Evacuation and Shelter Plans for Asteroid Impacts Informed by Hurricanes and Nuclear Explosions

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Abstract

Evacuation zone recommendations are determined for potential asteroid impacts. In most impacts on land, the dominant damage mechanism is the blast wave. Hurricane evacuations in the United States show that on average people evacuate to a 1 in a million risk of fatality level. To achieve the equivalent risk from a blast wave, preliminary estimates show that everyone within the 1 – 2 psi (≈0.07 – 0.14 atm or bar) blast radius should evacuate as even when taking shelter the risk threshold is probably exceeded. From there out to the 0.4 – 0.5 psi radii, seeking shelter in the basement of a reinforced concrete building or storm shelter, or in a home built shelter in the basement of a house would suffice as alternatives to evacuation while keeping the fatality risk below 1 in a million. From 0.4 down to 0.1 – 0.2 psi, windows may break but little to no structural damage to buildings is expected so simply staying away from windows and doors would be sufficient.

Introduction

The International Academy of Astronautics has held a Planetary Defense Conference every couple of years since 2008 which features an exercise, the goal of which is to test the capabilities of the planetary defense community and how it might respond to a potential impact, and where improvements can be made. NASA has also conducted several tabletop exercises with FEMA (US Federal Emergency Management Agency) (https://cneos.jpl.nasa.gov/pd/cs/). One aspect of the response that has been highlighted as currently lacking in detail is recommendations for evacuation and shelter and how to inform emergency managers and the public.

Experts in risk assessment create detailed maps of probabilities of damage. The predicted damage changes over time as more observations are made of an asteroid on a potential collision course with Earth. Initially the orbit is poorly known, meaning there may be a significant chance the asteroid won't hit Earth at all. The orbit and miss-distance or impact location improve relatively quickly with more observations, especially with precoveries where the object is found in old astronomical images by knowing roughly where to look. The mass of the object (and hence energy) is also initially poorly constrained. Mass depends on size and density, but only the brightness and distance are initially known. The albedo of asteroids has a long tail of coal-black objects that are much less reflective than the average asteroid, which means that an asteroid could potentially be much more massive than the average value

(Wright, et al., 2016). This means that the uncertainty in the blast radius for an asteroid (or comet) impact is usually dominated by uncertainties in the mass. This may be improved in the future using concepts that allow the mass to be determined during fly-by and not just rendezvous missions (Bull, et al., 2021), but would still require the time and expense of a fly-by mission, and the uncertainty in mass cannot be completely eliminated.

Risk due to an asteroid impact is currently often quantified using an estimate of the expected fatalities if the impact were to occur without warning (Mathias, et al., 2017), (Rumpf, et al., 2017). However, with modern telescopes scanning the skies for potential threats and better capabilities such as the NEO Surveyor infra-red space telescope coming online soon (Sonnett, et al., 2021), it is becoming much more likely that an asteroid big enough to cause significant ground damage will be detected at least a few days before impact. The bigger and more hazardous the asteroid, the brighter it will appear in the sky, making it easier to detect, and likely providing a longer warning time. Warning times should therefore usually be sufficient to complete evacuations of an area, minimizing fatalities and injuries. Better metrics, in future, may therefore be the number of evacuees and the cost of damage to infrastructure which cannot be moved out of the damage zone. Given sufficient warning time, the cost of evacuation and replacing damaged infrastructure can be weighed against the cost of in-space mitigation.

For determining evacuation recommendations, hurricanes provide a useful analog that many people are familiar with, at least in the US, and can provide useful insight into evacuation procedures that might be followed in the event of an asteroid impact. They also provide a useful analog to blast winds at large distances from a large impact. Blast waves from nuclear weapons provide a better analog to damage expected at close range to an asteroid impact, in particular from testing in the 1950s on houses and basement shelters.

Hurricanes

In modern times hurricanes are well monitored, but the average error in storm track forecasts is 100 miles for a 24 hour forecast (NOAA, 2021) (Senkbeil, et al., 2019), and predictions more than a few days ahead can be unreliable as storms stall or change direction as famously illustrated by Hurricane Dorian in 2019 (Figure 1). This means there is a trade-off in time required for evacuation vs the chance of the hurricane changing course. The extent of hurricane force winds is typically only about 100 miles from the eye, with winds in the arms of the hurricane dropping to storm and gale force (Alsweiss, et al., 2014), and as in Figure 2. In contrast, asteroids are fortunately much more predictable in terms of location, provided there is sufficient warning to obtain enough observations to narrow-down the orbit, but may still be highly unconstrained in terms of density and energy, and thus in extent of damage. The only expected change in impact location will be due to an in-space deflection or disruption from a mitigation mission.

Figure 1. Hurricane Dorian in 2019, stalled off the coast of Florida and changed direction from that predicted a few days before, heading up along the Atlantic coast instead of crossing into the Gulf of Mexico. https://www.nhc.noaa.gov/archive/2019/DORIAN_graphics.php.

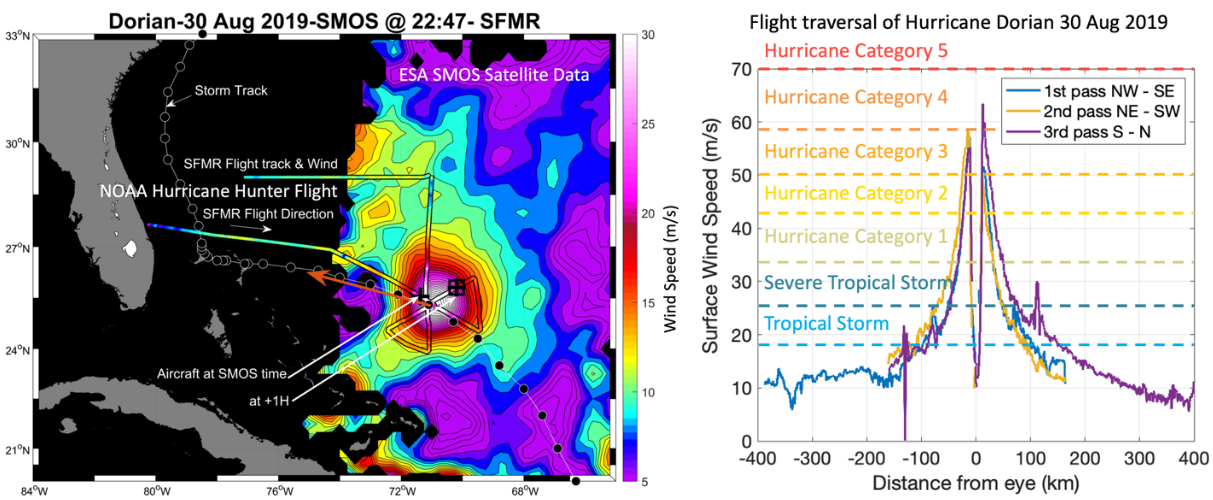


Figure 2. Hurricane force winds typically extend less than 100 km from the eye as shown here for Dorian when at category 4. Data from European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite (https://www.smosstorm.org/Results/Dorian-2019) and NOAA hurricane hunter flight's Stepped Frequency Microwave Radiometer (SFMR) instrument. (https://www.aoml.noaa.gov/hrd/Storm_pages/dorian2019/).

News media typically communicate the hurricane risks initially through the forecast ground track, and once it threatens the coast through watches and warnings (Figure 3), and finally through evacuation orders. A "warning" is issued where hurricane conditions (winds >74 mph (33 m/s)) or tropical storm conditions (>39 mph (18 m/s)) are *expected*, and a "watch" is issued where hurricane and storm conditions are *possible*. Thresholds can vary between agencies but the National Weather Service threshold for a watch is 50% and a warning is 80% chance within 36 hours. An "advisory" is issued where conditions are expected to pose significant inconvenience but are unlikely to be life threatening provided reasonable caution is taken. A watch and warning system for asteroid impacts could be especially useful in the early stages when an impact is not certain and the impact may occur at any location along a corridor spanning the globe.

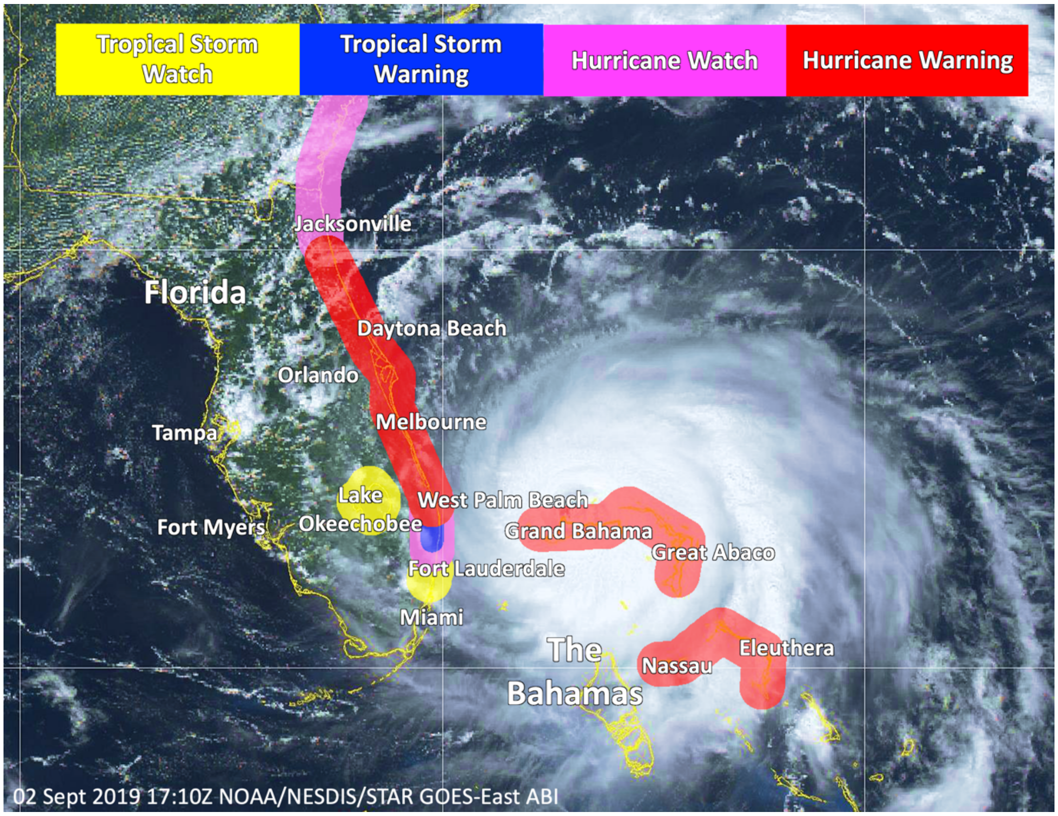


Figure 3. Hurricane watches and warnings indicate whether a hurricane is possible or probable, providing people a sense of risk and generally precede evacuation orders, and giving them time to prepare for an evacuation if one becomes necessary. Satellite photo of Hurricane Dorian from https://www.star.nesdis.noaa.gov/goes/floater.php?stormid=AL052019. Watches and warnings from https://www.nhc.noaa.gov/archive/2019/DORIAN_graphics.php?product=current_wind.

In hurricane and tornado prone areas in the US, building codes mean most houses can withstand most winds they are likely to experience over a 50 year period (Figure 4) (American Society of Civil Engineers, 2016). Consequently, the people that need to evacuate are mostly those in mobile or prefabricated houses not designed to withstand the winds, and those in storm surge flood areas (Figure 5). Most people therefore only need to evacuate 10 – 20 miles inland to a building designed to withstand high winds, although many may go further to bigger cities farther from the landfall location to stay with friends or relatives or find hotels. For an asteroid impact the blast pressure and wind speed versus distance can be predicted, and conveyed to the public using similar maps, so that people can understand whether or not they need to evacuate based on their home.

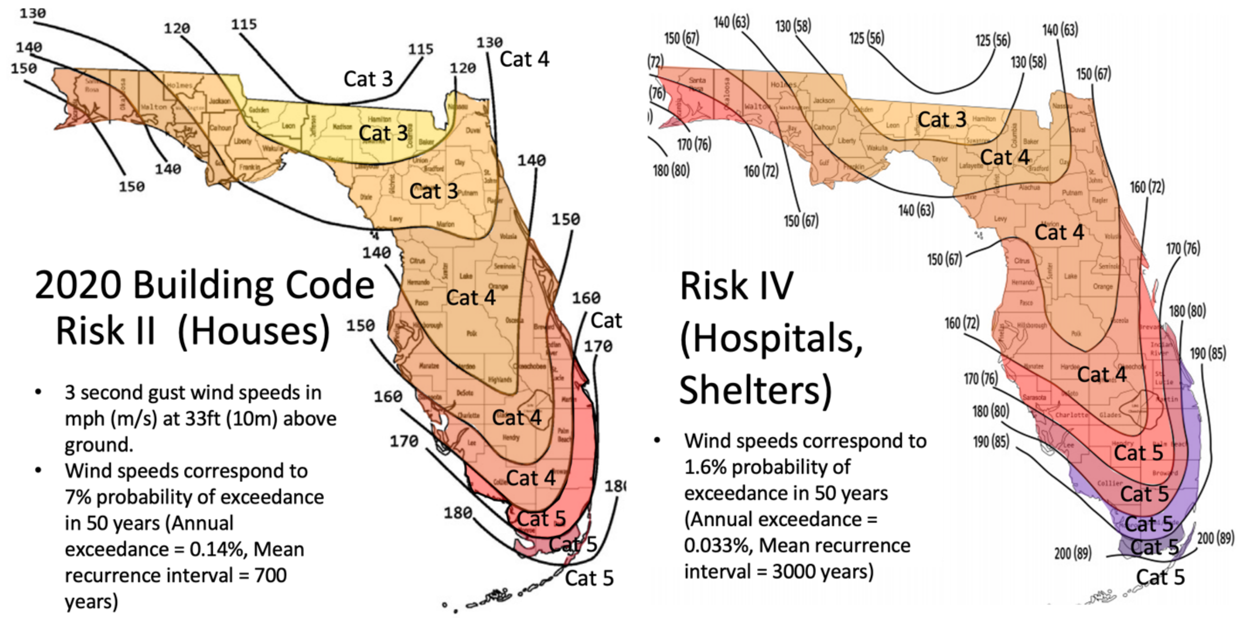


Figure 4. Building codes. There is a significant reduction in loss rate for recently built homes due to improved building codes, particularly as a result of Hurricane Andrew in 1992. Buildings are separated into four risk categories: I. Agriculture and storage, II. Houses, III. Public buildings (e.g. schools), IV. Critical infrastructure (e.g. hospitals, power stations, emergency services, hurricane shelters). The 2020 standards mean that a new house should be able to withstand a category 4 storm for most of the peninsula (Florida Building Commission, 2020).

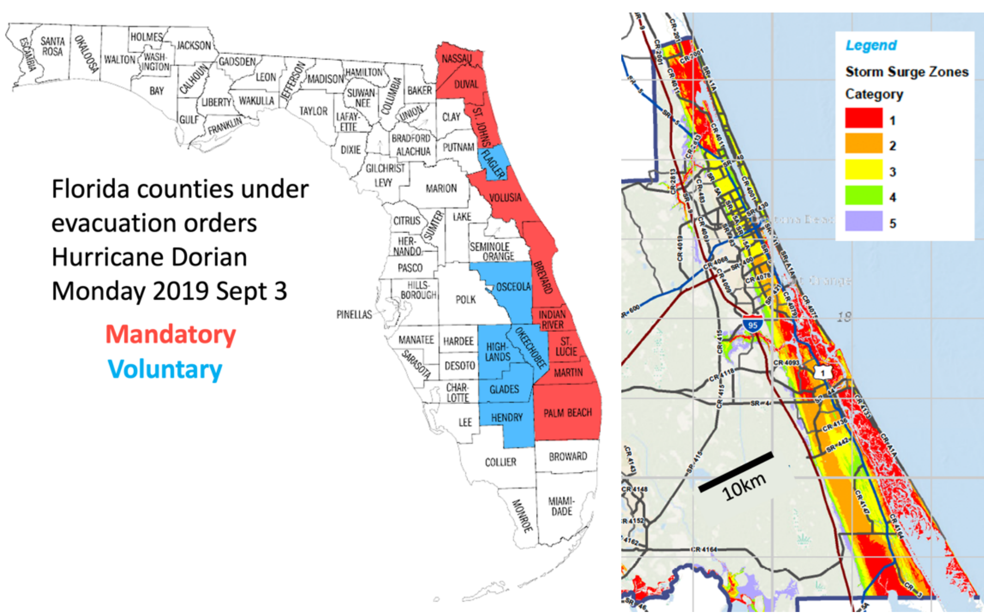


Figure 5. Evacuation maps. For Hurricane Dorian in 2019, most counties on Florida's Atlantic coast were under an evacuation order (https://www.floridadisaster.org/news-media/news/20190903-governor-ron-desantis-holds-press-conference-with-fema-acting-administrator-pete-gaynor-issues-update-on-hurricane-dorian/). However as seen for Volusia County near Daytona Beach only the barrier island and areas around the river behind it are in

danger of flooding during from the storm (https://www.floridadisaster.org/planprepare/disaster-preparedness-maps/). People living in houses built to Building Code Risk II or better standards may choose to evacuate but can reasonably shelter in place for up to a category 4 hurricane if not in a storm surge zone.

During a hurricane event, preparations are made at the state and local level in the US. The Louisiana Office of Emergency Preparedness uses five levels of operation (Wolshon, et al., 2001).

- Level V is normal operations.
- Level IV is triggered when a tropical system forms in the Gulf of Mexico or nearby Atlantic. In level IV the storm is closely monitored with situation reports sent to the Governor, FEMA, and local agencies.
- Level III is when the Louisiana coastline is threatened, which causes the National Guard to be activated; evacuation routes are cleared of obstructions; and coordination is begun with neighboring states to handle emergency services and evacuees.
- Level II occurs when the hurricane is 2 to 3 days from landfall. A publicity campaign is started via local media to encourage preparations for evacuation and shelter. A declaration of emergency gives the office control over state services usually managed by the Governor. The Office of Emergency Preparedness coordinates with police and the Transport Office on evacuation routes.
- Level I is imminent landfall (<2 days). Evacuation orders are given if not already done so by local authorities. Evacuations are rated as Precautionary, Recommended, Mandatory. Help is provided to evacuate low-mobility facilities such as hospitals, nursing homes, and prisons. 2 hours prior to landfall, all evacuation routes are closed, and traffic enforcement and media go to refuge locations. Coordination is begun on post-storm recovery efforts.

A similar process can be used for asteroid impact evacuation. The timeline will typically be much longer (up to years or even decades) although an impact may still occur without any warning at all. Assuming a reasonable time to prepare, evacuation orders need only be issued days or weeks in advance depending on the size of the area needing evacuation, but as with hurricanes many people will self-evacuate before the order is issued. If the impact zone is well known sufficiently well in advance, many people and businesses may relocate well ahead of the impact.

There are variations from state to state, and also at the local level. No-one actually enforces mandatory evacuations. People can ignore evacuation orders at their own peril, so Texas only has “Recommended” evacuations (Wolshon, et al., 2001). Evacuation orders depend on the local emergency management and vary depending on risk tolerance, but a general procedure is given using the HURREVAC software from FEMA, US Army Corps of Engineers, and NOAA (https://www.hurrevac.com/). Maps of storm surge inundation and flash flooding are precomputed, as are clearance times in which a given area could be evacuated, depending on the size of the storm. NOAA tracks storms and every day runs 1000 simulations of the future evolution of the storm, from which it generates maps of the arrival time of tropical storm winds

(Figure 6). The earliest reasonable arrival time is set to having a 10% chance of the wind arriving sooner. Based on the clearance time for an area, the earliest reasonable tropical storm wind arrival time will dictate the earliest evacuation start time, and the most likely (mean) arrival time will determine the latest evacuation start time to clear the area before the storm arrives (Figure 7). Local storm management will usually call for evacuations sometime within that window depending on risk tolerance.

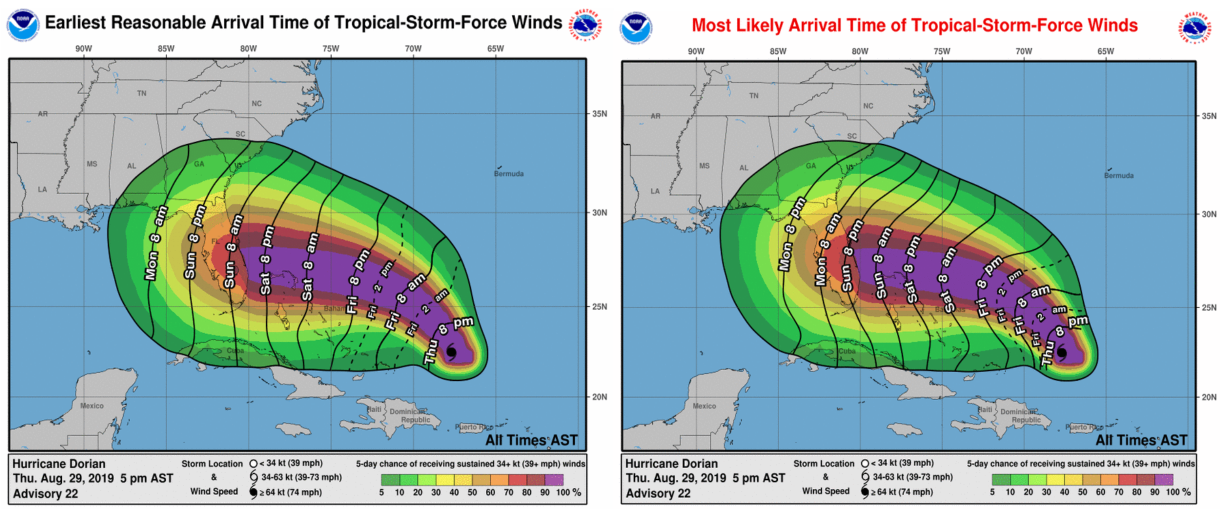


Figure 6. Earliest reasonable and Most-likely arrival time of tropical storm force winds. Outline covers areas with at least a 5% chance of experiencing sustained tropical storm winds within a 5 day period. Majority of the width of the extent is due to uncertainty in the track of the hurricane. Except for the biggest cities, most areas can be evacuated within a couple of days or less.

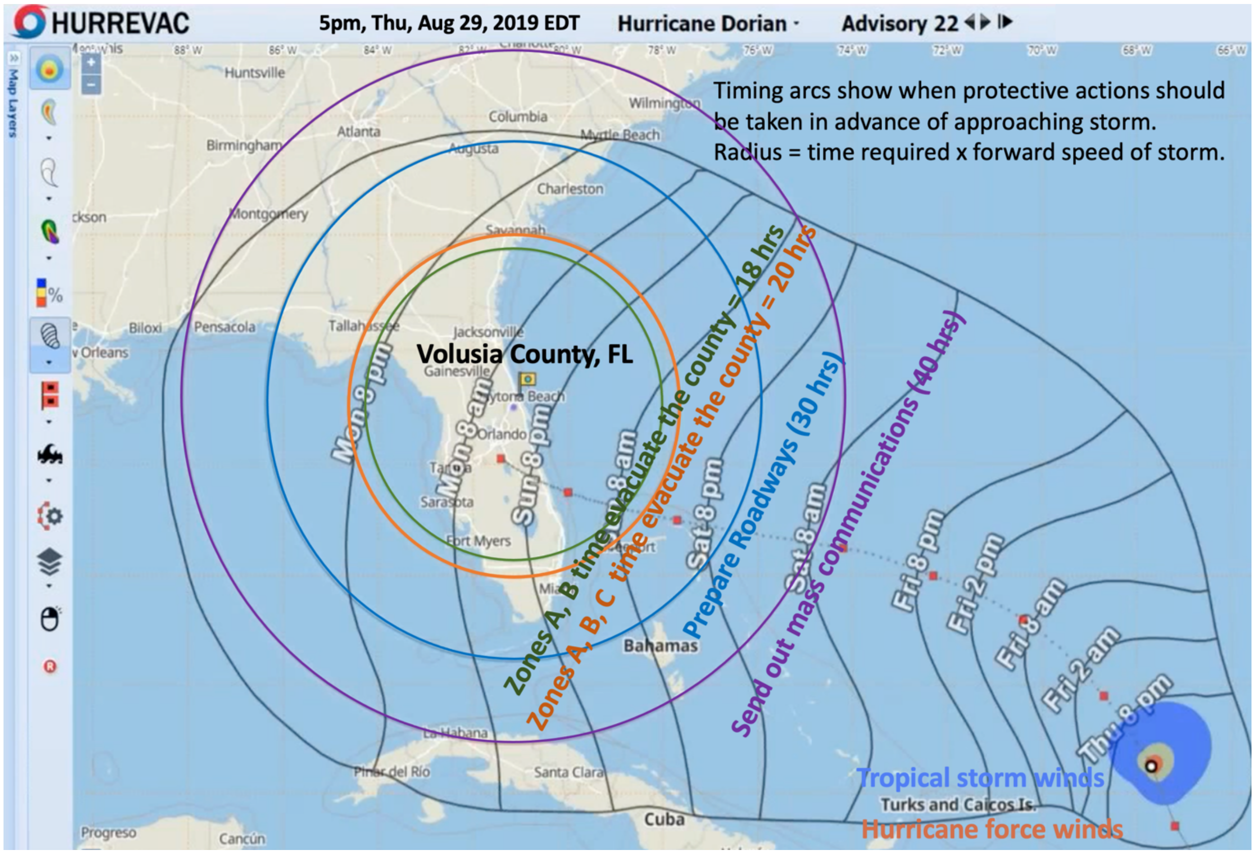


Figure 7. Based on the predicted forward speed of the hurricane at the time of the forecast (Thursday Aug. 29, 2019), and the time required, unless the hurricane speed or trajectory changed, mass communications would be sent out at about 8am Saturday (Sept. 1, 2019) when a hurricane watch or warning is issued, telling officials and the public to prepare for evacuation. Road preparations would begin late Saturday afternoon, and evacuation would begin very early Sunday morning. The tropical storm winds would be predicted to arrive very early Monday morning, at which time the evacuation should be complete. This is all subject to modification as the trajectory and forward speed of the storm changes.

Similar maps of the probability of a location suffering blast pressures exceeding a given level are generated for asteroid impacts (https://cneos.jpl.nasa.gov/pd/cs/), which can be used to inform local emergency management teams and the public, although public communication will likely focus on the simpler watch/warning followed by evacuation orders.

The number of people who evacuate depends on the strength of the storm, how close it comes and the location of the home (Figure 8). This means almost 100% of people will evacuate when facing a category 5 hurricane, which may destroy even “hurricane-proof” houses, but only about 30% of people will evacuate for a category 1 hurricane (Lindell, et al., 2006) (Lindell, 2008) (Czajkowski & Kennedy, 2010) (Xu, et al., 2016).

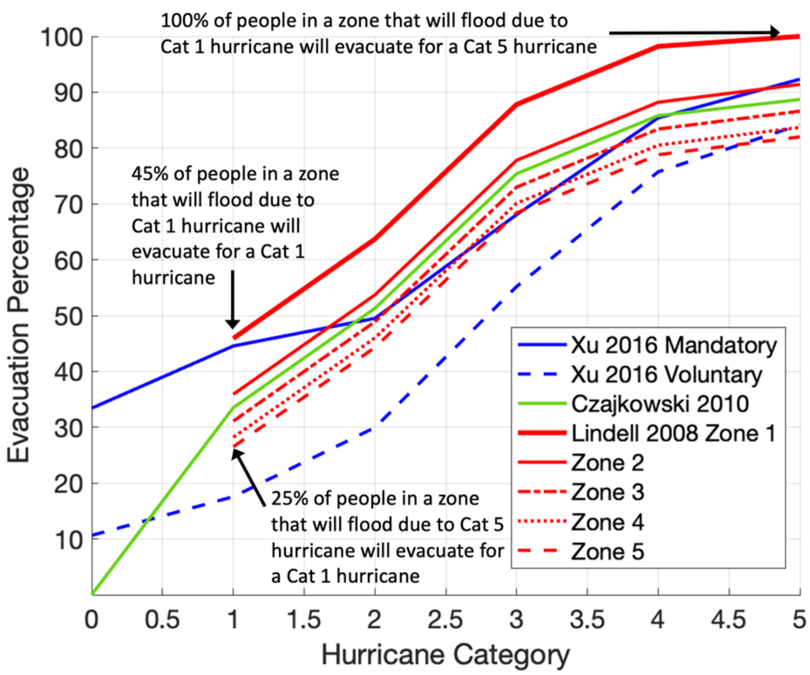


Figure 8. Evacuation percentages. Category 0 is a tropical storm, and evacuees are mostly those living in mobile homes and other structures not designed to weather high winds. Lindell (2008) further splits out the evacuation percentages by flood zone. These correspond roughly to the storm surge expected from an equivalent category hurricane. Understandably the more likely a house is to flood, the more likely the residents are to evacuate.

The expected fatalities and probability distribution of fatalities can be estimated from the model in (Czajkowski & Kennedy, 2010) which gives the evacuation percentage,

$$E = 100(1 - e^{-0.46\,S}).$$

Equation 1

where S = hurricane scale (0=tropical storm). The probability of zero deaths in a county of 500 000 people is given by

$$P_0 = a/(1-a), \quad a = exp(-1.07\,D - 2.19\,M + 0.07\,E - 0.65)$$ Equation 2

where D = 1 for a direct hit, 0 otherwise. M = 1 for a major storm (S≥3), 0 otherwise. The mean expected fatalities is given by

$$\bar{F} = (1 - P_0)\,\mu, \quad \mu = \exp\,(0.73\,S + 0.88\,D - 3.66 + 1.05\,Y)$$ Equation 3

where μ is the mean fatalities of the non-zero distribution, Y = 1 for hurricanes since 1990, and 0 for hurricanes before 1970, which may reasonably represent locations with much lower wind resistant building codes. The full probability distribution is a zero-inflated Poisson distribution:

$$P(F) = (1 - P_0)\,P_1, \qquad P_1 = \frac{\mu^F\,e^{-\mu}}{\Gamma(F+1)}$$ Equation 4

where F is the number of fatalities, and Γ is the gamma function. The result as shown in Figure 9 is that in the US people evacuate hurricanes to the 1 in a million fatality risk independent of the strength of the hurricane. In modern times the probability of zero deaths is higher than historically due to better storm monitoring giving people more warning time, and a better estimate of the severity, and also better building codes.

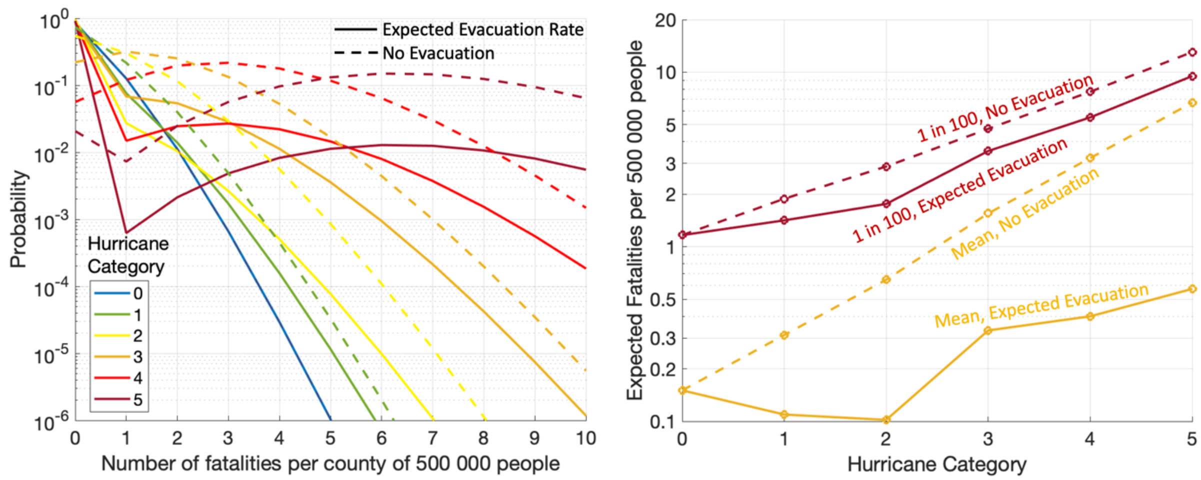


Figure 9. The expected number of casualties from (Czajkowski & Kennedy, 2010) follows a zero-inflated model, where there is a high probability of no deaths, but otherwise follows a distribution where the expected fatalities increase with hurricane strength. The expected fatality distribution depends on the percentage of the population that evacuates. For nobody evacuating, the expected fatalities grow exponentially with storm category, but with modern weather forecasting, more people will evacuate a more severe storm. The net result is that in the USA people will evacuate to give all hurricanes about a 1 in a million fatality risk on the pre-evacuation population in an area.

A similar fatality probability distribution can be calculated for the blast wave from an asteroid impact, which can be obtained from data on large explosions. Data from nuclear explosions generally stops around 1 psi overpressure where most buildings can survive the blast and the fatality rate drops below ~1 in 100 (Glasstone & Dolan, 1977). However, for civil defense and evacuation purposes the risk is needed down to ~1 in a million, for which the data on hurricanes in Figure 9 can also serve as an analog by calculating the wind speed behind a blast wave of given overpressure.

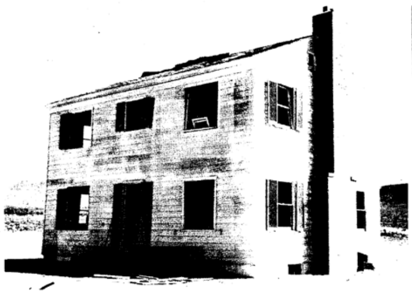
Nuclear Explosions

The damage from nuclear blasts is known from World War II and testing done afterwards. In the bombing of Hiroshima (16±2 kt) and Nagasaki (21±2 kt), outdoors at 0.5 – 1.2 km radius (0.3 – 0.75 mile) fatalities were 100 – 90%. Patients were treated for lacerations out to about 3.5 km. This corresponds roughly to the distance at which moderate damage occurred to wooden frame houses, including the shattering of windows. For people who were indoors, casualties corresponded with the extent of structural damage (Glasstone & Dolan, 1977). Figure 10 shows that a blast overpressure of 20 psi destroys even reinforced concrete buildings, and normal houses would be destroyed by 5 psi, but probably remain standing from a 1.7 psi blast, even though all the doors and windows were blown in.

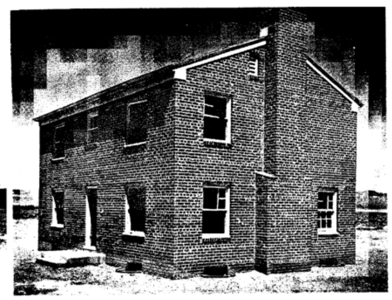
5 psi vs Wood frame house.
House levelled but limited breakthrough to basement.
Reasonable survival chance in basement.

5 psi vs Brick house.
House levelled and partially collapsed into basement.

27 psi vs Reinforced concrete building.
Partially collapsed. Gutted by fire.



1.7 psi vs Wood frame house.
Badly damaged but still standing.
Flying debris likely fatal, but basement safe.



1.7 psi vs Brick house.
Badly damaged but still standing.
Flying debris likely fatal, but basement safe.

17 psi vs Steel + Reinforced concrete building.
First story collapsed dropping second story to ground.

Figure 10. Damage to buildings from Hiroshima, Nagasaki, and nuclear tests Operation Doorstep and Cue at the Nevada test site. From (Glasstone & Dolan, 1977). Declassified video of the tests can be found at https://www.youtube.com/watch?v=G2-8f-V5sFY

Figure 11 shows the results of many tests of different explosive yields on different buildings. Light damage is defined as doors and windows blown in and minor damage to roof or siding, but still habitable with minor repairs. Moderate damage implies damage to the structure of the house, necessitating major repairs before being habitable. Severe damage means collapsed or incipient collapse. Houses and reinforced concrete buildings designed to withstand blasts suffer damage that is mostly just dependent on the overpressure and independent of the yield. Office buildings do worse against large yields where the blast winds are sustained for a longer time at a given overpressure, so have a large total impulse.

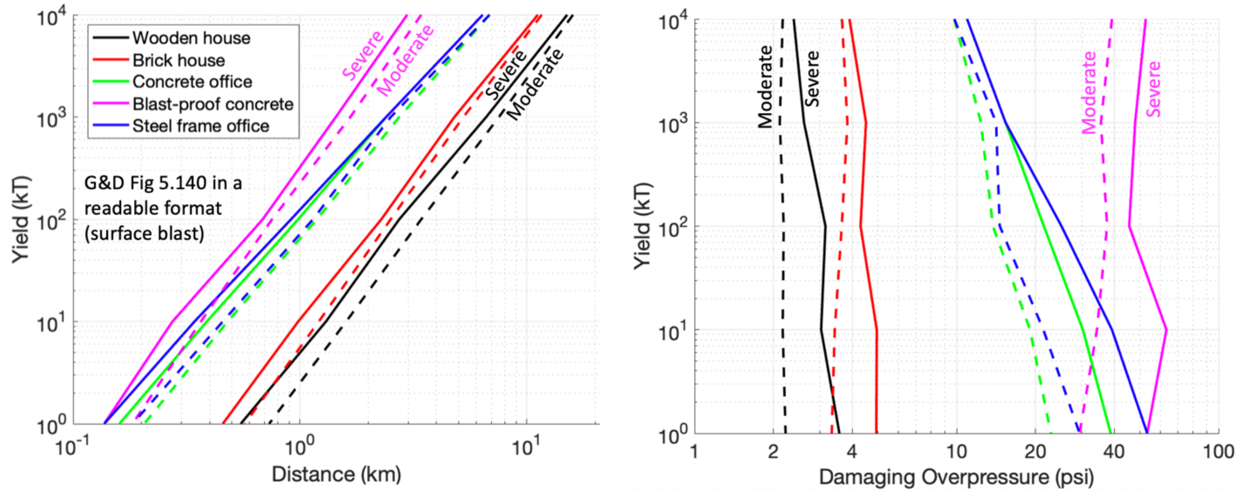


Figure 11. Wood frame houses perform the worst against blast waves suffering moderate damage at 2 psi (0.14. bar), and severe damage at about 3 psi (0.2 bar). Brick houses only perform marginally better. Both concrete and steel framed office buildings do better, suffering moderate damage at 10 psi (0.7 bar) for a large blast (10 Mt), but will do better against smaller blasts, presumably due to a shorter blast wind duration. Buildings specifically designed to withstand blasts typically can withstand about 30 psi (2 bar). Light damage occurs at 10 psi for the blast-proof building and 1 psi for all other buildings.

Nuclear testing in Operations Doorstep and Cue and later also investigated the use of simple basement shelters that were designed to be easily buildable by homeowners, to improve survivability of those taking shelter in the basement. They also tested underground concrete bunkers which would take more effort and expense to build, but would be safer choices closer to the impact site. A dirt covered Anderson shelter (UK Home Office, 1939) would be an alternative, and many modern storm shelter designs are available commercially or could be custom built (FEMA, 2021). Figure 12 shows two of the basement shelters designed to reduce the likelihood of debris penetration into the occupied space, and would be viable alternatives to evacuation in areas where the risk is already reasonably low.

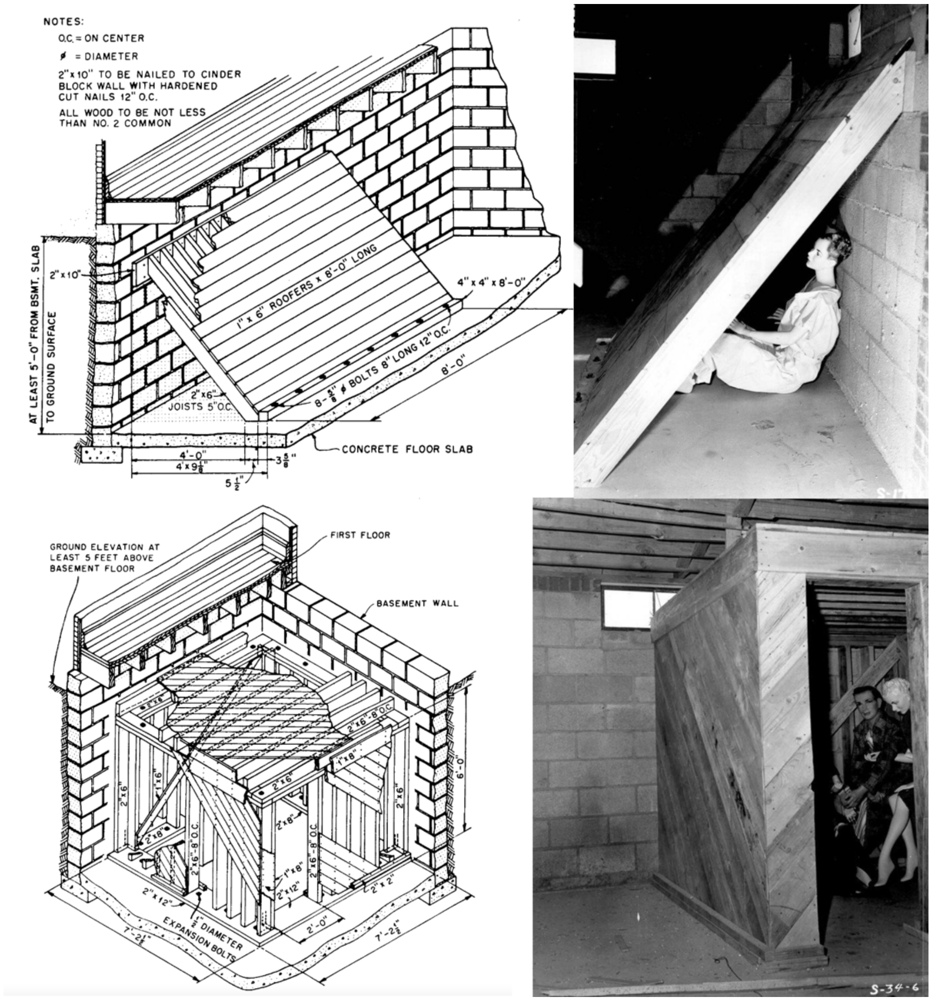


Figure 12. Improvised basement shelters tested in Operations Doorstep and Cue. Wooden frame shelters are bolted to the floor and basement walls. (Beck, 1969) and National Nuclear Security Administration Nevada Field Office Nuclear Testing Archives (http://www.nv.doe.gov/library/photos/doorstep.aspx) or https://commons.wikimedia.org/w/index.php?search=operation+doorstep.

The fatality risk from nuclear explosions both when caught by surprise and when taking shelter can be combined with the risk from hurricane force winds and used to inform the hazard from an asteroid impact. Equivalent blast overpressure is found by matching the wind speed behind the blast to the hurricane wind speed. This neglects dynamic effects from the sharp onset of high winds, which may break windows at lower wind speeds, but should be reasonable for structural damage to buildings which are usually the result of high winds sustained over at least several seconds. The blast pressure and wind speed are calculated using the equation of (Jones, 1968), but the overpressure ΔP doubled to account for the ground reflection;

$$\frac{\Delta P}{P_{atm}} = 2 \times \frac{0.305}{(1+5.892\, Z^3)^{5/18}-1}, \qquad Z = R/R_J, \qquad R_J = (2.01\, E/P_{atm})^{1/3}$$

Equation 5

where P_{atm} is the atmospheric pressure (Pa), Z is the distance R (m) scaled by the characteristic distance R_J for a spherical explosion in air of energy E (J). Wind speed, u, is calculated from the shock Hugoniot, assuming the Mach number of the incident shock:

$$u = \frac{\Delta P}{\rho_{atm} U_{shock}}, \qquad U_{shock} = \mathrm{M\ a}\,, \qquad M = \sqrt{1 + \left(\frac{\Delta P/2}{P_{atm}}\right)\frac{(\gamma+1)}{2\gamma}}$$

Equation 6

where ρ_{atm} is atmospheric density, U_{shock} is the shock speed, M is the Mach number, a is the atmospheric speed of sound, and γ is the ratio of specific heats. The result is shown in Figure 13. At overpressures below 10 psi the wind speed can be approximated by

$$u\ (m/s) = \ 32.4\, P(psi)^{0.986}$$

Equation 7

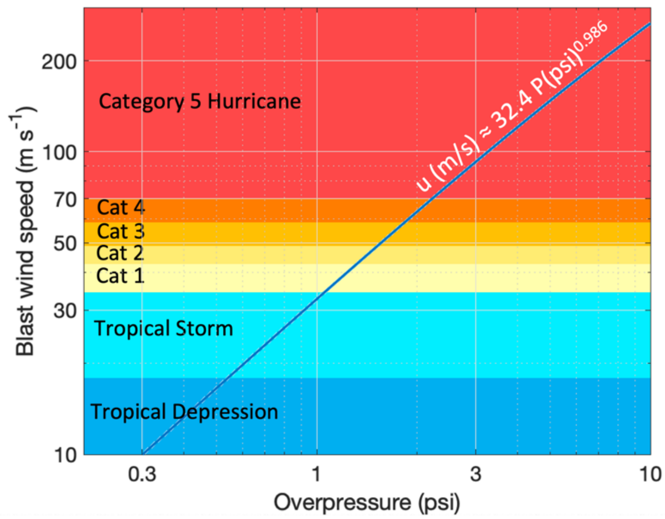


Figure 13: Wind speed behind a blast wave including a ground reflection. Assuming buildings suffer damage due to wind speeds sustained over a few seconds it also gives the equivalency of storm winds and blast waves. This will allow risk estimates to be calculated at both high and low overpressures when taking appropriate shelter.

Asteroid Impacts

The only really well characterized asteroid impact including estimates of the blast pressure versus distance is the Chelyabinsk 2013 meteor, as shown in Figure 14 (Aftosmis, et al., 2016) (Popova, et al., 2013). The blast wind behind the ~0.5 psi shock wave over the city caused 2 nearly-fatal injuries, 112 hospital admissions, and 1491 people who needed medical care out of a population of 1.1 million. This roughly matches both the expected windspeed and casualties if a tropical storm had hit instead of a meteor.

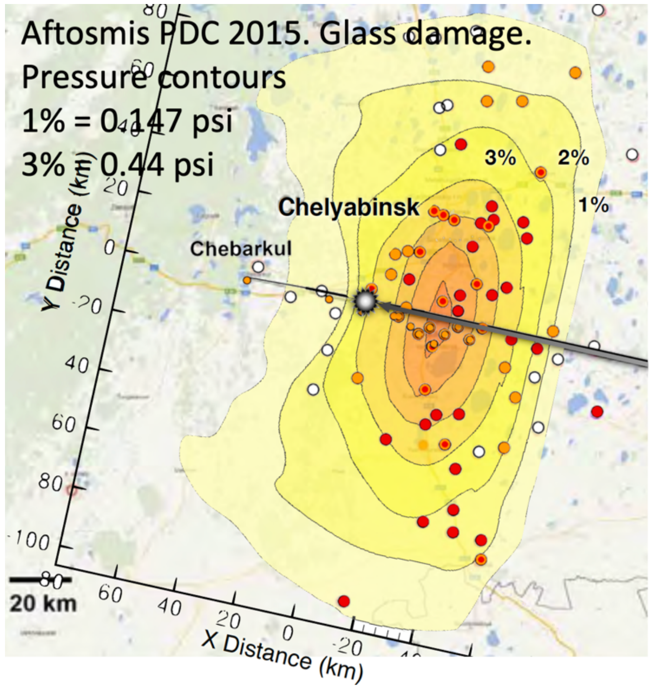


Figure 14. Estimated blast peak overpressure and map of broken windows. The peak pressure required to break windows is about 0.1 – 0.2 psi. (Aftosmis, et al., 2016)

Combining the casualty estimates from hurricanes, nuclear explosions, and Chelyabinsk allows casualties to be estimated for both a surprise impact and when taking shelter or evacuating as shown in Figure 15. The data is fitted with the curves

$$\bar{F}_{surprise} = \exp(-6.49\ \Delta P^{-1.27}) \qquad \bar{F}_{shelter} = \exp(-33.12\ \Delta P^{-1.27})$$

Equation 8

Where F is the expected fatality rate, and ΔP is the blast overpressure. For a blast pressure of 2 psi when caught by surprise the expected fatality rate is about 10% due to many people being outdoors with flying debris, and normal houses suffering significant damage. By evacuating or taking shelter the casualty rate drops to about 1 in a million.

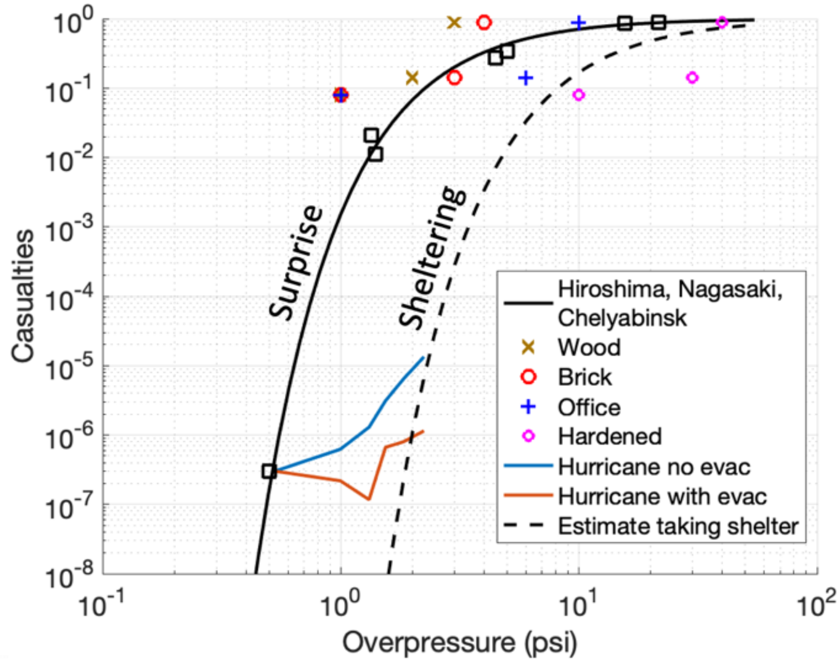


Figure 15. Expected casualty rate for a blast in scenarios when blast is a surprise, and when precautions are taken. Both asymptote towards 100% fatalities at about 50 psi when even blast-proof buildings will be destroyed.

For the fictional PDC 2021 impact exercise (https://cneos.jpl.nasa.gov/pd/cs/pdc21/), a week before impact when evacuations might begin, the impact location is known to be a forested area near the border of Germany, Austria, and Czechia. The asteroid size is known to be 105±11 m and as shown in Figure 16, the energy is most likely about 35 megatons of TNT equivalent, but has a 1 in 1000 chance of exceeding 100 Mt. The probability distributions for blast overpressure levels move out with decreasing pressure level, but interestingly shows a bimodal distribution for the 1psi pressure level. This is due to increased ground damage in fairly narrow range of burst heights (Aftosmis, et al., 2019), followed by a slower increase due to large impact in the tail of energy distribution.

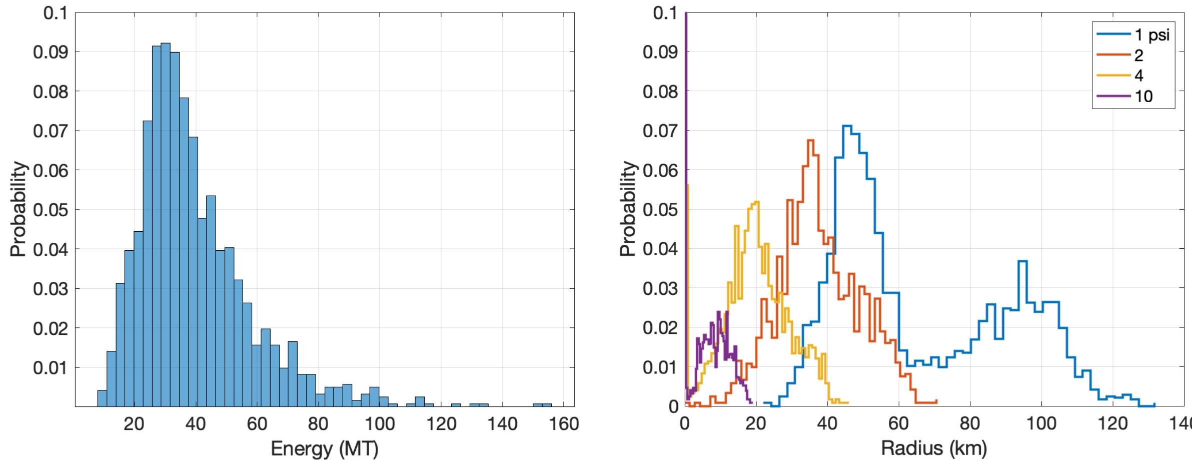


Figure 16. Asteroid impact energy follows a distribution due to uncertainties on composition, density, and porosity, despite the diameter being well constrained from radar measurements. Distance at which a given pressure level is felt from the blast varies additionally with uncertainties on strength and height of burst.

Combining the blast pressure vs distance (Equation 5) and the casualties vs overpressure in Figure 15 gives the fatality rate vs distance for each possible impact scenario. Summing the fatality rate vs distance over the distributions in Figure 16, gives the probability of exceeding a given fatality rate at a given distance, and thus the mean expected casualties at a given distance, and also the expected casualties at less likely probabilities as shown in Figure 17.

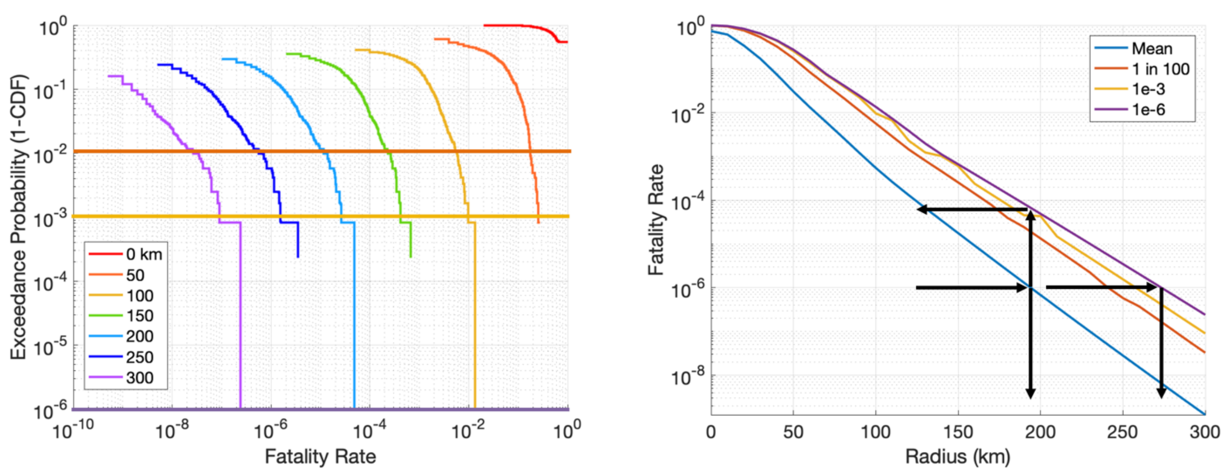


Figure 17. Probability of exceeding a given fatality rate vs distance. The closer to the blast the more likely a higher fatality rate is. The mean value for the 1 in a million fatality rate is at about 200 km, but there is a 10^{-3} (1 in 1000) chance of the fatality rate at that distance actually being 10^{-4} (1 in 10 000) and the 1 in million rate actually being at 270 km distance.

Considering the fatality rate in Figure 15 when people are given warning and have time to evacuate or take shelter yields Figure 18. When evacuating the mean fatality risk drops below 1 in a million at 55 km which corresponds to a mean blast pressure of 1.3 psi. To have less than a 1 in a million fatality risk, everyone within the 55 km radius should evacuate. Without evacuating or taking shelter the fatality risk drops to 1 in a million at 0.44 psi which is 190 km from ground zero. Between 55 and 190 km fatality risk can be reduced to acceptable levels by taking appropriate shelter or evacuating. Appropriate shelter would be the basement of a reinforced concrete building, ideally an actual bomb shelter, or a homemade shelter such as the basement shelters shown in Figure 12. In this scenario 190 km would be an appropriate distance to evacuate to, beyond which the only necessary precaution would be to stay away from windows to avoid injury from broken glass.

An important caveat is that these are mean expected casualties. There is close to a 50% chance that the blast wave will be more damaging, resulting in more casualties. For example in the 1980 volcanic eruption of Mount Saint Helens, 57 people were killed when the explosion was much bigger than expected, closer to a worst case scenario, and also strongly focused towards the north. The evacuation areas were set to a red zone in danger from a “small eruption”, and blue zone for a “medium” size eruption. There were plans to expand the evacuation area but these were not implemented before the eruption occurred. Of those who died, only 3 were within evacuations zones: 1 homeowner who refused to evacuate, and 2 volcanologists monitoring the volcano. The rest of the 57 were in areas open for recreation. If the explosion had occurred on a weekday, hundreds of loggers would have been working in the blue zone and the death toll correspondingly higher (Olson, 2017). To account for a worst case for the PDC21 scenario at the 1 in million level, the 100% evacuation radius should be 72 km and the shelter radius should be 270 km. Reasonable evacuation radii would lie between the mean and 1 in a million levels depending on personal and official risk tolerance.

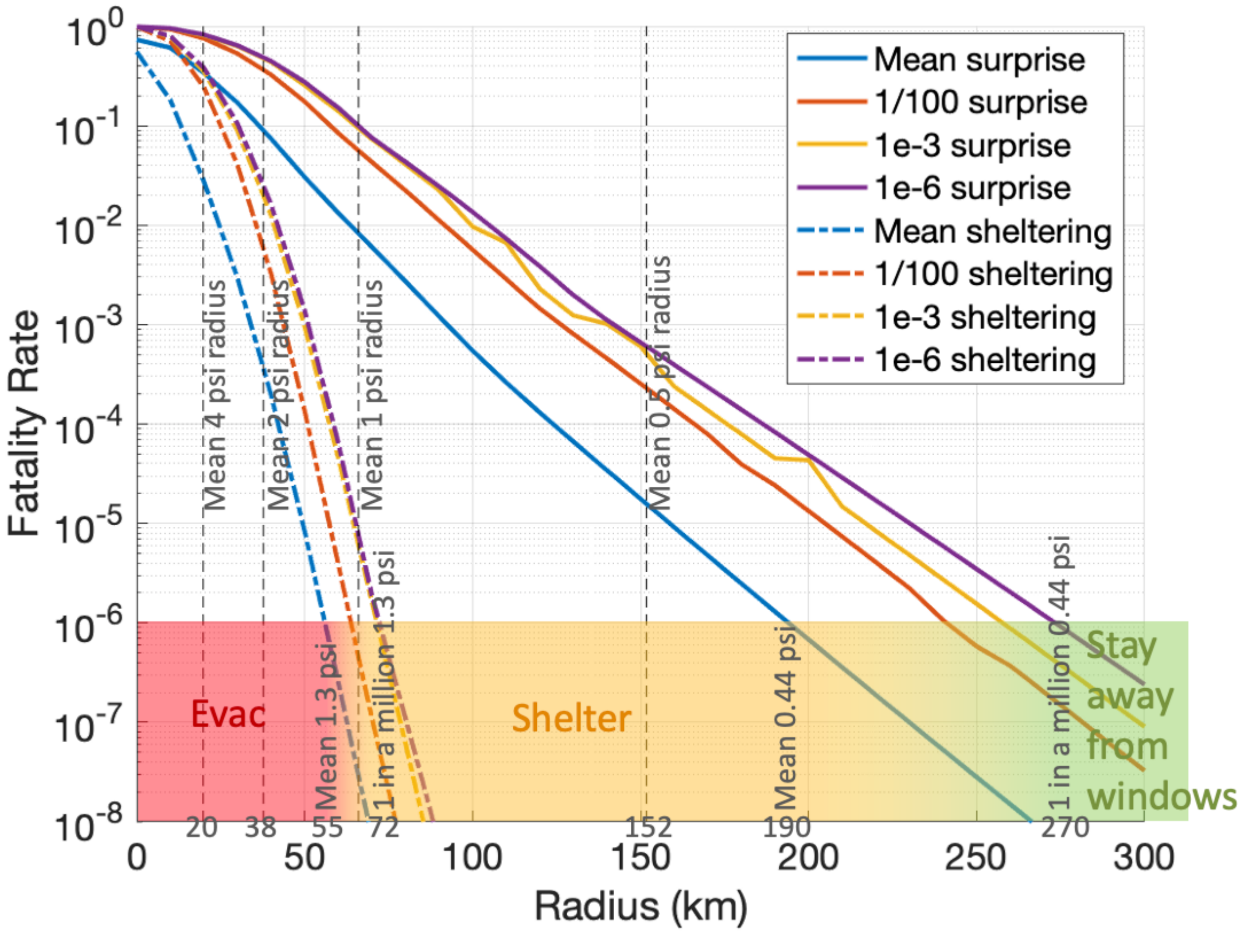


Figure 18. Fatality rates when evacuating or taking shelter are much lower than those if an impact occurred by surprise.

The evacuation zones are shown in Figure 19 overlaid on the population data from (CIESIN, SEDAC, 2020). Although the impact occurs in a relatively unpopulated forest, 0.8 million people live within the 55 km evacuation zone, and 1.8 million if it is extended to 72 km. 15M people live within the 190 km shelter zone, and 32M within the worst case shelter radius at 270 km. 100M live within the expected window breaking zone, and 330M in the worst case (925 km).

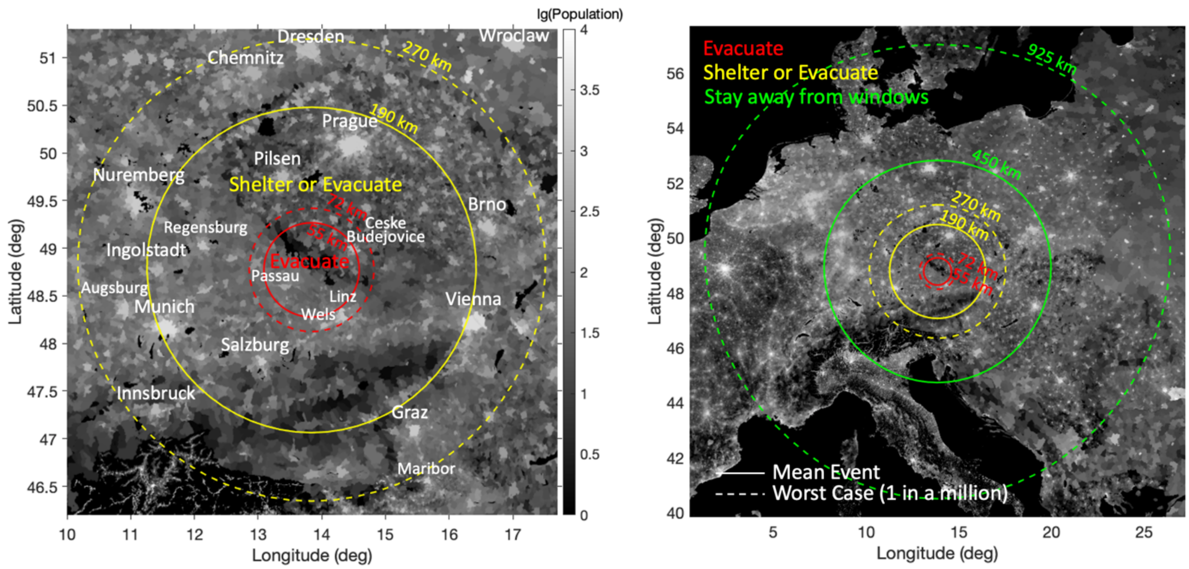


Figure 19. Evacuation zones. Everyone within 1.3 psi would need to evacuate or face greater than 1 in a million fatality risk even when taking shelter, as many buildings will collapse, outside will be deadly projectile debris, and there is a significant chance of fires. The mean distance for 1.3 psi is 55 km, and in the worst case (1 in a million probability) it is 72 km. From (1.3 – 0.44 psi) a 10^{-6} risk can be achieved sheltering in the basement, which is between 190 km (mean) and 270 km (worst case). This includes the cities of Prague (population 2.8 million), Munich (6.0M), and possibly Vienna (2.9M), Brno (0.7M), Nuremberg (3.6M), Dresden (1.3M). From there to the limit of breaking windows (0.2psi, mean = 450 km, worst case = 925 km), people would just need to avoid windows to reduce their risk below 10^{-6}. This zone covers a large part of Europe. Population data from (CIESIN, SEDAC, 2020).

The total number of expected casualties can be obtained by summing the fatality rates over the population as shown in Figure 20. It is assumed that beyond 190 km the fatality rates follow the mean surprise rate from Figure 18. Between 55 and 190 km it is assumed people only actually evacuate or shelter to the 1 in a million risk level, and closer than 55 km it is assumed people would evacuate to the 1 in a million level given sufficient warning time as in the PDC21 scenario. If only given enough time to find shelter the rates would follow the mean sheltering rate from Figure 18. The result is that if the impact occurred by surprise the expected casualties would be 100 000. For a short warning time only sufficient to seek shelter, the casualties would be reduced to 7000, but with ample time to evacuate the expected fatalities are just 17 people.

If warning time is short, care must be taken in evacuation orders not to leave people out in the open where their risk will be higher than if they sought shelter at or near home. As an example of an evacuation mismanaged, in the case of the Hurricane Rita evacuation of Houston in 2005, roads quickly became gridlocked, and due to the heat wave at the time, lack of water and facilities, more people died in the evacuation than would have been expected from the hurricane itself (Zachria & Patel, 2006) (Texas House of Representatives, 2006).

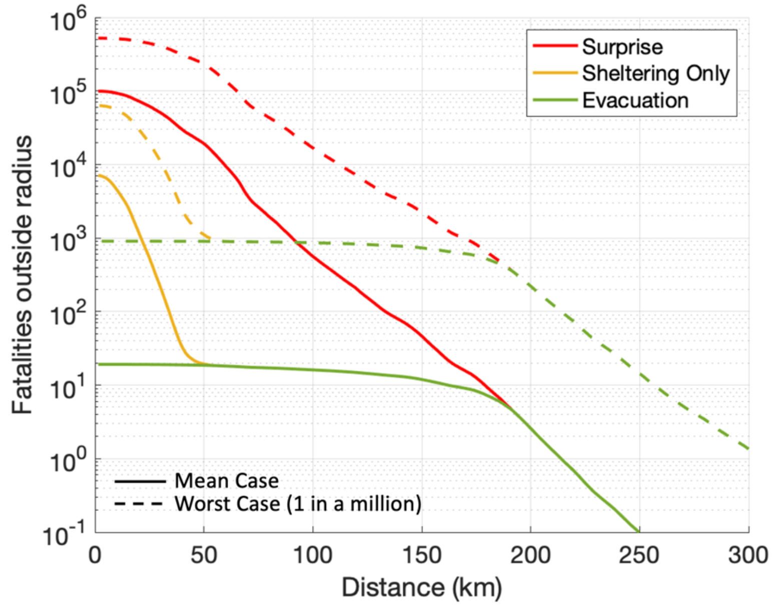


Figure 20: Expected casualties outside a given radius. Graphs show cumulative mean fatalities summed from far distance to the epicenter. If the impact were to occur without any warning the expected fatalities would be 100 000, and in the worst case (1 in million probability) 500 000. The majority of the casualties are within what would have been the evacuation zone. With a short warning time, sufficient for people to find a nearby safe building or take shelter in their basement, but not to evacuate, the risk follows the sheltering rate until it drops below the 1 in million fatality rate. This decreases the casualties to 7000 (mean event) and 60 000 (worst case). With sufficient warning to evacuate or make adequate shelters, at a flat rate of 1 in a million out to 190 km, the expected fatalities is just 17 people, 2 of which occur outside the shelter radius at 190 km, both probably in Vienna. In the worst case though, the higher fatality rate leads to 900 casualties.

In practice the evacuation may not be as successful as predicted here (1 in a million risk level out to 190 km). An event as dramatic as an asteroid impact may actually draw in adventurous people willing to accept a much higher risk than 1 in a million to witness an extremely rare event. Many adventure sports carry risks in the range of 1 in 100 000 to 1 in 10 000 per trip (Ocampo & Klaus, 2016), and spaceflight or climbing Mount Everest carries a risk of approximately 1 in 100 per flight/climb (Huey, et al., 2020).

The current NASA Ames Probabilistic Asteroid Impact Risk (PAIR) model uses risk pressure levels of 10 psi (Unsurvivable), 4 psi (Critical = 50% fatality), 2 psi (Severe), 1 psi (Serious), which correspond to levels of structural damage to buildings, which in turn correspond to fatality risk levels. At 10 psi even reinforced concrete buildings are destroyed, 4 psi destroys most houses, and 1 psi corresponds to only minor damage to most houses. Current estimates of affected population are 100% of people within the 10 psi radius plus 60% of people within the 4 – 10 psi radii, 30% within 2 – 4 psi, and 10% within 1 – 2 psi. This gives an affected population of 190 000, which is about twice the expected surprise fatalities in this scenario. However, to meet the risk tolerance level of 1 in a million, the evacuation rate needs to be $E = 1 - \frac{10^{-6}}{f}$, where f is the fatality rate of those who do not evacuate. The exponentially increasing fatality rate with distance towards ground zero in Figure 18 means that essentially everyone within the 1.3 psi radius (55 km) should evacuate (770 000 people) and shelter if not evacuation should be sought out to 0.44 psi (190 km = 14.4M people). It is hard to estimate the number of people in the shelter zone who will chose to do so versus evacuate and will depend on how close they are to the evacuation zone, the cost of evacuation versus building an appropriate shelter, and people's finances or government assistance to do either. Evacuation to visit friends and relatives may be very cheap, but finding a hotel space may be difficult and expensive. The cost of an appropriate shelter may be substantial close in, but merely be a basement or interior windowless room further out. In either case, the number of people who will need/want to evacuate or will need somewhere safe to shelter is therefore far larger than the expected casualties if no-one evacuates.

An interesting contrast to the PDC 2021 scenario is the PDC 2023 scenario https://cneos.jpl.nasa.gov/pd/cs/pdc23/), where a much larger 800 m diameter asteroid impacts in Nigeria. In this scenario a reconnaissance mission rendezvoused with the asteroid so the mass, size, and energy are known to within less than 1%, as shown in Figure 21. It is also big enough that it hits the ground mostly intact regardless of assumptions on strength and other properties. Most of the uncertainty in this scenario comes from uncertainty in the models, rather than uncertainties in the physical properties. Close to the impact site thermal radiation dominates the damage. In NASA's PAIR model, thermal thresholds of wooden structure ignition, clothing ignition, 3rd and 2nd degree burns are used. Radiation from the impact is easier to hide from than blast waves, but only if the building does not catch fire either directly or from a wildfire (dry grass ignition is between 2nd and 3rd degree burn levels). Electrical fires can also start due to damage from blast or earthquakes. In the PDC23 scenario blast takes over as the dominant risk right around the grass fire ignition level. Thermal damage exceeds blast damage in 17% of cases at the "severe" level (2 psi, 3rd degree burns) and 2.5% of cases at the "serious" level (1 psi, 2nd deg. Burns), so evacuation radii are mostly set by blast. It does however highlight model sensitivity. The blast waves and thermal radiation from an explosion this big are not well studied. In particular the atmosphere in the region of the impact will be blown out into space, and the atmosphere further away may act as a waveguide so pressure waves decay less quickly than the spherical expansion assumed. Collapse of the super-heated ejecta plume back onto the atmosphere around the impact site may also cause damaging thermal radiation over a wider area than directly from the initial fireball. In any case, evacuations from an even larger impact will most likely be driven by thermal damage, not blast damage, but this requires further impact simulation and risk model development.

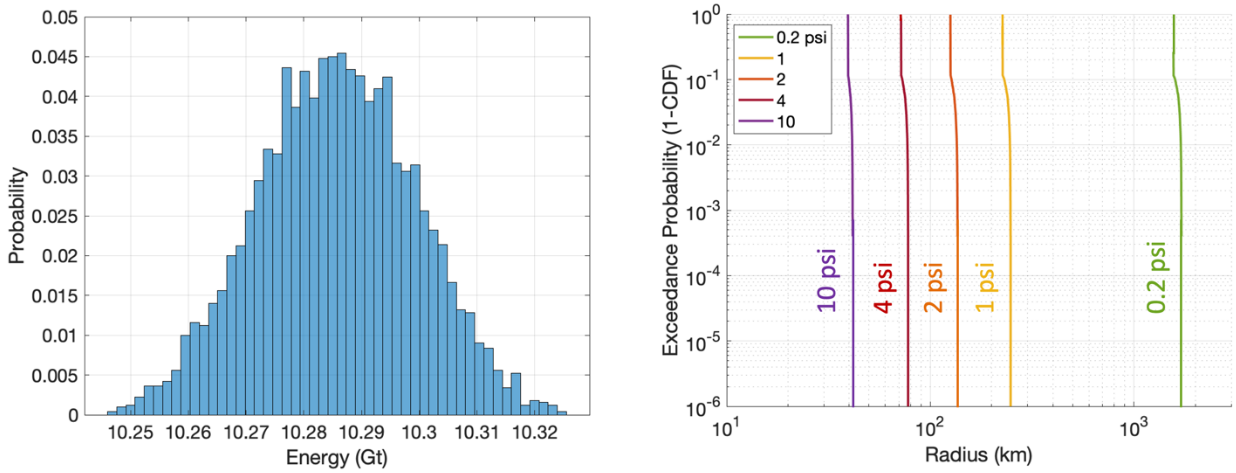


Figure 21: Rendezvous mission very precisely determines the mass, velocity, and hence impact energy of the asteroid. The large mass means the asteroid hits the ground mostly intact so the predicted blast radii are also very precise. Model uncertainties (not accounted for here) will be greater than the uncertainties in the asteroid.

The fatality rates are shown in Figure 22. Due to the asteroid size and energy being precisely known there is much less difference between the mean and worst cases, and the 1 in a million risk level when sheltering is now at the 2 psi level matching the sheltering curve in Figure 15, since it is not reduced by the long asymmetric tail of potentially higher energy impacts seen in the PDC 2021 scenario. Figure 23 shows maps of population and the areas requiring evacuation, shelter, or simply staying away from windows. About 7 million people live in the 100% evacuation zone, and 150 million in the shelter zone out to 470 km. With sufficient evacuation and shelter preparations the expected fatalities can theoretically be reduced to about 150.

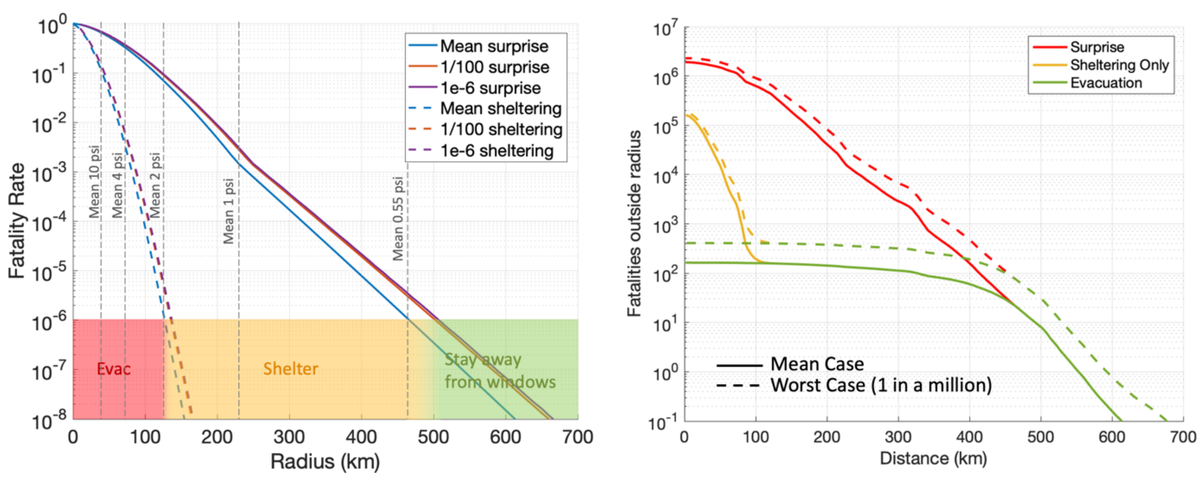


Figure 22: Mean and worst case fatality rates are close since the asteroid properties are well known and model uncertainty is not accounted for. To reduce risk below 1 in million, everyone needs to evacuate to the 2 psi level at 130 km radius, and should evacuate or take shelter out

to about 500 km. If the impact were to occur without warning expected casualties would be 1.9 million people, and worst case 2.3 million. A short warning time allowing sheltering but no evacuation would reduce expected casualties to 160 000 and worst case 165 000. Sufficient warning to allow evacuation reduces expected casualties to 145, worst case 165.

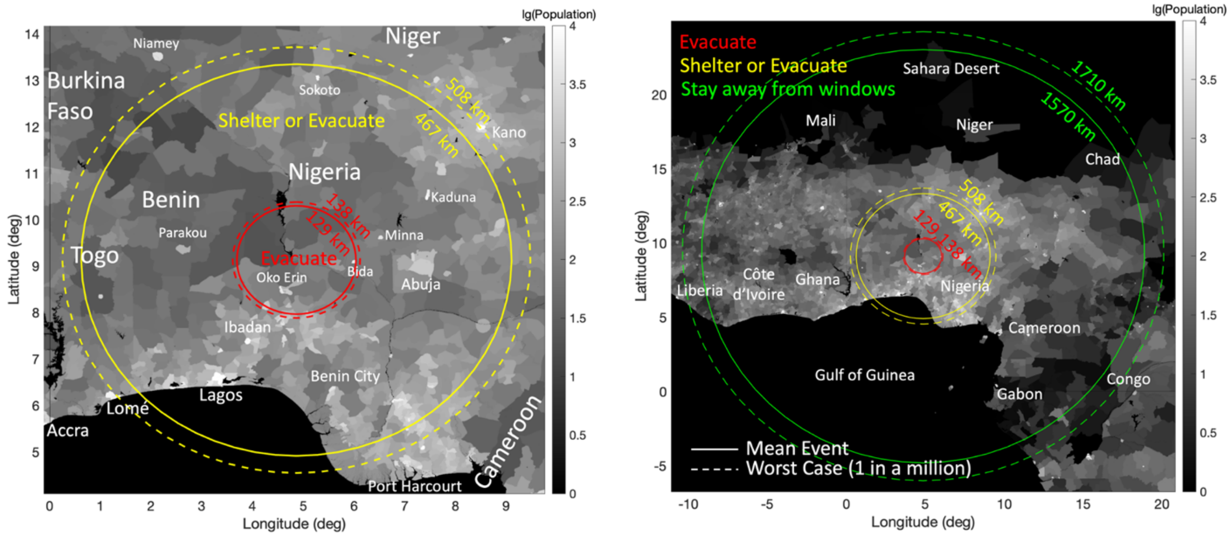


Figure 23: Everyone within 130 km needs to evacuate to meet the 1 in a million fatality rate which is 7 million people in western Nigeria. Out to about 470 km everyone needs to either evacuate or find an appropriate shelter or build one. This corresponds to 150 million people from most of Nigeria, all of Benin, and most of Togo. Significant numbers of windows will still be breaking out past 1700 km, covering a good fraction of the entire African continent.

Conclusions and Future Work

Hurricane evacuation management provides a template for asteroid impact evacuations, including how to communicate with emergency managers and the public. Emergency managers and the interested public can be provided details on expected damage probabilities and survivability levels and choose their own level of risk tolerance. The less interested public can be provided with impact watches and warnings before the exact location is well defined (depending on warning time), and evacuation and shelter orders once the location is known and the impact is reasonably ahead of the evacuation clearance time. For those choosing to shelter instead of evacuate guidance on homemade basement shelters, purpose built underground bunkers, or other safe places can be made available, as informed by nuclear testing and tornado shelters, again dependent on the warning time available.

Unsurprisingly the evacuation and shelter distances match the amount of blast damage expected to buildings. At the 1 in million fatality risk level this requires evacuation within areas likely to experience 2 psi or higher if the blast radii can be accurately predicted, but if the asteroid is not well characterized (such as through a rendezvous mission) there may be a long asymmetric tail of potentially heavy asteroids that cause more damage and push the mean fatality risk to lower mean overpressure levels.

The pressure levels for evacuation and shelter should however be considered preliminary since the fits to fatality rate in Equation 8 rely on relatively sparse data in Figure 15. This can be improved in future as there is lots of data on hurricanes, tornadoes, and explosions available in the literature. Use of the hurricane wind speed as equivalent to the wind speed behind a blast wave needs refining since the wind drops off quickly away from the eye of the storm and most people experience much lower wind speeds.

There is also some uncertainty of the blast decay versus distance, that may become important for large impacts. The current calculation assumes spherical expansion which should be reasonable for locations up to a few hundred kilometers corresponding to a few times the thickness of the atmosphere. Beyond that the atmosphere can act as a waveguide, and at the scale of thousands of kilometers the atmosphere is really a spherical shell. For large explosions the whole atmosphere is oscillated in Lamb and gravity waves, rather than just a usual sound pressure acoustic wave. These waves were observed in the Krakatoa volcanic eruption of 1883 (Harkrider & Press, 1967) and more recently in the 2022 Hunga-Tonga eruption (Wright, et al., 2022) (Amores, et al., 2022). As a non-dispersive wave confined to a layer, Lamb waves theoretically decay as $r^{-0.5}$, and in a spherical shell as $(\sin{(r/R_{\oplus})})^{-0.5}$. This fits very well to the Hunga Tonga data in (Díaz & Rigby, 2022), including the spike at the antipode, but also shows in practice a spread in the decay as $r^{-0.45\pm0.15}$. (Díaz & Rigby, 2022) also give a value of $r^{-0.68}$ which is a better fit to the 1980 Mount St. Helens eruption blast data. Either value decays much less quickly than the theoretical $r^{-1.2}$ for weak shock waves used in this paper to extrapolate the 1 psi pressure level to 0.2 psi. For most impacts that will hopefully only affect the window breaking distance where avoiding windows and doors is the only precaution required and could easily be done with no cost and little effort out to much further distances than the predicted 0.2 psi radius.

Thermal radiation damage needs more investigation. The radiative efficiency is not currently well constrained leading to significant uncertainty in the thermal flux received at a given distance. In this paper it was uniformly sampled in log-space from 10^{-4} to 10^{-2} (0.01 – 1%) covering the range of simulations from airbursts (Johnston & Stern, 2019). Simulations by (Svetsov & Shuvalov, 2019) suggest it could be as high as a few percent for ground impact cases. In particular, impacts of kilometer scale asteroids may also have significant thermal effects from the ejecta plume lofted into space as the superheated material rains back down on the top of the atmosphere, and could potentially cause thermal damage over a wider area. Better understanding of the radiative efficiency and thermal damage mechanisms is therefore important to properly estimate the risks from large ground impacting asteroids, since the thermal damage may be larger than the blast damage. Fire propagation models may also be useful. If a house can withstand the blast but is likely to catch fire either from direct radiation or from vegetation and other objects around the house catching fire, sheltering in the basement will not be a good choice.

With modern telescopes and better capabilities coming online soon it is becoming much more likely that an asteroid big enough to cause significant damage will be detected in time to take shelter, evacuate, or launch a mitigation mission. In addition to the expected casualties if an impact occurred without warning, the number of evacuees, cost of evacuation, and cost of damage to infrastructure that cannot be moved out of the danger zone, will be useful metrics. If warning time allows, the cost of allowing the impact can be weighed against the cost of in-space mitigation, particularly for relatively small impacts in remote or rural areas where civil defense may potentially be easier, more cost effective, and less risky than a mitigation mission.

References

Aftosmis, M., Mathias, D. & Tarano, A., 2019. Simulation-based height of burst map for asteroid airburst damage prediction. *Acta Astronautica,* Volume 156, pp. 278-283.

Aftosmis, M., Nemec, M., Mathias, D. & Berger, M., 2016. *Numerical simulation of bolide entry with ground footprint prediction.* s.l., s.n., pp. AIAA 2016-0998.

Alsweiss, S. et al., 2014. A non-MLE approach for satellite scatterometer wind vector retrievals in tropical cyclones. *Remote Sensing,* Volume 6, pp. 4133-4148.

American Society of Civil Engineers, 2016. *Minimum design loads and associated criteria for buildings and other structures.* s.l.:s.n.

Amores, A. et al., 2022. Numerical simulation of atmospheric Lamb waves generated by the 2022 Hunga-Tonga volcanic eruption. *Geophysical Research Letters,* Volume 49.

Beck, C., 1969. *Nuclear weapons effects tests of blast type shelters,* s.l.: s.n.

Bull, R. et al., 2021. Optical gravimetry mass measurement performance for small body flyby missions. *Planetary and Space Science,* Volume 205, p. 105289.

CIESIN, SEDAC, 2020. *Gridded population of the world, version 4.11.* [Online] Available at: https://sedac.ciesin.columbia.edu/data/set/gpw-v4-data-quality-indicators-rev11

Czajkowski, J. & Kennedy, E., 2010. Fatal tradeoff? Toward a better understanding of the costs of not evacuating from a hurricane in landfall counties. *Population and Environment,* Volume 31, pp. 121-149.

Díaz, J. & Rigby, S., 2022. Energetic output of the 2022 Hunga Tonga - Hunga Ha'apai volcanic eruption from pressure measurements. *Shock Waves,* Volume 32, pp. 553-561.

FEMA, 2021. *Safe rooms for tornadoes and hurricanes,* s.l.: s.n.

FEMA, 2021. *Taking shelter from the storm. Building or installing a safe room for your home,* s.l.: s.n.

Florida Building Commission, 2020. Florida Building Code: s.n.

Glasstone, S. & Dolan, P., 1977. *The effects of nuclear weapons,* s.l.: s.n.

Harkrider, D. & Press, F., 1967. The Krakatoa air-sea waves: an example of pulse propagation in coupled systems. *Geophysical Journal of the Royal Astronomical Society,* Volume 13, pp. 149-159.

Huey, R., Carroll, C., Salisbury, R. & Wang, J., 2020. Mountaineers on Mount Everest: Effects of age, sex, experience, and crowding on rates of success and death. *PLoS ONE,* 15(8).

Johnston, C. & Stern, E., 2019. A model for the thermal radiation from the Tunguska airburst. *Icarus,* Volume 327, pp. 48-59.

Jones, D., 1968. Intermediate strength blast wave. *Physics of Fluids,* 11(8), pp. 1664-1667.

Jones, R., Jurić, M. & Ivezić, Z., 2015. Asteroid discivery and characterization with the Large Synoptic Survey Telescope.. *Proceedings of the International Astronomical Union,* Volume 10 (S318), pp. 282-292.

Lindell, M., 2008. EMBLEM2: An empirically based large scale evacuation time estimate model. *Transportation Research Part A,* Volume 42, pp. 140-154.

Lindell, M., Prater, C., Perry, R. & Nicholson, W., 2006. *Fundamentals of emergency management.* s.l.:FEMA.

Mathias, D., Wheeler, L. & Dotson, J., 2017. A probabilistic asteroid impact risk model: assessment of sub-300m impacts. *Icarus,* Volume 289, pp. 106-119.

Ocampo, R. & Klaus, D., 2016. Comparing the relative risk of spaceflight to terrestrial modes of transportation and adventure sport activities. *New Space,* Volume Sept., pp. 190-197.

Olson, S., 2017. *Eruption: The untold story of Mount St. Helens.* s.l.:s.n.

Popova, O. et al., 2013. Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization.. *Science,* 342(6162), pp. 1069-1073.

Rumpf, C., Lewis, H. & Atkinson, P., 2017. Asteroid impact effects and their immediate hazards for human populations.. *Geophysical Research Letters,* 44(8), pp. 3433 - 3440.

Rumpf, C., Lewis, H. & Atkinson, P., 2017. Population vulnerability models for asteroid impact risk assessment. *Meteoritics and Planetary Science,* 52(6), pp. 1082-1102.

Senkbeil, J., Collins, J. & Reed, J., 2019. Evacuee perception of geophysical hazards for hurricane Irma. *Weather, Climate, and Society,* 11(1), pp. 217-227.

Sonnett, S. et al., 2021. *NEO Surveyor cadence and simulations.* s.l., s.n., p. https://www.youtube.com/watch?v=2D71dpfH8lg.

Svetsov, V. & Shuvalov, V., 2019. Thermal radiation from impact plumes. *Meteoritics and Planetary Science,* 54(1), pp. 126-141.

Texas House of Representatives, 2006. *Evacuation planning in Texas: Before and after Rita,* s.l.: Government of Texas.

UK Home Office, 1939. *Air raid precautions. Directions for the erection and sinking of the galvanised corrugated steel shelter,* s.l.: s.n.

Wolshon, B., Urbina, E. & Levitan, M., 2001. *National review of hurricane evacuation plans and policies,* s.l.: LSU Hurricane Center.

Wright, C. et al., 2022. Surface-to-space atmospheric waves from Hunga Tonga-Hunga Ha'apai eruption. *Nature,* 609(22 Sept.), p. 741.

Wright, E. et al., 2016. The albedo distribution of near Earth asteroids. *The Astronomical Journal,* 152(79).

Xu, K. et al., 2016. Hurricane evacuation demand models with a focus on use for prediction in future events.. *Transportation Research Part A,* Volume 87, pp. 90-101.

Zachria, A. & Patel, B., 2006. Deaths related to hurricane Rita and mass evacuation. *American College of Chest Physicians*.