High-Fidelity Modeling of Asteroid Ocean Impacts:
Understanding Tsunamis Generation and Atmospheric Responses

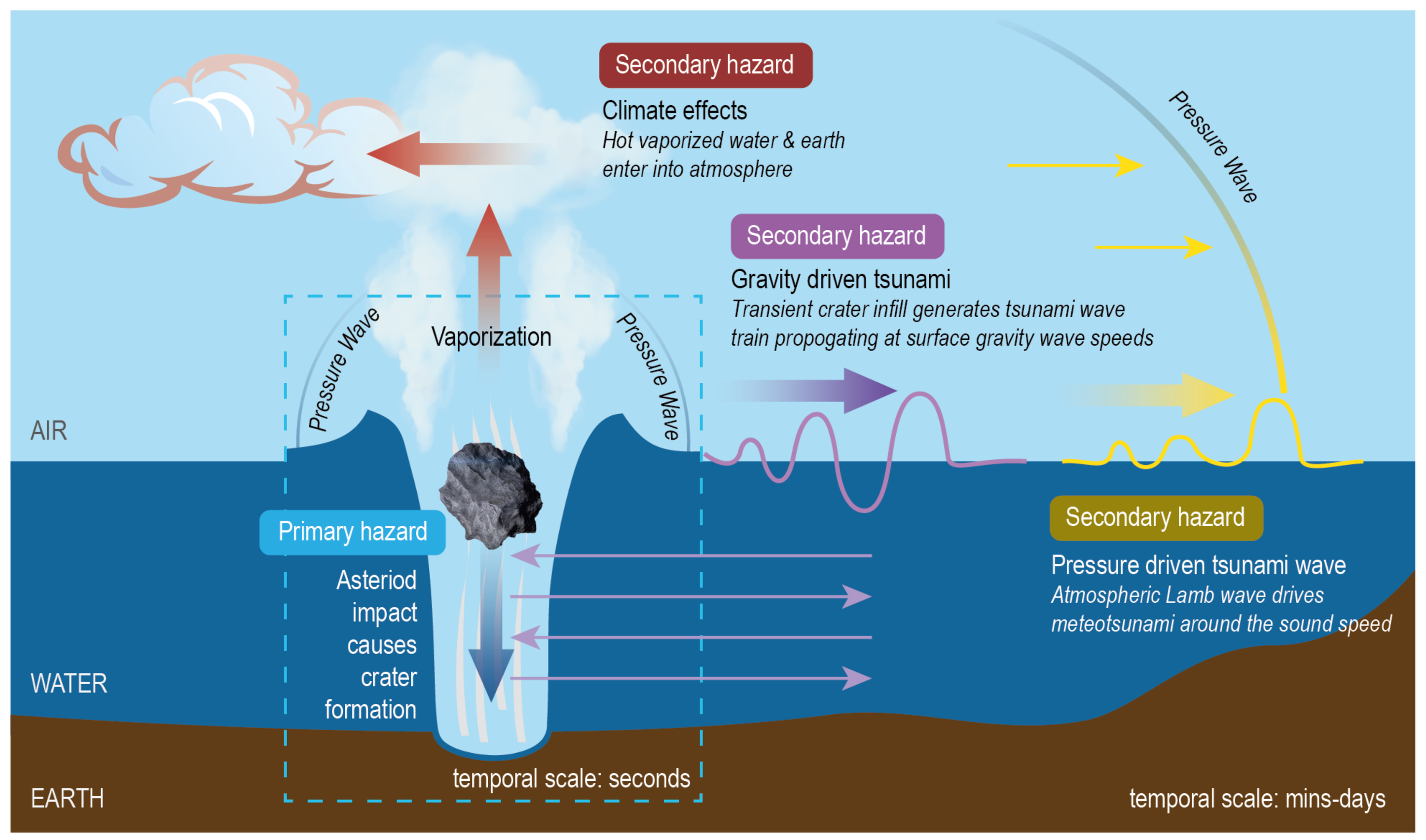
Lawrence Livermore National Laboratory

STRATEGIC DETERRENCE

Lauren S. Abrahams, Dana L. McGuffin, Betsy R. Seiffert, Megan Bruck Syal, and Donald D. Lucas
Lawrence Livermore National Laboratory (LLNL)

Capture hazard through linking models

Near Earth Objects (NEOs), such as asteroids on an Earth-impact trajectory, are low probability, high consequence natural hazards. This study focuses on numerical modeling of asteroid ocean impacts and the secondary hazards they generate, including tsunami wave generation and regional atmospheric effects.



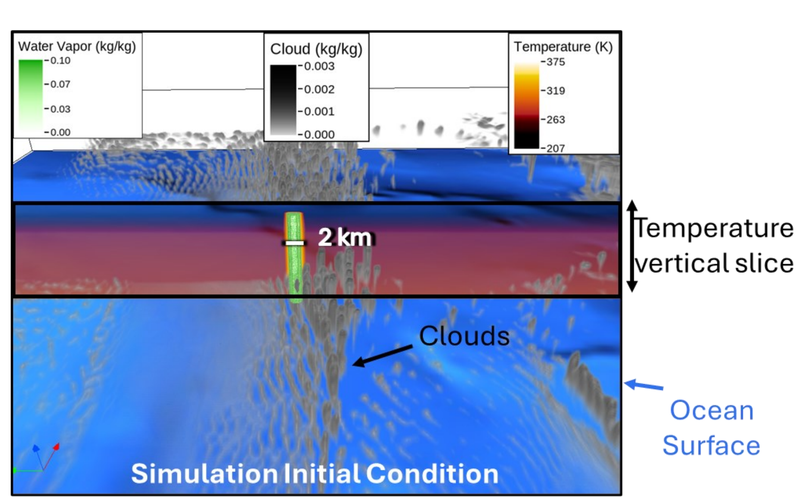
The goal of this work is to create a method for transferring local early time effects of an asteroid impact, computed with a high-fidelity hydrocode, to simulations that can model secondary hazards over extended timescales and distances.

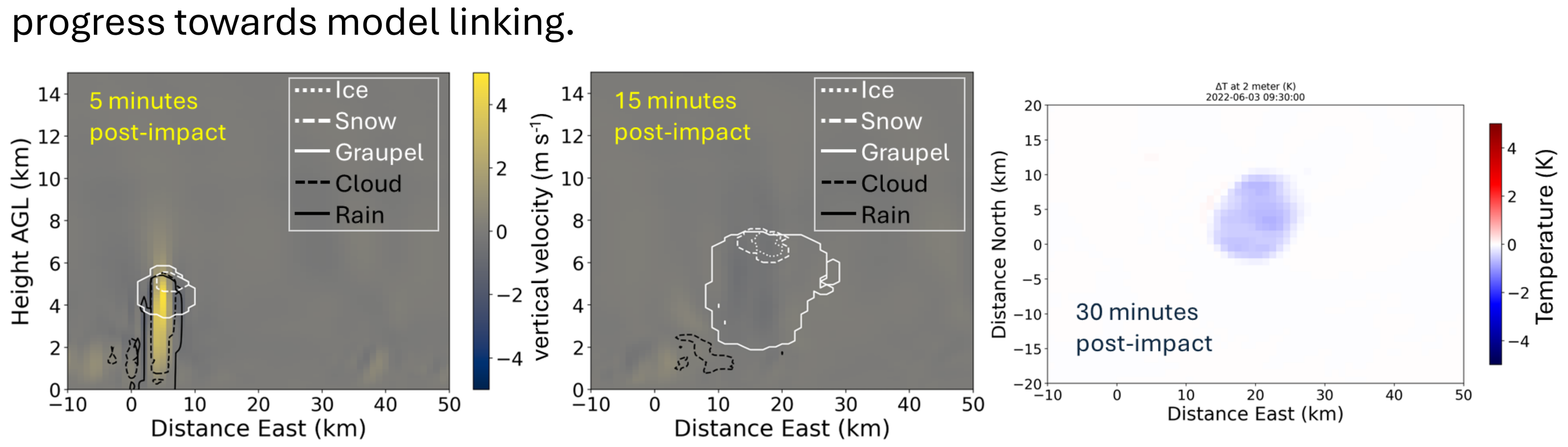
Primary Hazard	Gravity Driven Tsunami	Atmospheric Effects
ALE3D captures vaporization, crater formation, and pressure wave generation from an asteroid impacting the ocean	Tsunami wave generate as the transient crater infills, with gravity acting as a restoring force, short wavelengths perturbations form highly dispersive tsunami waves	Atmospheric effects are caused by the rise of vaporized seawater and earth particles into the atmosphere leading to local cooling and convection events.

Initial WRF findings with cylindrical vapor source

To model the atmospheric response to vaporized ocean water, we utilized the Weather Research & Forecasting Model (WRF) to capture the convection of the injected fluid and the associated local cooling effects.

In this study, we injected 7.8e5 kg of seawater, creating a vaporized cylindrical water column that is 2 km wide and 5 km high. These results provide preliminary insights into the effects of vapor as we progress towards model linking.

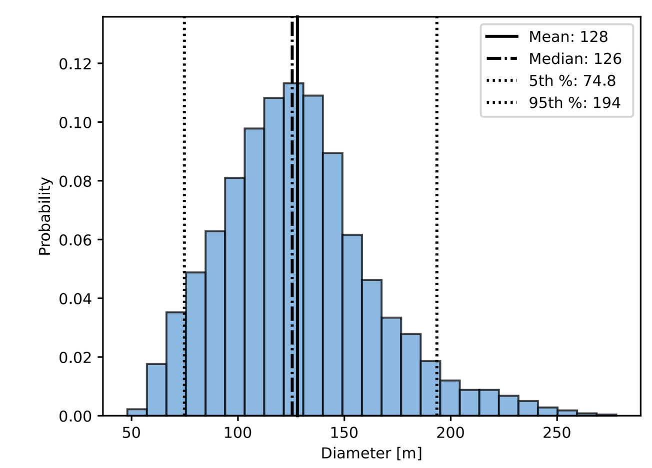




2025 Planetary Defense Conference hypothetical scenario

The parameters for the asteroids were selected to align with the hypothetical exercise. The range of values considers that, in a real-world scenario, asteroid sizes and physical properties would be determined through remote observations, which come with a significant uncertainty.

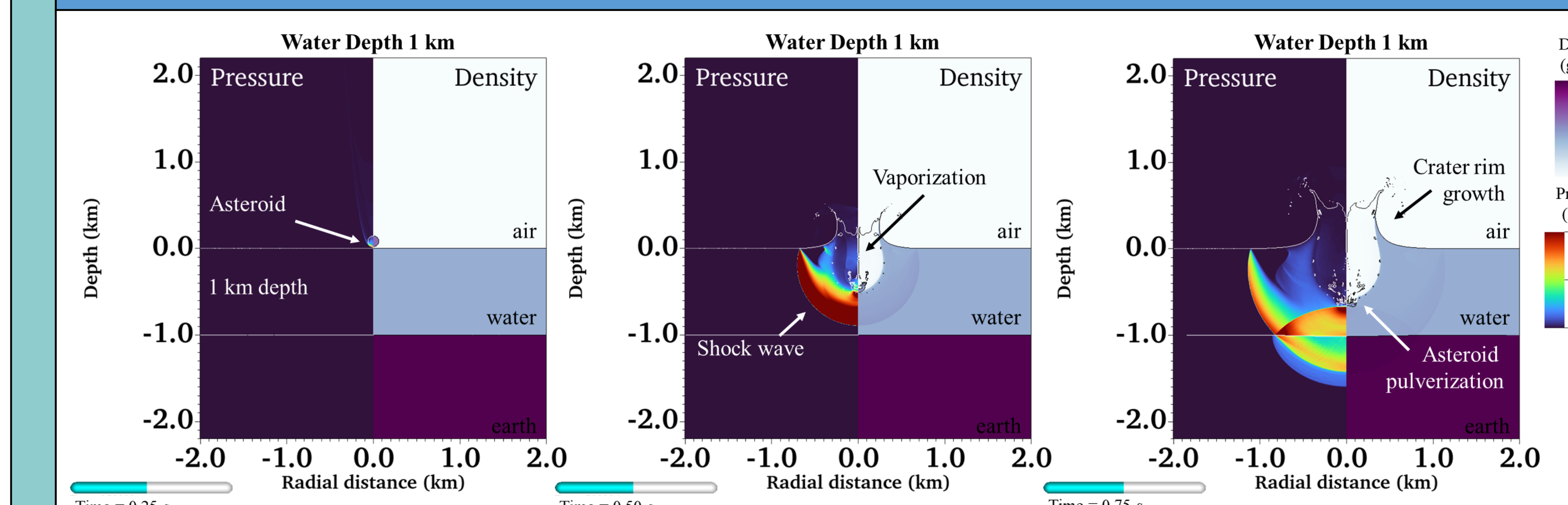
Stat	Diameter [m]	Mass [kg]	Energy [Mt TNT]
5%	75	4.52E+08	10
50%	126	2.22E+09	50
95%	194	8.84E+09	200



ALE3D: Initial Vaporization and Crater Formation

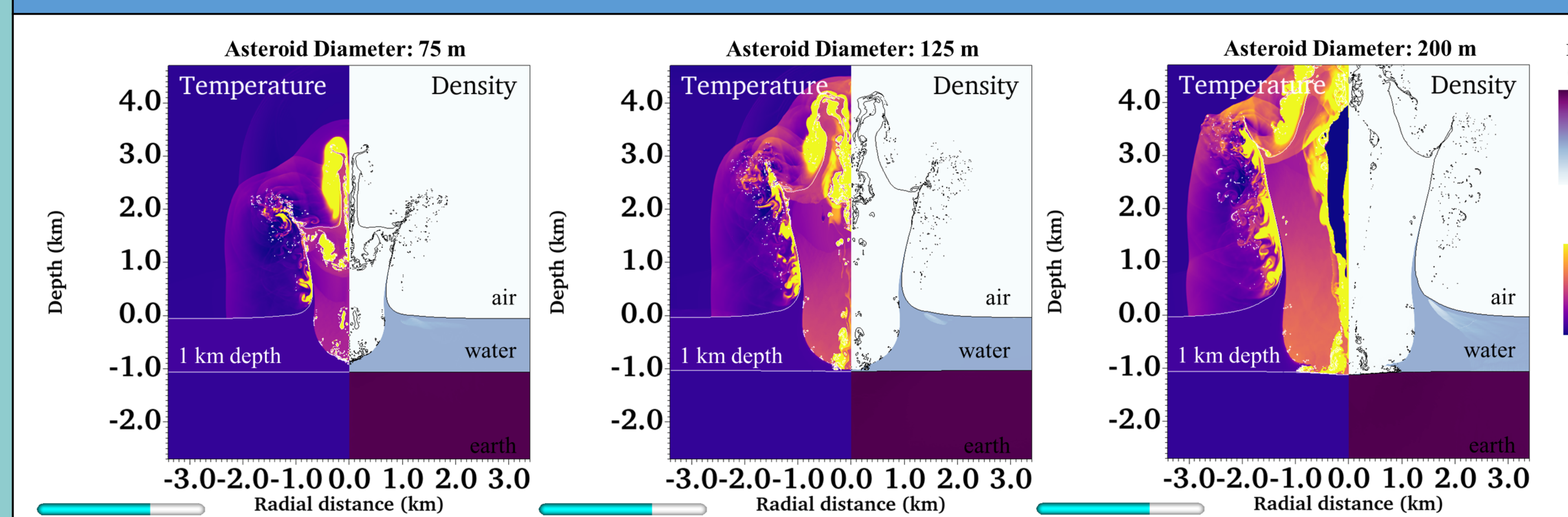
The modeling workflow includes linking high-fidelity hydrocode (ALE3D) simulations to atmospheric (WRF) and tsunami (FUNWAVE) models. ALE3D captures the initial impact dynamics, while WRF simulates atmospheric effects and FUNWAVE models tsunami wave generation and propagation.

Crater formation and vaporization



The hydrocode captures asteroid pulverization, water crater formation, vaporization, and conversion to wave energy on a refined domain capturing the evolution of the asteroid impact on a microsecond timescale.

Crater size dependence on asteroid diameter



Vaporized water and earth are injected into the atmosphere. This hypothetical scenario considers various potential asteroid sizes. Analyzing the 5%, 50%, and 95% size ranges aids in assessing the potential hazards

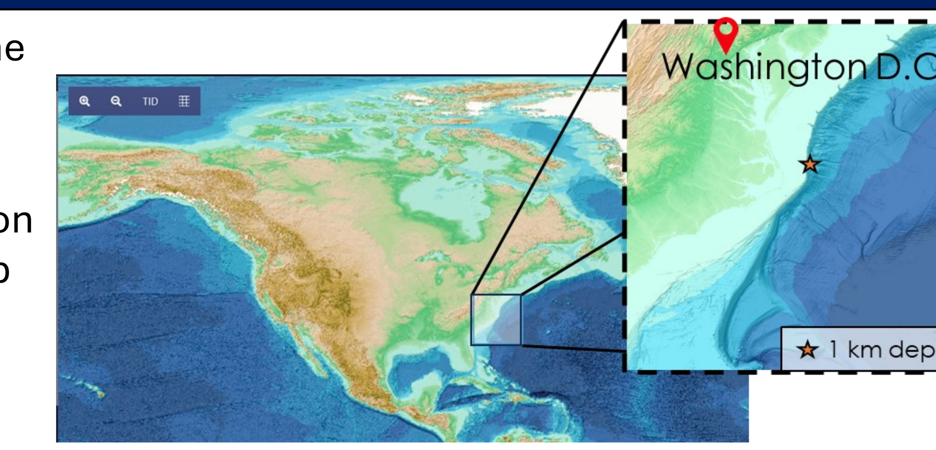
References

General Bathymetric Chart of the Oceans (GEBCO). 2021.
Shi, F., Kirby, J. T., Harris, J. C., Geiman, J. D., & Grilli, S. T. (2012). A high-order adaptive time-stepping TVD solver for Boussinesq modeling of breaking waves and coastal inundation. Ocean Modelling, 43, 36-51.
Wheeler, Dotson, Coates, Aftosmis, Stern, & Mathias (2025), Impact Risk Assessment: PDC25 Hypothetical Asteroid Impact Exercise, 9th IAA Planetary Defense Conference

Capturing tsunami propagation with Boussinesq solver

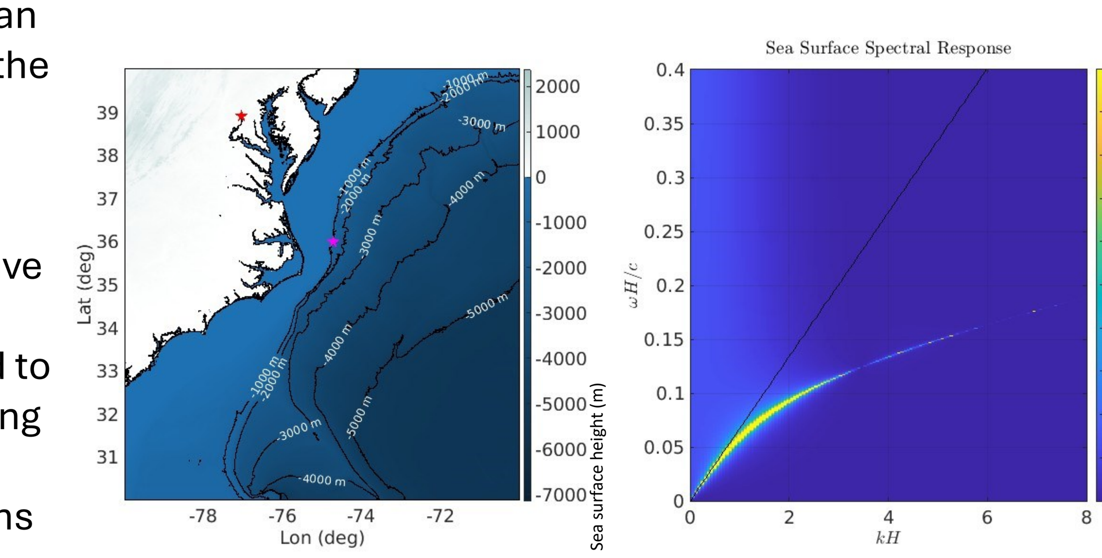
The simulation is handed off to the Nonlinear Boussinesq tsunami propagation model, FUNWAVE.

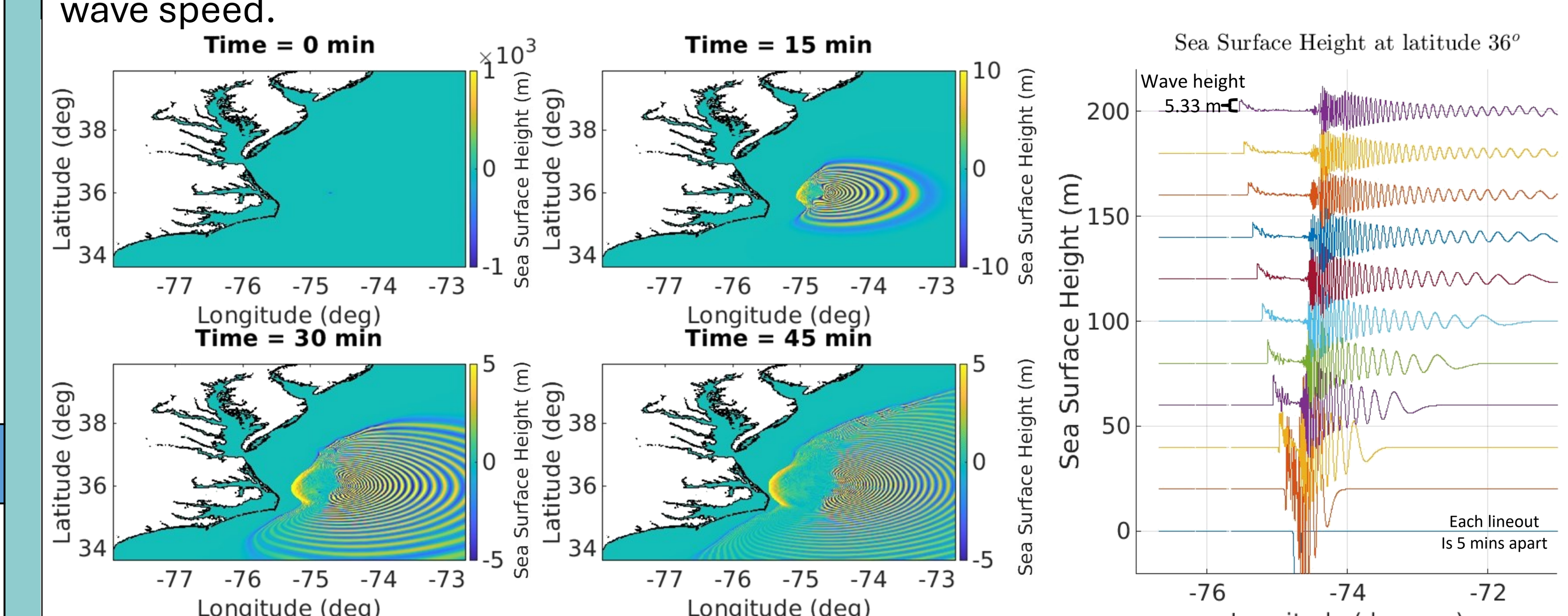
Here we model tsunami generation from a crater formed in 1 km deep water, examining tsunami propagation and runup.



Tsunami dispersive behavior

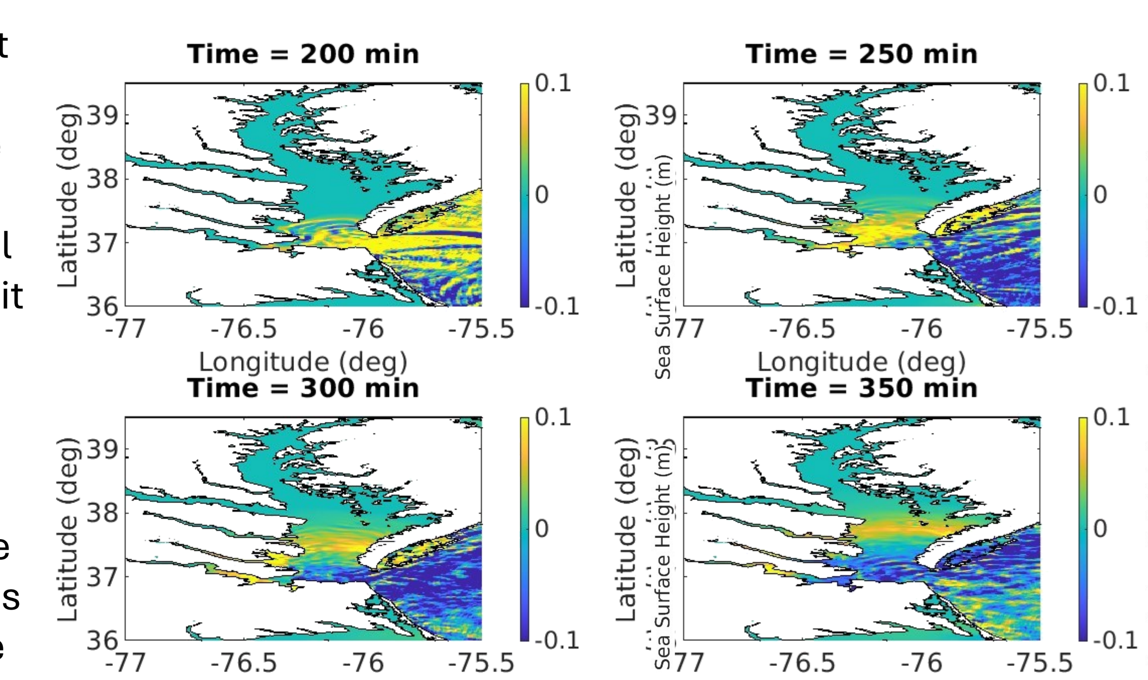
The collapse of the transient crater during an asteroid impact forms the initial wave train, generating a series of outward-propagating waves. These waves have relatively small wavelengths compared to ocean depth, highlighting their dispersive nature, where short wavelengths travel at slower speeds than the shallow water wave speed.





Inlet bay tsunami height

This view illustrates the tsunami wave as it propagates into the local bay. As the wave slows down, in shallower water, initial observations suggest it is unlikely to cause significant tsunami heights. However, further studies will be conducted to examine the wave's interactions at inlets and along the beach to better understand its potential impact.



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