SAND20XX-XXXXR
LDRD PROJECT NUMBER: 184520
LDRD PROJECT TITLE: Can Asteroid Airbursts Cause Dangerous Tsunami?
PROJECT TEAM MEMBERS: Mark Boslough

ABSTRACT:

I have performed a series of high-resolution hydrocode simulations to generate "source functions" for tsunami simulations as part of a proof-of-principle effort to determine whether or not the downward momentum from an asteroid airburst can couple energy into a dangerous tsunami in deep water. My new CTH simulations show enhanced momentum multiplication relative to a nuclear explosion of the same yield. Extensive sensitivity and convergence analyses demonstrate that results are robust and repeatable for simulations with sufficiently high resolution using adaptive mesh refinement. I have provided surface overpressure and wind velocity fields to tsunami modelers to use as time-dependent boundary conditions and to test the hypothesis that this mechanism can enhance the strength of the resulting shallow-water wave. The enhanced momentum result suggests that coupling from an over-water plume-forming airburst could be a more efficient tsunami source mechanism than a collapsing impact cavity or direct air blast alone, but not necessarily due to the originally-proposed mechanism. This result has significant implications for asteroid impact risk assessment and airburst-generated tsunami will be the focus of a NASA-sponsored workshop at the Ames Research Center next summer, with follow-on funding expected.

INTRODUCTION:

Hydrocode simulations suggest that the 1908 Tunguska explosion was a plume-forming airburst analogous to those caused by Comet Shoemaker-Levy 9 (SL9) collisions with Jupiter in 1994. A noctilucent cloud that appeared over Europe following the Tunguska event is similar to post-impact features on Jupiter, consistent with a collapsed plume containing condensation from the vaporized asteroid. Previous workers treated Tunguska as a point explosion and used seismic records, barograms, and extent of fallen trees to determine explosive yield. Estimates were based on scaling laws derived from nuclear weapons data, neglecting directionality, mass, and momentum of the asteroid. That point-source assumption, with other simplifications, led to a significant overestimate.

Tunguska seismic data were consistent with ground motion from a vertical point impulse of 7×10^{18} dyn sec caused by the downward blast wave of a 12.5-megaton nuclear explosion at an altitude of 8.5 km. However, old low-resolution simulations of a 3-megaton collisional airburst suggested that the upward-directed momentum contained in a ballistic plume can reach this level within the first minute after the explosion. The reaction impulse from such an airburst is therefore similar to a much larger non-plume-forming nuclear explosion. Momentum can only be coupled through the atmosphere to the surface, generating disproportionately large seismic signatures.

The purpose of this project was to run simulations to test the hypothesis that coupling from an over-water plume-forming airburst could be a more efficient tsunami source mechanism than a collapsing impact cavity or direct air blast because the characteristic time of the plume is closer to that of a long-period wave in deep water. According to the original hypothesis first presented by at the 2013 IAA Planetary Defense Conference in Flagstaff, AZ, (Boslough, 2013), the plume accelerates upward and creates a slowly-rising and sustained overpressure with a ramp wave that propagates outward at the speed of sound, generating a tsunami in deep ocean by the same mechanism that yields slower meteotsunami in shallow basins. This hypothesis is consistent with the observation of prominent internal waves observed propagating radially outward from several SL9 impacts, even though the waves were not in Proudman resonance. Because of slow compression, the SL9 waves grew with a Froude number of ~1.6, the same as that of the sound speed in air over ~4.6-km-deep water.

This hypothesis has significant implications for probabilistic assessment of the asteroid risk. The tsunami component of risk is highly uncertain and has never been included quantitatively as anything much more than an educated guess. There is little agreement in the published literature on the mechanism by which asteroid impacts can produce tsunami, and estimates of tsunami sizes for a given impact scenario vary widely. Current tools used to generate tsunami predictions for both emergency management exercises and for risk quantification are little better than educated guesses.

The tsunami component of original asteroid risk assessments of the early 1990s was relatively small, so tsunami uncertainty did not have a large effect on the overall risk uncertainty. At that time, the risk was dominated by asteroids greater than 1 km in diameter. That risk is what motivated the Spaceguard Survey and that is still used to justify current planetary defense efforts. In recent years the dominant risk has shifted downward to smaller airburst-generating impacts because of the success of surveys (see Boslough, 2014). We have greatly reduced the risk uncertainty by improving our estimates of the small-asteroid population (Boslough et al, 2015) and by using hydrocodes to better model the blast from low altitude airbursts (Boslough & Crawford, 2008). Proper simulations of airburst-generated tsunami will allow us to more confidently include them in our risk assessments which will be used to inform emergency response managers as well as policymakers in the planetary defense community.

DETAILED DESCRIPTION OF EXPERIMENT/METHOD:

This project had two components. First, I performed a series of 2D and 3D hydrocode runs as a sensitivity and convergence analysis to determine how robust my airburst simulations would be to differences in resolution, equation of state, and height of burst. Second, I performed an array of 2D airburst simulations to generate time-dependent boundary conditions to input into a shallow wave propagation model. For all my simulations for both components, I used Sandia's multi-material Eulerian shock physics code.

The CTH suite of computer codes is a flexible software system designed to treat a wide range of shock wave propagation and material motion phenomena in up to three dimensions. CTH uses finite-volume analogs of the Lagrangian equations of momentum and energy with continuous rezoning to construct Eulerian differencing. The code also employs a powerful method of adaptive mesh refinement (AMR) to maximize resolution in regions of interest. AMR is required for simulations involving extreme ranges in spatial scale, such as atmospheric airbursts that require a small object (~10m) to be resolved in the same simulation that accurately models propagation of an air shock at distances of 10-100 km.

CTH employs constitutive models suitable for most conditions encountered in shock physics including material strength, fracture, distended materials, high explosives, and a variety of boundary conditions. The available equation-of-state models allow CTH to model most states of matter that are encountered in shock physics. The CTH suite of codes includes on-the-fly and post-processing analysis options to generate three-dimensional, two-dimensional, and one-dimensional color and contour plots. Tabular data can also be exported into modern commercial data and visualization packages and I was able to exploit this feature to provide time dependent boundary condition data to my collaborators. Users can generate history plots of thermomechanical data at spatially fixed and material fixed points. CTH is available for a variety of computers ranging from a single PC to massively-parallel distributed-data systems. For this project, I ran most of my simulations on Sandia's Red Sky supercomputer.

CTH and its predecessor codes have been widely used for decades by the planetary science and NEO defense communities to model planetary impacts and airbursts. It was the first hydrocode used to test the giant impact hypothesis for lunar formation, and was employed to make successful predictions of phenomena observed during the impact of comet Shoemaker-Levy 9 on Jupiter in 1994, which led to our prediction and discovery of the ballistic plume phenomenon that was the basis for the hypothesis of airburst-generated tsunami. Since then we have used it extensively for asteroid deflection analysis and NEO impact risk assessments. Most recently, I used it to characterize the February, 2013 airburst over Chelyabinsk, Russia, producing a simulation that was highlighted on the cover of *Nature* and *Physics Today*.

1. Convergence & Sensitivity Analysis

In 2007, I ran a massive simulation of the 1908 Tunguska airburst over Siberia. This was a one-off "hero" calculation that required many nodes of Red Storm, which was Sandia's flagship supercomputer at the time. This simulation was featured as a centerfold in National Geographic magazine, and appeared in several television documentaries including PBS/NOVA. Since that time, asteroid airbursts have become much more accepted as the most likely dangerous impact scenario, and to many workers in the field this simulation has become the prototypical airburst despite the fact that many of the decisions (entry angle, equation of state, height of burst, energy deposition method and rate, velocity, kinetic yield, mesh resolution, etc.) were, within bounds, arbitrary. Because of its near-canonical status in the community, I chose it as my starting point for a convergence study that was never performed in 2007. The original simulation used 32-meter cells within the symmetry plane (refinement level 4). For the convergence analysis I also ran simulations with 16-meter cells (level 5) and 8-meter cells (level 6) and also explored effects of impactor properties, yield, and energy deposition rate. I was able to locate my original CTH input deck from 2007 and with minor modifications to make it compatible with the current version of CTH. I re-ran it, this time requiring only a small number of Red Sky nodes due to hardware advances in the last 8 years. One time step (Figure 1) is identical to the image that was published in the June, 2008 issue of National Geographic. Results of the convergence analysis are in the following section.

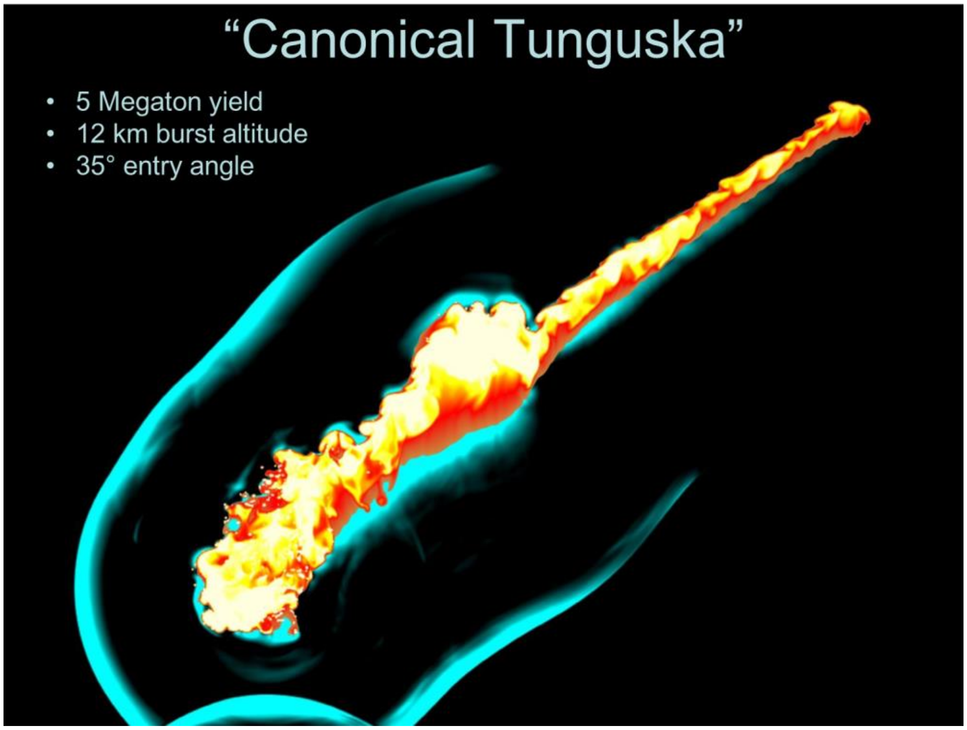

Fig. 1. Reproduction of 2007 Tunguska simulation as starting point for this study

2. **Tsunami Source Function Generation**

To generate time-dependent boundary conditions for the tsunami simulations, I ran a series of 2D axially-symmetric simulations. Since the primary purpose of this project was to test a new hypothesis for airburst-generated tsunami, I chose a geometry that would tend to maximize the effect (vertical impacts generate the strongest plumes) but minimize the post-processing and data transfer requirements (the axial symmetry allows a 2D field to be generated from a 1D profile at each time step). I varied parameters over a wide range to assess the affects.

RESULTS:

The results are given in two subsections for each of the project components: 1) convergence and sensitivity analysis and 2) tsunami source function generation. The results of the first component were presented as part of an invited talk at the First International Workshop on Potentially Hazardous Asteroids Characterization, Atmospheric Entry and Risk Assessment, NASA Ames Research Center (July 7-9, 2015). The results of the second component have been submitted for presentation at the American Geophysical Union (AGU) Fall Meeting, San Francisco (Dec. 13-17, 2015). Actual tsunami simulations based on the time-dependent boundary conditions resulting from this work have not yet been performed but my external collaborators anticipate finishing them in time to present at the AGU meeting.

1. Convergence & Sensitivity Analysis

Because a convergence and sensitivity analysis had never been performed on the simulations that led to the hypothesis being tested here, such a study became a necessary part of this project. The complexity of the problem, and the many orders of magnitude range in scale (from tens of meters in projectile size to tens of kilometers in domain size), require simulations with high enough resolution to capture the physics with sufficiently high fidelity to model the relevant phenomena but at a low enough resolution that many variations of the problem can be run on available resources. Figures 2-4 show a set of snapshots at equivalent time steps for simulations based on the one shown in Fig. 1, but with differences in resolution and distribution of cells. Other simulations (not shown) tested stability of various adaptive mesh refinement (AMR) indicators that prescribe the criteria for refinement and unrefinement.

Fig. 2 shows the exact same simulation as that shown in Fig. 1, but at an earlier time step (6.5 seconds in to the simulation). In all figures, axis dimensions are in kilometers. In all cases, the asteroid has a diameter of 54.5 meters and a density of 2.2 g/cm^3. It enters a gravitationally-stabilized atmosphere at 14.23 km/sec at an angle of 35° from the horizontal. The kinetic yield of the asteroid was 4.5 megatons, and an additional 0.5 megatons was sourced directly into it at an altitude of 12 km to initiate the explosion. This original simulation was run with a resolution of 32 meters on the symmetry plane, so the asteroid was very poorly resolved prior to the explosion. After the explosion the size of the jet consisting of asteroid vapor grows very rapidly and is much greater than the cell size.

Figs. 3 and 4 use exactly the same input decks, but with resolution reduced to 16 and 8 meters, respectively. These two simulations also had a thinner layer of refinement, and the 8-meter simulation (Fig. 4) had a slower rate of energy deposition. Minor differences can be seen in the penetration of the hot jet which leads to slightly different quantitative pressure and velocity fields on the surface, but these differences are small compared to differences created by slightly different assumptions in burst height, entry angle, etc. For purposes of hypothesis testing, this analysis suggests that 32 meters is sufficient resolution.

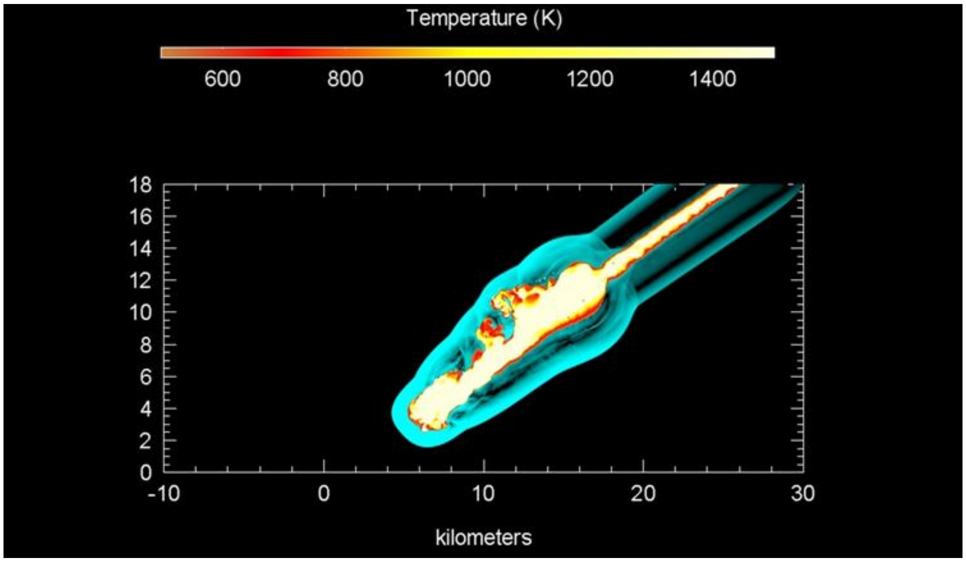

Fig. 2. Tunguska simulation with 32-m maximum resolution, t=6.5 s

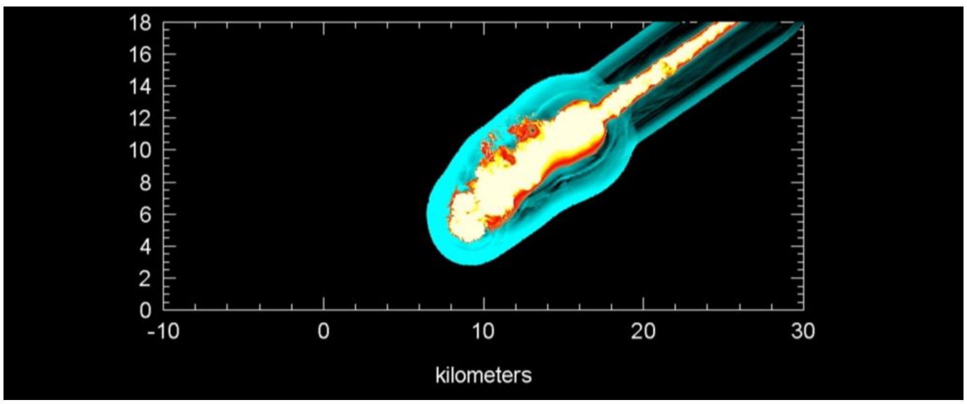

Fig. 3. Tunguska simulation with 16-m maximum resolution, t=6.5 s

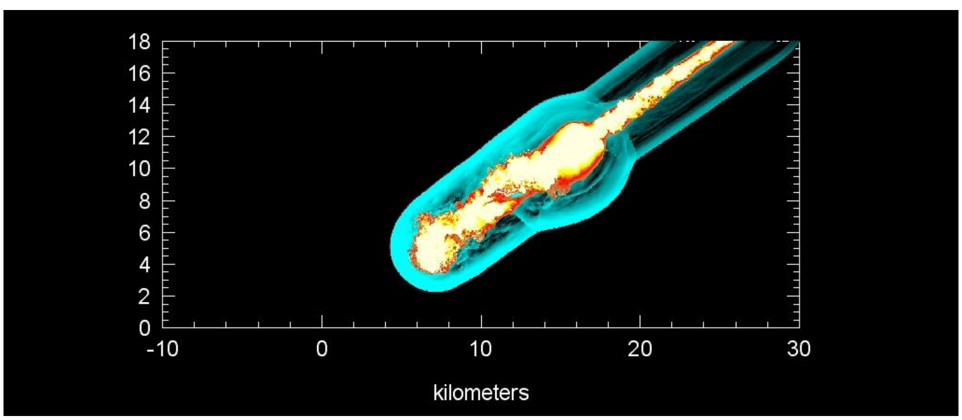

Fig. 4. Tunguska simulation with 8-m maximum resolution, t=6.5 s

2. Tsunami Source Function Generation

For the second element of the project all runs were performed in 2D axial symmetry. I performed at least 40 unique simulations to explore the effects of asteroid size, equation of state, density, speed, resolution, height of burst, and domain height and width. For each simulation I output images, pressure and velocity fields at the surface, and global diagnostic data. Image data can be used to quickly determine if the simulation is running properly with realistic results, and global diagnostic data helps determine when interactions with the domain boundaries start to affect the results. Since only the data at the surface is going to be used for tsunami simulations, reflections from the top boundary do not matter until they return to the bottom of the mesh, which allows useful simulations to be run about twice as long as would be useful for tracking the high-altitude plume. Because of the large number of simulations and output data, only one example is presented here for illustration purposes.

Since Simulation hv1_p is a Tunguska-scale airburst using a SESEME water equation of state for a vertically-impacting asteroid at 20 km/s for a kinetic yield of 5 Mt. Only 0.1 Mt, or 2% of the kinetic energy, was sourced into the asteroid as it passed 50 km above the surface to explore the bounding case of a high-altitude airburst in which the jet does not reach the surface (a Type I airburst as defined by Boslough, 2013).

Figure 5 shows a sequence of time steps as the jet approaches the surface. Figure 6 is a zoom-out of the same simulation, showing the formation of a high-altitude plume. Figure 7 is a sequence of pressure profiles at the surface, and Figure 8 shows the global upward momentum associated with plume ejection and coupling to the bottom boundary.

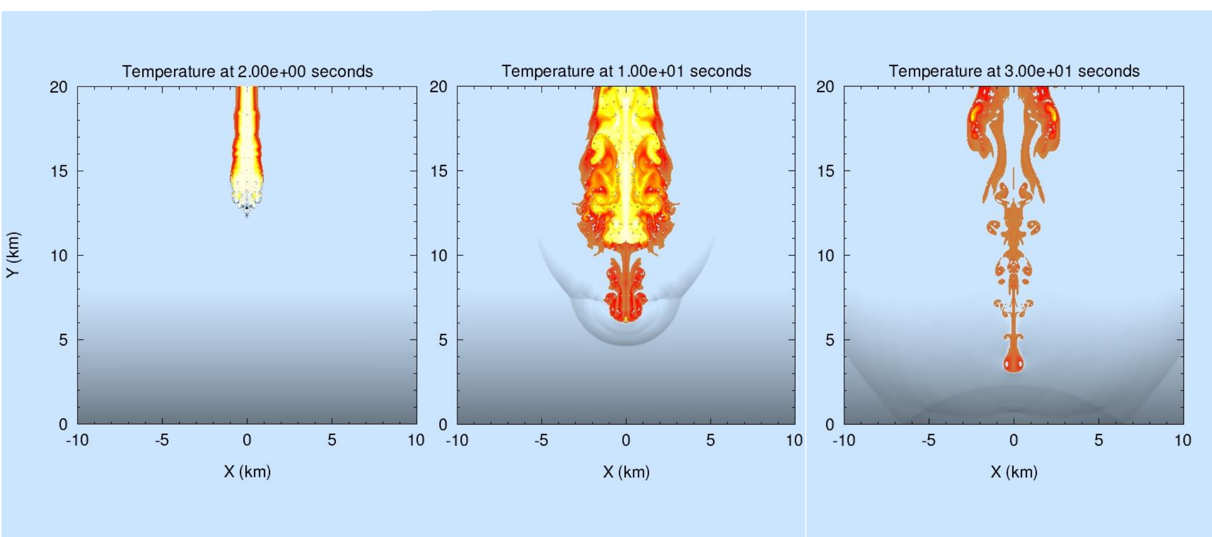

Fig. 5. 2D plume-forming airburst simulation at 3 time steps

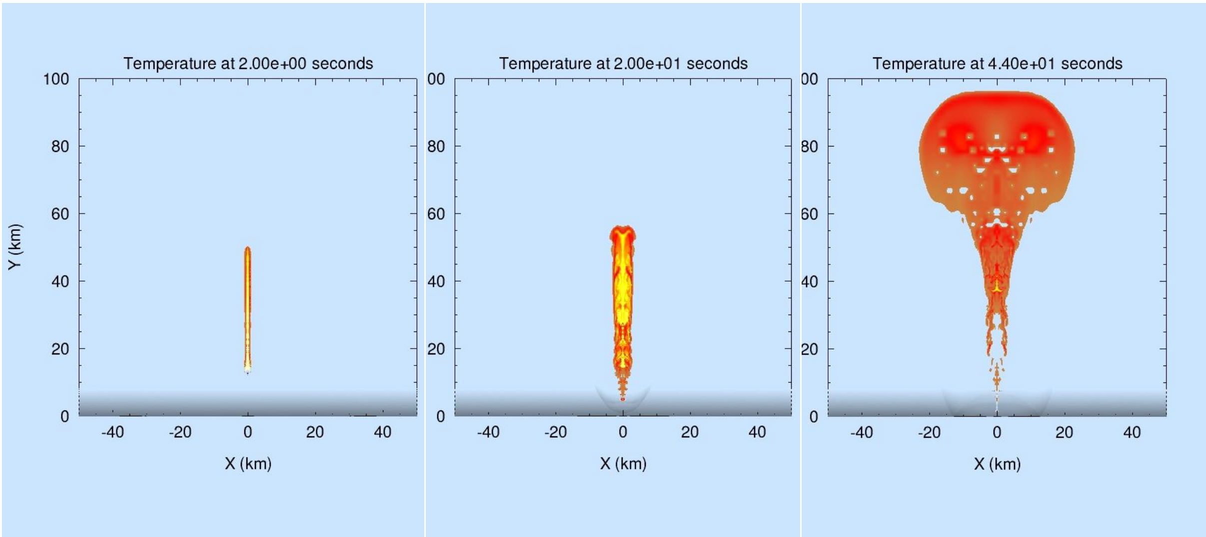

Fig. 6. Zoomed-out view of 2D plume-forming airburst simulation at 3 time steps

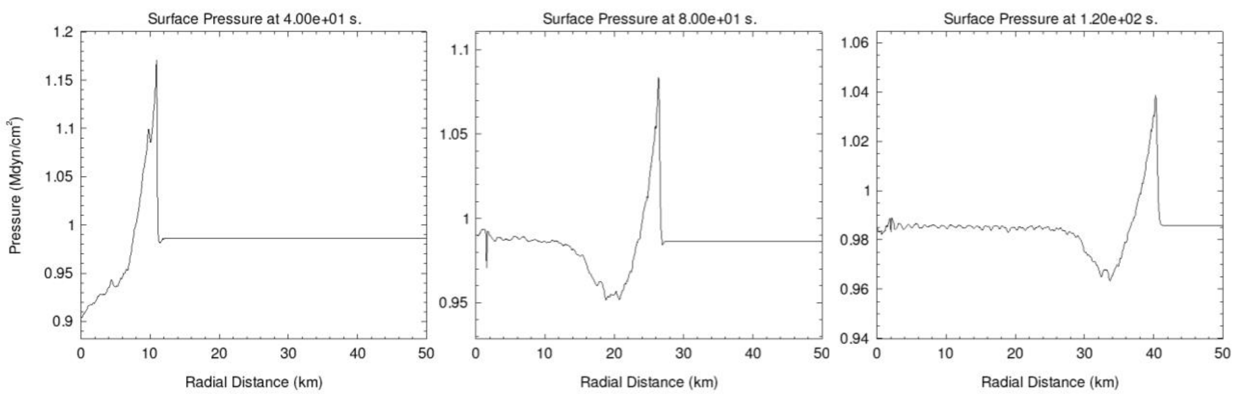

Fig. 7. Propagation of blast and rarefaction wave across surface due to 5-megaton airburst

DISCUSSION:

The convergence and sensitivity studies, while showing some dependence on resolution and details of mesh distribution and refinement, suggest that these simulations have sufficient resolution to generate realistic quantitative time-dependent boundary conditions for airburst-generated tsunami simulations. The simulations generate a strong pressure wave that propagates across the surface, followed by a rarefaction wave. These profiles have been shared with tsunami modelers who will use them as source functions for tsunami simulations to test the hypothesis that asteroid airbursts can generate dangerous tsunami.

The original hypothesis suggested that generation of the ballistic plume must require the transfer of momentum through the air to the surface, leading to a slowly-rising compression wave that propagates across the surface at the speed of sound. The profiles shown in Fig. 7 (and similar profiles for other simulations in the series) show that this is not what actually happens. In all cases, the first disturbance to reach any point on the surface is a strong blast wave followed by a slowly-declining decompression or rarefaction wave. This is very much analogous to what is observed from a point-source explosion such as an atmospheric nuclear test in which the rarefaction is known as the "suction phase" in which surface wind direction reverses.

Nuclear explosions do not couple strongly to tsunami generation because of an impedance mismatch between the sharp and rapid blast wave that traverses the air, and the slower shallow wave speed associated with the tsunami. At a given location on the water surface, the blast wave essentially passes before the water has time to respond. Natural tsunami-generation mechanisms usually involve ground motion and are most efficient when there is a strong earthquake and permanent subsidence or uplift that displaces water over a wide area on time scale that is long compared to the characteristic time associated with wave propagation.

However, there is one known atmospheric-driven tsunami mechanism that occurs in nature: meteotsunami. These are driven by weather systems involving large changes in barometric pressure and winds that propagate across water surface at speeds that come close to matching the shallow-water wave speed in that body (a perfect match would be a Proudman resonance). They are common in shallow bodies such as the Great Lakes and the Mediterranean Sea, for which tsunami propagate much more slowly that they do in the deep water of ocean basins. Because they are not driven by seismic events, the sometimes appear without warning as large "rogue waves" and have led to extensive damage and even fatalities.

The physics of meteotsunami generation requires coupling between an incipient wave and the wind or pressure gradient that drives it. A sustained gradient that propagates at the speed of the wave will pump energy into it as long as they are aligned. However, a slow compression or decompression wave that propagates at a significantly different speed than the water wave can still drive energy into it as long as there is a gradient at the water wave front. There is an analogy with a surfer, who can gain energy as long has she is riding the wave. If a ramp-shaped wave is faster or slower than she is moving she will continue to gain energy but her position on the wave will change and eventually it will pass her, or she will run out ahead of it. In the case of an airburst-driven meteotsunami, the air wave is faster than the water wave and eventually runs out ahead of it. The question that will be addressed by the tsunami-modeling portion of this study is whether or not a dangerous tsunami can form under these conditions at all.

Based on the results thus far, the hypothesis needs to be modified but the basic idea and physics remain the same. Figure 7 in the results section shows a shock wave propagating across the surface, followed by a ramp-shaped decompression, which is in turn followed by a ramp-shape re-compression. Even at times between one and two minutes after the burst, at a distance of tens of kilometers from ground zero, the peak-to-peak overpressure change is 5% to 10% of atmospheric pressure, which corresponds to a hydrostatic head pressure of 1 or two meters. The transient pressure, or time that it takes for the overpressure to return to near zero, is about one minute at a distance of tens of kilometers. The reaction pressure from the plume acceleration contributes to the overall shape of the wave. Figure 8 shows the global momentum of the system in the y direction that is included in the plume as well as the upward-directed blast wave and the reflected blast. In this simulation the upper boundary of the domain was chosen such that no disturbance reached it within the first fifty seconds, so the entire vertical momentum change up to that time is due to coupling to the lower boundary, representing the water surface. The initial momentum represents only the downward motion of the asteroid itself, about 2×10^{17} g-cm/s. The total momentum couple to the surface is about an order of magnitude greater, suggestion that the momentum multiplication factor (β) for this case was at least 10 but still growing when the plume reached the upper boundary. This strong momentum multiplication, relative to a nuclear blast of the same magnitude, suggests that the surface pressure profiles and histories are different, and therefore tsunami coupling will also be different. We anticipate pursuing this idea further with NASA funding in the next fiscal year (see next section).

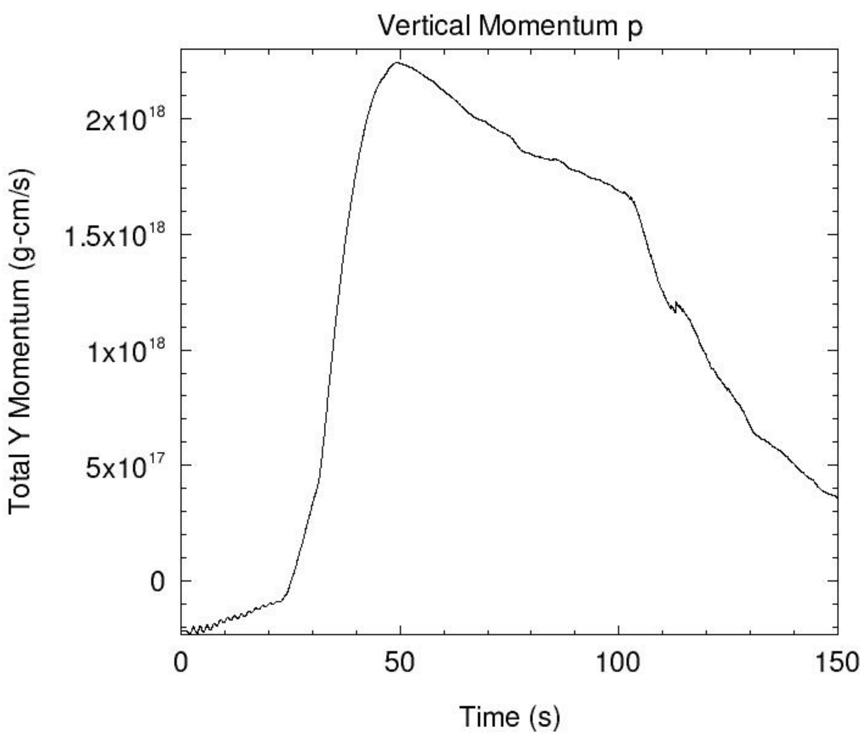

Fig. 8. Global vertical momentum history from 5-megaton airburst simulation

ANTICIPATED IMPACT:

The concept of an airburst-generated tsunami has generated interest and excitement in the planetary defense community, which is increasingly recognizing the fact that uncertainty in the mechanism of tsunami formation and resulting wave size and run-up distance dominates the impact risk uncertainty. The purpose of the July workshop at NASA Ames research center was to identify gaps and make recommendations for which aspects of planetary defense should receive the most attention as we move forward. Impact-generated tsunami emerged at that top of the list of gaps in our understanding that should be addressed.

As a result of Sandia's participation in the Ames workshop, James Arnold (Manager of NASA's Threat Assessment Project) sent the following message:

> We received positive feedback from our Program Executive, Lindley Johnson, that we focus our second workshop on tsunami. Highlights and outcome of the workshop can lead to a series of presentation at the next PDC planned for late spring 2017.
>
> We are in the very early stages of planning for the workshop to be held in late July or early August 2016. The proposed workshop will focus on the meteor-tsunami scenarios, with the goal of advancing the state-of-the art in simulations of surface damage they cause. We spoke by telephone about this recently. The workshop will be held at an easily accessible location (TBD). Before we start the planning for the workshop, we need to be sure we all have the required resources. The primary purpose of this e-mail is to get commitment from you to support the workshop and to get an idea of the resources you require. Once we get your commitment and a specification of resources needed, we will work with your management and funding sponsors to be sure that you have adequate support.
>
> The workshop goal could be that the experts define about (5-6) scenarios or cases that scope the breadth of damage expected from a tsunami created by asteroid impacts. Each participant would simulate two or more of these cases with the highest fidelity available to them. Each case would be independently simulated by at least two researchers assuming identical initial conditions. Possibly, cases already done and presented at our first workshop could be revisited. The workshop might be held over two days. The first day would be dedicated to study of the results presented by the invited speakers. The second day would be devoted to discussing differences in the results with the objective of understanding them, and what is needed to advance the state-of-the art in simulation of tsunami damage caused by asteroid impacts. The presentations and discussions would be recorded and published on a web site in a fashion similar to that done for the first workshop.

NASA's Near Earth Object program manager, Lindley Johnson, has specifically requested that Sandia include tsunami-related tasks in a Statement of Work for FY16 funding which is pending and could start as soon as October.

We also anticipate being asked to include airburst-generated tsunami in a future impact scenario for a tabletop exercise with the emergency response community at FEMA. According to recent correspondence from NASA headquarters, the next exercise is likely to take place at one of FEMA's regional centers, probably in southern California in April or May, 2016.

Sandia has been directly involved in four such tabletop exercises (TTX). In the first (April 2-3, 2013 at FEMA headquarters), the scenario involved a tsunami-generating impact off the coast of Virginia. The second TTX (April 15-19, Planetary Defense Conference, Flagstaff, AZ) included an impact into the Mediterranean Sea off the coast of France. At the third TTX (May 20, 2014 at FEMA headquarters) the scenario included an impact into the Gulf of Mexico. The most recent TTX (April 13-17, Planetary Defense Conference, Frascati, Italy) included several wave-forming impact scenarios along a corridor from the eastern Pacific Ocean to the South China Sea. Based on my specifications in collaboration with a Souheil Ezzedine, a tsunami modeler from LLNL, the Sandia team presented several graphic representations of various possible impacts, including the one shown in Fig. 10. We anticipate doing something similar at a future TTX but using our newly-developed airburst-generated tsunami capability. Two of these exercises are described in detail by Boslough et al. (2015b, 2016).

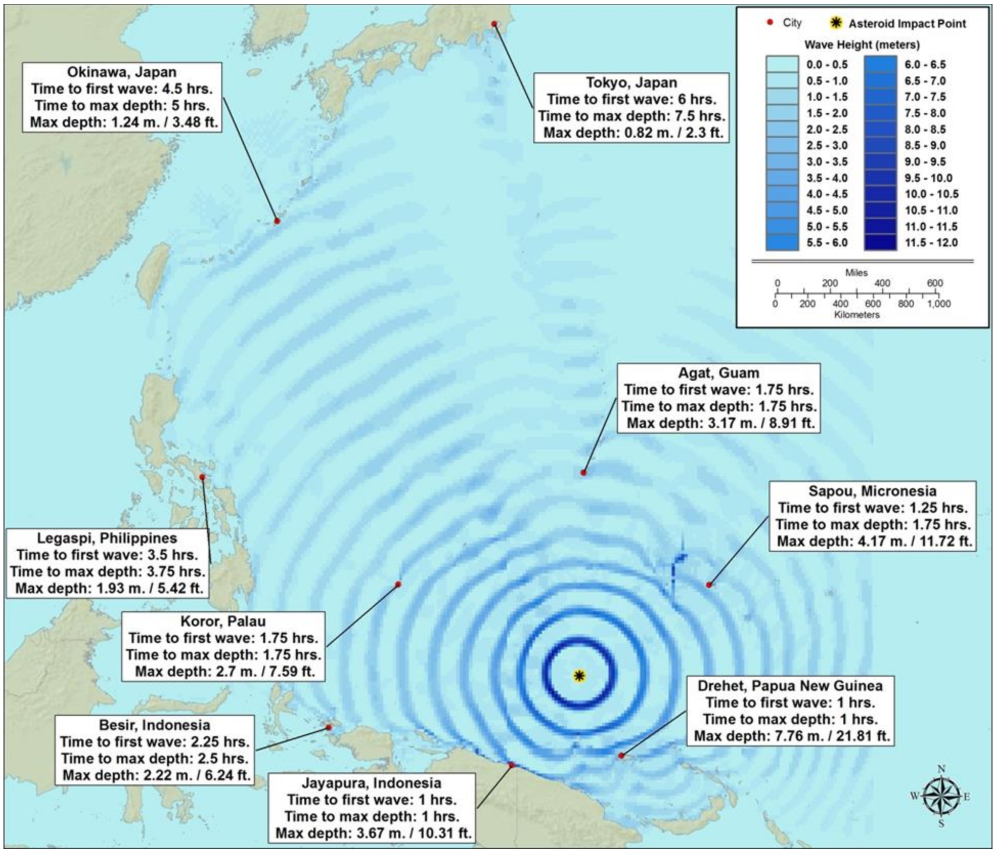

Fig. 10. Impact tsunami generation from 2015 tabletop exercise (Boslough et al., 2016)

CONCLUSION:

Analysis of the simulations performed for this project support a modified version of the original hypothesis, that asteroid airbursts can generate tsunami waves without an actual surface impact. I have sent results of the airburst simulations, including time-dependent pressure profiles at the surface, to two different tsunami modelers who are both involved in NASA's planetary defense program: Souheil Ezzedine of LLNL and Vasily Titov of NOAA, who will be running the tsunami simulation component of the hypothesis test. Final conclusions will depend on their results. We will continue this work with follow-on funding from NASA.

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