based on GTSMv2 calculation of the tides directly, instead of the FES2012 database [8]. This will improve the re-analysis especially in locations with a small tide, but a strong spring-neap cycle.

3.2.5 Improved NWP models
Global NWP models are moving toward ever higher resolution, which allows them to better represent smaller phenomena like tropical storms. When these products become available, they will be applied in GLOSSIS.

4. GLOSSIS live - Hurricane Matthew

In October 2016 category 5 Hurricane Matthew affected the Caribbean Sea and the East coast of the USA. Based on the GFS meteorological forcing for hurricane Matthew, GLOSSIS produced a forecast surge level and corresponding alert levels at the DIVA output locations (Figure 9). Significant water levels were achieved for this event (i.e. red alert level). The maximum potential inundation was derived from the forecast water level as well.

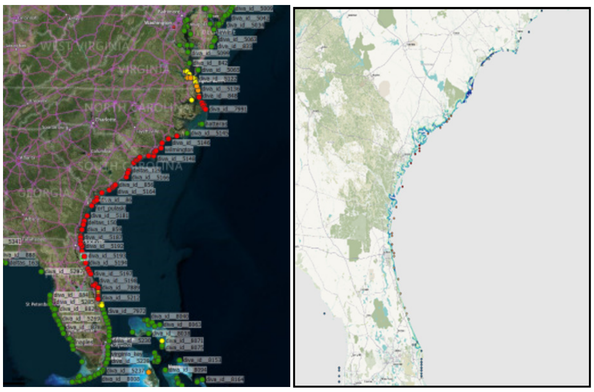

Figure 9: Forecast of alerts (r) and inundation level (l)

Further analysis showed that, although significant water levels were achieved during this actual event, alert levels shown in GLOSSIS are overestimated (see section 3.2.4).

5. Value of coastal data for surge modelling

The accuracy of storm surge modelling largely depends on data quality and availability. This is especially the case at the coast where local variations in wind fields, bathymetry and bed roughness can significantly influence surge heights. However, for many global-coast applications, high-resolution data are not available. Moreover, observations with which to validate model results at these locations are often lacking, meaning the accuracy of modelling in data-poor regions is difficult to measure.

An ongoing collaboration between Deltares and Risk Frontiers aims to quantify the influence of coastal data on surge modelling by investigating a range of model sensitivities to different data types. Results are not available at the time of writing, but will be presented at Coast & Ports 2017.

GTSM will be applied in a data-poor and data-rich scenario. The data-poor example is based on a project completed by CIMA and Deltares on the Mozambique coast (East Africa) where no high-resolution coastal data was available. The same modelling technique will then be repeated for the North Queensland coast, to represent a comparable data-poor approach. These locations offer interesting synergies in terms of geography and storm surge vulnerability as both are Southern Hemisphere east coasts of similar latitudes (15 – 25° S); and both experience impacts from tropical cyclones.

5.1 Mozambique

Tropical cyclones originating in the tropical latitudes of the Indian Ocean occur about once a year across any one segment of the Mozambique coastline. The impact of each storm greatly depends on the local characteristics (e.g. shape and depth) of the coastline and shelf, the storm track and local vulnerabilities. The specific objective of a recent study [4] was to develop a probabilistic national-level coastal surge hazard model for Mozambique, accounting for Sea Level Rise projections for 2050 and extreme still water level. The model includes extreme tidal water levels, wave setup (from ERA-interim) and cyclone storm surge levels. They are determined for flood levels representing the 10, 25, 50, 100, 250, 500, and 1,000 years return periods. The resulting levels from individual cyclones were processed into inundation maps for different frequencies of occurrence. This entails a number of statistical operations to integrate individual surge and tide setups into water levels associated with a set of given return periods.

5.1.1 Generation of synthetic Tropical Cyclones
Historical storm tracks from the IBTrACS archive were used to prepare a large sample of synthetic storm tracks for a period of 1000 years [2], with a statistical resampling technique to increase the amount of possible storms and make the probability density function of hazard much more accurate. From this, tracks passing the area of

interest were selected. With use of the Wind Enhance Scheme (WES), selected tropical cyclone parameters are transformed into high-resolution tropical cyclone wind and pressure fields in a so called 'spider web' grid, which are used to drive the hydrodynamic model.

5.1.2 Storm Surge, Wave Setup and Tides

The regional model used, was based on GTSM. For the purposes of this study, the resolution near the Mozambique coast was refined even further, to approximately 1.5 km. The depth data of the computational grid is based on the GEBCO bathymetry [10], at 0.5 minute resolution (Figure 11).

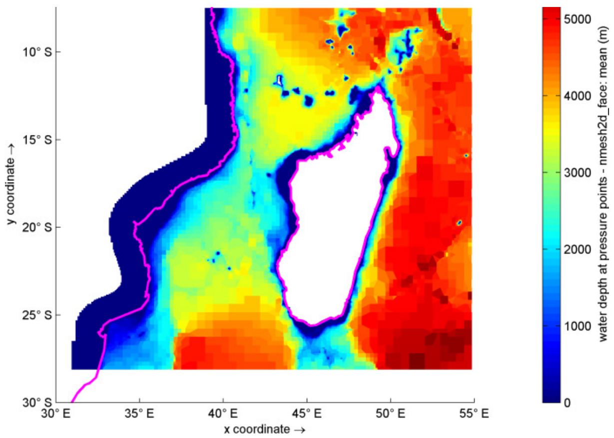

Figure 10: Map showing bathymetry as used in computational grid. Entire model extent is shown. Coastline is shown in magenta

Continental shelf widths vary significantly, from wide in central Mozambique, to medium in the south and narrow in the north. This is a relevant factor for the storm surges that are simulated.

The extreme tidal water levels along the coast were obtained using FES2012 [8], and the extreme storm surge levels were obtained using GTSM for the selected tropical-cyclones. These extreme water levels together with the wave set-up were used to produce the desired return values of the total water levels for Mozambique, which were subsequently used to determine the flood hazard and associated risk.

In many cases the wide shelf at Beira clearly stands out from the other locations, with much higher peak surges than cities with a narrower shelf (Figure 11). For some events, however, even Maputo observes high surges, despite its surrounding narrow shelf – but enhanced by the local shallow bay. The maximum peak surge value shown in Figure 11 indicates how extreme a rare large storm surge may be. However, these maximum values may vary significantly for a different realization from the Stochastic Cyclone Generator Tool [2].

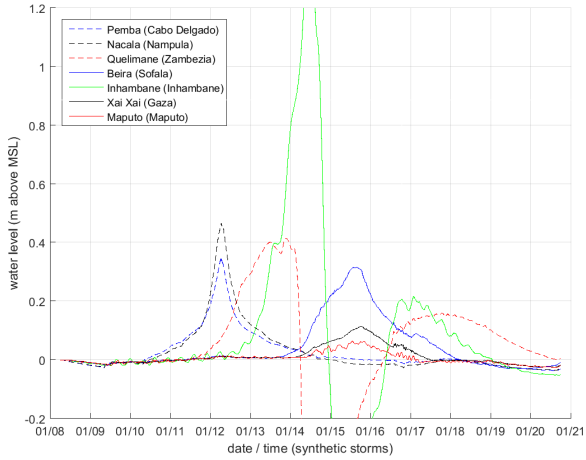

Figure 11: Time series of storm surge, for synthetic storm #366 in the stochastic experiment, at each of the seven coastal province capitals

5.1.3 Conclusions Mozambique case

This study showed how in a relatively data poor area, the GTSM can be used to create a model to perform a sensible coastal surge hazard assessment study. Furthermore, the regional model used in this study was relatively large, to be able to simulate all possible storm tracks across the complete eastern shore of Africa, rather than a limited, Mozambique-only coast line stretch. The benefit is that the resulting water level extremes can also be used to extend the analysis to other countries along the East African coast, which will severely lower the efforts required for performing this analysis for other countries in the region.

5.2 North Queensland, Australia

A regional cut-out of the GTSM mesh will be taken for the North Queensland region, focussing on the coastal strip between Townsville and Cairns (Figure 12). This mesh will form the basis of a standalone Delft3D-FM model of North Queensland (NQLDFM1), retaining the same model parameters (including 0.5 minute GEBCO bathymetry [10]) as used for Mozambique.

The NQLDFM1 model will be run for two tropical cyclone (TC) events; TC Larry (17 to 20 March 2006) and TC Yasi (30 Jan – 3 Feb 2011), with a 1-week model spin-up period prior to each event. Time series boundary conditions (tides + surge) will be provided by the GTSM hindcast. For each event, storm tide heights will be validated against coastal gauge observations (Figure 12). This represents the 'data-poor' scenario, comparable with Mozambique.

Sensitivities of the NQLDFM1 model to improved bathymetric data (100m^2 3DGBR bathymetry [11]), better wind fields (generated from a Weather Research and Forecasting (WRF) model for each TC event) and spatially-varying roughness for reef and non-reef areas, will then be investigated. We call the model with updated boundary data 'NQLDFM2', representing the 'data-rich' scenario.

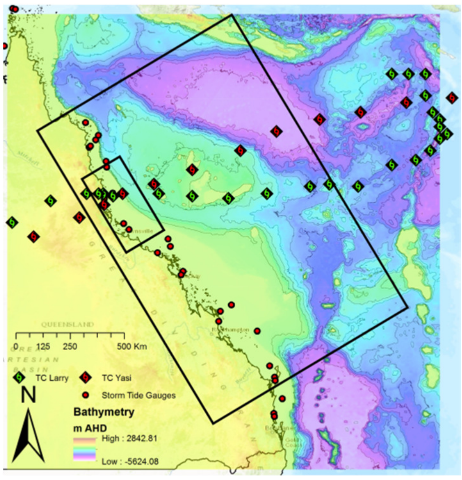

Figure 12: Regional modal extents of NQLDFM1 model with storm tide observation stations [5], 3DGBR bathymetry [10] and tracks of TC Larry and TC Yasi [1]

5.3 Future Work

Model sensitivities to a range of coastal data types will be tested for the North Queensland model. This will provide useful information for coastal managers about the value of coastal data for surge modelling, and for the continued development of the GTSM. We aim to answer questions like:

- What is the optimal depth, for coupling a coastal model to GTSM? This is not only a function of computation time but also of process. For example, ocean-scale processes (like internal wave dissipation and SAL as included in GTSMv2) are usually ignored in coastal models, while flow resistance induced by different seabed types is often not parameterised in global-scale models.
- How important is wave setup in the estimation of total storm tides? For high-energy coasts, wave setup is likely to be significant. However, wave modelling often requires an order-of-magnitude higher horizontal resolution than surge modelling because waves are much more sensitive to variations in nearshore bathymetry. As a result, it is often impractical to model this over large coastal domains. Instead, could machine-learning algorithms be used to translate boundary wave conditions (provided by a global wave model) to nearshore wave setup?

6. Summary

GLOSSIS has proven to be effective during recent storm events in providing alerts. Future addition of high resolution NWP and data assimilation will further increase the accuracy of the forecast information.

The accuracy of GTSMv2 has much improved compared to version 1. This paper shows a number of significant improvements to the modelled physics and numerical accuracy. The formulations for Self Attraction and Loading and dissipation by generation of internal tides have been improved significantly. The grid has been refined where this had most impact, at steep bathymetry. Although the grid size has increased the model can still run easily on a few nodes.

Through the use of a flexible mesh GTSM has a coastal resolution of only 5km, not far from the resolution of many regional models. With a global tide and surge model like this, the concept of appropriate scale in surge modelling is rapidly being re-defined.

7. References

[1] Bureau of Meteorology's Database of Past Tropical Cyclone Tracks, www.bom.gov.au/cyclone/history/.

[2] Deltares, 2016: Cyclone generator methodology with a focus on southwest Indian Ocean, Deltares memo ref. 1230818-000-ZKS-0005. October 2016.

[3] Deltares, 2017. Delft-FEWS wiki [Online], publicwiki.deltares.nl/display/FEWSDOC/25.+Using +the+Deltares+Open+Archive

[4] Deltares website, 2017: www.deltares.nl/en/news/tropical-cyclone-and-storm-surge-risk-in-mozambique-and-cabo-verde/

[5] Department of Science, Information Technology and Innovation of Queensland (DSITIA) maintains and operates storm tide observation stations, see www.qld.gov.au/environment/coasts-waterways/beach/storm/

[6] Emmerton, R., et al. "Continental and Global Scale Flood Forecasting Systems", WIREs Water (2016). doi: 10.1002/wat2.1137, 2016.

[7] Kuhlmann, J., et al. "Improved modeling of sea level patterns by incorporating self-attraction and loading." Journal of Geophysical Research: Oceans (1978–2012) 116.C11 (2011).

[8] Muis, S. et al. " A global reanalysis of storm surges and extreme sea levels". Nature Communications 7 (2016, online). doi:10.1038/ncomms11969 www.nature.com/articles/ncomms11969

[9] Verlaan, M., et al. (2015) GLOSSIS: Global Storm Surge Forecasting and Information System, Coast and Ports 2015

[10] Monahan, D. (2008) Mapping the floor of the entire world ocean: the General Bathymetric Chart of the Oceans, Journal of Ocean Technology, v. 3, p. 108

[11] Beaman, R.J., 2010. 3DGBR: A high-resolution depth model for the Great Barrier Reef and Coral Sea. Marine and Tropical Sciences Research Facility (MTSRF) Project 2.5i.1a Final Report, MTSRF, Cairns, Australia, pp. 13 plus Appendix 1.