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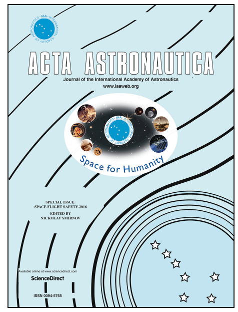

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Air-coupled tsunamis generated from impacts and airbursts: Our understanding before Hunga-Tonga Hunga-Ha'apai

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INTRODUCTION

The effort to prevent or mitigate the effects of an impact on Earth is known as planetary defense. A significant component of planetary defense research involves risk assessment. Much of our understanding of the risk from near-Earth objects comes from the geologic record in the form of impact craters, but not all asteroid impacts are crater-forming events. Small asteroids explode before reaching the surface, generating an airburst, and most impacts into the ocean do not penetrate the water to form a crater in the sea floor. The risk from these non-crater-forming ocean impacts and airbursts is difficult to quantify and represents a significant uncertainty in our assessment of the overall threat. We are currently working to better understand impact scenarios that can generate dangerous tsunamis.

One of the suggested mechanisms for the production of asteroid–generated tsunamis is by direct coupling of the pressure wave to the water, analogous to the means by which a moving weather front can generate a meteotsunami. To test this hypothesis, we ran a series of airburst simulations and provided time-resolved pressure and wind profiles to use as source functions for tsunami models. We used the CTH hydrocode to model the various airburst scenarios to compare to the results of other simulations and provide time dependent boundary conditions as input to shallow-water wave propagation codes. The strongest and most destructive meteotsunamis are generated by atmospheric pressure oscillations with amplitudes of only a few hPa[1] (mbar), corresponding to changes in sea level of a few cm. The resulting wave is strongest when there is a resonance between the ocean and the atmospheric forcing. A Proudman resonance takes place when the atmospheric disturbance's translational speed (U) equals the longwave phase speed $\sqrt{gh}$ of shallow water wave. Coupling is strongest when the Froude number (Fr=U/c) is unity. A weather front propagates much slower than the speed of sound, so meteotsunamis are most common and dangerous in shallow bodies of water such as the Mediterranean Sea or Lake Michigan.

By contrast, the blast wave from an airburst or crater-forming impact propagates at a speed faster than a tsunami in the deepest ocean, and a Proudman resonance cannot be achieved even though the overpressures are orders of magnitude greater. However, blast wave profiles are N-waves in which a sharp shock wave leading to overpressure is followed by a more gradual rarefaction to a much longer-duration underpressure phase. Even though the blast outruns the water wave it is forcing, the tsunami should continue to be driven by the out-of-resonance gradient associated with the suction phase, which may depend strongly on the details of the airburst or impact scenario. The open

[1] 1 hPa = 1 mbar, and has been adopted as the standard SI unit by meteorologists. SI units are given in this paper to comply with this SI convention.

question is whether there are any conditions under which such an airburst-driven tsunami can be dangerous enough to contribute to the overall impact risk.

We have also identified other potential mechanisms for airburst-generated tsunamis: 1) reaction force at the surface from the plume ejected into space, which carries significant momentum, 2) expanding toroidal vortices at the surface, which travel more slowly than the shock wave and can generate a Proudman resonance in relatively shallow ocean (such as continental shelf), and 3) steam explosion from seawater ablation by a "Type II" (Libyan Desert Glass-type) airburst in which the hot vapor jet descends to the surface.

On January 15, 2022, the Hunga-Tonga Hunga-Ha'apai volcano, located approximately 60 km north of Tongatapu, the main island of Tonga, violently erupted with a powerful explosion, culminating the period of volcanic activity that started in December of 2021. This event and resulting tsunamis provided an existence proof for the air pressure wave coupling mechanism we proposed. It also suggests that it can be stronger and more significant over much greater distances than we contemplated, leading to global tsunamis associated with impact events on land as well as in the water. Large atmospheric explosions generate global Lamb waves with larger amplitudes, longer periods, and slower speeds than the local and regional blast waves we modeled prior to that event. This paper reviews our analysis and modeling of airburst-driven tsunamis prior to the 2022 Hunga-Tonga Hunga-Ha'apai tsunami, which was the subject of two presentations at the 2023 Planetary Defense Conference [1,2] and is the subject of another paper currently in preparation [3].

AIRBURST-GENERATED GRAVITY WAVES AND TSUNAMIS

The notion of airburst-generated tsunamis was first presented at the 2007 Planetary Defense Conference by Boslough [4] who concluded that "momentum coupling to atmosphere, solid earth and tsunami is higher because of plume ejection." This atmospheric momentum enhancement was based on simulations of a 3-megaton collisional airburst by Boslough and Crawford [5] which showed that within the first minute of impact, the upward-directed momentum associated with the atmospheric plume reaches 7×10^{18} dyn sec. The reaction impulse from a 3-megaton collisional airburst is therefore similar to that of a 12.5 megaton nuclear explosion. This momentum is coupled through the atmosphere to the surface, so its seismic signal gave it the appearance of being a larger explosion than it actually was.

Boslough and Gisler [6] suggested that similarly enhanced long-period momentum coupling from an over-water airburst is a possible third impact-induced tsunami mechanism (in addition to cratering and air blast-driven wave generation). As the atmospheric plume accelerates upward, it generates sustained high pressure at the surface, creating a long-period source function that displaces the water downward and radially outward from the epicenter. Boslough [7] argued that features on Jupiter observed by the Hubble space telescope after the impact of fragments of Comet Shoemaker-Leve 9 were analogous to a tsunami waves that were generated by this mechanism. According to Hammel et al [8], "In images taken within 3 hours of the larger impacts, we detected transient 'rings' that are most likely caused by atmospheric waves. The most dramatic example was the multiple ring system created by the large G fragment. The circularity of the rings suggests that they are waves; debris features are asymmetric."

According to Ingersoll and Kanamori [9], "Images of Jupiter taken by the Hubble Space Telescope (HST) reveal two concentric circular rings surrounding five of the impact sites from comet Shoemaker-Levy 9 (SL9). The rings are visible 1.0 to 2.5 hours after the impacts. The outer ring expands at a constant rate of 450 ms^{-1}. The inner ring expands at about half that speed. The rings appear to be waves…" They argued that internal gravity waves trapped in a stable layer within the putative water cloud are the only waves that could match the observations.

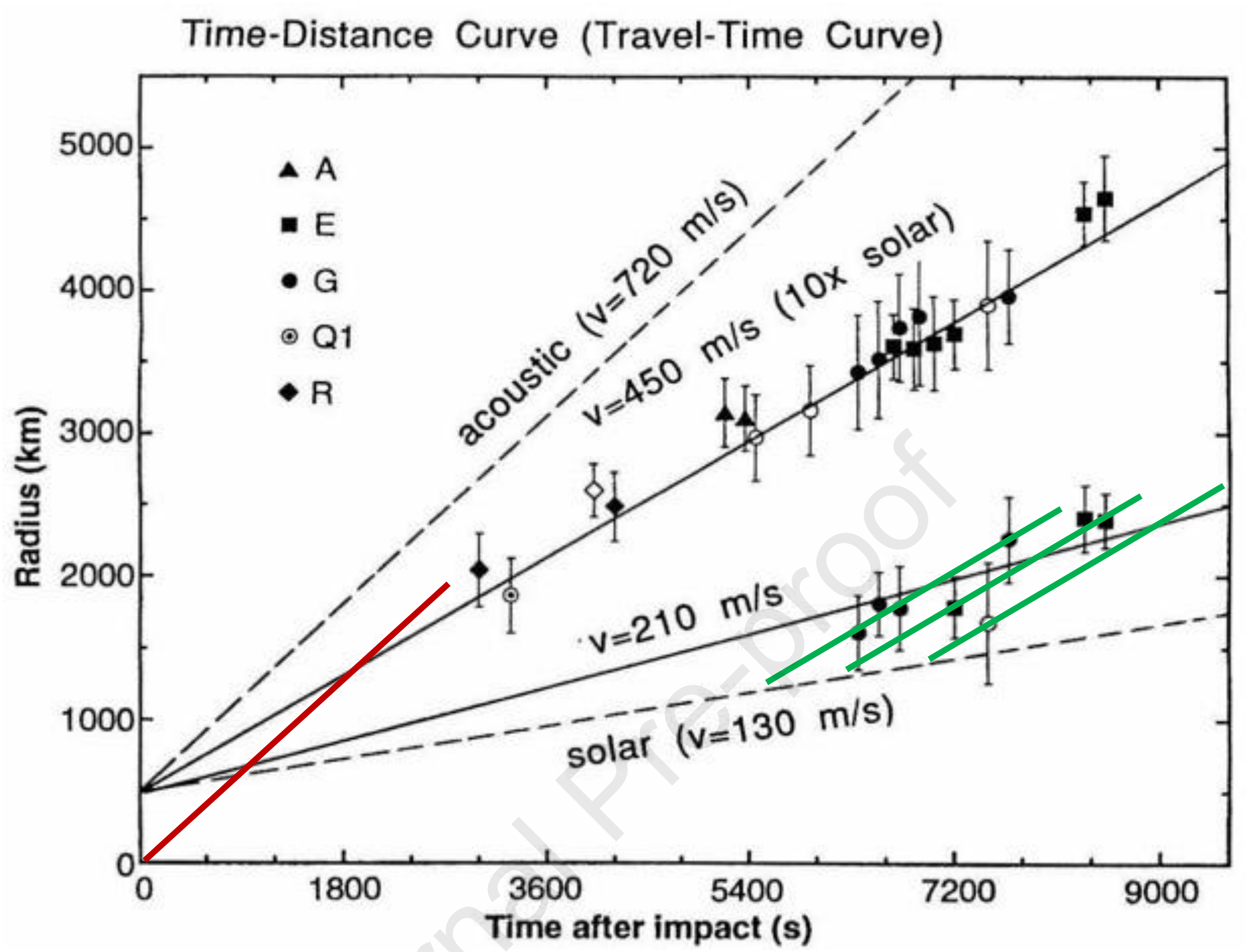

Fig. 1. From Ingersoll and Kanamori [9], after Hammel et al [8] "Time-distance curve for the circular rings... The shape of the symbol identifies the fragments A, E, G, Ql, and R. Open symbols identify data taken with the methane (889 nm) filter. Closed symbols are for all other filters. The intercept was determined from the fit to the upper set of points. 'Acoustic' refers to the speed of sound at the temperature minimum. 'Solar' and '10x solar' refer to the speed of a gravity wave in the water cloud with solar and 10x solar abundance of water." The red line corresponds to a shock wave that couples to the first gravity wave and then outruns it after about 2000 s. The green lines correspond to the second gravity wave which has the same speed as the first one but with an origin time that depends on the plume collapse extent which depends on the size of the impactor.

Boslough [7] offered an alternative interpretation of the same data, in which an acoustic wave is produced at time zero, and ground zero, by the impact (Fig. 1). This acoustic wave couples to the first gravity wave over time, even though it is moving significantly faster. The ballistic plumes rose to about 3000 km and took about a half hour to collapse. This collapse covered an area of Jupiter comparable to the diameter of the Earth, generating long period waves as the collapsed Jovian atmosphere and comet vapor slid outward, generating a second gravity wave with the same speed but by a different mechanism and with a different apparent time of origin that depends on the size of the impactor. If this interpretation is correct, then the 1994 comet impact on Jupiter would provide an "existence proof" that a gravity wave can be generated by atmospheric coupling from an impact-generated shock wave. It can also put constraints on the Froude number, the ratio of the driving wave to the driven wave (Fr=U/c) at which significant coupling can occur for an impact to generate a strong gravity wave, with implications for impact-generated tsunamis on Earth and the associated risk.

Atmospherically-driven tsunamis on Earth are a well-known and understood phenomenon, called meteotsunamis. These waves can be very destructive to the point of catastrophic, and the strongest are driven by atmospheric pressure oscillations on scales of only a few hPa (mbar) [10]. The dangerous amplification occurs when the speed of the weather front (U) over which the atmospheric pressure changes is the same as the shallow water wave's phase speed (c). This allows energy to be transferred from the air to the water for a long time, and over a long fetch. The efficiency of the coupling is determined by the Froude number and is maximized when Fr=1, which defines the "Proudman resonance".

If the waves observed after SL9 fragment impacts on Jupiter are indeed gravity waves, then they are analogous to the tsunami and acoustic wave caused by the impacts and plume collapses (a rapid shock wave followed by a long rarefaction). If that was the source of energy, then the HST observations can be used to estimate the ocean depth range over which an impact on earth could generate tsunamis through atmospheric coupling of a similar wave. Figure 2 from Boslough [7] provided an argument that dangerous tsunamis could be generated on Earth from airbursts.

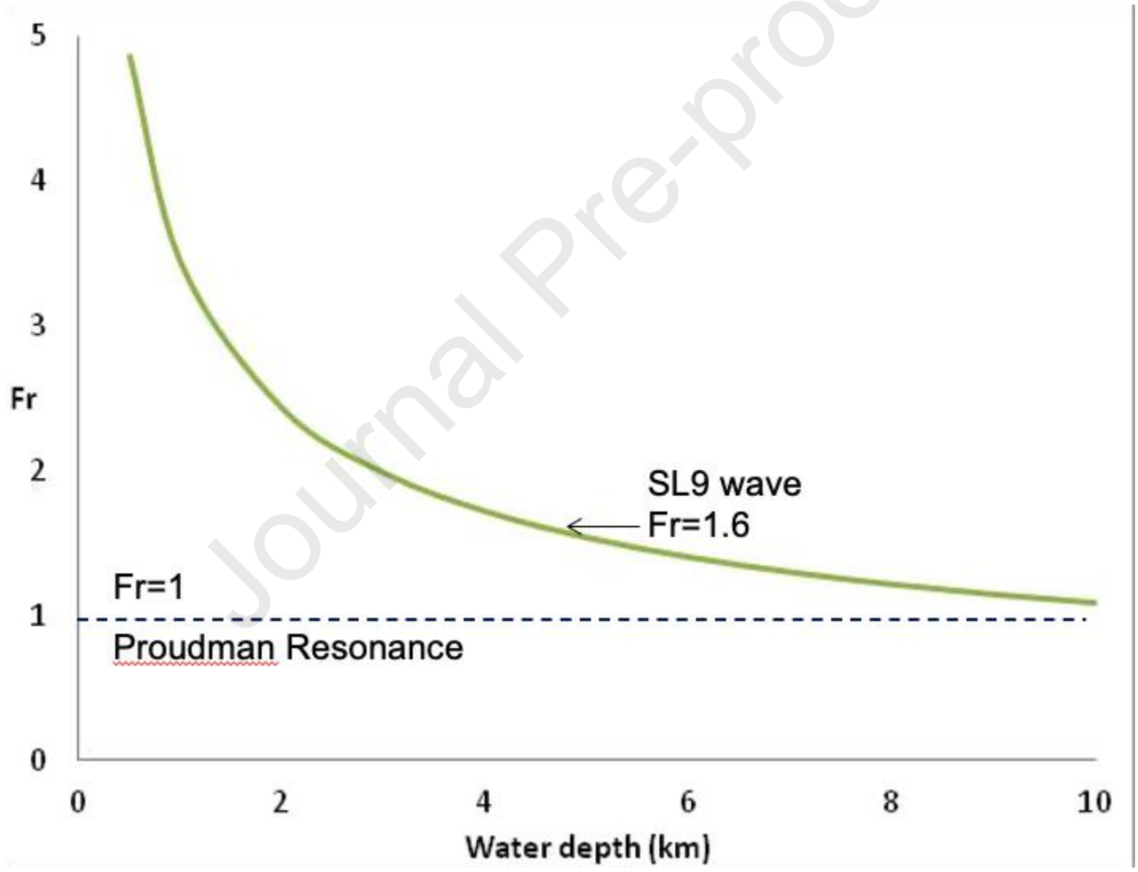

Fig. 2. A Proudman resonance takes place when the atmospheric disturbance translational speed (U) equals the longwave phase speed $c=\sqrt{gh}$ of a shallow water wave. A shock wave moving near the atmospheric sound speed at sea level cannot achieve a Proudman resonance even over the deepest trenches (about 10 km), but internal waves appear to have been generated by an airburst on Jupiter at a Froude number of 1.6, which corresponds to an ocean depth of about 4.6 km.

FIRST AIRBURST-GENERATED TSUNAMI SIMULATIONS

By 2014, one of the most widely-reported conclusions from computational airburst modeling was that previous risk assessments may have significantly underestimated airbursts. Early that year the National Nuclear Security Administration (NNSA) identified asteroids as a national security issue and began collaborations with the National Aeronautics and Space Administration (NASA). The two agencies held a joint workshop to discuss planetary defense. The primary purpose of the interagency agreement was to analyze the means for nuclear deflection. Sandia National Laboratories was asked to participate in large part due to the success and visibility of airburst models, and its work with emergency management agencies. There were two reasons for upgrading the risk: 1) Most airbursts deliver more blast energy to the ground than a nuclear explosion of the same yield, and 2) It was recognized, in part because of the Chelyabinsk airburst, that there is a higher flux of small but dangerous asteroids than previously thought. A third reason had never been tested: 3) It had been argued, as described in the previous section, that under some conditions, airbursts can couple energy directly into ocean tsunamis much more efficiently than surface impacts can. In January, 2015 Sandia provided internal funding to attempt, for the first time, to couple the output of an airburst simulation to the input of a tsunami model to address that question.

The idea of airburst-coupled tsunamis was novel and not yet accepted (or even considered) by NASA or the planetary defense community. The purpose of the Sandia project was to perform convincing proof-of-principle simulations to determine whether or not the downward momentum from an inclined airburst could couple energy into a dangerous tsunami in deep water using the CTH hydrocode to generate source functions for various airburst scenarios. To achieve the primary goal, we ran simple 2D simulations of vertical impacts and calculated time-resolved overpressures and wind fields at the surface. These surface fields could then be used as a time-dependent boundary condition for a shallow-water wave code. This was later extended with 3D simulations of airbursts with different sizes, entry angles, strengths, and velocities. The next step was to run the initialized wave propagation code to determine whether or not airbursts could generate dangerous tsunamis to improve the risk assessment by including the airburst/tsunami component.

By this time, impact-generated tsunamis were recognized as potentially hazardous enough to warrant a fiscal appropriation in the NASA Authorization Act of 2015 (February 9, 2015), which stated, "SEC. 324. RESEARCH ON NEAR-EARTH OBJECT TSUNAMI EFFECTS. (a) REPORT ON POTENTIAL TSUNAMI EFFECTS FROM NEAR-EARTH OBJECT IMPACT.—The Administrator, in collaboration with the Administrator of the National Oceanic and Atmospheric Administration and other relevant agencies, shall prepare a report identifying and describing existing research activities and further research objectives that would increase our understanding of the nature of the effects of potential tsunamis that could occur if a near-Earth object were to impact an ocean of Earth."

The first opportunity to respond was the First International Workshop on Potentially Hazardous Asteroids Characterization, Atmospheric Entry and Risk Assessment (July 7-9, 2015, NASA Ames Research Center). The vision of the workshop was to "advance our understanding of Potentially Hazardous Asteroids (PHAs) through modeling of their atmospheric entry/breakup, risk assessments of surface impact (land and tsunami), and characterization of their pre-entry properties with the long-term goal of developing reliable predictive and assessment tools enabling decision makers to take appropriate mitigation action in the event of pending PHA strike."

We presented the first results of the Sandia-funded project at the 2015 American Geophysical Union Fall Meeting [11]. We ran a 2D cylindrical (vertical impact) plume-resolving simulation of a 5 megaton airburst at about 10 km above a reflecting surface. After the explosion, the jet of debris continues downward, pushing a bow shock ahead of it. The associated overpressure is followed quickly by a suction phase and underpressure. The pressure change magnitude is about 0.1 atmosphere and takes place on timescales of several seconds. For the 2D case, surface pressure coupling is enhanced by plume ejection and collapse. The pressure disturbance at the surface propagates at the speed of sound, which is significantly faster than waves in all but the deepest ocean.

We generated a time-dependent boundary condition by converting pressure to wave height using the hydrostatic approximation as a crude preliminary model. This was intended to provide information about how the mismatch in wave speed will inhibit tsunami generation. The pressure wave propagated with a speed of about 348 m/s out to the edge of our domain (x = 50 km).

We placed the impact 1000 km off of San Francisco, using Etopo1 for our tsunami model (MOST) bathymetry with dx=1 arcmin (1.85 km) resolution. Average water depths at impact are ~5000 m, giving us a CFL time step of 3.2 sec, which we reduced to 2.0 sec to match hydrocode output files.

This simulation showed that the wave dissipates fast initially (as expected), but it still generates a very significant tsunami after the generation phase is passed, comparable with a very large earthquake-generated tsunami. A comparison run with deeper bathymetry (~11,000m) shows much larger tsunami generation, consistent with Proudman resonance, as the longwave speed is 331 m/s.

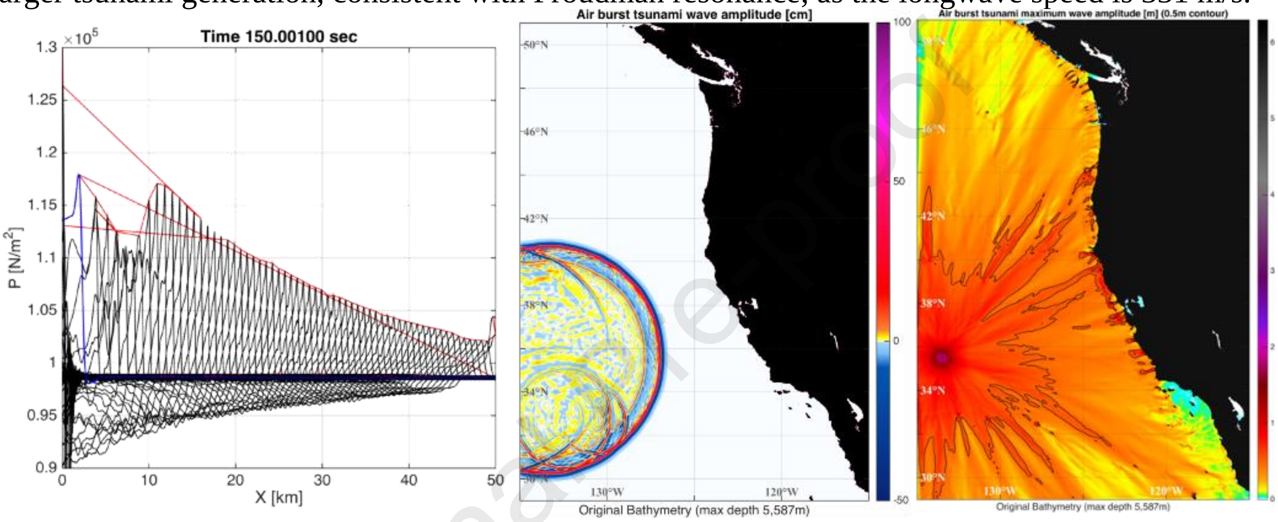

Fig. 3. Left: Family of hydrocode-generated pressure profiles at surface for 5 megaton airburst at about 10 km altitude. Center: Single time step of tsunami generated by crudely coupling hydrocode output from airburst simulation to tsunami model. Right: Maximum wave amplitude of airburst-generated tsunami (Boslough et al, 2015).

2016 ASTEROID-GENERATED TSUNAMI (AGT) WORKSHOP

By January, 2016, Marsha Berger had independently confirmed that tsunamis could be generated by coupling of an airburst through the atmosphere, using the output of a 100 Mt explosion modelled by Michael Aftosmis [12]. The increasing interest in asteroid-generated tsunamis, as a potentially significant component of the NEO hazard led to the Second International Workshop on Asteroid Threat Assessment was held at the Pacific Marine Environmental Laboratory in Seattle on Aug 23-24, 2016. This workshop consisted of three sessions: 1) tsunami creation from airbursts and impacts, 2) tsunami propagation, and 3) tsunami hazard and risk. Session 1 was most relevant to the topic of this paper, and the following paragraphs are based on a report written immediately after the workshop by one of us (MB).

This session was tasked with modeling the physical processes of airbursts and direct water impacts, performing code-to-code comparisons, and providing data to the Session 2 group to understand the coupling to tsunamis as well as to short-period waves, ejecta, and other disturbances. I think it would be fair to say that our overall best estimate of the severity of the risk from asteroid-generated tsunamis has decreased, but that our uncertainty in that assessment remains high and still needs to be addressed. At this time, we cannot say with certainty that the consensus will not change again after further analysis.

All four speakers (Mark Boslough, Galen Gisler, Michael Aftosmis, and Darrel Robertson) focused primarily on hydrocode modeling with various levels of sophistication ranging from simple 2D axially symmetric static explosions over a reflecting boundary condition at the surface, to high-resolution 3D simulations of oblique impacts over a layer of compressible water with a realistic equation of state that allows it to respond to shock compression and expansion. The simplest 2D scoping simulations could be run in less than an hour on a handful of cores, whereas the largest required entire supercomputers and ran for many weeks.

The simplest simulations are useful for exploration of parameter space and development of insight, but the processes that can be explored are limited (*e.g.* entry angle is fixed, axial symmetry is imposed, and the surface interaction is not realistic). At the other extreme, the massive 3D simulations require commitment to the study of just a few examples but are much better at representing the actual physics. By pursuing these orthogonal approaches, the speakers were able to explore a wide range of phenomena and build confidence in their understanding of the modeled phenomena.

There was a broad consensus among the speakers and attendees that the tsunami threat is *probably* not as great as previously thought (as stated by the 2003 NASA Science Definition Team Report), but there was a wide range in degree of confidence among the participants because of the limited number of cases that were modeled, the idealized nature of the simulations, and the possibility that we have missed something important. Everyone appeared to be satisfied with the coordinated comparisons among the various codes, and to published nuclear weapons effects. We agreed that differences among hydrocode results are explainable by minor differences in assumptions, equations of state, energy sourcing, etc., and do not contribute significantly to uncertainty in the bottom line.

The uncertainty in risk from asteroid-generated tsunamis is *epistemic*: it is dominated by our lack of complete understanding. Prior to this workshop and the associated research, there were *known unknowns*: we did not–as a group–have a strong consensus about the efficiency of coupling to tsunamis from an oblique cavity-forming impact or whether the blast wave from an airburst could drive a damaging long-period wave. Whereas there is still some degree of uncertainty, we mostly agree that we now know the answer: there may be conditions under which dangerous waves can be generated by these mechanisms (*e.g.* airburst over very deep water or impact near shore) but the probability of such events is relatively small and they do not significantly contribute to the ensemble risk. With some further analysis, these contributions can be better quantified and will become *known knowns*.

Nevertheless, we would argue that we have identified a few more known unknowns, *i.e.* other potential coupling mechanisms that we have not sufficiently analyzed. These include: 1) The reaction force from ejection and collapse of the atmospheric plume which must (by Newton's 3rd Law) increase atmospheric pressure over a large area; 2) Powerful vortices in the air that propagate across the water at speeds that yield strong coupling by Proudman resonance and/or wind; 3) Steam blowoff over large area by thermal radiative coupling and convective ablation of a surface water layer over a large area. These are known physical processes and in some cases are robustly confirmed by hydrocode models over large ranges of assumptions and parameter space, but have not been sufficiently studied or quantified so their contribution to the risk remains unknown and has not been eliminated.

The philosophy applied to other elements of planetary defense is to focus effort on eliminating uncertainty that might contribute to aleatory risk. When an asteroid is discovered that has some nonzero assessed probability of impact, resources are applied toward follow-up observations and pre-discovery images are sought–even when it is exceptionally unlikely that this will do anything other than eliminate the risk. The "search and destroy" method of Milani et al. [13] is a clever and elegant application of this method: if it can be shown that the worst-case scenario (a "virtual impactor") does not exist for a potentially-hazardous asteroid, then its contribution to the risk can be retired *even when its actual position remains uncertain*. If an object has an uncertain orbital solution that includes the possibility of an Earth impact, it is not necessary to re-find the object and compute a better orbit. Is far simpler and more efficient to take a one very deep image of the location the impactor would occupy if it were on a collision course. If it's not there, then recovery is not required. If it *is* there, then resources can be marshaled to characterize it and begin planning for mitigation.

A consistent approach to epistemic uncertainty would be to prioritize possible worst-case scenarios. If we show that even the most extreme, contrived case with the most generously pessimistic assumptions (burst height, ocean depth, etc.) will not form a dangerous tsunami that propagates long distances, then we will have eliminated this component of the risk. If, on the other hand, we find cases that do form dangerous tsunamis, we can begin to use more realistic assumptions to quantify the associated risk with ensemble simulations.

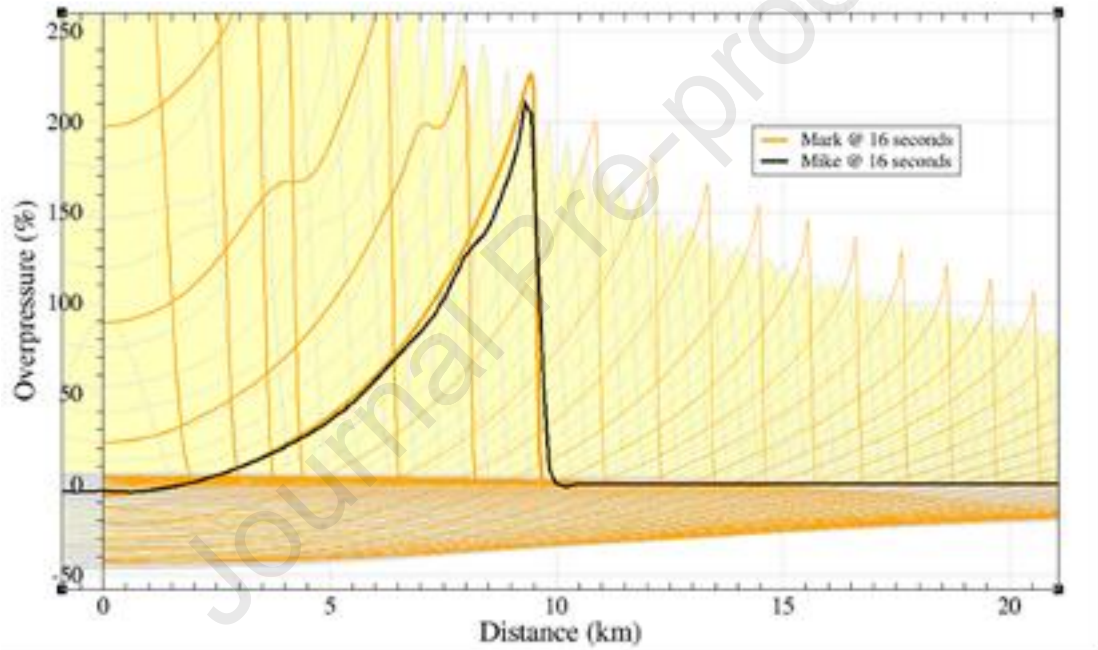

Fig. 4. The workshop included inter-code comparison studies such as wave profiles from a 250 Mt explosion at an altitude of 10 km run by Mark Boslough and Michael Aftosmis. The differences are too small to have a significant effect on the resulting tsunami. This figure was created by Michael Aftosmis.

David Morrison wrote a summary of all three sessions [14]. The following excerpts are relevant to the topic of this paper.

"The workshop resulted in a broad consensus that the asteroid impact tsunami threat is not as great as previously thought (as stated by the 2003 NASA Science Definition Team SDT Report), and that airburst events in particular are unlikely to produce significant damage by tsunami."

<u>Session 1: Tsunami Creation (Airburst and Direct Impact)</u>

"The speakers agreed that for both airbursts over water and water impacts with energies of 5 MT, 100 MT, and 250 MT, the resulting waves would not travel long distances. For a given energy, airbursts were less effective in generating waves, but in both cases, the waves formed are essentially circular (unlike a typical seismic tsunami) and dissipate rapidly due to the localized nature of the source and the turbulence of the wave. Local damage from impacts into the water may be similar to the cases of landslides into fjords, but these disturbances do not travel far. The potential for severe damage from asteroid generated tsunami over the energy range studied is therefore limited to impacts near the shore, and even in these cases the air blast, fireball, and possible ejection of sediment in shallow water areas may exceed the damage from the wave."

"While there may be conditions under which dangerous waves can be generated (e.g. airburst over very deep water or impact very near shore), the probability of such events is relatively small and therefore they do not significantly contribute to the ensemble hazard. There was a solid consensus among the workshop attendees that impact far from shore of asteroids <250m do not endanger coastal populations and infrastructure, and that the 2003 SDT report substantially overestimated the hazard from ocean impacts."

Session 2: Tsunami Propagation

"These models showed that the shorter wavelength waves produced from asteroid airburst or surface impact do not travel for great distances and that they also produce less inundation and flooding when they reach the shore. For these waves, the wave height is not a good measure of the potential damage; we must consider how much water is actually moving. The panelists found it very difficult to produce major inundations even with large (250 MT) airbursts near shore."

Session 3: Tsunami Hazard and Risk

"Titov and LeVeque described inundation model results from AGT or seismic events, respectively. Titov showed that very large (250 MT) airburst events could, in some cases, lead to significant inundation at isolated locations even hundreds of km from the airburst due to wave focusing effects. Leveque demonstrated the effectiveness of GeoClaw for modeling inundation from seismic events, but did not explicitly model the kind of waves produced from asteroid impacts."

"Wheeler and Mathias presented perspectives on the ensemble risk based on NASA Ames "engineering models". Mathias concluded that the current assessment of the AGT hazard is substantially reduced relative to the best understanding from a decade ago. He noted that the modeling results presented earlier in the workshop consistently showed less efficient coupling of the impactor energy into wave production, and lower damage from short-wavelength waves. The ensemble hazard assessment concluded: (1) The impact tsunami hazard is negligible for asteroid diameters below 200 m. (2) For asteroids larger than about 300 m, the hazard peaks at about an order of magnitude lower casualty rate than the land impacts. (3) Larger than about 500 m the global hazard (based on previous work) dominates over either land or ocean impact. (4) The average annual casualties from land and ocean impacts (not including global effects) are in the range of 1-10."

Workshop conclusions and recommendations

"Airbursts over water do not generate substantial tsunami-like waves. The waves generated by water impacts are quite different from seismic tsunami, having shorter wavelength and higher turbulent dissipation. There was a broad consensus that the tsunami threat is not as great as previously thought… but there are variations in the degree of confidence among the participants because of the limited number of cases that were modeled and the possibility that we have missed something important."

"In the case of airbursts and surface impacts from objects less than about 250 m diameter, most damage to coastal populations is limited to impacts close to the shore, in which case the direct blast damage may be more important than the wave generated. Detailed evaluation of the inundation is highly dependent on the near-shore bathymetry and shore configuration; these effects generally require higher resolution models than those used in the workshop. The risk from near-shore impacts may be important for considering individual cases, but they do not contribute significantly to the ensemble hazard."

2017 IAA PLANETARY DEFENSE CONFERENCE

In an attempt to address the large epistemic uncertainties that remained unresolved after the 2016 workshop, Boslough and Titov [15] ran new simulations to assess various coupling mechanisms. They addressed coupling through the atmosphere by 1) blast wave and rarefaction, 2) expanding toroidal vortices, and 3) plume ejection and collapse. Smaller airburst coupling mechanisms (plume ejection, steam explosion, & toroidal vortices) were not eliminated, but because the associated pressure disturbances are far from resonance (the Froude number is either much larger or smaller than unity) they are not efficient. On the other hand, the rarefaction or "suction" phase that follows a blast wave was found to be much more efficient at coupling than the compression wave because it has a much longer period and more time to couple energy to a nascent tsunami wave even if it is out of resonance. This finding suggested that despite the consensus of the 2016 workshop attendees, air-driven impact and airburst tsunamis may be significant contributors to overall risk and still needed to be quantified.

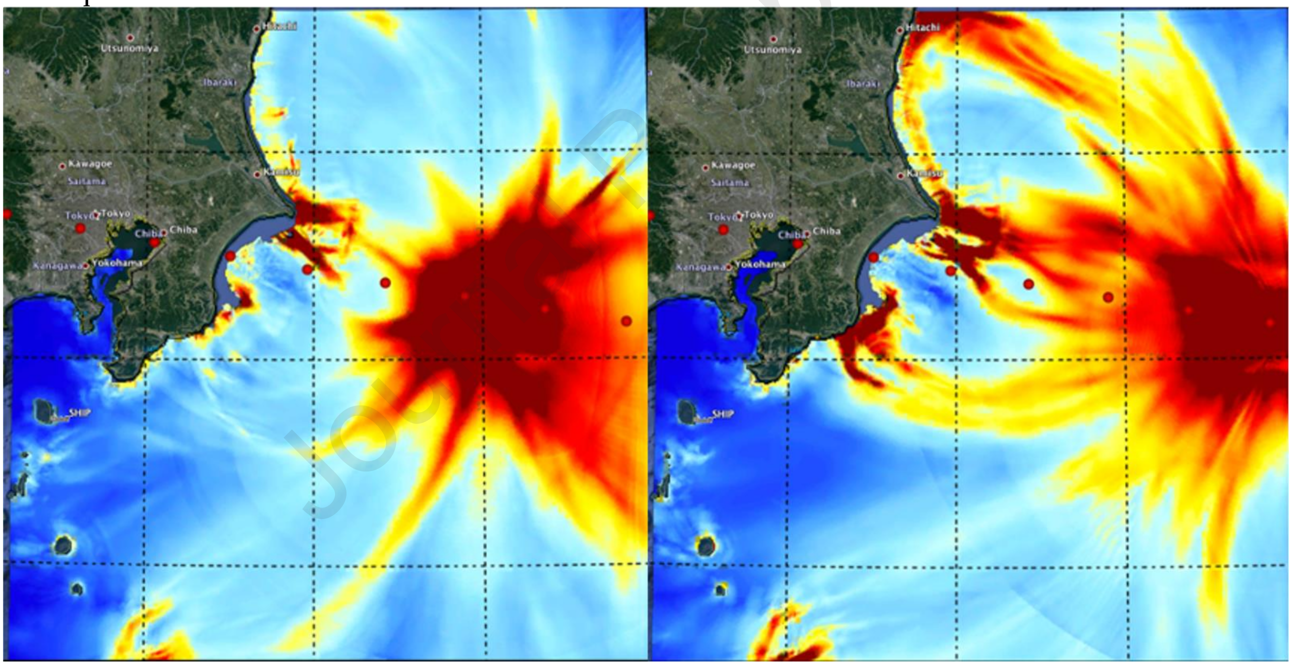

Fig. 5. Boslough and Titov (2017) simulations of the air-coupled tsunami from an ocean impact of the separated satellite of hypothetical asteroid 2017 PDC. Colors indicate maximum wave heights, which depend on bathymetry. Coupling is strongest in the deepest waters where the Froude number is closer to unity. Left: Impact on the shore side of the Japan Trench. Max wave height at shore = 25 m. Right: Impact on the offshore side of the Japan Trench. Max wave height at shore = 29 m.

CONCLUSIONS

Prior to the violent explosion of the Hunga-Tonga Hunga-Ha'apai volcano on January 15, 2022, and the observation of Lamb wave forcing of tsunamis around the globe, the planetary defense community had made significant progress in understanding and quantifying air-driven tsunamis generated by impacts and airbursts. By the time of the 2017 Planetary Defense Conference, there was no strong consensus for how much this phenomenon contributed to the overall risk and the community recognized that there was significant epistemic uncertainty associated with lack of knowledge about various ways impacts and airbursts can generate atmospheric waves, and how those waves can drive dangerous tsunamis. We now know from the Tonga explosion that Lamb waves are much more efficient at coupling energy to tsunamis around the world and that these waves are likely to have a much larger contribution to the risk that we previously thought. This is discussed in another paper in preparation [3] and will be the subject of our future work.

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HIGHLIGHTS

- The 2022 Tonga eruption confirmed that explosions can produce air-driven tsunamis
- Lamb waves from large explosions are one way to generate and drive global tsunamis
- Airbursts from comets and asteroids can produce tsunamis by atmospheric coupling
- Several mechanisms are proposed for air-driven tsunami generation and amplification
- Impact plume collapse, vortices, and steam blowoff are hypothetical tsunami sources

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I have no conflicts of interest to declare.