Solution of shallow water equations via an hybrid approach by using CaMEL storm surge model in order to set up an emergency plan

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Abstract

In this paper, we present a numerical technique based on hybrid finite element and finite volume formulations in order to solve the induced hurricane storm surge flow. The model for the problem is the 2D shallow water equations which are solved on unstructured meshes by means of an implicit fractional step technique. An intermediate velocity field is first obtained by solving the momentum equations with the implicit cell-centered finite volume method. The nonlinear wave equation is solved by the node-based Galerkin method with Newton-Raphson to overcome the nonlinearity. The whole code was depeloped and referred as CaMEL (Computation and Modeling Engineering Laboratory), which has been extended and paralellized for its use in high performance computing platforms.

Hurricane Katrina (2005) storm surge is selected as a case of study and it has been simulated to demonstrate the robustness and applicability of the implementation. Based on the solution for the hurricane associated flooding, an emergency plan could be set up. This includes to perfom an infrastructure assessment of the buildings in the critical areas and to determine possible evacuation routes. This is an emergency management tool to aid the decision-makers and first responders in preparation for the appropriate response to an impending hurricane disaster.

Keywords: storm surge; shallow water equations; hybrid numerical methods; finite volume method; finite element method; hurricane modeling.

1. Introduction

In the recent past, our society has experienced the devastation caused by many hurricanes especially within the Gulf of Mexico area. This associated destruction demands for a reliable and fast simulation tool capable of predicting storm surges and floods so that emergency and preparation plans could be set up effectively in advance.

Hurricanes induce storm surges, which are generated by extreme wind stress acting on shallow, continental shelf seas. As a consequence, this leads to severe coastal floods. This phenomena is particularly damaging when coinciding with a high tide and can provoke the sea defenses to collapse (Pugh, 1987). It may result in substantial economic and social impacts, including loss of life, damage to property, and disruption of essential services (Knabb et al., 2005; Wilkinson, 2006; Gram-Jensen, 1991; Tsuchiya and Shuto, 1995). Hurricane Katrina, which made landfall over the Mississippi and Louisiana coastal regions in August 2005, is a perfect example of such a disastrous scenario.

Although many aspects of a possible evacuation, such as the uncertainties associated with human behavior, seem uncontrollable and practically impossible to predict, many other aspects of evacuation can be planned by having an efficient evacuation strategy. To achieve such a plan, it is demanded deep knowledge about hurricanes, storm surge and flooding. A timely and accurate prediction of the critical events, e.g. landfall, infrastructure failure, and transportation network failure, is crucial to establishing an effective emergency plan.

In the event of a hurricane, the emergency plans start with the determination of the track path and intensity of the hurricane using a so-called forecasting model. This is a computer program that uses meteorological data to predict the path, motion and intensity of hurricanes. There are three types of models: statistical, dynamical, or combined statistical-dynamic. Among several well known track models, one can find GFS (Global Forecast System), CLIPER (CLImatology and PERsistence), WRF (Weather Research and Forecasting). WRF (Michalakes et al., 1998), an open source parallel model, is extensively used the National Oceanic and Atmospheric Administration (NOAA), and the academic community.

Once the hurricane track path and intensity are known, storm surge models can be executed to solve for the associated flooding phenomena. Storm surge models are based on the so-called shallow water equations (commonly referred as SWE in the literature), which are numerically solved in a domain containing ocean and coastal regions.

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The storm surge models need wind stresses and pressure force terms that are obtained from the hurricane forecast models. WRF model is used in the present study in order to obtain such information. Sea, Lake, and Overland Surge from Hurricanes (SLOSH) (Jelesnianski et al., 1994), is a well-developed computerized flooding model used by the Federal Emergency Management Agency (FEMA), United States Army Corps of Engineers (USACE), and the National Weather Service (NWS). The SLOSH model uses structured grid, which limits its use in resolving complicated coastlines and thus severely restricts its capability for accurate simulation of flooding. The ADvanced CIRCulation (ADCIRC) (Luettich Jr. et al., 1992; Westerink et al., 1994) model is another semi-open source parallel storm surge model, which employs an unstructured grid and is able to resolve the complex coastline and the bathymetry of shallow water quite well. In ADCIRC, the SWEs are formulated using the traditional hydrostatic pressure and Boussinesq approximations and have been discretized in space using the Galerkin finite element method and in time using the finite difference method (Kolar et al., 1994a,b; Luettich Jr. and Westerink, 2004; Dawson et al., 2006). ADCIRC is widely used by the academic community and federal agencies such as the US Army Corps of Engineers, NOAA, and the Naval Research Laboratory.

The Computation and Modeling Engineering Laboratory—Shallow Water Equation program (referred to as CaMEL$^{\text{SWE}}$ or CaMEL from here after) is a recently developed storm surge model (Aliabadi et al., 2010) that uses an implicit solver, primarily developed with the capability to use larger time step sizes with great numerical stability. CaMEL uses a hybrid finite element (FE) and finite volume (FV) technique to implicitly solve the conservation equations. It was recently parallelized so that to ensure its use in large scale computing applications and it is the one used in the present study.

If the storm surge model supports wet-dry components, such as ADCIRC and CaMEL, the same model can be used for overland flooding in the coastal region as well, provided the domain mesh contains the overland region. Alternately, a standalone flood model could be used to predict the overland flood. In this study, CaMEL is also used for predicting overland flooding.

Based on the hurricane and related storm surge and flood prediction, evacuation plans are setup. Currently, there are a number of evacuation programs that are in use (Lindell and Prater, 2007), such as HURREVAC (Hurrevac, 2010) and HURRTRAK ((Products, 2010). HURREVAC (Hurricane Evacuation) is used to enable tracking hurricanes and assist in evacuation decision-making. It is a restricted-use Internet based computer program, which includes an ETIS (Environment Transport Integrated planning System) module which allows for inclusion and access to real-time traffic information by emergency managers.

Recently, we have developed an integrated scheme fully automated via computer programs and scripts so that users can interact with the tool using a Graphical Users Interface (GUI). The scheme is seamless to the point that any emergency personnel with moderate training can execute it and produce results successfully.

We organize the rest of the paper as follows. We present the equation of the model, i.e. the shallow water equations in Section 2. Section 3 deepely describes the details of the hybrid FE/FV formulation as well as the projection method. After that in Section 4 we provide some results to demonstrate the performance of the integrated scheme taking hurricane Katrina as an example problem. In Section 5, we include some ideas of the emergency plan. Finally, we conclude with the final remarks in Section 6.

2. Governing equations

The shallow water equations are a system of partial differential equations which govern the fluid flow in the ocean, coastal regions, rivers and channels. SWEs are derived from the incompressible Navier-Stokes after performing the Reynolds averaging procedure and integrating both conservation of mass and momentum equations for a column of fluid. In SWEs, it is assumed that vertical motions are negligible and that pressure is hydrostatic. The dimensions in the horizontal plane are by far larger than the vertical dimension. Therefore, it is reasonable to assume that flow is homogeneous along the vertical axis.

Consider a point $\boldsymbol{x}(x, y)$ of a moving domain Ω with boundary $\partial\Omega = \Gamma_g + \Gamma_h$. For a time interval $t \in (0, T)$, the continuity and momentum equations expressed in a non-dimensionalized form are,

$$\frac{\partial h}{\partial t} + \boldsymbol{\nabla} \cdot (H\boldsymbol{u}) = \dot{n}, \tag{1}$$

$$\begin{aligned} \frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla}\boldsymbol{u} - \nu\boldsymbol{\Delta}\boldsymbol{u} + c_b\boldsymbol{u} = &- \boldsymbol{\nabla}h - \boldsymbol{C} - \boldsymbol{\nabla}p \\ &+ \kappa\boldsymbol{\nabla}\eta + c_w\boldsymbol{V} \end{aligned} \tag{2}$$

being $\boldsymbol{u}$ the velocity of the flow, h the water hydrodynamic head, H the water depth, $\dot{n}$ any possible net source term (rain, tides, etc.), p the atmospheric pressure on the water surface, κ the earth tidal potential reduction factor, η the tidal internal forcing water elevation, ν the kinematic viscosity of water, $\boldsymbol{C}$ the Coriolis force, c_b is the bottom friction coefficient, c_w is the wind coefficient and $\boldsymbol{V}$ is the wind velocity obtained from the forecasting model, respectively. Note that we have included bold letters for the vectorial variables. In Figure 1 down below, we include a basic problem description used in CaMEL. One should recall here that, as the bottom of the ocean is not an smooth surface, i.e. there might be trenches or elevations, one needs to define a reference for measuring, in this case it is called geoid.

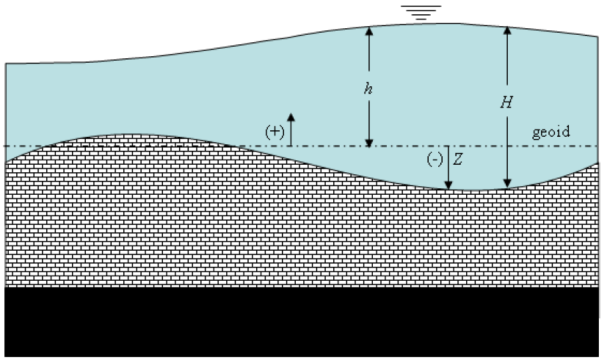


Figure 1: Problem description for CaMEL with the definition of the geoid. Z is the ocean bottom elevation.

3. Hybrid Formulation

3.1. General description

The hybrid finite volume/element solver is aimed to take advantage of the merits of both the FV and the FE methods and reduce their shortcomings. On the one hand, the finite volume approach is very insensitive to the aspect ratio of the mesh elements and high-aspect-ratio mesh elements are commonly used inside the boundary layer for high Reynolds number flows to reduce the number of elements.The stabilization parameters in the typical stabilized FE approach (Aliabadi et al., 2003, 2006) directly depend upon the characteristic element length which is not well defined for high-aspect-ratio mesh elements. Due to this, it is very difficult to control the numerical dissipation for this kind of formulations. For this reason, the finite volume method is used to solve the momentum equation. On the other hand, the classic Galerkin FE method is very suitable for elliptic typed equations like the pressure Poisson equation emerging from the segregated approach. Therefore, the combination of the FV method and the FE method perform well in the incompressible flow solvers based on the pressure projection method, e.g. (Tu and Aliabadi, 2007).

The momentum equation can be discretized in time as follows,

$$\begin{aligned}&\frac{\theta_1 \boldsymbol{u}^{n+1} + \theta_0 \boldsymbol{u}^n + \theta_{-1} \boldsymbol{u}^{n-1}}{\Delta t} + \boldsymbol{u}^{n+1} \cdot \boldsymbol{\nabla} \boldsymbol{u}^{n+1} \\ &- \nu \boldsymbol{\Delta} \boldsymbol{u}^{n+1} = -\boldsymbol{\nabla} h^{n+1} - \boldsymbol{C}^{n+1} - \boldsymbol{\nabla} p^{n+1} \\ &+ \kappa \boldsymbol{\nabla} \eta^{n+1} + c_w \boldsymbol{V}^{n+1}\end{aligned} \tag{3}$$

for certain values of the parameters θ_1, θ_0 and θ_{-1}. It is easy to see that $\theta_1 = 1$, $\theta_0 = -1$ and $\theta_{-1} = 0$ provides accuracy of first order in time and that the combination $\theta_1 = 1$, $\theta_0 = -2$ and $\theta_{-1} = 1$ is of second order.

The hybrid FV/FE approach evolves by considering a perturbation of the hydrodynamic water head h of the form,

$$h^{n+1} = h^n + h' \tag{4}$$

where h' is small in comparison to h^n which is the current water elevation within the nonlinear iteration in a given time step.

The solution procedure is based o projection (fractional step) method, with similar rationale to the one originally developed by Chorin and Temann for the incompressible Navier Stokes equations, (Chorin, 1968; Temam, 1969). Within this framework, Equation (3) can be rewritten in a predictor-corrector form after considering the split done in Equation (4).

3.1.1. Predictor

The predictor step of the formulation for Equations (3) and (4) is stated as,

$$\begin{aligned}&\frac{\theta_1 \tilde{\boldsymbol{u}}^{n+1} + \theta_0 \boldsymbol{u}^n + \theta_{-1} \boldsymbol{u}^{n-1}}{\Delta t} + \boldsymbol{u}^{n+1} \cdot \boldsymbol{\nabla} \boldsymbol{u}^{n+1} \\ &- \nu \boldsymbol{\Delta} \boldsymbol{u}^{n+1} + c_b \boldsymbol{u}^{n+1} = -\boldsymbol{\nabla} h^{n+1} - \boldsymbol{C}^{n+1} - \boldsymbol{\nabla} p^{n+1} \\ &+ \kappa \boldsymbol{\nabla} \eta^{n+1} + c_w \boldsymbol{V}^{n+1}\end{aligned} \tag{5}$$

where the end of step velocity at time $n+1$ in the iterative non-linear scheme, $\tilde{\boldsymbol{u}}$ is introduced. Likewise, the variable $\boldsymbol{u}^{n+1}$ is referred as the intermediate velocity field during the non-linear iteration. Note thas as $h' \to 0$, $\boldsymbol{\nabla} h' \to 0$ and thus $\boldsymbol{u}^{n+1} \to \tilde{\boldsymbol{u}}$.

Then, by approximating $\boldsymbol{u}^{n+1}$ with $\tilde{\boldsymbol{u}}$ for a small h' in Equation (5), it is obtained

$$\begin{aligned}&\frac{\theta_1 \tilde{\boldsymbol{u}}^{n+1} + \theta_0 \boldsymbol{u}^n + \theta_{-1} \boldsymbol{u}^{n-1}}{\Delta t} + \tilde{\boldsymbol{u}}^{n+1} \cdot \boldsymbol{\nabla} \tilde{\boldsymbol{u}}^{n+1} \\ &- \nu \boldsymbol{\Delta} \tilde{\boldsymbol{u}}^{n+1} + c_b \tilde{\boldsymbol{u}}^{n+1} = -\boldsymbol{\nabla} h^{n+1} - \boldsymbol{C}^{n+1} - \boldsymbol{\nabla} p^{n+1} \\ &+ \kappa \boldsymbol{\nabla} \eta^{n+1} + c_w \boldsymbol{V}^{n+1}\end{aligned} \tag{6}$$

which represents the fully implicit version of the predictor step, i.e. momentum equation, that is coded in CaMEL. The next step, using the results from the predictor equations, is the correction phase (projection).

3.1.2. Corrector

The corrector equation from Equations (3) and (4) can be derived as

$$\frac{\Delta t}{\theta_1} \boldsymbol{\nabla} h' = \tilde{\boldsymbol{u}} - \boldsymbol{u}^{n+1} \tag{7}$$

This equation can be multiplied by H^{n+1}, next one can take the divergence of the resultant equation, and time-discretize the wave equation to obtain

$$\begin{aligned}&\frac{\theta_1}{\Delta t} h' + (\boldsymbol{\nabla} \cdot \tilde{\boldsymbol{u}}) h' + \tilde{\boldsymbol{u}} \cdot \boldsymbol{\nabla} h' - \frac{\Delta t}{\theta_1} \boldsymbol{\nabla} \cdot (C^2 \boldsymbol{\nabla} h') = \\ &- \left(\frac{\theta_1 h + \theta_0 h^n + \theta_{-1} h^{n-1}}{\Delta t} - \dot{n} \right) - \boldsymbol{\nabla} \cdot (H \tilde{\boldsymbol{u}})\end{aligned} \tag{8}$$

where $C = \sqrt{H}$ is the wave speed. This is a wave equation which is coded in to CaMEL.

3.2. Finite volume formulation

Equation (6) is a time-discretized form of the momentum equations. One can realized that it represents a non-linear convection-diffusion equation for a certain source term. The Finite Volume method will be used to discretized this equations in space whereas the non-linearity for the velocity is resolved by means of the Newton-Raphson method.

The computational domain is therefore discretized using control volumes. Equation (6) can be rearranged into an appropiate format for the application of FV as,

$$M\boldsymbol{u} + \boldsymbol{\nabla}\cdot(\boldsymbol{u}\otimes\boldsymbol{u}) - \nu\boldsymbol{\Delta u} = \boldsymbol{S} \tag{9}$$

with the definition of M and S respectively as

$$M = \left(\frac{\theta_1}{\Delta t} + c_b - \boldsymbol{\nabla}\cdot\boldsymbol{u}\right)$$

and

$$\begin{aligned}\boldsymbol{S} = &-\frac{\theta_0\boldsymbol{u}^n + \theta_{-1}\boldsymbol{u}^{n-1}}{\Delta t} - \boldsymbol{\nabla}h - \boldsymbol{C}^{n+1}\\ &- \boldsymbol{\nabla}p^{n+1} + \kappa\boldsymbol{\nabla}\eta^{n+1} + c_w\boldsymbol{V}^{n+1}\end{aligned}$$

for the fully implicit version in CaMEL. Note that we have dropped the tilde symbol for the sake of simplicity.

Then, Equation (9) can be integrated over the i^{th} fluid volume element Ω_i and after using the divergence theorem one gets,

$$\begin{aligned}\int_{\Omega_i} M\boldsymbol{u}\; d\Omega + \int_{\partial\Omega_i}(\boldsymbol{n}\cdot\boldsymbol{u})\boldsymbol{u}\; d\Gamma&\\ - \int_{\partial\Omega_i}\nu\boldsymbol{n}\cdot(\boldsymbol{\nabla u})^T\; d\Gamma = \int_{\Omega_i}\boldsymbol{S}\; d\Omega&\end{aligned} \tag{10}$$

3.3. Finite element formulation

The wave equation defined in Equation (8) is solved via the classical Galerkin Finite Element method, where the equation is tested against weighting functions and integrated over the computational domain. One also needs to define the proper functional spaces for the solution, i.e. the trial space S^h and for the weighting functions, i.e. the weighting function space V^h. Then, the problem could be stated as,

Find $h' \in S^h$ *such that* $\forall\ v \in V^h$

$$\begin{aligned}&\int_\Omega \bar{B}vh'\; d\Omega + \int_\Omega v\boldsymbol{u}\cdot\boldsymbol{\nabla}h'\; d\Omega + \int_\Omega \bar{D}\boldsymbol{\nabla}v\cdot\boldsymbol{\nabla}h'\; d\Omega =\\ &-\int_\Omega \bar{L}v\; d\Omega + \int_\Omega \boldsymbol{\nabla}v\cdot\boldsymbol{u}\; d\Omega - \int_{\Gamma_h} v(\boldsymbol{n}\cdot\boldsymbol{u})H\; d\Gamma\end{aligned} \tag{11}$$

where we have used integration by parts to reduce continuity requirements on the solution, we take into account that $\boldsymbol{n}\cdot\boldsymbol{\nabla}h' = 0$ (from equation 10) and $v = 0$ on Γ_g. We also define,

$$\bar{B} = \frac{\theta_1}{\Delta t} + \boldsymbol{\nabla}\cdot u,\quad \bar{D} = \frac{\Delta t}{\theta_1}C^2$$

$$\bar{L} = \frac{\theta_1 h + \theta_0 h^n + \theta_{-1}h^{n-1}}{\Delta t} - \dot{n}$$

This leads to the solution of a linear algebraic problem after assuming that our solution is of the form of a linear combination of the so-called shape functions and the nodal values.

3.4. CaMEL solution strategy

As mentioned in the previous section, CaMEL is a hybrid shallow equation model based on the predictor - corrector method. An implicit cell-centered finite volume method is used to solve the momentum equation, Equation (10), to obtain an intermediate velocity field. The classical Galerkin finite element method is used to solve the continuity equation, Equation (11), to obtain the water elevation. The water elevation is used to update the velocity field.

The discretization of conservation equations results in a huge sparse linear system, which is solved using the Generalized Minimal Residual (GMRES) iterative method. Similar to any other iterative method, the performance of the GMRES solver is highly dependent on the preconditioning technique.

In the main subroutine of the CaMEL model, there is a global time loop. Within each time step there is a nonlinear iteration loop to solve for the water velocity and elevation for each cell and node, respectively. The steps are summarized in the next algorithm, down below.

Algorithm 1 CaMEL solution strategy

for i = 1 to **number of time steps**

(1) Solve Equation (10) to obtain an intermediate velocity field $\boldsymbol{u}$. The GMRES method is implemented so compute the solution of the resulting linear system of equations.

(2) Solve Equation (11) to obtain the incremental water elevation h' via the FE method. The resulting linear system of equations after the discretization process is solved again by the GMRES in its preconditioned version.

(3) Update water elevation by using Equation (4).

(4) Update velocity field $\boldsymbol{u}^{n+1}$ using Equation (7).

(5) Go back to step one until the solution converges for the present time step.

end

4. Results

The hurricane Katrina storm surge in the Mississippi and Louisiana coastal region is solved using the hybrid CaMEL code. The grid used for this case study consists of 254,565 nodes and 492,179 elements, which covers the entire Gulf of Mexico and about half of the Atlantic Ocean. The domain is about 4500 km times 4400 km in size. The grid element length ranges from 150 m to 25 km in the region of interest and far field, respectively. The mesh is displayed in Fig. 2. The domain is spread deep in the ocean for better tidal forcing implementation. Zero-flux boundary conditions are applied on the land and island boundaries, and tidal conditions in the open ocean boundary.

The mesh has the bathymetric (i.e., Z elevation) information of the domain for every node, which is used as a source term in Equation (10). The domain consists of patches where ground elevation can be higher than the sea level. As such, some nodes may be wet and dry in the course of simulation. A wet–dry algorithm is implemented to deal with this phenomenon. A node is assumed to be wet if its water depth H is higher than a threshold value, typically 0.01 or 0.02 (m). An element is assumed to be wet if all of its nodes are wet. Similarly, an element is dry if all nodes are dry. An element having one or two wet nodes and the average element water height exceeding the threshold value is considered to be mixed.

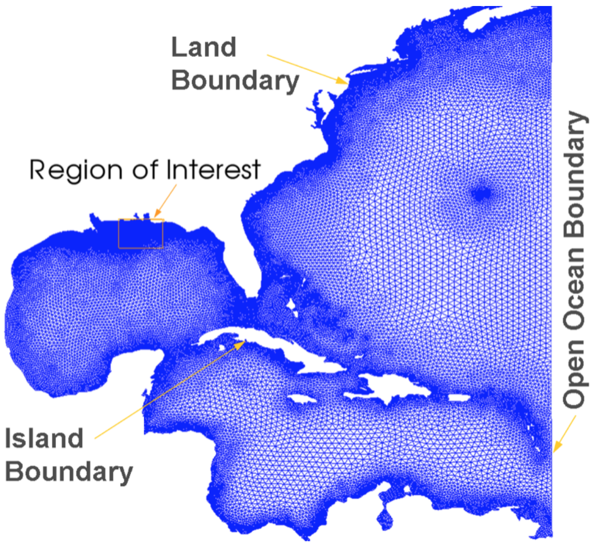
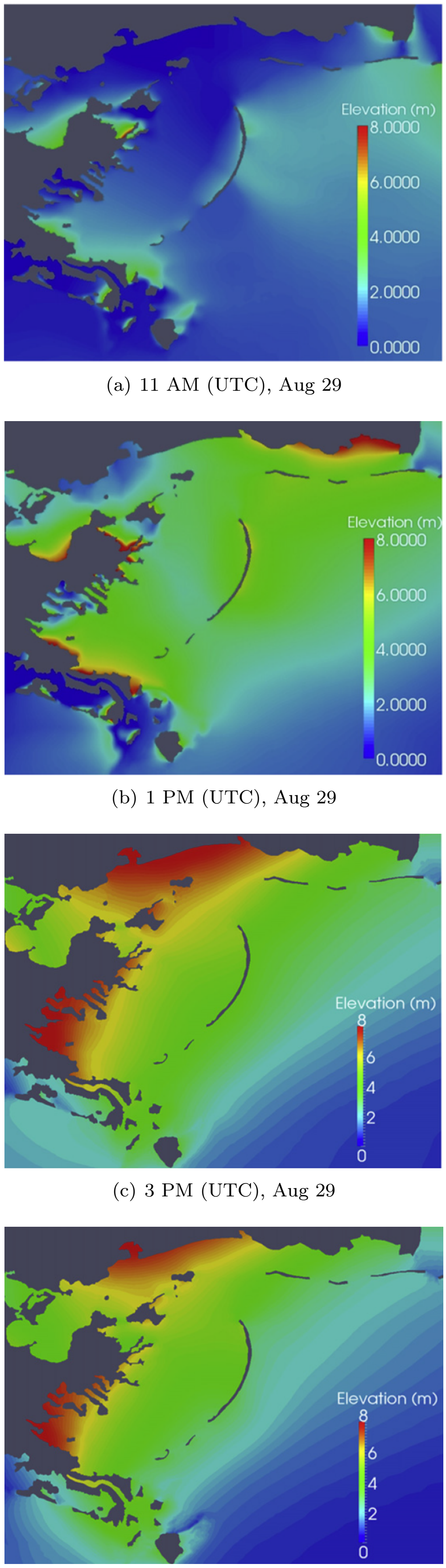


Figure 2: Mesh used in CaMEL for solving the water elevation and velocity.

The storm surge was computed for the duration between Aug 27, 00 AM and Aug 29, 6 PM (UTC). The hurricane winds pushed the water over the coastal lands in the Gulf of Mexico. Surge water heights well over 7 m occurred in some parts of the Mississippi and Louisiana coastal areas, which indicates the wind power of Katrina. Fig. 3 shows the CaMEL-SWE snapshots of water elevation at different times of the simulation. The solution has been contrasted with reference marks stored for Katrina in that time, and proved to generally match the recorded data.

5. Emergency plan

Based on the computation of the solution obtained from the CaMEL model, the emergency plan can be set



(a) 11 AM (UTC), Aug 29

(b) 1 PM (UTC), Aug 29

(c) 3 PM (UTC), Aug 29

(d) 5 PM (UTC), Aug 29

Figure 3: Time series snapshots for the water elevation associated with hurricane Katrina (2005).

up. For this we will first assess the infrastructure vulnerability due to hurricane in the coastal region, and sets up dynamic evacuation plan in the wake of an impending hurricane.

This part of the whole project is referred as the critical one since it establishes the direct connection of the project with the public and emergency management. The WRF model provides estimated hurricane touchdown time, as well as, wind speed and pressure. CaMEL Overland provides ocean water surge and inland flooding results, respectively. Using these output data sets, models developed by partner organizations predict infrastructure failure and optimal evacuation routes for the affected area.

5.1. Infrastructure assessment

Using the storm surge and flood water elevation and velocity criteria, infrastructures are categorized as flooded, damaged, or undamaged. Fig. 4 displays an example of the failure status of church buildings in the coastal Mississippi area. Same technique is used to analyze any other buildings considered as important, such as hospitasl, schools, airports, etc.

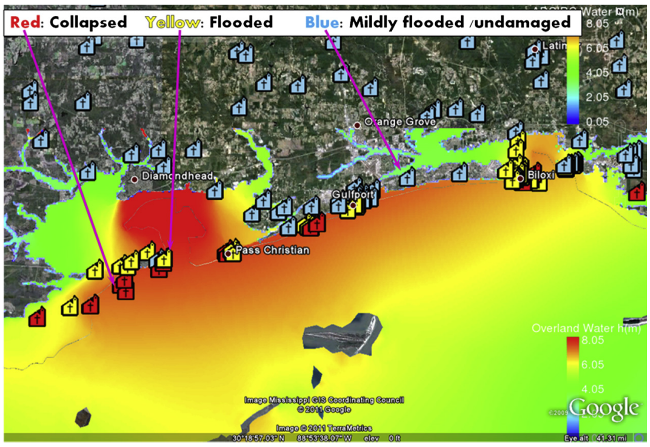


Figure 4: Flood assessment for church buildings in the coastal Mississippi area for hurricane Katrina.

5.2. Evacuation set up

Based on the hurricane track path, wind speed, and flooding assessment, the coastal areas are prioritized for evaluation. The coastal region is divided into several zones. The evacuees are assumed to be concentrated in the centroid of each zone. The evacuation paths are drawn from each zone centroid to the safe zone. The evacuation paths are optimized based on many different parameters including travel time, current traffic condition, population distribution, etc; and a particular path may not be the shortest possible (Lim et al., 2009a,b). The paths are dynamically updated based on the traffic condition. Fig. 5 displays a few sample evacuation paths from selected centroids to the safe zone. Evacuee population is displayed in Google Earth as dynamic bars in both danger and safe zones. As the evacuees reach the safe zone, the safe bar increases, while the danger bars decrease.

In the evacuation plan, priority is given to the immediate danger subzones, determined by proximity to the hurricane landfall location. However, evacuation paths dynamically change based on current traffic conditions, which is reflected on Google Earth. The whole emergency plan is provided within a Graphical User Interface (GUI) so that it makes it easy to produce results with small training. For detail of the dynamic evacuation plan developed by partners, please refer to (Aliabadi, 2010).

Figure 5: Evacuee population bars and sample evacuation paths from centroids to the safe zones for hurricane Katrina.

6. Concluding remarks

In this paper, a shallow water equation model is presented for associated hurricane storm surge. It is a hybrid approach based on finite volume and finite element methods. The GMRES strategy was adapted to solve the final linear system after discretization. The momentum equation is solved with a cell-centered finite volume method. The nonlinear wave equation is solved using a finite element method with linear interpolation functions in space and Newton-Raphson scheme. This hybrid numerical scheme is of the form of an implicit predictor-predictor model.

The whole numerical implementation is referred as the CaMEL storm surge model, which is a code that is available also for parallel computations which ensures its application in large scale simulations. The example selected to test the code was hurricane Katrina (2005), known as one of the most devastating hurricanes in U.S. modern history.

Based on the solution of the storm surge model, CaMEL also solves for the inland flooding which is the starting point to set up the emergency plan. Here, first we perfom an infrastructure assesment to determine whether a building is collapsed, partially affected or undamaged. After that, evacuation routes can be draw from the coastal regions. In order to interact with the whole code, a GUI was developed so that emergency personnel can produce useful results with small training.

7. Acknowledgements

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