Asteroid Impact Risk Across Transitional Hazard Regimes

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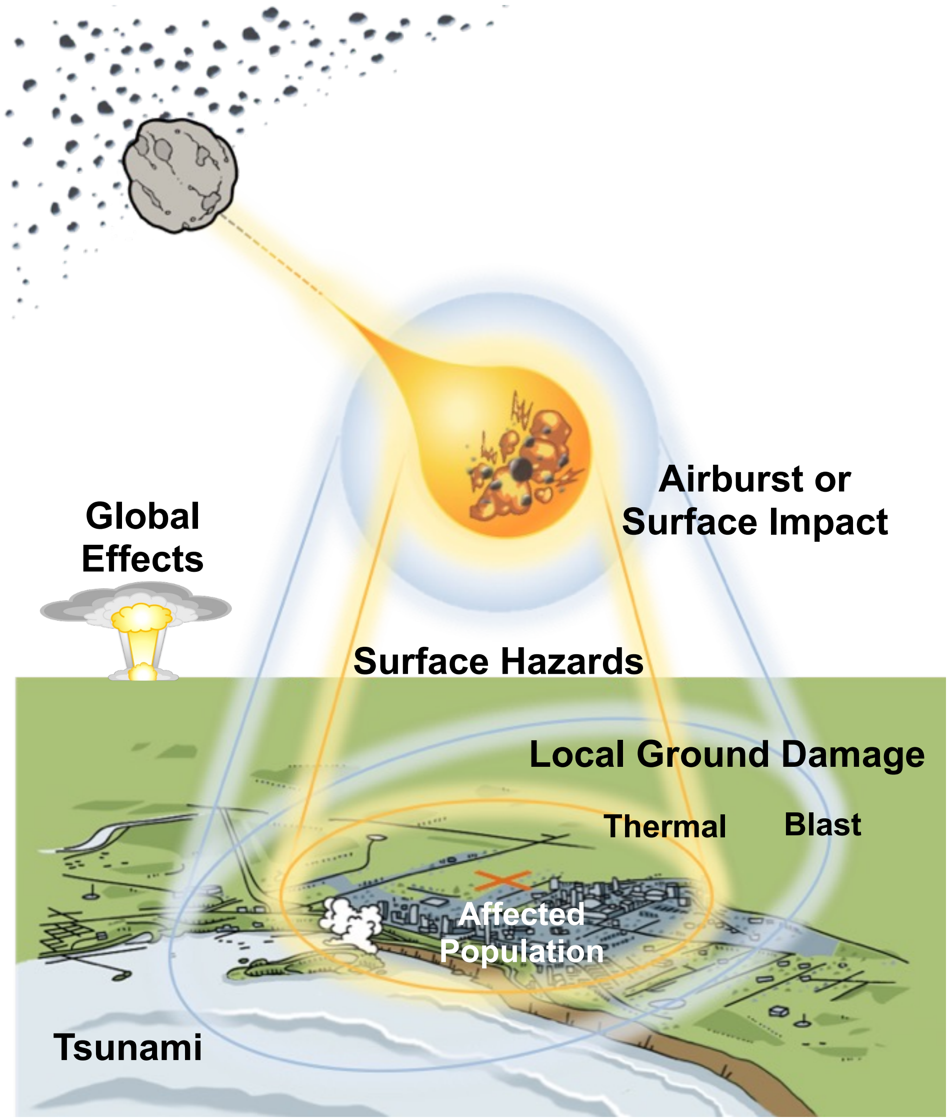
HYPOTHETICAL EXERCISE

Impact Risk Across Transitional Hazard Regimes

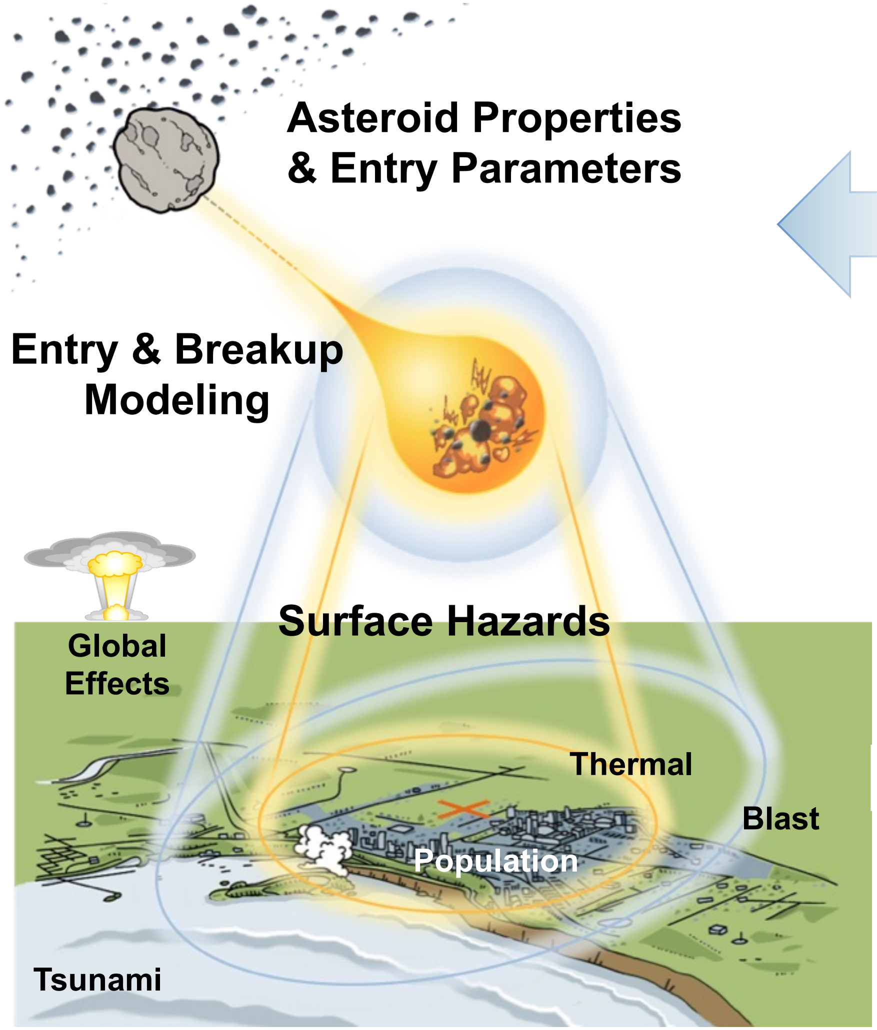


- Asteroid impacts can cause different types of hazards, depending on their size and impact location:
  - Local ground damage from blast waves or thermal fireballs
  - Tsunami inundation from larger ocean impacts
  - Global effects (GE) from largest kilometer-scale objects
- Transitional hazard regimes:
  - Impactor sizes approaching onset of global effects, large enough to span all hazards, with a large range of potential damage severities and uncertainties
  - Current 2023 PDC hypothetical impact scenario falls across this size range
- This study compares affected population damage and risk among the potential hazards for the 2023 PDC scenario:
  - Hazard likelihoods and population damage ranges across the asteroid size range for the initial scenario
  - Hazard damage ranges along the scenario's initial impact corridor
  - Total population risk probabilities from each hazard

[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

Asteroid Impact Risk Assessment

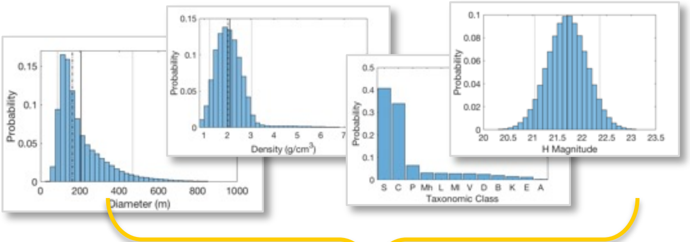
Probabilistic Asteroid Impact Risk (PAIR) Model



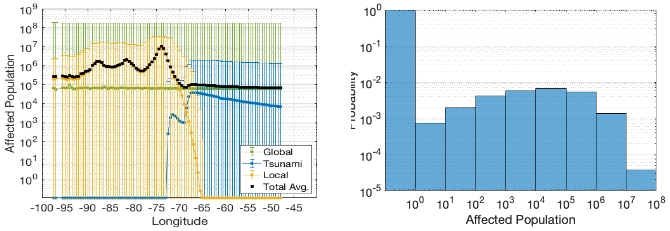
[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

Impact Threat Scenario

Asteroid Property Distributions



Probabilistic Damage and Risk



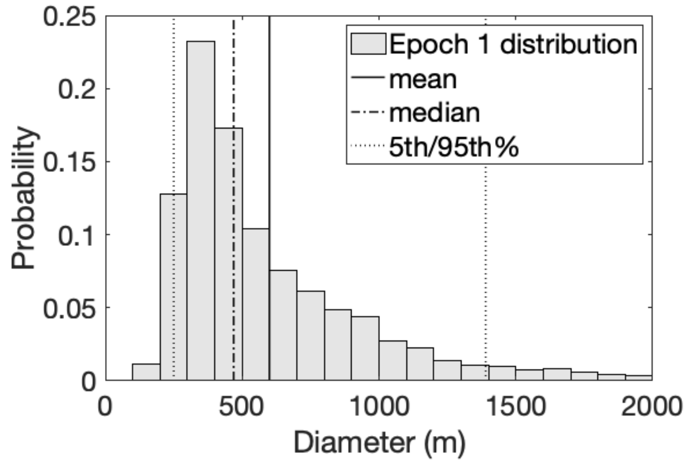
- Risk model uses fast-running physics-based models to assess millions of impact cases representing the range of possible asteroid properties and impact locations
- Entry, airburst or impact, and resulting hazards (blast, thermal, tsunami, global effects) are modeled for each case
- Local population data are used to estimate the number of people affected within the damage regions
- Probabilities of the resulting damage sizes, severities, and affected populations are computed among cases

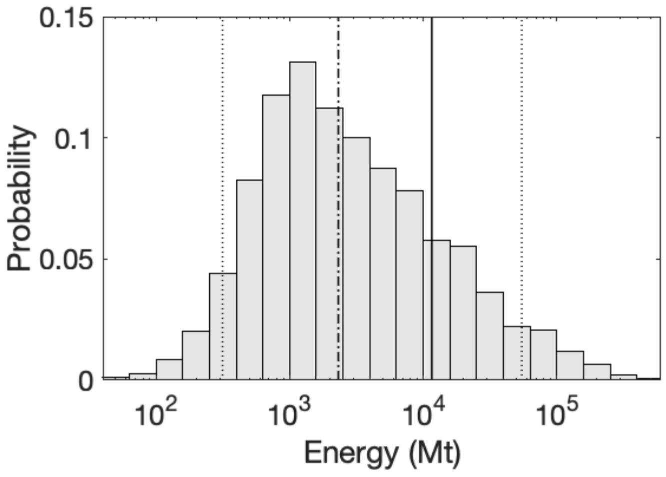
HYPOTHETICAL EXERCISE

Impact Hazard Assessment for the 2023 PDC Asteroid Impact Scenario

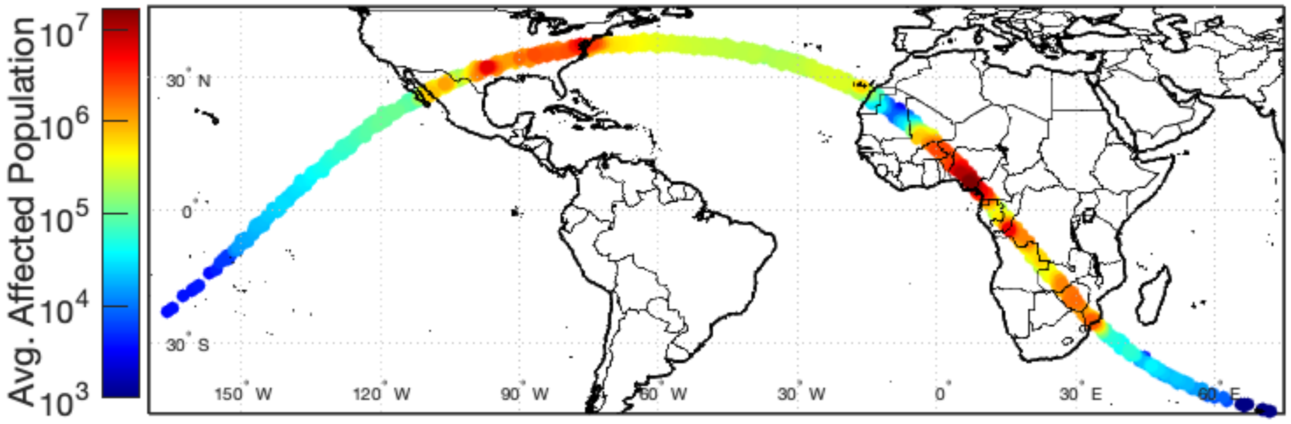
- Evaluated impact hazard damage & risks for Epoch 1 of the 2023 PDC hypothetical impact scenario
  - Large impactor scenario with size range spanning all hazard regimes
  - Epoch 1 represents scenario at initial threat discovery, with large uncertainties in asteroid properties and impact locations
- Asteroid Size & Properties:
  - Diameter range: ~150–2000 m
  - Impact energy range: ~50–160,000 Mt (given scenario entry velocity ~12.7 km/s)
  - *[See J. Dotson's 2023 PDC asteroid property modeling talk for details]*
- Impact Locations:
  - Potential impact locations span the globe
  - 52% over land, 48% over ocean

2023 PDC Epoch 1 Asteroid Properties: Diameter and Impact Energy Distributions





2023 PDC Epoch 1 Impact Swath



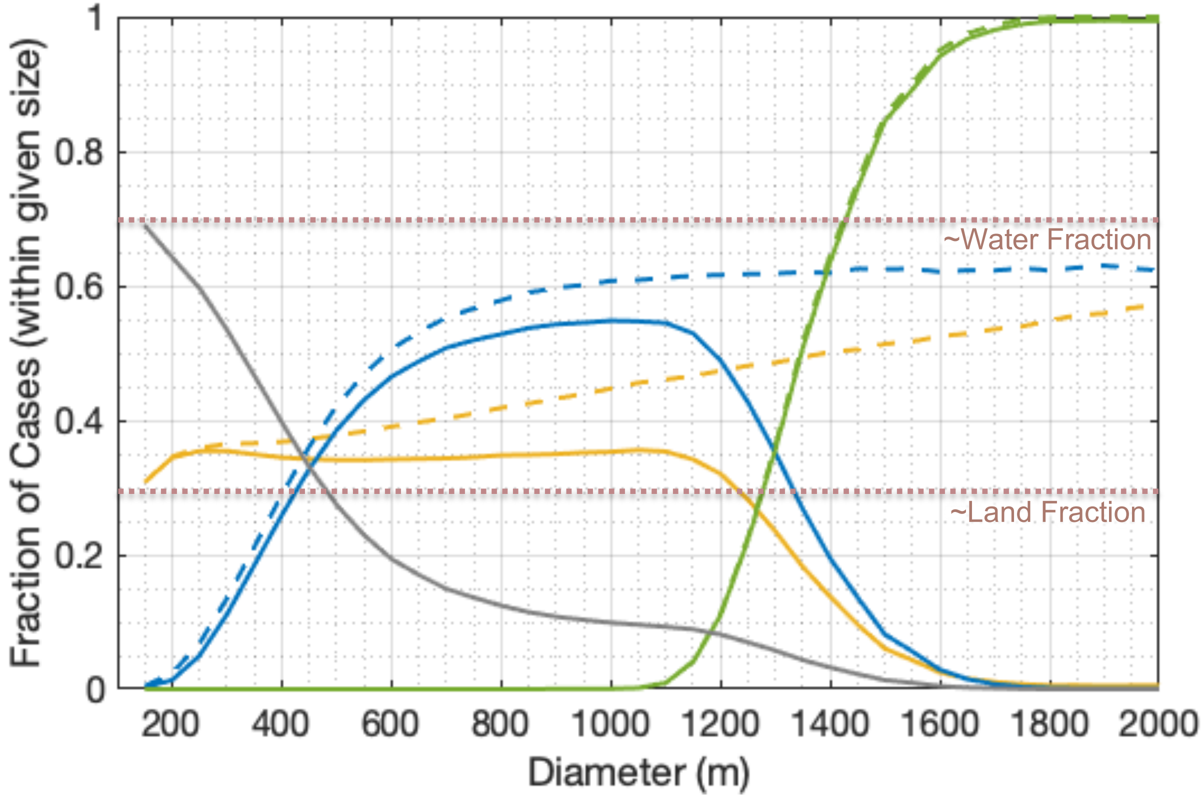
Ames Research Center

Hazard Likelihood by Asteroid Size

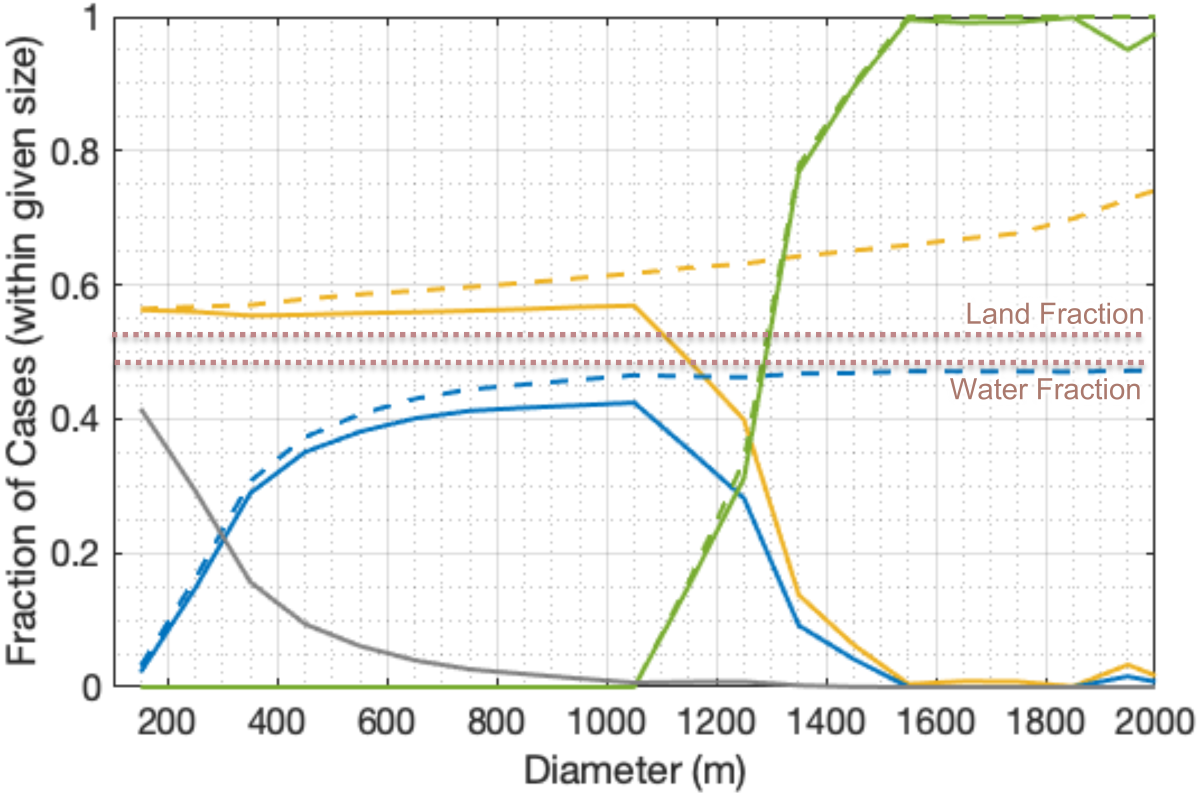
For each asteroid size, plots show relative likelihood (fraction of cases) that each hazards occurs (dashed lines) and that it drives the most damage (solid lines).

Local Occurs	Tsunami Occurs	Global Occurs	No Damage
Local Drives	Tsunami Drives	Global Drives	

Random worldwide impacts
(12 km/s entry, similar to PDC scenario)



2023 PDC Epoch 1 Swath
(52% land, 48% ocean, 12.7 km/s)



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For each asteroid size, plots show relative likelihood (fraction of cases) that each hazards occurs (dashed lines) and that it drives the most damage (solid lines).

- Comparison of generic worldwide impacts and PDC cases shows sensitivity of hazard rates to specific impact swaths for sizes in the ~500-1000m range

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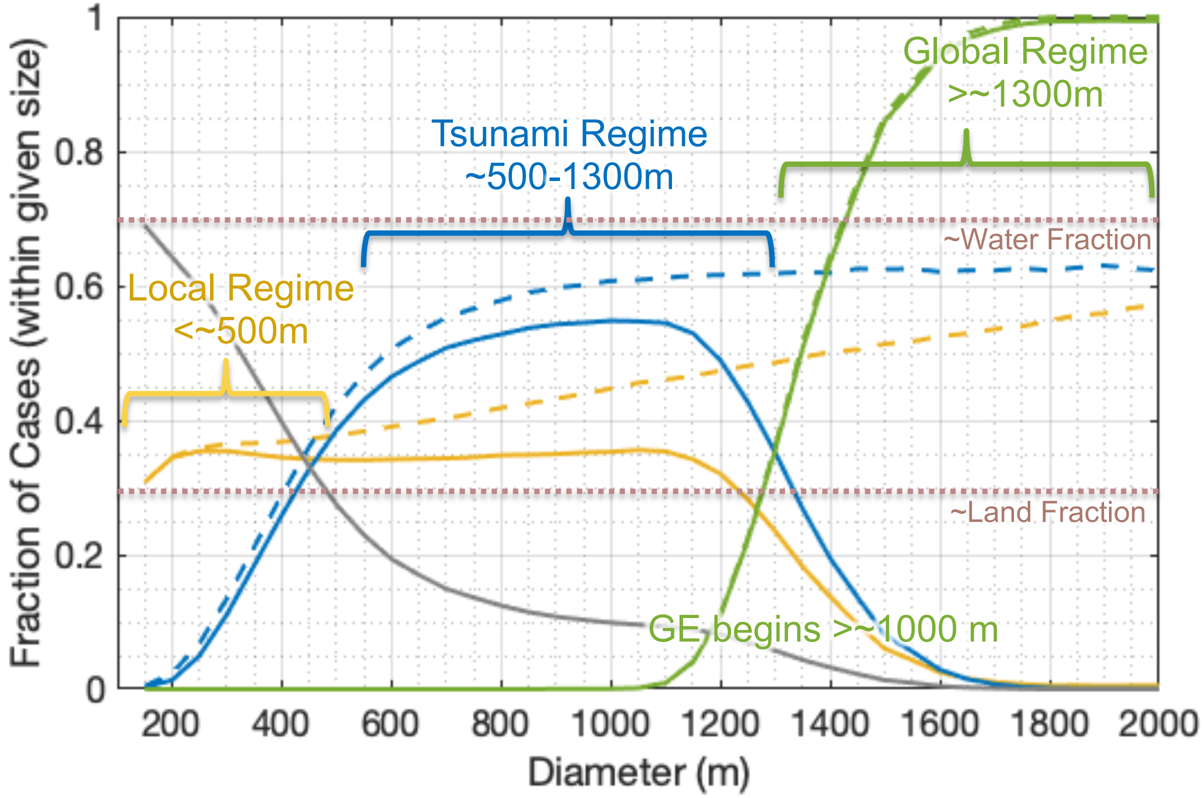

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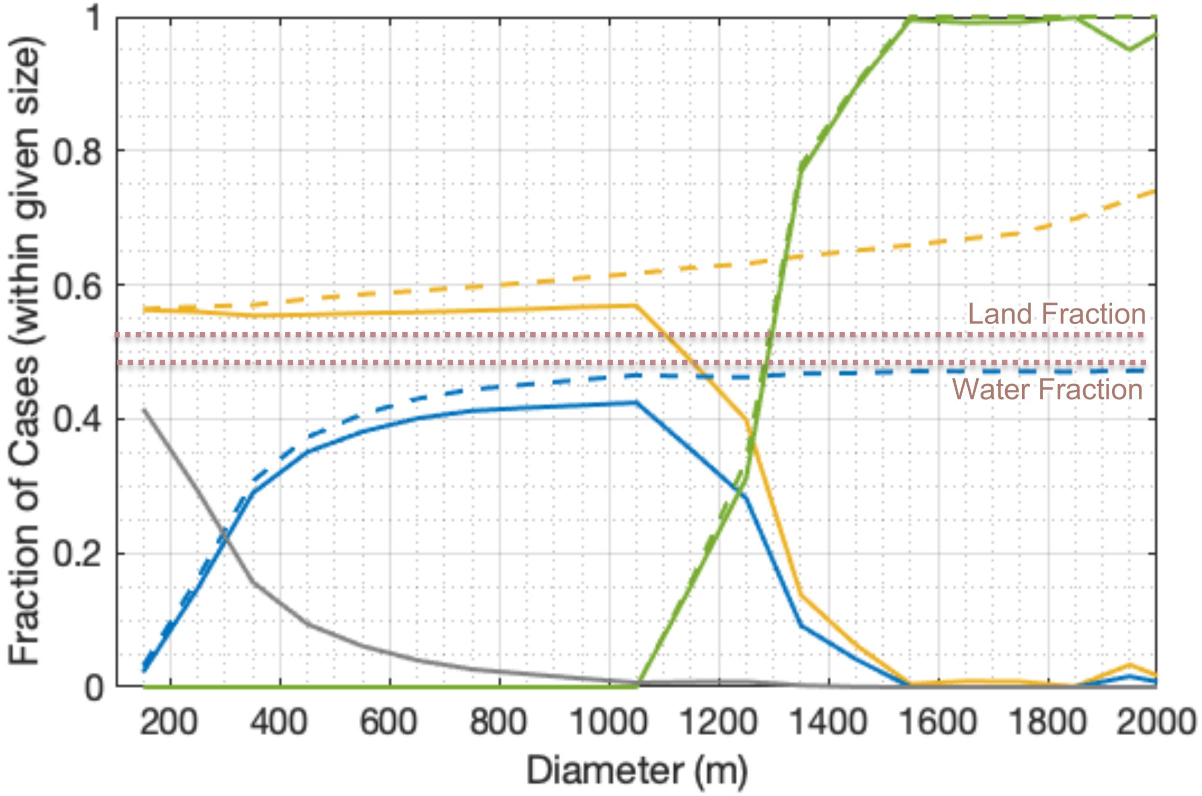
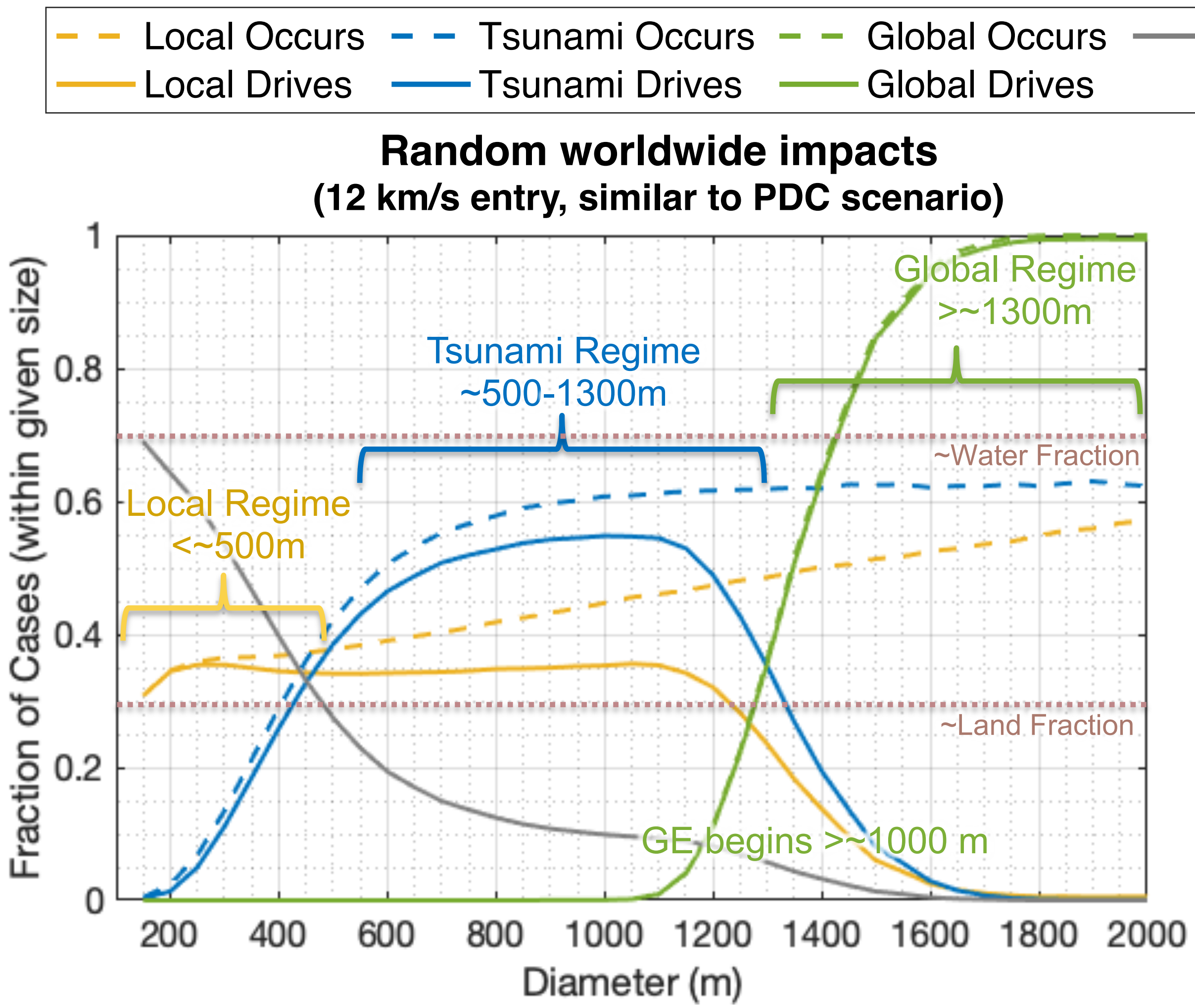


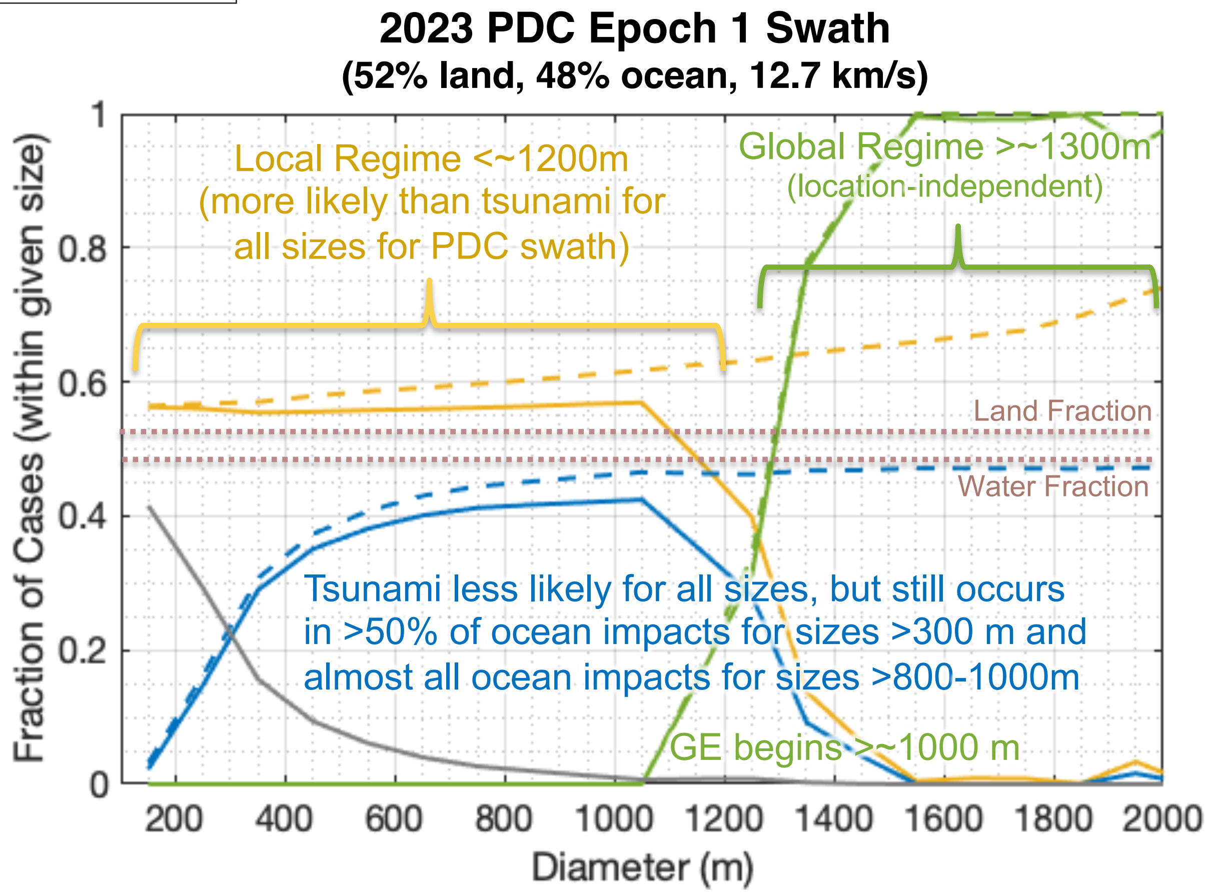
Hazard Likelihood by Asteroid Size

Worldwide vs 2023 PDC Epoch 1 Impact Locations

For each asteroid size, plots show relative likelihood (fraction of cases) that each hazards occurs (dashed lines) and that it drives the most damage (solid lines).

- Comparison of generic worldwide impacts and PDC cases shows sensitivity of hazard rates to specific impact swaths for sizes in the ~500-1000m range



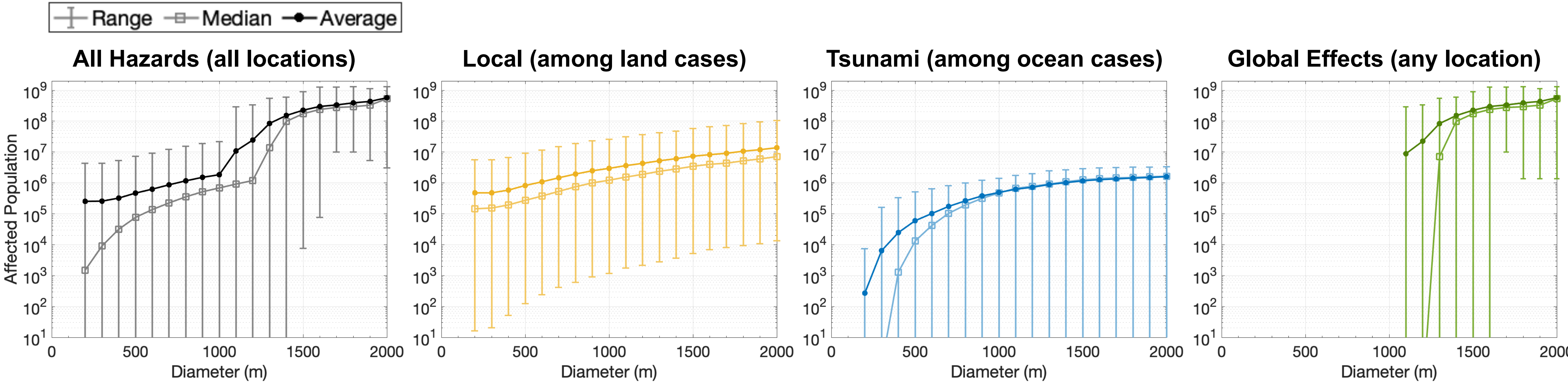


Population Damage Ranges By Asteroid Size

2023 PDC Scenario Epoch 1

Affected Population Ranges & Risk by Asteroid Size for each Hazard Type

Range bars encompass the most likely 99% of values modeled in each 100m-wide size bin. "All Hazards" values represent the people affected by the largest driving hazard for each individual impact case modeled (not sums of all hazards within each asteroid size). Local and Tsunami ranges are taken among the swath's land or ocean locations respectively.



	All Hazards	Local (Land)	Tsunami (Ocean)	Global
Upper Ranges (99%)	~4M–1B	~5M–100M	~8K–3M	~300M–1B
Average Ranges	~250K–600M	~500K–15M	~300–2M	~10M–500M
Median Ranges	~2K–600M	~100K–7M	~0–2M	~0–500M

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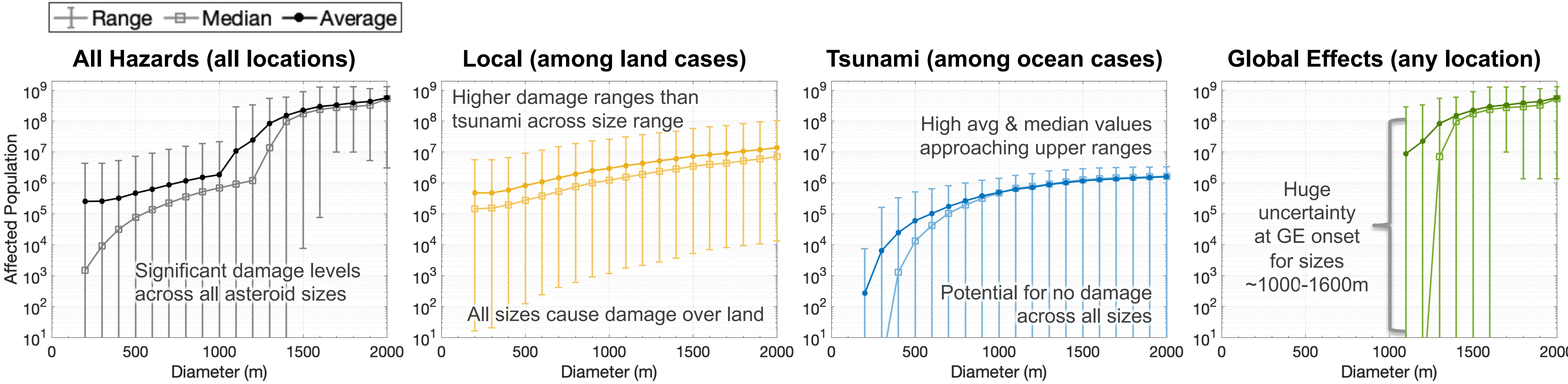
- **Significant damage levels across all asteroid sizes and from all hazards.**
- **Each hazard has large uncertainty in range of damage from each size.**



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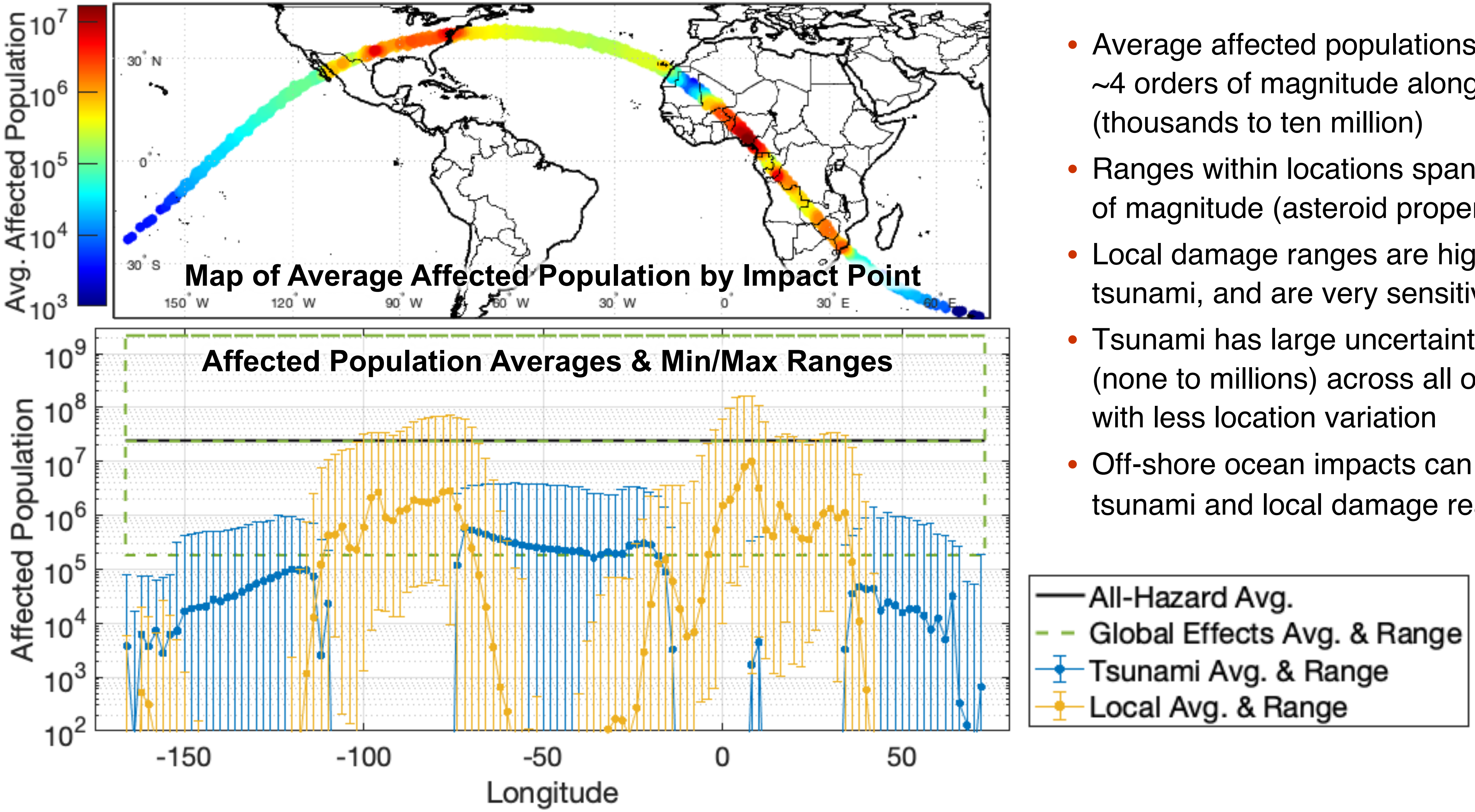
Population Damage Ranges along Impact Corridor

2023 PDC Scenario Epoch 1

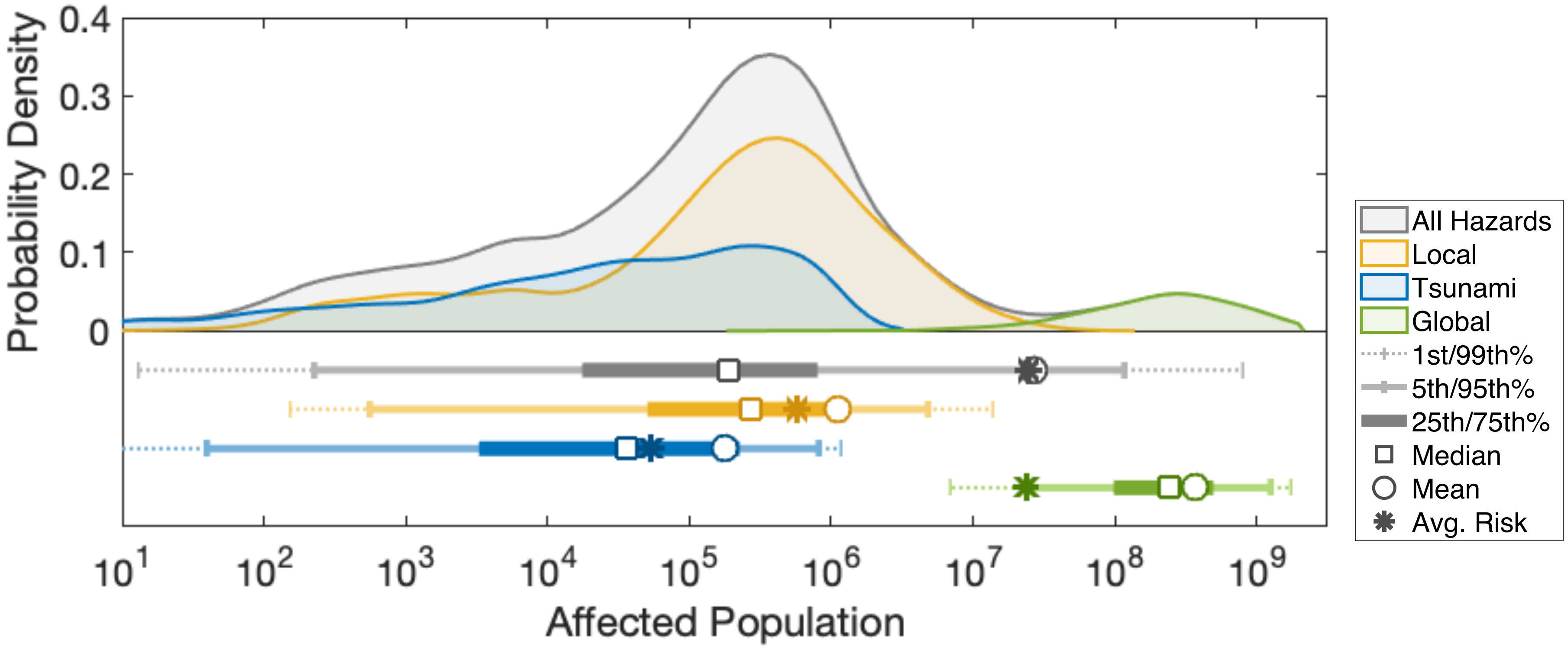


- Average affected populations vary by ~4 orders of magnitude along locations (thousands to ten million)
- Ranges within locations span multiple orders of magnitude (asteroid property uncertainties)
- Local damage ranges are higher than tsunami, and are very sensitive to location
- Tsunami has large uncertainty ranges (none to millions) across all ocean regions, with less location variation
- Off-shore ocean impacts can cause both tsunami and local damage reaching coasts

Total Population Risk by Hazard

2023 PDC Scenario Epoch 1

Affected Population Probabilities by Damage-Driving Hazard



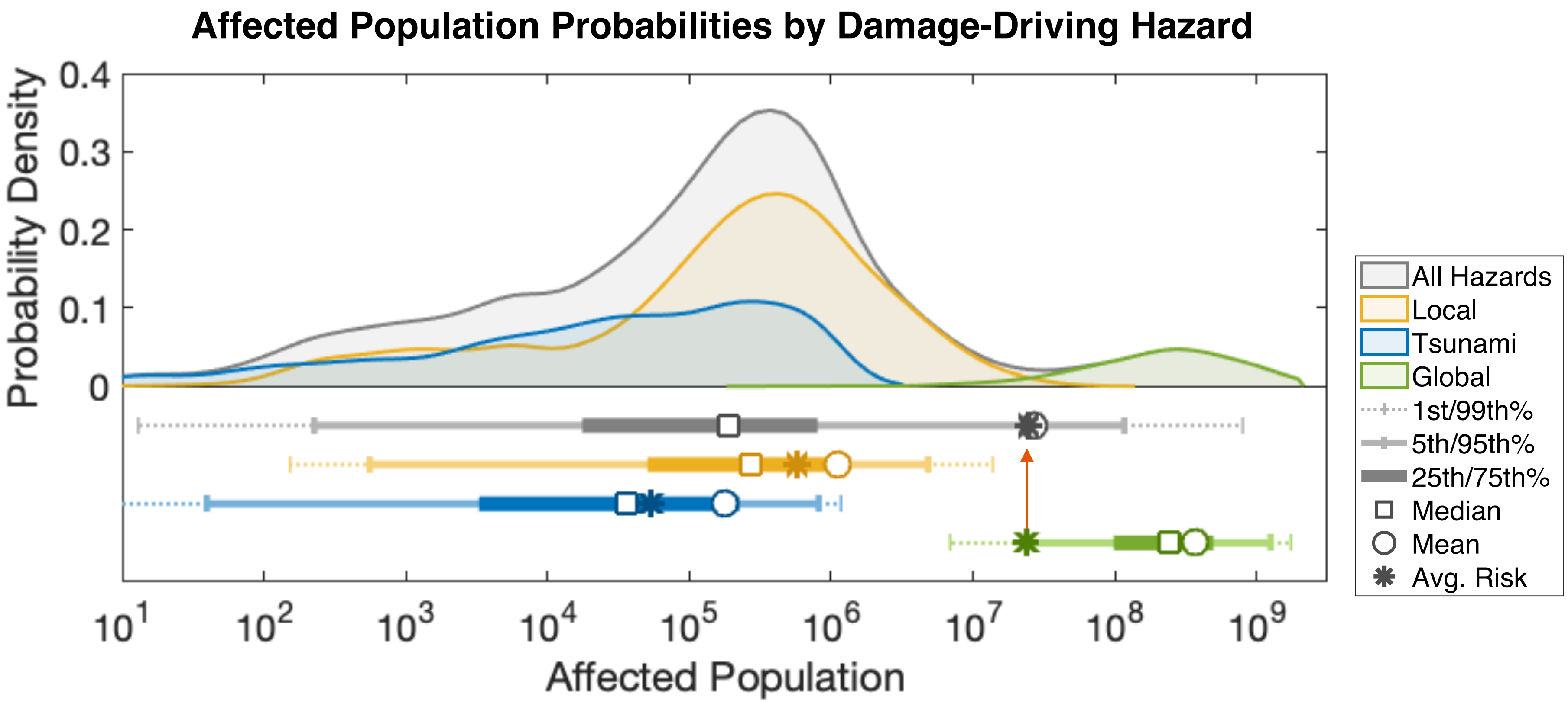
- Plot shows distribution of total affected population probabilities among all impact sizes and locations.
- Hazard curves are scaled to show their overall relative likelihoods.
- Bars show stats among damage-driving cases.
- Average risk scales the hazard's average damage by its relative probability

	All Hazards	Local	Tsunami	Global
Hazard Likelihood	89%	52%	31%	6%
Damage Range (1st/99th%)	13 – 810M	150 – 14M	3 – 1.2M	7M – 1.8B
Median Damage	190K	270K	36K	240M
Average Damage	27M	1.1M	180K	370M
Average Risk	*24M*	*580K*	*54K*	*24M*

HYPOTHETICAL EXERCISE

Total Population Risk by Hazard

2023 PDC Scenario Epoch 1



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- Global effects drives total average risk levels up to 24M, despite low 6% probability of occurring
- Local damage is the next greatest risk driver in terms of likelihood, damage levels, and total average risk
- Upper ranges of local damage overlap lower ranges of global effects
- Tsunami damage drives least risk relative to other hazards for this scenario, but still poses significant damage and risk levels

Result Summary

- Comparison of damage and risk levels among hazards for the initial 2023 PDC Scenario showed:
  - All hazards pose significant risk and potential damage levels across these larger asteroid sizes.
  - Potentially extreme global effects drive overall scenario risk despite low 6% probability of occurring.
  - Global effects begin for sizes over ~1000m, drive most damage for sizes over ~1300m, and have huge uncertainty at initial onset for sizes around ~1000-1600m.
  - Local ground damage is the most likely hazard overall, occurs for all land impact cases, and is the main damage-driving hazard for asteroid sizes up to ~1200m or so (when global effects start to dominate).
  - Largest local damage ranges could affect as many people as initial global effects (tens of millions).
  - Tsunami damage/risk levels are lower than local damage for all sizes, but could still contribute significant damage and risk levels across full span of the scenario's Atlantic ocean points.
  - Tsunami has large uncertainties, from no-damage to large damage, for all sizes over several hundred meters and across all ocean points.
  - Local damage ranges are very sensitive to location, while tsunami damage ranges appear to be less so.
- Modeling implications:
  - Significant risk contributions from all hazards warrant further hazard modeling improvements for large-scale impacts.
  - Simulation studies of potential global effects onset for impactor sizes ~1000-1600m, for tsunami damage from impactor sizes over several hundred meters, and blast damage for large ground-impacting cases could help improve areas of large uncertainty in current risk models.

HYPOTHETICAL EXERCISE

RISK MODEL DETAILS & REFERENCES

ATAP Impact Risk & Hazard Modeling Papers

Probabilistic Asteroid Impact Risk (PAIR) Model

- **Mathias et al., 2017.** A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009
- **Stokes et al., 2017.** Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
- **Wheeler & Mathias, 2018.** Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- **Rumpf et al., 2020.** Deflection driven evolution of asteroid impact risk under large uncertainties. Acta Astonautica 176, 276–286. https://doi.org/10.1016/j.actaastro.2020.05.026
- **Reddy et al., 2022.** Apophis planetary defense campaign. Planetary Science Journal, 3:123 (16pp). https://doi.org/10.3847/PSJ/ac66eb
- **Reddy et al., 2022.** Near-Earth Asteroid (66391) Moshup (1999 KW4) Observing Campaign: Results from a Global Planetary Defense Characterization Exercise. Icarus 374, 114790. https://doi.org/10.1016/j.icarus.2021.114790
- **Reddy et al., 2019.** Near-Earth Asteroid 2012 TC4 Campaign: results from a global planetary defense exercise. Icarus 326, 133–150. https://doi.org/10.1016/j.icarus.2019.02.018
- **Population data:** SEDAC GPW v4.11 gridded population counts, year 2020 (UN-adjusted values). CIESIN, Columbia University, 2016. http://dx.doi.org/10.7927/H4SF2T42

Entry & Breakup Energy Deposition Modeling

- **Wheeler et al., 2018.** Atmospheric energy deposition modeling and inference for varied meteoroid structures. Icarus 315, 79–91. https://doi.org/10.1016/j.icarus.2018.06.014
- **Wheeler et al., 2017.** A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus 295, 149–169. https://doi.org/10.1016/j.icarus.2017.02.011
- **Register et al., 2020.** Interactions between asteroid fragments during atmospheric entry. Icarus 337, 113468. https://doi.org/10.1016/j.icarus.2019.113468

Blast Modeling and Simulation

- **Aftosmis, et al., 2019.** Simulation-based height of burst map for asteroid airburst damage prediction. Acta Astronautica 156, 278-283. https://doi.org/10.1016/j.actaastro.2017.12.021
- **Robertson & Mathias, 2019.** Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus 327, 36–47. https://doi.org/10.1016/j.icarus.2018.10.017
- **Aftosmis, et al., 2016.** Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting. https://doi.org/10.2514/6.2016-0998

Thermal Radiation Modeling and Simulation

- **Johnston et al., 2021.** Simulating the Benešov bolide flowfield and spectrum at altitudes of 47 and 57 km. Icarus 354, 114037. https://doi.org/10.1016/j.icarus.2020.114037
- **Johnston & Stern, 2018.** A model for thermal radiation from the Tunguska airburst. Icarus, 327, 48–59. https://doi.org/10.1016/j.icarus.2019.01.028
- **Johnston et al., 2018.** Radiative heating of large meteoroids during atmospheric entry. Icarus 309, 25–44. https://doi.org/10.1016/j.icarus.2018.02.026

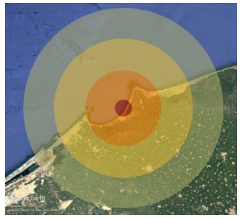
Tsunami Simulations

- **Robertson & Gisler, 2019.** Near and far-field hazards of asteroid impacts in oceans. Acta Astronautica 156, 262–277. https://doi.org/10.1016/j.actaastro.2018.09.018
- **Berger & Goodman, 2018.** Airburst-generated tsunamis. Pure Appl. Geophys. 175 (4), 1525-1543. https://doi.org/10.1007/s00024-017-1745-1
- **Berger & LeVeque, 2018.** Modeling issues in asteroid-generated tsunamis. NASA Contractor Report NASA/CR-2018-219786. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006617.pdf
- **Berger & LeVeque, 2022.** Towards Adaptive Simulations of Dispersive Tsunami Propagation from an Asteroid Impact. Proc. ICM, St. Petersburg, Russia, 2022 (submitted). https://doi.org/10.48550/arXiv.2110.01420

PAIR Affected Population Risks

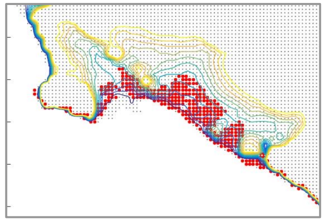
- For each impact case modeled, PAIR computes the estimated number of people affected by each hazard type, based on the modeled damage location, area, severity, and local population
  - **Local blast & thermal ground damage:** affects 10–100% of local population depending on severity (additional details in following slides)
  - **Tsunami:** affects up to 10% of the local population depending on flood depth in each coastal area (based on tsunami wave height and ground elevation)
  - **Global effects:** affects estimated fractions of total world population, based on total impact energy and a randomly sampled severity factor
  - **Total affected population** estimates for each impact case are taken as the number of people affected by the largest hazard produced (not sums of multiple hazards)
- **Affected population risks:** population results for each impact case are aggregated to compute total population ***risks,*** reflecting the likelihoods of the possible effects for the overall impact scenario (i.e., probabilities of the impact affecting given ranges or thresholds of people)
- **Population data source:** SEDAC Gridded Population of the World (GPW) v4.11 gridded population counts, year 2020 UN-adjusted values

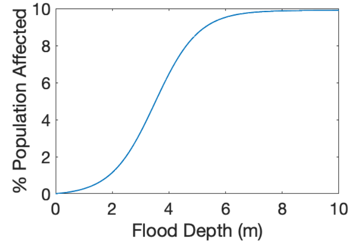
Local Blast & Thermal Affected Population



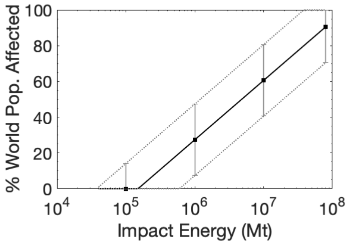
Severity	% Pop. Affected
Serious	10%
Severe	30%
Critical	60%
Unsurvivable	100%

Tsunami Affected Population



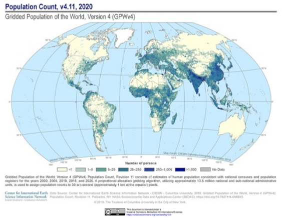


Global Effects Affected Populations

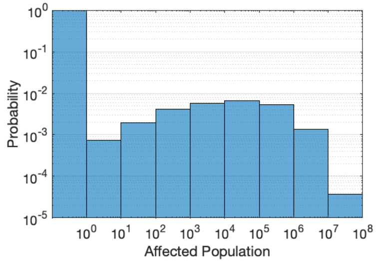


Impact Energy (MT)	% Population Affected		
	Min	Nominal	Max
4.E+04	0	0	0
8.E+04	0	0	10
2.E+05	0	0	20
3.E+05	0	10	30
6.E+05	0	20	40
1.E+06	10	30	50
2.E+06	20	40	60
5.E+06	30	50	70
1.E+07	40	60	80
2.E+07	50	70	90
4.E+07	60	80	100
8.E+07	70	90	100

SEDAC Gridded Population Data



Population Risks

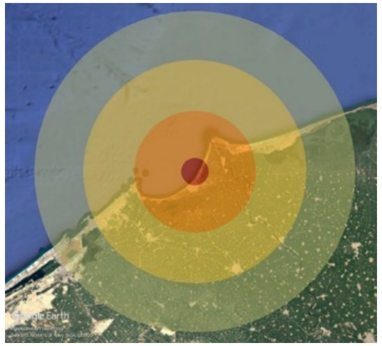


[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

HYPOTHETICAL EXERCISE

PAIR Local Blast & Thermal Ground Damage

- Large impacts or airburst can generate destructive blast waves and thermal heat that can cause various levels of injury, fatalities, structural damage, and/or fires extending far around the impact location.
- Risk model assesses blast and thermal ground damage *independently* at four equivalent severity levels
  - The damage region for each severity level is determined from the *larger* of the equivalent blast *or* thermal damage area
  - Local ground damage regions indicate *either* blast or thermal effects could exceed the given severity threshold (*not* necessarily the occurrence of both effects within the entire region)
  - Local affected population estimates within each region are scaled by the relative severity of each damage level
- Blast is the predominant hazard for most sub-global-scale asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases, and usually define the larger outer serious and severe risk regions for emergency response planning
  - Critical and unsurvivable thermal damage areas can be larger than equivalent blast levels for the larger impact sizes



Damage Level	Relative Severity	Blast Damage Effects	Thermal Damage Effects
Serious	10%	Shattered windows, some structural damage	2nd degree burns
Severe	30%	Widespread structural damage	3rd degree burns
Critical	60%	Most residential structures collapse	Clothing ignites
Unsurvivable	100%	Complete devastation	Structures ignites, incineration

HYPOTHETICAL EXERCISE

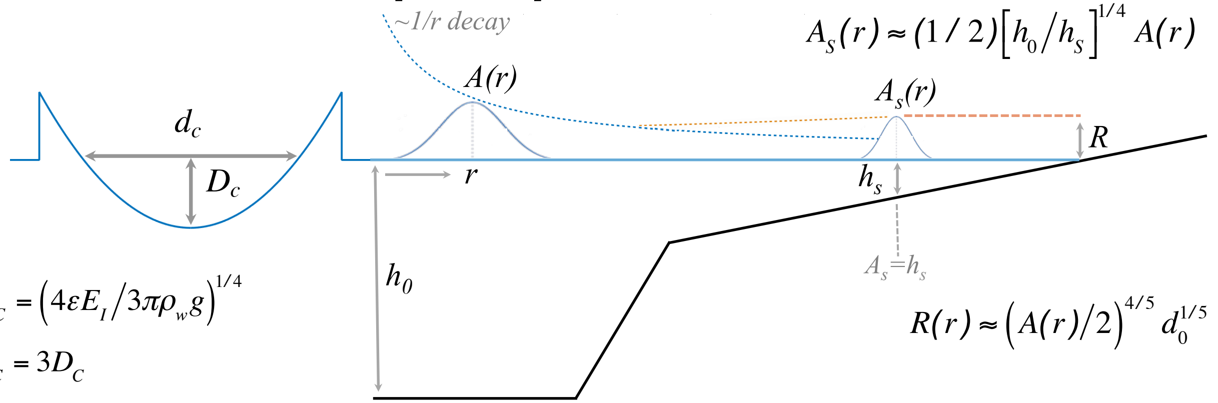
PAIR Tsunami Model

- Tsunami wave run-up
  - Analytic model based Chesley & Ward 2006, with refinements to wave initiation energy based on comparisons with high-fidelity ALE3D and GEOCLAW simulations.
  - Model gives maximum wave run-up heights as function of initial cavity size, ocean depth, and distance from impact to shore.
  - Initial water cavity size based on fraction of impact energy that goes into tsunami, which is taken to be 1.5% of remaining KE impacting water surface based on simulation comparisons.
  - Wave is propagated to shore using deep-water wave decay with a shoaling factor.
- Inundation and affected population
  - Wave run-up height is compared with elevation of regional coastal topography to determine flood depths.
  - Location-specific inundated population is determined using gridded population data.
  - Fraction of population affected is determined based on flood depth.

Tsunami Run-up Model

$$A(r) = \min\left[h_0, D_C\right]\left[\frac{1}{1+2r/d_C}\right]^{\psi} \qquad \psi = 1/2 + 0.575\exp\left[-0.0175 d_C / h_0\right]$$

$$A_S(r) \approx (1/2)\left[h_0/h_S\right]^{1/4} A(r)$$

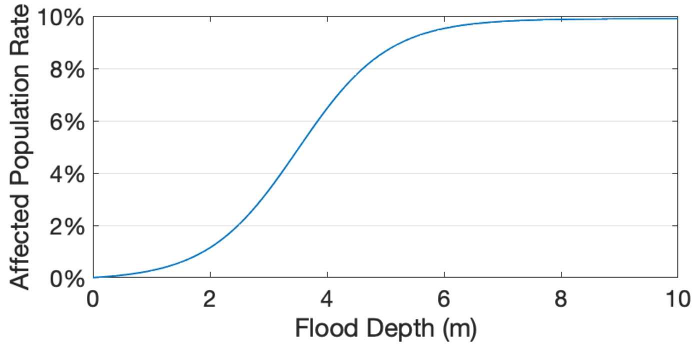


$$D_C = \left(4\varepsilon E_I / 3\pi\rho_w g\right)^{1/4}$$

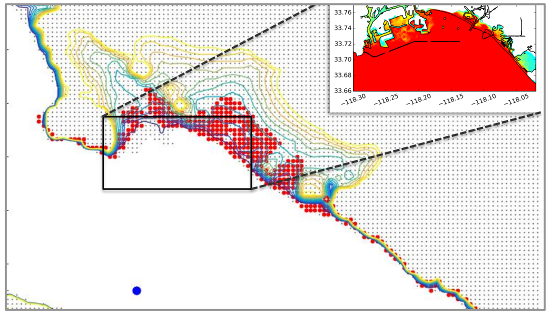
$$d_C = 3D_C$$

$$R(r) \approx \left(A(r)/2\right)^{4/5} d_0^{1/5}$$

Affected population rate by flood depth



Sample tsunami model inundation (red) shown over local elevation contour



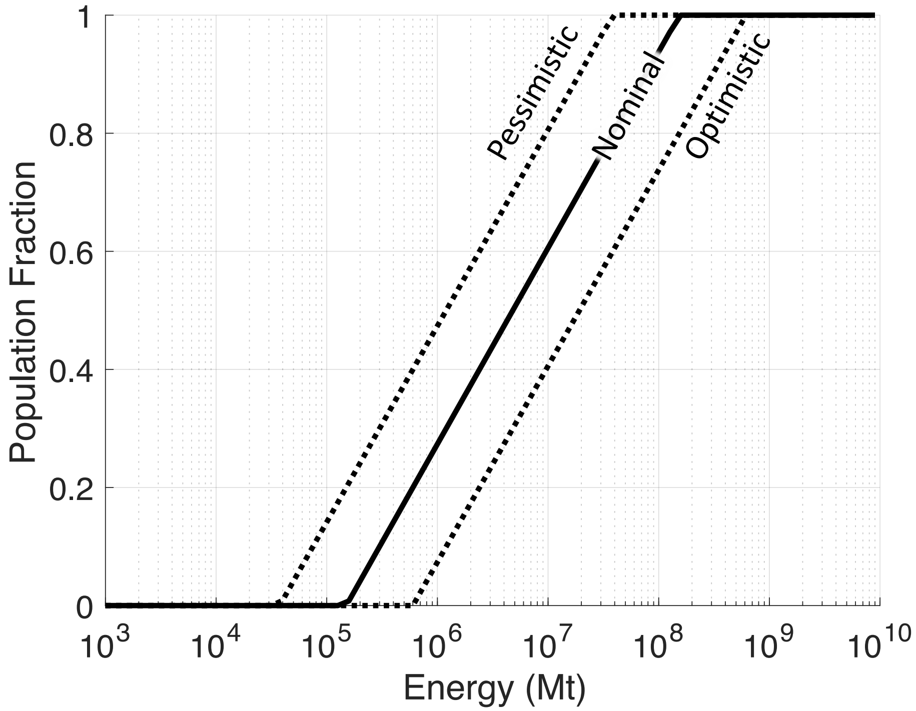
PAIR Global Effects Model

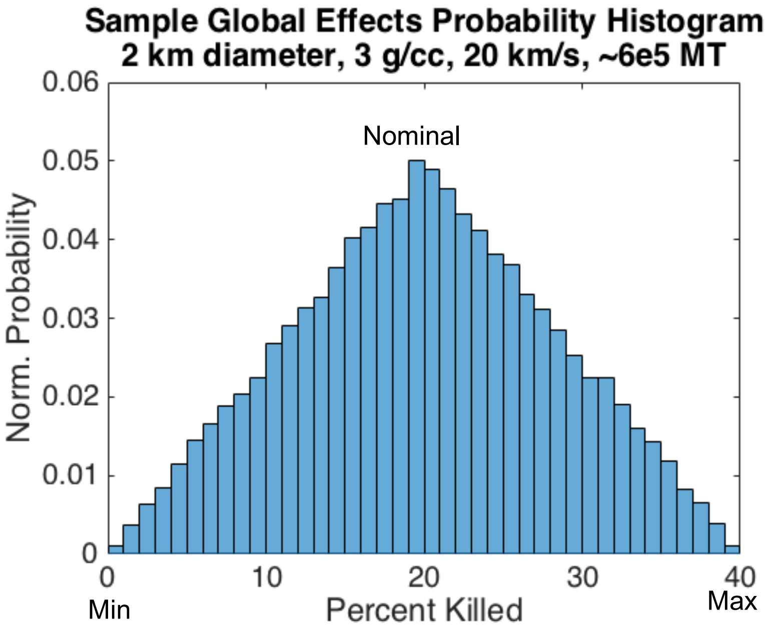
- Based on Stokes et al. 2003 NEO report,
- Samples from triangular distribution of minimum, maximum, and nominal casualty percentages based on impact energy.
- Serves as proxy for large-scale impact effects.
- Represents a generic range of consequences from regional weather disruption through global extinction.

$$\%Pop = \begin{cases} a_{\min} + \sqrt{U_{rand}(b_{\max} - a_{\min})(c_{nom} - a_{\min})} & for \quad 0 \le U_{rand} < F_c \\ b_{\max} - \sqrt{(1 - U_{rand})(b_{\max} - a_{\min})(b_{\max} - c_{nom}} & for \quad F_c \le U_{rand} < 1 \end{cases}$$

$$where \quad F_c = (c_{nom} - a_{\min})/(b_{\max} - a_{\min})$$

Impact Energy (MT)	Percentage Population Affected		
	Min	Nominal	Max
4.E+04	0	0	0
8.E+04	0	0	10
2.E+05	0	0	20
3.E+05	0	10	30
6.E+05	0	20	40
1.E+06	10	30	50
2.E+06	20	40	60
5.E+06	30	50	70
1.E+07	40	60	80
2.E+07	50	70	90
4.E+07	60	80	100
8.E+07	70	90	100





HYPOTHETICAL EXERCISE