VULNERABILITY TO COASTAL FLOODING INDUCED BY TROPICAL CYCLONES

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Hurricanes are a recurrent feature on Mexican coasts; the floods they create often cause great economic and social damage. The evaluation of the natural hazards related to storm surge is fundamental in reducing risks for the populations of coastal areas. In order to generate flood hazard maps, storm surge associated with different return periods is computed with a 2D numerical model. The first part of this work explains the data and numerical models used to calculate the storm surge, the second part contains the results obtained with the simulations. This work has been done for the entire Mexican coastline.

Keywords: hurricanes; numerical model; storm surge

INTRODUCTION

This paper presents a methodology developed for computing the storm surge levels for different return periods associated with hurricanes on Mexican coasts. It is based on two numerical models (HURAC and HD23) developed by the Engineering Institute of the UNAM and the Center EPOMEX-UAC. The results presented are for the Gulf of Mexico and the North Pacific area of Mexico.

METHODOLOGY

Bathymetry

Getting the bathymetry is always a task in itself in Latin-American countries; this stage was achieved through a digitalization process using navigation and bathymetry charts belonging to the Mexican Navy. Figure 1 shows the final bathymetry used to evaluate the storm surge levels on the Gulf of México.
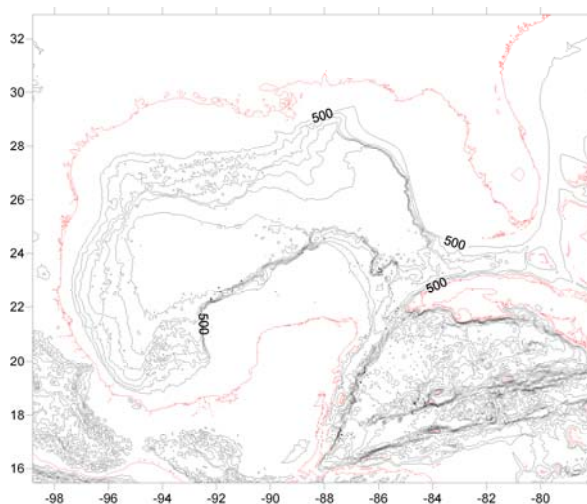

Figure 1. Gulf of Mexico bathymetry

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HURAC Model

The next step was to use the database, with main hurricane parameters, which had been previously gathered by the Engineering Institute of the National University of Mexico, from meteorological reports published by NOAA for the years 1949 – 2008. Figure 2 indicates all the cyclones which crossed Mexican seas in this period. For the Atlantic basin there is a total of 659 cyclones, for the Pacific the data base contains 860. The hurricanes considered relevant were those which had passed closer than 200 km from the coasts of the states that are part of Gulf of Mexico (Yucatán, Campeche, Tabasco, Veracruz and Tamaulipas) and the Mexican Pacific (Chiapas, Oaxaca, Guerrero, Colima, Jalisco, Nayarit, Sinaloa, Sonora, Baja California Sur and Baja California).
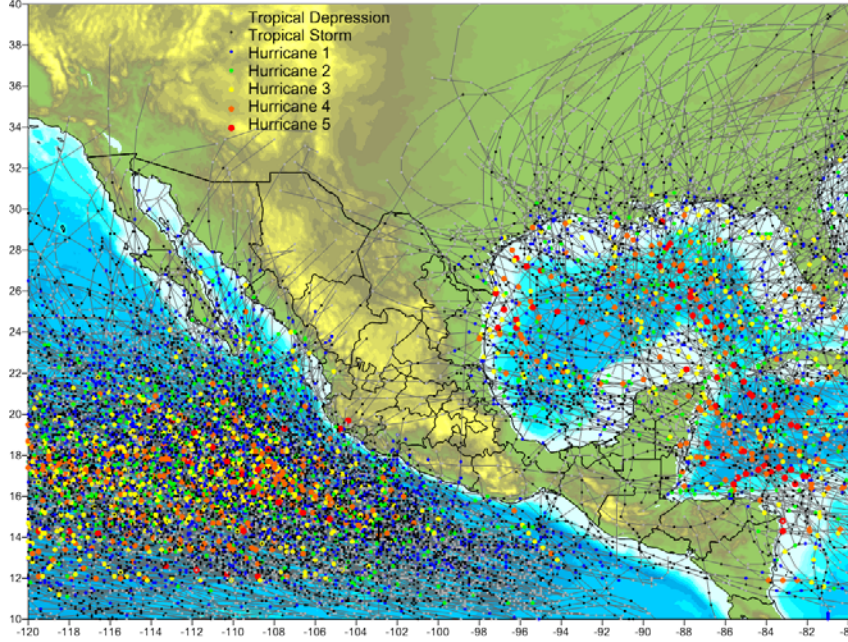

Figure 2. Tropical cyclones on Mexican Coasts, 1949-2008

From this information, the parametric cyclone model, HURAC, developed by Ruiz *et al* (2009) was executed. This model estimates the wind, wave and pressure fields knowing the position and cyclostrophic radius of the hurricane, and is based on the work presented by Bretschneider, 1990 and modified by Silva, 2000. The atmospheric field pressure is calculated with equation (1) and the wind module solves the equation (2)

$$P_r = P_0 + (P_N - P_0)e^{\left(-\frac{R}{r}\right)} \quad (1)$$

$$W = 0.886\left[F_V U_R + 0.5 V_F \cos(\theta + \beta)\right] \quad (2)$$

$$U_R = 21.8(P_N - P_0)^{1/2} - 0.5fR$$

$$f = 2\omega\sin\phi$$

$$\omega \approx 0.2618\frac{rad}{h}$$

Figure 3a presents the atmospheric pressure variations for Cozumel Island, calculated with the pressure module and measured at one of the meteorological stations of the Mexican Meteorological System (SMN). For Hurricane Wilma, 2005, the good agreement between the two graphs can been observed. Figure 3b represents the calculated wind velocity module and that measured by a NOAA buoy for the same hurricane. Illustrations 5 and 6 represent the pressure and velocities fields calculated with HURAC for Hurricane Emily, 2005.
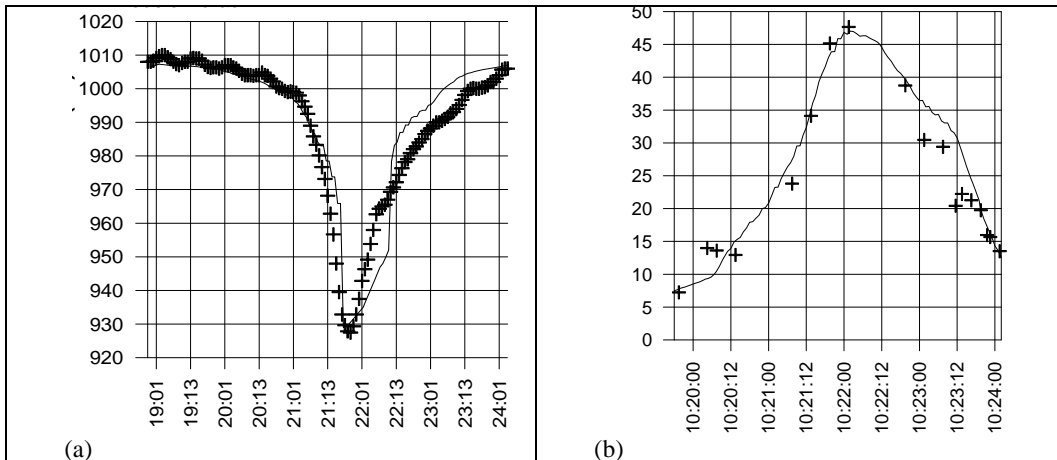
Figure 3. Pressure and wind velocity variations calculated and measured for hurricane Wilma, 2005
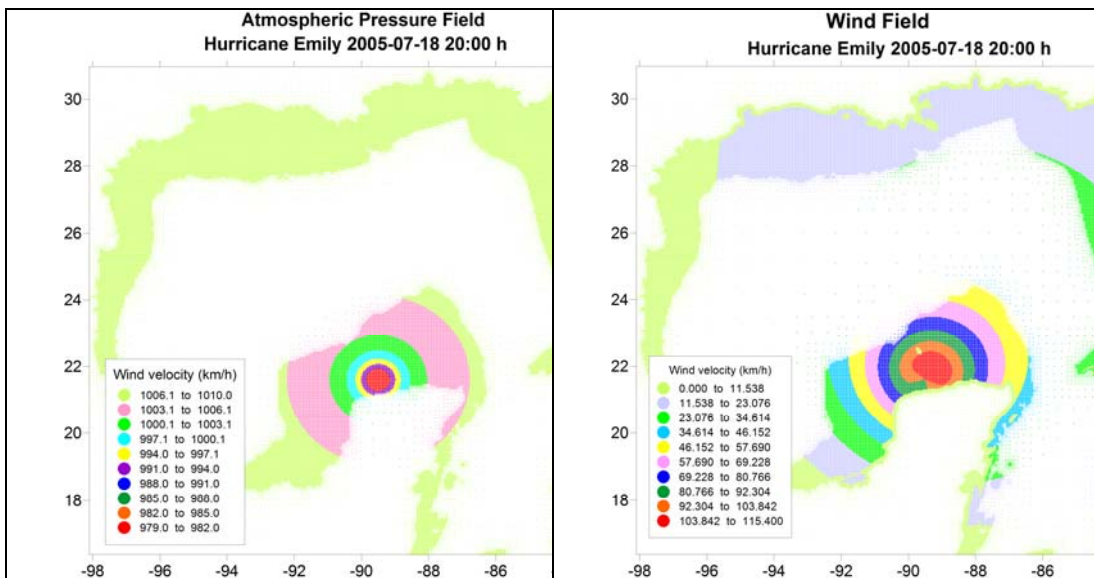

Figure 4. Atmospheric pressure and wind fields calculated for hurricane Emily, 2005

Numerical model, HD23

From the pressure and wind fields the storm surge level is calculated with a model developed by Posada *et al* (2008). This numerical model solves the governing equations with a finite volume scheme in two dimensions, based on a Gudonov scheme, using the hierarchical mesh. To resolve in-viscid flows we employ a Riemman solver to calculate the approximation proposed by Roe, in a similar way to Bautista, 2005. The time integration is carried out with a first-order Adams-Bashforth scheme.

The depth-averaged equations, solved by the model in 2 dimensions are:

Continuity Equation

$$\frac{\partial(UH)}{\partial x} + \frac{\partial(VH)}{\partial y} + \frac{\partial H}{\partial t} = 0 \qquad (3)$$

Where $H = h + \eta$

η = free surface elevation with respect to the bottom.

h = the bottom depth with respect to the mean water level.

Momentum equation in X-direction

$$\frac{\partial(UH)}{\partial t} + \frac{\partial U^2 H}{\partial x} + \frac{\partial}{\partial x}\int_{-h}^{\eta}(u`)^2\,dz + \frac{\partial UVH}{\partial y} + \frac{\partial}{\partial y}\int_{-h}^{\eta}u`v`dz =$$

$$fVH - gH\frac{\partial \eta}{\partial x} + \frac{1}{\rho_o}\left(\tau_{xz(\eta)} - \tau_{xz(-h)}\right) + H\varepsilon_h\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) + \qquad (4)$$

$$2H\frac{\partial U}{\partial x}\frac{\partial \varepsilon_h}{\partial x} + H\frac{\partial \varepsilon_h}{\partial y}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)$$

Where:

$u_{i,k}^{'}$ = vertical variation of velocity with respect to depth averaged value

f = factor de Coriolis

C_d = wind drag coefficient

C_D = bottom friction coefficient

ε_h = eddy viscosity coefficient

Momentum equation in Y-direction

$$\frac{\partial(VH)}{\partial t} + \frac{\partial UVH}{\partial x} + \frac{\partial}{\partial x}\int_{-h}^{\eta}u`v`dz + \frac{\partial V^2 H}{\partial y} + \frac{\partial}{\partial y}\int_{-h}^{\eta}(v`)^2\,dz =$$

$$-fUH - gH\frac{\partial \eta}{\partial y} + \frac{1}{\rho_o}\left(\tau_{yz(\eta)} - \tau_{yz(-h)}\right) + H\varepsilon_h\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + \qquad (5)$$

$$2H\frac{\partial V}{\partial y}\frac{\partial \varepsilon_h}{\partial y} + H\frac{\partial \varepsilon_h}{\partial x}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)$$

Momentum equation in Y- Boundary Condition 2D Model

The boundary conditions employed by the model are as follows:

Closed boundaries

At closed boundaries, the normal component of the velocity is set at zero whilst a slip condition preserves the tangential velocity.

Open Boundaries: lateral
In the case of open borders two boundary conditions are considered. First, for the free surface and the parallel components of velocity, the boundary is totally absorbing so that these boundary values are set equal to zero. Secondly, for the perpendicular velocity components, the border is totally transmissive, thus these components are unaffected across the boundary.

Open boundary: upper
The shear stress due to the wind is of the form

$$\tau_{xz(\eta)} = C_a\rho_a W_x W \qquad (6)$$

Where Ca is the drag coefficient of the wind, which has a value of 0.0026, Falconer, 1994. The shear stress due to friction at the sea bed is calculated with the expression

$$\tau_{xz(-h)} = \rho_o C_D \left| \overline{v} \right| u_{-h} \tag{7}$$

where C_a it is the friction coefficient, which is a function of the Chezy coefficient

Eddy Viscosity coefficient in 2D

The numerical model provides two options. The first is to consider this coefficient as a constant. The second is to consider the viscosity coefficient as a variable, calculated with the following expression.

$$\varepsilon_h = l^2 \left[\left(\frac{\partial U}{\partial x} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 + \frac{1}{2} \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)^2 \right]^{1/2} \tag{8}$$

Where: $l^2 = 0.1 \Delta x \, \Delta y$ according to Castanedo 2000.

Quadtree mesh

The numerical model described in the last section works on a quadtree mesh. The advantages and the means of generating this kind of mesh is described in detail in Posada *et al* 2008. The quadtree mesh is easily generated and resolution is good for the area of interest. In figure 5, the numerical mesh for the Gulf of Mexico is presented; note the high resolution for the cells on the coastline (3,150 m) in contrast to the coarser resolution for the center of the Gulf (101,000 m). In this mesh the total number of cells is 79,537, covering an area of 2´560.000 km^2 The Mexican Pacific littoral was divided in two areas, one for the north-west part (Baja California, Baja California Sur, Sonora, Sinaloa states) the other one for South-east part that include the states of Nayarit, Jalisco, Colima, Michoacán, Guerrero, Oaxaca and Chiapas). Figure 6 shows the mesh for the North Pacific area, in which the minimum cell size is 3,900 m and the large cells 120,000 m. This mesh has 44,227 cells.

STORM SURGE LEVELS

The hurricane analysis consisted in the modeling of all the hurricanes for each year, between 1949 and 2009, which had passed closer than 200 km to the Mexican coast, obtaining the maximum yearly storm surge. Where a year has 2 or more such hurricanes all of them were modeled, and the maximum storm surge level for a specified cell is the maximum level of all the simulations for this year. Later, extreme analyses were made, applying the Weibull distribution to the maximum levels for each of the cells that are part of a state region. With this statistical analysis it was possible to obtain flood hazard forecasts for hurricanes for each Mexican coastal state with return periods from 5-1000 years.

Figures 7a,b and c represent the maximums storm surge levels reached in Campeche State for hurricanes Emily, Stan and Wilma in 2005. Figure 7d, represents the maximum level for each cell based on the calculated maximums levels.

Figure 8, shows the Weibull distribution for maximum levels for different return periods for San Francisco de Campeche, Campeche, a city located in the western part of the Yucatan Peninsula. This kind of graph was obtained for all the coastal cells of the littoral.

RESULTS

Figure 9 shows the time evolution of the pressure and storm surge associated with hurricane Gilbert, a tropical cyclone that caused tremendous damage in Mexico, in 1998, principally in the states of Quintana Roo, Tamaulipas and, associated with rain, in the inland state of Nuevo Leon. The maximum storm surge level modeled was in the Yucatan Peninsula and had a value of almost 4.0 m.
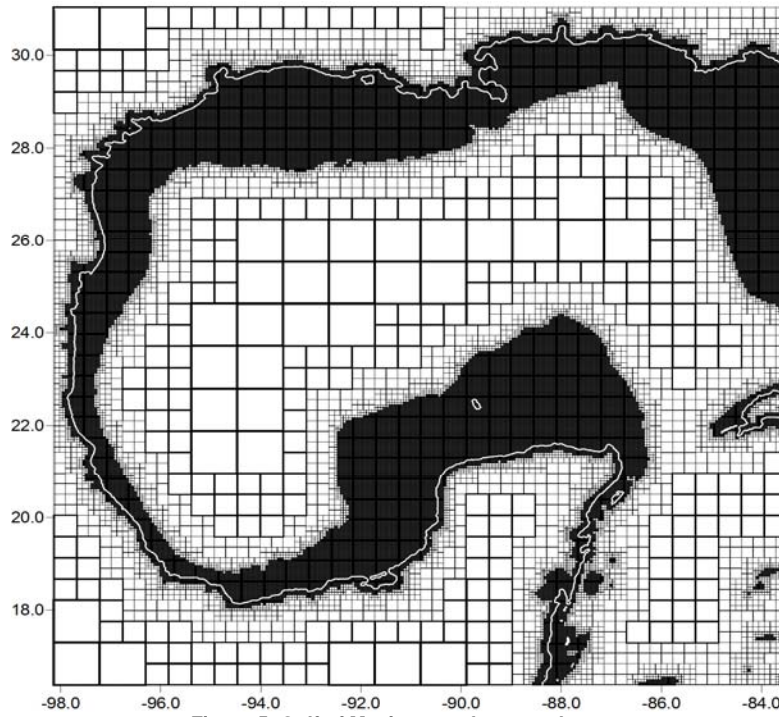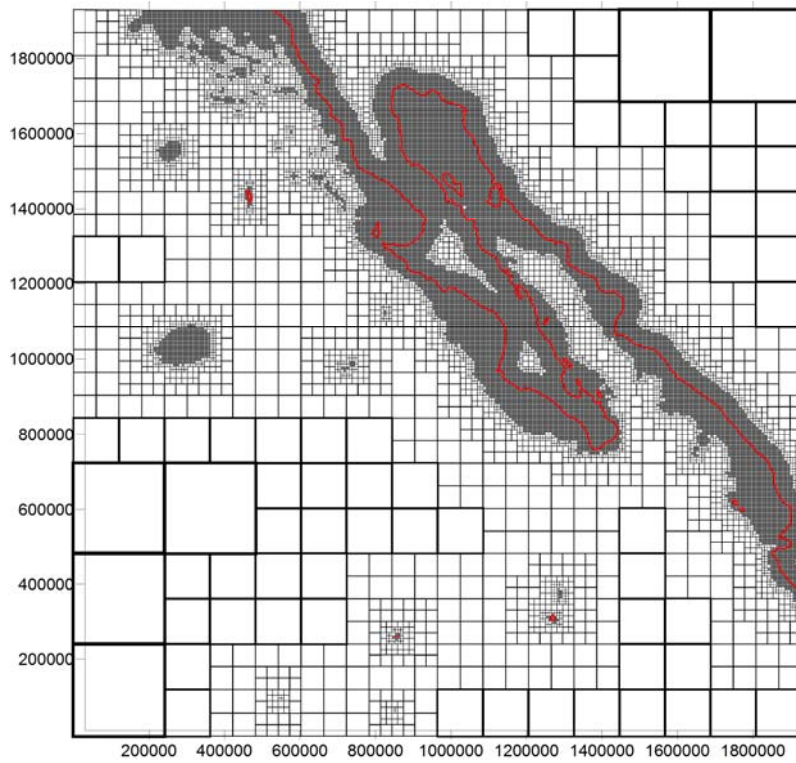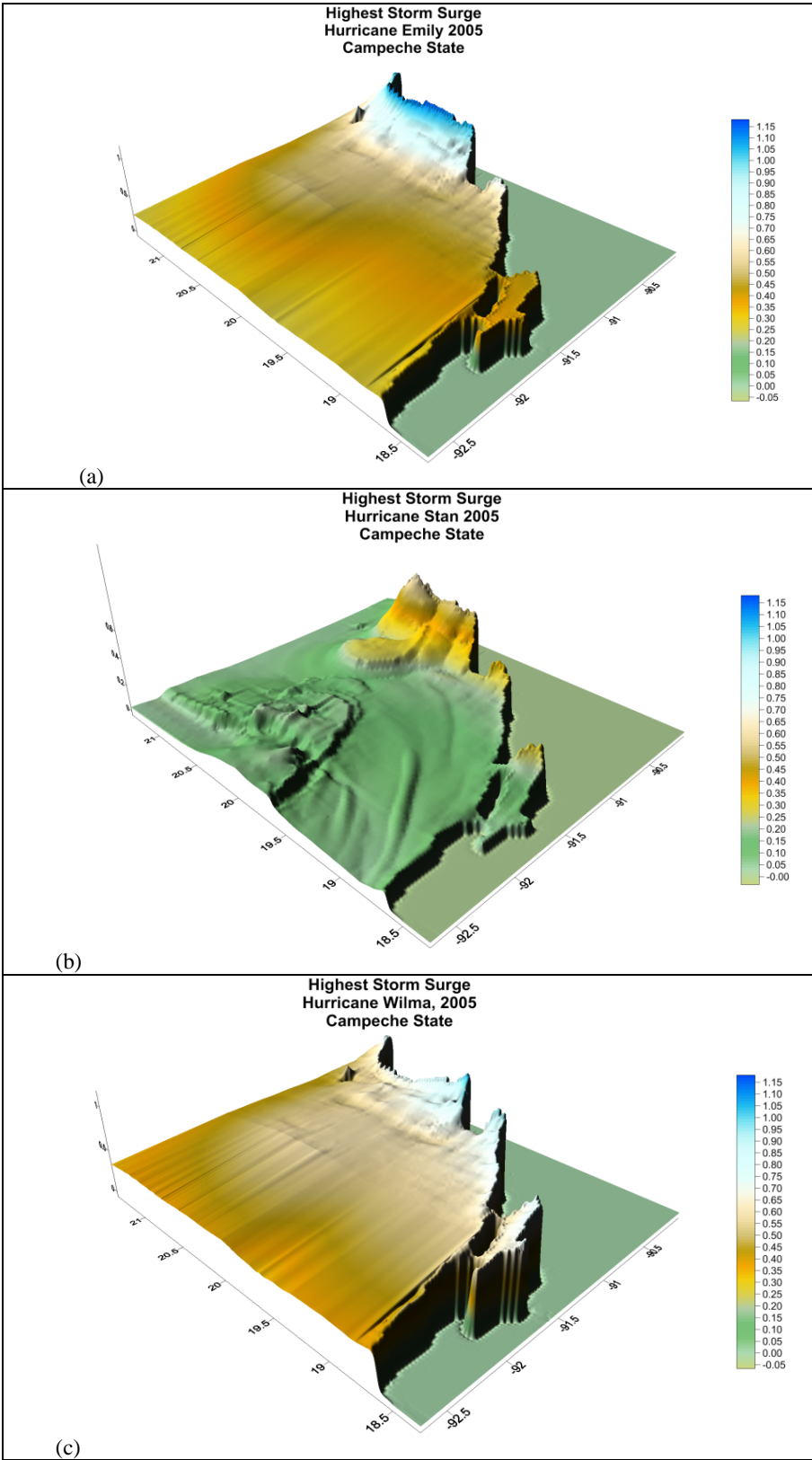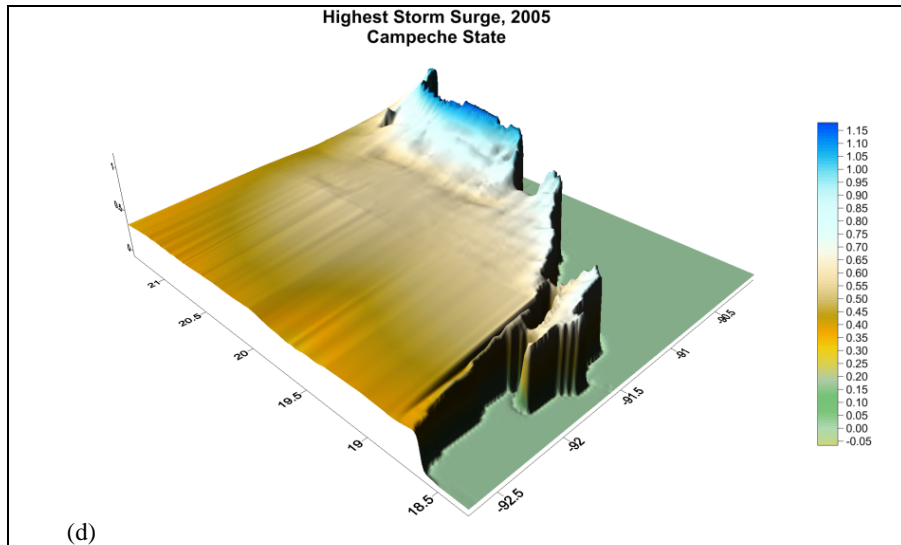
Figure 5. Gulf of Mexico, quadtree mesh

Figure 6. North Pacific Mexican Area, quadtre mesh

**Highest Storm Surge
Hurricane Emily 2005
Campeche State**

(a)

**Highest Storm Surge
Hurricane Stan 2005
Campeche State**

(b)

**Highest Storm Surge
Hurricane Wilma, 2005
Campeche State**

(c)

(d)

Figure 7. Storm surge levels for Campeche State, 2005
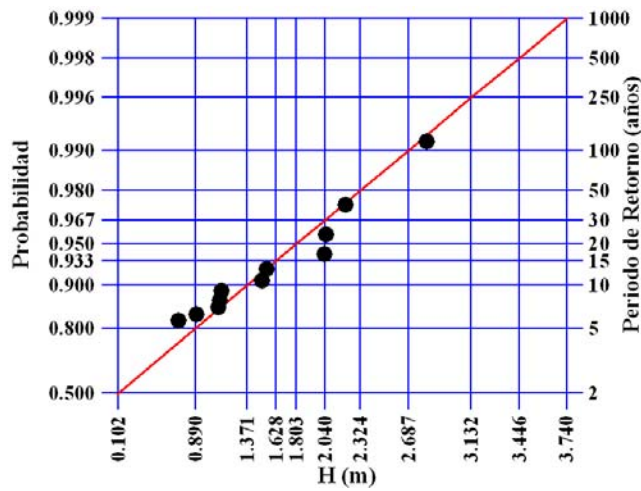
Figure 8. Storm surge levels for San Francisco de Campeche, Campeche

Figure 10, gives the storm surge levels for 10, 30 50 and 100 year return periods, for the Gulf of Mexico. These results were obtained from the Weibull distribution of each cell of the numerical domain.
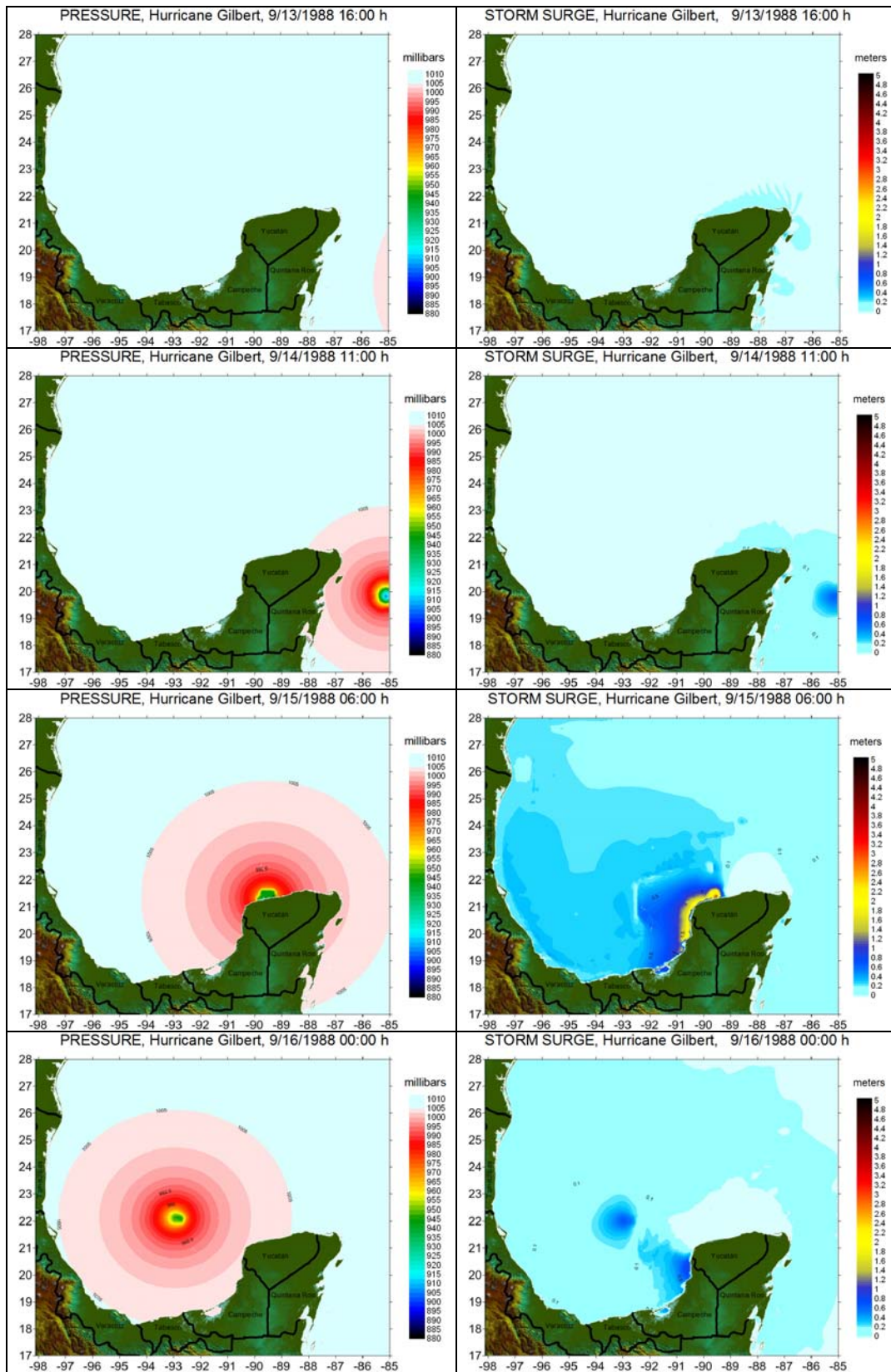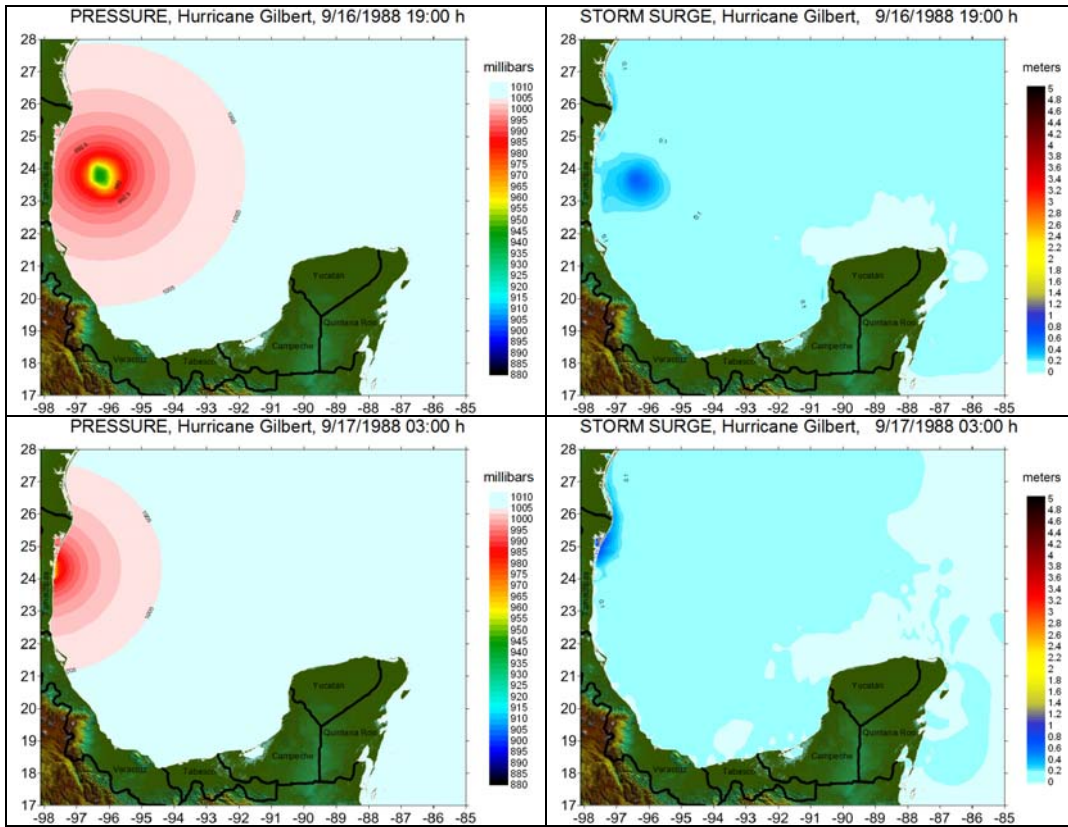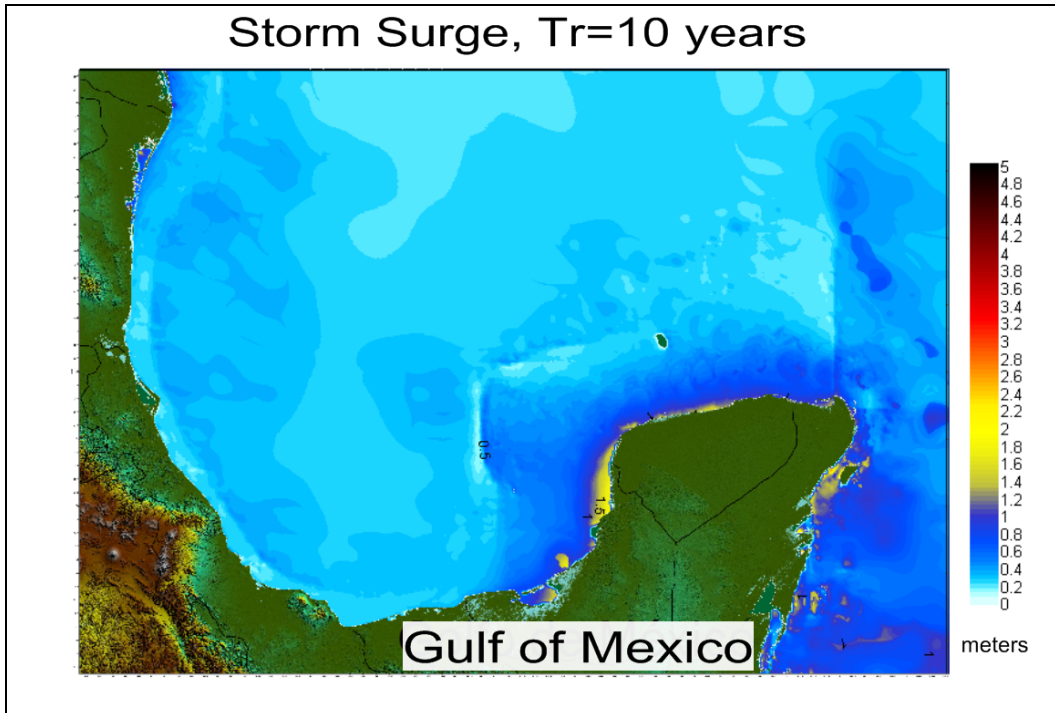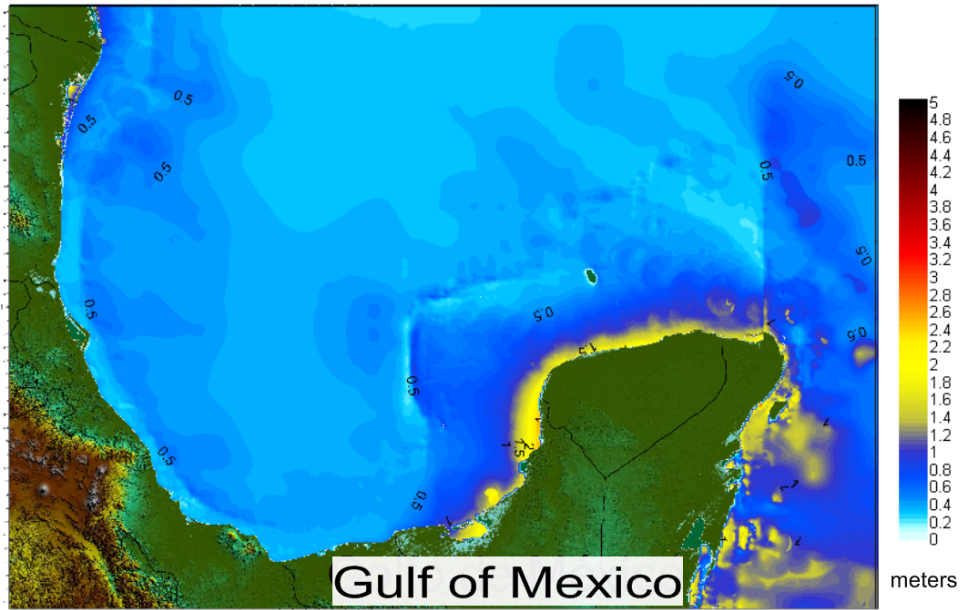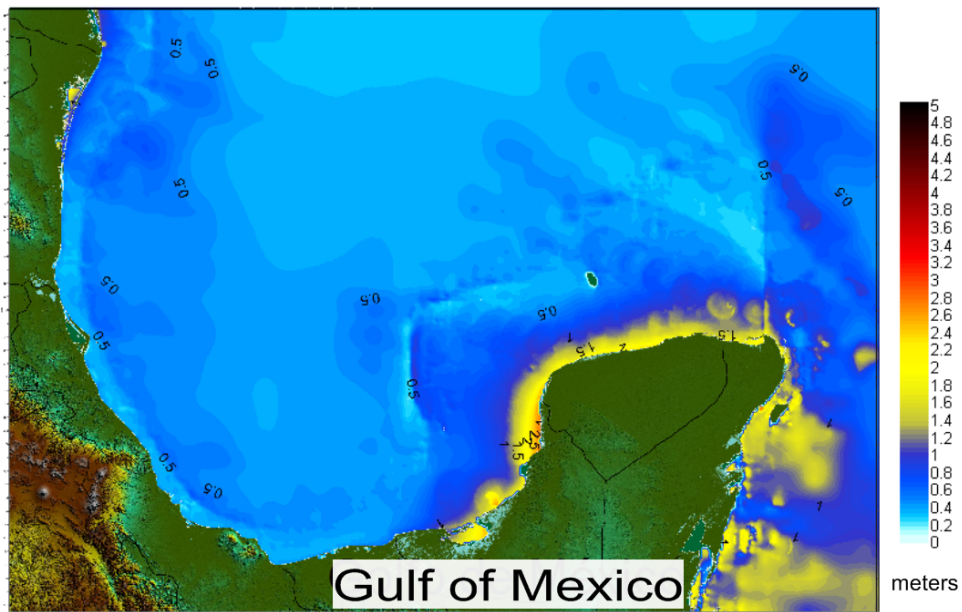
Figure 9. Pressure and storm surge levels, hurricane Gilbert, 1988

Storm Surge, Tr=30 years

Gulf of Mexico

meters

Storm Surge, Tr=50 years
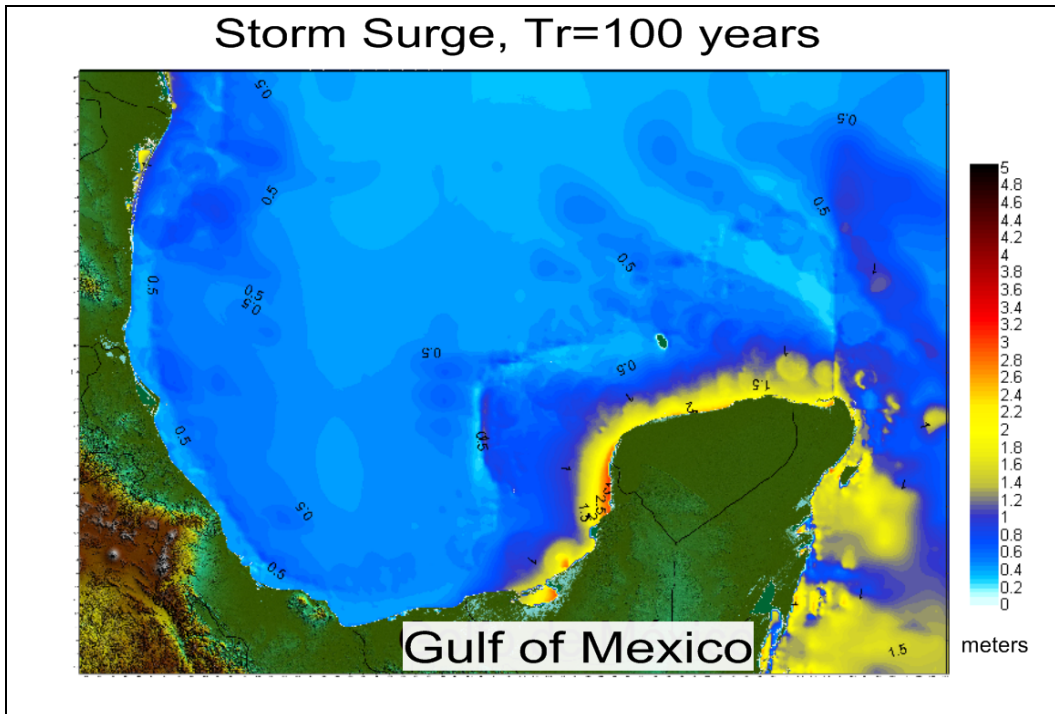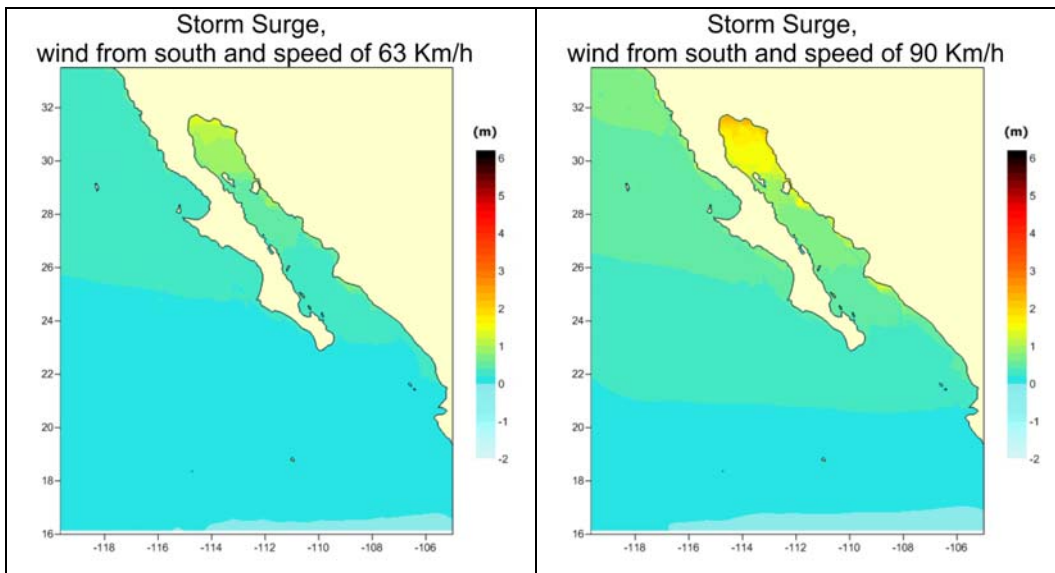
Gulf of Mexico

meters

Figure 10. 10, 30, 50 and 100 years return period levels for Gulf of Mexico.

Figure 11 represent the storm surge in the north Pacific grid caused by wind with constant direction and variable magnitude from 63 to 155 km/h,
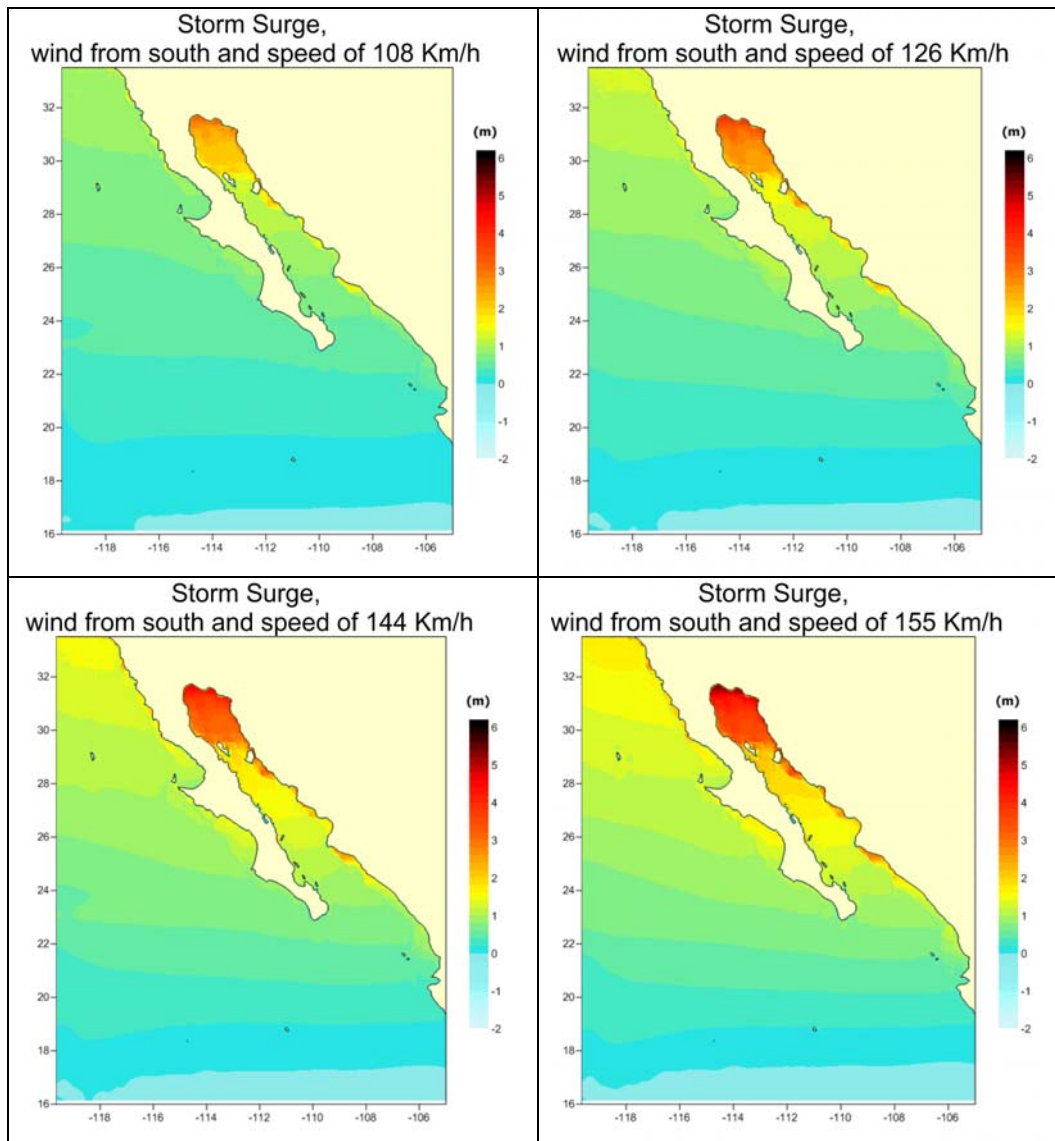
Figure 11. Storm surge for wind with constant direction and variable magnitude, North Pacific grid

Geographic Information System

All the information obtained for this work was compiled in a Geographic Information System, useful for Civil Protection Agencies and infrastructural developers in México, figure 12.

CONCLUSIONS

The methodology implemented is useful for the calculation of storm surge induced by tropical cyclones and synthetic winds. For this study almost 200 hurricanes that had impact in the last 62 years the Mexican Coasts were modeled, the highest storm surge level being 4.5 m.

The numerical model was validated with field and qualitative information. One of permanent objectives of the authors is the annual modeling of the last hurricane season and updating of the extreme values analysis.

A Geography Information System which can be useful for Civil Protection and Coastal Management authorities was developed.

ACKNOWLEDGMENTS

Figure 12. Geographic Information System.

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