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Forecasting tropical cyclone surge

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Abstract – **Tropical cyclones, with strong winds and low central pressure, can produce very large coastal surges and have led to the most devastating flooding in history. For example, in Bangladesh, flooding from cyclones in 1970 and 1991 has been estimated to have cost the lives of over 300,000 and 150,000 people respectively. While forecasting of cyclones and emergency management have improved dramatically, flooding from cyclone surge still represents one of the most serious global natural hazards and a considerable challenge for humanitarian organisations.**

In 2020, Cyclone Amphan was forecast to make landfall on the border of Bangladesh and India and the UK Foreign, Commonwealth and Development Office (FCDO) approached HR Wallingford to provide a forecast of the potential cyclone surge. Following that event, the FCDO commissioned a pilot study to develop the forecasting of flooding globally, including surge modelling, response of rivers to rainfall, modelling of flooding from both fluvial and coastal sources and analysis of the impact on local population and infrastructure. The aim of the forecast is to provide advance warning of the location, extent and severity of flooding and impact on population in order to aid the coordination of humanitarian relief. The service is provided by a partnership of ECMWF, the Universities of Reading and Bristol, Fathom and HR Wallingford.

As part of this service, a surge forecast system was developed using TELEMAC-2D forced by cyclonic wind and atmospheric pressure fields. The development of the system had to overcome a number of challenges:

- **The TELEMAC-2D models have to be large enough to cover all areas of interest to the FCDO and humanitarian agencies and at risk of flooding from cyclone surge;**
- **The models must adequately resolve the wind and pressure fields of cyclones and coastal bathymetry and topography;**
- **The models must include tide as it is the combination of both tide and surge that determines the elevation of the water and hence the extent and severity of flooding;**
- **The models must run quickly. The goal is to provide a bulletin within one working day and the target for the surge model runtime is less than one hour.**

The surge modelling system includes a number of regional TELEMAC-2D models covering areas of the world vulnerable to cyclone surge flooding and of interest to the FCDO. The regional models include tide and atmospheric forcing. Cyclone tracks are downloaded from relevant meteorological agencies responsible for forecasting tropical cyclones. Within the modelling system, these are converted into wind and pressure fields to force the model. Model results are extracted along the coastline for input into an inundation model and population exposure analysis. The combined results showing areas forecast to be affected by flooding and the impact on the local population and infrastructure are summarised in a concise bulletin for the FCDO. The bulletin is then circulated to local and international aid organisations including the UN OCHA and International Federation of Red Cross and Red Crescent.

Since the start of the pilot study in October 2020, the team have responded to tropical cyclones affecting Central America, Mozambique, Madagascar and the Philippines.

Keywords: Hydrodynamic modelling; surge; flooding; tropical cyclones; forecasting.

I. Introduction

Tropical cyclones, with strong winds, low central pressure and intense rainfall can produce extensive and severe inundation whether from fluvial flooding, pluvial flooding or coastal surge. Flooding from tropical cyclones is one of the most serious global natural hazards and is a large risk to life, infrastructure, agriculture, food supply and shelter. One severe tropical cyclone can affect a very large area and population.

The humanitarian response to tropical cyclone flooding is challenging, often involving getting supplies of food and emergency shelter to remote areas and contending with damaged infrastructure and lines of communication. In addition, aid is required rapidly. Advance warning of a disaster can, therefore, be extremely useful in the planning and carrying out of humanitarian relief.

A. Background

In 2019 during the approach of Cyclone Idai to Mozambique, Malawi and Zimbabwe, a number of organisations were brought together to provide advance warning of fluvial flooding, and the impact on population, to the UK Department for International Development (DfID) to assist the coordination of humanitarian relief. These institutions (ECMWF, the Universities of Reading and Bristol and Fathom) produced warnings for fluvial flooding a month later during Cyclone Kenneth which affected a similar area of southeast Africa [1].

In 2020, as Cyclone Amphan approached northeast India and Bangladesh, HR Wallingford was approached by DfID as the flooding risk was from coastal surge. Using a model adapted from previous studies in the northern Bay of Bengal, a forecast for coastal surge was provided showing flooding was likely in eastern West Bengal and southeast Bangladesh.

Following these events where forecasts were provided on an ad hoc basis, the Foreign Commonwealth and Development Office (FCDO, formed by the merger of DfID with the Foreign and Commonwealth Office) brought the organizations together to develop a formal process to provide advance warning for fluvial and coastal flooding from tropical cyclones as part of an ongoing service.

Since 2020, ECMWF, the Universities of Reading (UoR) and Bristol (UoB), Fathom and HR Wallingford (HRW) have developed a Flood Early Warning (FEW) advice service for potential severe flooding events from tropical cyclones including fluvial and coastal flooding.

This paper describes the use of TELEMAC-2D to provide forecasts of tropical cyclone surge as part of the flood forecasting system. Section II provides a brief overview of the whole flood forecast process. Section III describes the application of TELEMAC-2D and the challenges encountered in setting up a capability to model surge over wide areas of the globe. Section IV shows some results from two years of forecasting and Section V provides conclusions from the development and delivery of surge forecasts and discussion on further work.

II. THE FLOOD FORECAST PROCESS

The Flood Early Warning service is designed to provide a rapid response to a request from FCDO for advice in advance of a tropical cyclone making landfall and crossing vulnerable areas.

There are a number of stages to the FEW process. Some of the fluvial and coastal flood modelling and analysis is carried out in parallel. The main stages, also summarised in Figure 1, are as follows:

1) The FEW process is triggered by the FCDO following daily advice from the UK Met Office about global extreme weather,

2) The FCDO meets with the partner organisations (online) to decide on the appropriate response. The options are:

   a. Activate the FEW process,

   b. Pause, monitor and re-assess situation, with the option to issue a short (one paragraph) summary of the situation,

   c. Stop the process.

3) Following a decision to proceed, fluvial and surge flood modelling are carried out in parallel,

   a. Fluvial forecasting is carried out by ECMWF, UoR, UoB and Fathom,

   b. Surge modelling is carried out by HRW with predicted water levels passed to Fathom for inundation modelling,

4) Exposure analysis is carried out by UoB and Fathom to assess the impact on local populations and infrastructure,

5) The results of the forecasts and analysis are compiled in a bulletin delivered to the FCDO. The bulletin contains a one page summary followed by more detailed information and is designed to provide advice for the coordination of humanitarian relief.

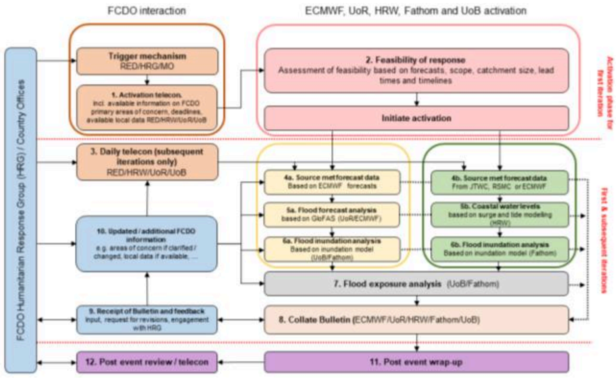

Figure 1. Flowchart showing the Standard Operating Procedures for the Flood Early Warning system following a trigger and activation

The above process is designed to be carried out over the duration of one working day. FCDO have shared the bulletin with organisations within the affected countries and international organisations such as the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA) and the International Federation of Red Cross and Red Crescent (IFRC).

The process may start up to five days in advance of cyclone landfall and may be repeated a number of times before and during the passage of the cyclone. After each event, the forecasts, advice and process are reviewed and compared with observations, reports from on-the-ground and feedback from FCDO.

III. MODELLING TROPICAL CYCLONE SURGE WITH TELEMAC-2D

TELEMAC-2D has been shown to be capable of simulating tropical cyclone surge [2] and has been used extensively either to hindcast surge caused by historical cyclones or synthetic cyclones to examine surge risk at a location or along a potentially vulnerable coastline [2]. Using TELEMAC-2D to forecast surge in advance of landfall throws up a range of technical and practical challenges.

A. *Challenges*

There are a number of factors that influence the arrangement and running of the TELEMAC-2D models in order to provide a good quality forecast of surge within the time scale and constraints of the FEW system.

- Models have to be large enough to cover all areas that are at risk of flooding from cyclone surge and of interest to the FCDO;

- Models must adequately resolve the wind and pressure fields of cyclones, coastal bathymetry and topography;

- Models must include tide as it is the combination of both tide and surge that determines the elevation of the water and hence the extent and severity of flooding;

- Models must run quickly. The target for the surge model runtime is less than one hour to fit in with the FEW schedule (Section II).

The cyclone modelling procedure and the basis of the models used in for FEW have been based on experience gained in projects where it has been necessary to model cyclones, for example to estimate extreme conditions for design of coastal and offshore infrastructure.

B. Meteorological forecast sources

The World Meteorological Organisation (WMO) recognises six Regional Specialised Meteorological Centres (RSMC) and four Tropical Cyclone Warning Centres (TCWC) as responsible for issuing tropical cyclone warnings within designated areas. In addition, the Joint Typhoon Warning Center (JTWC), based in Honolulu, issues warnings for the western Pacific, southern Pacific and Indian Ocean. The European Centre for Medium-Range Weather Forecasts (ECMWF) also provides global cyclone forecasts.

In order to have consistent forecasts and methods the surge forecasting system has initially been set up to run with forecasts from JTWC and the National Hurricane Center (NHC) in Miami. Both are US agencies and provide the same information in the warnings. In addition, and following the Flood Early Warning response provided for Cyclone Eloise, warnings produced by RSMC La Réunion have been included for southwest Indian Ocean cyclones and the Indian Meteorological Department (IMD) for the northern Indian Ocean.

The averaging period for which wind speeds are quoted is not consistent across the agencies. The US agencies, JTWC and NHC, use a 1-minute average wind speed as their maximum sustained wind speed convention. Most other agencies quote a 10-minute average wind speed. For modelling purposes, the 10-minute averaging period is more appropriate, so all wind speeds are converted to that standard following WMO guidance [3].

The agencies provide forecasts in the form of warning bulletins, an example of which is shown in Figure 2 from JTWC. Warning bulletins provide a forecast path of the cyclone at 12 or 24 hour intervals together with the maximum wind speed (V_{max}). Also provided by JTWC, NHC and RSMC La Réunion are the radii at which standard wind speeds are expected. These data are used to create time-evolving 2D fields of atmospheric pressure (at sea level) and wind (10m above sea level (ASL)) which are then used to drive the surge model.

```
WTXS32 PGTW 220900
MSGID/GENADMIN/JOINT TYPHOON WRNCEN PEARL HARBOR HI//
SUBJ/TROPICAL CYCLONE 12S (ELOISE) WARNING NR 011//
RMKS/
1. TROPICAL CYCLONE 12S (ELOISE) WARNING NR 011
   03 ACTIVE TROPICAL CYCLONES IN SOUTHIO
   MAX SUSTAINED WINDS BASED ON ONE-MINUTE AVERAGE
   WIND RADII VALID OVER OPEN WATER ONLY
    ---
   WARNING POSITION:
   220600Z --- NEAR 18.8S 38.0E
     MOVEMENT PAST SIX HOURS - 255 DEGREES AT 15 KTS
     POSITION ACCURATE TO WITHIN 020 NM
     POSITION BASED ON CENTER LOCATED BY SATELLITE
   PRESENT WIND DISTRIBUTION:
   MAX SUSTAINED WINDS - 065 KT, GUSTS 080 KT
   WIND RADII VALID OVER OPEN WATER ONLY
   RADIUS OF 064 KT WINDS - 025 NM NORTHEAST QUADRANT
                            025 NM SOUTHEAST QUADRANT
                            025 NM SOUTHWEST QUADRANT
                            025 NM NORTHWEST QUADRANT
   RADIUS OF 050 KT WINDS - 040 NM NORTHEAST QUADRANT
                            040 NM SOUTHEAST QUADRANT
                            040 NM SOUTHWEST QUADRANT
                            040 NM NORTHWEST QUADRANT
   RADIUS OF 034 KT WINDS - 110 NM NORTHEAST QUADRANT
                            100 NM SOUTHEAST QUADRANT
                            090 NM SOUTHWEST QUADRANT
                            110 NM NORTHWEST QUADRANT
   REPEAT POSIT: 18.8S 38.0E
```

Figure 2. Example of a warning bulletin from JTWC

C. Cyclone wind and pressure fields

1) Wind and pressure profile

For each tropical cyclone selected for modelling, time-evolving wind fields are set up based on the information included in the track data. At each model time step, a cyclonic wind field is set up based on the Holland parametric profile model [1][5][7].

The Holland model describes a profile of wind speed radially from the centre of the cyclone. Here, as the warning bulletins list maximum wind speed much more often than central pressure, we have followed [5][7] where the radial wind speed profile at 10 mASL is defined relative to the reported maximum wind speed (rather than central pressure), skipping the need to convert from gradient-level to 10 mASL wind speeds.

The cyclonic wind speed at radius *r* from the centre of the cyclone is:

$$V_{cyc}(r) = V_{max}\left\{\left(\frac{R_{max}}{r}\right)^{B} e^{\left[1-\left(\frac{R_{max}}{r}\right)^{B}\right]}\right\}^{1/2} \qquad (1)$$

where V_{max} is the maximum wind speed, R_{max} is the radius of maximum wind and B is a shape parameter which describes the rate of decay of the wind speed beyond the radius of maximum wind.

The cyclonic wind direction is applied tangentially with an inflow angle, β, dependent on radius from the centre [8]:

$$\beta = 10\frac{r}{R_{max}} \qquad r < R_{max}$$

$$\beta = 75\frac{r}{R_{max}} - 65 \qquad R_{max} \le r < 1.2R_{max} \qquad (2)$$

$$\beta = 10 \qquad 1.2R_{max} \le r$$

Added to the cyclonic wind is the velocity of forward motion of the whole cyclone [8]:

$$V_{tot}(r) = V_{cyc}(r) + \frac{V_{fm}}{2}\{1 + \cos(\theta_{fm} - \theta_{cyc})\}\frac{V_{cyc}(r)}{V_{max}} \quad (3)$$

where V_{fm} is the velocity of forward motion and $\theta_{fm} - \theta_{cyc}$ is the difference between the direction of the cyclone motion and the direction of the cyclonic wind at the location under consideration. Hence, on the side of the cyclone where the cyclonic wind and the forward motion are in the same direction, wind speeds are higher than on the opposite side. The contribution from the forward motion velocity also decreases as the cyclonic wind speed decreases so that at the outer limits of the cyclone, there is no residual wind speed.

The sea level atmospheric pressure field is also based on the Holland model [1] and is assumed to be circularly symmetric. Pressure increases from the minimum at the centre of the cyclone and at radius *r* is defined by:

$$p(r) = p_c + (p_a - p_c)e^{-\left(\frac{R_{max}}{r}\right)^B} \quad (4)$$

where p_c is the cyclone central pressure and p_a is the ambient atmospheric pressure outside the cyclone.

2) Estimating R_{max} and B

The parameters used in the Holland wind field model, R_{max} and *B*, are estimated by fitting a Holland profile, with R_{max} and *B* as free parameters, to the V_{max} and the radii of wind speeds quoted in the warnings (Figure 2). An example is shown in Figure 3.

The fitting procedure is first carried out for the quadrant where the cyclonic wind and forward motion are in the same direction which is where the winds are strongest and, for a simple case of a cyclone making landfall on a long coastline, is the quadrant where winds are blowing onshore. This determines *B* and R_{max} for the forward quadrant. R_{max} is assumed to be constant for all quadrants but *B* is varied by fitting Holland profiles to the other quadrant wind speeds. Hence the wind field has some 2-dimensional structure. An example is shown in 0.

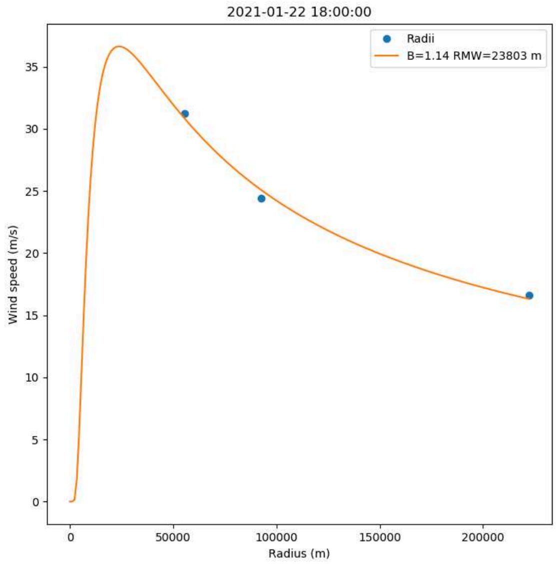

Figure 3. Example of fitting a Holland profile to radii specified in a JTWC warning bulletin

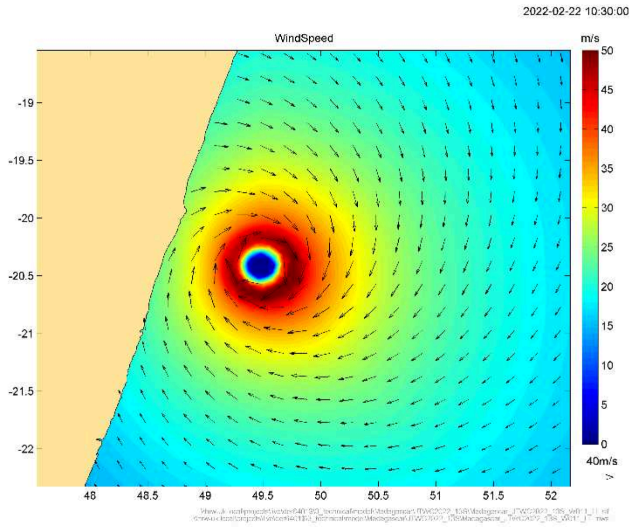

Figure 11 An example wind field from Cyclone Emnati as it approached the east coast of Madagascar in February 2022.

IV. RESULTS AND DEVELOPMENTS

At the time of writing, seven forecast responses have been provided to the FCDO which are listed in Table I. Development of the process has progressed as the forecasts have been run. Cyclone Amphan occurred before the formal start to the project and Hurricane Amphan very soon afterwards. Each response was an opportunity to learn and the modelling methods were developed. A sample of these cyclones, and the modelling process, are described below and used to illustrate the development of the system and how the challenges (listed in Section III.III.A) have been addressed.

Table I Tropical cyclones for which a TELEMAC2D model was run and a forecast provided to the FCDO

Cyclone name	Date	Affected countries
Cyclone Amphan	May 2020	India, Bangladesh
Hurricane Iota	November 2020	Nicaragua
Cyclone Eloise	January 2021	Mozambique
Typhoon Rai	December 2021	Philippines
Cyclone Batsirai	February 2022	Madagascar
Cyclone Emnati	February 2022	Madagascar
Cyclone Gombe	March 2022	Mozambique

A. *Cyclone Amphan*

The response for Cyclone Amphan was carried out hurriedly using an existing model of the northern Bay of Bengal. The TELEMAC-2D model of the Bay of Bengal was extended over the low lying land around the area of landfall. Automated systems had not been created and much of the preparation, such as interpretation of the warning advisory from the IMD, had to be done manually. The model was run with a constant tidal water level of +1.7 mMSL, equivalent to MHWS at the forecast location of landfall.

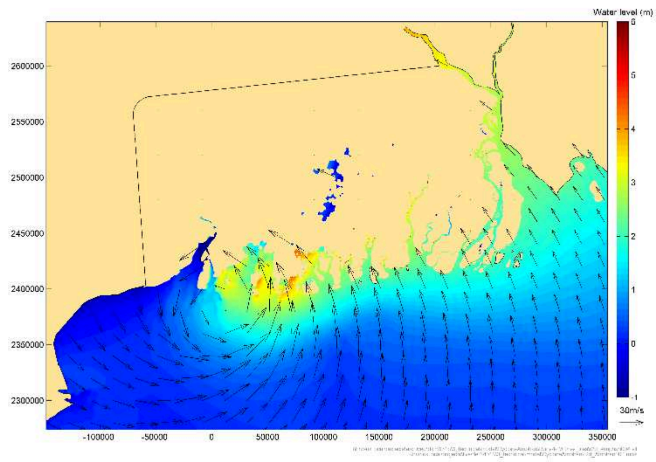

Figure 4. Water level as Cyclone Amphan made landfall close to the border of India and Bangladesh.

Figure 4 shows the predicted water level (relative to MSL) close to the time of landfall. While this was a very rushed response and some short cuts and approximations had to be made to achieve results in the time available, it was a valuable experience and a number of lessons were learnt :

- The model predicted flooding over an extensive area and, while quantitative data were not available to validate the predictions, the approximate location of inundation was consistent with anecdotal reports;
- The model did not include time-varying tide so predicted maximum water level could have been too high by up to 3 m depending on the time of peak surge relative to tidal phase;
- The response demonstrated the feasibility of forecasting cyclone-generated surge rapidly;
- For an effective operational service, the event showed the necessity for a well-organised system and models with as much automation as possible to ensure a fast delivery.

B. *Hurricane Iota*

Hurricane Iota developed in the Caribbean Sea and headed towards the east coast of Nicaragua. No existing local model was available at the time so it was decided to use the The Earth TELEMAC-2D model [9]. The global model works on a regular triangular mesh and the version relevant to cyclone forecasting has a grid spacing of approximately 16 km. There are finer resolution versions but these are computationally too expensive to run, at present, in a responsive forecast system.

The Earth TELEMAC-2D model bathymetry and coastline is based on GEBCO bathymetry data [10]. The Earth model has the advantage that it covers everywhere so can be deployed for any cyclone. However, there are disadvantages owing to the coarse mesh and generic nature of the model.

The model was used to predict surge for Hurricane Iota which made landfall on the Nicaraguan coast in November 2020 and this test illustrated both the benefits and drawbacks of the global model. The tidal range on the Caribbean coast of Nicaragua is very small so the model was run with a constant tidal level of mean sea level (MSL).

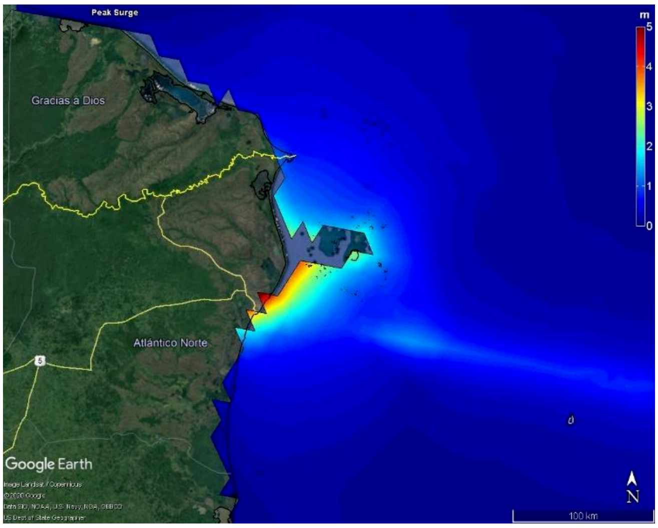

Figure 5. Hurricane Iota peak surge predicted by The Earth by TELEMAC.

Figure 5 shows the peak surge predicted by the Earth by TELEMAC model superimposed on Google Earth image. The effect of the coarse, regular grid can be seen in the artefacts in the model coastline, which joins node to node, creating the jagged line, compared to the smoother natural coastline. In addition to artificial triangular bays, the model has interpreted the offshore islands as a peninsular connected to the mainland.

- The Earth model is useful for identifying the locations at risk of large surge and potential coastal inundation in locations where no regional high resolution surge model is available,

- The coarse resolution, regular mesh and bathymetric errors lead to unrealistic coastlines which affects the accuracy of predicted surge,
- The Earth at present does not represent tide well enough to be included in a model run and would require a longer spin-up period.

C. Cyclone Eloise

Following Hurricane Iota, and with the northern hemisphere cyclone season coming to a close, the focus moved to the southern hemisphere, with Mozambique identified as a country vulnerable to cyclones and coastal flooding. A regional model was set up covering the Mozambique channel and the full coast of Mozambique (Figure 6).

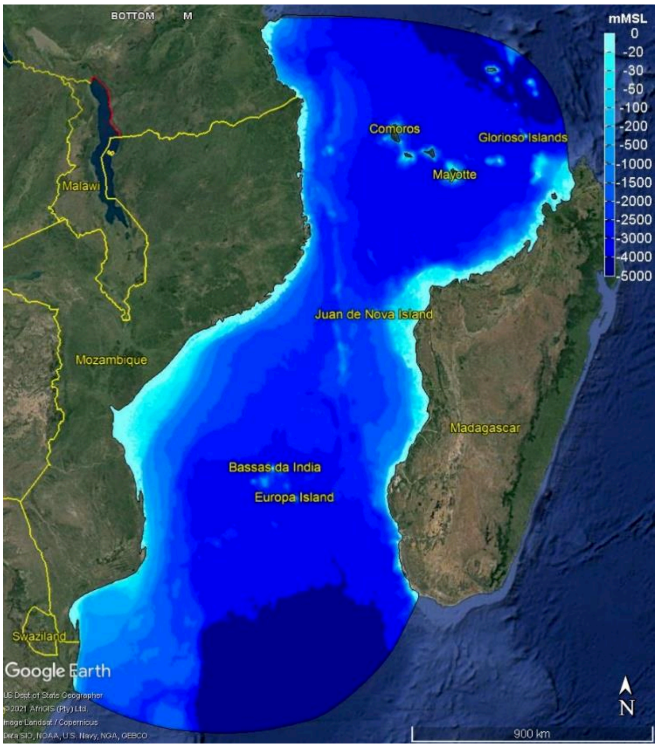

Figure 6. The TELEMAC-2D model area and bathymetry of the Mozambique Channel

The Mozambique Channel mesh spacing varies from 10 km in the open ocean to 1 km close to the shore. The flexible mesh allows the model boundary to follow the coastline. The model was extended to include coastal land up to approximately 10 mAMSL. Tide is imposed from the global tide model TPXO [11][12] along the offshore boundary of the regional model. The model was calibrated and represents the tidal water level variation well compared to Admiralty tide tables at ports around the coastline.

Cyclone Eloise made landfall on the coast of Mozambique just south of the city of Beira on 23/01/2021. The cyclone surge was forecast using cyclone warning bulletins from RSMC La Réunion and JTWC. Cyclone-generated surge was forecast from 21/01/2021.

The regional surge model was run with tide and atmospheric forcing based on the cyclone track forecasts from RSMC La Réunion and JTWC. The predicted high water mark, which includes both surge and tide, based on RSMC La Réunion warning bulletin No. 27 released at 0600 UTC 22/01/2021 is shown in Figure 7. The model is able to resolve the coastal features – such as the Rio Pùngué estuary next to Beira and the Baia de Sofala – where the water level is highest owing to constriction of waters driven into the inlets by the wind.

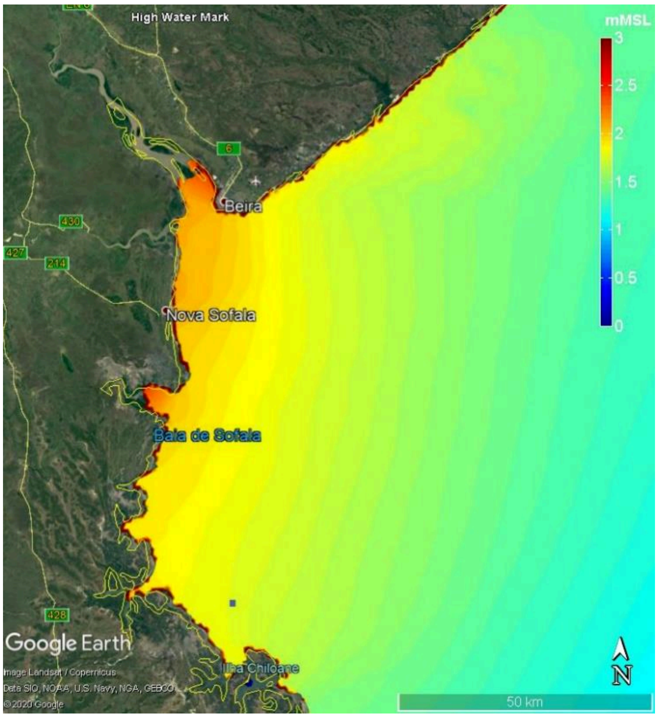

Figure 7. Maximum water level during Cyclone Eloise predicted by the Mozambique Channel TELEMAC-2D model

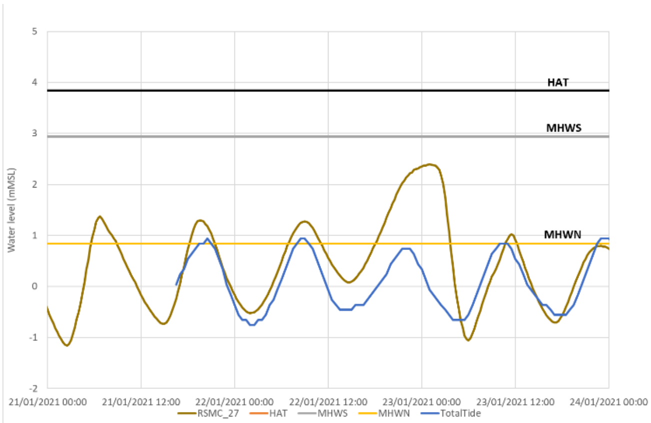

Figure 8. Time series of forecast water levels at Beira during Cyclone Eloise. Also shown are the tidal planes from Admiralty Tide Tables (horizontal lines) and a tide-only prediction from TotalTide.

The TELEMAC-2D runs resulted in time varying water levels which include tide and surge (Figure 8). Cyclone Eloise coincided with neap tides so, while the residual surge exceeded 2 m, the maximum water level was predicted to be lower than MHWS and so no widespread coastal flooding was expected. This appears to have been confirmed by anecdotal reports from the area.

- The model run was successful and included both atmospheric driven surge and time-varying tide.
- The model run-time was approximately 30 minutes on 36 cores of an HPC,
- The exercise demonstrated the advantage of a dedicated regional model.

D. Typhoon Rai

Typhoon Rai, known in the Philippines as Typhoon Odette, was a strong Typhoon that passed over the Philippines in December 2021. The storm underwent rapid intensification as it approached the Philippines and the JTWC estimated sustained wind speeds (1-minute average) of 140 kt before landfall.

A TELEMAC-2D model of the Philippines was available from previous projects but needed to be adapted to the purpose of predicting surge around the coast. The resolution was refined to approximately 1 km around all the Philippines coastline and the boundary and offshore resolution were optimised to maintain stability but with a practical run-time.

The complex topography and bathymetry of the Philippines make the representation of tides with a 2D hydrodynamic model particularly challenging. In addition to the complex coastlines with many islands and straits and a wide range of water depths, the western Pacific Ocean waters are stratified with a shallow mixed layer of typically less than 100m, and a steep thermocline below. The consequence is that currents, including those due to tide, are often baroclinic, and hence there are limitations to the use of a 2D model.

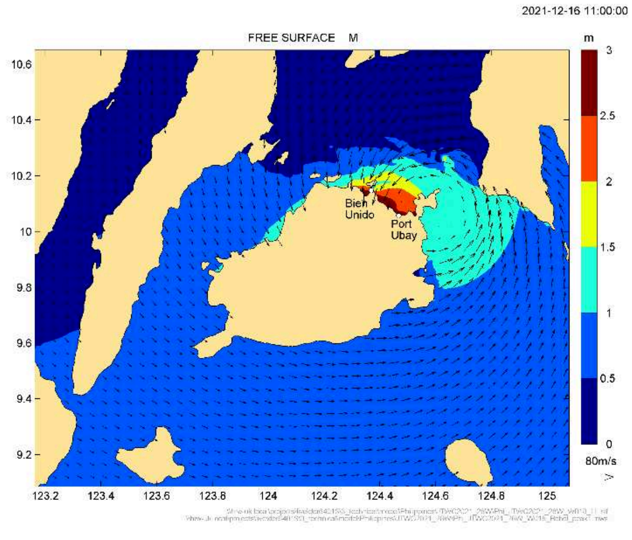

Figure 9. Predicted water level (relative to MSL) as Typhoon Rai passed the island of Bohol

The model was run with tide and no atmospheric forcing for a two-week spring-neap cycle in December 2021. Water levels were extracted at standard and secondary ports around the archipelago and compared with water levels based on harmonic analysis. TELEMAC-2D performs well at sites along the Pacific and South China Sea coasts but in some internal ports has a tendency to overpredict the range of the spring tide. This discrepancy may be because of the inability of a 2D model to represent baroclinic effects, as described above. Further tests to improve the model are ongoing but for now, overprediction of the tide will be compensated after the modelling stage with adjustments to the final water level predictions.

Some lessons from the exercise are:

- There are circumstances where 3D processes, which cannot be simulated by a 2D model, may make a significant contribution to the water level. This is likely to affect tide more than surge and may need compensation during in post-processing.
- In the case of islands, onshore winds may occur from any direction and therefore it is important to replicate the 2-dimensional structure of the wind field. The method, described in Section III.C, had been implemented before the Typhoon Rai. It is not possible, with this approach, to include the effects of island orography on wind fields which would a require a high-resolution atmospheric model.
- As the islands in the Philippines are of a similar scale to that of a cyclone, the predicted surge is very sensitive to the forecast track. TELEMAC-2D simulations using tracks forecast at different times and by different agencies produced noticeably different predicted surge although tracks varied by only tens of kilometres. This highlights a limitation of a deterministic approach and that a probabilistic approach should be considered.

V. Conclusions and Further Work

A system to forecast tropical cyclone surge has been set up, is able to respond quickly when a cyclone is approaching and is a potential threat to a coastline and vulnerable population. TELEMAC-2D run times are typically 0.5 to 1 hours on 36 cores of a Linux HPC and, together with coastal inundation modelling, fluvial flood modelling and population exposure analysis, allow a warning bulletin to be provided to the FCDO within one working day. Forecasts have been provided with up to five days lead time with updates before and during landfall.

Warning bulletins have been shared with local government and non-governmental organisations, UN OCHA and IFRC and have allowed a head start to the humanitarian relief process.

A system has been developed to automatically download and process cyclone track warnings from meteorological agencies and create the steering files and atmospheric inputs required to run a surge forecast. Regional models have now been set up, calibrated and tested for:

- Bay of Bengal,
- Mozambique Channel,
- Philippines,
- Madagascar east coast,
- Caribbean Sea.

Validation data are very difficult to obtain in these areas of interest – there are very rarely tide gauge measurements available during the cyclones. Anecdotal reports have been generally consistent with predictions but it is often difficult to differentiate damage due to surge from other sources such as wind, fluvial and pluvial flooding. TELEMAC-2D has previously been validated for predicting cyclone surge in Australia [2], Bangladesh and The Bahamas. As more events are responded to, data may become available to assess the performance of the forecasting.

In terms of the location of cyclone surge, the largest source of uncertainty is the atmospheric forecast. As demonstrated by the Typhoon Rai tests, where the coastline is complex and detailed, a small change in cyclone track can lead to large differences in both the location and severity of the surge. This highlights a limitation of a deterministic approach.

ECMWF currently run a deterministic cyclone forecast on a high resolution model and ensemble model runs on a lower resolution model. The forecast tracks are publicly available and allow for the possibility of ensemble modelling of cyclone surge and the use of a probabilistic approach. There are practical implications for running 50 ensemble runs as well as the deterministic and the handling and processing of the resultant data. There will also be a need to consider the presentation of the results and how to effectively convey the predictions in a way that is comprehensible and useful to the recipients of the Flood Early Warning bulletins. A research project to investigate a probabilistic to surge and coastal flood forecasting is being discussed with the FCDO.

Acknowledgements

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