Tsunami Generation, Consequences on Coastlines, and Potential Global Climate Effects due to Asteroids Impacting Earth’s Oceans

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Outline

- Motivation
- Numerical framework
- Background on entry & impacts
- Ocean impacts & consequences
- Conclusions

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Motivation: Near Earth Objects

Few asteroids were recognized in the inner solar system 100 years ago (~100s). Y2K, more than 90,000 asteroids have been identified (~1000s). 2010, more than 200,000 asteroids have been identified (10482, 11/29/13).

Physical characteristics of Apophis

- **Dimensions**: 325 ± 15 m
- **Mass**: $4 \times 10^{12}$ kg
- **Density**: ~3.2 g/cm³
- **Escape velocity**: ~0.52 km/h
- **Rotation period**: 30.4 h
- **Temperature**: 270 K
- **Orbital speed**: 30.73 km/s
Motivation:
Quantitative hazard assessment of NEOs impacts

Key buildings of Washington, D.C.
**LLNL Numerical Modeling Framework**

- Most tsunamis are generated by EQ or LS & there are several open-source SWW codes.
  
  Fully couple the source (asteroid impact), ocean wave propagation (flooding) and seismic propagation if asteroid impact the land or reaches ocean floor.

**Exercised different versions:**
- TTX 2013 Maryland (Semi-analytical solution)
- TTX 2014 Gulf of Mexico (Geodyn-2DSWW + Global Effects)
- TTX 2015 PDC Italy + NASA 1\textsuperscript{st} WS (Geodyn-2DSWW)
- 2\textsuperscript{nd} NASA’16 Workshop (Geodyn-2& 3D SWW, NLWW)
- TTX 2016 Los Angeles (Geodyn-3D NLWW, Global effects)
- TTX 2017 PDC Japan (Geodyn-3D NLWW, Global effects)
- TTX 2019 PDC Baltimore (Geodyn-3D NLWW, Global effects)
GEODYN-WWP is a state-of-the-art coupling for simulating asteroid impacts on ocean surfaces

- **Near-field (GEODYN)**
  - Non-linear processes
  - Time scale from micro-sec to 1 hour
  - Spatial scales from millimeters to ½ - 1km
    - ½ - 1 Billion cells
    - 10K CPUs x days HPC
    - 50 TB storage

- **Far-field (WWP)**
  - Linear processes
  - Time scale from ½hr - days
  - Spatial scales from meters to 1000s km
    - 10 – 100 Millions cells *(1/2-1 Billion for 3D)*
    - 1K-50K CPUs x hours HPC
    - 1 TB storage *(5TB for 3D)*

Coupling between GEODYN and WWP enables bridging the spatiotemporal scale disparities between the non-linear near-field and the linear far-field physics.
GEODYN suite of codes have been extensively used for asteroid mitigation studies

**GEODYN**: Massively parallel
- High-order Godunov scheme
- Shocks and large deformations
- Structured Eulerian grids
- Material interface tracking with interface reconstruction
- Adaptive Mesh Refinement
- Coupled to WPP

**MML**: Flexible material model library
- Analytic and tabular EOS
- Wide range of constitutive models
- Special attention to response of geophysical media
- Includes a variety of yield strength models

**WPP/SW4**: Massively parallel
- Elastic high order FD wave propagation
- Surface topography + refinement
- WPP is already coupled to GEODYN
- Acoustic solver of atmospheric conditions
Large asteroids usually breakdown during entry, however conditions may shield large chunks which may well impact earth
Water impact source generation using 3D GEODYN

Slice through 3D Geodyn numerical simulations of an asteroid impact on ocean surface. Physics include air and water; phase transformation, convection, mixing, and more…
“Crater” is too “big” more effective coupling. Compressible rim reaches the ocean bottom. Bottom stresses may be significant to be neglected. Depth average momentum is inappropriate. Direct coupling Hydrocode and WWP is critical.
PDC 2019 TTX vs. TTX 2016

- Assume 100, 200 & 300m diameters
- Density of 2g/ccm
- Trajectory is given
- East & West US coasts

Impact risk corridor was established by Paul Chodas from NASA for the PDC 2019 TTX
http://neo.jpl.nasa.gov/pdc19/2019pdc_mts.txt
The largest domain I have simulated for asteroid impacts – open ocean – deep/shallow waters

Bathymetry not very complex at far east, more challenging closer to USA East coast

Impact on US East coast and Canada and more…
PDC19 Scenario: Pacific patch – US West Coast

Impact on Hawaii and US west coastline
Hawai’ian Islands Water Wave Height Gauge Stations
West Coast Water Wave Height Gauge Stations
Examples of water wave propagation for 100m asteroid impacted at site #340
Examples of water wave propagation for 100m asteroid impacted at site #320
Examples of water wave propagation for 100m asteroid impacted at site #306
100 vs 200 vs 300 m diameter asteroid
Min & Max of Water Height along US East Coast

- FL/NC
- MD
- NJ
- NY
- CT
- RI
- MA
- NH
- ME

100m AST
200m AST
300m AST

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Min & Max of Water Height along US East Coast
Example of a Hazard Map based on a hypothetical threshold for 300m AST
Min & Max of Water Height along Hawai’i

[Graph showing water height variations along different Hawaiian islands, with stations marked at various points.]
Impact creates significant amount of water vapor

Slice through 3D numerical simulations of an asteroid impact on ocean surface. Physics include air and water; phase transformation, convection, mixing, and more...

Chemical SPECIATION

Only 15 to 25% of the energy is “impact” energy the rest is mainly used to a) vaporize the asteroid and ocean and b) create wind and shear wave.

Ocean depression

Rim breakup

Vapor

Salt water vapor dissociates into chlorine which reacts with oxygen and bromine and Destroys the stratospheric ozone

Water rims

Ocean
A 250m Diameter impactor over deep water section in Gulf of Mexico produces no significant effect

- NASA’s Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM)
- Source impact for a ~250 m object striking the Gulf of Mexico.
- Total Vaporized seawater - \( \sim 6 \times 10^{10} \) kg
  Additional products:  
  - HCl - \( \sim 1.2 \times 10^8 \) kg
  - HBr - \( \sim 1.8 \times 10^5 \) kg
  - NO - \( \sim 6 \times 10^7 \) kg
- Product amounts from Pierazzo et al. 2010
- Pierazzo showed significant impact on the stratospheric ozone layer from 0.5 – 1 km impactors,
A 400m Diameter Impactor over deep water section in Gulf of Mexico produces sizeable effects.

- Perturbation is ~2x the current background concentrations of Cl
- Smaller change in Br (30-50%) compared to Cl
- 15-30% change in stratospheric water vapor
- Less H$_2$O vapor in the troposphere up to 5-10%
- Changes in both stratospheric & tropospheric ozone: 10-15% decrease in the stratosphere
- Temp. decreases (1-3 K) in the stratosphere mostly responding to the ozone loss
A 400m Diameter Impactor over deep water section in Gulf of Mexico produces sizeable effects.
Changes in the Global signatures of Cl\textsubscript{v} (%), Br\textsubscript{v} (%), H\textsubscript{2}O(%), O\textsubscript{3}(%) & Temp (K)

We have also computed to changes w.r.t. Control North Hemisphere
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