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Simulation of Asteroid Impact on Ocean Surfaces, Subsequent Wave Generation and the Effect on US Shorelines

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Abstract

As part of a larger effort involving members of several other organizations, we have conducted numerical simulations in support of emergency-response exercises of postulated asteroid ocean impacts. We have addressed the problem from source (asteroid entry) to ocean impact (splash) to wave generation, propagation and interaction with the U.S. shoreline. We simulated three impact sites. The first site is located off the east coast by Maryland's shoreline. The second site is located off of the West coast, the San Francisco bay. The third set of sites are situated in the Gulf of Mexico. Asteroid impacts on the ocean surface are conducted using LLNL's hydrocode GEODYN to create the impact wave source for the shallow water wave propagation code, SWWP, a shallow depth averaged water wave code. The GEODYN-SWWP coupling offers unique capabilities to address the full scale interactions of asteroids with the ocean and the interactions of the water waves with the shorelines.

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1. Introduction

Two third of the earth surface is covered by seas and oceans. If an asteroid of any size survives the atmospheric journey it would probably hit the ocean surfaces than ground surfaces. Impact of asteroids on ocean surface can lead to the generation of high amplitude long water waves that propagate to shorelines with possible catastrophic consequences such as flooding the coasts, destroying infrastructures, debilitating several industries, and impacting any emergency evacuations. In the present paper, we will simulate several scenarios of impact of a "typical" asteroid in several locations nearby the US shorelines. We will emphasize the coupling between a hydrodynamic code, GEODYN, and a shallow water wave code, SWWP, both built under the same adaptive mesh refinement (AMR) structure. First, we will simulate the high velocity impact of the asteroid on the ocean surface. This step is essential to create the source of the wave. In a second stage, we will initiate SWWP with the source previously created. SWWP will then propagate the surface waves to shorelines. To the best knowledge of the authors, none has attempted to couple a hydrocode with a surface water wave code. We believe that the present coupling is the first in its kind and opens several opportunities in mimicking the non-linear dynamics at the impact location with the linear long wave propagation of water waves and, in particular, tsunamis. The current coupling could be extended, in a straight forward manner, to include non-linear flooding models to assess flow of debris and inundation of the coast region in general and, in particular, coastal cities.

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2. Brief description of GEODYN and SWWP

2.1. General guidelines for the preparation of your text

Following Lomov et al. [1, 2], simulations presented in this paper are conducted using GEODYN – a parallel Eulerian compressible solid and fluid dynamics code with AMR capabilities [3, 4]. Among its many features are high-order material interface reconstruction algorithms [5] and advanced constitutive models that incorporate salient features of the dynamic response of geologic media [6]. GEODYN is able to: a) simulate materials under extremely large deformations, b) resolve details of wave propagation within grains with high accuracy, and c) use a continuum damage mechanics approach to represent fracture. The Eulerian framework of adaptive mesh refinement [7] is a relatively mature technique. Adaptive mesh refinement can help simulating the entire domain while allowing focus on greater details in regions of interests. In combination, Eulerian Godunov methods with AMR have been proven to produce highly accurate and efficient solutions to shock capturing problems. The method used here is based on several modifications of the single-phase high-order Godunov method, which is not as straightforward as Lagrangian FEM. For completeness we will be briefly summarize the method. For solid mechanics, the governing equations consist of the laws of conservation of mass, momentum and energy, equation of distortional elastic deformation, and a number of equations that represent specific rheological time-history dependent parameters (i.e. porosity, plastic strain). The viscoplasticity is modeled with a measure of elastic deformation as a symmetric, invertible, positive definite tensor which is determined by integrating the correspondent evolution equation [8]. The numerical scheme for a single fluid cell is based on the approach of Miller [9], with some modifications to account for the full stress tensor associated with solids. The multidimensional equations are solved by using an operator splitting technique, in which the one-dimensional Riemann problems for each direction are solved using Strang-splitting order to keep second-order accuracy, while the source term is always applied at the end of the time step. Each directional operator is the update of the cell from two-consecutive present-future time steps with fluxes computed at the edges of the cell. The approach to modeling multi-material cells is similar to that in Miller [9] but extensively improved in Lomov et al [1,2].

2.2. The shallow water wave propagation code SWWP

It is often assumed that any source of disturbance, in particular tsunamis, propagates in the open ocean are linear, non-dispersive surface waves [10]. Therefore, the shallow water equations (SW) have often been used. Assumption of linearity of the waves stems from the fact that the ratio of water surface displacement to the depth is small. For non-dispersive waves, the propagation speed does not depend on their frequency. Dispersion alters wave speeds leading to waves with shorter wavelength to travel more slowly. In the long-wave limit (or hydrostatic approach), all waves travel with the same speed $C=(gH)^{1/2}$, where g is the acceleration of gravity, and H is the local water depth [10]. This wave speed relationship makes it relatively easy to estimate travel-time for a tsunami event. Tsunami modeling based on linear shallow water equations (LSW) can predict initial arrival times quite accurately, because the leading wave in a real wave train is the longest and propagates with the biggest wave speed. The models that include nonlinearity but still neglecting effects of frequency dispersion are governed by the nonlinear shallow water equations (NLSW). NLSW-based models can quite often provide good prediction of run-up heights of the leading wave [11]. The principal limitation of their accuracy in predicting shoreline inundation in tsunami application stems from factors that are not covered by the basic theory: a) frequency dispersion that can lead to different wave heights and wave forms, b) inability of wave breaking simulation due to singularity in the free surface description, c) interaction with fixed structures, and the interaction with the mass of transported debris resulting from destruction of structures. While effect of dispersion still can be included as an extension to SW equation, other effects mentioned above require more complicated approach [10, 11]. One of the most advanced examples of NLSW modeling is MOST (Method of Splitting Tsunami; [12]) used at National Oceanic and Atmospheric Administration (NOAA). A number of applications of this model to different tsunami scenarios are described in the literature (e.g. [13, 14]). Another model that uses NLSW using Godunov method and Adaptive Mesh Refinement technique was proposed by LeVeque [15]. SWWP is essentially a Godunov NLSW implementation using LLNL's SAMRAI (Structured Adaptive Mesh Refinement Application Infrastructure [16]).

3. Water wave source generation using GEODYN

We have set up GEODYN to simulate the source wave at the impact site. The size of the assumed spherical asteroid is 50m in diameter. The density of the asteroid is assumed to be 2.2 g/cm^3 and the impact velocity is 15.4 km/s. The entry angle is set to 39° . This scenario corresponds to the 3rd scenario of an asteroid hitting the Gulf of Mexico that will be

discussed later in section 4.3. We are using this scenario for illustration purposes for creating the source for the SWWP code. This 3D simulation required ~9 million cells, and 4 levels of AMR and a total of ~10,000 CPU-Hrs.

Figure 1 shows three side views at 3.211ms time-snapshot of the numerical simulation. The domain is composed of 3 materials: atmosphere (air), ocean (water) and ocean base (no shown here) assumed to be basalt. Both vertical side views show the entry trajectory (yellow arrow), cavity created by the impact, splash/rim of the water ejecta, and phase changes. It is worth noting that the ring of compressed water around the impact site, while the phase changes take places at the shoulder of the “crater” and at the bottom end of the impact which is in good agreement with several observations in real tests conducted at the Nevada Test and the Pacific Ground Test. The aerial view is a slice view at the sea/air interface level. Time-history of the height of the water wave at the source were recorded around the impact location, 300m away from the source at 36 azimuthal directions (one marker point every 10°). These time-histories are then passed directly to SWWP for wave propagation at long distances until their interceptions to the shorelines.

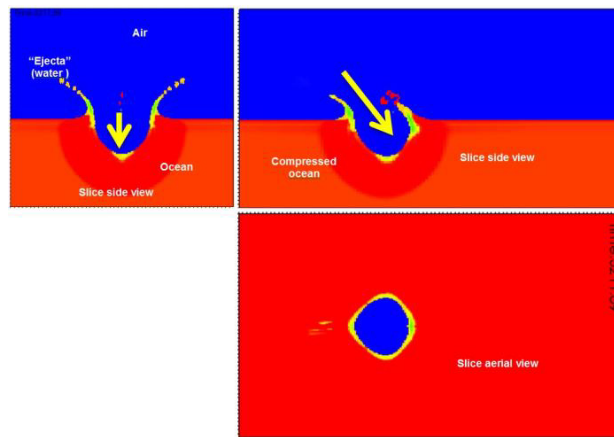


Figure 1: Three views of the simulation of the source of the water waves at 3.211 milliseconds calculated using GEODYN. Air (bleu) and ocean (red) are shown; a basaltic ocean floor is not shown here.

4. Water wave propagation using SWWP

In the present section we will illustrate the application of GEODYN-WPP coupling to three sites. The first site is located off the shorelines of Maryland and is referred to as Scenario #1. The impactor is an asteroid of same characteristic than for the 2nd scenario, but different from the 3rd. Scenario #1 was designed for the first table-top exercise (TTX1) conducted in 2013. The site is characterized by open seas and the trajectory of the impactor is away from the shorelines (divergent waves). The second site, referred to as Scenario #2, is located off the San Francisco Bay (SFB), the impactor and its trajectory are the same as in Scenario #1 except the impact location, thus oriented toward the shorelines of the SFB (convergent waves). Waves are then propagated and funneled through the Golden Gate channel and get trapped in the SFB. The third site, Scenario #3, is located in the Gulf of Mexico where the impactor characteristics and its trajectory are totally different from the former scenarios. Scenario #3 was designed for the second table-top exercise (TTX2) conducted in 2014 and features four different impact site locations and the waves are mainly contained within the Gulf (entrapped waves).

4.1. Scenario #1: Impact off of the shorelines of Maryland

The following scenario is based on a hypothetical near-earth-object (NEO). The impact was set at 3 May 2013, 8:00am EDT. The terrestrial impact location, not considered here, is located near Cedarville State Forest, Maryland, with longitudinal/latitude coordinates (38.635377, -76.820211), while the ocean impact location is at longitudinal/latitude coordinates (37.0, -74.0). The impactor (asteroid) is assumed to be iron with a density of 7.9 g/cm³. The final impact velocity is estimated to be 12.7 km/s with impact energy of 10MT or ~4.17E+16 Joules. The entry angle is set to 20° from the horizon (see Figure 2). Simulation of the impact and wave propagation was conducted using SWWP and overlaid on Google earth. Example of the waves after 30min of the impact is given on Figure 3. The shoreline flooding surface waves reach +12 feet followed by -12 feet troughs. Much of the East coast is affected (see Figure 4). Assessment of the impact of the waves intercepting and flooding the shorelines was conducted for several sectors such as: maritime (coast guard posts,

navigation), military infrastructures (bases, national guard), transportation (road and bridges), utilities (electric, gas and nuclear power plants), government agencies (law enforcements, post offices, and prisons), emergency (shelter, hospitals etc...) but not shown in the present paper. It is worth noting that the floods take 1-3 days to recede.



Figure 2: TTX-1 impact location off Maryland shorelines

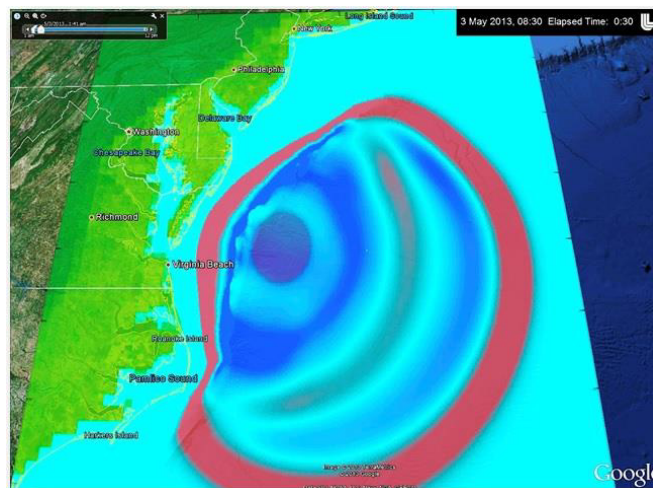


Figure 3: State of the wave propagating off of Maryland shorelines after 30minutes from impact. Surface waves reach $\pm 12\text{m}$.

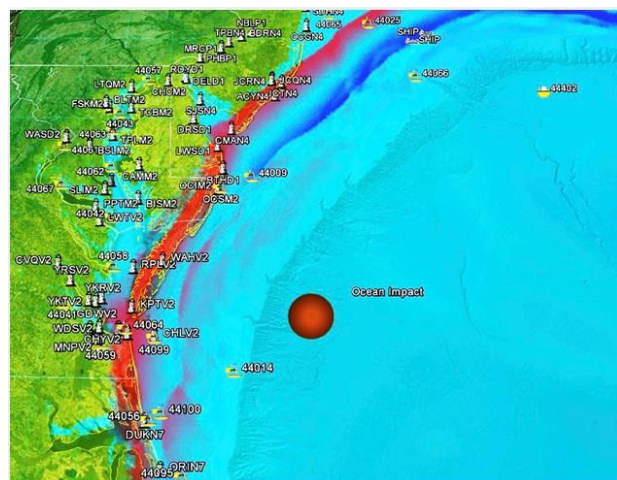


Figure 4: Surface waves reach $+12\text{m}$ followed by -12m troughs. Much of the East coast is affected warning stations and live ship feed are highlighted here. Floods take 1-3 days to recede.

4.2. Scenario #2: Impact off of the shorelines of the San Francisco Bay

Trajectory and characteristics of the impactor are exactly the same as in the previous scenario except the impact location is moved off of the San Francisco Bay. Location of the impactor is shown on Figure 5 on the upper left corner frame. Time history of the wave propagation is also given on the same figure. One can notice the distinct waves moving toward the SFB coast after the first half hour from impact, followed by several wave refractions from the shorelines. Within half hour the waves penetrate the Golden Gate channel reaching the East Bay (i.e. Berkeley, Oakland etc...). Waves are then entrapped into the SFB and reaches as far as the North and South of the bay. All shores within the Bay are affected after 4 hours from impact. Water waves reaches as high as 3m above sea level. It is worth noting that the California Energy Commission (CEC) has conducted in 2012 a study on the impacts of sea level rise on the flooding of the SFB shores. It was found that due to global warming the sea level rise can reach 1.4m in 100 years and subsequently several utility companies such as PG&E and EBMUD and others with plants on the shorelines are subject to floods. The CEC [17] has identified those stations and they are given on Figure 6. This leads us to conclude that the consequence would be the same if not more severe – every power plant decommissioned by 1.4m flood should succumb to the same fate under 3m of water wave generated by the impact of the asteroid, we would expect higher consequences.

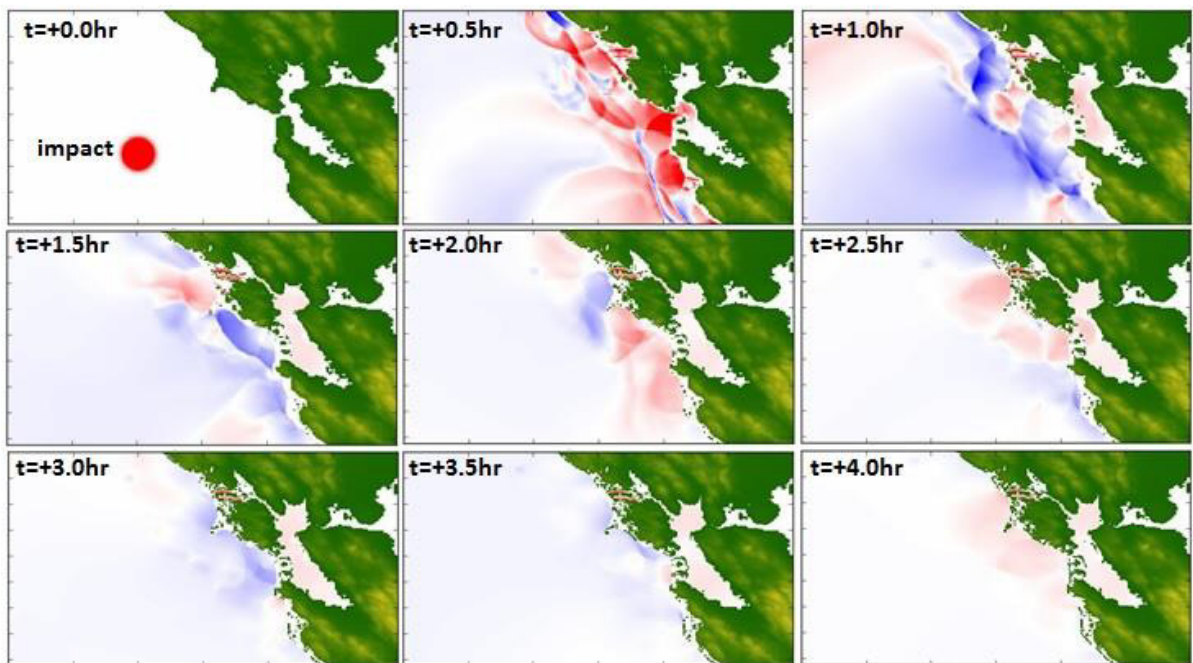


Figure 5: Time snapshots every half hour, notice wave intrusions into the SF Bay. Wave heights reach ± 3 meters.

4.3. Scenario #3: Impact in the Gulf of Mexico

The following scenario is based on a hypothetical NEO orbit very similar to that of the Chelyabinsk impactor, thus the final approach occurs on the sunward side of the Earth, which makes observations in the last couple weeks very challenging. The orbit is somewhat eccentric, with an aphelion out in the Main Belt, which is not atypical. The $\sim 140\text{m}$ object is very faint for much of the time; but it should still be observable with large aperture telescopes. Since the distance from Earth is large, however, the orbit is difficult to determine with great precision, and the impact probability takes almost two years to reach 100% [18]. The following is a compilation of material developed for the second FEMA-NASA asteroid-impact tabletop exercise (TTX2) held at FEMA HQ on 20 May 2014. In preparation for the exercise, participants from LLNL conducted simulations of possible water impacts in the Gulf of Mexico and provided the results to TTX2 team members at Sandia National Laboratories. Figure 7 depicts the locations of 5 scenarios of which scenario #0 will not be discussed since it is a ground impact and has been addressed by Sandia National Laboratories. The characteristics of the other impact locations are: TTX2-1: shallow-water impact (near Louisiana), TTX2-2: deep-water impact (central Gulf), TTX2-3: shallow-water impact (near Florida Keys), and TTX2-4: Straits of Florida (near Cuba). Results of the numerical simulations are given hereafter.

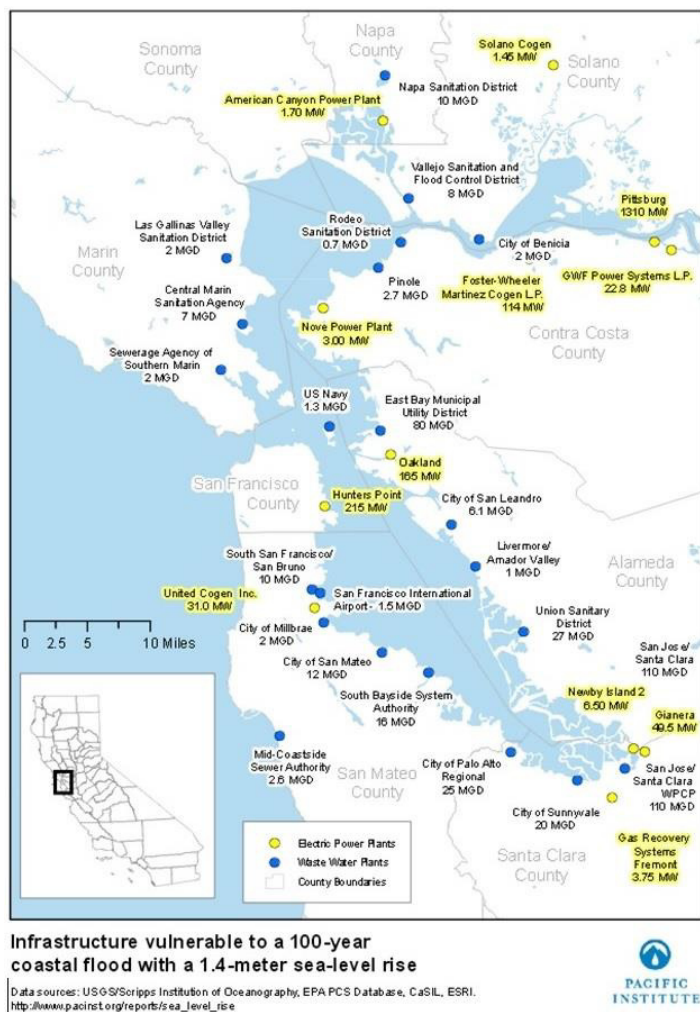


Figure 6: Study of infrastructure vulnerability due to global warming [17]. The impacts of sea level rise (1.4m) on the San Francisco Bay shores [17]. Yellow labels represent PG&E's power plants while blue circles depict the location of EBMUD's water pumping stations.

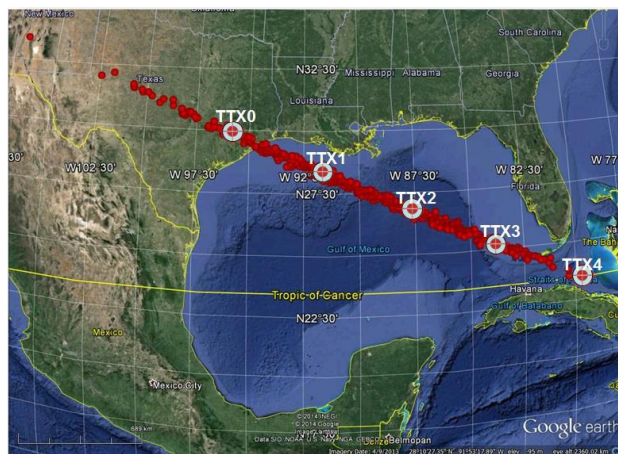


Figure 7: location of different impact locations for the TTX2 table top scenario

- Scenario TTX2-1: a wave of 1.5 to 2.0m hits the Louisiana coast within the first four hours. Yucatán peninsula receives waves of up to ~1m to 1.5m; however the Florida, Alabama and the Mississippi coasts receive waves of up to 1-0.75m (see Figure 8A).
- Scenario TTX2-2: Louisiana, Mississippi, Alabama, Florida and the Yucatán peninsula all receive waves of up to 1.2m in height. It is worth noting that most of the energy dissipates toward the South/East direction (see Figure 8B).
- Scenario TTX2-3: Cuban coast will severely be hit by a large wave of ~2.5m within the first hour from impact. The south/south-west tip of Florida and the Florida-Keys receives ~2m water waves for almost two hours. The coasts of Alabama, the Mississippi and Louisiana are subject to waves and ripples of ~0.5m height (see Figure 8C).
- Scenario TTX2-4: the impact location is close to Anguilla-Cays. Florida and Cuba are the most affected states with waves as high as 1.25m registered in West Palm Beach. The Bahamas receives waves and ripples of 0.5m waves. Waves reach as far as Freeport grand Bahamas (see Figure 8D).

It is worth noting that most of floods take place in the first 4 hours since impact in most scenarios and that the waves and floods subside within 6 to 8 hours from impact.

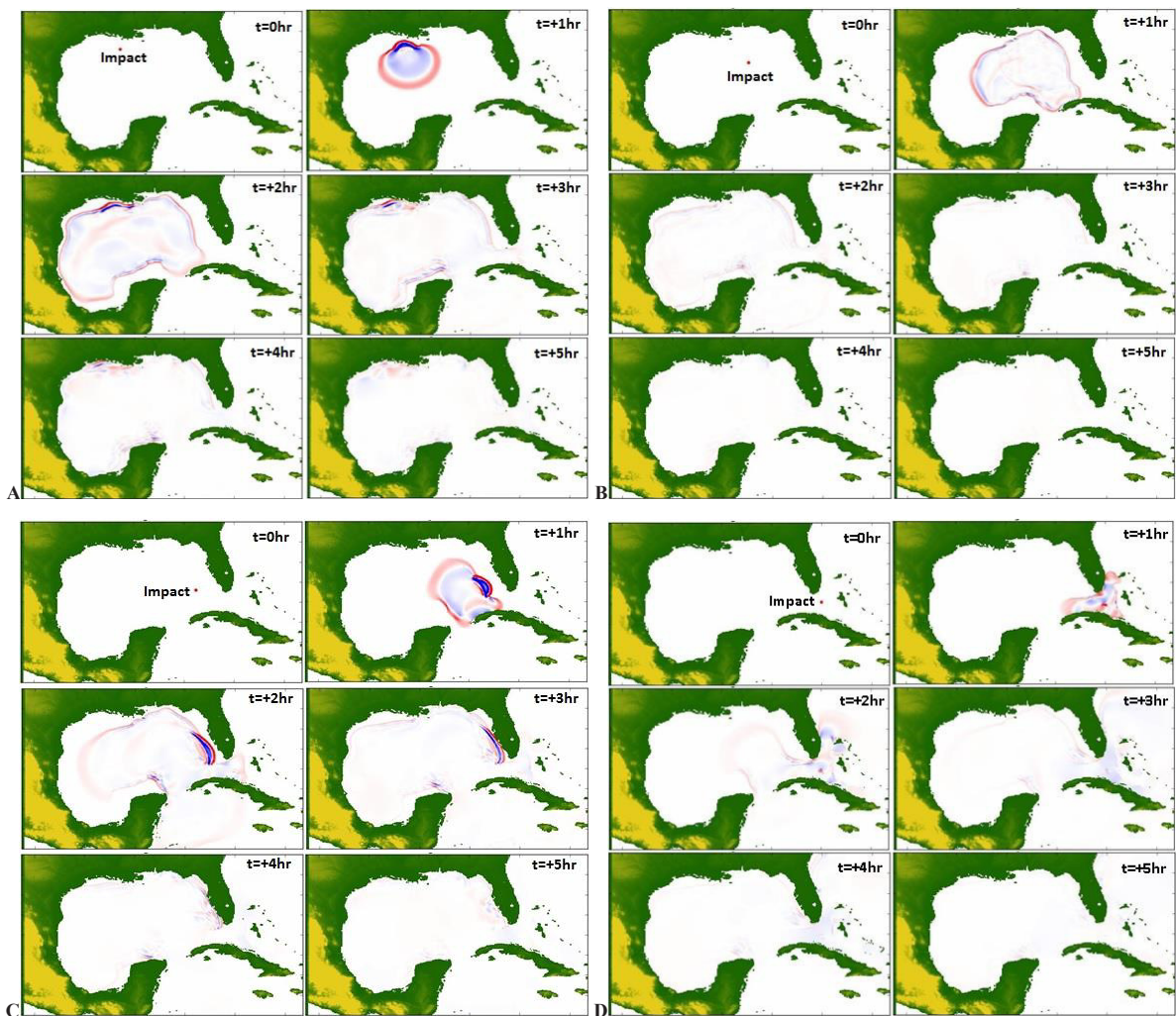


Figure 8: water waves in the Gulf of Mexico due to impact at A) TTX2-1, B) TTX2-2, C) TTX2-3, and D) TTX2-4. Heights of the water waves are scaled between -3m (blue) and +3m (red).

5. Conclusions

We have uniquely established a numerical coupling between the hydrocode GEODYN and the shallow water wave program SWWP to address impacts of asteroid on surface oceans, the subsequent long water wave generation and their interception with the shorelines. The GEODYN-SWWP has been exercised for the second FEMA-NASA asteroid-impact tabletop exercise (TTX2) held at FEMA HQ on 20 May 2014, while an early version using similar approach to [19] has been used in TTX1. The current approach, using GEODYN-SWWP, offers unique capabilities to address the full scale interactions of asteroids with the ocean (source) and the interactions of the water waves with the shorelines and maritime structures for consequence analyses.

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