



Simulating Kilometer-Size Asteroid Impacts on Earth

Darrel Robertson, Lorien Wheeler, Donovan Mathias

NASA

Ames Research Center

Larry Mastin, Tim Titus, Francis Rengers

U.S. Geological Survey

Asteroid Threat



- 10's of tons of harmless dust enters Earth's atmosphere every day
- An asteroid the size that hit the city of Chelyabinsk in 2013 is expected to hit Earth about every 100 years. 1500 people were injured and US\$33 million of damage.
- A kilometer size asteroid may only hit Earth every 100 000 years but could devastate a country and possibly worse.
- One such as killed the dinosaurs, every 100 million years

Chelyabinsk Meteor

Creative Commons license. Credit: Konstantin Kudrov

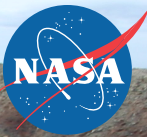
Asteroid Defense



- NASA and partners are developing asteroid defense capabilities
- Telescopes have already found most near-Earth asteroids larger than 1 km in size
- Infra-red space telescopes such as NEO Surveyor (launch date 2027) will help find smaller ones.
- DART mission in 2022 successfully impacted a spacecraft into an asteroid changing its trajectory

DART impact

NASA & Italian Space Agency



Small Asteroids

- Asteroids $< 100\text{m}$ (300 ft) across are difficult to detect and may only be discovered shortly before impact
- Rocky or icy meteors likely to be broken up during atmospheric entry and only cause damage locally
- Meteor crater, Arizona, estimated to have been created by a 50 m (150 ft) wide iron asteroid, 50 000 years ago.
- Even if discovered in time, a deflection or disruption attempt would only be likely if heading for a city
- Impact in the ocean or rural areas may be easier to evacuate, given some warning time

Meteor Crater, Arizona

Creative Commons License. Credit: Kevin Walsh



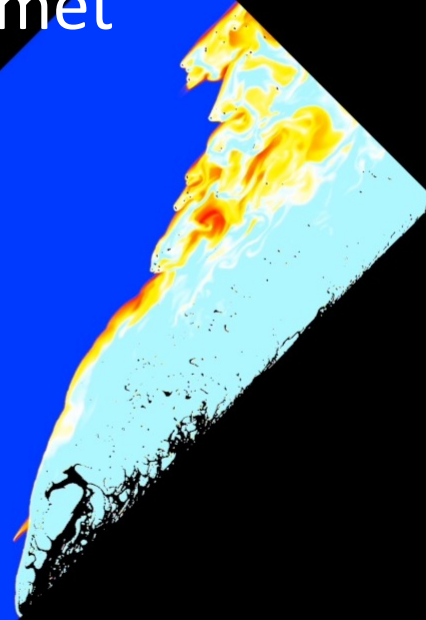
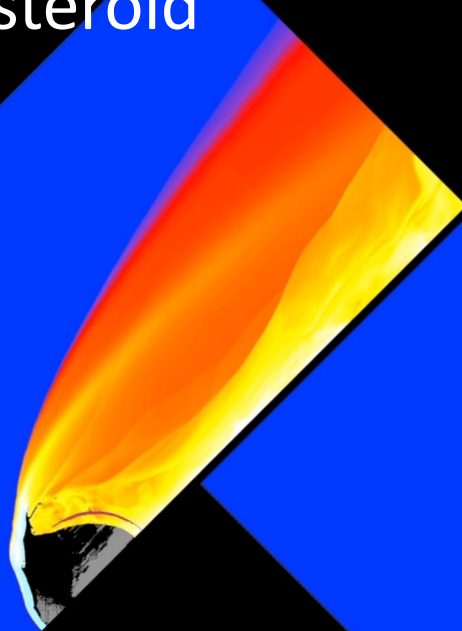
Simulation of Meteor Airburst

Ø50m, 45°, 20km/s, 2g/cc, 0.1MPa

Asteroid

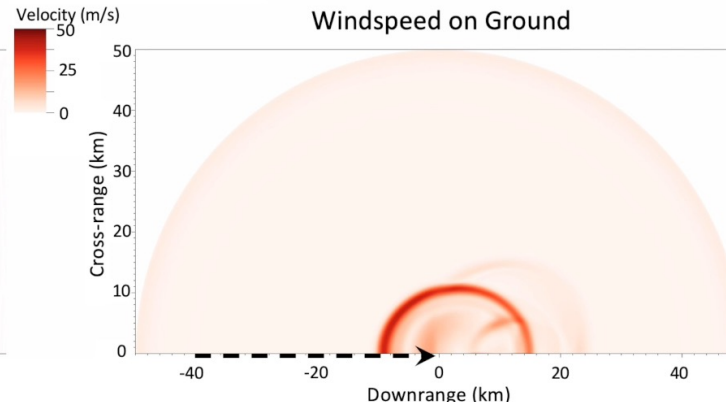
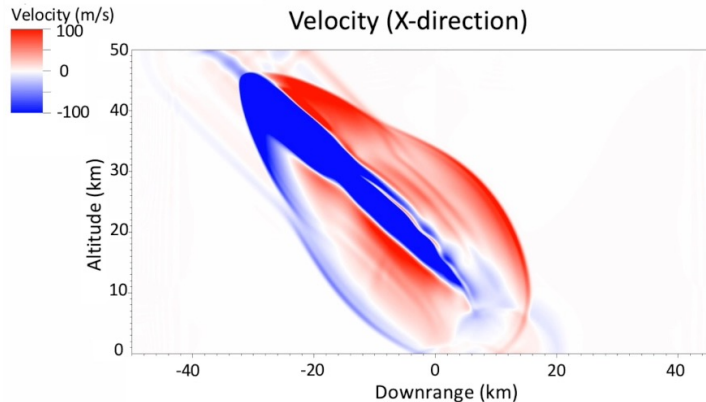
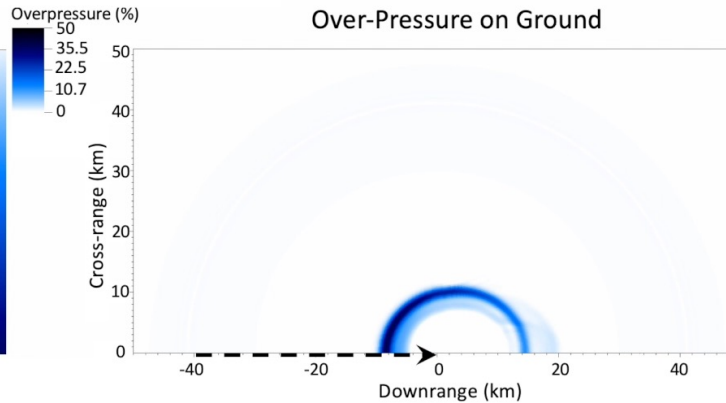
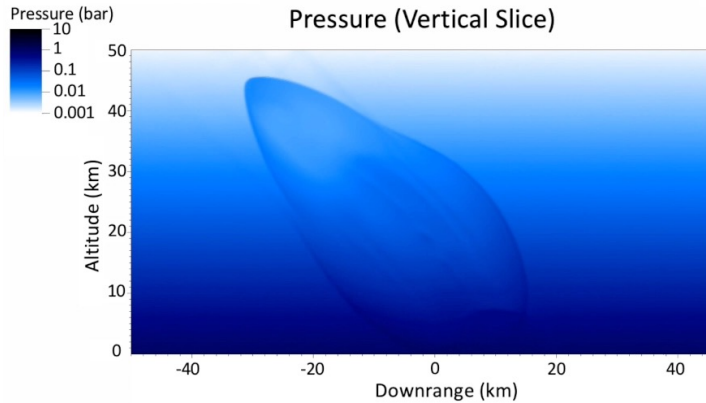
Ø50m, 45°, 35km/s, 1g/cc, 10MPa
(Jupiter family = short period)

Comet

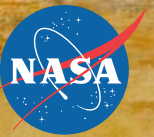


- Break-up in the atmosphere of two candidates for the 1908 Tunguska meteor which flattened over 2000 km² (~45 km radius) of forest in Siberia.

Simulation of Ground Effects



- Blast pressure and wind speed on the ground from airburst of a 70m asteroid (equivalent to 12 million tons TNT)
- Damage similar to 1908 Tunguska meteor



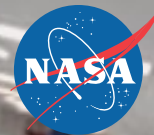
Kilometer-size Asteroids

- Most kilometer-size asteroids have already been found but may still be surprised by some or by a comet
- Thankfully no large meteor impacts in recent history, but this means don't have good observational data and likely damage currently poorly understood
- May be at the onset of climate effects where dust ejected from the crater and smoke from wildfires could affect global crop production
- As an analog the Tambora volcanic eruption in 1815 ejected at least 100 km^3 of material. Resulting temperature drops caused frost and snow in summer, damaging crops and causing a global famine in 1816.
- If an asteroid is big enough to cause comparable damage it may not matter where it hits. This will tell us the maximum size asteroid we could allow to impact even in the remotest location

Yellow skies from 1816 "Year without summer"

Painting by J.M.W. Turner

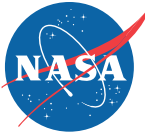
Supercomputer Simulations



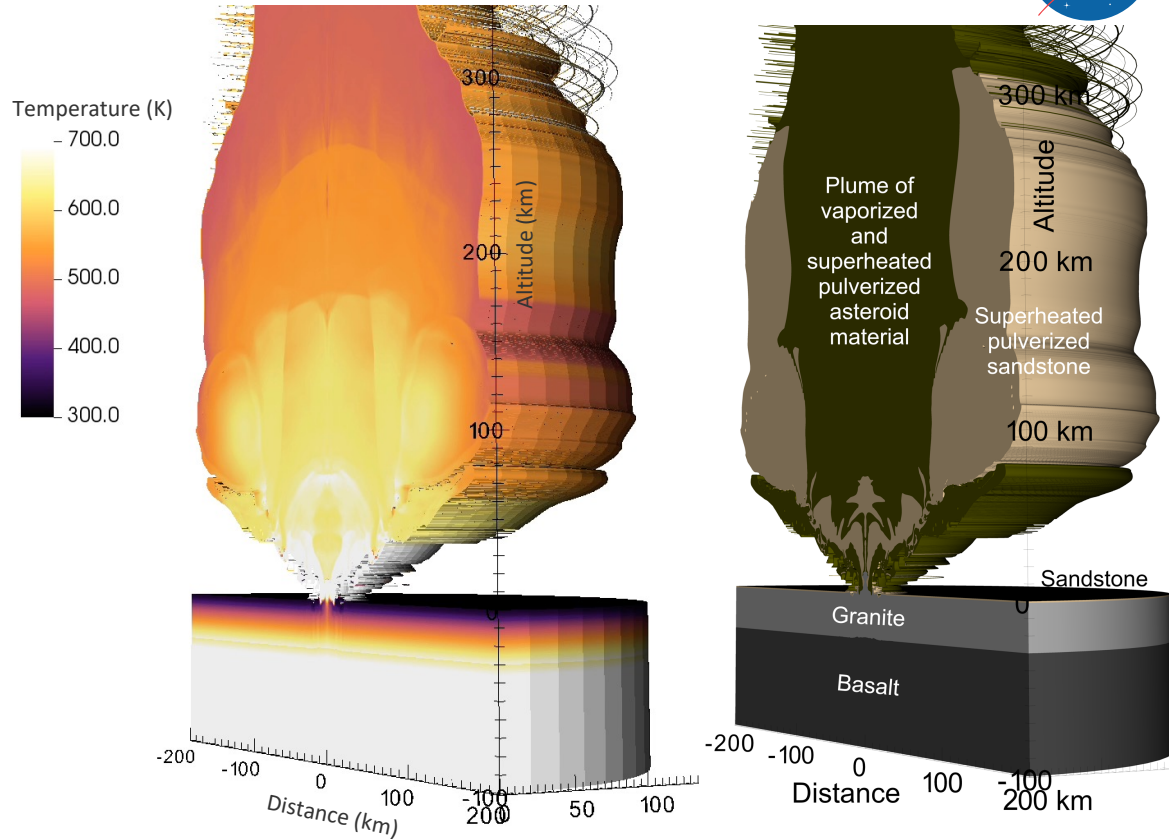
- To better predict the effects of a kilometer-size asteroid impact scientists run simulations on the Pleiades, Electra, and Aitken supercomputers at the NASA Ames Advanced Supercomputing facility.
- Simulations use anything from 40 – 4000 CPUs and anywhere from hours to weeks of runtime.
- NASA scientists collaborate with scientists from U.S. Geological Survey and the National Center for Atmospheric Research.
- Computer codes used include the ALE3D hydrocode from Lawrence Livermore National Lab, ASH3D from the USGS, and CESM the Community Earth System Model from NCAR.

Pleiades Supercomputer
NASA Ames

Simulation of a 2.5km asteroid impact



- Impact vaporizes the asteroid
- Excavates a crater 10 km deep
- Much more ground material (~2000 km³) than asteroid
- Vaporized, melted, and hot pulverized rock is ejected into space.
- Plume initially at 10's of 1000's of degrees cools as it expands into space.
- Bottom of plume forms a cloud of hot material that extends hundreds of kilometers which could potentially ignite wildfires



Plume Effects



- Large pieces of ejecta will rain out of the plume causing a hazard on the ground
- Smaller pieces will be blown downwind by the weather, raining down similarly to volcanic ash.
- Sub-micron dust may stay aloft for months or years, blocking sunlight and cooling the Earth.
- Simulations like the previous one are being improved to calculate the size distribution of the ejecta. In the meantime estimates can be fed into models of the plume fallout and climate simulations.

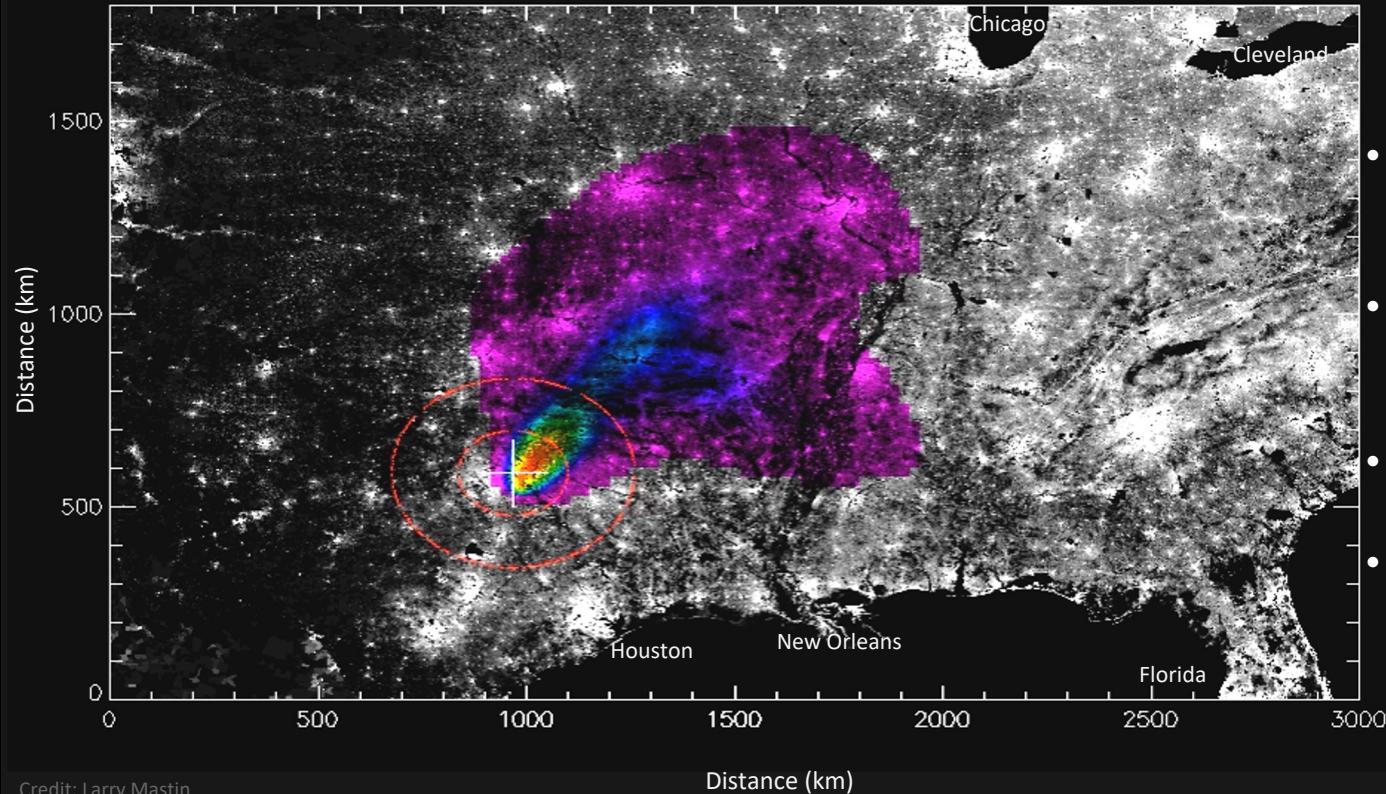
Calbuco, Chile volcanic eruption 2015

Public domain. Credit Andiseño Estudio

Fallout simulations from a 800m size impact

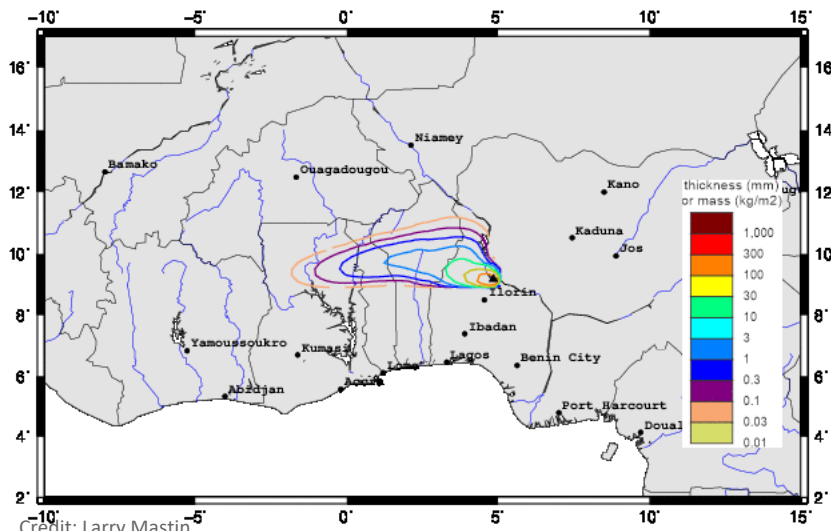
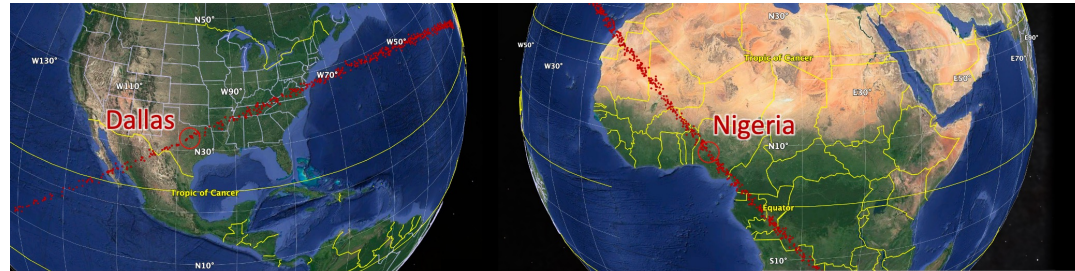
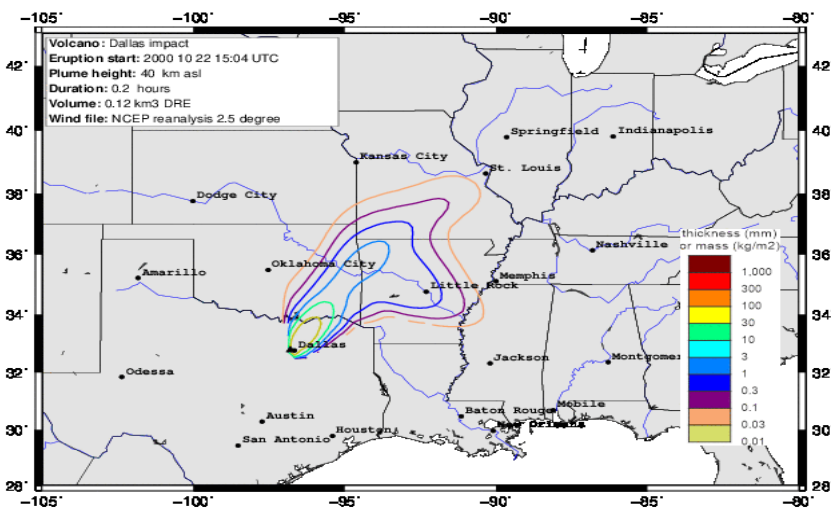


Impact of 800m asteroid in Dallas, Texas. Estimated 1 billion tons pulverized rock lofted into atmosphere



- Each frame of movie shows expected fallout for the weather from a different year
- Each simulation began October 22nd for the past 20 years.
- Wide range of possible outcomes depending on the weather that week
- Plume will affect airlines, roads, crops, air quality
- On average 10 million people live in areas affected by more than 1mm thickness of dust (enough to damage crops)

Simulations of fallout vs location



- The 2023 Planetary Defense Conference considered the same 800m asteroid hitting Nigeria
- While winds in Dallas are mostly westerly they are very unpredictable in strength and direction
- Nigeria in the trade wind belt has very predictable easterly winds so less variable fallout

Need for Supercomputer



- The impact simulations are similar to many fluid dynamics simulations but include material strengths
 - Space is split into millions of tiny cells on a mesh
 - Cells are updated based on the properties of the surrounding cells at each timestep.
 - Maximum timestep is time it takes either moving material or the speed of sound to cross the cell
 - Large domains extending hundreds of kilometers, and small timesteps from hypersonic speeds means simulations require large amounts of memory, many CPUs, and long run times
- The fallout simulations are similar and require less computer resources per run, but variability of the weather means hundreds if not thousands of runs are needed to obtain statistics on the fallout thickness and locations
- Aim is to determine effects on people and crops for different asteroid sizes and impact location, so many sets of simulations are required

Wildfires



- The hot plume will act like a broiler and may start wildfires on the ground
- An important addition to the impact simulations will be radiative heat transfer using the NASA computer codes HARA or NEQAIR, to predict where wildfires start
- The USGS has wildfire propagation models and can predict the spread of wildfires started by the impact
- As well as direct damage from the fires, smoke from the wildfires will add to the plume making air quality worse, and if widespread enough, the climate effects may be worse than the dust from the plume.



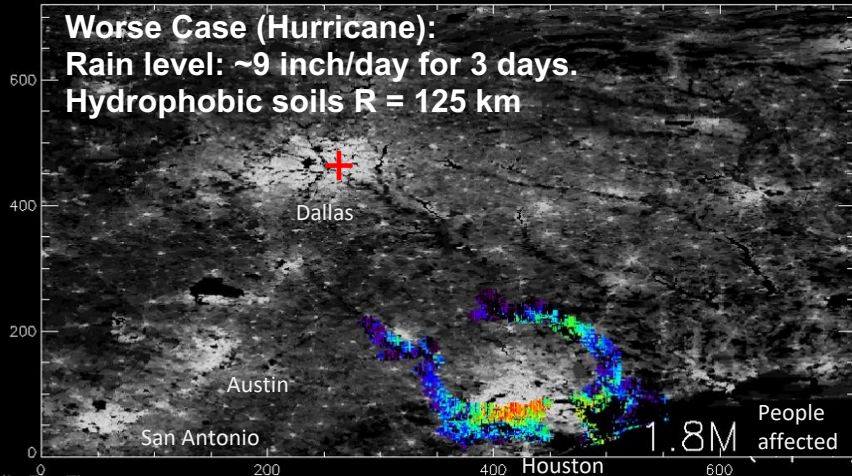
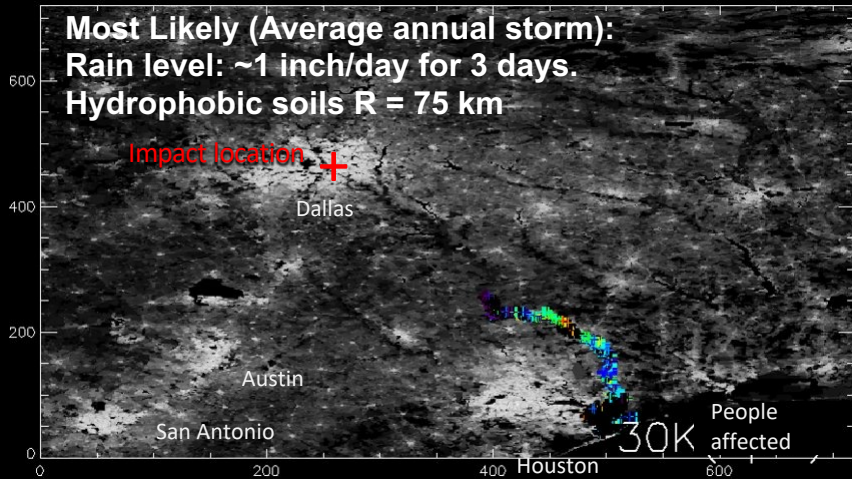
Pine Gulch Fire, Colorado, 2020

US Forestry Service. Credit Kyle Miller



Flooding Simulations

- Heat from the plume and wildfires bakes the ground making it difficult to absorb rain water which runs off instead
- Ejecta and dust fallout washes into streams and rivers clogging them
- Result is downstream flooding. In the Dallas impact scenario, the majority of the flooding is downstream in Houston.
- This is a recurring hazard every time it rains, potentially for years after the impact.
- As with the dust fallout, damage varies enormously with the weather, and location, requiring 1000's of simulations to obtain statistics.



Credit: Tim Titus

Climate



- NASA is collaborating with the National Center for Atmospheric Research and the University Corporation for Atmospheric Research to predict the climate effects of a large (but not extinction level) impact
- Large amounts of dust, soot, and aerosols in the atmosphere block out light reducing photosynthesis in plants and algae, and reducing the temperature
- Next step will be model crop and productivity reductions and resulting famine
- Climate effects may vary significantly with location of impact, particularly due to amount of vegetation burnt, land vs ocean vs arctic impact.





Mitigation

- Ideally any asteroid discovered to be on a collision course with Earth would be deflected to miss
- Small asteroids hitting in remote areas may be more cost effective to simply let hit
- Kilometer-size asteroids have regional effects and are on the cusp of global effects. Largest size that might potentially allow to hit if particularly remote with negligible global effects.
- Large impacts with short warning time, may not be able to deflect sufficiently to miss Earth, but might be able to move to an impact location with less damaging regional and global effects.
- Goal of this work is to predict the regional and global effects and determine when they are and are not significant, and the potential cost of damage.
- Trade off cost of impact vs cost of in-space mitigation. Trade off damage costs with impact location if cannot deflect enough to miss Earth.



Deep Impact spacecraft
hits comet Tempel1, 2005

NASA