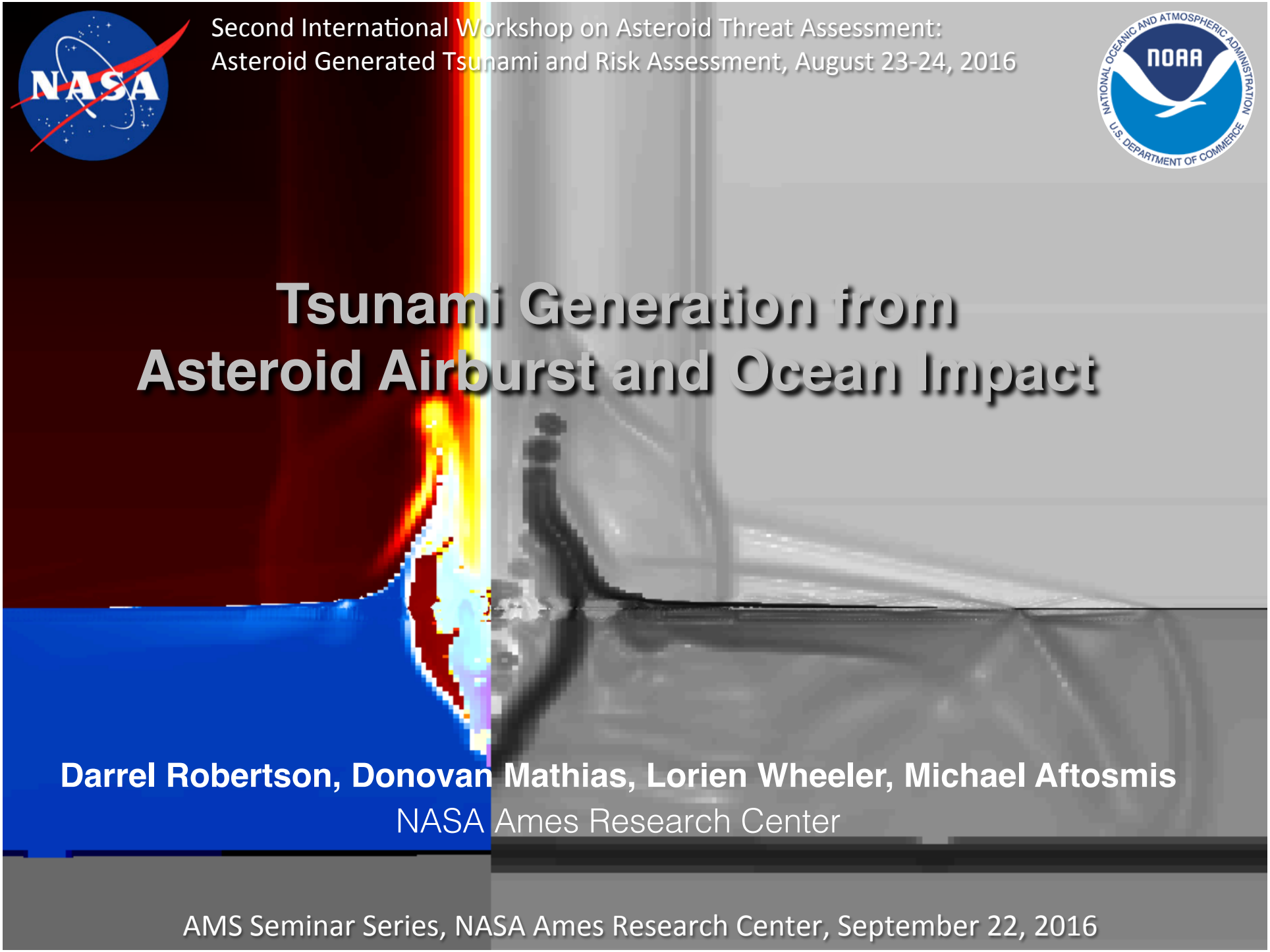


Second International Workshop on Asteroid Threat Assessment:
Asteroid Generated Tsunami and Risk Assessment, August 23-24, 2016

Tsunami Generation from Asteroid Airburst and Ocean Impact

Darrel Robertson, Donovan Mathias, Lorien Wheeler, Michael Aftosmis
NASA Ames Research Center

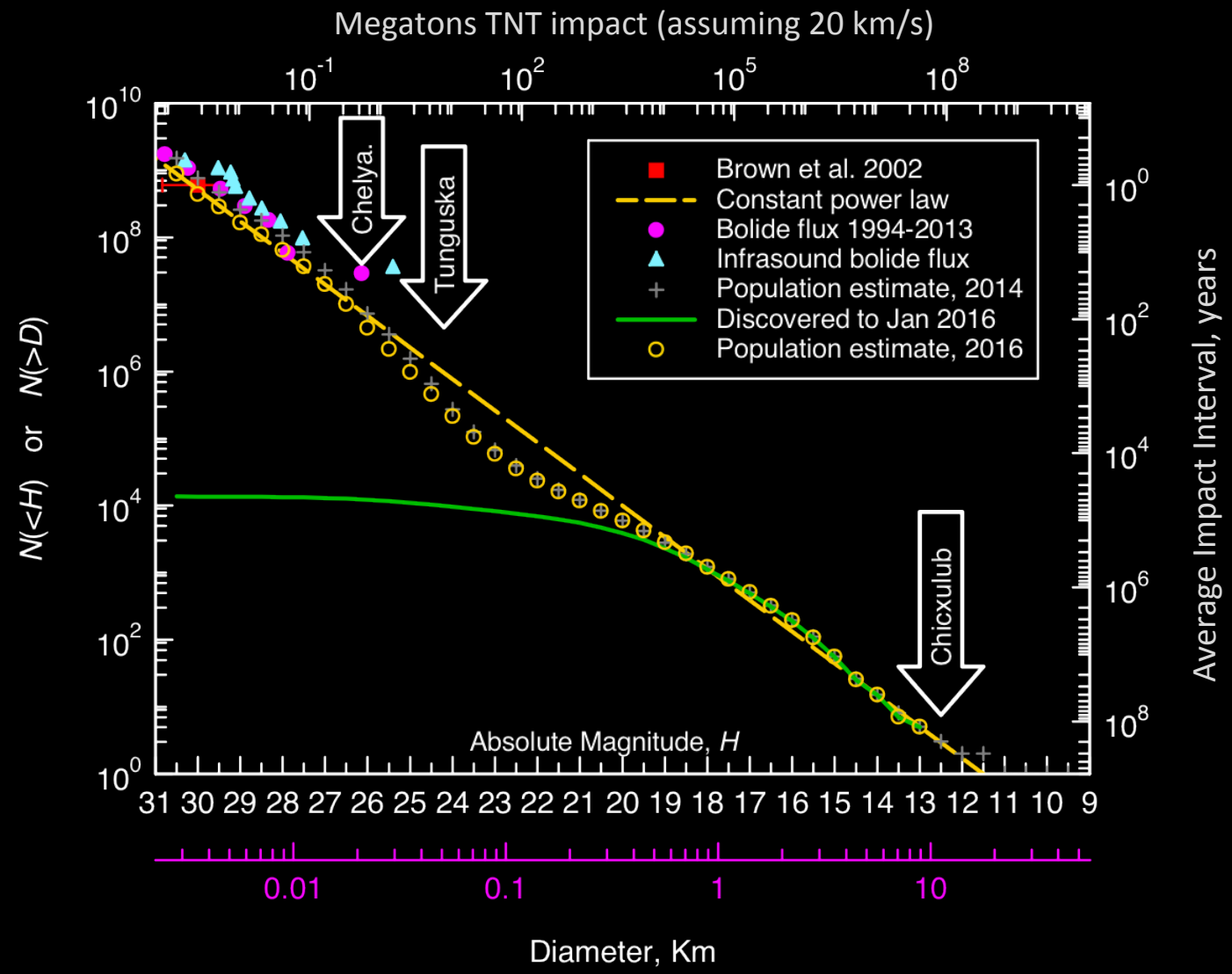
AMS Seminar Series, NASA Ames Research Center, September 22, 2016

Asteroid Defense

- What will hit us?
- When?
- How much damage will it do?
- What should we do about it?

Asteroid Lutetia (ESA flyby 2010) superimposed near Earth.

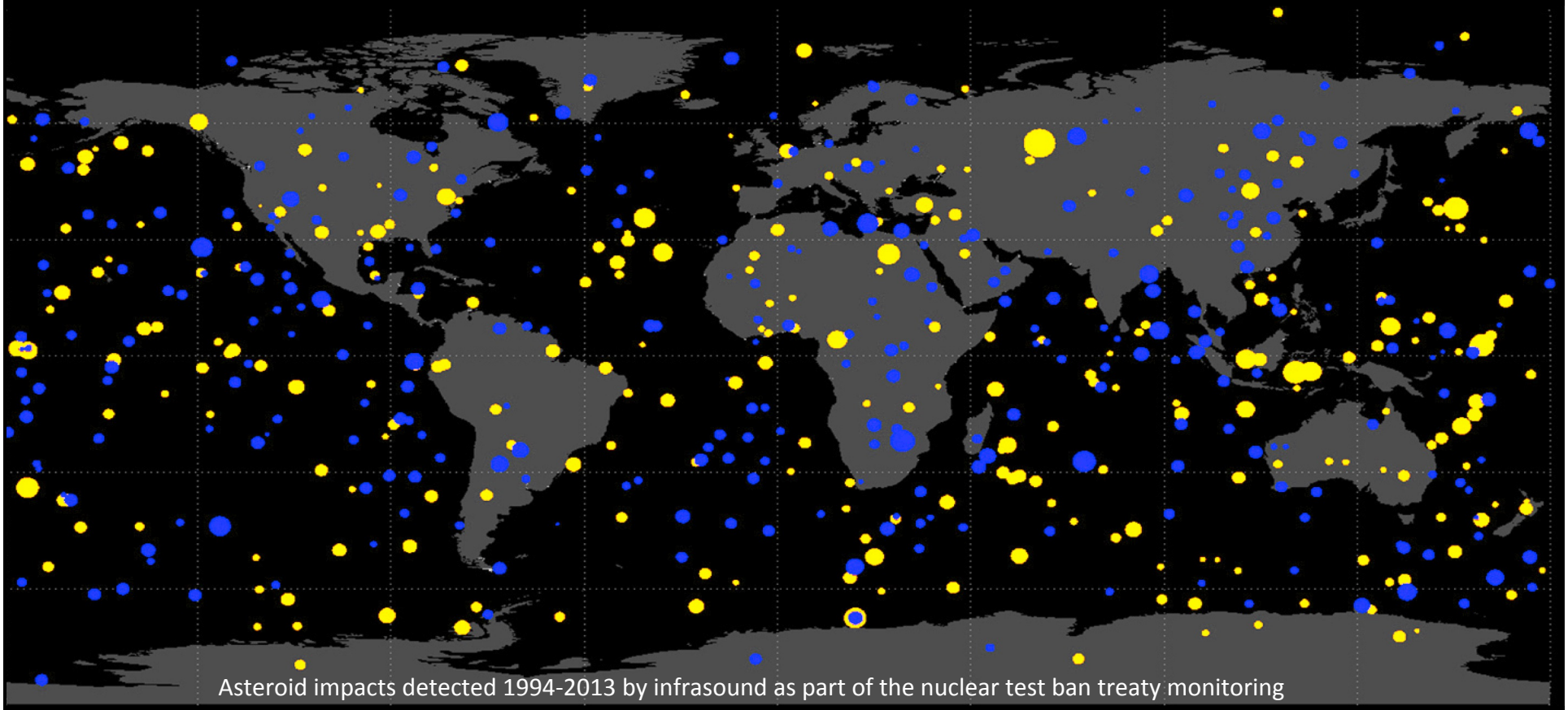
Asteroid Populations



Data from Al Harris, May 2016

D. Mathias. "Asteroid Threat Assessment", International Space Development Conference 2016, San Juan, Puerto Rico, May 21, 2016

Impact Frequencies



Asteroid impacts detected 1994-2013 by infrasound as part of the nuclear test ban treaty monitoring

Day (255) Night (301) Energy (GJ) 1 10 100 1000 10000 100000 1000000

Lightning bolt

Hoover Dam output in 1 minute

Hiroshima Nuclear Blast

Chelyabinsk Meteor

D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

Chelyabinsk, February 2013

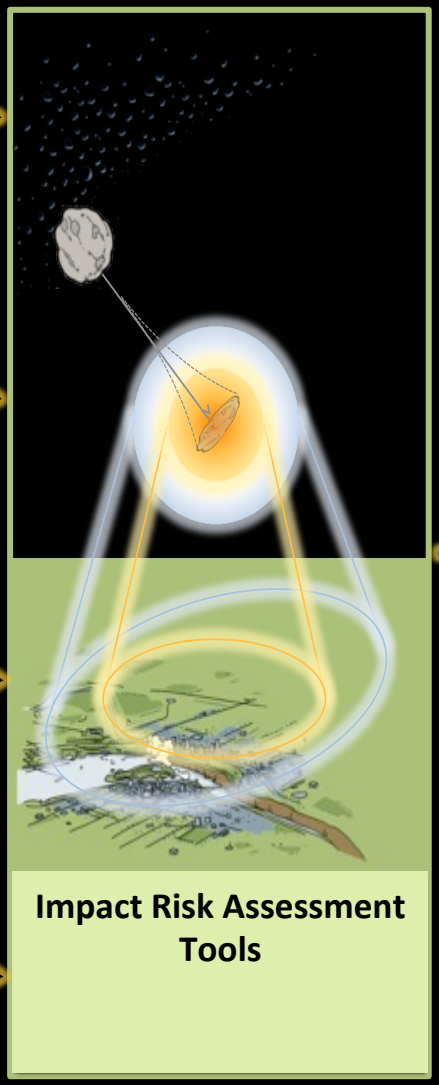
Asteroid Threat Assessment Project

Characterization
- Physical Properties
- Orbital Trajectories

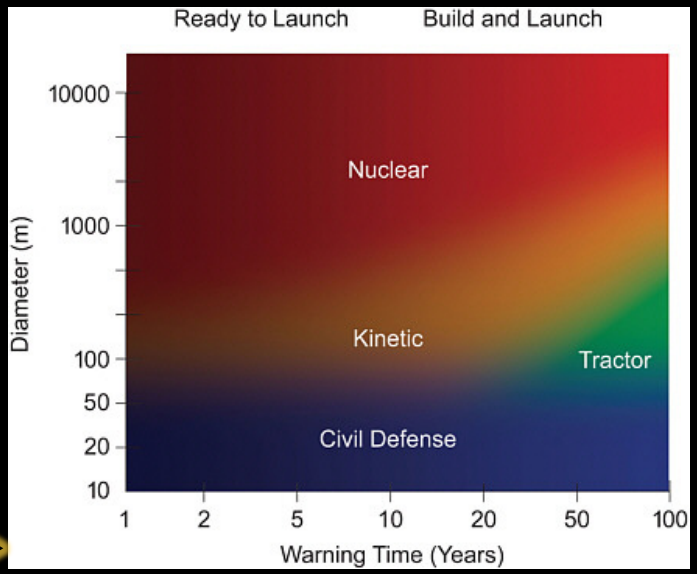
Atmospheric Entry & Airburst Modeling
- Entry Trajectories/Ablation
- Energy Deposition

Surface Impact Effects Modeling
- Ground Damage
- Tsunami Propagation

Physics-Based Impact Risk Modeling
- Quantitative Risk Metrics
- Sensitivity to Uncertainty



Impact Risk Assessment Tools



Credit: Tim Warchocki

Risk-Informed Decision Support
- Mitigation Planning
- Defense Strategies
- Response Decisions
- Policy Development

D. Mathias. "Asteroid Threat Assessment", International Space Development Conference 2016, San Juan, Puerto Rico, May 21, 2016

Physics-Based Impact Risk Model

Asteroid Characterization → **Input Parameter Distributions**

Monte Carlo Sampling

Initial Conditions

Flight Integration
(meteor equations of motion, ablation)

Airburst Altitude
(peak energy deposition)

Fragment-Cloud Model
(breakup and energy deposition)

PHA Measurements
- H-magnitude
- Albedo
- Orbital trajectory
- Asteroid class
- Composition

Impact Parameters
- Diameter
- Density
- Strength
- Luminous efficiency
- Velocity
- Entry angle
- Azimuth angle
- Impact coordinates

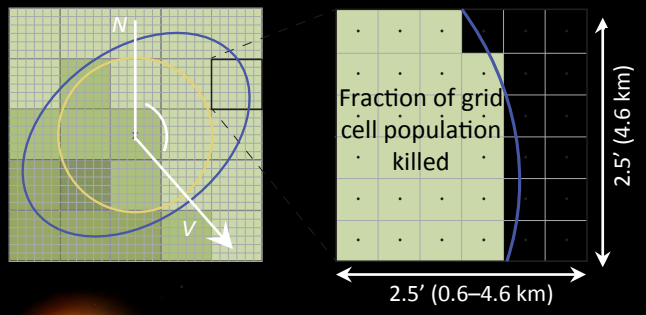
Blast and Radiation Propagation

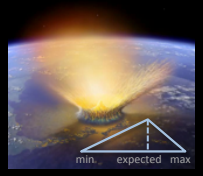
Thermal Damage
(3rd degree burns)

Impact Coordinates

Overpressure Damage
(Peak overpressure ≥ 4 psi)

Local Land Impact Casualties
(Gridded population within largest damage area)





Global Effects Casualties
(Percentage world population killed by climatic effects)

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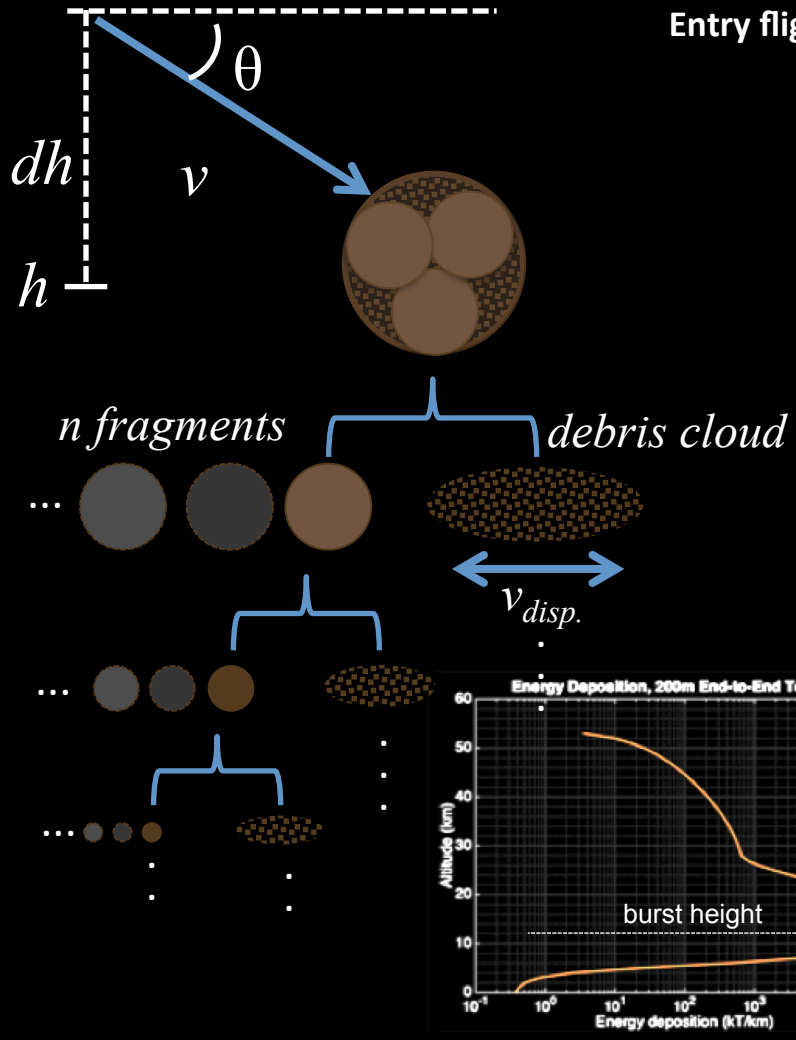
Analytical Modeling

- Analytic model of asteroid entry/breakup to estimate energy deposited in the atmosphere
- Combines progressive breakup of independent fragments and "pancaking" debris clouds.



Entry flight: integrates meteor equations of motion and ablation

$$dm/dt = -0.5\rho_{air}v^3A\sigma$$
$$dv/dt = \rho_{air}v^2AC_D/m - gsin\theta$$
$$d\theta/dt = (v/(R_E+h) - g/v)cos\theta$$
$$dh/dt = vsin\theta$$

Fragmentation when pressure > strength

$$\rho_{air}v^2 > strength$$

Each break yields:

- Multiple independent, identical fragments (baseline 2)
- Debris cloud of specified mass fraction (baseline 50%)

Fragment strengths increase with decreased size

$$S_2 = S_1(m_1/m_2)^{\alpha}$$

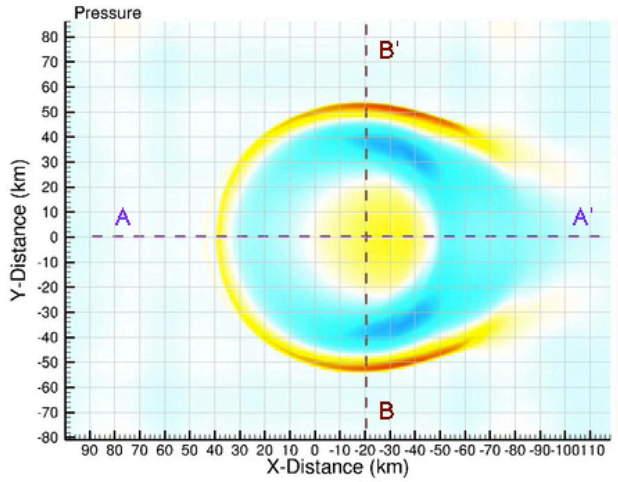
Clouds broaden and slow under common bow shock

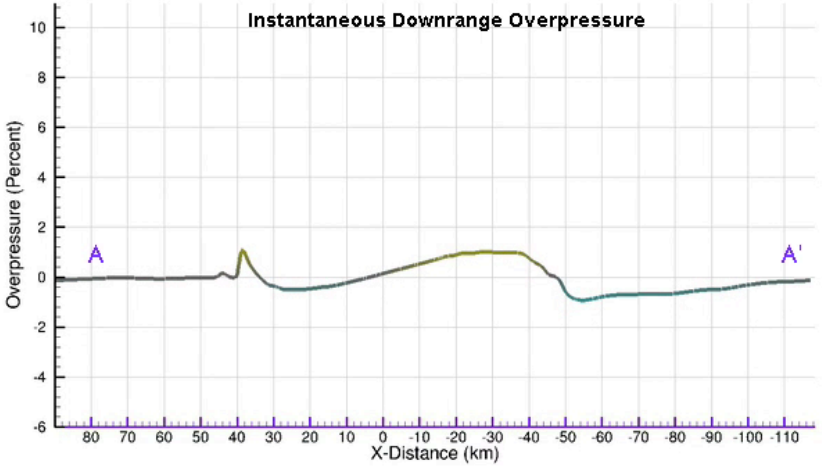
$$v_{dispersion} = v_{cloud}(3.5\rho_{air}A/\rho_{cloud})^{1/2}$$

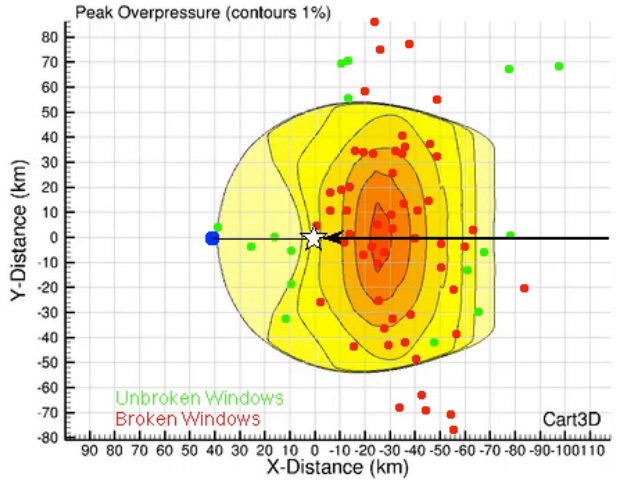
Energy deposition computed as change in total KE of all fragments/clouds as a function of altitude.

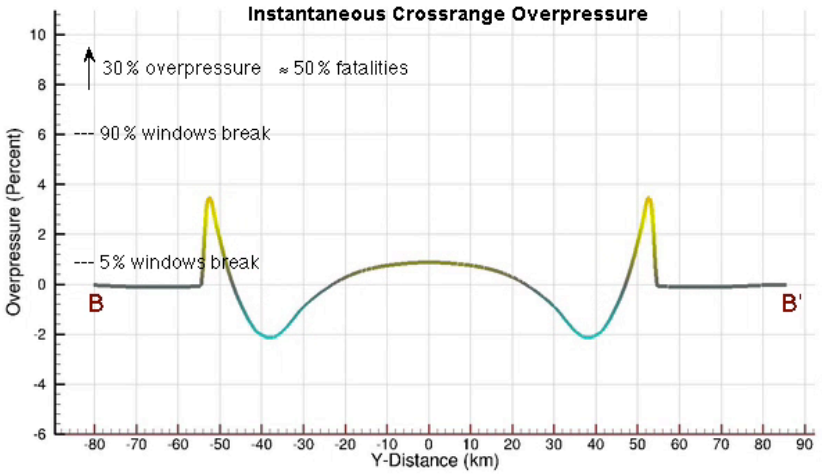
Airburst at altitude of peak energy deposition.

Blast Propagation and Damage









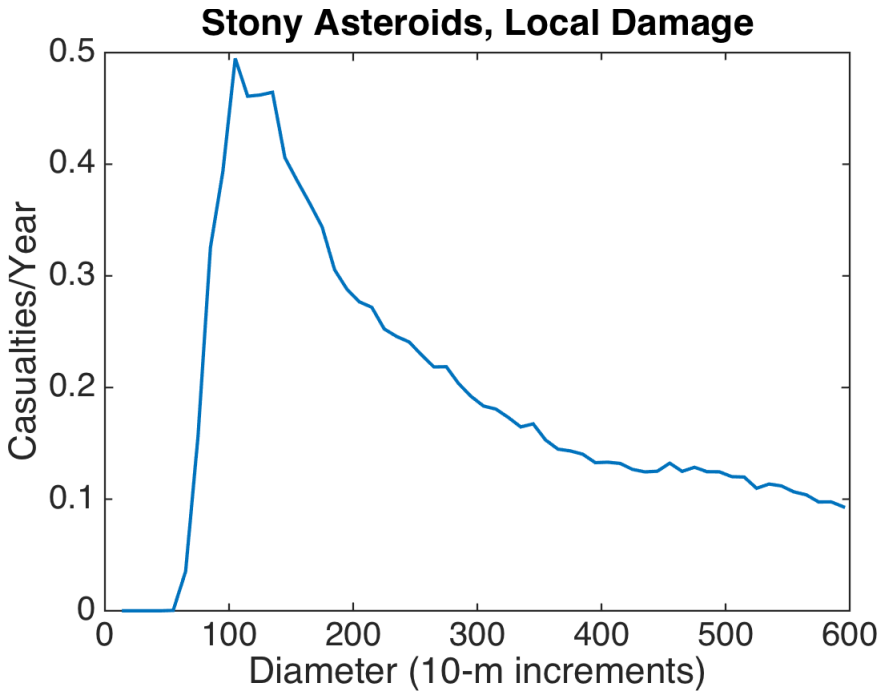
Credit: Michael Aftosmis

D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

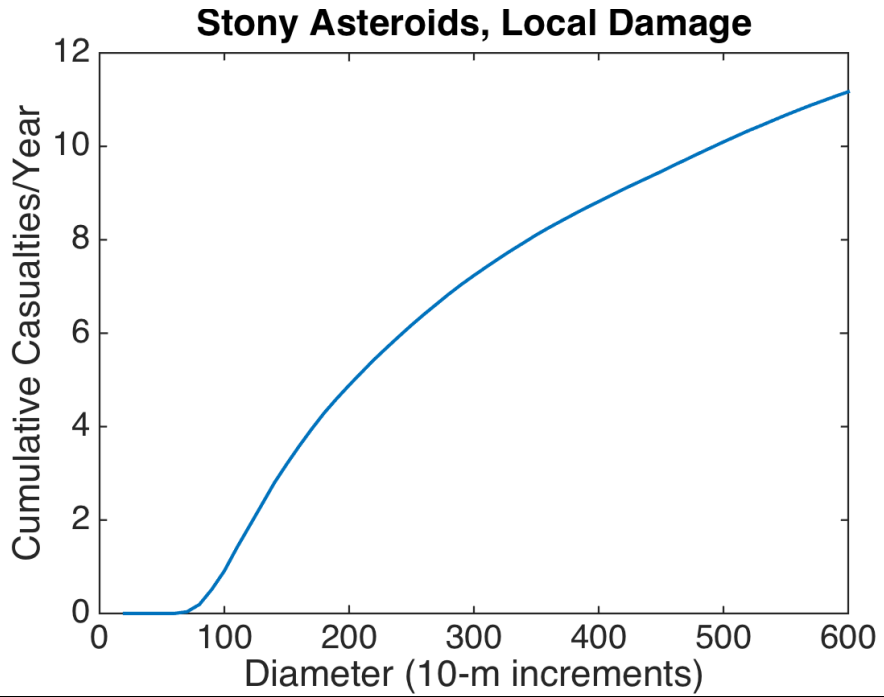
Average Casualties/Year

- Average potential casualties from impacts within a given size range, multiplied by the expected impact frequency/year of that size range.

Expected casualties for each given size range (changes with bin size)



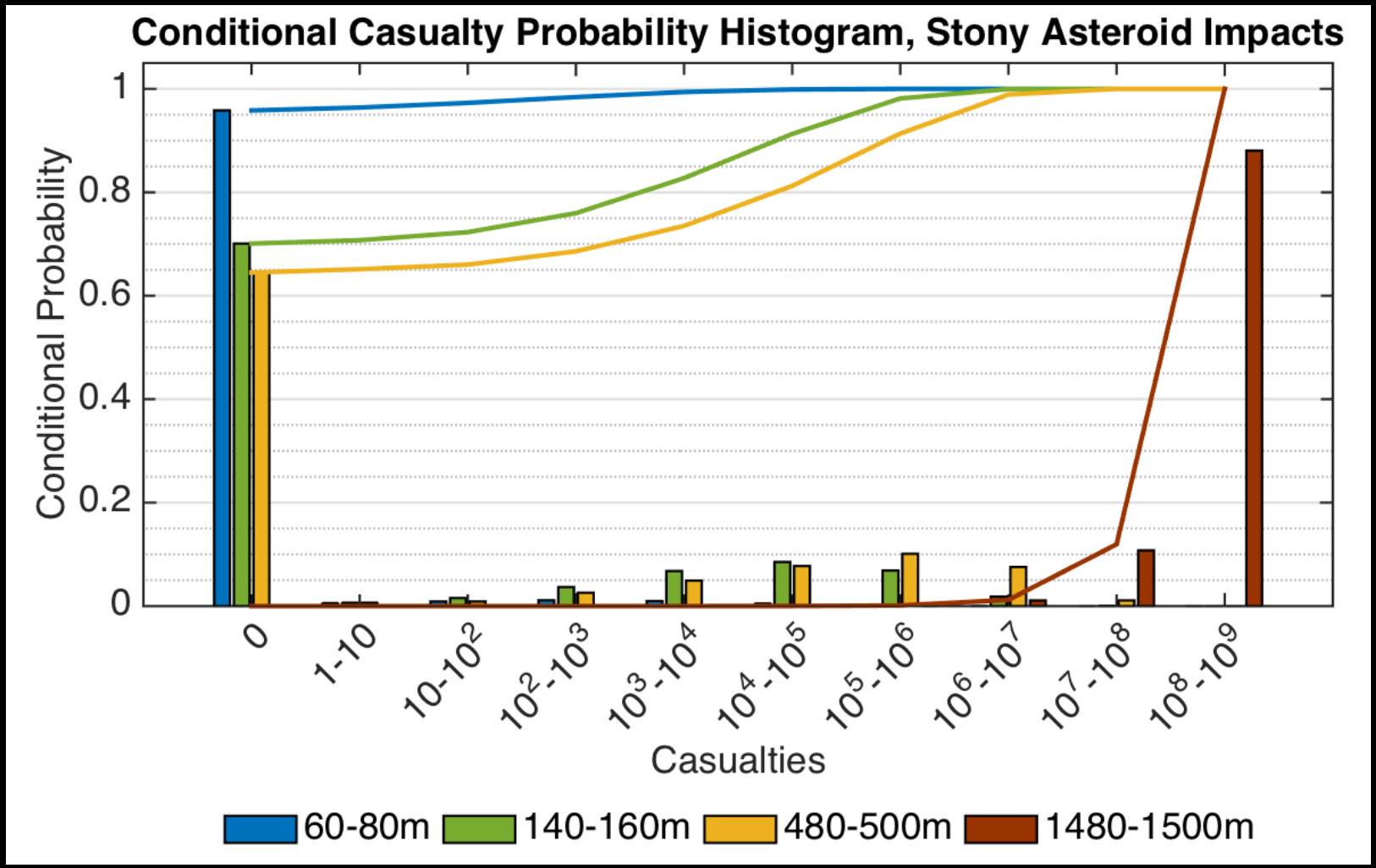
Cumulative casualties for impacts up to given size



D. Mathias. "Asteroid Threat Assessment", International Space Development Conference 2016, San Juan, Puerto Rico, May 21, 2016

Beyond Average Casualty Rates

- Expected values based on averages misrepresent likely outcomes



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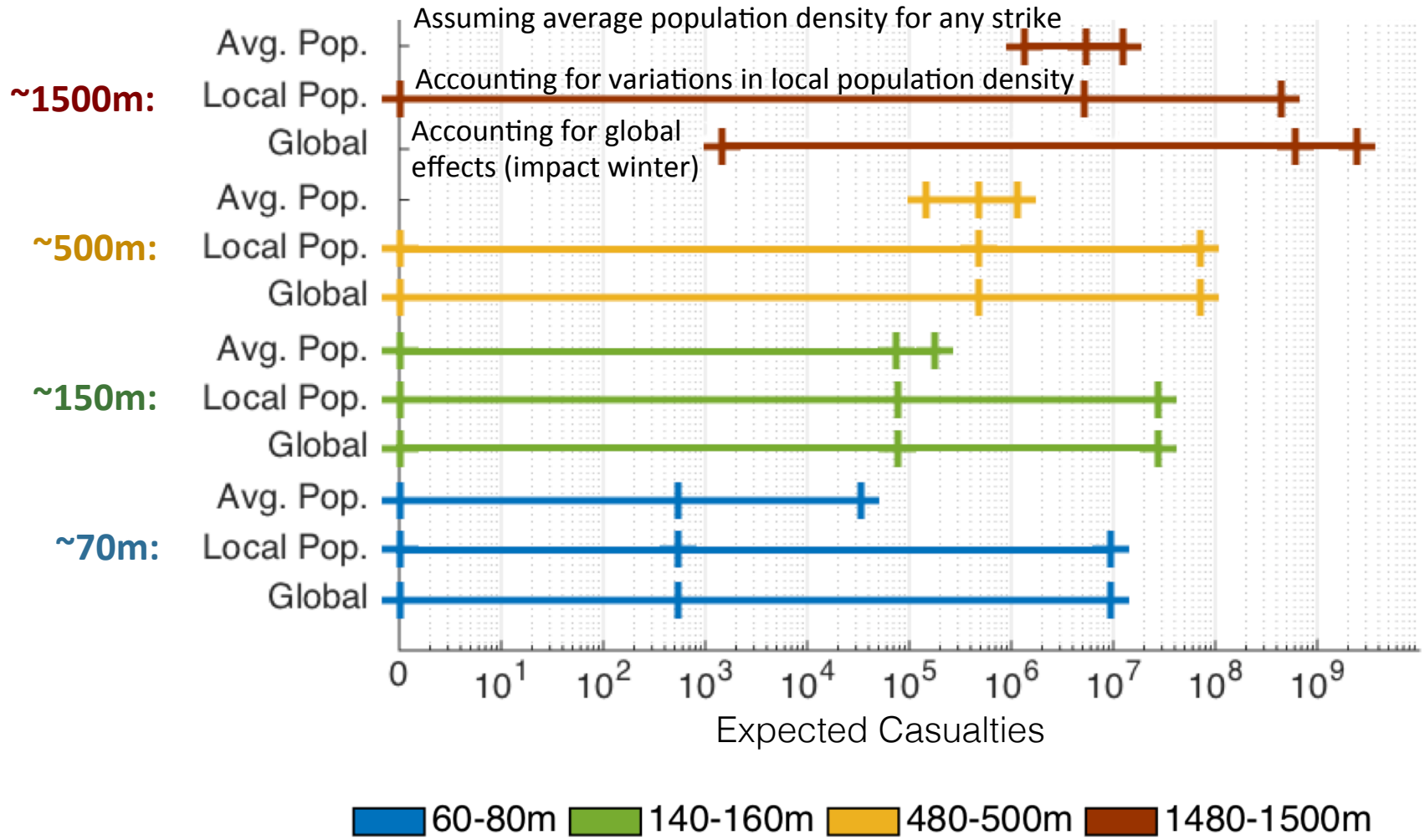
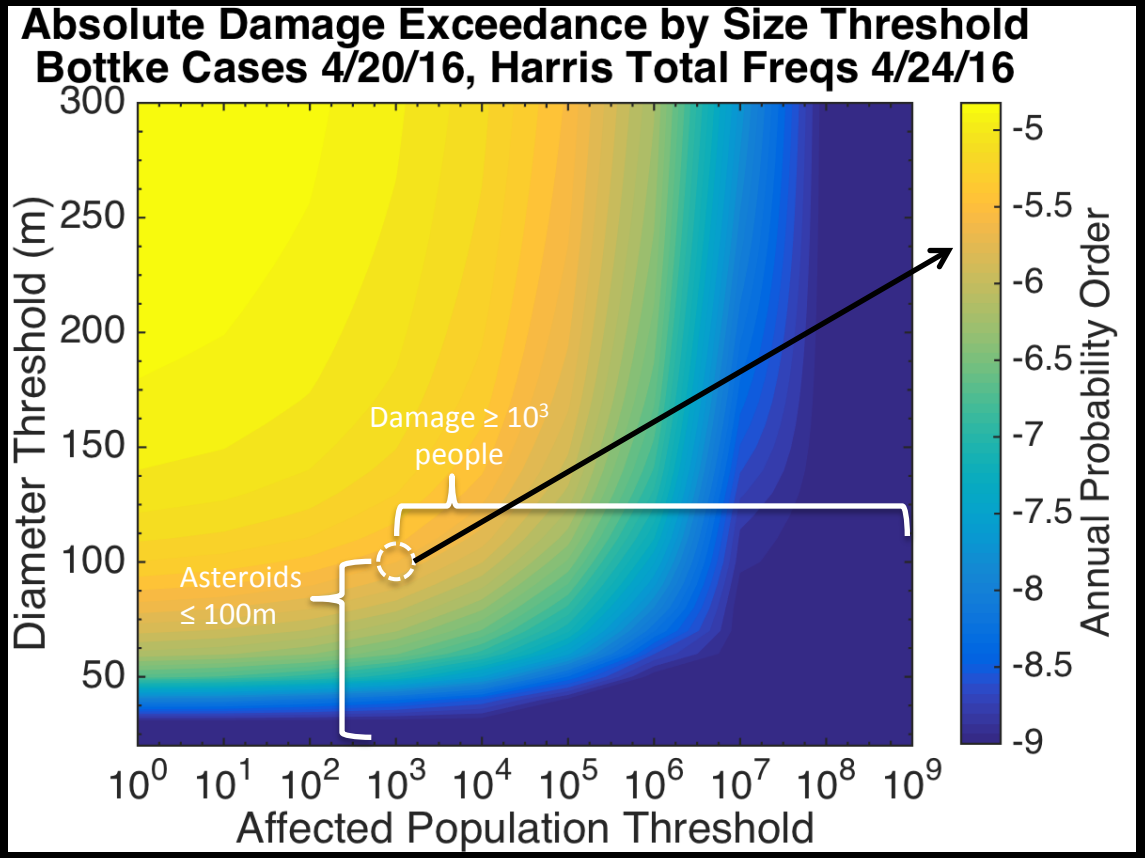
Population Distribution and Global Effects



Annual Exceedance Probabilities by Maximum Size Threshold

- Annual probability of an asteroid ***up to a given size*** impacting Earth ***and*** affecting ***at least*** a given population threshold or greater.



- *Example shown:* Probability of asteroids ≤100m diameter affecting more than 1000 people is given by the color scale.
- Probabilities are shown on log-scale so -6 = one-in-a-million (10^{-6}) chance per year.
- Affected population represents 100% of the population within a 4-psi blast damage radius (50% expected casualties)

D. Mathias. "Asteroid Threat Assessment", International Space Development Conference 2016, San Juan, Puerto Rico, May 21, 2016

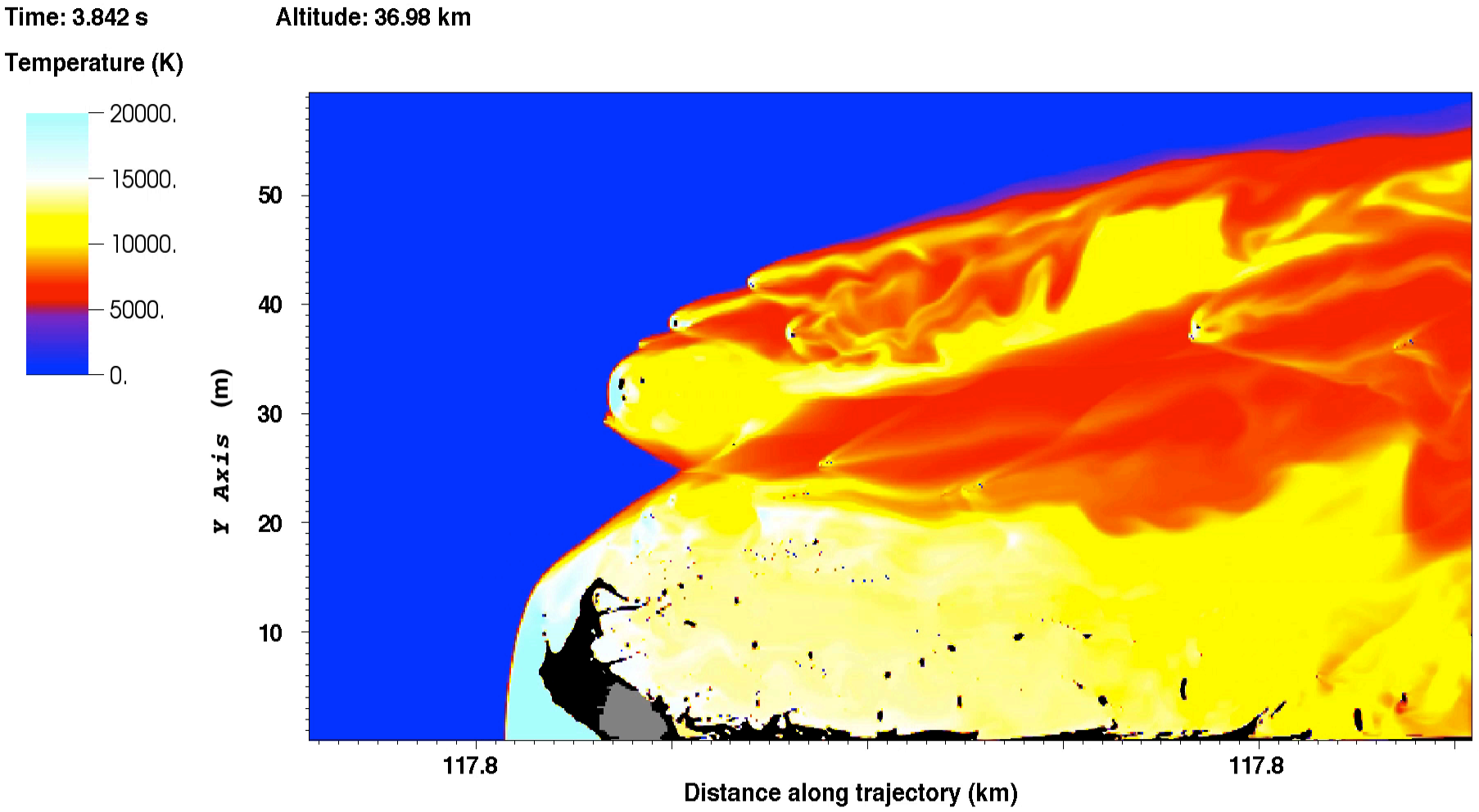
Why Simulate Impacts?

- Prior to Chelyabinsk event, 20 m size asteroids were not considered dangerous.
- The explosion of the asteroid 30 km above the Russian city of Chelyabinsk caused 1500 injuries (mostly from broken glass) and $33M in damage.
- Simulate asteroid impacts using state-of-the-art hydrocodes on NASA supercomputers to obtain best estimates of damage areas and sensitivity to variables. Use simulations to improve analytical models.
- Use results to inform trade-offs in asteroid characterization, detection, and mitigation efforts.

Damage from the Chelyabinsk event

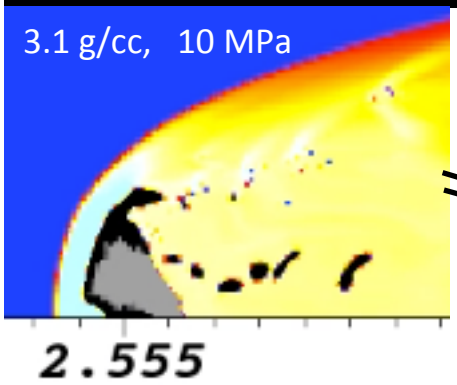
D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

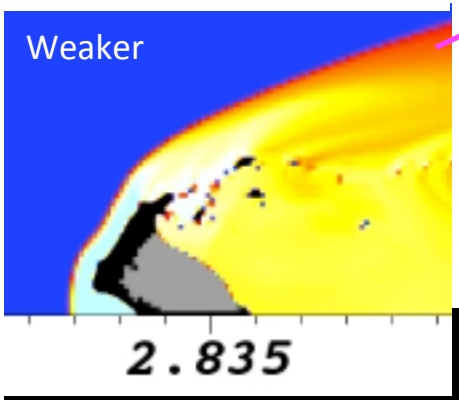
Chelyabinsk (1.2MPa strength)

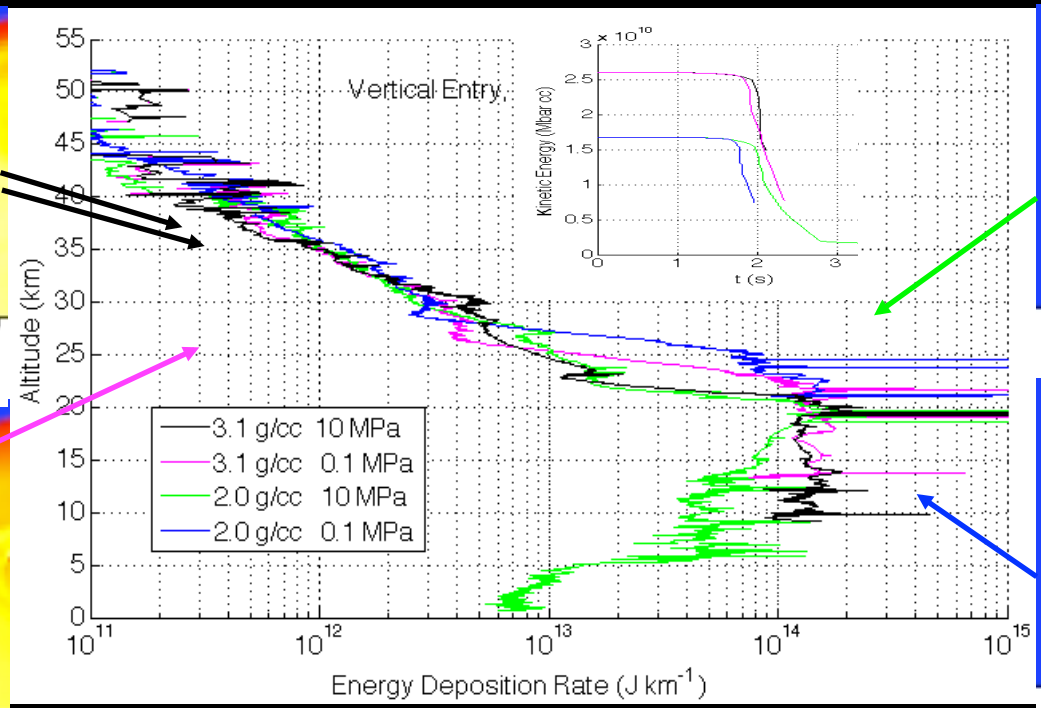


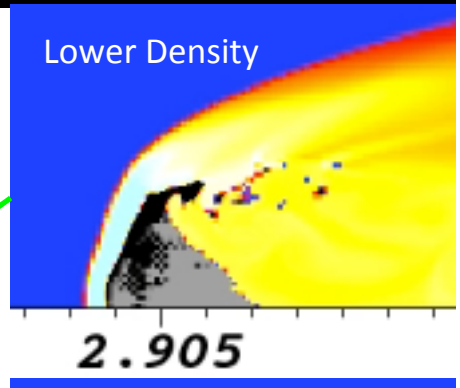
D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

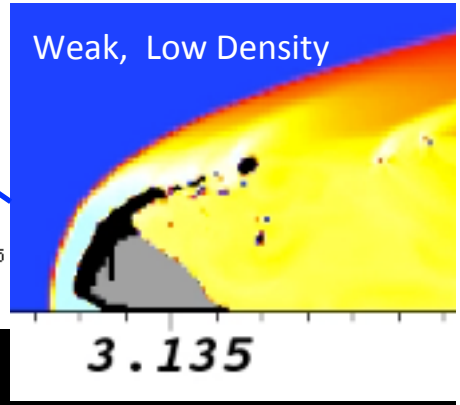
Energy Deposition Rates











- **Energy deposition into atmosphere fed into CFD simulation to propagate blast to ground.**
- **Blast wave knocks down walls, breaks windows, and creates hurricane force winds that throw debris into the air.**

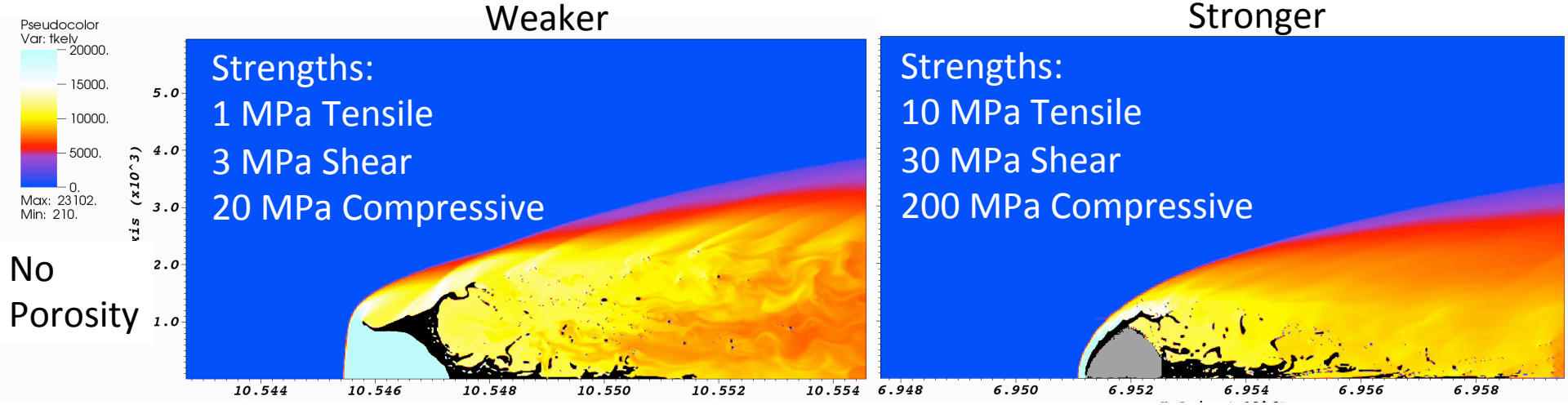
D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

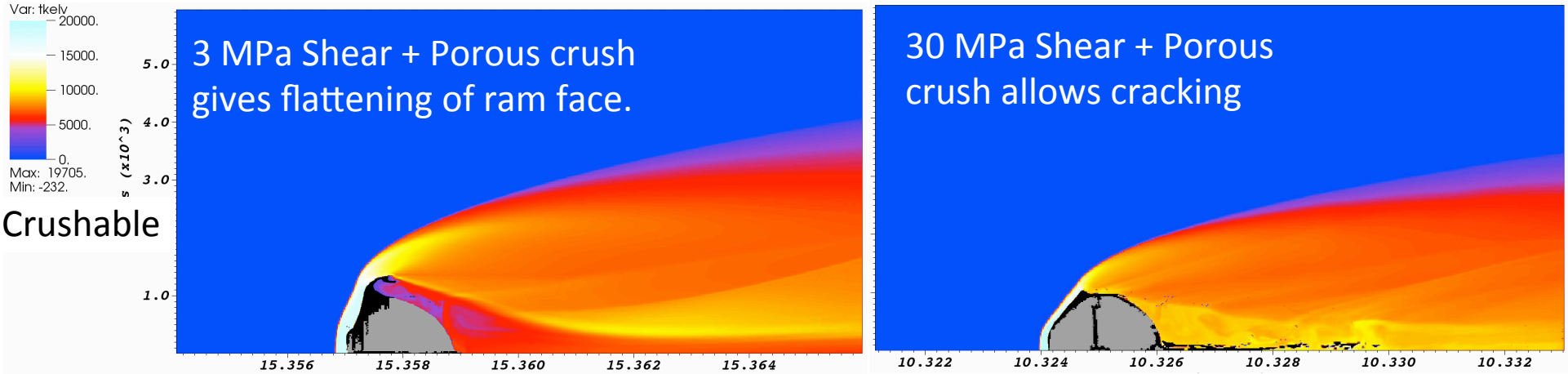
Effect of Rock Models

- Asteroids may be:
  - Rubble piles or monolithic boulders
  - Highly porous or non-porous
  - Highly fractured or intact

Weaker

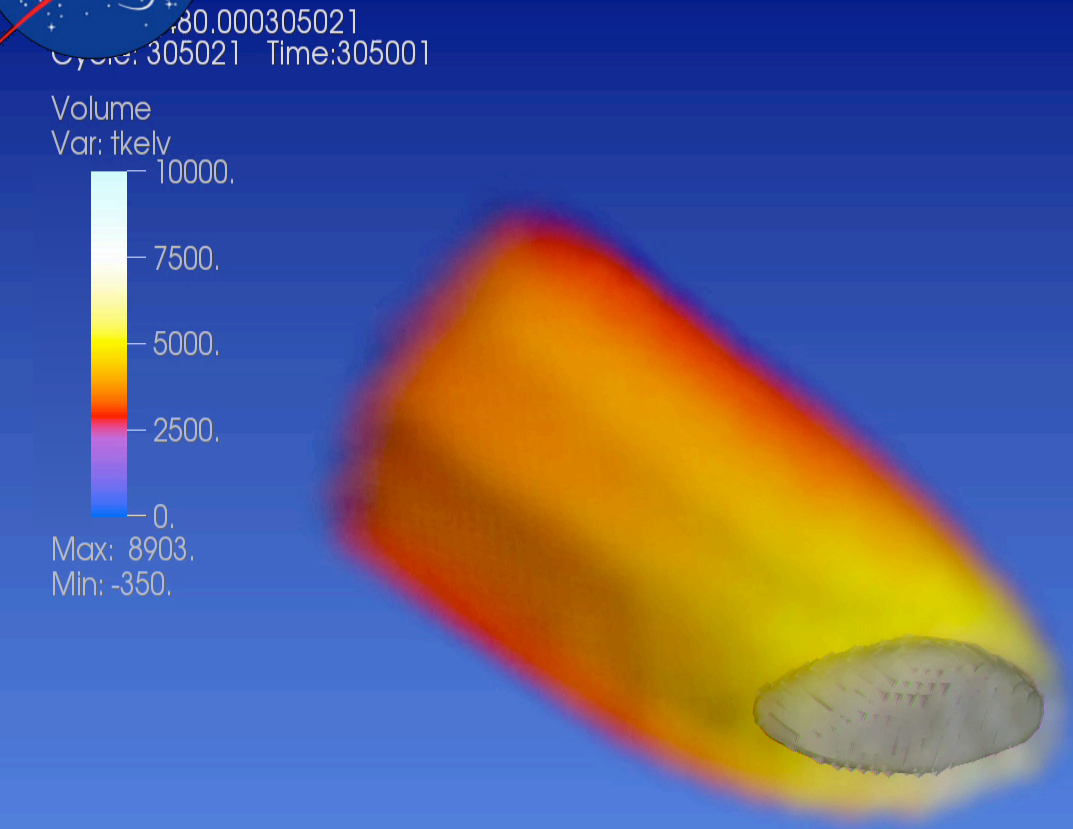
Stronger

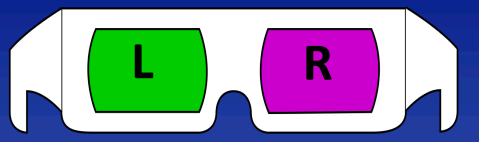




D. Robertson. "Effect of Different Rock Models on Hydrocode Simulations of Asteroid Airburst", American Geophysical Union Fall Meeting, San Francisco, CA, Dec 14, 2015

TC3 Airburst (Sudan 2008)



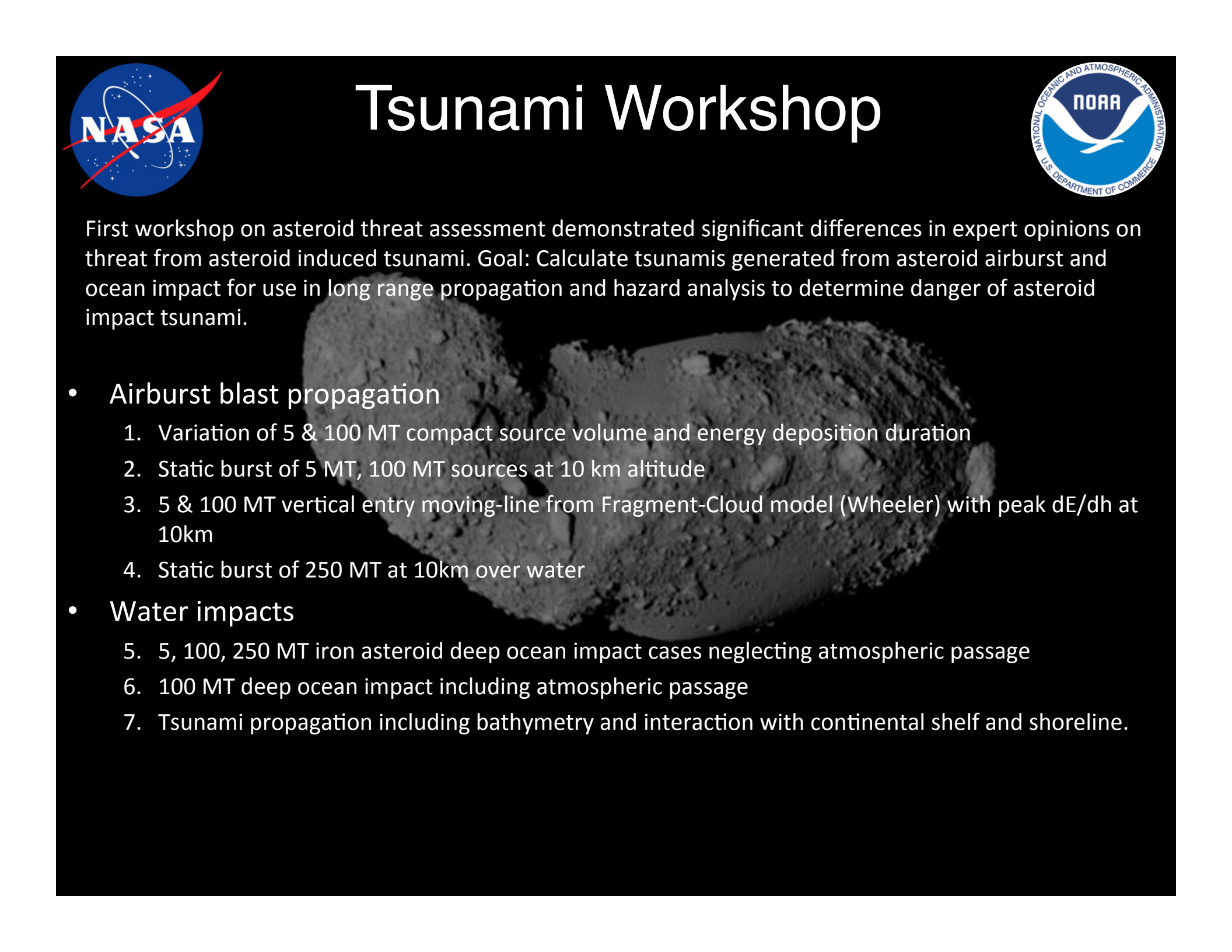


- **TC3 was the first asteroid who's shape was known prior to entry**
- **Satellites observed airburst at altitude of 37km above Nubian Desert in Sudan. Many meteorites recovered**
- **Too small to have been a threat to anything not directly under trajectory, but a useful test/validation case.**

D. Robertson. "Predicting Damage from an Asteroid Strike on Earth", Supercomputing 2015, Austin TX, Nov 16, 2015

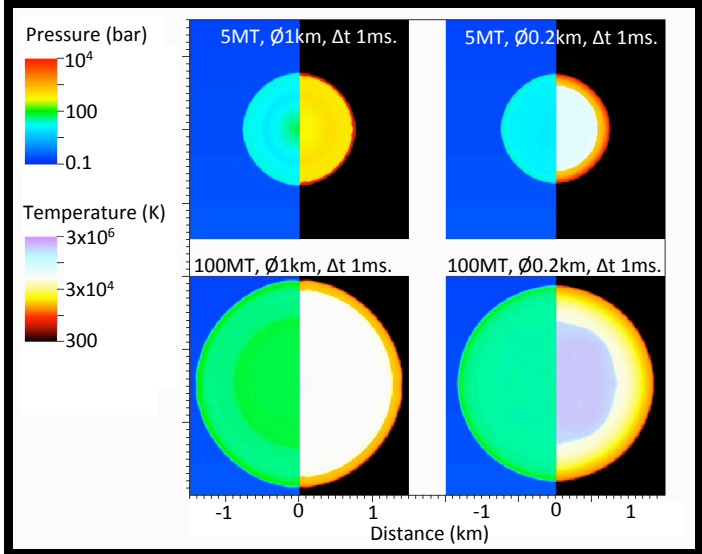
Tsunami Workshop

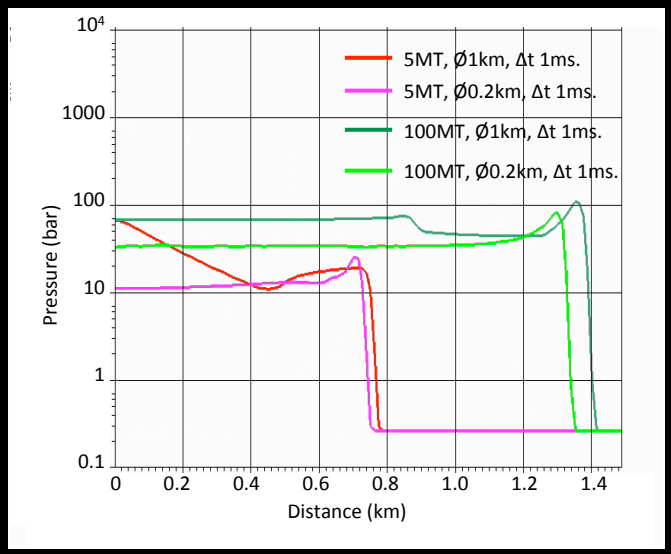
First workshop on asteroid threat assessment demonstrated significant differences in expert opinions on threat from asteroid induced tsunami. Goal: Calculate tsunamis generated from asteroid airburst and ocean impact for use in long range propagation and hazard analysis to determine danger of asteroid impact tsunami.

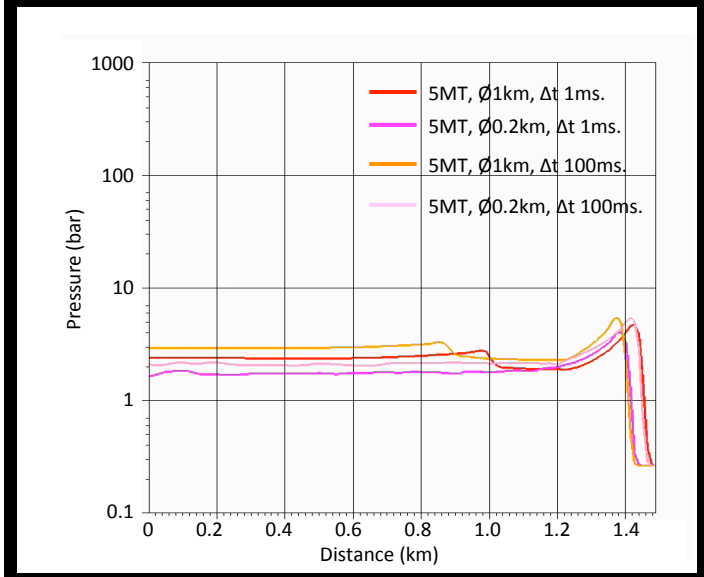


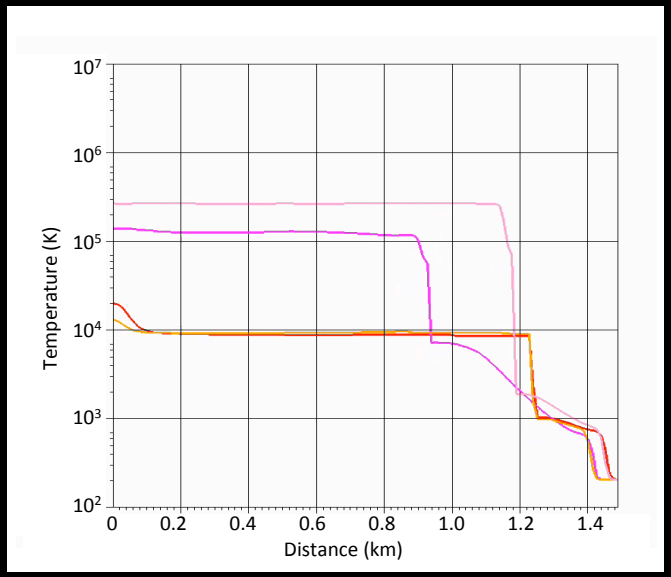
- Airburst blast propagation
  1. Variation of 5 & 100 MT compact source volume and energy deposition duration
  2. Static burst of 5 MT, 100 MT sources at 10 km altitude
  3. 5 & 100 MT vertical entry moving-line from Fragment-Cloud model (Wheeler) with peak dE/dh at 10km
  4. Static burst of 250 MT at 10km over water
- Water impacts
  5. 5, 100, 250 MT iron asteroid deep ocean impact cases neglecting atmospheric passage
  6. 100 MT deep ocean impact including atmospheric passage
  7. Tsunami propagation including bathymetry and interaction with continental shelf and shoreline.

1. Compact Source Time/Volume Variation







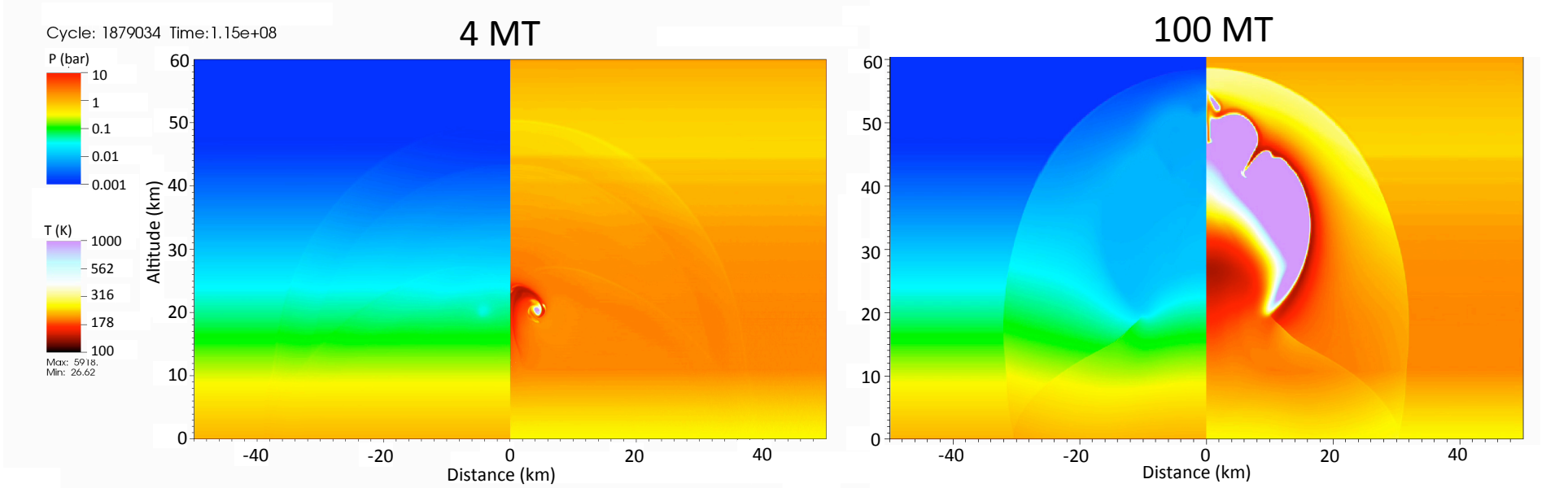


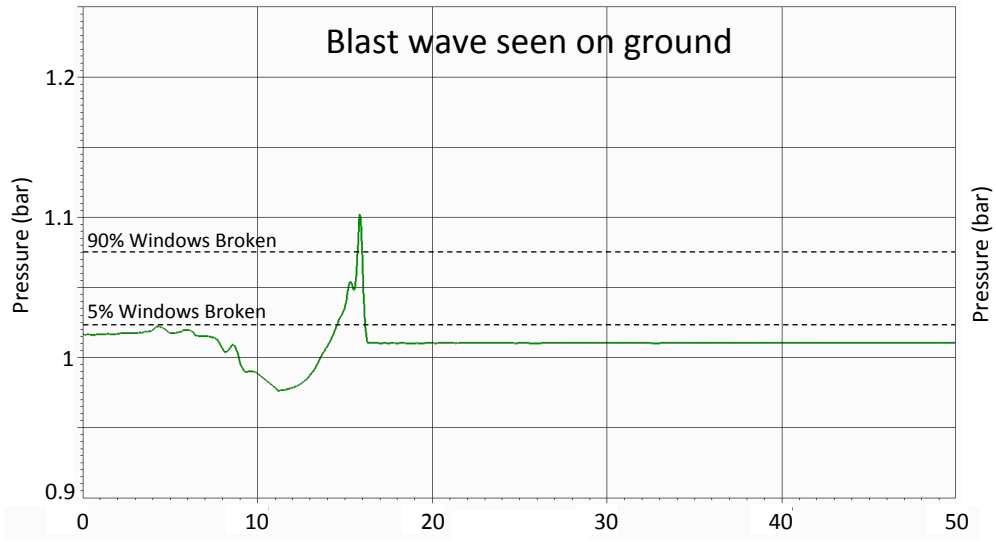
Test #	Yield (MT)	Diameter (km)	Δt (ms)
1	5	1	1
2	5	0.2	1
3	100	1	1
4	100	0.2	1
5	5	1	100
6	5	0.2	100

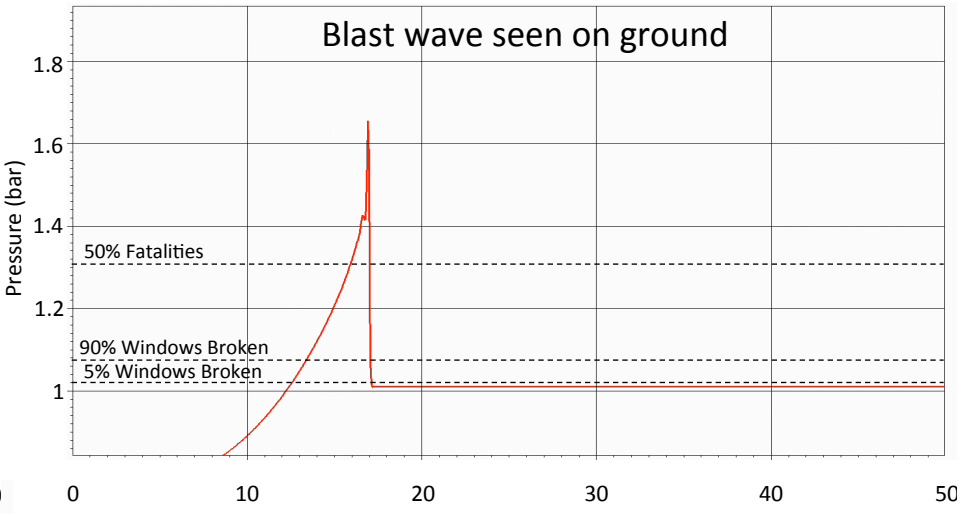
- A relatively short distance from the source they shock-up to very similar blast wave profiles
- Might be more important for entry profiles where velocity from imparted downward momentum will depend on volume of air.

2. Static Compact Airburst

- Propagation from 4MT and 100MT static point sources
- Energy sourced directly into air

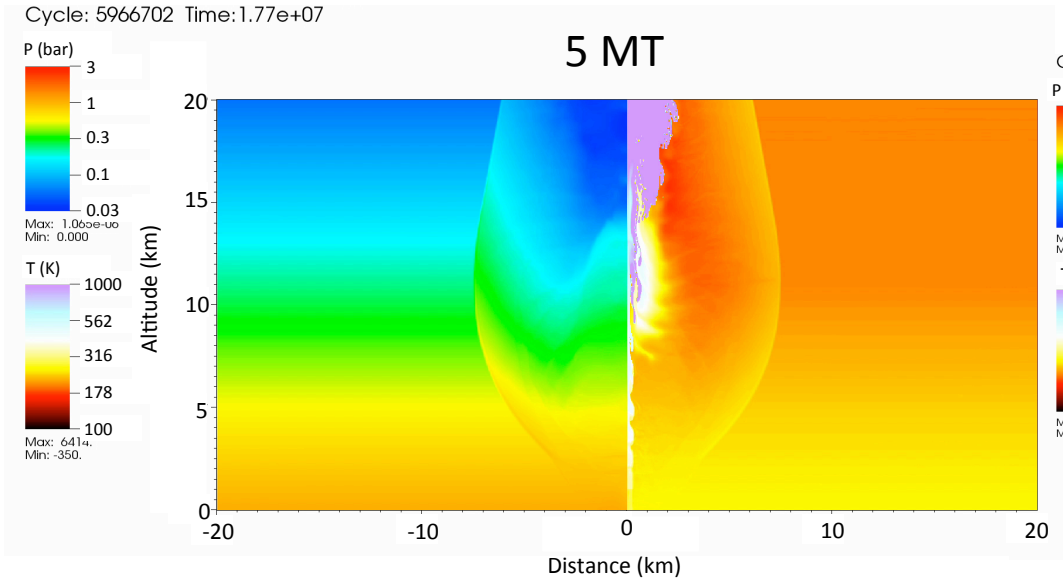


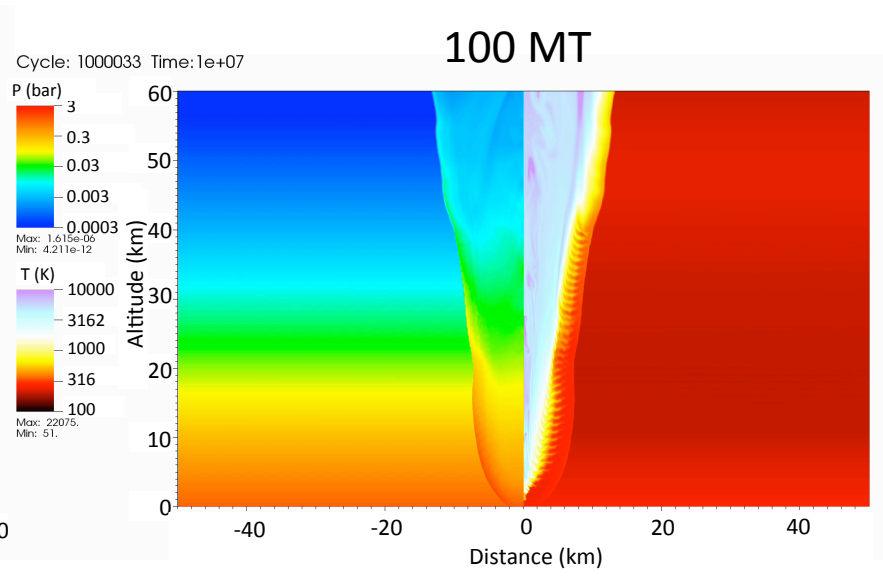


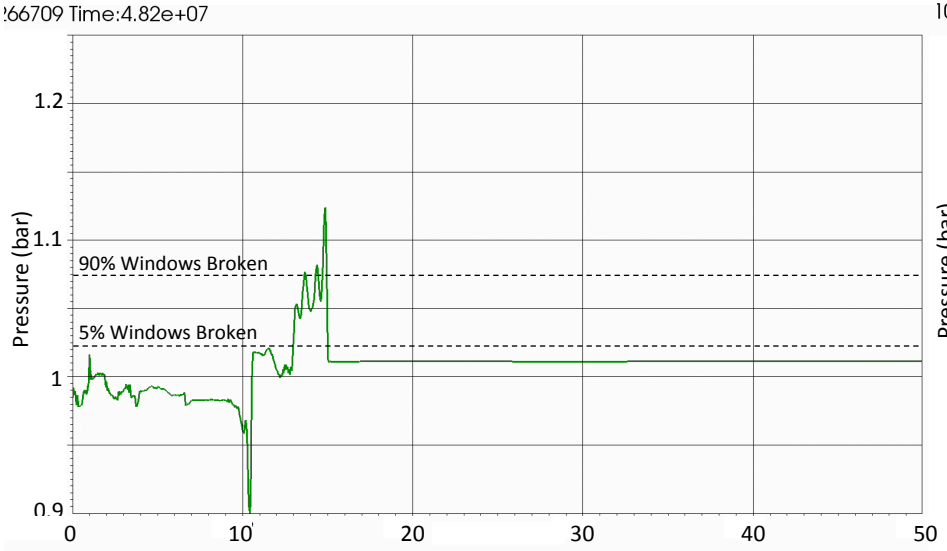


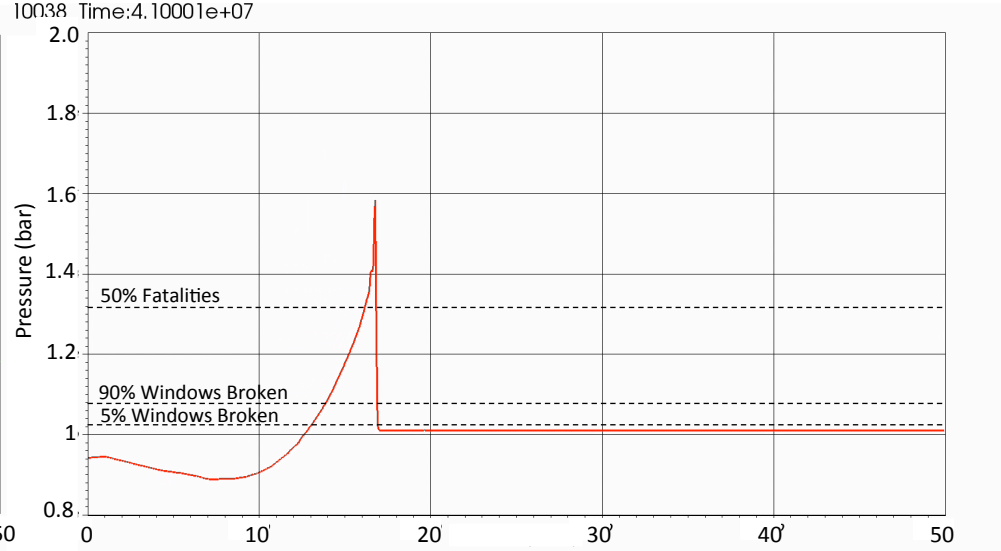
3. Blast from Asteroid Entry

- Energy sourced directly into air in 1km cylinders
- Downward velocity from momentum deposition into Ø500m air block
- Times from entry profile

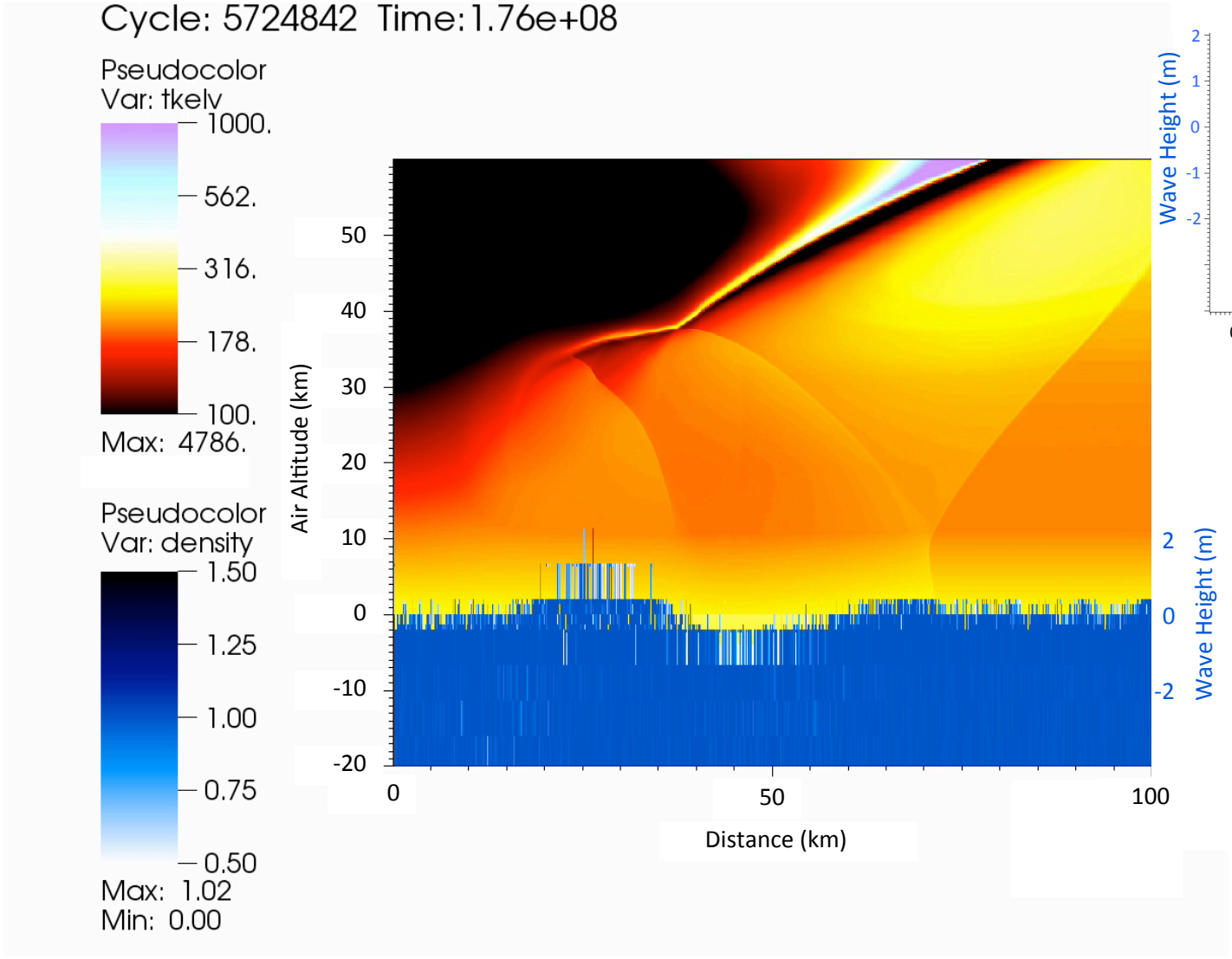






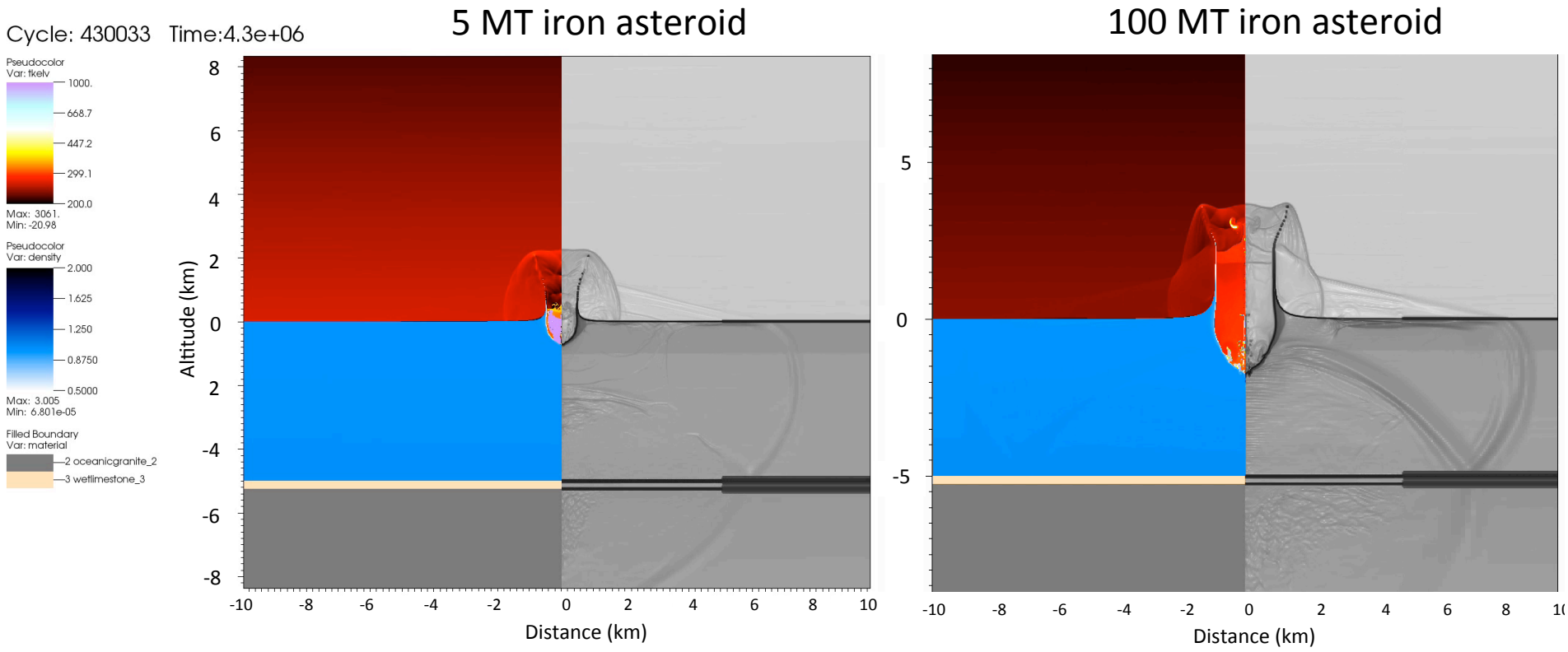


4. Compact airburst over water 250 MT, altitude 10km



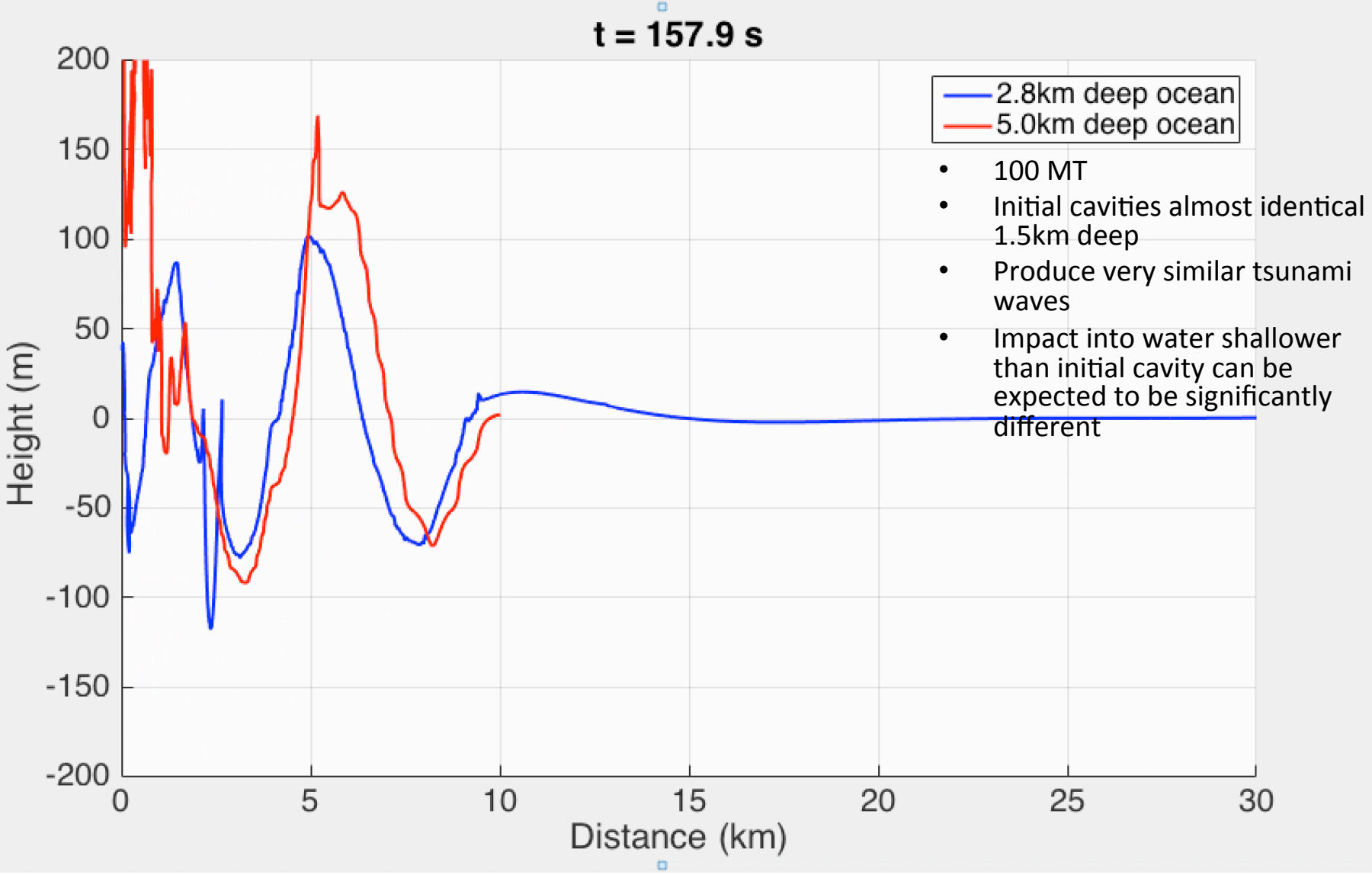
- Creates tsunami 1m high and 20km long when 50km from ground zero
- 4km deep ocean

5. Deep Ocean Impact



- 5km deep ocean, 250m loose sediment, oceanic granite

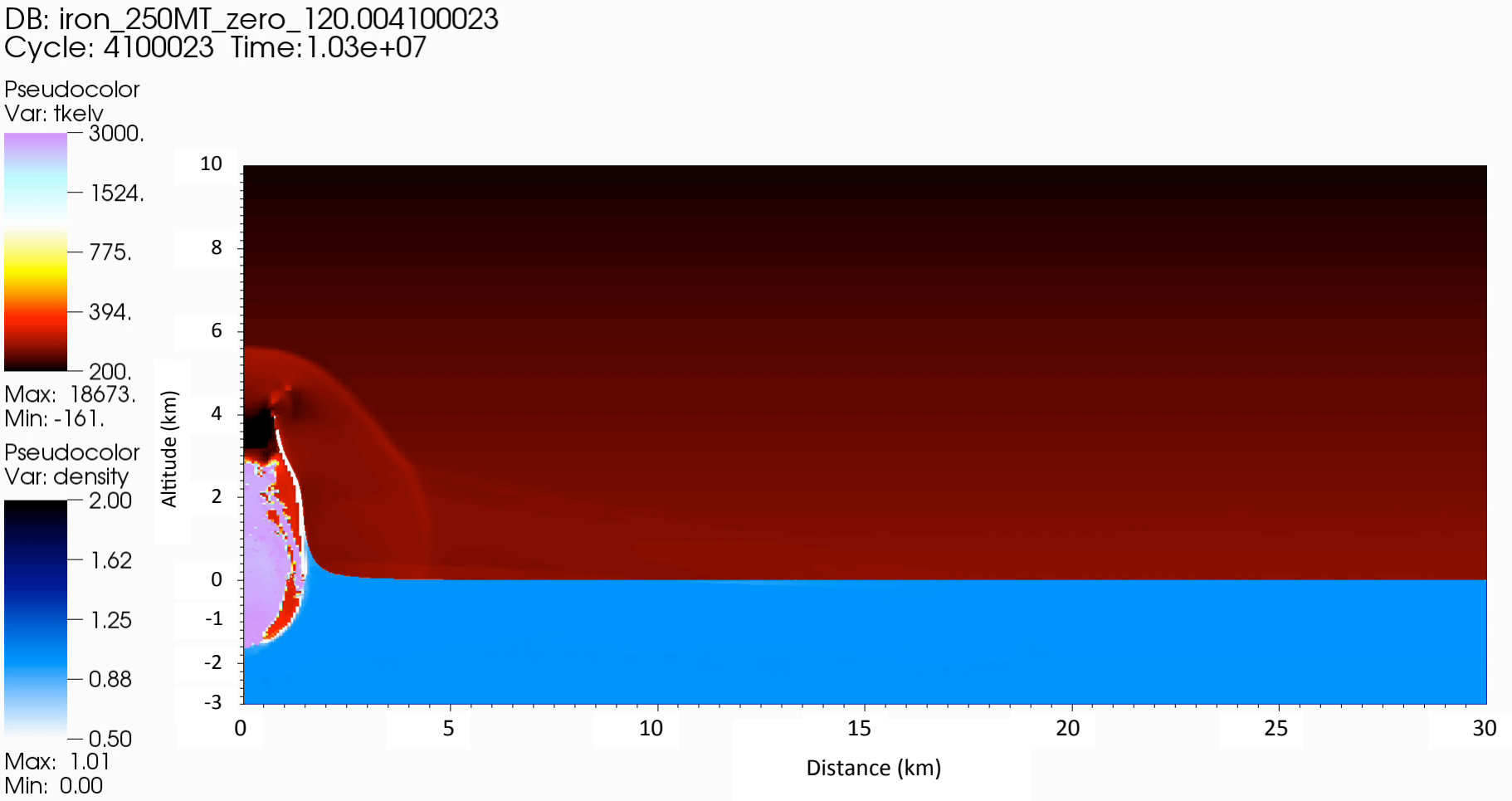
3 vs 5 km Deep Oceans



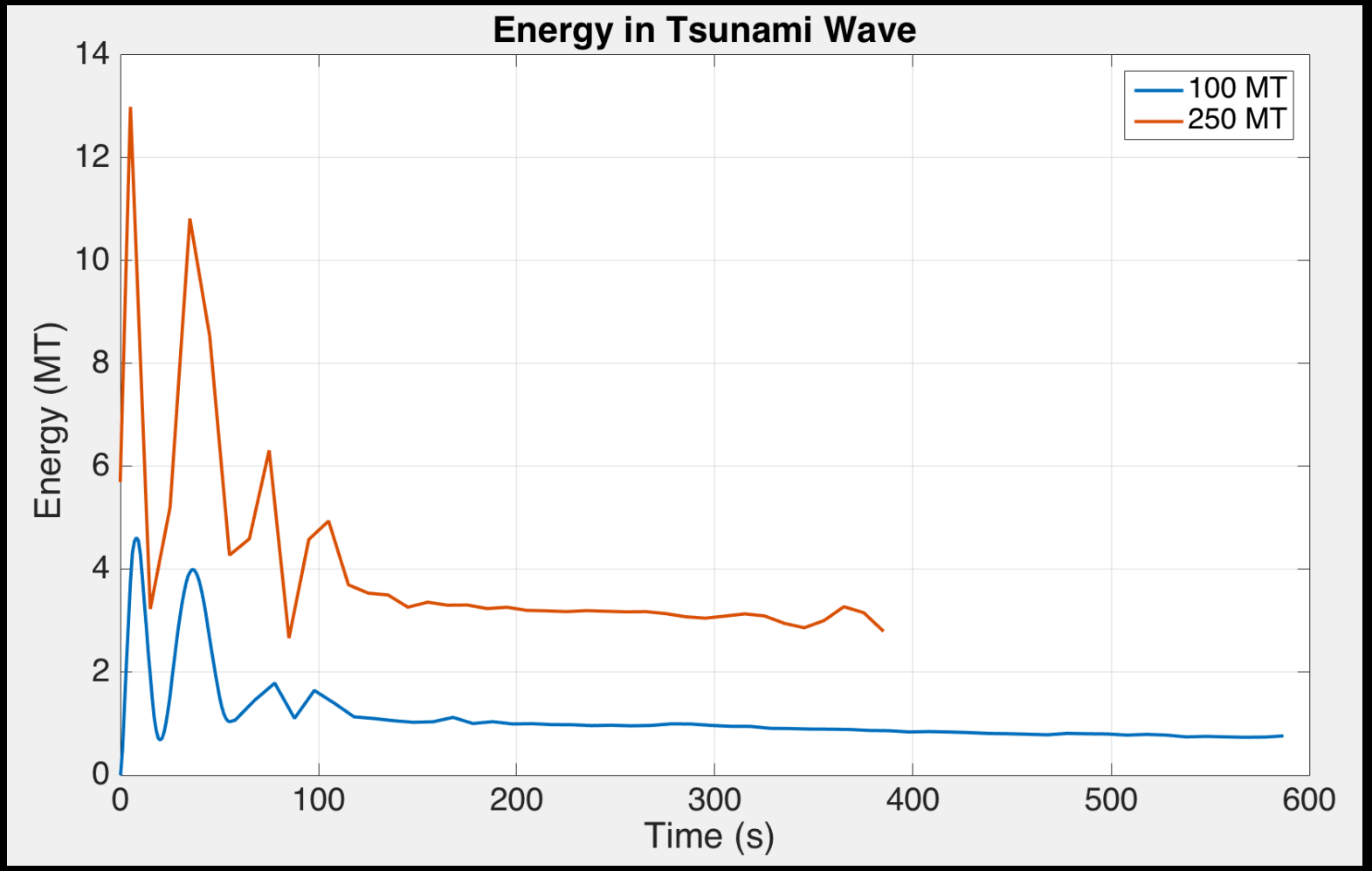
- 100 MT
- Initial cavities almost identical 1.5km deep
- Produce very similar tsunami waves
- Impact into water shallower than initial cavity can be expected to be significantly different

250 MT

- 3km deep ocean. Hard ocean floor

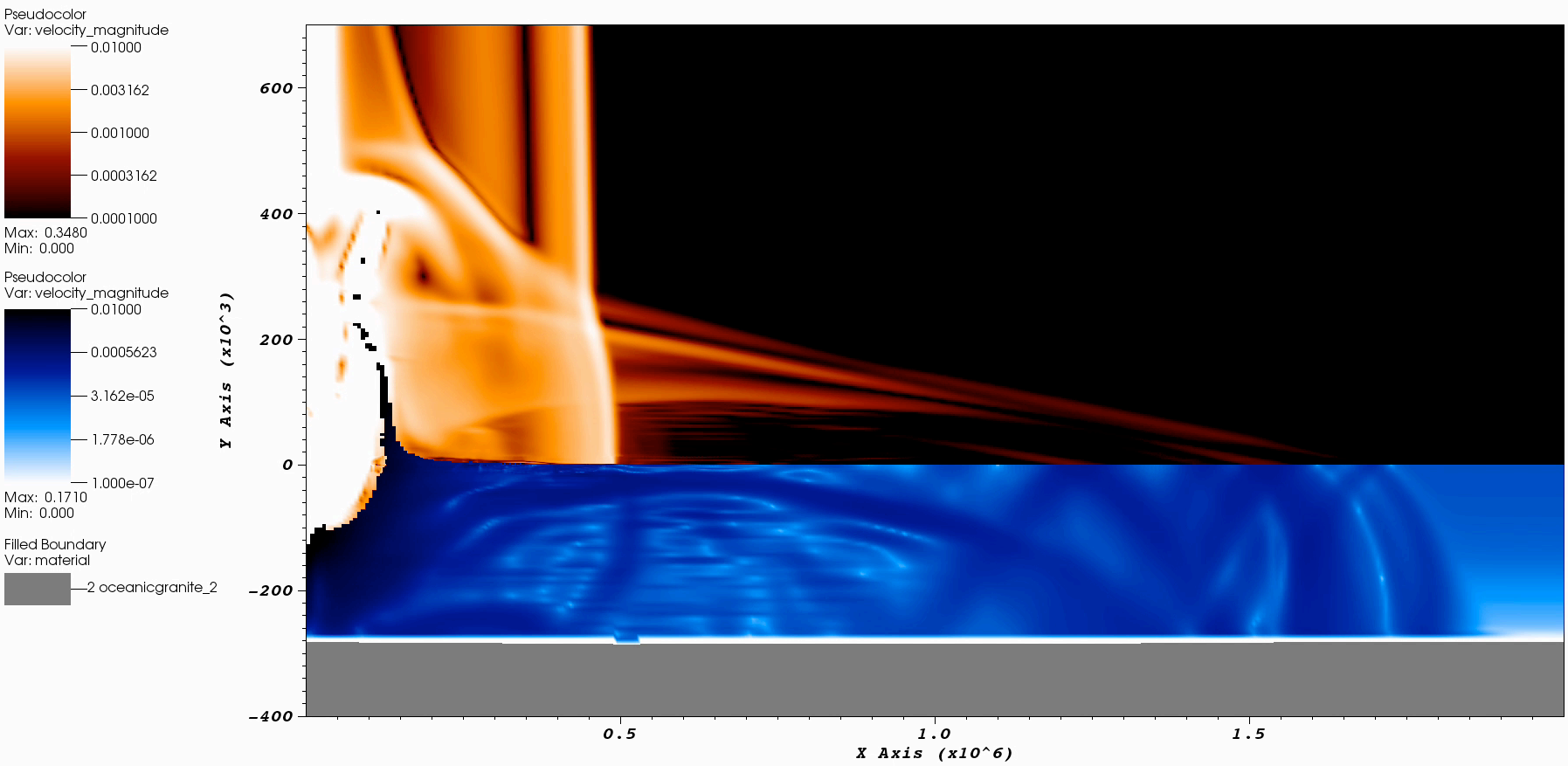


Energy in Tsunami Wave



- Approximately 20% of the initial energy goes into kinetic energy in the water, but most of this goes into the pressure (compression) wave.
- 1% of energy goes into surface (gravity) wave

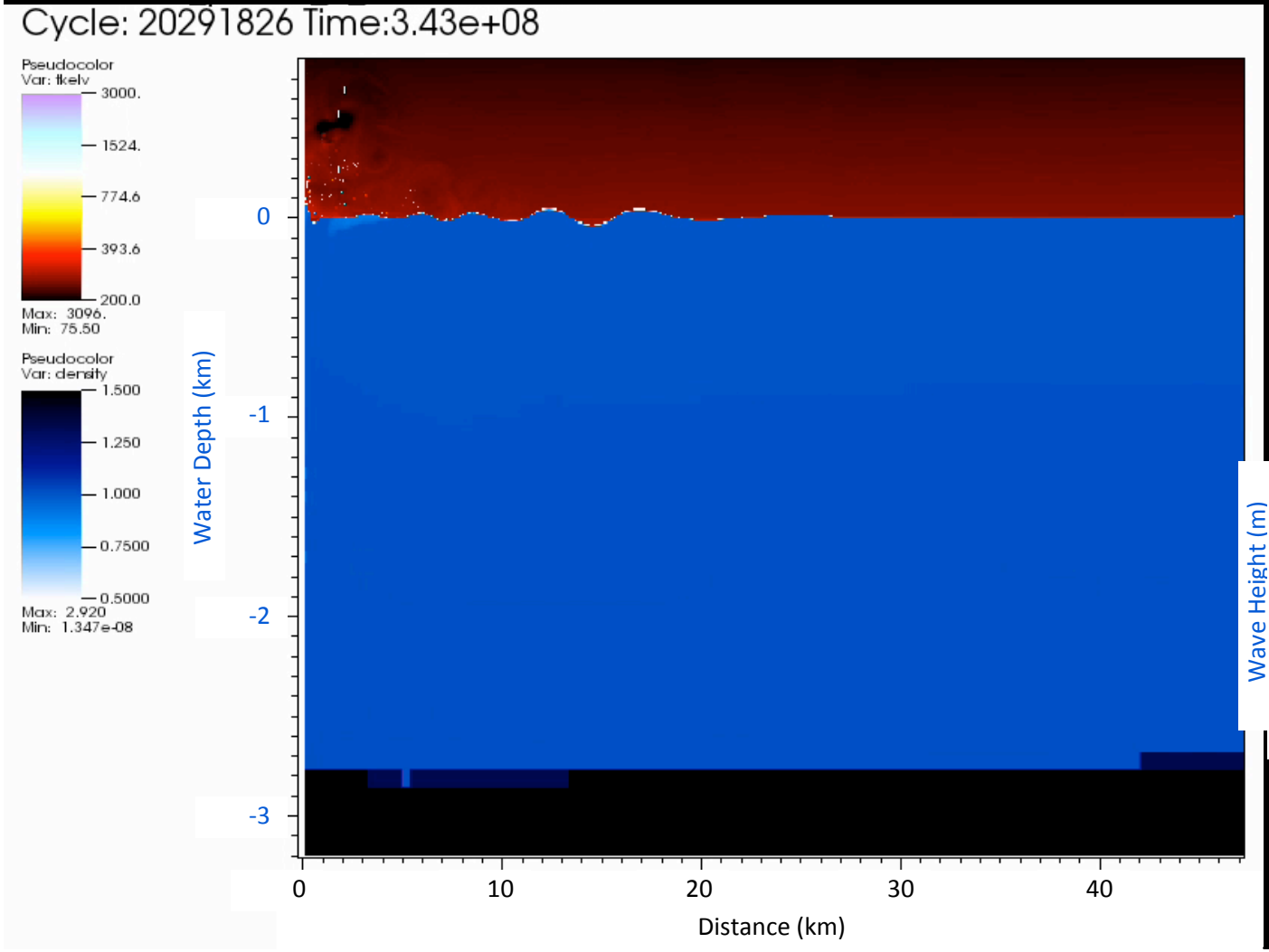
Including Atmospheric Passage



user: dkrober2
Tue Aug 16 11:47:23 2016

6. Continental Shelf

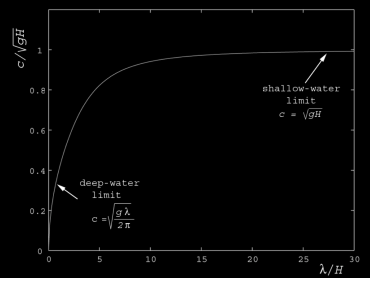
- Van Dorn predicted that when tsunami waves from asteroid impacts encounter the continental shelf they would break, dissipating significant amount of energy.



- 100 MT initial energy.
- Creates 1 MT tsunami wave train
- Waves appear to be deep not shallow water waves.

  Vphase = 91 m/s

  Vgroup = 46 m/s



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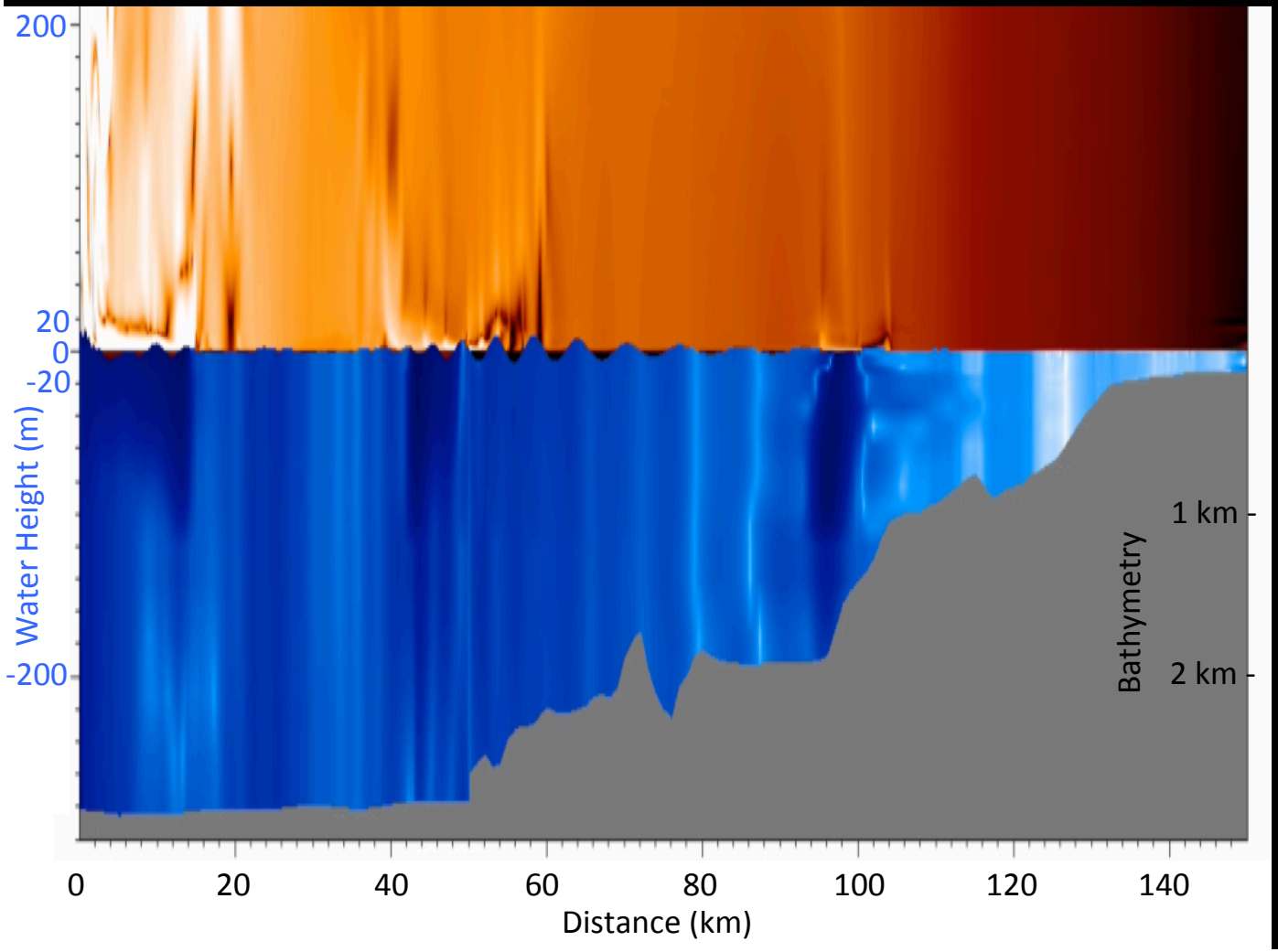

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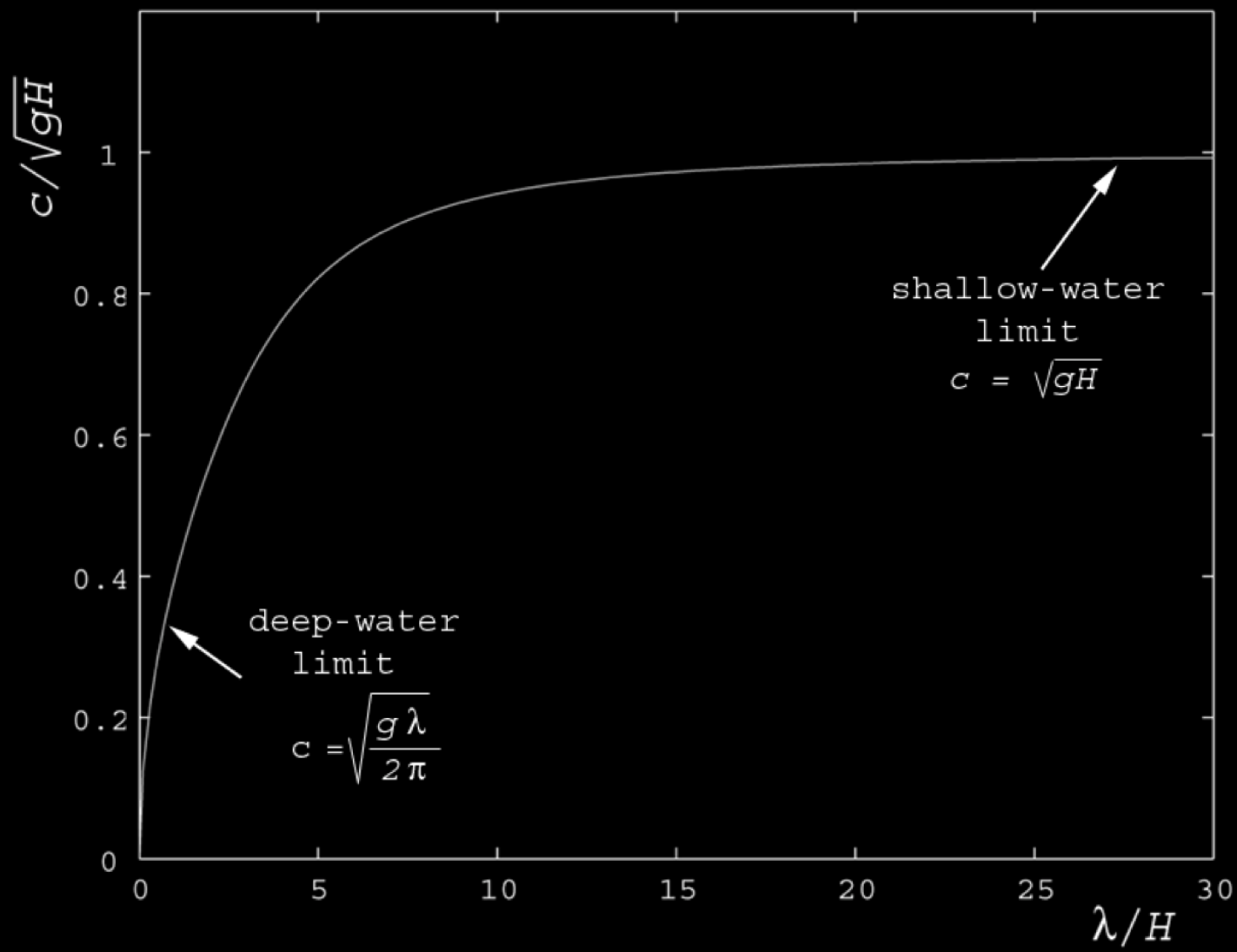
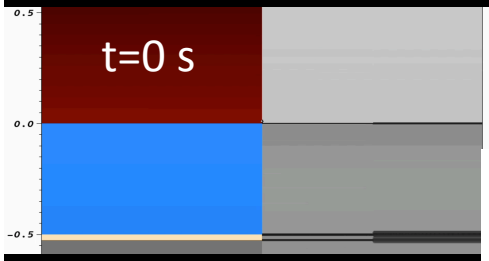
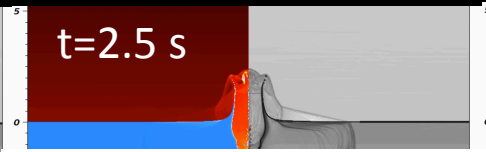
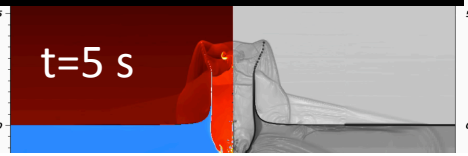
Shallow vs. Deep Waves

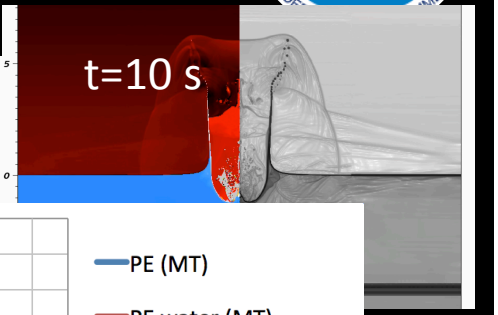


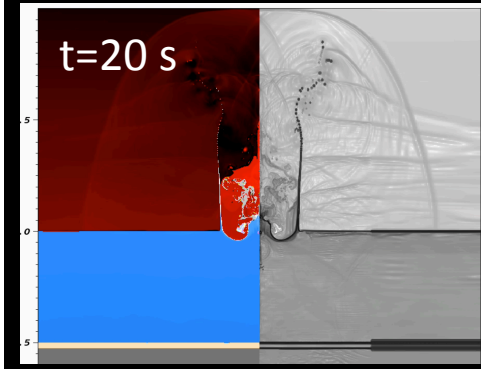
Energy Distribution

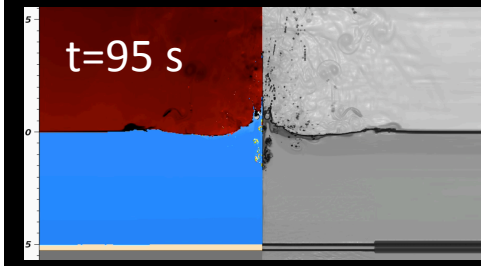


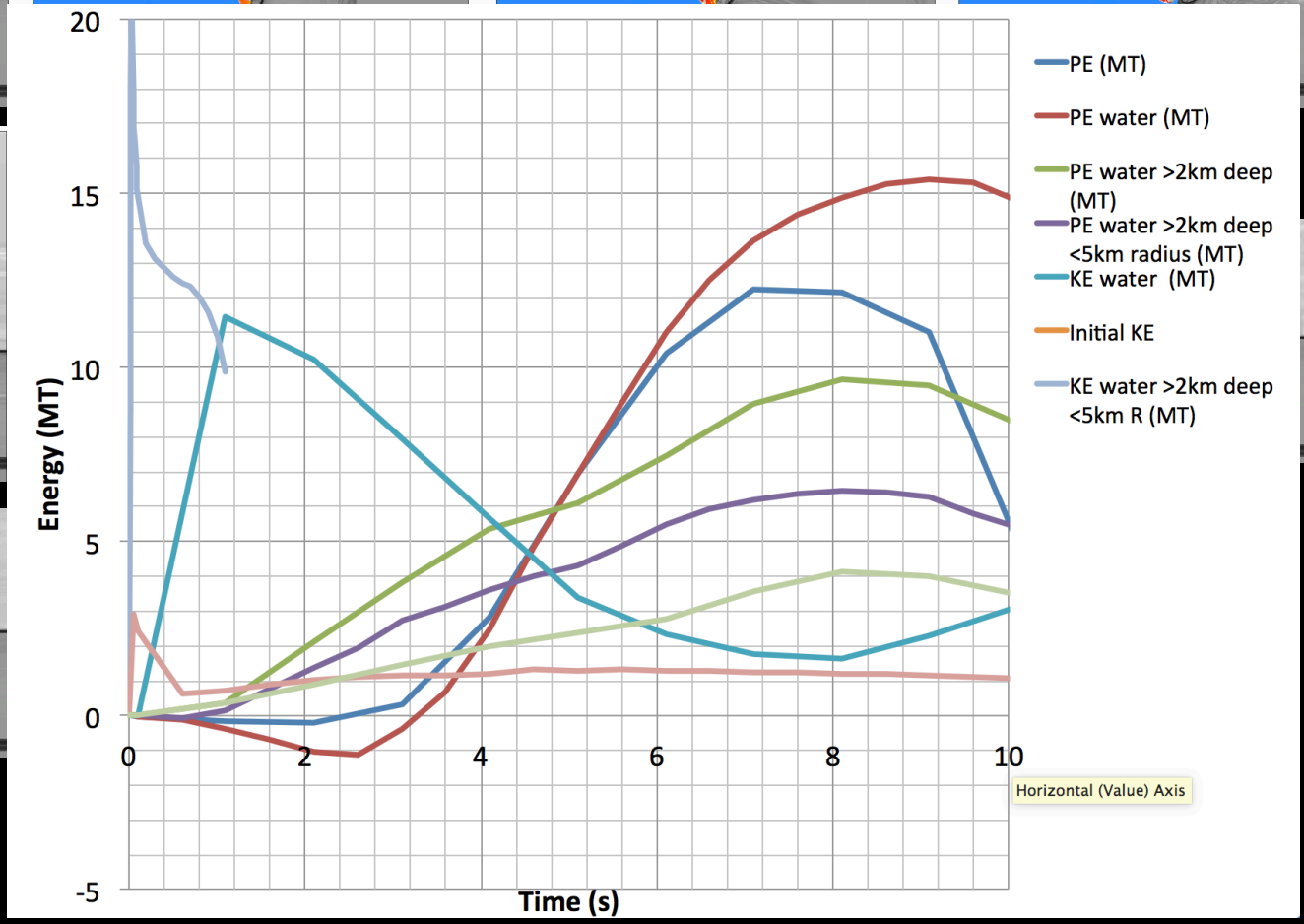










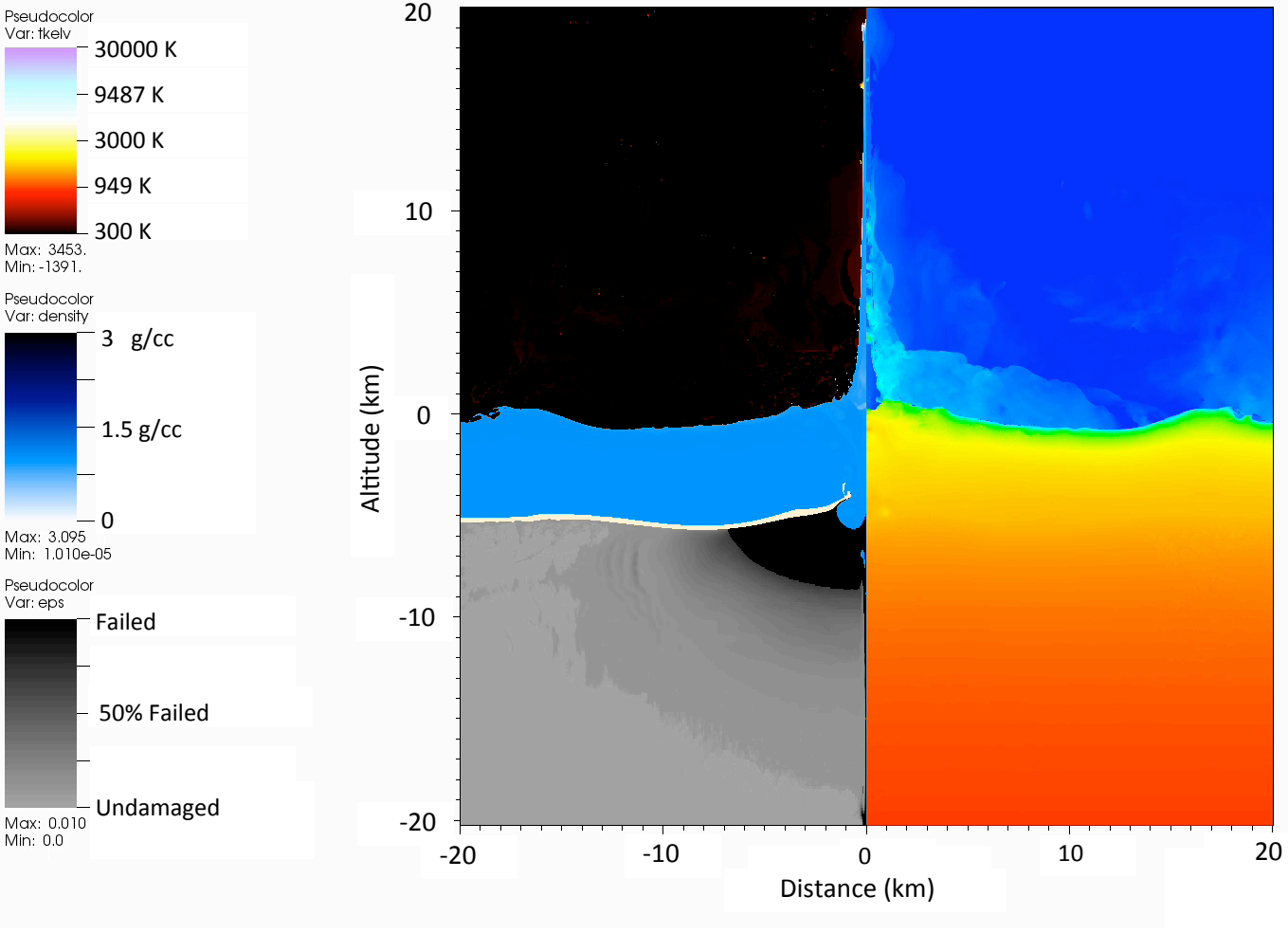


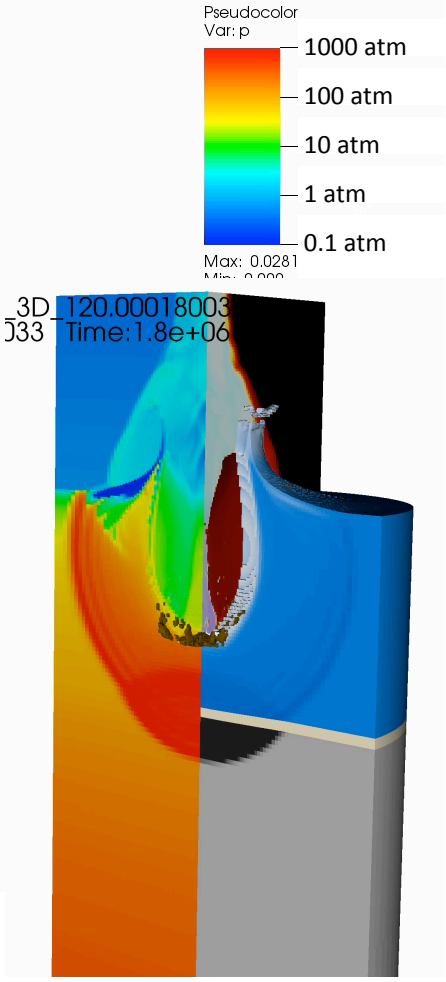
Eltanin (10GT)

- 2.1 Million years ago in South-East Pacific Ocean
- Only known impact into deep Ocean Basin
- Evidence of mega-tsunami debris on coasts of Chile and Antarctica as well as drill cores from Bellingshausen Sea.
- Current estimates Ø750m rock at 12 km/s vertical (10 GT) or 18 km/s at 45°.
- 5000m deep ocean, 250m sediment, basalt crust.

DB: eltanin_120.018800033
Cycle: 18800033 Time:1.88e+08

Preliminary Test Simulation.





Novaya Zemlya Nuclear Test

3.5 kT, detonated just below the surface

https://www.youtube.com/watch?v=2fyrHW5djuA

Conclusions and Future Areas of Interest

- Airburst
  - In the simulations explored energy from the airburst couples very weakly with the water making tsunami dangerous over a shorter distance than the blast for asteroid sizes up to the maximum expected size that will still airburst (~250MT).

  Future areas of investigation:
  - Low entry angle airbursts create more cylindrical blasts and might couple more efficiently
  - Bursts very close to the ground will increase coupling
  - Inclusion of thermosphere (>80km altitude) may show some plume collapse effects over a large area although with much less pressure
- Ocean Impact
  - Asteroid creates large cavity in ocean. Cavity backfills creating central jet. Oscillation between the cavity and jet sends out tsunami wave packet.
  - For deep ocean impact waves are deep water waves (Phase speed = 2x Group speed)
  - If the tsunami propagation and inundation calculations are correct for the small (<250MT) asteroids in these simulations where they impact deep ocean basins, the resulting tsunami is not a significant hazard unless particularly close to vulnerable communities.

  Future work:
  - Shallow ocean impact.
  - Effect of continental shelf and beach profiles
  - Tsunami vs. blast damage radii for impacts close to populated areas
  - Larger asteroids below presumed threshold of global effects (Ø200 – 800m)