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Storm surge forecast calculus on the Mexican Pacific coast using SWASH numerical model

Cálculo del pronóstico de marea de tormenta en la costa del pacífico mexicano utilizando el modelo numérico SWASH

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Abstract

Storm surge is a phenomenon that occurs on coasts with a higher incidence in the rainy season. The factors that promote its appearance are the wind and the tide whose force has been sometimes catastrophic. The objective of the study is to provide a storm surge forecast using the SWASH numerical model for some points on the Mexican Pacific coast. The approach of the experiment refers to previous works that use the infrastructure and data available from NOAA and SEMAR; the use of unstructured meshes used in a wave model to conclude in a beach wave model. In the validation of the results, the tide gauges of the study locations will be used; with the feedback obtained, the necessary adjustments are expected until the model has at least 60% correct measurements. Some authors agree that global warming affects the power with which the phenomenon has been manifesting itself, so that the development of technology could help minimize the consequences.

Storm surge, SWASH model, Unstructured mesh

Resumen

La marea de tormenta es un fenómeno que se presenta en costas con una mayor incidencia en temporada de lluvias. Los factores que promueven su aparición son el viento y la marea cuya fuerza ha resultado en ocasiones catastrófica. El objetivo del estudio es proveer un pronóstico de marea de tormenta usando el modelo numérico SWASH para algunos puntos de la costa del pacífico mexicano. El planteamiento del experimento hace referencia de trabajos anteriores que utilizan la infraestructura y datos disponibles de la NOAA y SEMAR; el uso de mallas no estructuradas utilizadas en un modelo de oleaje para concluir en un modelo de olas de playa. En la validación de los resultados se utilizarán los mareógrafos de las localidades de estudio; con la retroalimentación obtenida, se esperan los ajustes necesarios hasta que el modelo tenga al menos 60% de mediciones acertadas. Algunos autores concuerdan con que el calentamiento global incide en la potencia con la que el fenómeno se ha venido manifestando, por lo que el desarrollo de la tecnología pudiera ayudar a minimizar las consecuencias.

Ola de tormenta, Modelo SWASH, Malla no estructurada

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Introduction

This article describes the first stage of the project that seeks to implement a storm surge forecasting model along the Mexican coast. The paper explains the SWASH numerical model (Delft University of Technology (TUDelft), n.d.) implementation as an accurate low cost open source alternative for storm surge forecasting. The storm surge phenomenon is described by the world meteorological organization as “an abnormal rise of water generated by a storm. Strong winds in a tropical cyclone or a sever mid-latitude storm are their primary cause.

However, ocean bottom topography, tides, waves and freshwater input from rivers affect the water level rise during a storm surge. The depth of a storm surge can rise quickly — from centimeters to a meter or more in a matter of minutes. It can push an incredible distance beyond the coast.”. (Bautista *et al.*, 2001; World Meteorological Organization (WMO), n.d.) Once the components of the phenomenon have been described, its magnitude is understood until the affectations derived from its formation are evaluated; for example during Hurricane Ike, the storm surge reached up to 50 kilometers inland (Musinguzi *et a*l., 2019). A storm surge can travel across bays and up rivers, in essence, it can traverse any body of water that is on or near the shoreline as showed in Figure 1.

Carrying out a couple of calculations, one cubic meter of seawater (at 20 °C) weighs 1,024 kilos, that is, just over a ton. Thus, a storm surge carrying tons of water at speeds typically between 15 and 25 kilometers per hour has enormous force. A 50-centimeter storm surge can easily carry a car away, and it would be difficult for an adult to stand up against a 15-centimeter storm surge.

It is necessary to remember that by definition, the forecasts wave heights are the Significant Wave Height (Hsig); this is the average wave height (trough to crest) of the highest 1/3 of the forecast waves (Aguilera-Méndez *et al.*, 2022; Luke, 2006; Pecher & Kofoed, 2017; Zijlema, 2010). This definition is valid for waves generated in a storm surge forecast, that is, the prediction generated for storm surge also indicate that proportion of the wave; so its interpretation must consider the theory that supports these developments.

As a consequence of this measurement, we will continue using the *seas* variable (Aguilera-Méndez *et al.*, 2022) in the calculations of the experiment.

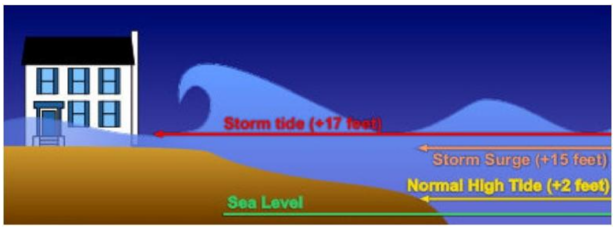


Figure 1 Storm surge
Source NOAA https://www.aoml.noaa.gov/es/hrd-faq/#storm-surge-v-tide

The formulas to generate the storm surge simulation are based on wave equations. The elevation of the water surface ζ is given by Equation 1:

$$\zeta = \frac{H}{2} \cos\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right] \tag{1}$$

The change in ocean surface elevation is the result of an elliptical motion of water particles, which extends below the surface. This movement is mainly affected by the wind speed and direction as well as the amount of water below the wave and the bathymetry (Aguilera-Méndez, Juárez-Toledo, Martínez-Carrillo, & Vera-Popoca, 2021; Pecher & Kofoed, 2017). As the changes in the storm surge are very fast, the equations used change considerably to establish a more realistic pattern, as shown by the equations used in Rijnsdorp's work (Rijnsdorp & Zijlema, 2016) where they propose the Equations 2, 3 and 4.

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0, \tag{2}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial wu}{\partial z} = -g\frac{\partial \zeta}{\partial x} - \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z}, \tag{3}$$

$$\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial ww}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zz}}{\partial z} \tag{4}$$

Where $u(x,z,t)$ is the velocity in x direction, $w(x,z,t)$ is the velocity in z direction, g is the gravitational acceleration, $\tau\ (x,z,t)$ represents the turbulent stresses, $p(x,z,t)$ is the non-hydrostatic pressure (normalized by a reference density), and $\zeta(x,t)$ is the piezometric head (which is equivalent to the free surface in the outer domain).

From Equation 2 which is the simple way to represent the hydrodynamic flow or wave movement on beaches they includes the gravitational factor and third axe to represent the internal wave movement in Equation 3; making a factor reduction and substitution they get Equation 4, which is the simplest way of wave movement in the SWASH numerical model.

In order to be functional, numerical storm surge forecast models must be applied in relatively small areas if their information is to be as close to reality as possible. As the interest of the forecaster is to know the places where the waves could impact with greater force, the information that is generated must be precise (Mcinnes *et al*., 2003; Musinguzi *et al*., 2019), leaving the global behavior of the tides and waves to the macro models. In this stage of the project, the calculation of storm surge was implemented in places where meteorological stations are located and with this, have reference and comparison measurements.

The meteorological stations with which we worked recorded the information every 60 seconds. Therefore, it will be taken as a measure for the simple comparison of the results; as well as in a second analysis using the mean square error method. The criterion to consider the resulting model as successful will be that the predicted data is within a range greater than or equal to 60% of approximation; even considering the Hsig criterion.

One aspect to keep in mind is the processing capacity available. Any model that grows in complexity necessarily reflects it in the time it takes to run the simulations and in their memory and disk space requirements. The computer where the operational model is mounted has 12 Pentium7 cores at 3.0 MHz, 128 GB memory, 500 GB storage on SSD and was compiled using gcc and gfortran on 64-bit Linux with MPICH libraries. Both SWAN and SWASH models were compiled using the parallel processing option; the product that is expected from the simulation of the 20 defined points, showed on Table 1, is an 8-hour forecast on the behavior of the waves on the beach. Simulation run time is expected to be 60 minutes.

Puerto Chiapas	Huatulco	Puerto Escondido	Salina Cruz
Puerto Vallarta	Isla Roqueta	Isla María Madre	Lázaro Cárdenas
Tuxtla	Manzanillo	Acapulco	San Blas
Zihuatanejo	San Lucas	Mazatlán	Los Cabos
La Paz	Guaymas	Ensenada	Rosarito

Table 1 Piers with weather stations that were considered in the study
Own Elaboration

Development

The locations that were modelled are indicated in Figure 2. Only those belonging to the Pacific Ocean coast; those found in the Atlantic Ocean will be the subject of further study, mainly due to the difference in sea physical conditions.

The development of the project was carried out using the procedure described by Aguilera (Aguilera-Méndez *et al*., 2022) where the Delaunay diagram is generated for each location, bathymetry data is obtained from the GEBCO site (GEBCO Compilation Group, 2021), data on waves and wind are downloaded from NOAA (*Global Forecast System*, n.d.; *WaveWatch III (WW3) Global Wave Model*, 2019). Once the information had been gathered and the SWAN model (Deftl University of Technology (TUDeftl), n.d.) had fulfilled the parameters, the model was executed. The marine physics variables were considered with the default model values, as well as the GEN3 calculations offered by SWAN and the RIPPLES quotient was used for friction. The regions into which the coastal strip was divided are identified in Figure 3.

Figure 2 Location of weather stations; dots in black mark those selected for the study Mexican Navy
https://meteorologia.semar.gob.mx/

One characteristic that the results of the SWAN numerical model can provide is the tabulation of different variables for a specific coordinate, with the understanding that it is within the defined domain; Thus, in order to obtain the value of the different variables that the SWASH numerical model needs for the execution of our study, the different coordinates of the points on the beach that are closest to the meteorological stations were declared.

The basis of the experiments was the model proposed by the developers for the case: Wind setup in closed basin, test 1: absolute wind velocity. Therefore the variables requested from the SWAN were sea height, wind direction as a vector, wave height and direction. The variables that the SWAN cannot process were captured manually in each definition for the different locations. The objective was to generate an 8 hours simulation for each of the proposed points with the initial conditions indicated by the SWAN using 12:00 (Z) as the start time. Once the model recognized and accepted the values of the variables and the study area was also validated with its bathymetry and the points of the structured mesh; SWASH model execution started processing the requested coordinates as sown in Figure 4.

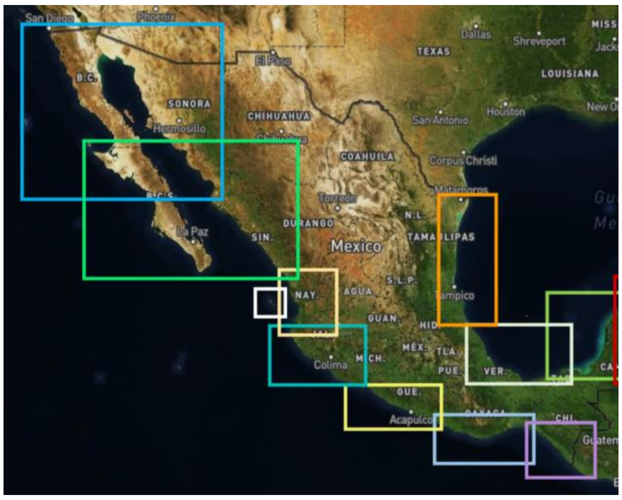


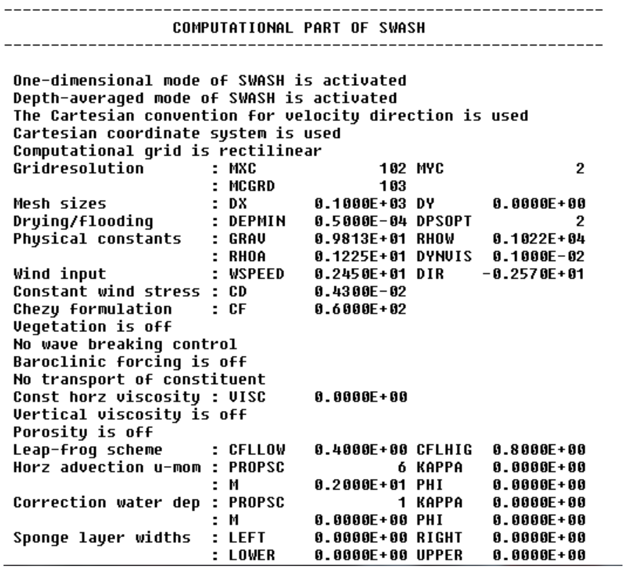
Figure 3 Coastal regions of the Pacific Ocean on which the simulations are carried out. Mexican Navy *https://meteorologia.semar.gob.mx/SWAN/regionSWAN.html*

The SWASH model physics parameters were changed to the same SWAN model physics parameters. To have a consistent principle; so as far as parameterization was possible, the rest of the variables were kept the default value. The most observed variables were those related to the friction and density of the water, because a low-level water coasts and chemistry contamination.

SWASH results were compared against data recorded at weather stations and tide gauges. At this point in the experiment, both the data processed by the model and the observed data were from past events, regardless of the season of the year; the only condition is that the records have a continuity of at least 12 hours, since the simulation configuration contemplates an 8-hour horizon in 60-second intervals given the continuity of the marine flow.

Results

The SWASH model was configured so that the simulation results were saved in a tabular format file; the information was graphed for a better understanding using Matlab. When analyzing the graphs, something that caught our attention was the tendency of the SWASH numerical model to normalize the event after a few hours of simulation. This could be due to the fact that the simulation does not admit more data at the time of execution and consequently, it assumes that there are no more elements that affect its behavior and tends to normalize its movement; doing so, what in natural conditions, the water would tend to stabilize its surface. Figures 5, 6 and 7 show the behavior of the wave simulated by the numerical model. It can be seen that around hour 4 the graph tends to normalize or be harmonic.



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----------------------------------------------------------------
                 COMPUTATIONAL PART OF SWASH
----------------------------------------------------------------

 One-dimensional mode of SWASH is activated
 Depth-averaged mode of SWASH is activated
 The Cartesian convention for velocity direction is used
 Cartesian coordinate system is used
 Computational grid is rectilinear
 Gridresolution       : MXC           102 MYC              2
                      : MCGRD         103
 Mesh sizes           : DX     0.1000E+03 DY      0.0000E+00
 Drying/flooding      : DEPMIN 0.5000E-04 DPSOPT           2
 Physical constants   : GRAV   0.9813E+01 RHOW    0.1022E+04
                      : RHOA   0.1225E+01 DYNVIS  0.1000E-02
 Wind input           : WSPEED 0.2450E+01 DIR    -0.2570E+01
 Constant wind stress : CD     0.4300E-02
 Chezy formulation    : CF     0.6000E+02
 Vegetation is off
 No wave breaking control
 Baroclinic forcing is off
 No transport of constituent
 Const horz viscosity : VISC   0.0000E+00
 Vertical viscosity is off
 Porosity is off
 Leap-frog scheme     : CFLLOW 0.4000E+00 CFLHIG  0.8000E+00
 Horz advection u-mom : PROPSC          6 KAPPA   0.0000E+00
                      : M      0.2000E+01 PHI     0.0000E+00
 Correction water dep : PROPSC          1 KAPPA   0.0000E+00
                      : M      0.0000E+00 PHI     0.0000E+00
 Sponge layer widths  : LEFT   0.0000E+00 RIGHT   0.0000E+00
                      : LOWER  0.0000E+00 UPPER   0.0000E+00
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Figure 4 SWASH processing log header
Own Elaboration

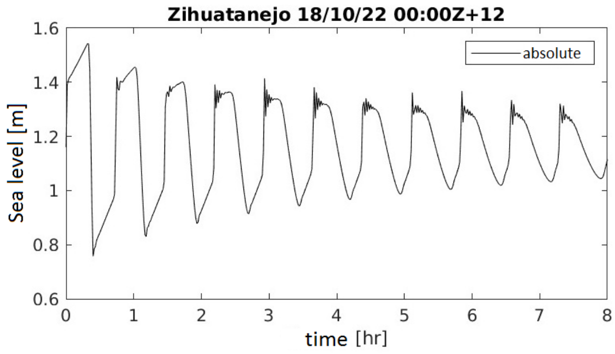

Figure 5 Tidal forecast for Zihuatanejo pier
Own Elaboration

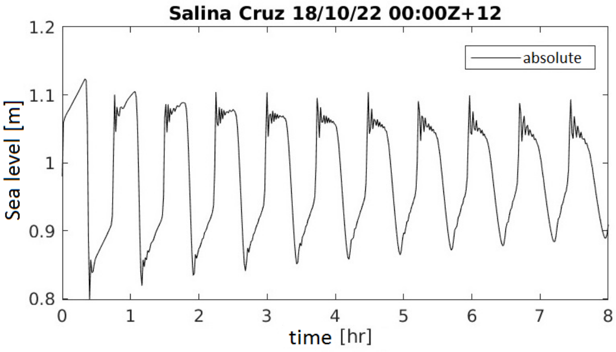

Figure 6 Tidal forecast for Salina Cruz pier
Own Elaboration

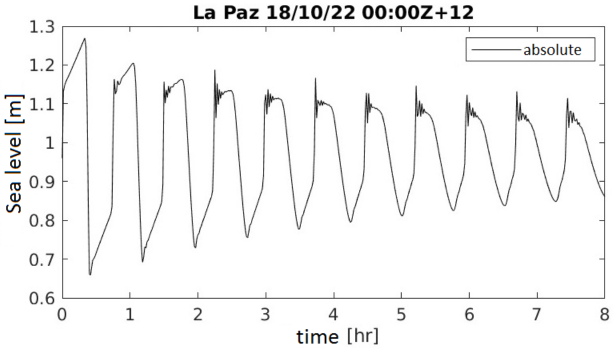

Figure 7 Tidal forecast for La Paz pier
Own Elaboration

After the elaboration of the graphs and the first analysis of the results, the reduction of the simulation time was raised, going from 8 to 3 hours. This change was sought due to two factors: the first has to do with the normalization of wave behavior and its application in highly changing conditions such as the ocean tide and second, the availability of information from different sources; NOAA updates its information in 6-hour periods with 120-hour forecasts; The Meteorological page of Secretary of the Navy (SEMAR, 2019) updates its models every 12 hours with 72-hour forecasts; the configuration of the outputs of the numerical model allow the data to be saved in seconds; For research purposes, the output will be sought every minute for two periods: 1 and 3 hours.

Therefore, there would be information to make the comparisons for one hour or up to three hours in one-minute intervals, so the simulation data would be analyzed prior to the normalization of the wave trend.

With the reduction of the simulation time the processing time was also reduced. Tweaks to the model build also brought better processor performance. With both adjustments it was reduced from an average processing time of 70 to 23 minutes for all domains. The Figure 8, 9 and 10 shows the new data set to be analyzed.

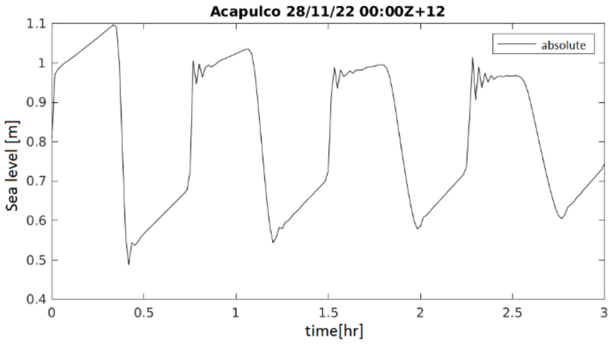

Figure 8 Tidal forecast for Acapulco pier
Own Elaboration

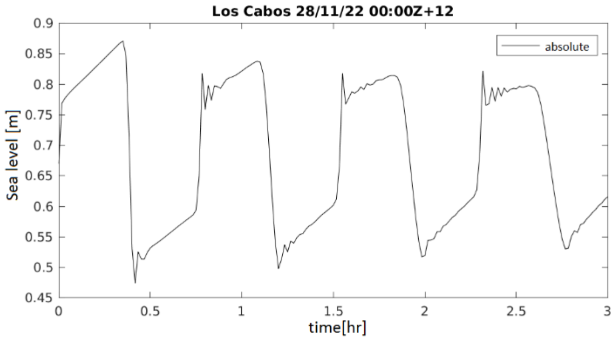

Figure 9 Tidal forecast for Los Cabos pier
Own Elaboration

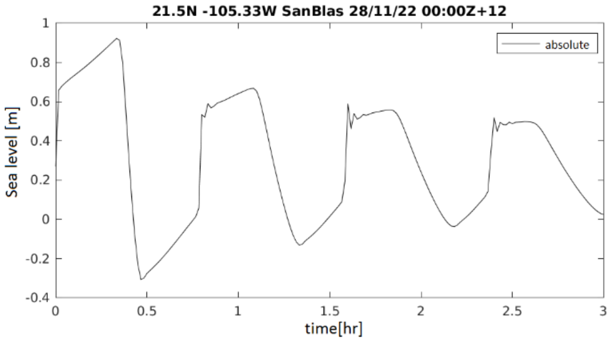

Figure 10 Tidal forecast for San Blas pier
Own Elaboration

This data set was more manageable and allowed a better understanding of wave behavior. It should be noted that the objective of the numerical model is to indicate storm surge height and the probability that it will occur within a time range that in our case is one hour; not so the exact moment in which it could appear.

The graphs generated by the tide gauges were obtained from the captured data. The points comparison was made considering that the information captured from the tide gauges and generated by the numerical model in periods of 1 minute was available. The tide gauges constantly capture information, recording the information every 60 seconds. Depending on the vendor of the equipment and the customer's preferences, these equipment record the average of the height that occurred in the 60 seconds, the weighted average or the result of applying a Fourier transform.

To facilitate the analysis, both graphs are presented instead of data tables. The correspondence of the figures is in pairs; therefore, Figures 11 and 12 correspond to the same point of analysis and so on for the pairs of Figures 13-14 and 15-16.

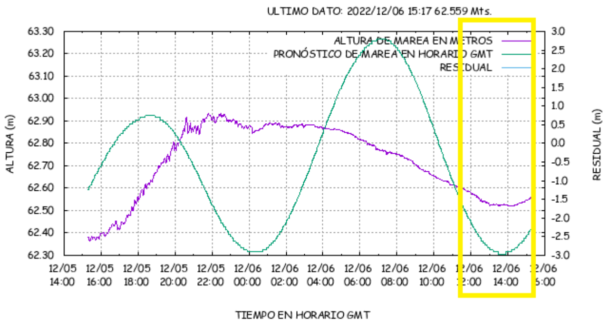

Figure 11 Tide recorded (in red) by the tide gauge located in La Paz pier
Network tide stations. https://oceanografia.semar.gob.mx/mapa_estaciones.html

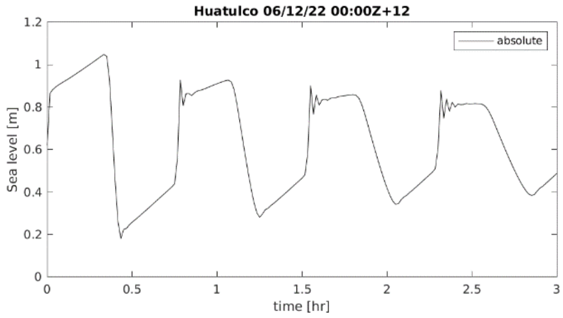

Figure 12 Tidal forecast for Huatulco pier
Own Elaboration

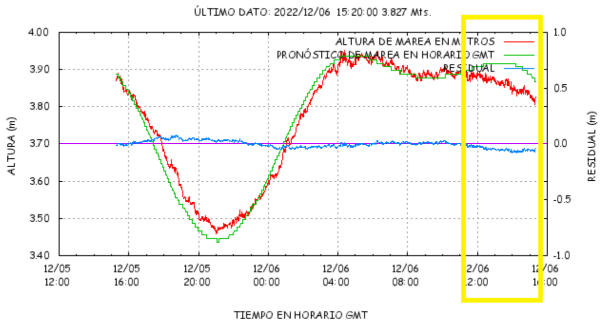

Figure 13 Tide recorded (in red) by the tide gauge located in Lazaro Cárdenas pier
Network tide stations. https://oceanografia.semar.gob.mx/mapa_estaciones.html

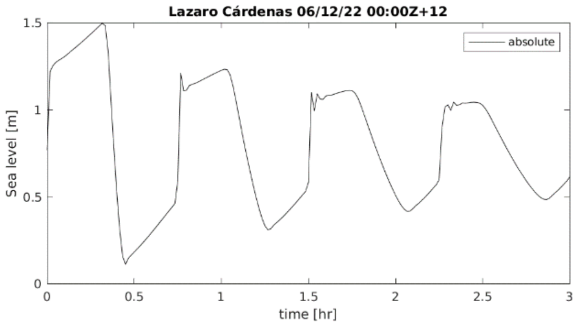

Figure 14 Tidal forecast for Lazaro Cárdenas pier
Network tide stations. https://oceanografia.semar.gob.mx/mapa_estaciones.html

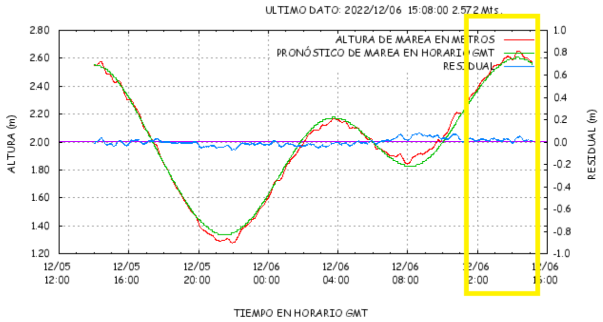

Figure 15 Tide gauge record (in red) for La Paz location
Own Elaboration

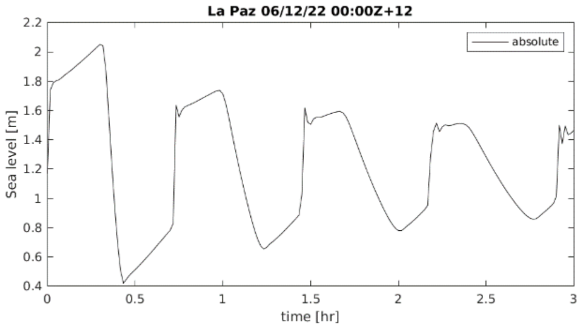

Figure 16 Tidal forecast for La Paz pier
Own Elaboration

Conclusions

The point-to-point analysis of the records showed important discrepancies, so it was discarded as validation. It was replaced by a trend analysis where the results showed a similar behavior within the established range of 60%. Considering that the time and the way in which the record is kept also influences the presentation of the results, it is the analysis of trends over longer periods of time, which will help to better understand the records obtained from the equipment. For this reason, we will work on the data from the tide gauges and the simulation in periods of 48 hours. In the case of the model that yields the results for a 3-hour forecast, the different periods will be concatenated until the 48 hours of observation required are obtained.

Using the definition of storm surge as drastic changes in the force, height and amount of water it throws, it is essential to have more tide gauges on the coastline that allow establishing a measurement grid to continue refining the models. The phenomenon as such contains a large number of variables that affect its development, making it vary in strength and height by a few meters, these variables could even be the area altimetry and bathymetry.

There are other storm surge models that could be useful. The data requirements prior to their execution is what makes them unfeasible due to our technical and economic limitations; although we do not rule out its execution with the available information using "mathematical adjustments" such as interpolation.

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