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

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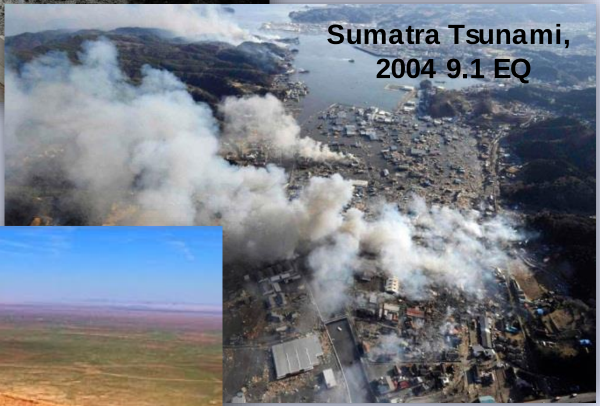
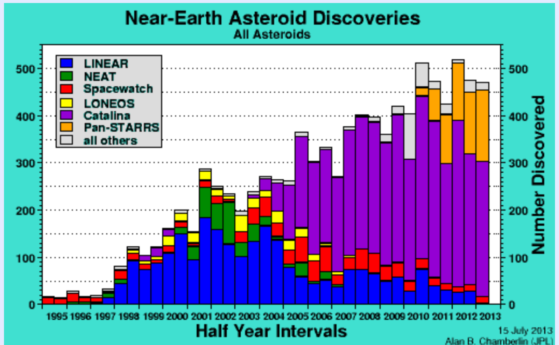
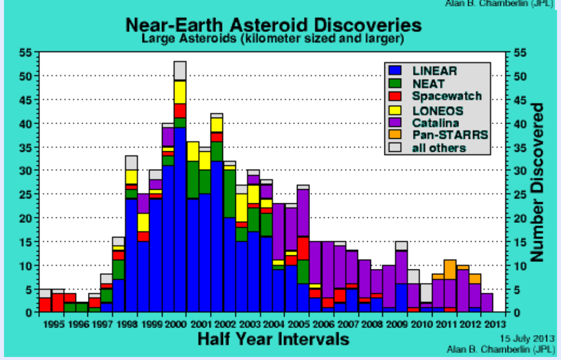
Outline

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

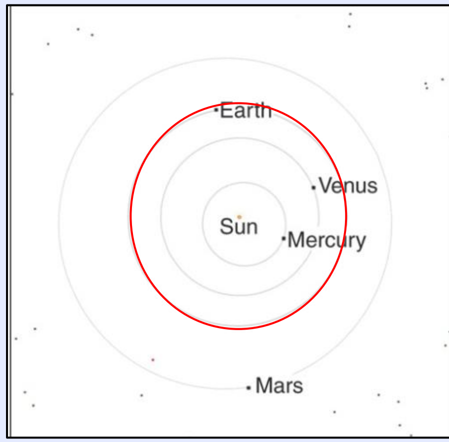


Motivation: Near Earth Objects

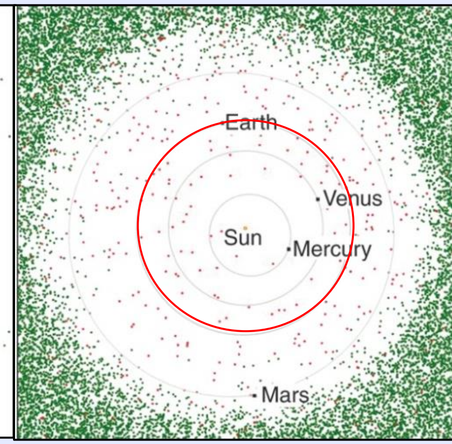




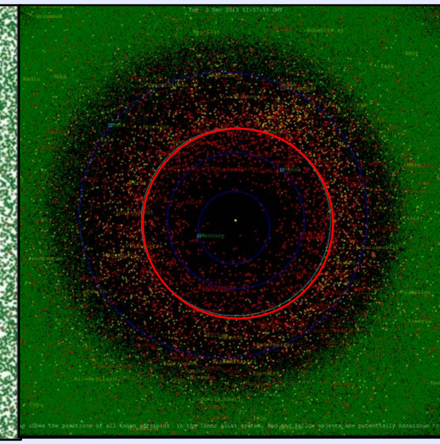
Few asteroids were recognized in the inner solar system 100 years ago (~100s).

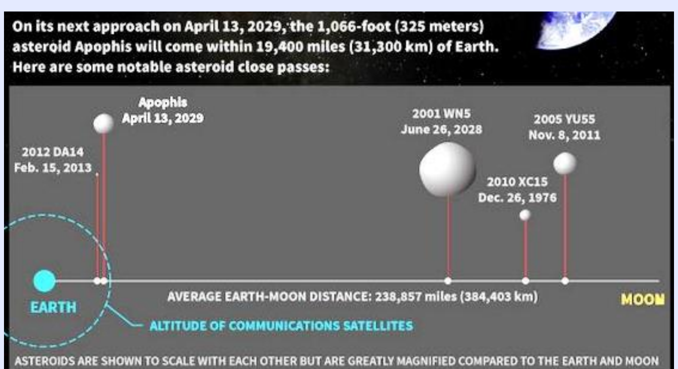


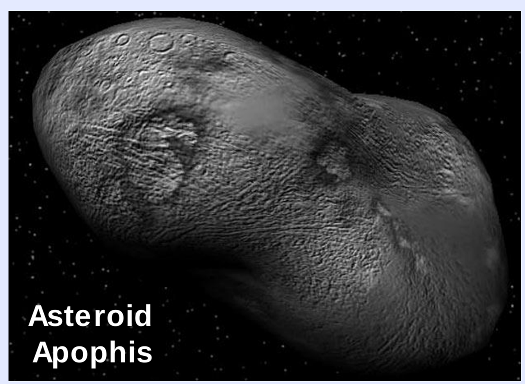
Y2K, more than 90,000 asteroids have been identified (~1000s).



2010, more than 200,000 asteroids have been identified (10482, 11/29/13).



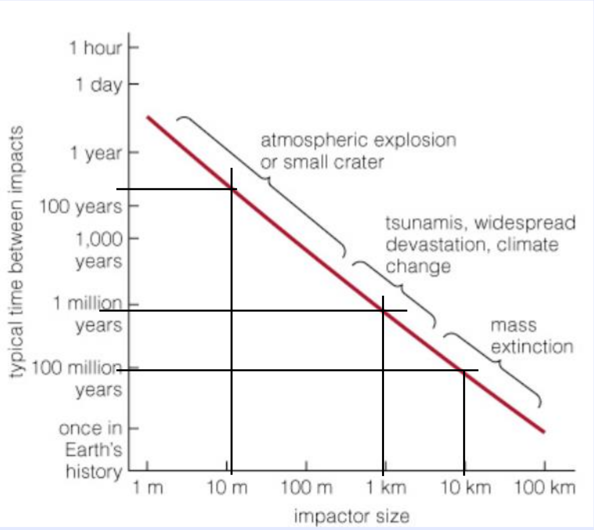


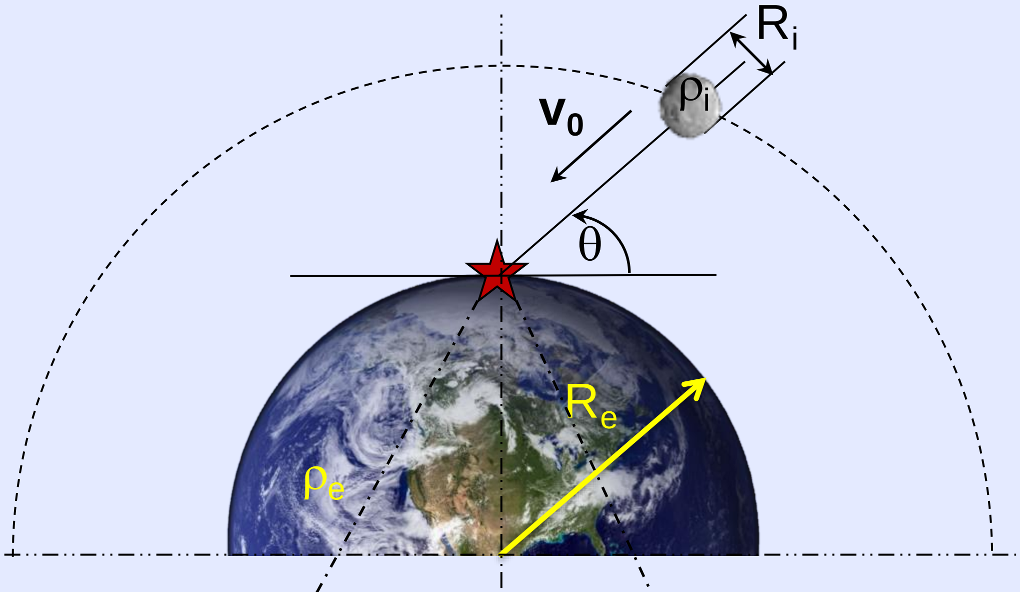


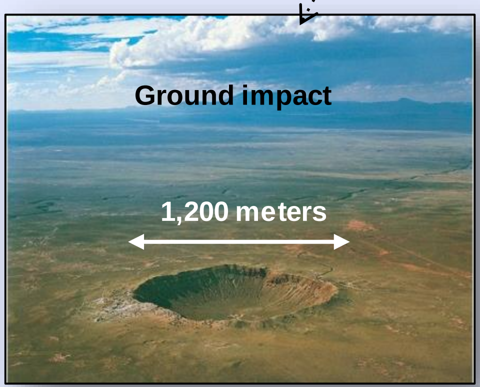
Physical characteristics of Apophis	
Dimensions	325±15 m
Mass	4×10^{10} kg
Density	~3.2 g/cm^3
Escape velocity	~0.52 km/h
Rotation period	30.4h
Temperature	270 K
Orbital speed	30.73 km/s

Motivation:
Quantitative hazard assessment of NEOs impacts

Key buildings of Washington, D.C.







Prob~1/3

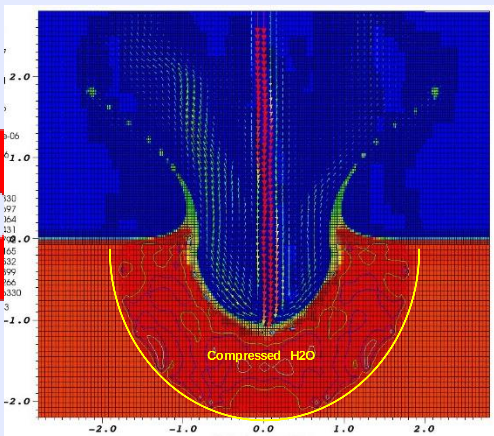
Prob~2/3

LLNL Numerical Modeling Framework

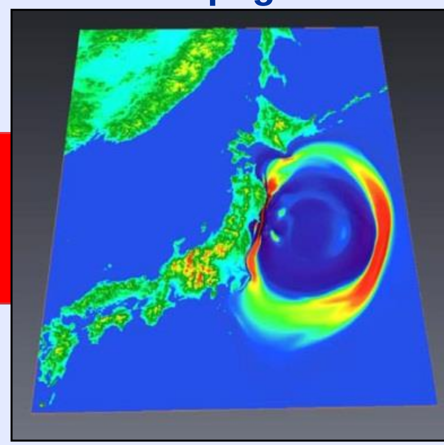
- **Most tsunamis are generated by EQ or LS & there are several open-source SWW codes.**

  Fully couple the source (asteroid impact), ocean wave propagation (flooding) and seismic propagation if asteroid impact the land or reaches ocean floor.

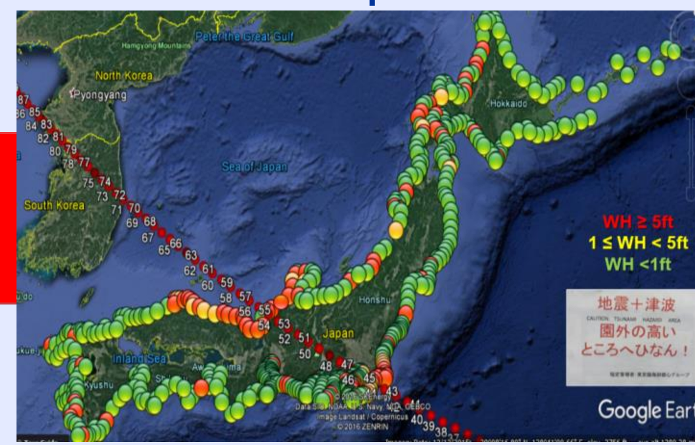
Impact Source



Water Waves Propagator



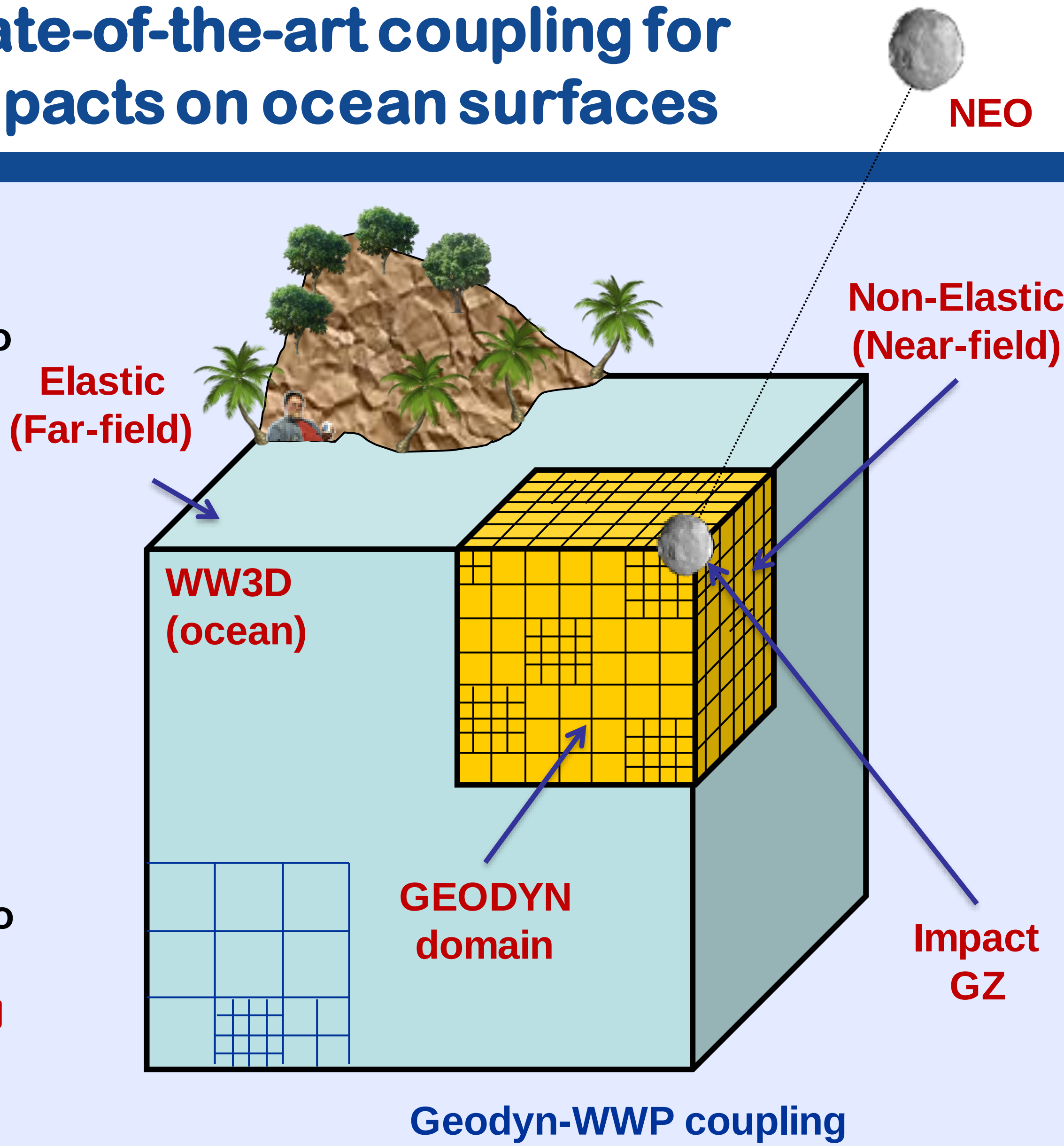
Vulnerability Consequences



- **Exercised different versions:**
  - **TTX 2013 Maryland (Semi-analytical solution)**
  - **TTX 2014 Gulf of Mexico (Geodyn-2DSWW + Global Effects)**
  - **TTX 2015 PDC Italy + NASA 1st WS (Geodyn-2DSWW)**
  - **2nd 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

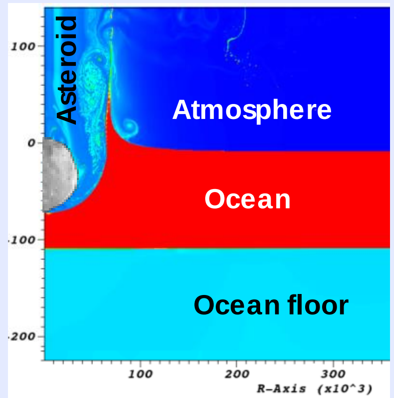
- Shocks and large deformations
- Structured Eulerian grids
- Material interface tracking with interface reconstruction
- Adaptive Mesh Refinement
- Coupled to WPP

MML: Flexible material model library

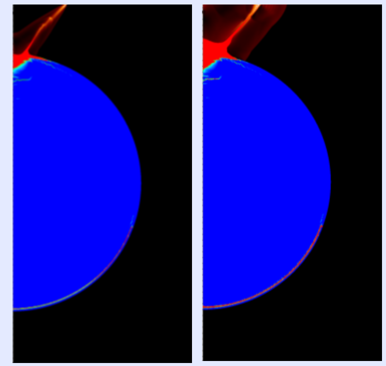
- Analytic and tabular EOS
- Wide range of constitutive models
- Special attention to response of geophysical media
- Includes a variety of yield strength models

WPP/SW4: Massively parallel

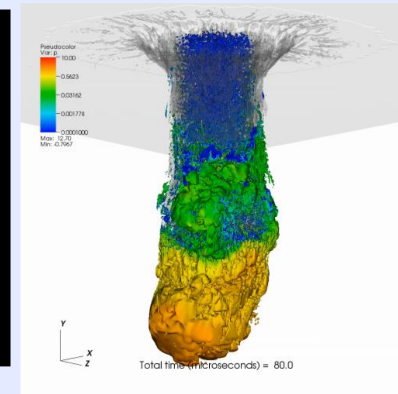
- Elastic high order FD wave propagation
- Surface topography + refinement
- WPP is already coupled to GEODYN
- Acoustic solver of atmospheric conditions



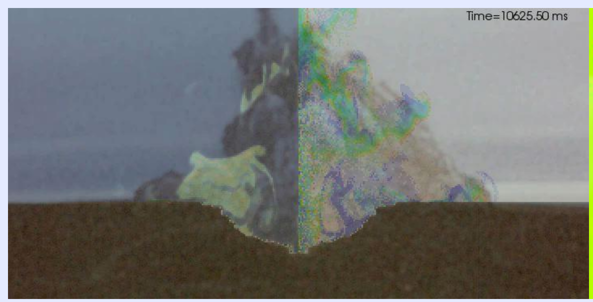
Offshore Asteroid impact



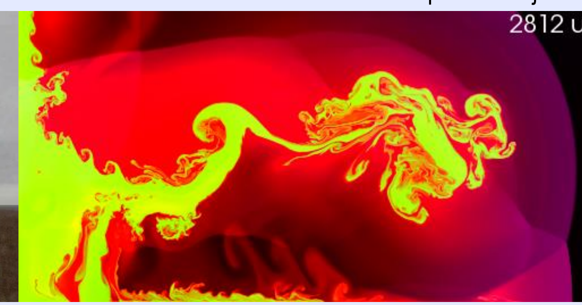
Standoff mitigation of asteroids



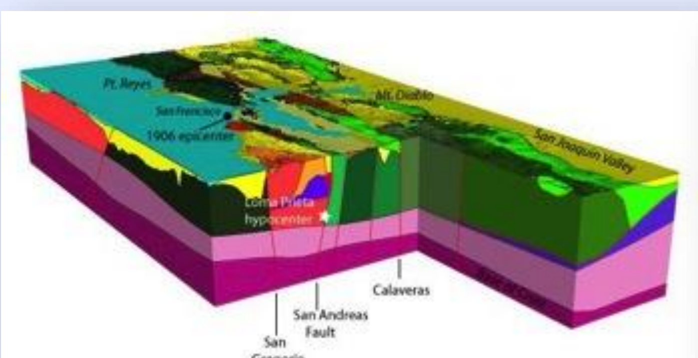
Penetration of a particulate jet

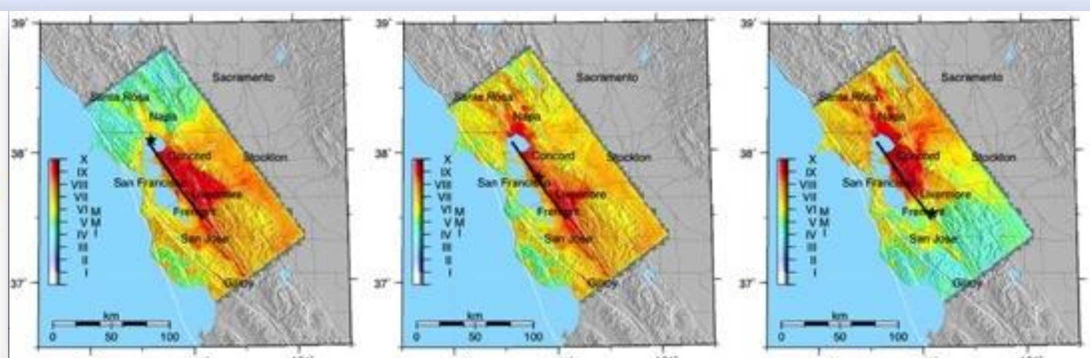


Multiphase particle cloud

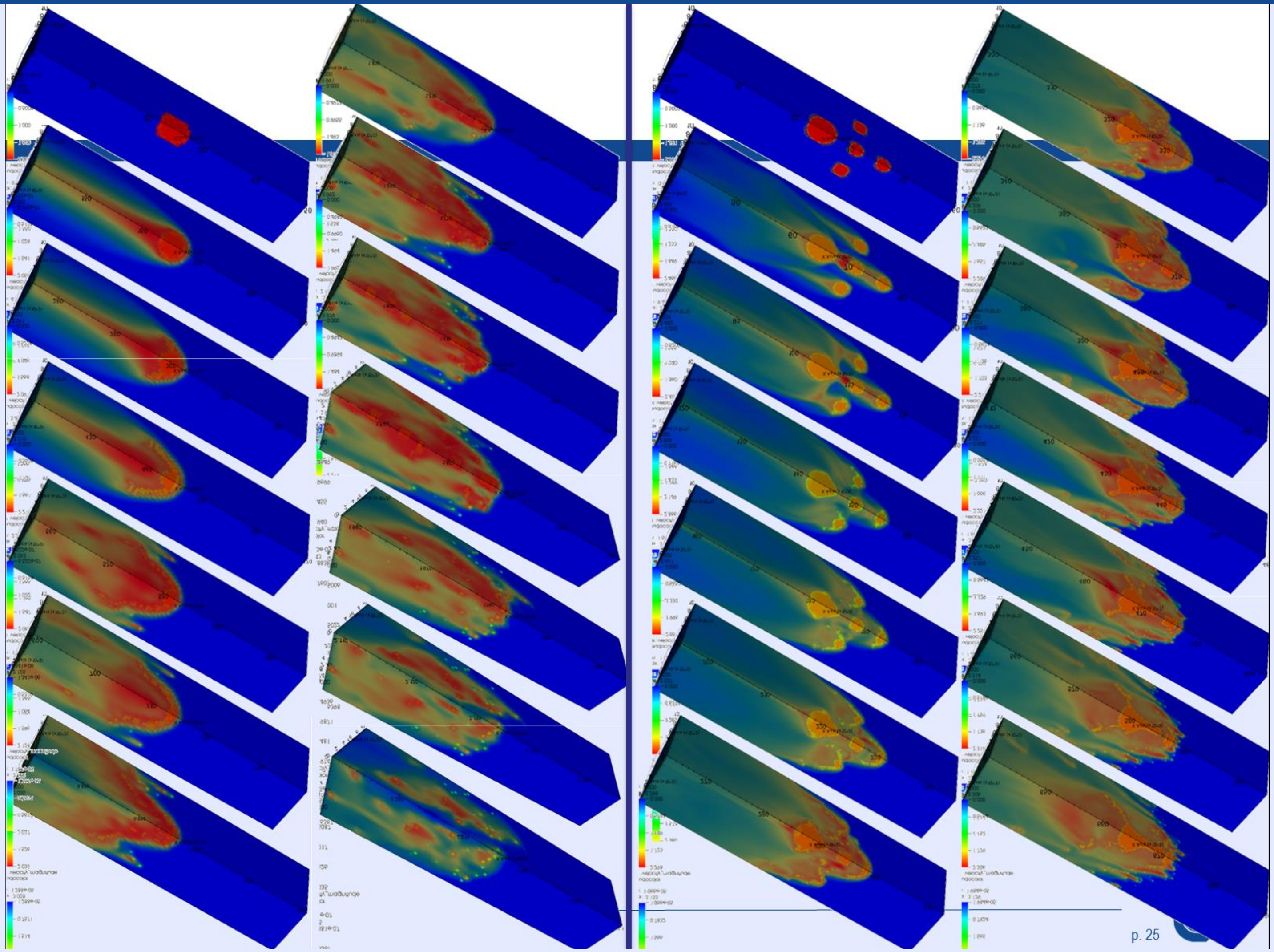


Afterburn of TNT charge



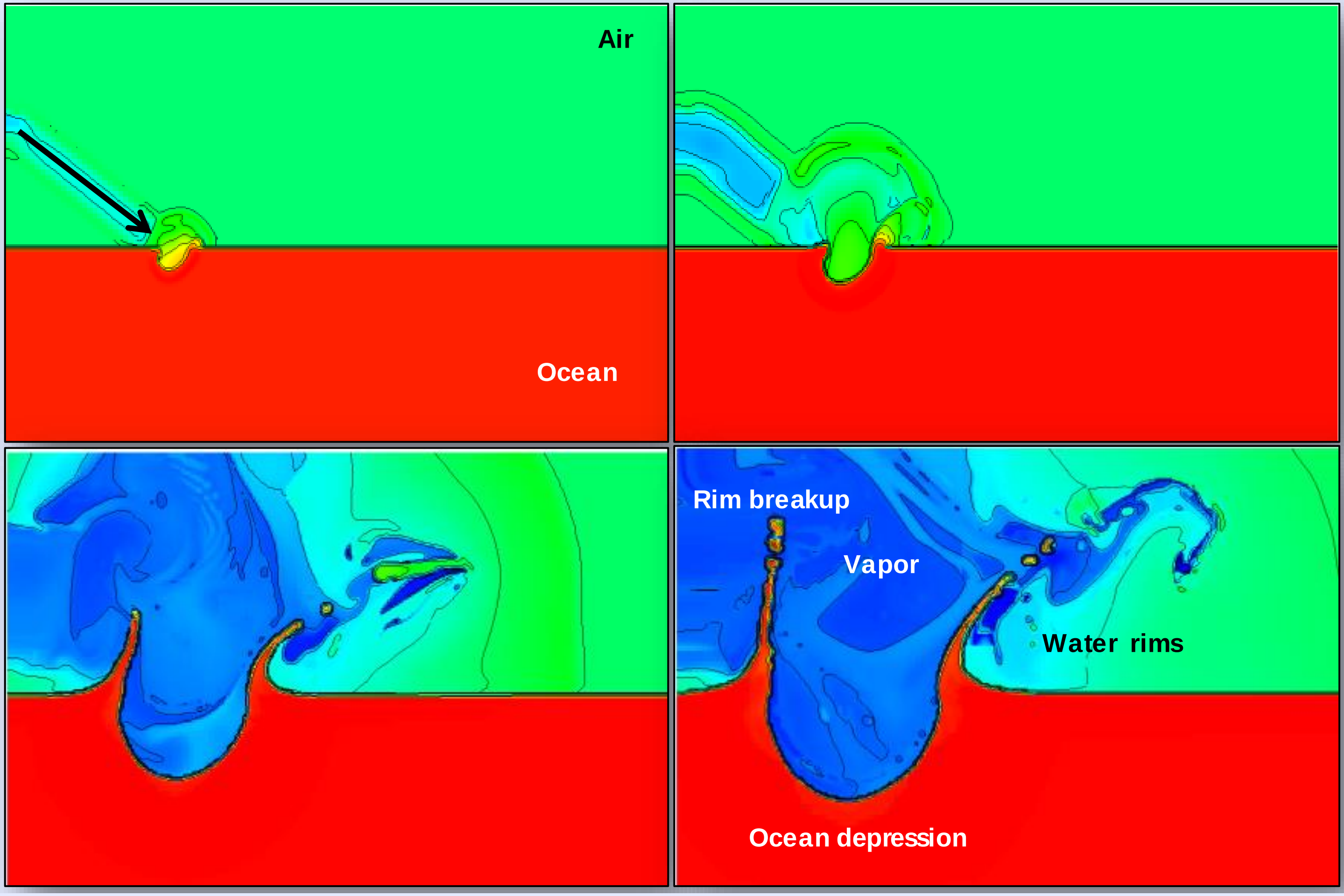


3D Simulation of Asteroid(s) atmospheric entry



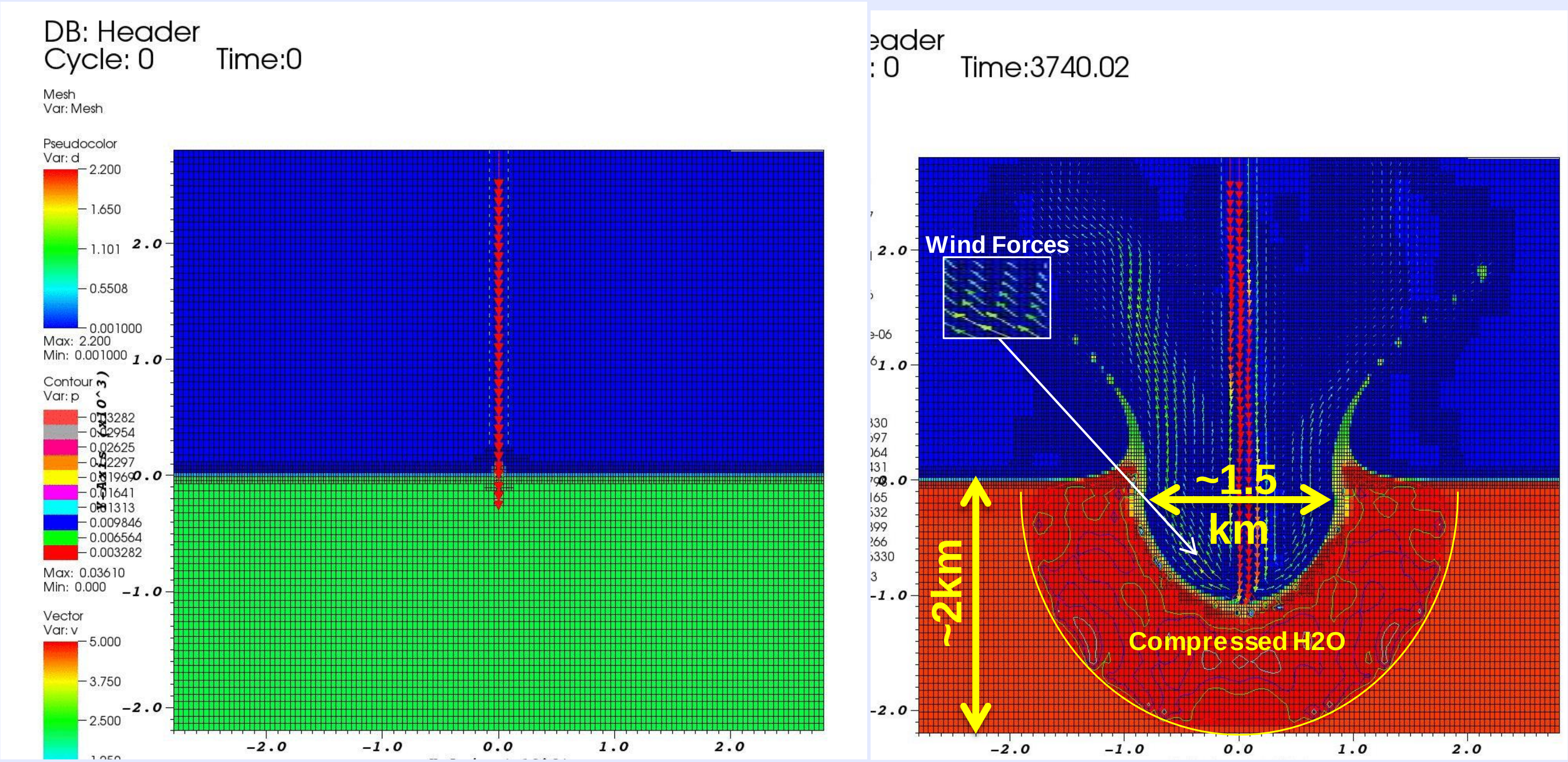
Large asteroids usually breakdown during entry, however conditions may shield large chunks which may well impact earth

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…

Water impact source generation using 3D GEODYN



Vertical cross-section (3D domain)

"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.

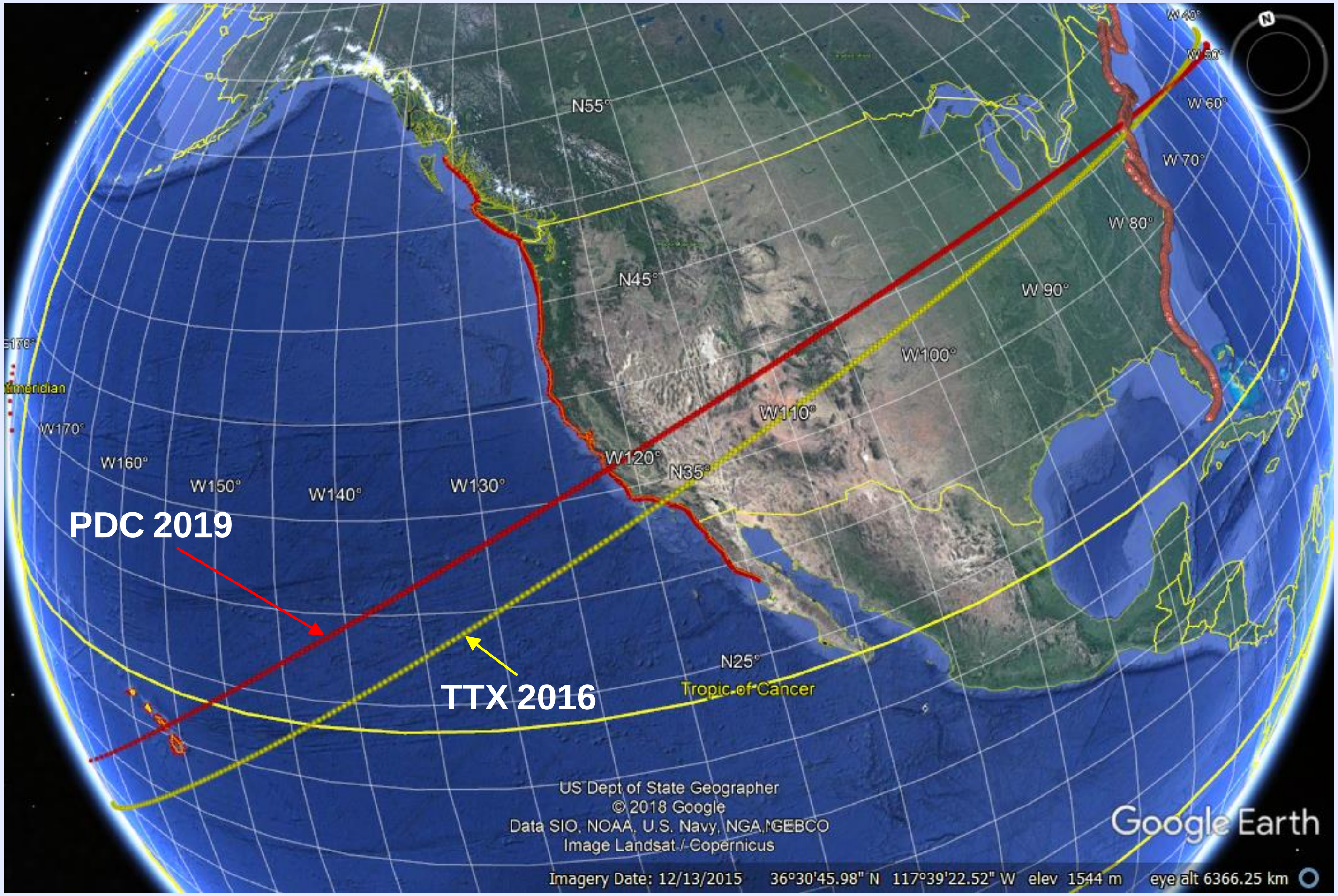
PDC 2019 TTX vs. TTX 2016

Assume 100,
200 &300m diameters

Density of 2g/ccm

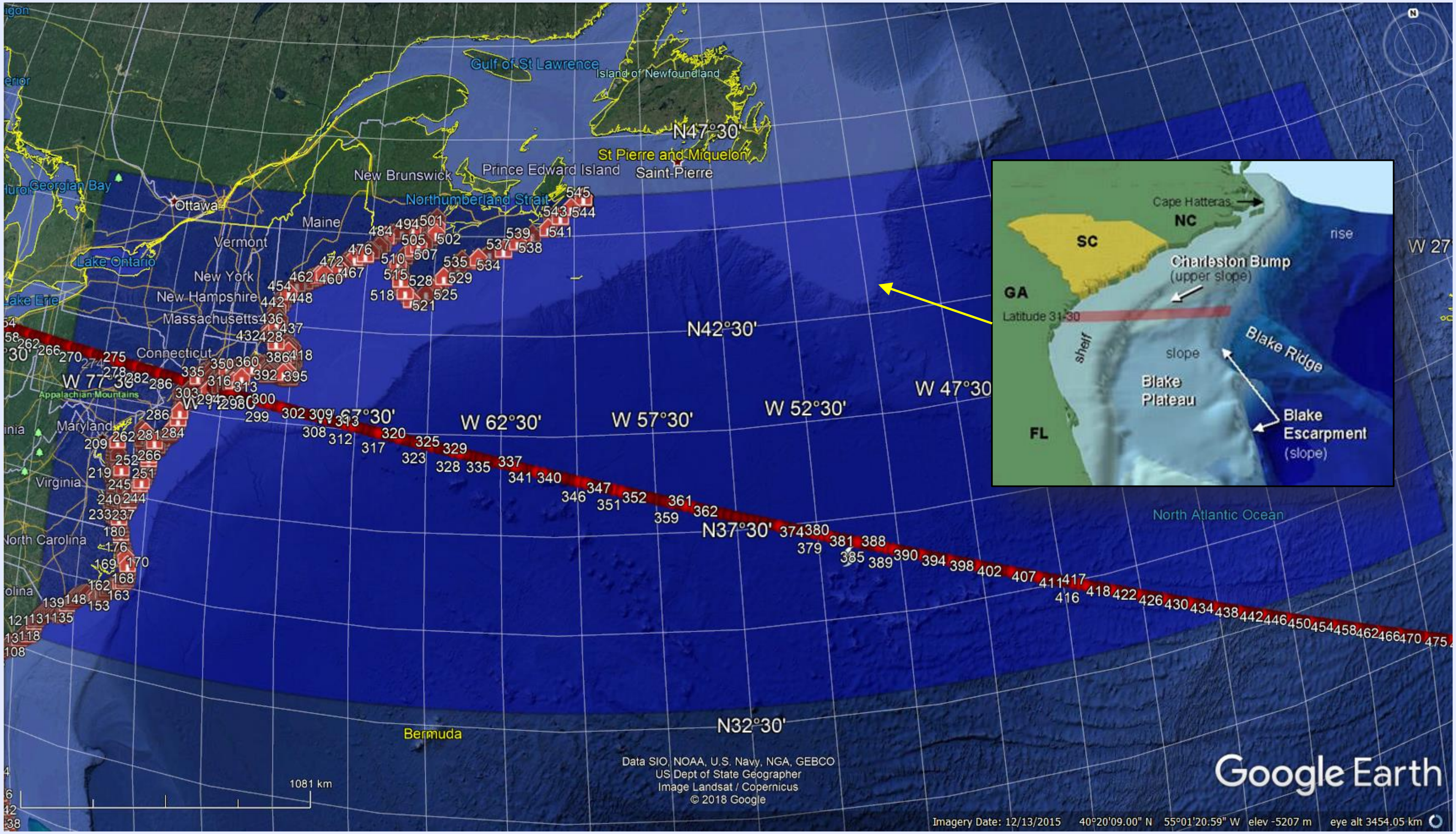
Trajectory is given

East & West US coasts



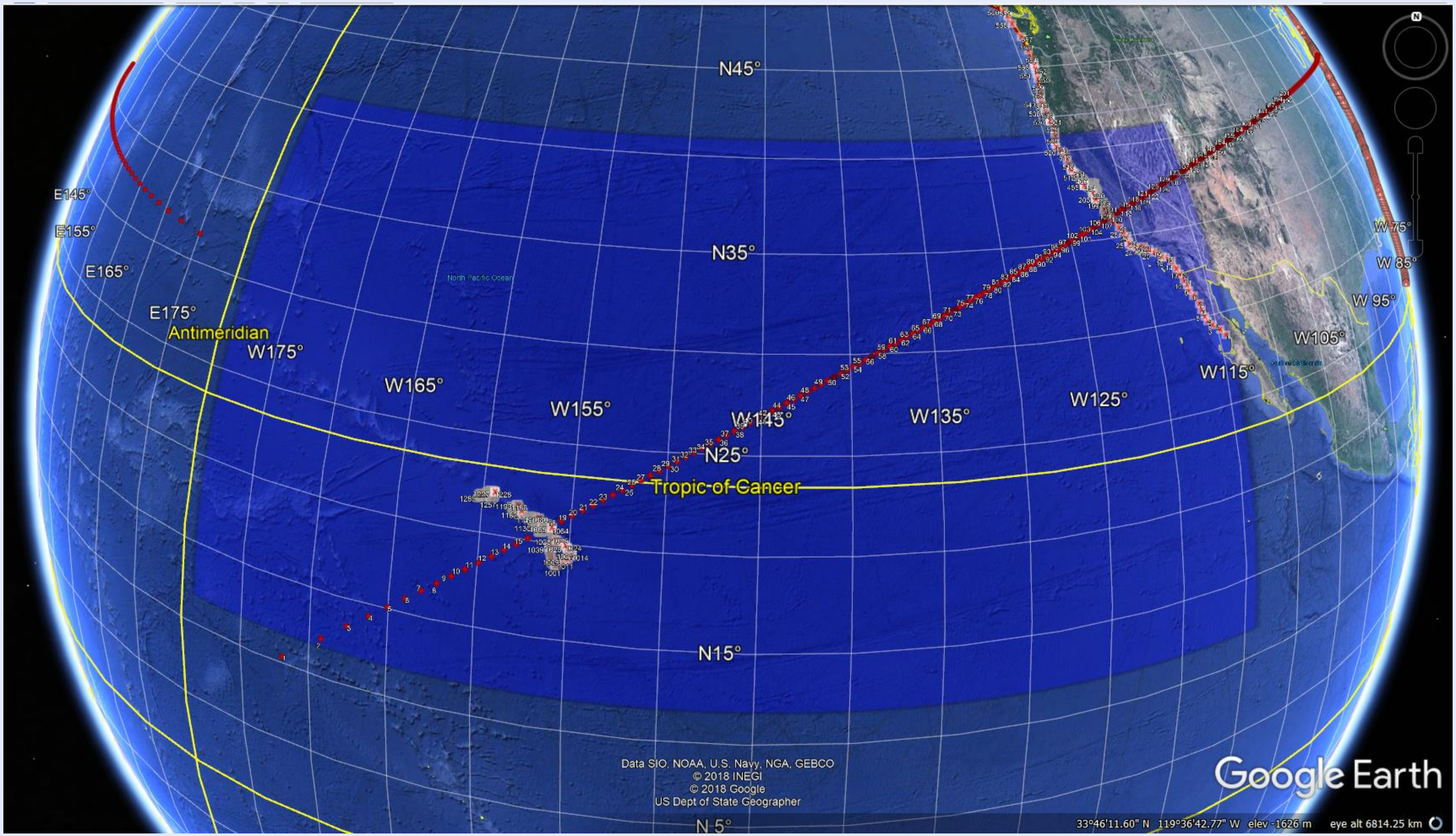
Impact risk corridor was established by Paul Chodas from NASA for the PDC 2019 TTX
http://neo.jpl.nasa.gov/pdc19/2019pdc_mts.txt

PDC19 Scenario: Atlantic patch – US East Coast



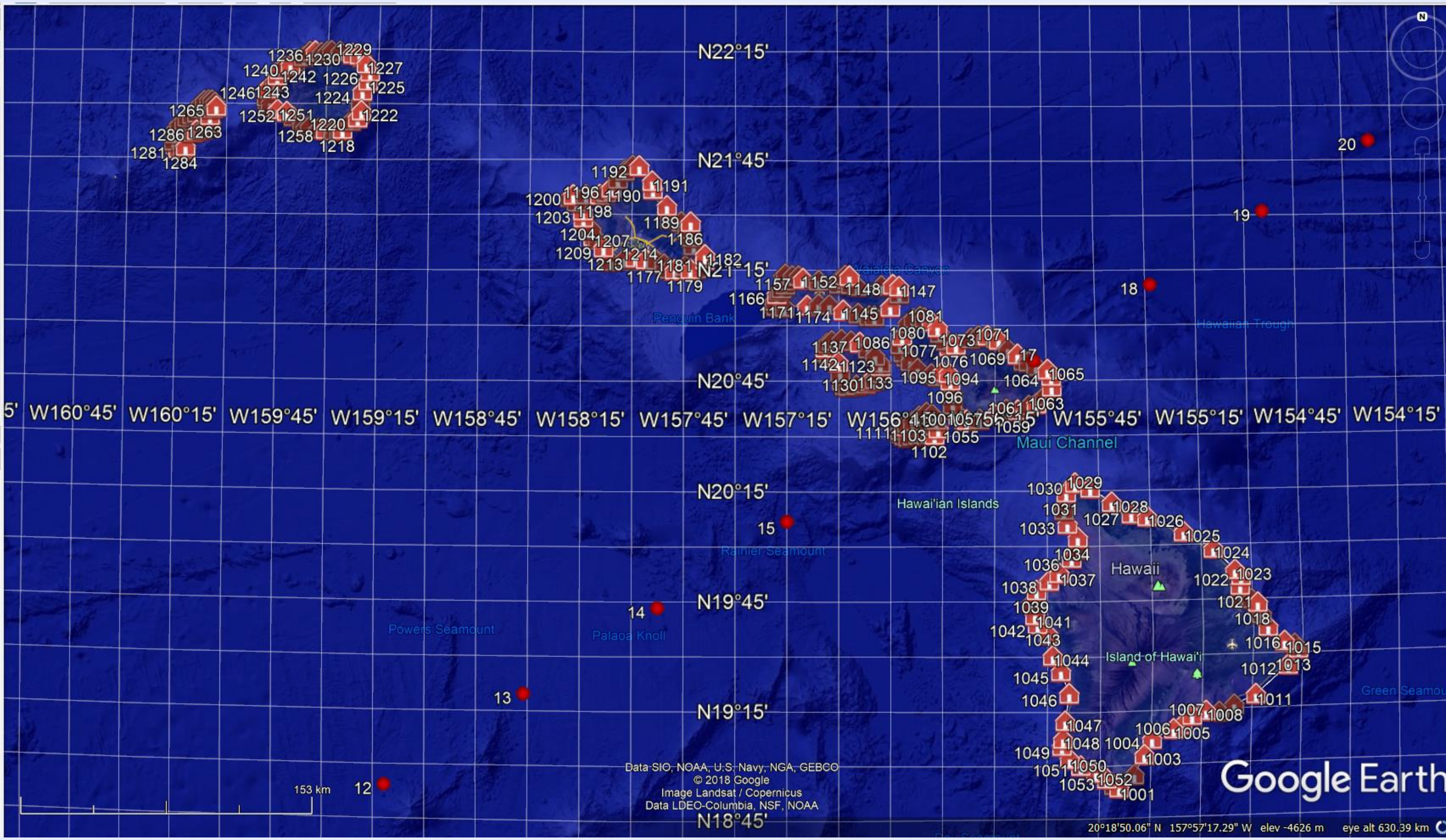
- The largest domain I have simulated for asteroid impacts – open ocean – deep/shallow waters
- Bathymetry not very complex at far east, more challenging closer to USA East coast
- Impact on US East coast and Canada and more…

PDC19 Scenario: Pacific patch – US West Coast

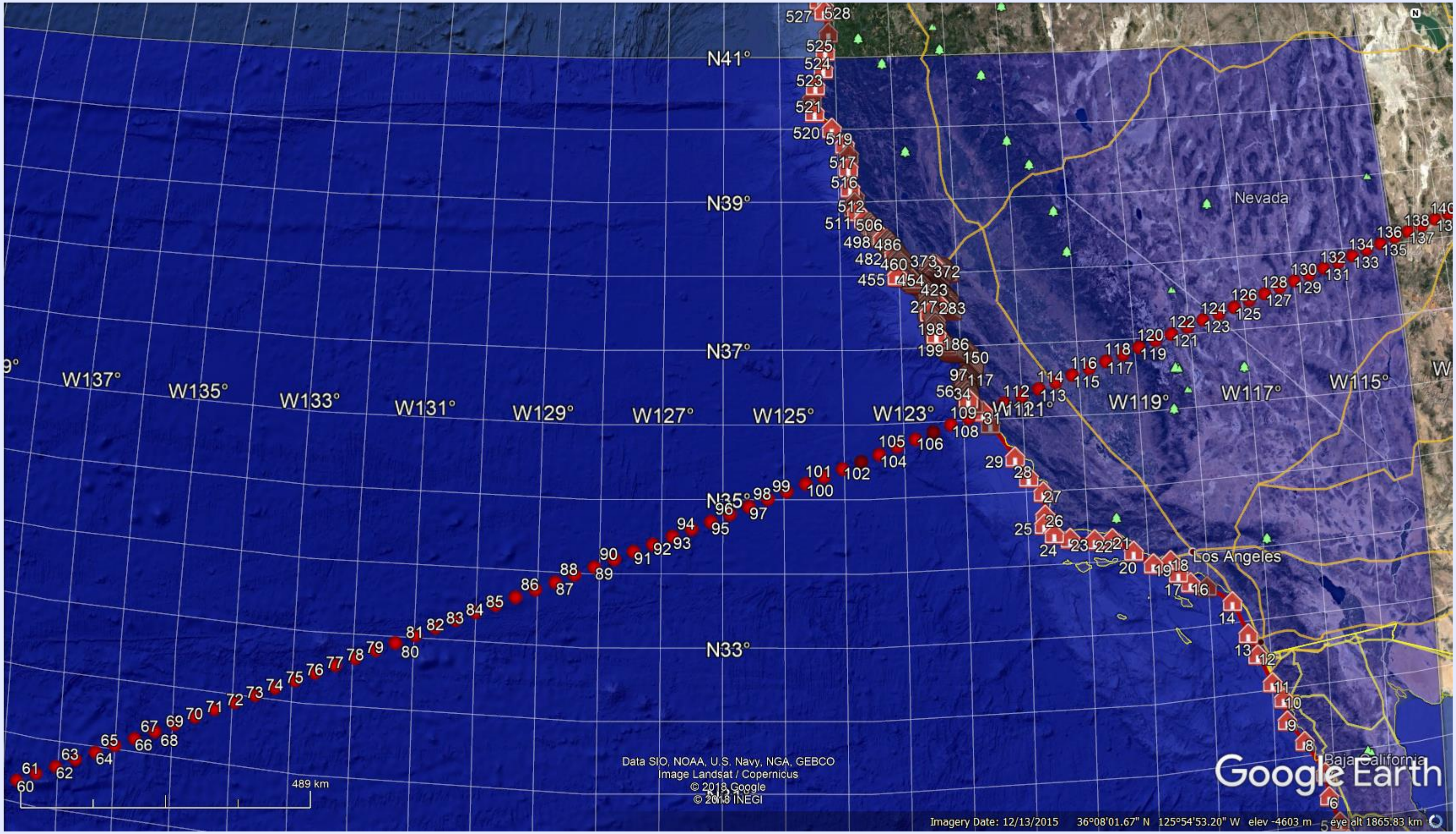


Impact on Hawaii and US west coastline

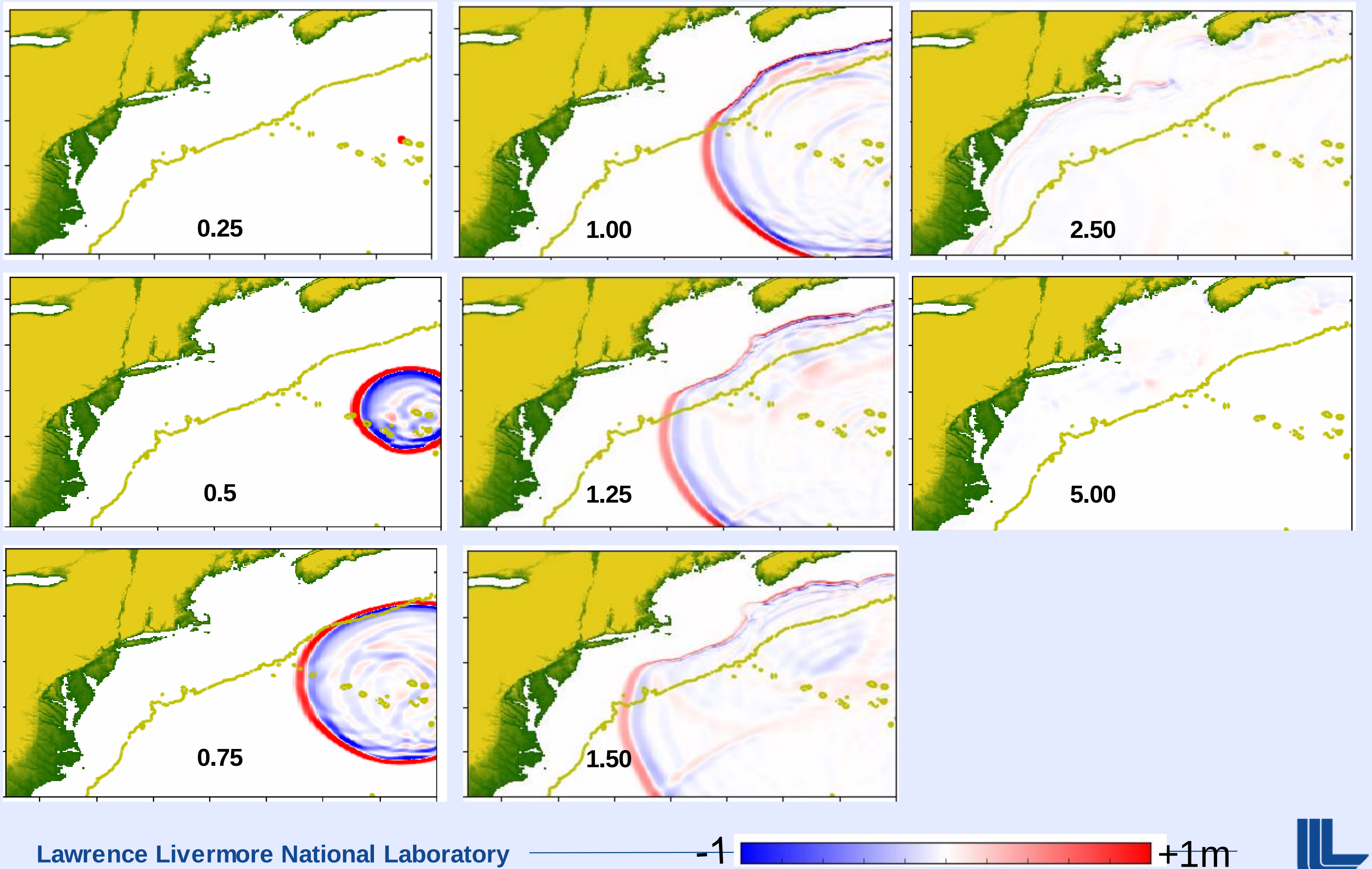
Hawai’ian Islands Water Wave Height Gauge Stations



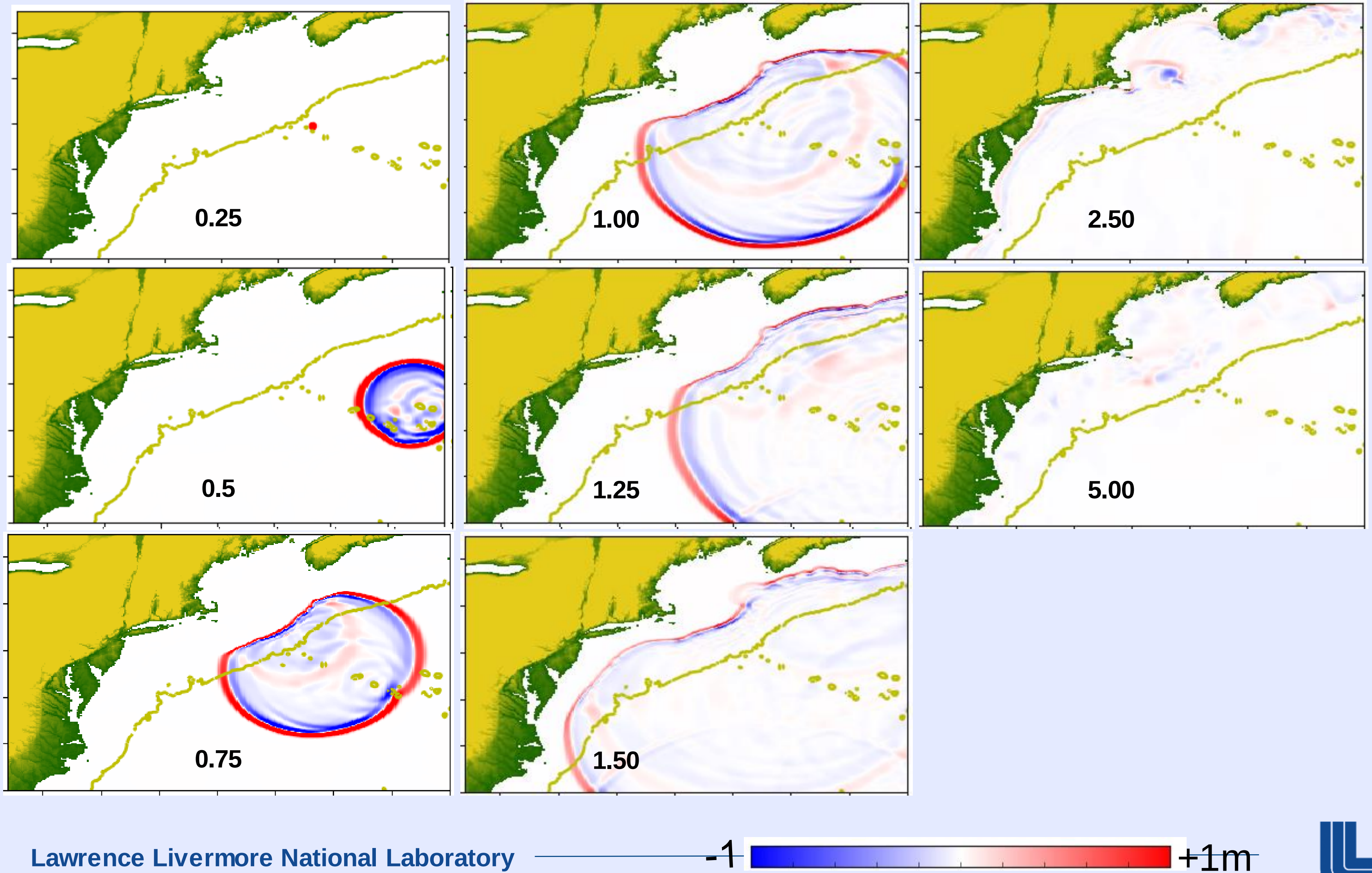
West Coast Water Wave Height Gauge Stations



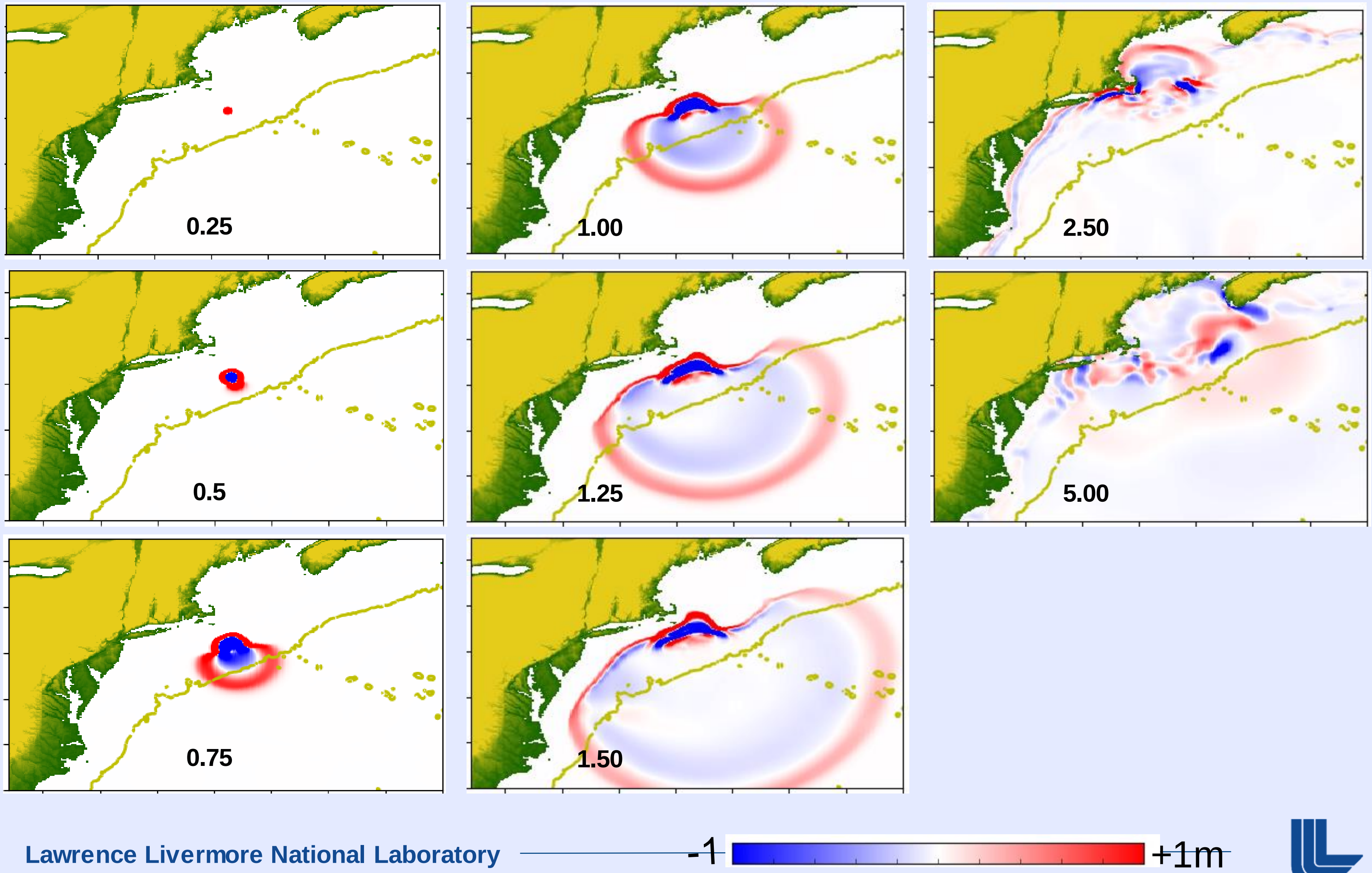
Examples of water wave propagation for 100m asteroid impacted at site #340



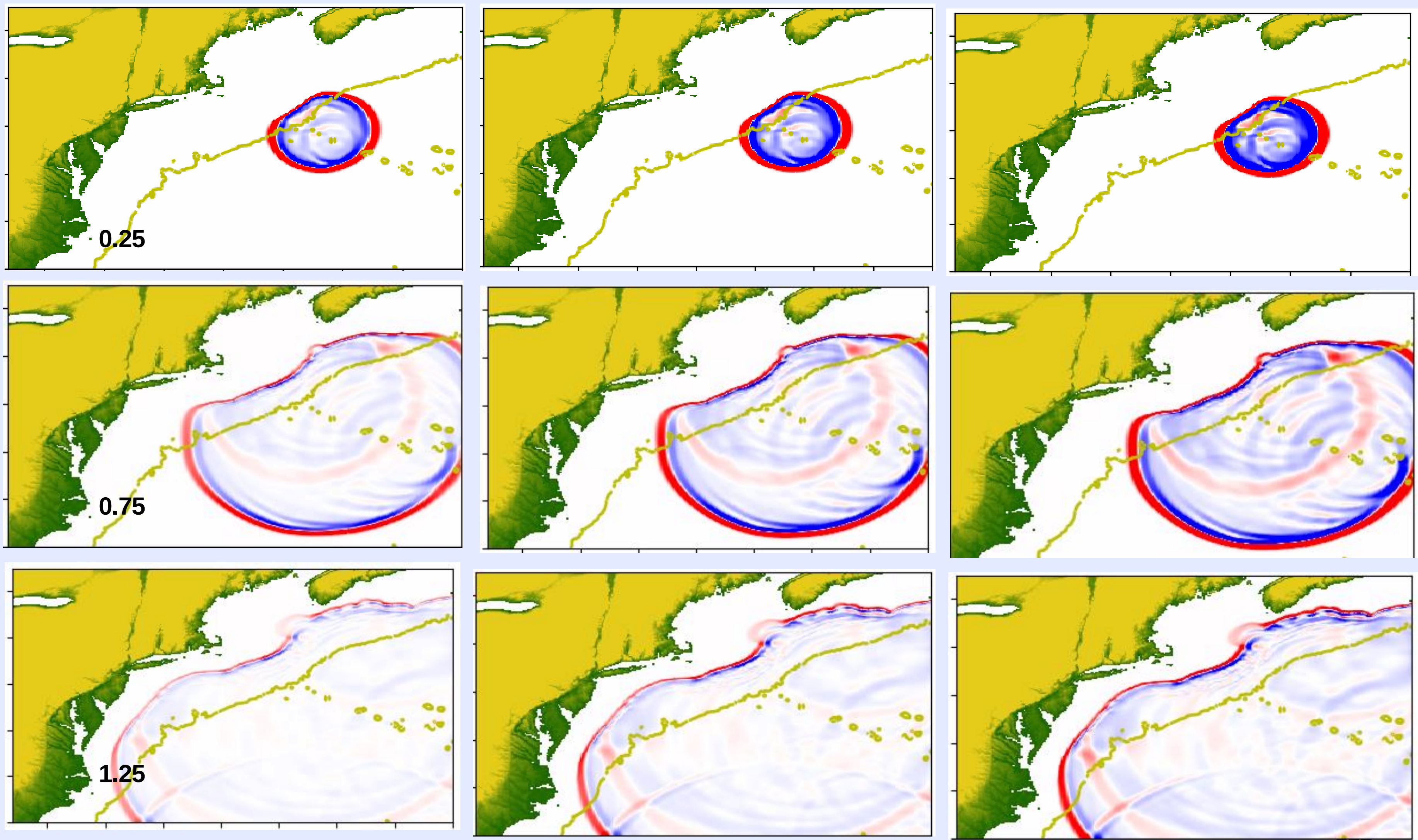
Examples of water wave propagation for 100m asteroid impacted at site #320



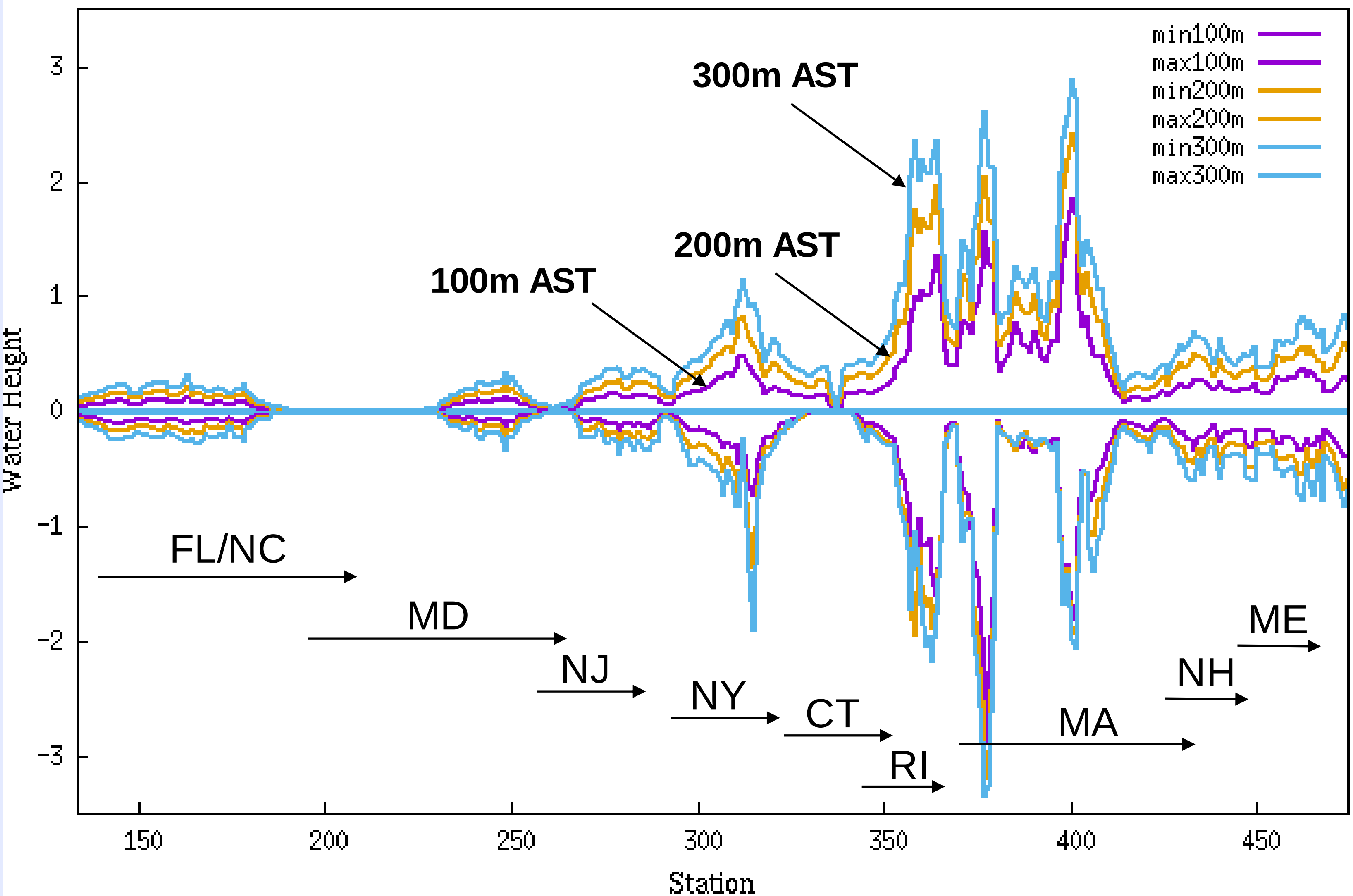
Examples of water wave propagation for 100m asteroid impacted at site #306



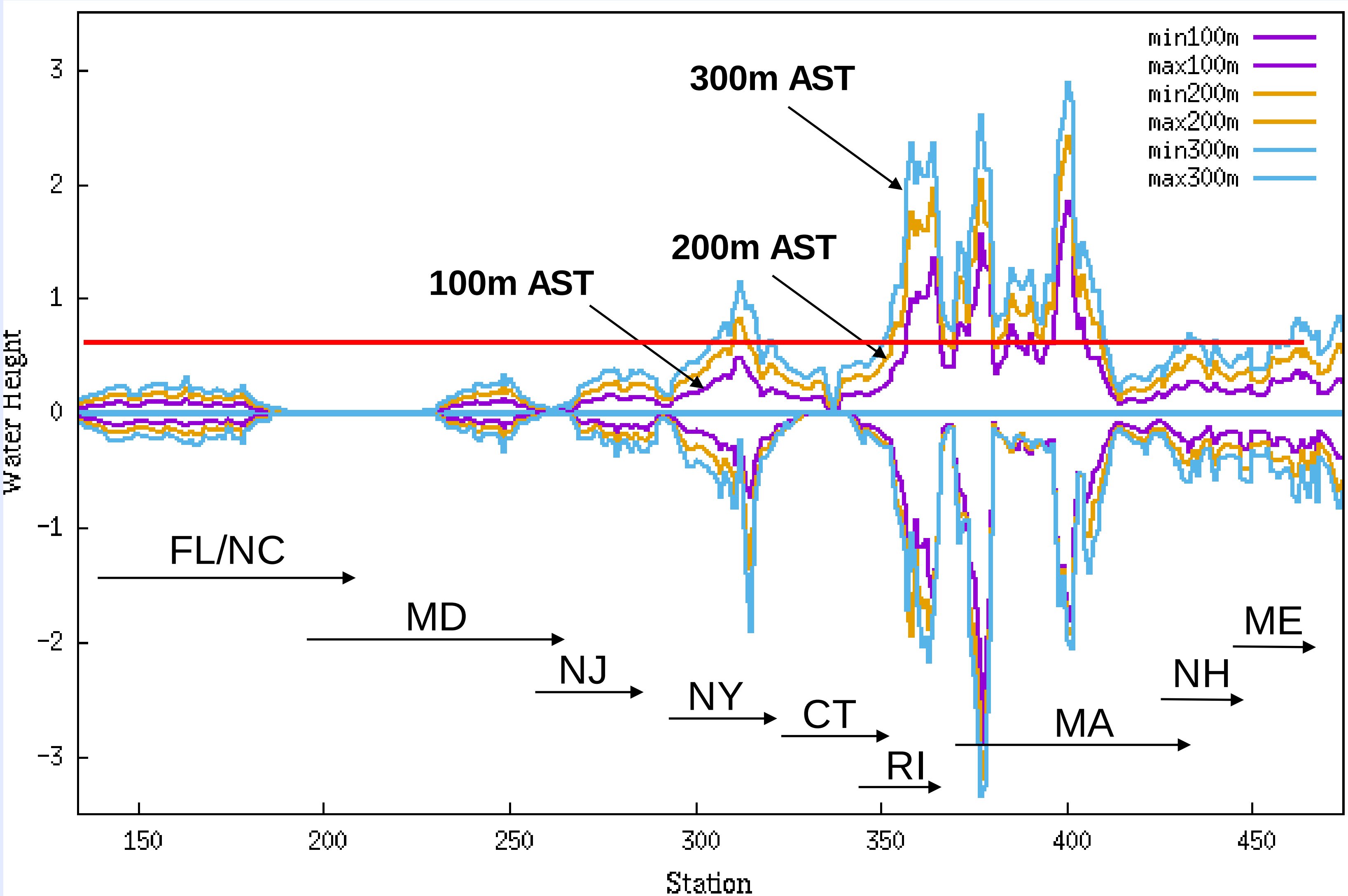
100 vs 200 vs 300 m diameter asteroid



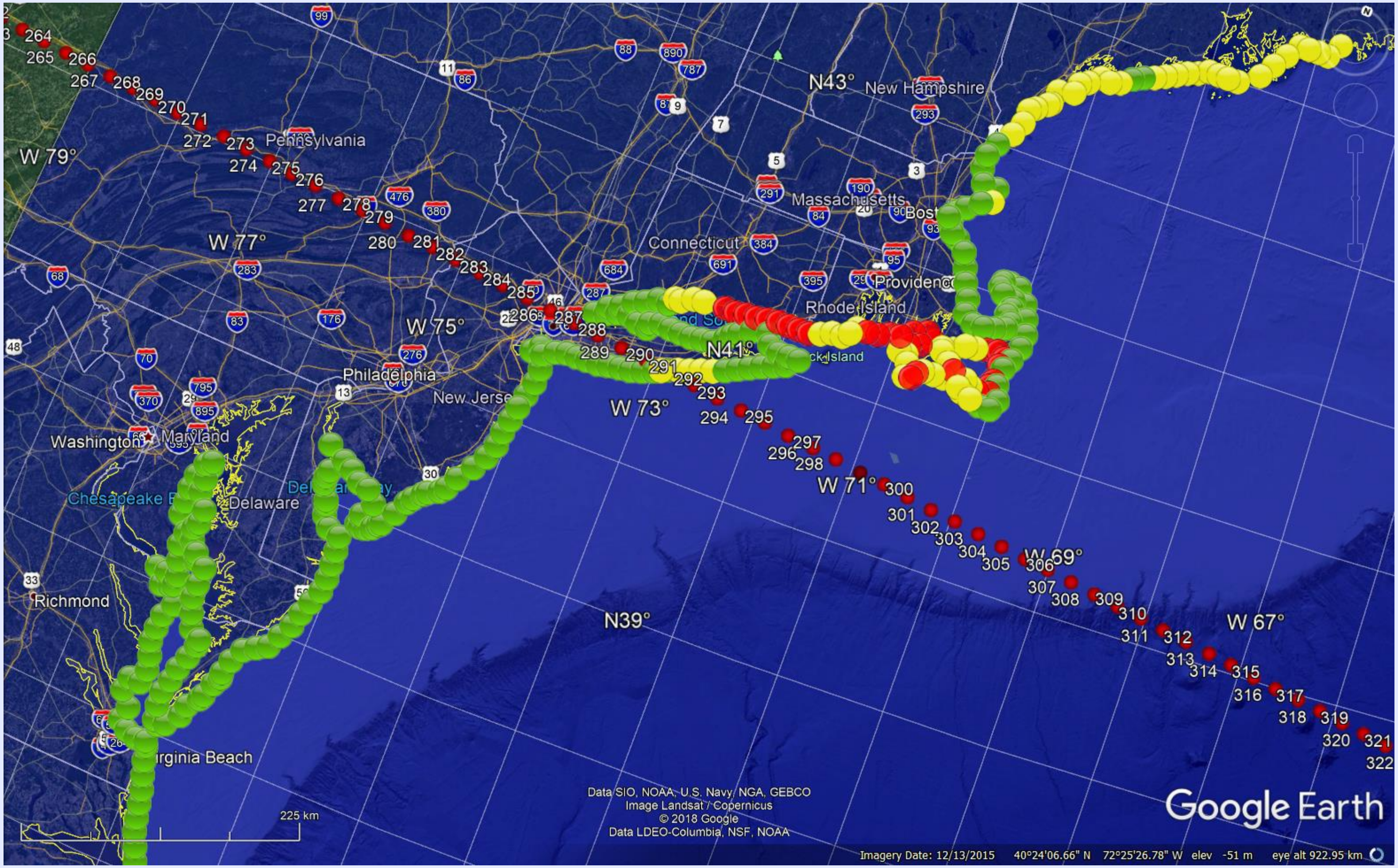
Min & Max of Water Height along US East Coast



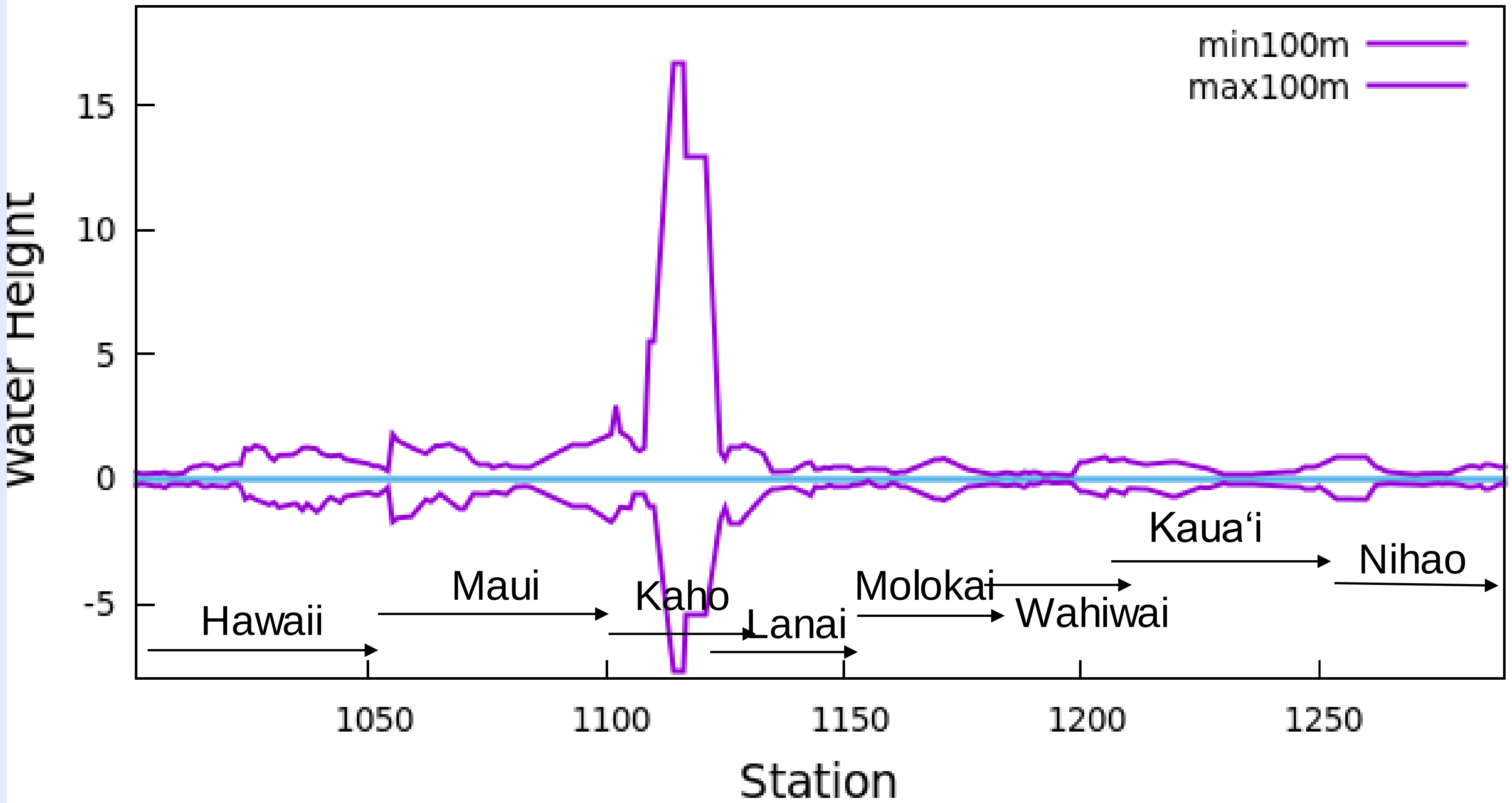
Min & Max of Water Height along US East Coast



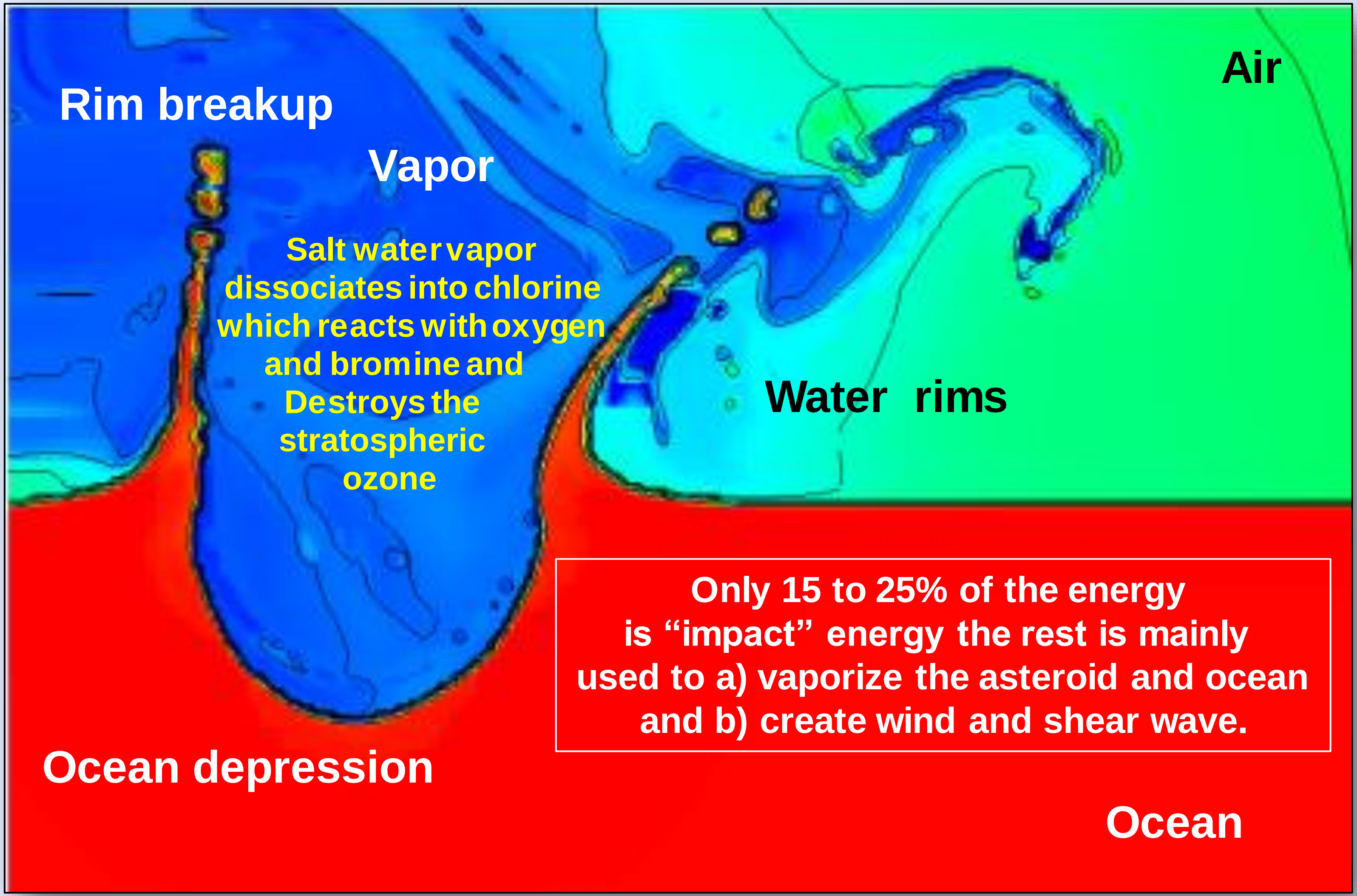
Example of a Hazard Map based on a hypothetical threshold for 300m AST



Min & Max of Water Height along Hawai'i



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**

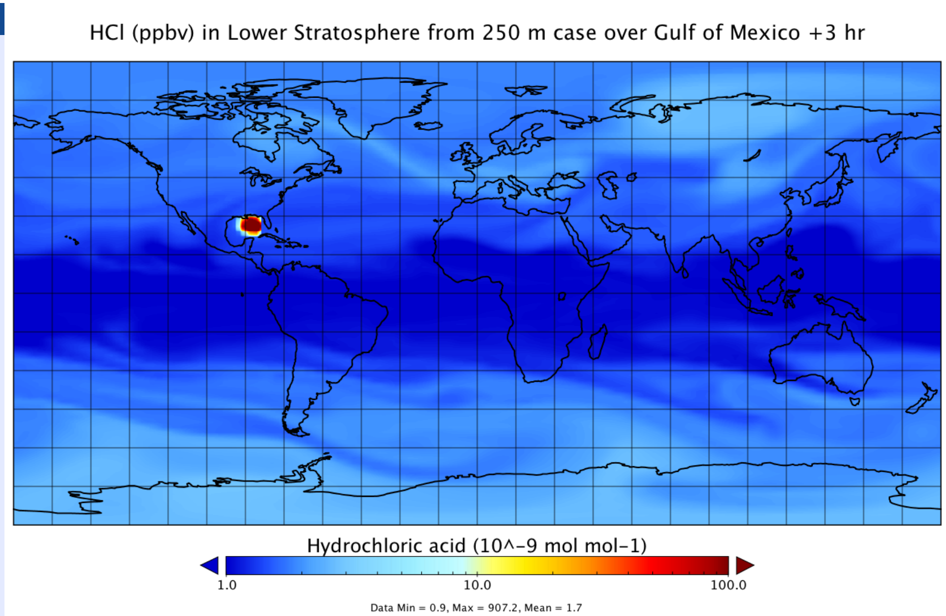
A 250m Diameter impactor over deep water section in Gulf of Mexico produces no significant effect

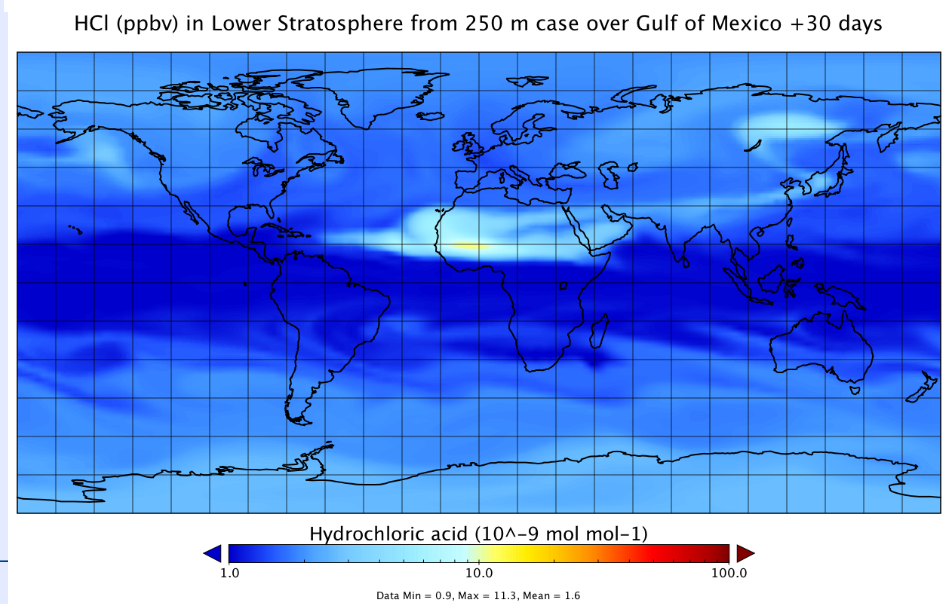
- NASA's Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM)
- Source impact for a ~250 m object striking the Gulf of Mexico.
- Total Vaporized seawater - ~ 6 x 10^{10} kg

  Additional products: HCl - ~ 1.2 x 10^{8} kg

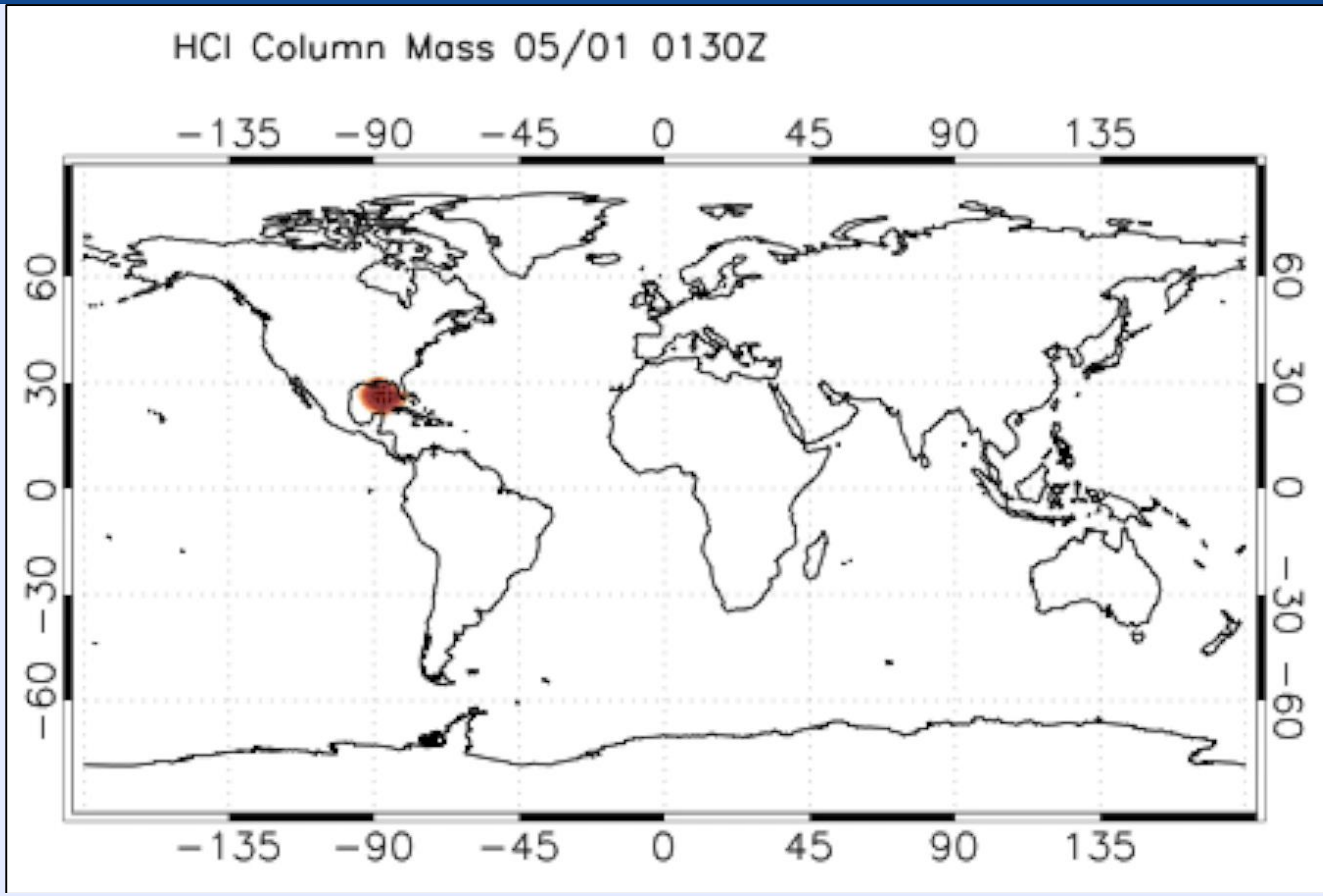
  HBr - ~ 1.8 x 10^{5} kg

  NO - ~ 6 x 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,



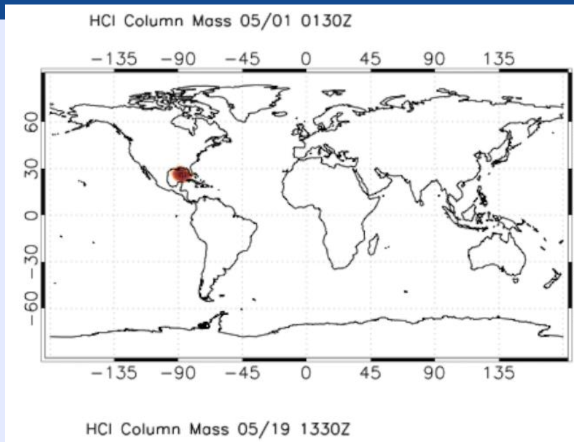


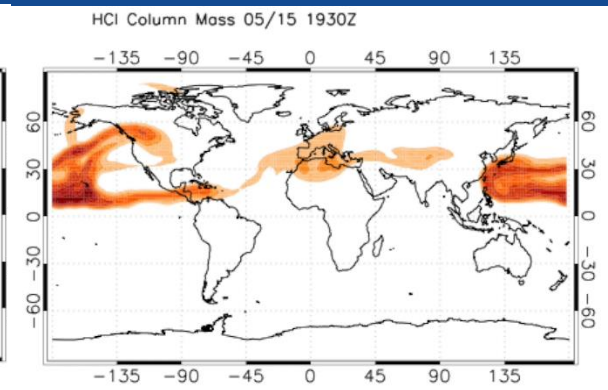
A 400m Diameter Impactor over deep water section in Gulf of Mexico produces sizeable effects.

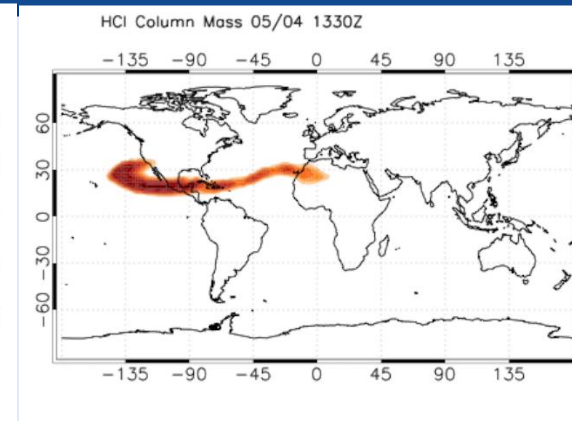


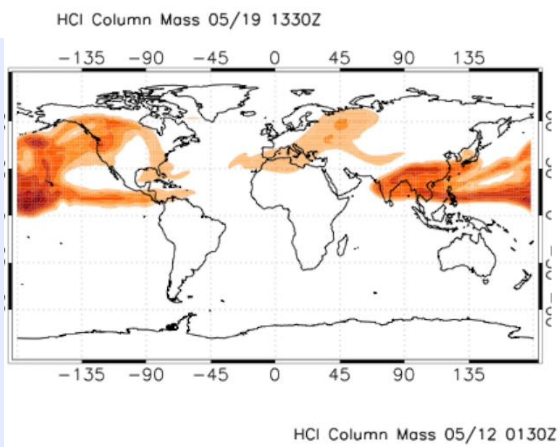
- Perturbation is ~2x the current background concentrations of Cl
- Smaller change in Br (30-50%) compared to Cl
- 15-30 % change in stratospheric water vapor
- Less H_2O vapor in the troposphere up to 5-10%
- Changes in both stratospheric & tropospheric ozone: 10-15% decrease in the stratosphere
- Temp. decreases (1-3 K) in the stratosphere mostly responding to the ozone loss

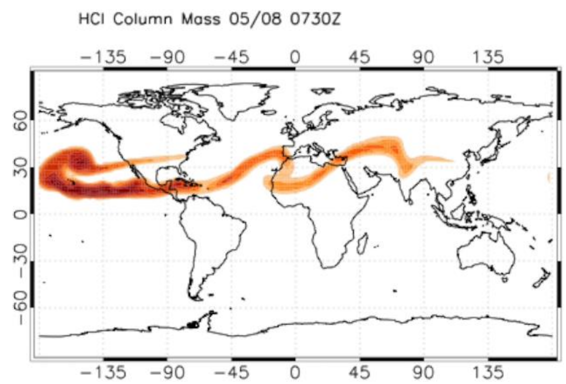
A 400m Diameter Impactor over deep water section in Gulf of Mexico produces sizeable effects.

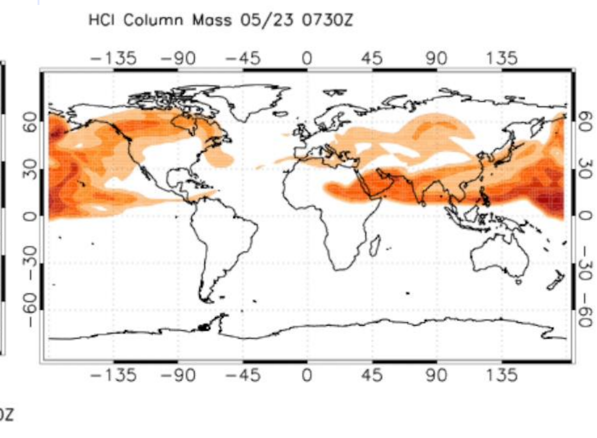


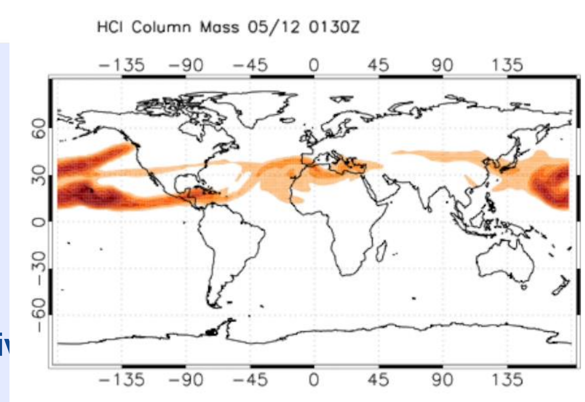


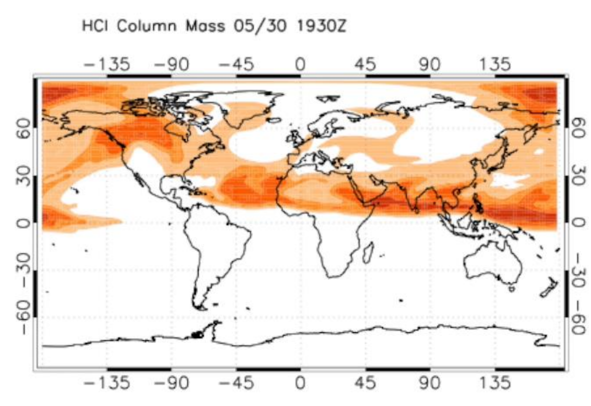




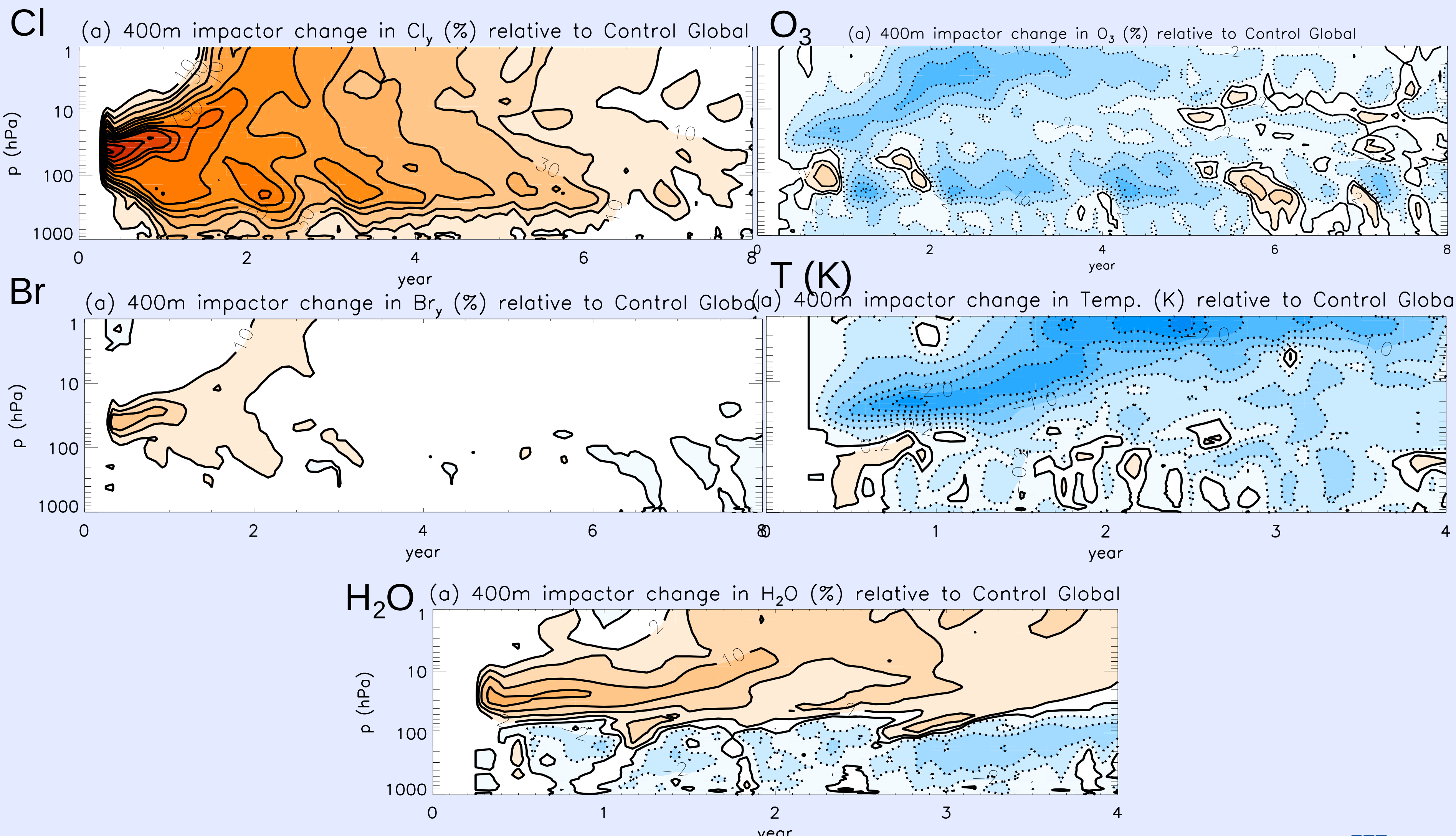








Changes in the Global signatures of Cl_y (%), Br_y (%), H^2O(%), O3(%) & Temp (K)



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

For more information:

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Auspices

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