AIR-DRIVEN TSUNAMIS FROM IMPACTS AND AIRBURSTS: IS THERE EVIDENCE IN THE GEOLOGICAL RECORD?

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Introduction: Much of our understanding of the risk from near-Earth objects comes from the geological 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. We suggest that paleo tsunami deposits might be the only evidence in the geological record of past airbursts and ocean impacts that left no other mark, and that it might be possible to test this hypothesis by linking such deposits to known impact structures or explosive volcanic eruptions.

Air-coupled 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. The strongest and most destructive meteotsunamis are generated by atmospheric pressure oscillations with amplitudes of only a few hPa (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 $\boxed{\sqrt{gh}}$ of a 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 than for a weather front. However, blast wave profiles are N-waves in which a 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 continues 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.

Prior to the January 15, 2022 explosive eruption of Hunga-Tonga Hunga-Ha'apai, the understanding of within the planetary defense community was that the mechanisms for air-driven tsunamis only acted in the vicinity of the impact or airburst, because the pressure and wind disturbances created by the blast wave or other suggested mechanisms (e.g. plume ejection and collapse, steam blowoff, expanding toroidal vortices) decayed rapidly with distance from ground zero, and none of these disturbances propagated at the resonant velocity except under rare conditions [1]. However, the Tonga eruption was powerful enough to generate a Lamb wave that extended to the top of the atmosphere, propagated at resonant or near-resonant speed in deep water, had a long period that allowed it to drive tsunami waves over a long fetch, and decayed so slowly that it traversed the entire globe multiple times. Tsunamis were observed in other ocean basins separated by continents (e.g. the Caribbean) and could only have been driven by atmospheric disturbances.

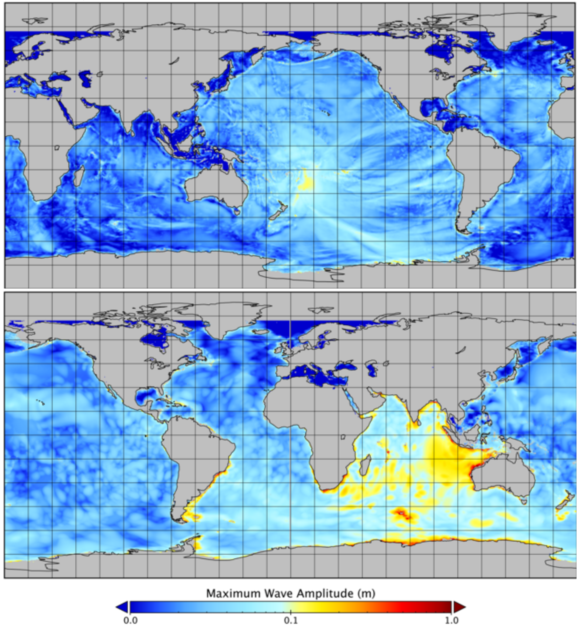

Figure 1: Maps of calculated peak tsunami amplitudes from two volcanic events: 2022 Tonga explosion (top) and 1883 Krakatau explosion (bottom). Similar maps can be generated for Lamb-wave coupled tsunamis generated by known impact or airburst events such as Meteor Crater or Tunguska.

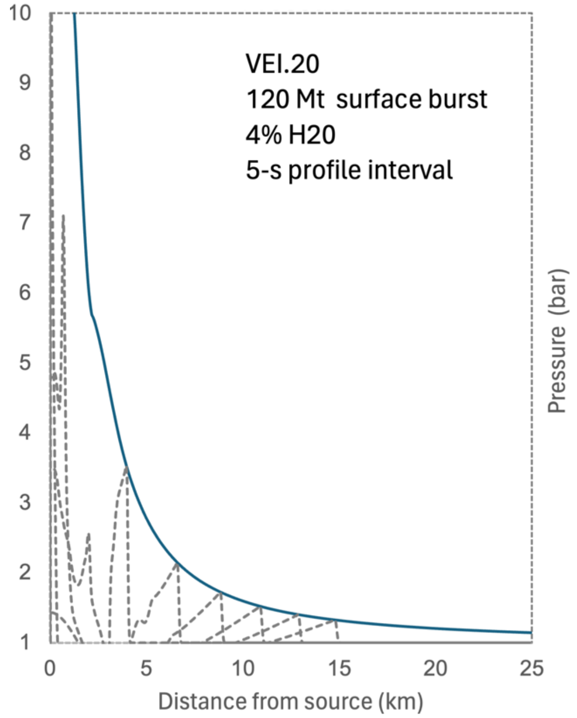

Figure 2: Shock waves (dashed) and peak pressure envelope (solid) generated by explosion of magma with 4% water.

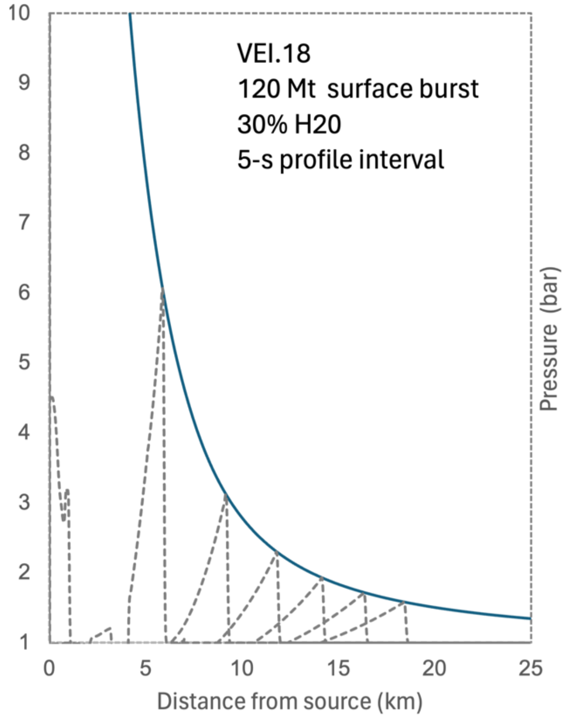

Figure 3: Shock waves (dashed) and peak pressure envelope (solid) generated by explosion of magma with 30% water.

Global Lamb-wave tsunamis: We have run simulations of tsunamis driven by Lamb waves generated by various explosive sources at various geographic locations, including volcanic eruptions, airbursts, and impacts. We used the CTH hydrocode to model the scenarios and to scale the resulting Lamb wave to generate time dependent boundary conditions as input to shallow-water wave propagation codes. Sources of include volcanos (Tonga, Krakatau, Laacher See, and Toba) and impacts (the hypothetical 2023 PDC asteroid). Because global Lamb Waves can be generated by sources that are nowhere near the ocean, tsunamis can result from crater-forming impacts and airbursts over land. Simulations of potential tsunamis from Meteor Crater and Tunguska are underway. Figure 1 shows calculated maps of the peak tsunami amplitudes resulting from the Tonga and Krakatau explosions.

Explosive coupling efficiency: Our preliminary simulations have shown, as expected, that volatile content of a volcanic magma or impact target rocks govern the efficiency by which the explosion transfers energy to the Lamb wave. For a given explosive yield, atmospheric wave amplitudes increase with water content of a magma (Figures 2 & 3). We expect that the Lamb wave from Meteor Crater would have high coupling efficiency due to carbonate-rich Kaibab Limestone and water-saturated Coconino Sandstone, and would therefore yield larger tsunamis than an impact of the same magnitude into target rocks that are volatile poor.

Global tsunami fingerprints: We suggest that this hypothesis can be tested by performing tsunami simulations for recent (Quaternary) known large explosive events (both impact and volcanic) in the geological record with known timing and source locations, and generating maps of peak tsunami amplitudes around the world. These maps will reveal the likely locations and ages of Lamb-wave coupled tsunami deposits from these events, which would provide confirming evidence for the hypothesis if found at the predicted locations with the right ages.

Acknowledgments: Mark Boslough's portion of this work was supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

References: [1] Boslough, M. B. and Titov, V. (2024) *Acta Astronautica*, 222, 641-646.