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ORIGINAL PAPER

Risk assessment of Tunguska-type airbursts

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Abstract: The Tunguska airburst, which devastated a taiga forest over an area greater than 2,000 km^2 in a remote region of Central Siberia in 1908, is a classic example of extraterrestrial encounter discussed in the asteroid/comet impact hazard and risk assessment literature (e.g. Longo 2007; Carusi et al. 2007). Although it is generally agreed that the cosmic body caused damage by bursting in the air rather than through direct impact on the Earth's surface, the Tunguska event is often referred to as an impact event. To the best of our knowledge, no detailed studies have been performed to quantify the risk of a similar-sized event over a populated region. We propose here a straightforward probabilistic risk model for Tunguska-type events over the continental United States and use established risk metrics to determine the property (buildings and contents) and human losses. We find an annual average property loss of $\sim$USD 200,000/year, a rate of $\sim$0.3 fatalities/year and $\sim$1.0 injuries/year ranging from a factor 3 below and to a factor 3 above the indicated values when a reasonable rate uncertainty for Tunguska-type events is taken into account. We then illustrate the case of an extreme event over the New York metropolitan area. While we estimate that this "nightmare" scenario would lead to $\sim$USD 1.5 trillion of property loss, $\sim$3.9 millions of fatalities and $\sim$4.7 millions of injuries, such event is almost impossible (occurrence once every $\sim$30 million years) and should only be considered as an illustrative example.

Keywords Tunguska event · Asteroid/comet impact hazard · Catastrophe risk model · Economic losses · Human losses

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1 Introduction

On June 30, 1908, a giant blast occurred over the basin of the Podkamennaya Tunguska River in Central Siberia, leveling a large fraction of trees over an area spanning over 2,000 km^2. It is at present well accepted that the blast was produced by the disruption of a small stony asteroid, when entering the Earth's atmosphere. The explosive yield, if equivalent to 10-15 megatons (Mton) of TNT (Ben-Menahem 1975; Shoemaker 1983), would have been about 1,000 times the energy released by the nuclear weapon launched over Hiroshima in Japan in 1945. However, this value is probably overestimated and could be as low as 3–5 Mton (e.g., Boslough and Crawford 2008]. The reader should refer to the review by Longo (2007) for more information about the 1908 event, its characteristics, and the different models proposed.

Although the 1908 event did not cause any significant damage to human settlements due to its remote location, the occurrence of a similar event over a populated region would be a major catastrophe. This issue is discussed in a number of studies but only in qualitative terms (e.g. Carusi et al. 2007).

In this paper, we develop a straightforward probabilistic risk model to quantify the expected property (buildings and contents) and human losses due to Tunguska-type events. The evaluation of the risk is based on the identification of the hazard, exposure, and vulnerability of property and human lives. First, we define a model for the continental United States and second, we illustrate the case of an extreme event over the New York metropolitan area. Finally, we discuss the limits of the proposed model and possible future research directions.

2 Probabilistic risk model

Although a "second Tunguska event" might have occurred in 1930 over the remote forests of the Rio Curuçà in Brazil (Bailey et al. 1995), because of the speculative nature of the evidence, the 1908 event remains the only confirmed historical airburst event to cause significant damage to the ground. An airburst, which evidence is erased by vegetation within a century or so, is a great "invisible hazard" as stated by Bailie (2007). Therefore, the rate of occurrence must be determined from indirect observations, such as the flux of bolide detonations in the Earth's atmosphere, the detection of Near-Earth objects (e.g., LINEAR project) or the flux of cratering on the Moon. A 2003 NASA report (Stokes 2003) reviews the different size-frequency distributions available and discusses the caveats on predicting the frequency of Tunguska-type events.

In the present work, we estimate the rate of occurrence from the frequency-size distribution derived by Brown et al. (2002). Using a realistic value of 10 Mton, the authors estimate the mean return period of Tunguska-type events to be approximately 1,000 yrs. To test the sensitivity of our model to rate uncertainty, we define the lower and upper bounds as a factor $\sim$3 below and above the mean return period of 1,000 years, i.e. 300 and 3,000 years, respectively. For a similar explosive yield, the 2003 NASA report indicates a return period of 600–1,000 years, based on a constant power-law frequency-size distribution. Our lower bound is closer to the Shoemaker (1983) estimate, although usually considered outdated, while our upper bound is closer to the Harris (2008) estimate, which takes into account a dip in the frequency-size distribution in the Tunguska size range (with a frequency 3 times lower than estimated in the 2003 NASA report).

As discussed in the recent literature (e.g., Stokes 2003; Longo 2007; Boslough and Crawford 2008), the 1908 explosive yield is probably overestimated and the return period of Tunguska-type events should thus be reassessed to lower values. With a yield as low as 3 Mton and using the Brown et al. (2002) frequency-size distribution, we find a mean return period of ~300 years, which is still in the proposed return period range. Similarly, an interval of ~250 years is found in the 2003 NASA report, and an interval of 500 years is proposed by Harris (2008). As a consequence, the return period range of 300–3,000 years defined for our risk model incorporates roughly both size and frequency-size distribution uncertainties for Tunguska-type events.

The severity of a blast is usually measured by the amount of overpressure (in pounds per square inch, or psi) and must be determined for any location from the source point. The relevant information on the blast effects of the 1908 event is obtained from the tree fall footprint, seismic and barograph records, and eyewitness testimonies (Longo 2007 and references therein). The most recent tree fall footprint (Longo et al. 2005) constrains the spatial extent of the 1908 blast. Another footprint with information on charred trees distribution (Serra et al. 1994) illustrates that large fires were ignited near ground zero (i.e., the point on the Earth's surface directly below the airburst) and spread outward. However, this information is of little help to quantify the intensity of the blast. Moreover, the vulnerability of buildings cannot be assessed directly, as the blast occurred in a remote location, and a comparison to tree vulnerability is not appropriate, as they are relatively brittle and are either standing or fallen. Therefore, empirical evidence for property vulnerability to Tunguska-type events (i.e., airbursts) is lacking.

One solution is to utilize empirical evidence of blast effects from man-made explosions. Figure 1 represents the footprint of an airburst occurring at an altitude of 5,000 m with a released energy of 10 Mton. Overpressure in psi per distance range, shown up to 40 km in radius, is determined by using the formulae and graphs from Glasstone and Dolan 1977. The 1908 Tunguska footprint is also shown for comparison (in dashed/dotted contour lines) with its "butterfly" shape due to the cosmic body's trajectory angle. While the chosen point source parameters seem to match the observed tree fall (e.g., Ben-Menahem 1975), yield estimates based on tree fall are too high because they account neither for topography nor forest health. This issue is discussed in much detail by Boslough and Crawford (2008) (and references therein). In the present work, we however define Tunguska-type events as 10 Mton point source explosions since we assume a flat terrain. The implementation of events with a lower explosive yield (3–5 Mton) would lead our model to possibly underestimate losses because the accumulation of blast wave energy at topography gradients is not taken into account.

Table 1 lists the effects of a 10 Mton point source explosion on buildings and populations per overpressure range, as defined in the nuclear weapons effects literature (Office of Technology Assessment 1979). It is worth noting that dynamic pressure (i.e. high winds), which can knock down people and objects such as trees, is not taken into account in Table 1. However, fatality and injury rate estimates consider people inside buildings, the damage of which is controlled by static overpressure (Office of Technology Assessment 1979). The potential property damage caused by a given overpressure is measured in terms of a mean damage ratio (MDR), which corresponds to the expected loss as a percentage of the replacement value. MDR values implemented in our analysis are roughly estimated from the damage observations described in Table 1. From these data, we define simple step-like vulnerability curves for buildings and populations, as shown in Fig. 2.

A stochastic event set is then developed to determine the expected losses due to Tunguska-type airbursts in the continental United States, considering the spatial distribution and vulnerability of buildings and populations. About 1,000 stochastic events with

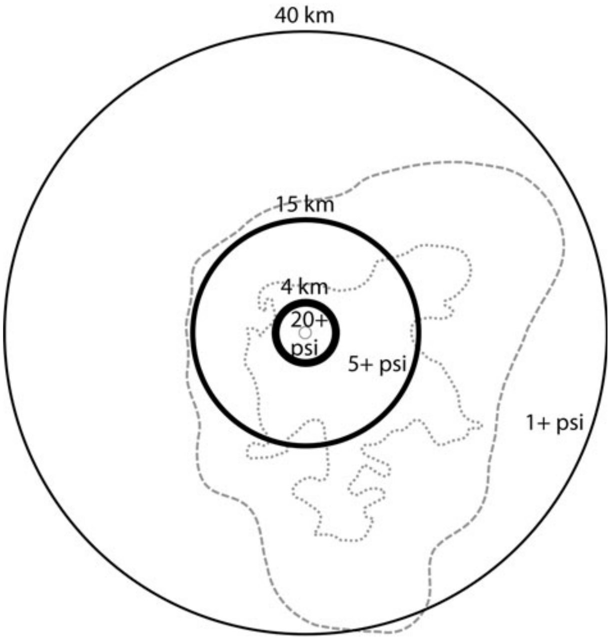


Fig. 1 Footprint of a point source explosion and of the 1908 Tunguska event. Overpressure (in pounds per square inch, or psi) is indicated per distance range from the source (*solid contour*) and computed for a 10 Mton airburst occurring at a 5,000-m height based on formulae and graphs from Glasstone and Dolan (1977). The extents of fallen trees (*dashed contour*) and of charred trees (*dotted contour*) from the Tunguska event (Serra et al. 1994) are shown for comparison, with the focus point from which all fallen trees radiate (i.e., ground zero) positioned at the center of the bulls-eye footprint

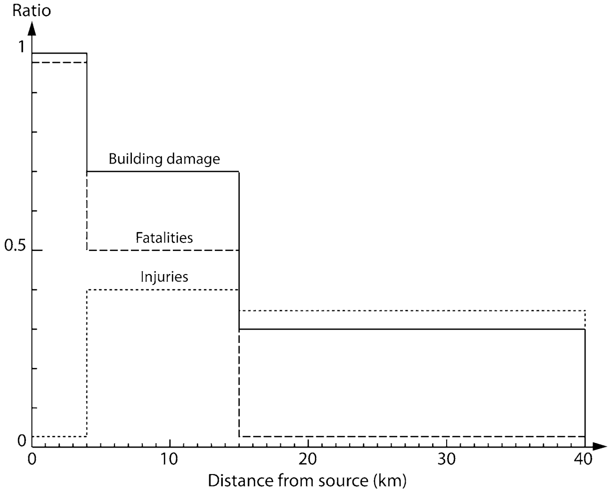
Table 1 Building mean damage ratio (MDR), fatality and injury rates as a function of overpressure derived from the Office of Technology Assessment (1979)

Overpressure	Damage description	Building MDR* (%)	Fatalities (%)	Injuries (%)
20 + psi	Reinforced concrete structures leveled/destroyed	~100	~98	~2
5 + psi	Factories, commercial buildings, and residential structures severely damaged or destroyed	~70	~50	~40
1 + psi	Residential structures moderately or severely damaged	~30	~2	~35

* Building MDR values are roughly estimated from the description of the damage observed

identical footprint and rate are generated and distributed homogeneously over the country in a grid with a bin of 1° in longitude and latitude (Fig. 3). The ratio of the surface of a 1° by 1° cell to the total area of the Earth (5.1×10^8 km^2) is about 2×10^{-5}, which leads to an individual mean return period of 50 million years at each defined location (or cell), assuming that the rate of an impact is the same anywhere on Earth. With a factor ~3 below or above the mean value, we obtain an individual return period ranging from 15 million to 150 million years. It is worth noting that these extremely low individual stochastic event rates are purely a construction of the bin width and are not reflective of the rate for an event outside of the stochastic event set. Coupling the bulls-eye footprint from Fig. 1 inside a 1°

Fig. 2 Vulnerability or damage curves defined for Tunguska-type airbursts (point source 10 Mton explosion occurring at a 5,000-m height) as a function of distance from the source. Building mean damage ratio, fatality and injury rates are obtained from Table 1



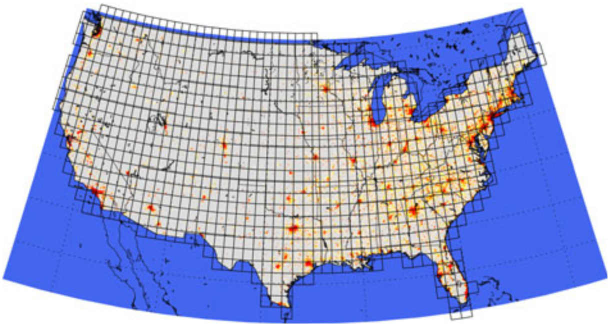


Fig. 3 Stochastic Tunguska-type event set defined for the continental United States. Each 1° by 1° cell (*black rectangle*) represents the location of one stochastic event. The heat color scale represents the population distribution (LandScan™ 2005)

by 1° cell to the vulnerability curves for buildings and populations from Fig. 2, we obtain a building MDR of 18%, a mean fatality rate of 5% and a mean injury rate of 18% per event footprint (weighted average based on each psi range area).

To calculate the expected property losses, we use the 2008 RMS® Industry Exposure Database (IED) developed by the firm Risk Management Solutions (Risk Management Solutions 2008), which 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 United States. Using exposure data for wind and fire, insurance coverage is appropriate in this case, since the hazard is due to hurricane-force winds [maximum wind speed of 502 mph, 163 mph, and 70 mph for an overpressure of 20, 5, and 2 psi, respectively (Glasstone and Dolan 1977)] and to fire ignitions due to thermal exposure. To calculate the expected fatalities and injuries, we use the 2005 United States LandScan™ dataset (LandScan™ 2005) for population concentrations, which gives a census count on a 30″ by 30″ latitude/longitude grid. Both exposure data sets—for property and population at risk—are then aggregated to the 1° by 1° grid cells to match the defined stochastic airburst data set.

Both property and human losses due to a given stochastic event are determined by multiplying the exposure at the corresponding location (or cell) by the average vulnerability to the event. All ~1,000 events are considered and the impacts are summarized using risk metrics, including the Average Annual Loss (AAL) and the Occurrence Exceedance Probability (OEP) curve, which illustrates the annual probability of exceeding a certain level of loss (e.g. Smolka 2006). The AAL can be calculated as the area under the EP curve or as the sum product of the mean loss and the event rate for each event in the stochastic event set.

Figure 4 shows the OEP curves for property losses (top) and human losses, i.e. fatalities and injuries (bottom). With an event return period of 1,000 years (on Earth), we estimate the AAL for the continental United States to ~USD 200,000/year, ~0.3 fatalities/year

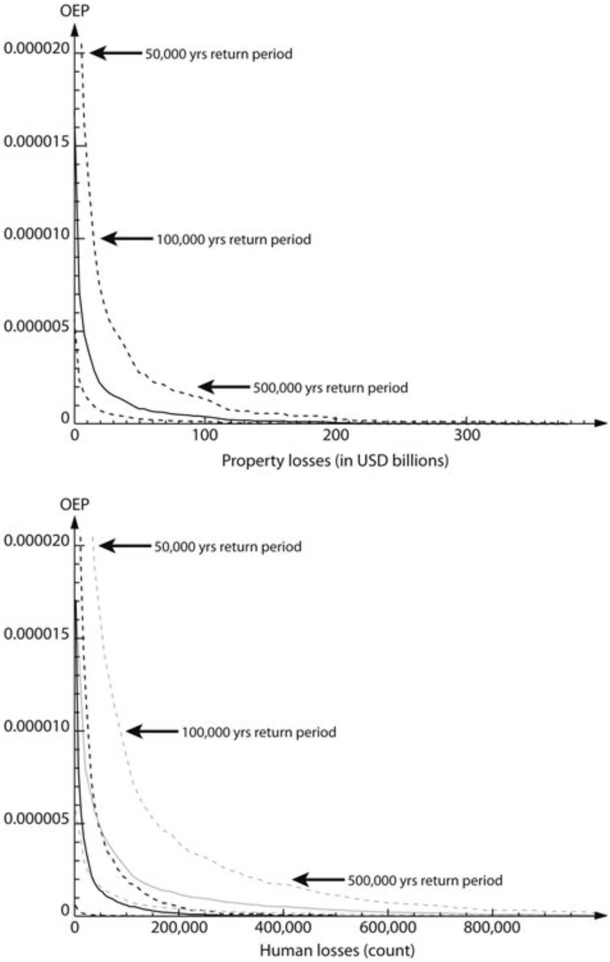


Fig. 4 Occurrence Exceedance Probability (OEP) curves determined for Tunguska-type events occurring over the continental United States. *Top*: for property loss in USD billions (buildings and contents). *Bottom*: for human losses: fatalities (in *black*) and injuries (in *gray*). *Solid curves* correspond to the estimates from the 1,000 years return period of Tunguska-type events on Earth, and *dashed curves* show the sensitivity of the model to the implemented rate uncertainty (i.e. 300–3,000 years return period)

and ~1.0 injuries/year, ranging from a factor 3 below and to a factor 3 above the indicated values when rate uncertainty is taken into account. The maximum expected losses in our model are ~USD 380 billion, ~500,000 fatalities, and almost 2 million injuries. Since the rate of Tunguska-type events is assumed the same everywhere, the OEP is dependent upon the population distribution in the continental United States. With the population concentrated in a few urban regions, an event is more likely to occur in a remote region than over a highly populated area. Very large losses are extremely rare, as this analysis shows return periods of the order of millions of years at the tail of the OEP curve.

In comparison, the 2003 NASA report proposes a nominal rate of 2.1 fatalities/year and a maximum rate of 11.8 fatalities/year for 50-m objects, based on a homogeneous distribution of the population on Earth. Harris (2008) states that the risk of death due to a Tunguska-type event is one in 6 million. With a world population of 6.8 billion and a life expectancy of 67 years, it corresponds to ~17 fatalities/year. As a rule of thumb, our regional model output of 0.3 fatalities/year corresponds to ~16 fatalities/year on Earth (the United States area being ~1/50 of the Earth area), which is a very good match to the Harris (2008) value and a reasonable match to the 2003 NASA report value when considering the different assumptions made in the 2 models (e.g., regional versus global, different footprints). Nevertheless, future studies should explore the different sources of discrepancy and their impact on risk quantification.

3 An illustrative scenario: a Tunguska-type event over the New York metropolitan area

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 populated cities in the world. The following scenario considers the occurrence of an event with an impact footprint similar to the one shown in Fig. 1 (i.e. 10 Mton point source explosion at a 5,000-m height) over the New York metropolitan area, which is the most populous metropolitan area in the United States and also one of the most populous in the world. The bulls-eye footprint is centered at 40.73°N; 73.99°W over central Manhattan, as shown in Fig. 5. The footprint of the 1908 event (Serra et al. 1994) is also indicated for illustration. Property and human losses are estimated using the vulnerability curves defined previously and not the weighted averaged vulnerability value used in the US Tunguska-impact model.

The property exposure dataset [2008 RMS® Industry Exposure Database (Risk Management Solutions 2008)] is aggregated at the ZIP Code resolution level throughout the New York metropolitan area for both commercial and residential properties (Fig. 5, top). For the population exposure, we use the 2005 LandScan™ dataset (LandScan™ 2005) at the original resolution of 30″ by 30″ latitude/longitude grid (Fig. 5, bottom). Table 2 lists the different property and population concentrations per overpressure range as well as the expected losses. While we estimate that this "nightmare" scenario would lead to ~USD 1.5 trillion of property loss, ~3.9 millions of fatalities and ~4.7 millions of injuries, such event is almost impossible and should only be considered as an illustrative example. If we consider that this scenario-event can occur anywhere over the New York metropolitan area, which measures 17,400 km^2, its return period would be ~30 million years (based on a 1,000 years return period on Earth).

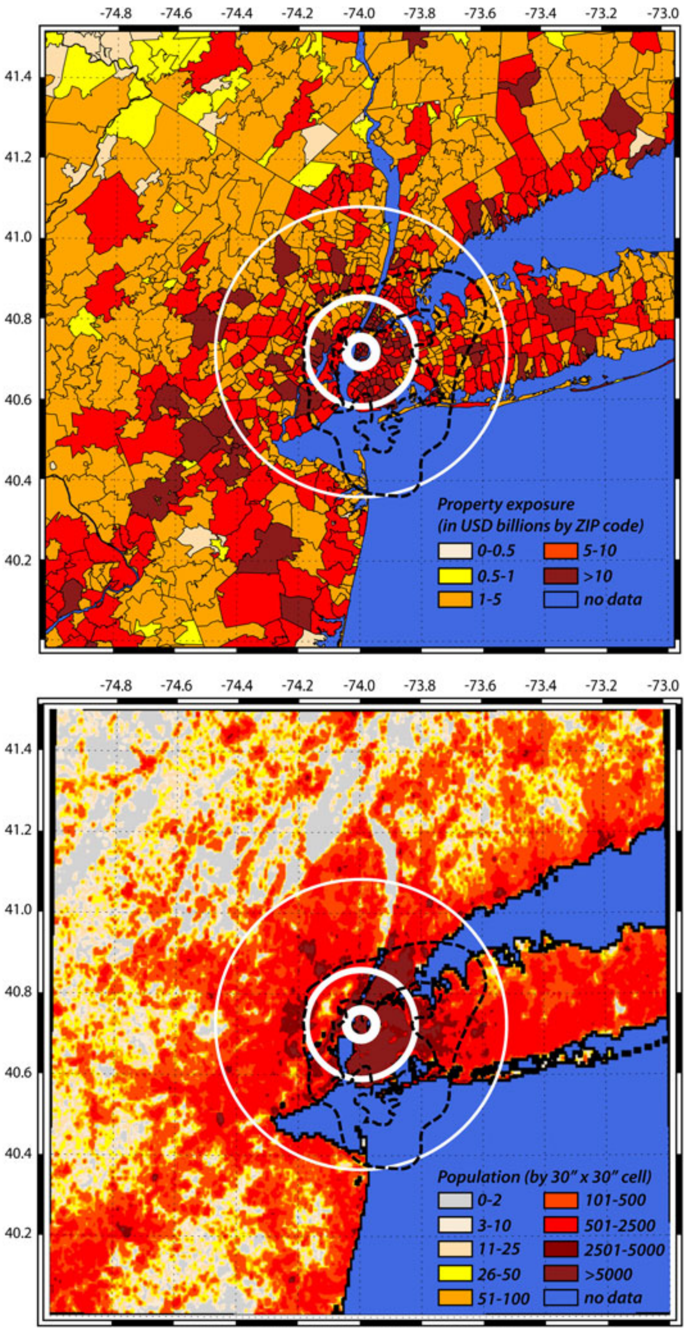


Fig. 5 An illustrative "extreme event" scenario—a Tunguska-type event over the New York metropolitan area. *Top*: property exposure (buildings and contents) (Risk Management Solutions 2008). *Bottom*: population exposure (LandScan$^{\mathrm{TM}}$ 2005). Losses are computed based on the location of the bulls-eye footprint (centered at 40.73°N; 73.99°W). The 1908 Tunguska footprint is shown for illustration only

Table 2 Property (buildings and contents) (Risk Management Solutions 2008) and population (LandScan^{TM} 2005) exposures and expected losses for the illustrative scenario of a Tunguska-type event over the New York metropolitan area

Overpressure range	Property exposure (in USD billion)	Population exposure	Property losses (in USD billions)	Fatalities	Injuries
20 + psi	~450	~1,000,000	~450	~980,000	~20,000
5 + psi	~950	~5,500,000	~665	~2,750,000	~2,200,000
1 + psi	~1,500	~7,000,000	~450	~140,000	~2,450,000
Total	~2,900	~13,000,000	~1,565	~3,870,000	~4,670,000

4 Discussion

As discussed in details by Kovacs and Hallak (2007), an assessment of the costs of asteroid/comet impacts requires many assumptions and the probabilistic risk model proposed in the present paper has several limitations, as explained below.

First, the losses determined for the New York metropolitan area scenario-event are much higher than the maximum losses expected on the tail of the EP curve in the proposed model for the continental United States. It shows that all aspects of the risk due to Tunguska-type airbursts are not implemented here, with the tail of the EP curves (Fig. 4) being underestimated. A next step would be to use a Monte Carlo simulation to define stochastic events that occur randomly in space instead of inside specific grid cells and by directly using the bulls-eye footprint instead of the weighted averaged damage ratio. Such approach would help better defining the EP tail and improve the resolution of the risk.

Second, the assumption that Tunguska-type impacts can be treated as point source explosions (e.g., Ben-Menahem 1975) is reasonable for the purpose of this work, but some recent models consider that such events are more analogous to explosive line charges (Longo 2007 and references therein). In such models, the cosmic object momentum carries energy to lower altitudes, and thus a smaller explosive yield is required to produce the phenomena associated with the 1908 event for instance (e.g., Boslough and Crawford 2008). However, sophisticated models are computationally intensive, and more realistic models taking into account 3-D topography are still to be generated (Boslough and Crawford 2008). Therefore, models based on point source explosions appear to remain the best alternative for risk assessment at the present time.

Third, the uncertainty associated with the vulnerability of buildings and populations to airbursts is high. There is no historical event and therefore no data (e.g. insurance claims) to directly calibrate and validate vulnerability curves. As indicated above, information from nuclear tests is used in this analysis, and although this assumption is reasonable, the MDR value defined for the model as a function of overpressure (Table 1) is a rough estimate, which could vary by several 10 s of percent. Moreover, no distinction between building types is made in the present model. One could consider a set of vulnerability functions corresponding to different construction types and other significant parameters.

Finally, a sophisticated model would need to account for loss amplification due to secondary perils, which result from an airburst, such as tsunamis, earthquakes, or fires. As discussed by Gusiakov (2007), with no object directly hitting the surface of the ocean, only very weak tsunamis can be generated. However, estimates are based on man-made explosions, and the real impact from Tunguska-type airbursts remains unknown at the present time. Moreover, there is a debate about a possible impact crater at the Tunguska site (Gasperini et al. 2007, 2008, 2009; Collins et al. 2008), which adds even more uncertainty on the potential of "Tunguska-generated" tsunamis. Although the 1908 Tunguska event caused a medium-sized earthquake, it is unclear how ground shaking would significantly increase losses compared to the shock wave. Fires, however, could potentially increase losses. Historically, there is precedent for fires following earthquakes to cause much larger losses than those due to ground shaking (e.g. following the 1906 San Francisco Earthquake and the 1929 Great Kanto Earthquake). Risk assessment of earthquake and fire perils is common practice (e.g., HAZUS-MH). It is worth noting that Carusi et al. (2007) discusses in detail the social implications of Tunguska-type airbursts and that business interruption is also likely to increase economic losses.

It is important to note that the proposed model is specific to Tunguska-type airbursts (i.e. objects of similar size that explode in the atmosphere), but the role of smaller and larger events should be considered in a more robust model. For smaller events, fragmentation along the trajectories of bolides, which leads to the formation of strewn fields (e.g. Simon et al. 2004), would need to be assessed. For much larger events, impacts on a global scale would need to be assessed too. To be fully comprehensive, one should consider both airbursts and crater-forming events. A cosmic body similar in size to the Tunguska object could, instead of exploding in the atmosphere, remain intact and create a crater, such as Meteor Crater in Arizona. The associated footprint can be computed with web routines such as *Crater* (Melosh and Beyer 1998). With irons less likely to be disrupted in the atmosphere than stony objects, event rates could be defined for the model based on the distribution of meteorites, knowing that irons correspond to approximately 5% of all meteorite falls. A simple logic-tree approach could be used to define different families of stochastic events.

5 Conclusions

We proposed a realistic probabilistic risk model for Tunguska-type events to compute expected property and human losses in the continental United States. Although the present model may appear simplistic, most of the limitations can be overcome through the realization of a more sophisticated model. Nevertheless, the lack of historical events still makes the exercise difficult, especially for the development of vulnerability curves.

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 whether, 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 all land areas (although a tsunami premium may also need to be added for coastlines), it seems unlikely that insurers would 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 a 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 asteroid/comet events can only increase through time and that more research to understand these extremely rare events should be encouraged.

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