Probabilistic Assessment of Tunguska-scale Asteroid Impacts

Lorien Wheeler[1,2], Donovan Mathias[2]
[1]RedLine Performance Solutions, [2]NASA Ames Research Center

Overview

The Tunguska meteor airburst that felled trees across >2000 km^2 of Siberian forest in 1908 has been extensively studied and modeled in attempts to deduce its size, properties, and impact characteristics. However, most of the existing modeling and simulation studies have investigated a small subset of cases based on assumptions of representative densities, velocities, or other properties. In this study, we use the Probabilistic Asteroid Impact Risk (PAIR) model to assess 50 million Tunguska-scale asteroid impacts, covering a full range of potential impactor properties. The impact cases are sampled from probabilistic distributions representing our current knowledge of asteroid properties, entry trajectories, and size frequencies, and the entry, airburst, and resulting ground damage are modeled for each case. The results provide a broader characterization of the range and relative likelihood of asteroid properties that could yield Tunguska-scale impacts. The full results of this study and a companion study on impact frequencies are pending publication in an upcoming Tunguska special edition of Icarus [1,2].

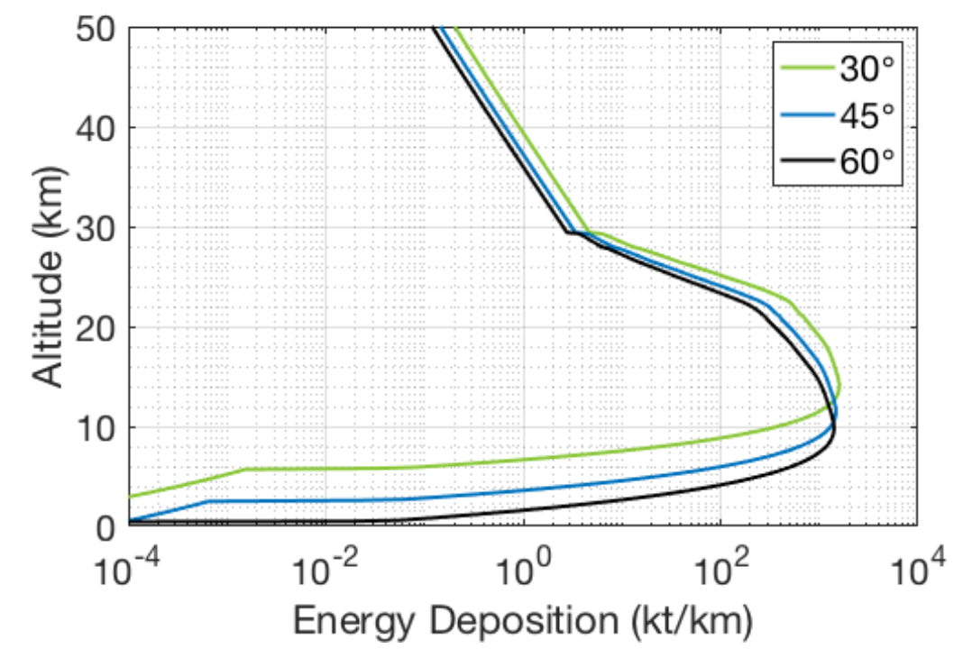
Result Summary

- Tunguska-like events can be produced by a broad range of impact scenarios.
- Prevailing size and energy estimates of 50–80 m or 10–20 megatons (Mt) remain within the relatively likely property ranges.
- Objects with slightly larger initial energies of 20–30 Mt and diameters 70–80 m are more likely to cause Tunguska-scale damage areas than objects on the smaller end of Tunguska size estimates.
- Even when size frequencies are accounted for, the greater damage potential of larger objects outweighs their rarity and makes them likelier to cause Tunguska-scale events, while the low damage potential of small objects counteracts their higher frequency.

Probabilistic Asteroid Impact Risk (PAIR) Model

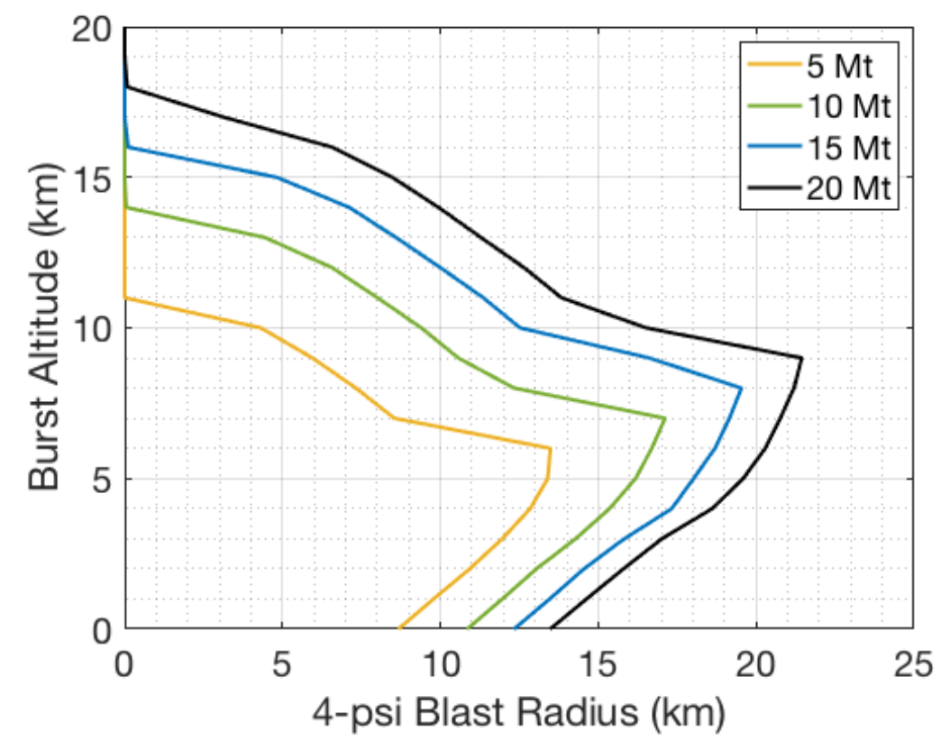
The PAIR model [3,4] combines physics-based analytic models of asteroid entry and damage in a probabilistic Monte Carlo framework to assess the risk posed by a wide range of potential impacts. The model samples from uncertainty distributions of asteroid properties and entry parameters to generate millions of hypothetical impact cases, and models the atmospheric entry, breakup, and resulting damage for each case.

Entry & Airburst Altitude: The Fragment-Cloud Model (FCM) [5,6] is used to model the energy deposited in the atmosphere during entry and breakup. The airburst altitude is taken as the point of maximum energy deposition.



Sample FCM energy deposition curves for a nominal 15-Mt Tunguska-scale impact with diameter ~70 m, density 3 g/cm^3, strength 5 MPa, entry velocity 15 km/s, and entry angle 30–60° from horizontal.

Blast Damage: Yield scaling and height-of-burst maps are used to estimate blast footprint radii as a function of burst altitude and total impact energy. PAIR uses a combination of nuclear-based height-of-burst maps [7] for smaller impact energies (<5 Mt) and simulation-based maps [8] for larger energies (>250 Mt), with intermediate cases interpolated between the two. This study considers a blast overpressure threshold of 4-psi, which would produce tree-felling windspeeds comparable to the observed Tunguska forest damage.



Sample height-of-burst maps showing 4-psi blast footprint radii vs. burst altitude for Tunguska-scale energies from 5–20 Mt. For each energy, there is an 'optimal' burst altitude that causes the maximum blast radius.

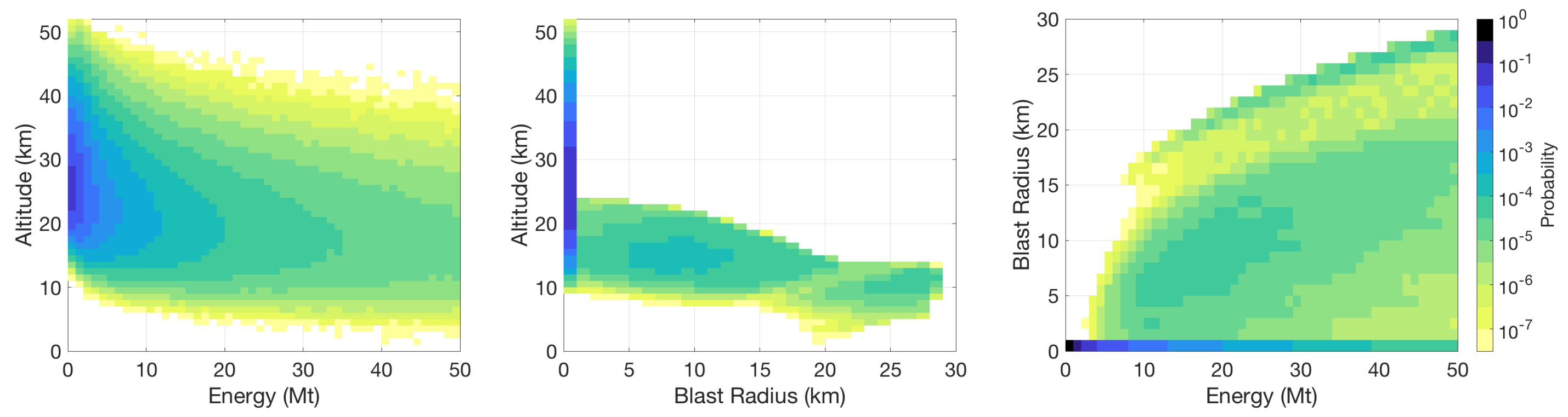
Tunguska-scale Impactor Set

Tunguska Event: The Tunguska blast event of 1908 caused substantial tree-fall across a butterfly shaped damage region that covered over 2,000 km^2 and extended 15–35 km outward from the epicenter. Prior assessments have estimated impact energies of 3–50 Mt with 10–20 Mt as the most prevailing consensus, diameters of 34–190 m, and burst altitude ranges of 5–15 km. [9-12].

Modeled Impact Cases: This study modeled 50 million Tunguska-scale asteroid impact cases. Sizes were sampled based on H magnitude impact frequencies [4] and the NEOWISE albedo distribution [13], covering initial kinetic energies up to 50 Mt and diameters 20–180 m. The asteroid, entry, and modeling parameter distributions used are adopted from Mathias et al. (2017) [1] and are shown as the gray baseline histograms in the result plots to the middle-right.

Impact Energy, Airburst Altitude, and Blast Damage Trends

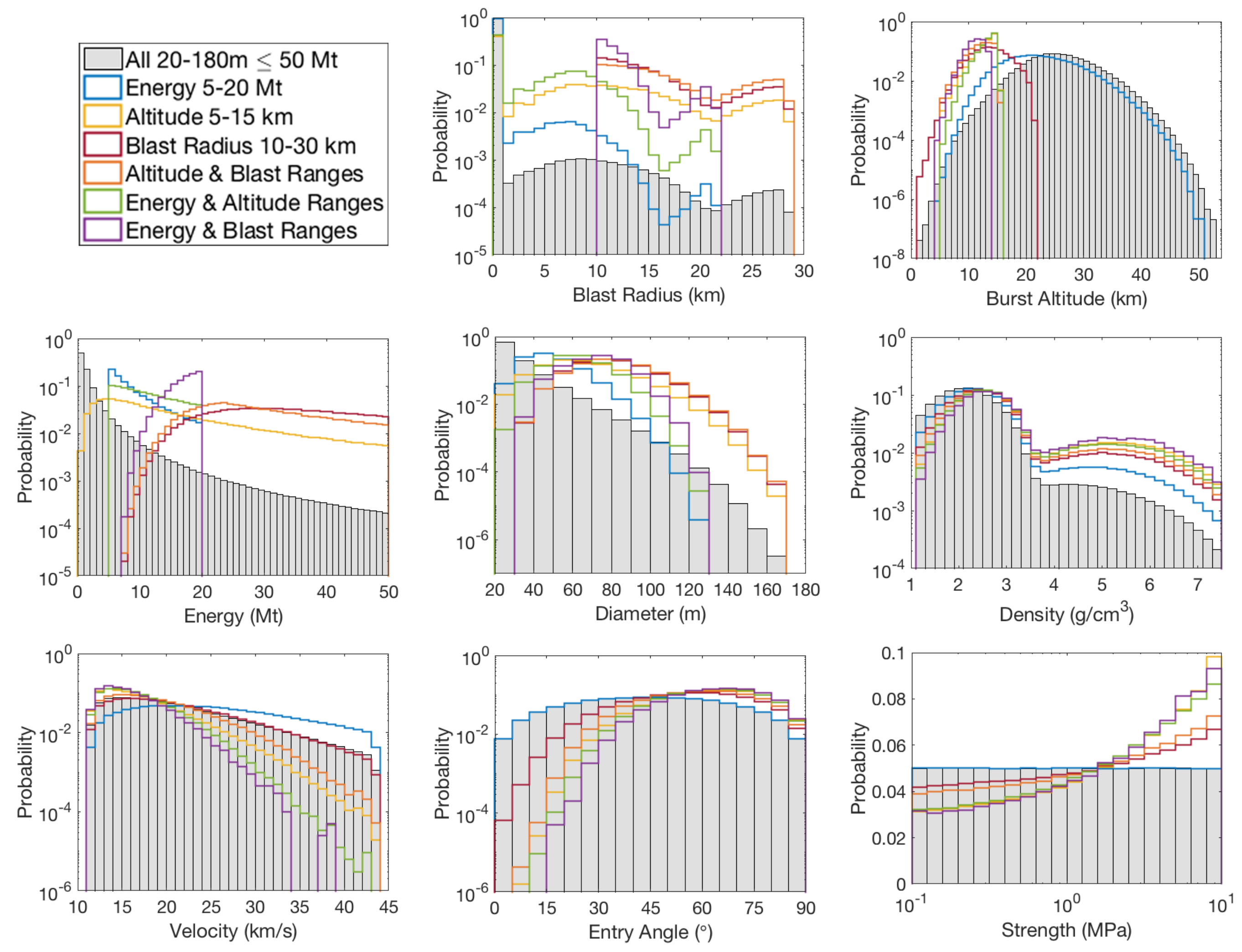
From our probabilistic set of modeled impact results, we compared the relative likelihoods of various impact energy, burst altitude, and blast damage combinations across Tunguska-scale size ranges.



Bivariate impact probability distributions as a function of impact energy, burst altitude, and blast radius, shown as color contours. Probability values are normalized across the full set of Tunguska-scale cases modeled, representing the relative likelihood of each parameter combination given an impact within the prescribed sized range.

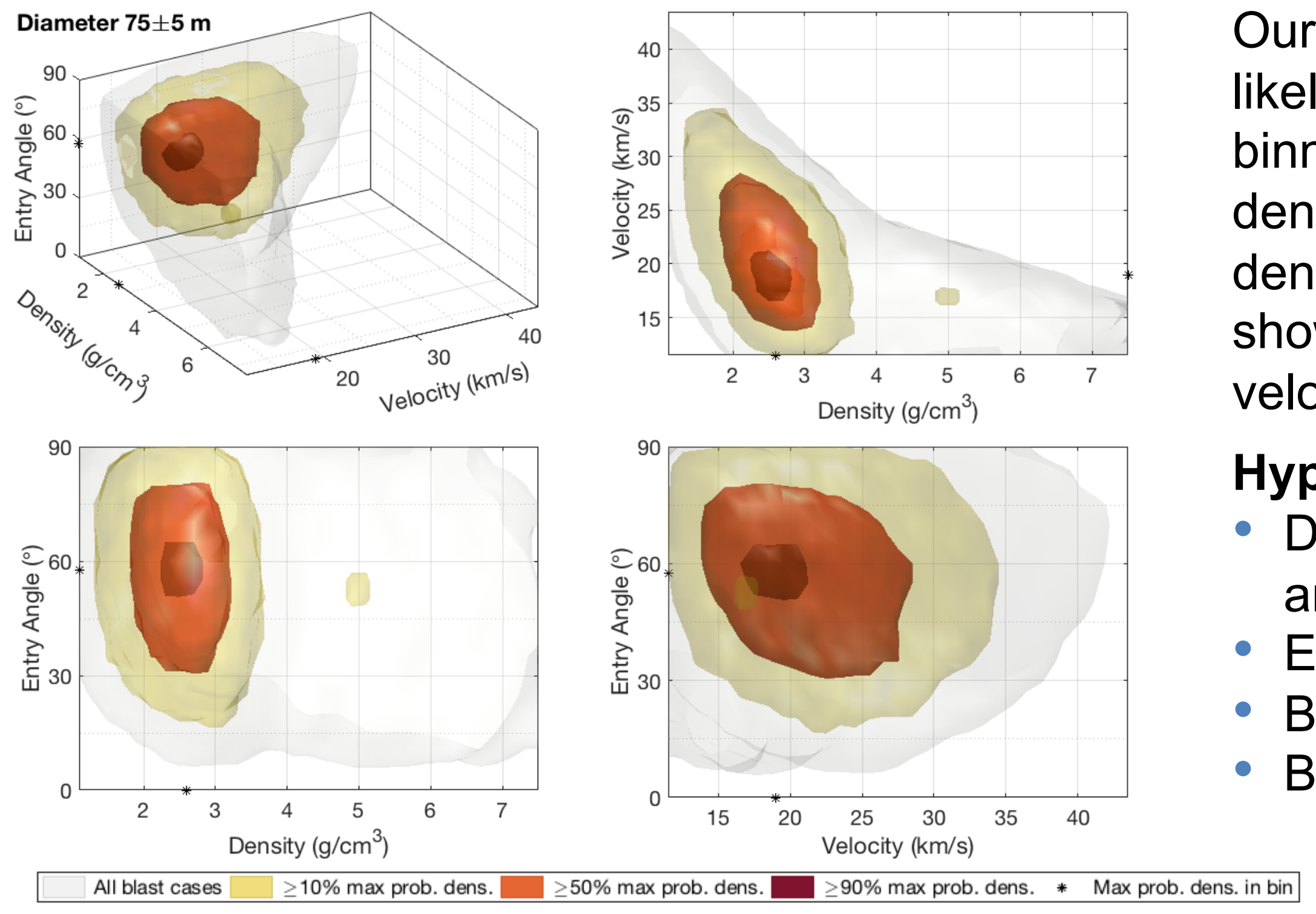
Probabilities for Meeting Tunguska-like Impact Criteria

We also investigated how likely various asteroid properties are to yield Tunguska-like impact energies, burst altitudes, and blast damage extents in our probabilistic impact results. The plots below show distributions of impact parameters and asteroid properties subject to various Tunguska-like criteria. Each plot compares the distributions for a given parameter, with the gray-filled background bars representing the entire set, and the colored bar outlines representing the subset of cases that meet the criteria listed in the legend. All distributions are independently normalized to be visible on similar scales.



- **Blast Radius:** Minimal 4-psi blast footprint remains most likely for Tunguska energy and/or altitude criteria, despite eliminating the low-energy/high-altitude cases.
- **Altitude:** To meet the blast radius criteria, impactors under 50 Mt must burst below 22 km with the most likely altitude ~14 km, and impactors 5–20 Mt burst between 4–14 km with ~12 km being most likely.
- **Energy:** For the blast radius criteria, larger energies ~30 Mt become more likely, as the smaller impacts are far less able to cause substantial damage.
- **Diameter:** Probabilities peak around 75 m for the blast damage criterion, 55 m for the altitude criterion, and 45 m for the energy criterion, with means of 48–80 m.
- **Density:** Tunguska criteria shift the density distribution slightly higher, but the full density range is able to meet all criteria and stony densities still dominate.
- **Entry:** Tunguska airburst and damage criteria tend to favor lower velocities and steeper entry angles.
- **Strength:** Tunguska criteria only slightly favor higher strengths relative to the base uncertainty distribution.

Multivariate Probabilities for Tunguska-scale Blast Damage



Our study also considered what *combinations* of asteroid properties are most likely to cause Tunguska-scale blast damage when considered together. We binned all the cases that met the blast criteria into 4D hypervolumes of diameter, density, entry velocity, and entry angle, and compared the resulting probability densities to determine the most likely parameter combinations. The plots here show surface contours of the relative probability densities, displayed in density-velocity-angle space for the highest-probability diameter bin of 70–80 m.

Hypervolume bin with highest probability density contains:

- Diameters 70–80m, densities 2.5–2.7 g/cm^3, velocities 18.5–19.5 km/s, and entry angles 55–60 degrees.
- Energies of 19–32 Mt with a mean and mode both around 25 Mt.
- Burst altitudes 10–20 km (mean ~13 km, mode ~12–13 km)
- Blast radii of 10–25 km (mean ~14 km, mode ~12–13 km).

Acknowledgements and References

This work was funded by NASA's Planetary Defense Coordination Office. Supercomputing resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center. References: [1] Wheeler and Mathias, 2018. Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus (submitted). [2] Wheeler and Mathias, 2018. Effects of asteroid property distributions on impact frequency estimates. Icarus (submitted). [3] Mathias, et al., 2017. A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. [4] Stokes, et al., 2017. Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration. [5] Wheeler, et al., 2017. A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus 295, 149–169. [6] Wheeler, et al., 2018. Atmospheric Energy Deposition Modeling and Inference for Varied Meteoroid Structures. Icarus 315, 79–91. [7] Glasstone and Dolan, 1977. The Effects of Nuclear Weapons. US Dep. Defense and US Energy Res. Dev. Admin. 3rd ed. U.S. Government Printing Office, Washington, D.C. [8] Aftosmis, et al., 2017. Simulation-based height of burst map for asteroid airburst damage prediction. Acta Astronautica, in press. [9] Artemieva and Shuvalov, 2016. From Tunguska to Chelyabinsk via Jupiter. Annu. Rev. Earth Planet. Sci. 44, 37–56. [10] Trayner, 1997. The Tunguska event. J. Br. Aston. Assoc. 107(3), 117–130. [11] Vasilyev, 1998. The Tunguska Meteorite problem today. Planetary and Space Science 46, 129–150. [12] Robertson and Mathias, 2018. Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus, in press. [13] Mainzer, A., et al., 2011. Neowise observations of near-Earth objects: preliminary results. Astrophys. J. 743 (2), 156–172.