COMET AND ASTEROID RISK: AN ANALYSIS OF THE 1908 TUNGUSKA EVENT

RMS Special Report

INTRODUCTION

Early in the morning on June 30, 1908, a giant airburst occurred over the basin of the Podkamennaya Tunguska River in Central Siberia, Russia, leveling trees over an area of 2,000 km^2 (770 mi^2) (Figure 1). Eyewitnesses described a "fire ball, bright as the Sun" (Longo, 2007). The event produced seismic and pressure waves that were recorded all over the world and led to atmospheric phenomena (e.g., bright nights, noctilucent clouds) observed over much of Eurasia. The released energy was later estimated to be equivalent to a 10 megaton (Mton) TNT explosion, about 1,000 times as powerful as the nuclear bomb dropped over Hiroshima in 1945. Although the origin of this phenomenon has been widely debated for the past century, it is now generally accepted that the blast was due to the explosion of a comet or an asteroid in the lower atmosphere, occurring at a height of 5 to 10 km (3 to 6 mi) over the remote Siberian forest, and measuring approximately 50 m (164 ft) in diameter (Longo, 2007 and http://www-th.bo.infn.it/tunguska/).

Figure 1: Felled trees in the Tunguska impact area in Russia following an explosion of an asteroid or a comet in the atmosphere on June 30, 1908; about 80 million trees were leveled by the blast (Source: Soviet Academy of Science 1927 expedition led by Leonid Kulik)

Due to the remote impact location, this disaster did not cause any significant damage to human settlements. However, the occurrence of a Tunguska-type event over a populated region would constitute a major catastrophe. This report begins with a discussion of the risk associated with extraterrestrial bodies orbiting the sun, including comets and asteroids, which can become meteors and meteorites, hitting the Earth's atmosphere and surface, respectively. Examples of small and moderate-sized impact events in recent history are detailed. A Tunguska-type footprint is also developed, based on the available information from felled trees and inferences from blast impacts, to estimate the property and casualty impacts of a similar-sized event over the Manhattan Borough of New York City. Finally, the implications of comet and asteroid risk for the insurance industry are highlighted, including the recurrence probability of these types of events.

COMET AND ASTEROID RISK

When considering how to quantify the risks associated with asteroids or comets impacting the Earth's atmosphere and surface, the rarity of these very destructive events means that the threat is generally discounted. However, the 1908 Tunguska airburst reminds us that the threat is real. To understand this threat, it is useful to consider different categories of risk, depending on the size of the asteroid or comet as it enters the atmosphere and collides with the Earth's surface.

Massive (~ 1 km in diameter or larger)

A massive object colliding with the Earth's surface would have direct impacts on a continental scale, as well as global consequences with social, economic, and political implications. These events are extremely rare, with examples observed at geological timescales. For example, a massive asteroid led to the demise of dinosaurs 65 million years ago. Implications of major impacts are so extreme that the principles of insurability are not met, such as the pricing of the risk. As a result, managing massive asteroid and comet impacts are far beyond the scope of the insurance system. However, some work has been done to investigate mitigation and policy frameworks linked to major impacts (i.e., global destruction with inconceivable odds) (see Urias et al., 1996 and Sommer, 2005).

Medium (~ 10s-100s m in diameter)

An object up to 100s of meters in diameter impacting the Earth is also rare in human history. With the exception of the 1908 Tunguska event, there is no clear evidence of similar impacts in the past few centuries. The impact from such an event would be concentrated (affecting an area 10s to 100s of kilometers in diameter) but consequences could range from local to regional depending on where the collision occurs. For example, the 1908 Tunguska event led to very few casualties and no property losses because it occurred in a remote region of Siberia. A reproduction of this event over a highly populated region could lead to hundreds of thousands of casualties and hundreds of billions dollars of damage. It would also cause losses beyond the capacity of the insurance market. However, as long as a major city is not impacted, the consequences would be comparable to the impacts of a major earthquake. In this case, insurance companies would likely remain viable, even though premiums were not collected nor reinsurance purchased against an event of this size.

Small (~10 m in diameter or smaller)

The occurrence of small objects entering the Earth's atmosphere is frequent, with impacts on the surface several times per year. When the initial comet or asteroid is only a few meters in diameter, it is highly influenced by its journey through the Earth's atmosphere. It generally fragments along its luminescent path (commonly termed a "shooting star") and if the original mass is not completely lost by ablation, the remaining fragments hit the ground (i.e., become meteorites). In most cases, minimal energy is left at impact but on rare occasions, the impact produces a crater measuring a few meters to tens of meters large. In this case, resulting damage and insured loss depends on the location of the crater. For example, if a small meteorite were to strike a group of buildings, a small subset of the insurance industry would be affected by the impact. This itself is a highly improbable event; the chance of a small meteorite causing massive devastation by hitting something as potentially destructive as a nuclear power plant is even more remote.

Recent Small Meteorite Impact Events

There are numerous examples of small meteorite strikes over populated areas in recent history. In 2003, a meteorite shower occurred over the Chicago suburb of Park Forest, Illinois. While many stones fell, they only caused minor damage, including damage to roofs, windows, and car windshields. In some cases, stones broke through ceilings and damaged building contents. A map of the impact area and a picture of ceiling damage in the Park Forest event is shown in Figure 2, along with pictures of damage in two other recent examples of meteorite falls—the 2007 Cali, Colombia event (Figure 2(b)) and the 2008 Zunhua, China event (Figure 2(c)). The low levels of damage reflect the small size of the meteorites—a few kilograms at best—and the dissipation of their orbital velocities, as they simply fell from the sky. Although there is no definitive record of human casualties due to meteorite strikes, hundreds of claims have been made (Lewis, 1996). For example, in the 20th

century, a meteorite injured a woman in 1954 (in Sylacauga, Alabama) and another meteorite killed a cow in 1972 (in Valera, Venezuela).
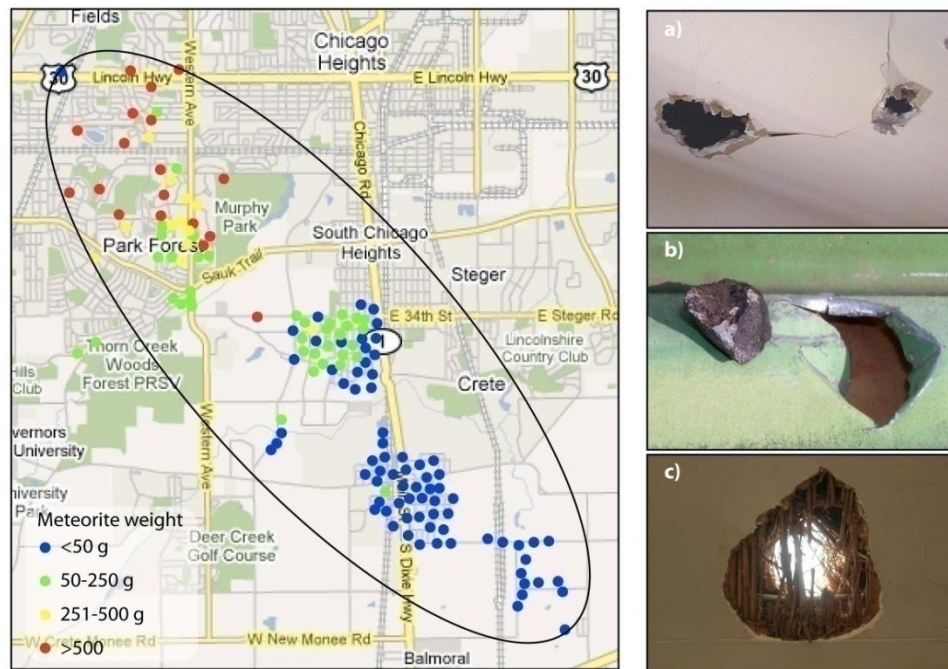

Figure 2: Impacts of small meteorite events over urban areas, with map showing the 2003 Park Forest, Illinois, meteorite field (left), redrawn from Simon et al., 2004 and examples of roof and ceiling damage caused by meteorites (right): (a) 2003 Park Forest, Illinois damage (Source: R. Elliott); (b) 2007 Cali, Columbia damage (Source: M. Farmer) and (c) 2008 Zunhua, China damage (Source: M. Farmer)

As previously indicated, contrary to the majority of objects that lose their initial energy by fragmenting in the atmosphere, on rare occasions, meteorites keep a large fraction of their kinetic energy and strike the Earth, creating large craters. For example, the 1947 Sikhote-Alin, Russia, event was the largest bolide (meteoritic fireball) ever witnessed in historical records (Figure 3(a)), impacting an elliptic area of approximately 1 km^2 (0.4 mi^2) in a remote region of Russia. More than 100 craters were found in the strewn field, with the largest crater measuring 28 m (92 ft) in diameter and 6 m (20 ft) deep (Gallant, 1996). Tons of meteoritic iron shrapnel were also found in the area. More recently, in 2007, a fireball appeared in the sky over Bolivia and Peru and remained intact while it traveled through the atmosphere, keeping a significant proportion of its pre-atmospheric speed (Brown et al., 2008). The impact caused the formation of a crater 13 m (43 ft) in diameter, very close to the small Peruvian village of Carancas (Figure 3(b)).
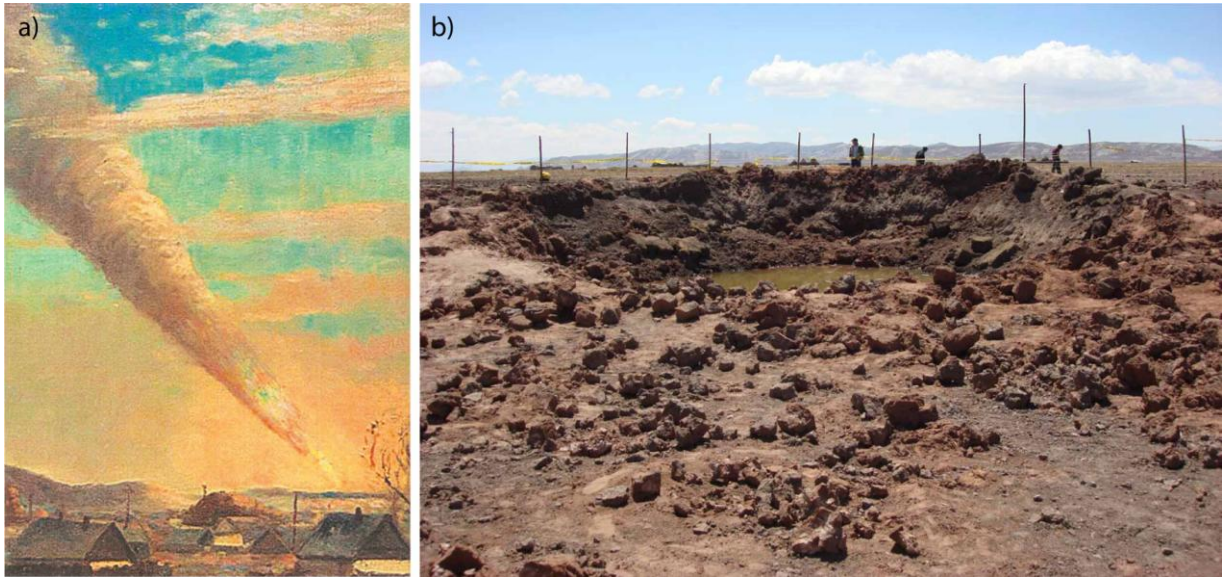
Figure 3: Crater-forming impacts of small meteorite events: (a) painting representing the 1947 Sikhote-Alin, Russia event by artist P. J. Medvedev and (b) the crater of the 2007 Carancas, Peru event, measuring 13 m in diameter (Source: M. Farmer)

Had these two events occurred in more populated regions, they would have certainly caused severe damage and led to many casualties. In this way, the damage caused by crater-forming meteorite strikes can be compared to wartime or terrorist bombing attacks—but with no target, striking at random across the Earth's surface.

Evidence of Medium (Tunguska-type) Events

Larger objects measuring 10s to 100s of meters in diameter, such as the object that exploded in the 1908 Tunguska event, are far less common. Moreover, there is no clear evidence of similar-sized objects exploding over the Earth in recorded human history. This does not mean, however, that no similar-sized events have occurred. The Tunguska event would likely have been missed or forgotten had no one gone to the Siberian forest to study the phenomenon. One century after the impact, the evidence has been mostly erased by the re-growth of vegetation. Moreover, had the strike occurred over the ocean, as is the case for approximately 70% of such events given the planet's land-ocean distribution, any trace of the impact would only be found on the ocean floor. As stated by Bailie (2007), this type of impact is a great "invisible hazard."

Objects of similar size to the Tunguska event can create a large crater upon impact if they do not explode and fragment in the atmosphere. For example, Meteor Crater in Winslow, Arizona (Figure 4) is an approximately 1,200-m (3938-ft) diameter crater created by the impact of a 50-m (164-ft) diameter iron meteorite 49,000 years ago. Based on the rarity of having a cosmic body composed of solid iron, crater-forming events are expected to be a lot less frequent than airburst events. Indeed, iron meteorites, which are less likely to explode in the atmosphere than rocks, represent only 5% of meteorite falls. This means that the majority of Tunguska-class events would leave no scar on the Earth's surface.

There is also a high probability that other impact craters would have been obliterated by erosion (note that Meteor Crater is subject to very low erosion rates) or remained unidentified until now (e.g., on the ocean floor, in dense forests, or camouflaged as circular lakes). As for recent craters identified as such, they are generally poorly dated and therefore difficult to relate to any past catastrophe.

Figure 4: Example of medium-sized meteorite impacts: Meteor Crater in Winslow, Arizona, measuring 1,200 m in diameter and occurring 49,000 years ago. (Source: United States Geological Survey)

The lack of evidence of Tunguska-type impacts in the historical or archeological record is arguably related to the fact that catastrophes of unknown origin have been linked to other hazards that are more frequent and better understood, such as major volcanic eruptions or earthquakes. The Holocene Impact Working Group (HIWG), formed in 2005, conducted a study to test this hypothesis. The results of the study indicate that impacts may have affected the movement of recent agricultural populations, collapsed past civilizations and even caused the Dark Ages (see review in Baillie, 2007). Some evidence can be obtained from tsunami deposits (Blakeslee, 2006), tree-ring and ice records, astronomical observations, and even myths[1]. One of the goals of the HIWG is to demonstrate that impacts have been more frequent in the recent past than currently believed. For example, impacts may have led to the end of the Clovis culture at 13,000 BCE, the Great Flood at approximately 5000 BCE (Carney, 2007), the "years without summers" at 535–545 CE, and the Little Ice Age at 1450 CE. (For more information, see http://tsun.sscc.ru/hiwg/hiwg.htm).

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[1] For more information about geomythology or the referencing of geological events in mythology, see Piccardi and Masse (2007).

MODELING THE IMPACTS OF A REPEAT OF THE 1908 TUNGUSKA AIRBURST

Damage Inference from Felled Trees

In order to model the effects of the 1908 Tunguska event, a damage footprint that estimates the geographic scope and magnitude of impacts must be developed. The challenge in doing so, however, is the lack of data from which damage inferences can be made. What really happened on June 30, 1908, in the middle of the Siberian forest still remains a mystery, particularly because no fragment of the cosmic body has ever been found. Further, no impact crater has been identified, although this last point has recently been challenged in the literature (Gasperini et al., 2007). It is only from sparse eyewitness accounts and the data on forest devastation that the footprint of this disaster can be estimated. Figure 5 shows two proposed footprints for the 1908 event based on a study of felled trees. The footprint in Figure 5(a) (Longo et al., 2005) provides the most accurate contour of the blast to date. The footprint in Figure 5(b) (Serra et al., 1994) offers additional information by distinguishing regions where fallen trees were partially burned (dark grey) from regions where they were only pushed down (light gray). In both illustrations, fallen trees form a radial pattern, which indicates the source of the blast (shown as a red dot in Figure 5(a) and a black dot in Figure 5(b)).
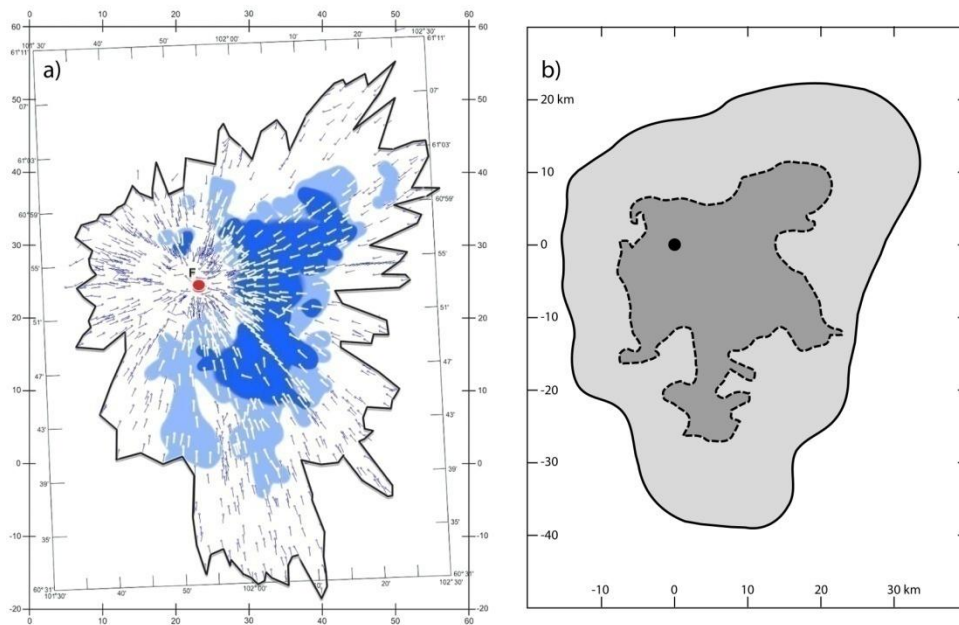

Figure 5: Damage footprint of the 1908 Tunguska airburst determined from the study of felled trees: (a) map of the blast impact from Longo et al. (2005), where the azimuths of felled trees converge to the focal point of the blast (red dot). The color range from white to dark blue indicates an increase in azimuth measures' reliability (Source: http://www-th.bo.infn.it/tunguska/); (b) damage footprint from Serra et al. (1994), indicating the limit of overthrown trees (solid line) and the limit of charred trees (dashed line). The black dot indicates the focal point of the blast.

From these tree footprints, two types of damage are observed. First, trees were leveled over an area covering approximately 2,000 km^2 (770 mi^2) (Figure 5(a)) and large fires were ignited near ground zero (Figure 5(b)). Although these felled trees give an indication about the size, the directivity, and the intensity of the Tunguska blast, converting this information into a damage footprint for analysis purposes is not a straightforward matter. There is no available information about damage attenuation from the source to the limit of the footprint, as trees have relatively brittle vulnerabilities and are either standing or fallen. The vulnerability of property and

people to a Tunguska-like blast, as compared to trees, must be determined. Contrary to other hazards, such as earthquakes and hurricanes, there are no historical events documenting the damage to property and people that can directly determine vulnerability. Comparisons to other perils must be made.

Comparison to Blast Damage

One solution is to utilize empirical evidence of blast effects from man-made explosions. For example, Figure 6 shows an example of a damage footprint for a 2-ton TNT equivalent explosion. The damage attenuation pattern, modeled from engineering blast analysis, is consistent with the damage seen in the truck bomb attack on the British Consulate in Istanbul in 2003, with an estimated yield equivalent to 2 tons of TNT (RMS, 2008). In this example, total destruction (i.e., 100% MDR or mean damage ratio) was observed within 15 m (50 ft) of the truck bomb.

Figure 6: Damage footprint for a 2-ton TNT equivalent explosion, illustrating mean damage ratio (MDR) as function of distance to source (i.e., attenuation) (Source: RMS, 2008)

However, the 1908 Tunguska event released the energy equivalent of 10 megatons (Mton) of TNT. Therefore, damage patterns seen in nuclear test explosions are more suitable for analysis purposes. Indeed, the 1908 radial pattern formed by leveled trees was replicated during atmospheric nuclear tests in the 1950s and 1960s. Using overpressure, in pounds per square inch (psi), as a measure of the severity of the blast and thus the damage, a footprint was developed for a Tunguska-type event. Figure 7 represents the footprint of an airburst occurring at an altitude of 5 km (3 mi) with a released energy of 10 Mton. Overpressure in psi per distance range, shown up to 40 km (25 mi) in radius, is determined by using the formulae and graphs from Glasstone and Dolan (1977). The 1908 Tunguska footprint, shown in Figure 5(b), is overlaid on this blast footprint for comparison (in dashed/dotted contour lines) with its "butterfly" shape due to the cosmic body's trajectory angle. Although the 1908 event footprint forms a butterfly pattern, the generic footprint is assumed to be circular (i.e., unknown meteor trajectory).
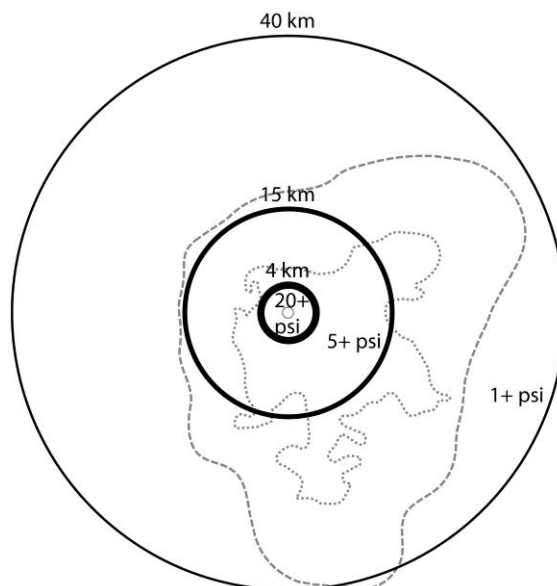
Figure 7: Footprint of a man-made airburst and of the 1908 Tunguska event. Overpressure in psi is indicated per distance range from source (solid contour) and computed for a 10-Mton airburst occurring at a 5 km altitude. The extent of fallen trees (dashed contour) and charred trees (dotted contour) from the Tunguska event (Serra et al., 1994) are indicated for comparison. The Tunguska footprint is centered such that the focus point from which the fallen trees radiate (i.e., ground zero) is located at the source of the man-made blast.

The potential property damage caused by a given overpressure is measured in terms of a mean damage ratio (MDR) and an MDR per distance range from the source of the explosion is developed, similar to Figure 6 (i.e., approaches used in terrorism modeling). Table 1 describes the expected property damage due to a 10-Mton TNT equivalent explosion for various levels of overpressure. These results are obtained from nuclear tests, taking only into account blast effects, as only approximately 50% of total energy released from a nuclear weapon is due to the blast. In this case, total destruction is expected for an overpressure greater than 20 psi. When the footprint in Figure 7, in combination with the damage information in Table 1, is superimposed over an area with built exposure, the losses can be calculated by multiplying the mean damage ratio by the value at risk.

Table 1. Expected mean damage ratio of building types as a function of overpressure (in psi) (Source: Office of Technology Assessment, 1979)

Overpressure (psi)	Damage Description	Mean Damage Ratio (%)
20+	Reinforced concrete structures leveled/destroyed	~100
5+	Factories, commercial buildings and residential structures severely damaged or destroyed	~70
1+	Residential structures moderately or severely damaged	~30

Fatality and injury rates are also defined from the Office of Technology Assessment (1979), for the same values of overpressure (Table 2). Note that the extent of damage was 50 km (31 mi) away from the source of the Tunguska airburst and other far field effects from the blast were recorded in eyewitness reports. For example, from an eyewitness at the Vanavara trading post, located 65 km (40 m) from the explosion: "…at that moment I became so hot that I couldn't bear it, as if my shirt was on fire…" (Kulik, 1930).

Table 2. Expected fatalities and injuries (in percentage), as a function of overpressure (in psi) (Source: Office of Technology Assessment, 1979)

Overpressure (psi)	Fatalities (%)	Injuries (%)
20+	~98	~2
5+	~50	~40
1+	~2	~35

Scenario: A Tunguska-type Event over New York City

Considering the 1908 Tunguska event, one might ask what the losses would have been if, instead of occurring over the Siberian forest, the airburst had occurred over one of the most important economic hubs and most populated cities in the world. The following scenario considers the occurrence of an event with an impact footprint similar to the one of the 1908 event over New York City. To assess probable maximum loss, the footprint is centered over the borough of Manhattan, as illustrated on Figure 8. The mean damage ratio, fatality rate, and injury rate are assumed to be 70%, 50%, and 40% in the inner contour of the footprint and 30%, 2%, and 35% in the outer contour of the footprint, respectively. These values are determined from Figure 7, where the majority of the inner footprint is located in the 5+ psi range and the majority of the outer footprint is within the 1+ psi range. In addition, it is appropriate that the part of the inner footprint which extends into the 1+ psi range, corresponds to higher damage ratios, as the ignition and spread of fires will increase losses. It is worth noting, however, that the spread of fires is assumed constant over the area to keep the scenario simple.
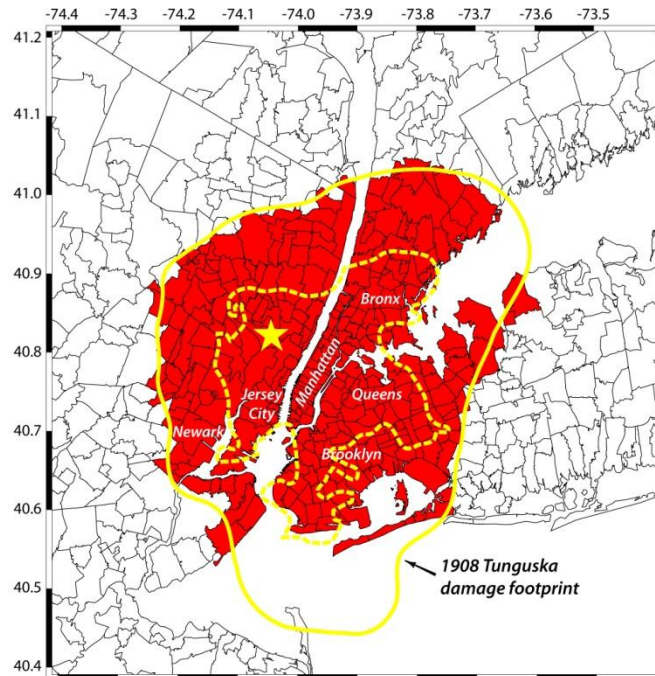
Figure 8: An extreme event scenario: reproduction of the 1908 Tunguska event overlaid (in yellow) over Manhattan, such that losses are maximized

Expected property damage and casualties

Figure 9(a) shows the residential and commercial property at risk in the New York region from this scenario, developed from the 2008 RMS® U.S. Industry Exposure Database (IED). The U.S. IED is a compilation of insured assets (buildings and contents) for properties at risk from wind and fire perils. Economic values are derived from the insured values, considering insurance penetration rates throughout the U.S. Using insured exposure to the perils of wind and fire is appropriate in this case, since the hazard is due to hurricane-force winds (e.g., maximum wind speed of 502 mph, 163 mph, and 70 mph for an overpressure of 20 psi, 5 psi, and 2 psi, respectively) (Glasstone and Dolan, 1977) and to fire ignitions due to thermal exposure. Total economic exposure measures $760 billion between the outer and inner contours of the footprint and $1.38 trillion inside the inner contour. As a result, property losses are estimated at approximately $1.19 trillion.

Figure 9(b) shows the location of the 1908 Tunguska event footprint in the proposed scenario, over the population at risk, employing the 2005 United States LandScan™ dataset for population concentrations (LandScan™, 2005), which gives census counts on a 30° by 30° latitude/longitude grid. With a population exposure of 3.61 million people between the inner and outer contours and 6.25 million people inside the inner contour, approximately 3.2 million fatalities and 3.76 million injuries are expected.
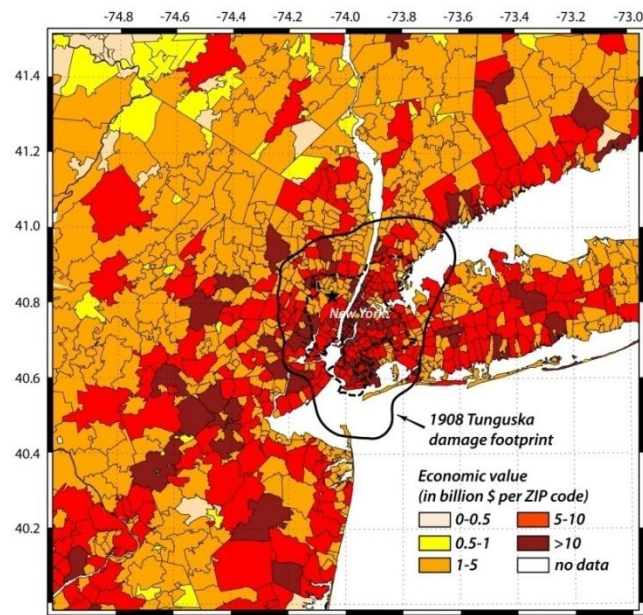
(a)
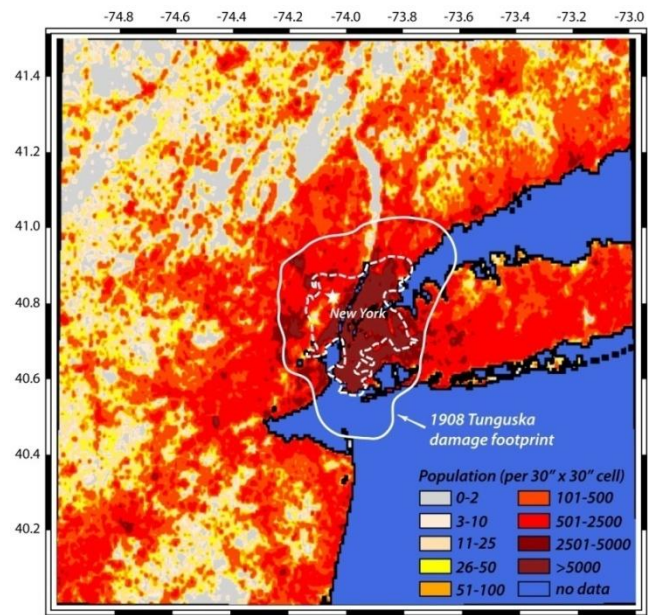
(b)

Figure 9: The 1908 Tunguska footprint centered over Manhattan with (a) economic exposure (building and contents), showing $2.14 trillion inside the outer contour of the footprint and $1.38 trillion inside the inner contour (Source: RMS, 2008b); (b) population exposure of 9.86 million people inside the outer contour of the footprint and 6.25 million inside the inner contour (Source: LandScan, 2005)

INSURANCE IMPLICATIONS

Recurrence probability of Tunguska-type events

A recent study on the recurrence of objects that collide with the Earth, based on a compilation of many data sets, estimates a mean return period of 1,000 years (range from 400 to 1,800 years) for collisions with objects similar in size to the 1908 Tunguska event (Brown et al., 2002). This rate of 1,000 years was previously estimated to be around 200–300 years (Shoemaker, 1983). Since the frequency cannot be assessed from historical events, Brown et al. (2002) extrapolated it from the rate of bolide detonations obtained from eight years of satellite records, as well as from a variety of astronomical observations (e.g., the Spacewatch project at http://spacewatch.lpl.arizona.edu/). Note that if some of the unknown events that led to major catastrophes (e.g., the Dark Ages) were proven to be asteroid or comet impacts, rate estimates would need to be revised upwards, by up to an order of magnitude.

Figure 10 shows the most up-to-date frequency-magnitude relationship for impacts of small to medium size objects (<100 m in diameter). From this relationship, Brown et al. (2002) determined the Tunguska-type event return period of 1,000 years. The relationship proposed by Shoemaker (1983) is also shown for comparison (dashed line in Figure 10). Following the results from Brown et al. (2002), bolides of approximately 10 m (33 ft) in diameter occur every decade and bolides of one meter in diameter occur roughly ten times per year. Although small events are frequent, they generally pose no threat. Only a fraction of these events would have enough high energy left at impact (e.g., the 1947 Sikhote-Alin, Russia event or the 2007 Carancas, Peru event) to cause localized damage over a populated region.
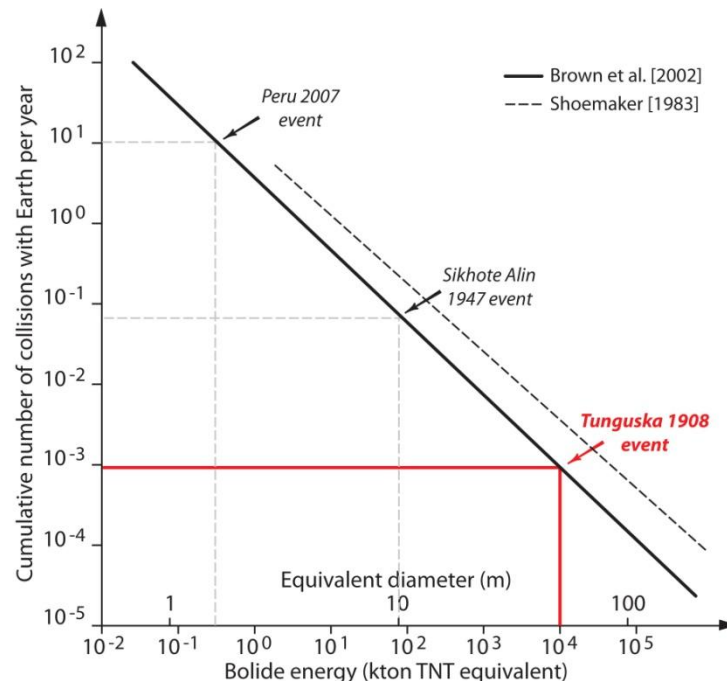

Figure 10: Frequency–bolide energy (or equivalent diameter) relationships proposed by Brown et al. (2002) (bold line) and by Shoemaker (1983) (dashed line) for small near-Earth objects (<100 m) colliding with the Earth. Tunguska-type events (~10 Mton TNT equivalent) are nowadays estimated to occur around once every 1,000 years (400–1,800 years) (Brown et al., 2002), lower than the 200–300 years return period proposed previously (Shoemaker, 1983).

Insurability of Tunguska-type events

In order to assess the impacts of a Tunguska-type event on insured exposure at risk, a probabilistic risk model based on realistic data must be developed. As discussed in detail by Kovacs and Hallak (2007), an assessment of the costs of asteroid and comet impacts requires many assumptions and the development of any proposed probabilistic risk model is difficult, given the lack of historical events.[2] While the accuracy of a risk assessment model is important, so is the importance of understanding the management of the risk. On the insurance side, comprehensive multi-peril or all-risk insurance policies cover all risks that are not specifically excluded, meaning that a Tunguska-type event is generally covered by this type of insurance. It is unclear if, on any current contractual grounds, insurers would exclude damage caused by such a peril. While the modest premiums appropriate to be charged for the risk would be uniform across land areas (although a tsunami premium may also need to be added for coastlines) it seems unlikely that insurers would bother to add this charge explicitly to their pricing models.

At the same time, an insurer should be aware (similar to managing earthquake risk), even at the extremely low probabilities determined here, that having a portfolio concentrated in single city creates a greater probability of ruin for an impact than a well-distributed portfolio. Loss statistics for natural disasters demonstrate a dramatic increase in losses since 1950. This increase is driven by a concentration of population and property in urban areas, the development of highly exposed coastal and valley regions, and the complexity of modern societies and technologies (Smolka, 2006). This shows that the risk associated with extreme asteroid and comet events can only increase through time and that more research to understand these extremely rare events should be encouraged.

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[2] For an example of a probabilistic risk model for Tunguska-type airbursts, see Mignan et al., 2009.

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