

**DRAFT CHAPTER FOR UNIVERSITY OF ARIZONA
SPACE SCIENCE SERIES VOLUME ON
THE HAZARDS OF IMPACTS BY COMETS AND ASTEROIDS**

Tom Gehrels and Mildred Matthews, editors

*superseded
by 2-7-94
version (#329 in
Guis J-list
file), except
that I pulled
the figures
from here
temporarily.*

THE IMPACT HAZARD

**David Morrison
NASA Ames Research Center**

**Clark R. Chapman
Planetary Science Institute**

**Paul Slovic
Decision Research and
University of Oregon**

Revised 16 August 1993

ABSTRACT

This overview of the impact hazard characterizes the consequences of impacts as a function of meteoroid energy, assesses the probability of death from impacts, compares these risks with those of other natural disasters, and reports on preliminary studies of the public perception of impact risks. Below 10 MT (equivalent TNT) energy there is virtually no risk since few meteoroids penetrate the atmosphere. Between 10 MT and the threshold for global catastrophe impacts are a moderate source of risk, but substantially less so than more common natural disasters such as earthquakes, severe storms, or volcanic eruptions. The greatest hazard is associated with impacts at or a little above a threshold for global catastrophe, where we define a global catastrophe as one that leads to the death of >25% of the Earth's human population. Following the analysis of environmental effects of impacts by Toon *et al.* (this book) we conclude that this threshold lies between 5×10^4 and 5×10^6 MT, with a nominal value of 5×10^5 MT, corresponding to an average interval between events of about half a million years. Above this threshold the entire world population is at risk from impacts, which are the only known natural disasters capable of killing a substantial fraction of the population or, at still larger energies associated with mass extinction, of threatening the survival of the species. As an extreme example of low-probability but high-consequence disasters, large impacts are without precedent in terms of public perception, but with increasing public awareness, demands may grow for action to deal with this newly-identified hazard. Over the entire range of impact energies from the atmospheric cut-off to above the global threshold, the risk level increases with the energy of the impact. Therefore the most prudent strategies deal with detection and protection against the largest projectiles; any program to mitigate the impact hazard should begin with a comprehensive NEO census such as the proposed Spaceguard Survey.

INTRODUCTION

Recent widespread scientific and public recognition of a cosmic impact hazard results in part from an increased sensitivity to the historic role of impacts in planetary evolution. The past 25 years have witnessed the discovery of numerous Earth-approaching comets and asteroids, while spacecraft images of planets and satellites show the craters that result from high-velocity impacts by these objects. However, the population of projectiles present today, few of which exceed a mass of a few teratons (1 teraton = 10^{15} kg) (diameter of order 10 km), are not capable of significant geological or geophysical modification to the Earth. Impacts by the current population of such objects pose a substantial hazard only as a consequence of the great sensitivity of the biosphere to relatively small perturbations.

The effect of impacts upon the biosphere is most dramatically demonstrated by the discovery (Alvarez *et al.* 1980) that the K/T mass extinction resulted from the impact of one or more comets or asteroids with a mass of 1-10 teratons. In this instance a relatively modest cratering event (produced by an object roughly the size of Comet Halley or one of the larger contemporary Earth-approaching asteroids) led to global collapse of ecosystems and the extinction of most terrestrial species, including the dinosaurs. It is clear that, far short of a mass extinction, an impact could lead to a lesser ecological catastrophe that might nevertheless kill large numbers of people and threaten the stability of society. Such a global catastrophe is qualitatively different from any other natural disaster and can be compared in its consequences only with the result of nuclear war (Chapman and Morrison 1989). In addition, our planet is subject to much more frequent strikes by smaller meteoroids, of which the Tunguska explosion of 1908 is the best historical example (Krinov 1963).

Following the Alvarez discovery of the impact origin of the K/T extinction,

NASA convened a workshop in 1981 in Snowmass, Colorado, to consider the impact hazard (Shoemaker 1982). Although the proceedings of that workshop were never published (see Chapman and Morrison 1989), conclusions reached there have influenced most subsequent work on this issue. In particular, the values for the terrestrial impact flux presented at that meeting and the discussion of a threshold for global environmental disaster do not differ greatly from those presented in this chapter.

A decade after the Snowmass meeting, NASA (at the request of the U.S. House of Representatives) asked a group of scientists (the Spaceguard Survey Working Group) to reconsider the magnitude of the hazard and to devise a strategy to greatly accelerate the discovery of potentially threatening asteroids. Much of the basic hazard discussion is derived from the work of that group (Morrison 1992) and our parallel publication of papers on the impact hazard (Morrison 1993a, 1993b; Morrison and Chapman 1992; Chapman and Morrison 1993).

We begin this chapter with an overview of the physical and environmental consequences of hypervelocity impact and an estimate of the size-frequency distribution of the comet and asteroid impactors. We then calculate the risk from projectiles of different sizes and the cumulative risk from all impacts. These risks are compared with a variety of other natural and technological hazards in an effort to place this source of risk within a broader context of societal concerns. New information is also reported on public perception of the impact hazard and the ways this perception may influence public policy in dealing with this issue.

IMPACT FLUX

The flux of meteoroids striking the Earth is composed of near-Earth asteroids and short-period comets (collectively called Near-Earth Objects or NEOs), and of long-period comets. The asteroids and short-period comets have dynamical similarities; both reside in the inner solar system and generally impact the Earth with speeds of order 20 km/s. Physically, however, they span a wide range of properties, from metal (like the iron meteorites) through various types of rock (like the chondritic and achondritic meteorites) to the low-density, volatile-rich assemblages associated with the comets. Less is known about the rarer long-period comets, but they are probably also composed of low-density, volatile-rich material. Long-period comets strike with higher velocities, sometimes greater than 50 km/s (McFadden *et al.* 1988; Chapman *et al.*, this book; Rahe *et al.*, this book).

The implied range in projectile density spans an order of magnitude, and the range in physical properties (e.g., strength) is likely to be much greater yet. At smaller sizes (masses of less than a megaton), the physical properties are important in determining the fate of a meteoroid as it plunges into the Earth's atmosphere (Chyba *et al.* 1993; Hills and Goda 1993). For some purposes, however, the composition of the meteoroid is of little significance, since the threat from larger impacts is related to the kinetic energy of the objects, which is typically nearly two orders of magnitude greater than an equivalent mass of TNT. In this chapter, we adopt this kinetic energy (usually expressed in megatons (MT) of TNT, where $1 \text{ MT} = 4.2 \times 10^{15}$ joules), rather than diameter or mass, as the most significant property of an impacting meteoroid.

By the end of 1992, 163 Earth-crossing asteroids had been cataloged (Rabinowitz *et al.*, this book); the largest is 1627 Ivar (diameter about 8 km, mass presumably about 1 teraton). Other still larger objects (up to 433 Eros, with mass

an order of magnitude greater) are in Earth-approaching orbits but are not currently classed as Earth-crossing. The census is complete only for objects with diameters of about 5 km or greater; for 1-km objects the completeness is less than 10% (Bowell and Muinonen, this book). From their large-amplitude variations in brightness, we know that many of these asteroids are irregular in shape (Chapman *et al.*, this book; Ostro, this book); at least two, 4769 Castalia (Ostro *et al.* 1990) and 4179 Toutatis (Ostro *et al.* 1993) appear to be almost contact binaries, consisting of two or more pieces in a dumbbell configuration.

The integrated or average flux of meteoroids over the past 3 billion years can be determined directly from crater densities observed on the lunar maria, which provide a convenient score-card for impacts in the Earth's vicinity. Current impact rates can also be derived, with less certainty, from the estimated population of NEOs and long-period comets together with calculations of their dynamical lifetimes. (For discussions of these flux rates see Shoemaker *et al.* 1979; Shoemaker and Wolfe 1982; Weissman 1982; Wetherill and Shoemaker 1982, Shoemaker 1983; Wetherill 1989; Shoemaker, Wolfe, and Shoemaker 1990; Weissman 1991, Ceplecha 1992, Rabinowitz *et al.*, this book; Rahe *et al.*, this book.) For this discussion we adopt the size-frequency distribution for impactors with energies between 1 KT (kiloton) and 10^8 MT published by Shoemaker (1983) and reproduced in the Spaceguard Survey Report (Morrison 1992). Although recent observations of small (<10 MT energy) asteroids (Rabinowitz 1993; Rabinowitz *et al.* 1993) suggest an enhancement in the asteroid fluxes in this size range, it is sufficient for our purposes to use the smooth curve (Figure 1) based on lunar crater data for estimations of impact hazard (Chyba 1993). Even if the enhancement of small objects is real, the risk statistics are dominated by larger objects (>100 m diameter) where the recent asteroid observations are in good agreement with the lunar cratering curve.

The majority of impacts contributing to the integrated flux are near-Earth asteroids and short-period comets. In addition, occasional long-period comets impact our planet, although they probably amount to less 25% of the asteroid flux at the same energy (Shoemaker and Wolff 1982; Weissman 1982; Weissman 1992). There may also be short-term enhancements in the flux rate (e.g., comet showers) related to the breakup of comets or possibly asteroids (Clube and Napier 1990; Steel *et al.*, this book), but for purposes of this chapter we treat impacts as occurring randomly in time.

NATURE OF THE HAZARD

Based on the average flux of comets and asteroids striking the Earth, we can evaluate the danger posed by impacts of different magnitudes. Of particular interest are the threshold for penetration through the atmosphere, and the size (energy) at which impacts begin to produce global environmental stress in addition to their direct blast damage.

We find the concept of thresholds to be useful for differentiating the qualitatively different effects of impacts, which span a range of 100 million in energy (from 10 MT to 10^9 MT). The concept of a threshold does not necessarily imply a sharp transition from one scale of risk to another, however. The transitions between local blast effects and global catastrophes, for example, may be quite gradual. It is also the case that the energy threshold at which, for example, an impact raises sufficient dust to influence the global climate will almost certainly depend on the location of the crater. However, a threshold is useful for discussing the impact energies at which one class of physical effects gives way to another.

Penetration through the Atmosphere

The atmosphere protects us from small impacts. The flux curve of Figure 1 indicates that an impact with the energy of the Hiroshima nuclear bomb occurs roughly annually, while a 1 MT event is expected at least once per century. Obviously, however, such relatively common events have not been destroying cities or killing people. Even at megaton energies, most meteoroids break up and are consumed before they reach the lower atmosphere.

Meteoroids as large as a few tens of meters in diameter usually fail to penetrate into the lower atmosphere because they are subject to aerodynamic stresses that cause fragmentation and transverse dispersal at high altitude (Chyba *et al.* 1993; Hills and Goda 1993). The height of fragmentation depends primarily on the meteoroid's physical strength; only the strongest irons reach the surface in one piece. Loose cometary aggregates and carbonaceous meteorites fragment at altitudes above 50 km.

Although the altitude of initial fragmentation is nearly independent of projectile size, the history of the resulting fragments depends critically on size; smaller objects rapidly disperse while sufficiently large objects produce a dense cloud of fragments that continues to the ground as a coherent whole. If the object explosively disperses within about 20 km of the surface, the resulting airburst can be highly destructive. Numerical models of atmospheric fragmentation and dispersal show that rocky objects >50 m diameter (10 MT energy) and cometary objects >100 m (100 MT energy) penetrate deep enough to pose significant hazards (Chyba *et al.* 1993; Hills and Goda 1993). To remain undispersed down to the surface and produce a crater upon impact, a stony body requires a diameter of 200-300 m (Melosh 1981, 1989).

If a large meteoroid penetrates to the troposphere or actually strikes the

surface at velocities of tens of km/s, the resulting sudden release of kinetic energy can result in damage analogous to that from nuclear bomb explosions of similar energies, but without associated radioactivity. The area of devastation scales approximately as the explosive yield to the 2/3 power and is somewhat greater for an airburst than for a groundburst explosion (Glasstone and Dolan 1977).

Tunguska provides a calibration, with a shock wave sufficient to fell trees over an area of 10^5 hectares and a fireball that ignited fires over a smaller area near ground zero (Krinov 1966; Sekanina 1983; Pike 1991a, 1991b; Chyba *et al.* 1993; Hills and Goda 1993). The yield of the Tunguska blast has been estimated at 10-20 MT from microbarograph measurements in Europe. If we assume that the radius of forest devastation would apply also to destruction of many buildings, the area of damage is given approximately by

$$A = 10^4 Y^{2/3}$$

where Y is the yield in MT and A is in hectares (Chapman and Morrison 1993). Applying this formula we find that at 100 MT, the radius of destruction is 25 km and the fraction of the Earth's surface that is affected is 0.001%, while 10^5 MT, the radius is 250 km and the area is about 0.1%. These are both examples of what we call local or regional events, rather than global catastrophes.

Tsunamis

The area of destruction is larger for impacts into oceans than for land impacts as a consequence of the great travel distances of impact-induced tsunamis. The radius of destruction for tsunamis scales approximately as the impact energy to the 1/2 power (Hills *et al.*, this book; Toon *et al.*, this book), rather than as the 1/3 power for land impacts noted above. On the other hand, a tsunami results in large-scale destruction and loss of life only when it encounters a populated coastal

region; a tsunami that dissipates before reaching a continental margin is a hazard only to oceanic islands.

From the expressions given by Hills *et al.*, a 5-m height tsunami has a range of approximately 1000 km for a 1000 MT explosion; it is at roughly this magnitude that the tsunami from a typical oceanic impact has a substantial probability of reaching land and producing large-scale destruction. For yields greater than about 10^3 MT, tsunamis associated with oceanic impacts contribute more to the hazard than the direct blast damage of impacts on land or in the continental margins.

Globally Catastrophic Impacts

At sufficiently great energies, an impact has global consequences. An obvious if extreme example is the K/T event 65 million years ago. This impact of a >1 teraton object released $>10^8$ MT of energy and excavated a crater (Chicxulub in Mexico) approximately 200 km in diameter (Sharpton and Grieve 1990; Hildebrand *et al.* 1991; Sharpton *et al.* 1992; Swisher *et al.* 1992; Grieve and Shoemaker, this book). Among the environmental consequences were devastating wildfires and changes in atmospheric and oceanic chemistry as well as a dramatic short-term perturbation in climate produced by some 10^{16} kg of submicrometer dust injected into the stratosphere (Alvarez *et al.* 1980; Toon *et al.* 1982; Wolbach, Lewis, and Anders 1985; Covey *et al.* 1990; Gilmore *et al.* 1990; Sharpton and Grieve 1990; Toon *et al.* this book).

The K/T impact probably darkened the entire planet for many months and precipitated a general destruction of terrestrial ecosystems. However, projectiles much smaller than the K/T impactor can still perturb the global climate by injecting dust into the stratosphere. An environmental shock that would leave

most natural ecosystems intact can still severely curtail human agricultural production around the world. Few nations store one year's worth of food, so mass starvation could be expected (Harwell and Hutchinson 1989). Compounded by other possible effects of the impact, this agricultural disaster might result in collapse of global economic, social, and political structures. However, we do not know the degree of coupling of these effects, and it is very difficult to estimate the resilience of society to such massive environmental insults.

Chapman and Morrison (1993) *define* a globally catastrophic impact as one that would destroy food crops and *lead to the deaths of more than a quarter of the world's population*. Such an event would affect the global climate in ways somewhat similar to those calculated for nuclear winter (Turco *et al.* 1983). Although such a global agricultural catastrophe would be *worse* in loss of life and destruction of property than the effects of the great World Wars, it is *far smaller* than the K/T impact. A globally catastrophic impact would probably destabilize modern civilization, but it would not threaten extinction of the human species or produce a mass extinction of marine fauna that might be visible in the fossil record.

Threshold for a Globally Catastrophic Climate Perturbation

A drop of a few degrees C in surface temperature over many months is sufficient to reduce crop yields dramatically and precipitate large-scale starvation (Covey *et al.* 1990; Turco *et al.* 1991). The energy threshold for a globally catastrophic impact is therefore determined by the explosive yield required to loft sufficient submicrometer dust into the stratosphere to lower the surface temperature by this amount.

The energy at which impacts lead to significant global climatic effects is

considered in detail by Toon *et al.* (this book). They identify 10^5 MT as the energy for land impacts at which submicrometer dust yields an atmospheric opacity near unity, with climate effects probably similar to that of large volcanic eruptions such as Tambora (Stothers 1984); at this level dust can lower surface temperatures on a regional scale and lead to crop loss on at least a regional scale. At 10^6 MT energy, for either land or ocean impacts, approximately 2×10^4 g/cm² of submicrometer dust is injected into the atmosphere. The optical depth is about 10 with an atmospheric transmission of less than 1%, sufficient to induce global freezing and large-scale crop loss. Toon *et al.* refer to the energy region between 10^5 and 10^6 MT as a "grey area between small effects and those that are obviously significant on the global scale." For a stony object striking at 20 km/s, 10^6 MT corresponds to diameter of about 2 km.

For purposes of this discussion, we adopt an energy of 5×10^5 MT, near the upper end of the "grey area" of Toon *et al.* (this book), as the nominal threshold for global catastrophe. The corresponding average interval between impacts of this size or larger is 500,000 years from Figure 1. This is slightly higher than the nominal asteroidal threshold diameter of 1.5 km adopted by Chapman and Morrison (1993) in their similar discussion. In any case, the error bars are large; it is important to recognize that this threshold is uncertain by at least an order of magnitude in energy (range from 5×10^4 to 5×10^6 MT), and hence a factor of two in projectile diameter (from just under 1 to just under 4 km for a stony asteroid). Indeed, the limit for the threshold could possibly be as low as 2×10^4 MT, as discussed by Chapman and Morrison (1993), who took a somewhat more conservative approach in their error analysis.

Misidentification of a Bolide

One additional source of hazard has frequently been discussed: the misidentification of a natural impact event with a nuclear attack (e.g., Shoemaker

1982). During the periods of high international tension that characterized much of the cold war, it was feared that a natural event in the megaton range might be mistaken for a nuclear attack and thereby trigger a nuclear war, with catastrophic global consequences. A megaton event is expected roughly once every few decades, but most such explosions take place at high altitude and have no observable consequences at ground level. There is no public record of such events having contributed to international tension during the cold war, and today surveillance satellites have the capability to detect natural high-altitude explosions over a wide range of energy (Reynolds 1993). However, such data are not available to many nations with emerging nuclear capability, and the proliferation of nuclear weapons causes continuing concern about the misidentification of such natural events.

HAZARD ANALYSIS

We now address the scale of destruction expected for impacts and the numerical hazard associated with impacts of various magnitudes. By numerical hazard we mean the probability of death for an individual due to this event.

Impacts on Land

We begin with the destructive effects of airbursts or groundbursts on land or in shallow coastal areas. We identify the average zone of mortality associated with impacting objects larger than our threshold for penetration into the lower atmosphere (10 MT) with the area of blast devastation defined earlier from the Tunguska example. The average number of fatalities per impact, using the average world population density of 0.2 person per hectare of land, is:

$$N = 2 \times 10^3 Y^{2/3}$$

Thus an event with the energy of the Tunguska blast, occurring every few centuries, would on average cause about 14000 deaths, although most such impacts can be expected to strike uninhabited parts of the planet, just as in 1908. Indeed, it is unlikely that a Tunguska-like impact would destroy even one city in the entire 10^4 year span of human history.

Ocean Impacts

Approximately half the target area of the Earth consists of ocean basins, and impacts into deep water generate tsunamis of substantial size (Pike 1993; Hills *et al.* this book). As the range of the tsunamis approaches the dimensions of the ocean basins, there is potential for destruction and loss of life far exceeding that associated with land impacts of comparable energy.

To estimate the potential mortality from tsunamis, we use the expressions for wave height and depth of penetration into coastal plains given by Hills *et al.* (this book). As a tsunami approaches the shore, it experiences an increase in height of a factor of 10 to 40; thus a nominal 5-m ocean wave might break at the shore with a height of order 100 m. As shown by Hills *et al.*, such a wave would penetrate a flat coastal plain to a depth of 22 km.

To calculate the casualties associated with such an event, we need to estimate the length of ocean margins that consist of flat coastal plains and the population density of such plains. For this order-of-magnitude estimate, we neglect the small-scale curvature of the ocean margins and adopt a length of the order 10^5 km. The associated area of coastal plains at risk from tsunamis, to a nominal width of 20 km, is 2×10^6 square kilometers or 2×10^8 hectares. If the population density of coastal plains is 10 times the average for the land area of the Earth (2/hectare), the total population at risk from tsunamis is a few times 10^8 , or roughly 10% of the world's population.

In the absence of modeling of the destruction of tsunamis on real coastlines, two additional rough estimates can be made of the population at risk. Kopec (1971) calculates that 19% of the world's population would be inundated by a rise of 100 m in sea level, a figure that considerably overestimates the numbers that would be flooded by most tsunamis, which would be much less than 100 m high after penetrating a few kilometers inland. Another overestimate of the population fraction at risk can be obtained from the fact that 30% of the population in the world's 50 largest urban areas occupy coastal plains or harbors (Hoffman 1990). Although the estimates are crude, they all suggest that the fraction of the Earth's population living in areas subject to flooding by tsunamis is no more than 10%.

Such estimates of the population in coastal plains permit us to set an upper limit to the mortality that might be associated with impacts having energy in the gigaton range (10^3 to 10^5 MT). The geometry of the Earth's ocean basins suggests that any one impact is unlikely to affect more than 10% of the total coastline, hence to place at risk more than about 1% of the planet's population (that is, fewer than 10^8 people). This is the maximum level of mortality expected for an ocean impact; presumably the average impact would be less lethal, with the order of 10^7 deaths. In addition, current tsunami warning systems permit at least partial evacuation of coastal areas in the several hours that elapse before a typical deep-ocean tsunami reaches the shore. For comparison, the mortality associated with an average 10^4 MT land impact is of order 10^6 . In a similar analysis, Pike (1993) concluded that the hazard from open ocean impacts is 4-8 times greater than for land impacts of similar energy. We conclude that the hazard associated with gigaton-energy impacts is dominated by ocean impacts, but the upper limit to the deaths associated with such events remains no more than 1% of the total population of the planet.

Globally Catastrophic Impacts

Above the threshold energy for global catastrophe (nominally 5×10^6 MT), the number of fatalities is (by definition) a substantial fraction of the Earth's total population (we adopt 1.5 billion). For example, for a land impact near 10^6 MT, the expected average mortality from the direct blast is (from the formula above) about 20 million, while indirect deaths are (by definition of the global threshold) 1.5 billion. This difference reflects the different areas affected: less than 1% of the Earth's surface for the direct blast, but the entire surface for the indirect effects.

When the threshold globally catastrophic impact is compared with a somewhat smaller impact in the deep ocean, the contrast is less. The maximum number of direct tsunami deaths from a 10^5 MT ocean impact are of order 100 million, as compared with the postulated 1.5 billion indirect deaths from a global environmental disaster. However, there remain substantial uncertainties in the estimates for tsunamis of this size, which dwarf anything experienced directly, so all of these numbers must be used with great caution.

At still higher impact energies, other environmental as well as climatic effects come into play, leading to mass extinctions (Toon *et al.* 1982; Lewis *et al.* 1982; Zahnle 1990; Toon *et al.*, this book). However, since such events are extremely rare, they constitute a smaller numerical risk than do impacts near the global threshold.

Dependence of Risk on Impact Energy

In spite of substantial uncertainties in the expected consequences of impacts of various energies, we can still draw some interesting conclusions about relative risk. The nature of the hazard and the possible means of protecting ourselves vary

greatly over the wide range in projectile size and energy from the atmospheric cutoff to the large mass extinction events. In order to assess the numerical risk as a function of projectile size or energy, we have integrated the cumulative damage over segments of the impactor size-frequency distribution to yield some quantitative estimates, as summarized in Table 1.

The smaller, frequent events larger than the 10 MT atmospheric cut-off (what we may call Tunguska-class impacts) yield equivalent annual fatality rates of tens of deaths/yr for the current world population. In reality, of course, most of the casualties will be associated with rare events that strike in heavily populated areas, while the majority of these impacts produce practically no fatalities. As urban centers have existed on this planet for only a few millennia, it is not surprising that none have yet been hit. The risks associated with Tunguska-class impacts, while not insignificant, represent mortality rates that are substantially less than those associated with many smaller and more frequent natural hazards, such as earthquakes, hurricanes, volcanic eruptions, floods, or mud slides. Thus the hazard from Tunguska-like impacts does not inspire special concern or justify heroic efforts either to predict such events or to attempt to avert them.

At the opposite, high-yield extreme, the K/T impact was vastly more devastating, but even though nearly everyone would be killed by such an event, they are so infrequent that the annual fatality rate is only about 50/yr for the world's present population (5 billion people killed per 100 million years). Even with present limited knowledge, we can say that no asteroid exists in an Earth-crossing orbit that could cause a disaster of this magnitude. However, we cannot exclude the possibility of a large comet appearing at any time and dealing the Earth such a devastating blow -- a blow that might lead to human extinction. This is the most extreme problem raised by this risk analysis -- the possible extinction of humanity from a large comet at an annual probability level of $< 10^{-8}$.

The greatest risks are associated with impacts near the threshold for global catastrophe; just above this threshold, we postulate that 1.5 billion people are killed. For the nominal threshold energy of 5×10^5 MT, such events occur roughly twice per million years, implying a fatality rate of a few thousand per year. The annual risk per individual is thus approximately one in 2 million. A smaller but still significant risk is associated with tsunamis caused by large impacts in the 10^4 - 10^6 MT range taking place in deep oceans, especially the Pacific and Indian Oceans. Although very uncertain, the annual fatality rate associated with such tsunamis may be hundreds per year.

The total lifetime risk from both the globally catastrophic impact and the large tsunami is about 1:20,000 that an individual will die as the result of the impact of a comet or asteroid. For our nominal range in threshold energies (5×10^4 to 5×10^6 MT), the probability of death from impact ranges from about 1:5,000 to 1:100,000. For most of the Earth's population, this risk is small compared to many other causes of death, both natural and accidental, but it is not smaller (at least in the economically advanced nations) than the risk associated with other natural disasters. For an average American, for example, the risk of death from an impact is greater than that from earthquake, flood, or severe storm, as is discussed in the next section.

Table 2 summarizes the effects of impacts as a function of energy from <10 MT to $>10^9$ MT. The most important conclusion from this analysis is that the hazard -- the annual equivalent mortality -- increases from small to large impacts across nearly this entire range of 8 orders of magnitude in energy. The power-law size-frequency distribution of the asteroid and comet population together with the physical consequences of the impacts results in a situation where the larger (and rarer) impacts are the most damaging, up to a few times the threshold for global catastrophe.

The nature of the hazard is further illustrated in Figures 2 and 3 (adapted from Chapman and Morrison 1993), which display schematically the dependence of risk on impact energy. Figure 2 shows the average anticipated number of fatalities per event; the solid line is calculated using nominal values for land impacts, and the dotted line suggests the (highly uncertain) fatalities associated with deep-ocean impacts. A possible energy range from 5×10^4 to 5×10^6 MT is shown for the transition from regional to global effects, at which point substantial fractions of the Earth's population will die in the aftermath of an impact. Figure 3 is similar, but in this case we illustrate the expected annual fatality rate as a function of impact energy.

IMPACT HAZARD COMPARED WITH OTHER HAZARDS

In a rational world, society's response to the threat of impact by an asteroid or comet should be evaluated against other hazards that people face. In a typical year, nearly 1,000 people in the United States alone are killed as a result of being struck by a falling object. None of these objects, at least so far, has been a meteorite, comet, or asteroid! Some causes of mortality are much more common than falling objects; illness, war, pestilence, and famine head the list. Other potential causes of mortality have received prominent attention in the news media as well as government action even though nobody has actually died; reported deliberate tampering with imported grapes is one example from several years ago. In this section, we put the impact hazard into perspective by comparison with other causes of mortality, particularly those that are the closest analogues -- natural disasters.

Current Risk Statistics

In the United States, motor vehicle accidents lead the list of hazards, followed by

falls, poisoning by solids or liquids, drowning, fires and burns, suffocation, firearms, and poisoning by gas (Anonymous 1989). Still other dangers are widely feared even though fewer than 100 people die per year in the U.S. (e.g. dog bites, lightning, poisonous snakes and spiders). All accidental deaths combined account for approximately 100,000 deaths/yr in the United States (half are motor-vehicle related), but they pale in comparison with cardiovascular and malignant diseases as a cause of mortality (Anonymous 1991).

Table 3 illustrates some selected causes of mortality for the world population. The closest analogues for the impact hazard are other low-probability/high-consequence disasters. These include natural disasters, which have accounted for only about 4% of the 150,000,000 catastrophic deaths in the world during the 20th century (Pike 1991a), and technological accidents. In contrast, the vast majority of catastrophic deaths are attributable to longer-acting famine, epidemics, and wars, which are less instructive as analogues to the impact hazard.

Mortality rates due to natural disasters vary greatly from one part of the world to another. For example, the contemporaneous severe flooding of the summer of 1993 in the United States and India resulted in thousands of deaths in India but only a handful in the U.S. In the United States during the second half of the 20th century, natural disasters rank quite low as causes of mortality; for example, during the period 1966-1989, the annual death toll in the United States has averaged 142 from floods, 80 from tornados, and 27 from hurricanes (Anonymous 1991), with earthquakes and tsunamis ranking even lower. Strict regulations and preventative measures have also reduced technological accidents (e.g. explosions, mining disasters, and building fires) to a very low level in the U.S. during recent years, despite some notable technological accidents during the first half of the twentieth century.

On a global scale, however, natural disasters are much more important causes of mortality than recent experience in the United States would suggest. In the developing world, natural disasters have been and remain a major cause of mortality. Eight natural disasters occurred between 1900 and 1985 that killed between 100,000 and 2,000,000 each (3 earthquakes, 3 floods, 1 cyclone, and 1 landslide, which occurred in China, Bangladesh, and Japan) (Anonymous 1988). This average 10 year interval between huge natural disasters may be compared with the thousands of years between asteroid impacts large enough to cause comparable fatalities.

Qualitative Distinction of Large Impacts

While cosmic impacts do not compete with other natural disasters at smaller sizes, they can dominate the risk statistics at large sizes. In this way the impact hazard appears to be qualitatively different from other natural disasters. As we have already noted, the size distribution of asteroids and comets follows roughly a power law, and continues without bound to at least 10 km diameter (the approximate size of the largest known Earth-crossing asteroid) and probably to much larger sizes (comets are known, although not now in Earth-approaching orbits, that extend to over 100 km in size). This size distribution is what allows the finite possibility of an impact destroying civilization, or even killing everyone on the planet.

In contrast to the impact hazard, it appears that other natural hazards are bounded at magnitudes that do not lead to global catastrophe. The greatest fatalities from historic natural disasters have killed only tiny fractions of the world's population: earthquake (2 million), cyclone (300,000), landslide (100,000), tsunami (100,000), volcano (30,000 immediate deaths, 92,000 immediate plus secondary deaths), and avalanche (20,000) (Cornell 1982; Encyclopedia Britannica, 15th ed.). Of course, asteroid impact has killed nobody over the same period, so

we must look at the fundamental nature of other natural disasters to see if they are bounded.

It is difficult to compare the magnitudes of different natural disasters because their effects on populations and infrastructure are so different. For example, the very largest earthquakes in history (Richter scale ~ 9) have estimated seismic energies equivalent to a few hundred MT. Yet that energy is manifested in a way -- shaking of the ground -- that is very effective at killing people who live in poorly constructed homes or in hilly terrain subject to landslides. The Mt. St. Helens volcanic eruption has been estimated at ~ 15 MT, similar to the Tunguska impact. However, the greatest damage from volcanoes is not from the direct blast effects but from either ground-hugging pyroclastic flows or (depending on the specific form of the eruption) from the indirect environmental effects of dust and aerosols ejected into the lower atmosphere and stratosphere. The same is true of the impact hazard: whether the killing is due to local blast damage, tsunamis, or starvation due to global climatic effects depends on the magnitude and location of the impact.

The frequency-magnitude distribution is poorly known for the largest natural disasters. For earthquakes with Richter magnitude > 6 , the cumulative frequency diminishes nearly a factor of 10 for each increase of 1 (corresponding to 32-fold increase in energy) in magnitude. This means that the very largest earthquakes are responsible for nearly all of the seismic energy released on our planet, a situation -- like the impact hazard -- that emphasizes the catastrophic potential of the biggest events. Earthquakes with a seismic moment exceeding 10^{31} dyne centimeters (roughly, Richter scale 9) may occur about once a century somewhere on Earth. Historical records during previous centuries are too imprecise to demonstrate an upper limit to earthquakes. However, unlike asteroidal or comet impact energies, there must be an upper bound to the energy of earthquakes, set by the geometry of seismic zones and the strength of crustal

material (Chinnery and North 1975).

In general, it is not possible for unlimited strain or unlimited pressure to build up in the Earth's crust. Earthquakes and volcanic explosions are the mechanisms of relief. One must expect that there are upper bounds to the magnitude of volcanic explosions just as there must be upper bounds to earthquakes. The largest explosive volcanic event noted in the recent geological record was the Toba, Sumatra, event 75,000 years ago, with eruptive volumes at least a thousand times greater than Mt. St. Helens (Rampino *et al.* 1985; Sigurdsson 1990). There are great uncertainties about how effective such an explosion might be in producing a global climatic shock, but it is plausible that the greatest volcanic events could rival the effects of impacts by asteroids up to 1 km in diameter. However, the energies of volcanic explosions do not approach the magnitude of impacts by teraton-scale cosmic projectiles.

In human history, the greatest mortality from natural disasters has been from effects of extreme weather: windstorms and flooding. There certainly must be limits to the largest possible atmospheric storms. Tornados exemplify a dangerous meteorological phenomenon that is limited in scale to widths of <2 km, and other weather phenomena also have characteristic scales that are not exceeded. There also are limits to the magnitude of weather-related flooding. On timescales related to our personal experiences, the biggest floods generally do more damage than the cumulative effects of all smaller floods. Nevertheless, the natural scale of storms, the vertical structure of the atmosphere, and the moisture holding capacity of air all limit the quantity of rain that could theoretically fall within a given watershed.

Independent of the maximum energy or destructive power of different modes of natural disasters, they all -- with the possible exception of explosive volcanism -- differ from the globally catastrophic impact hazard in one important

respect: they are localized. Even tsunamis, which can extend their reach around the world along ocean coastlines, cannot touch continental interiors. No matter how large the non-impact natural catastrophe, many nations would be unscathed by earthquakes, floods, or storms of the most exaggerated possible scale. Impacts are unique in producing global consequences at a scale that could threaten the entire world's population simultaneously.

Comparative Risk Summary

This discussion of comparative risk can be summarized by the schematic illustration in Fig. 4. For several representative natural disasters and accidents, Fig. 4 presents the world fatality rate (deaths/yr) as a function of the number of deaths per catastrophic event. At the left (1 death per event), automobile accidents dominate the mortality. Human caused catastrophic accidents (airliner crashes, mine explosions, Chernobyl) are of much smaller overall consequence, although individual events killing hundreds or thousands of people at once have great headline-producing potential. Natural disasters (especially floods, earthquakes, and cyclones) dominate the mortality for catastrophes that exceed about 100 fatalities/event. Tunguska-like impacts have an expected mortality rate hundreds of times less than those caused by these more familiar natural disasters.

As natural disasters approach their upper limits (at several million fatalities per event), cosmic impacts, occurring only once every 100,000 years, begin to rival the mortality potential of natural disasters. Near the threshold for global catastrophe, impact has the unique potential for killing much of the world's population, and the probability of that happening (low) multiplied by the enormous mortality yields an average fatality rate that probably exceeds that of other natural disasters of any scale.

PUBLIC PERCEPTIONS OF THE HAZARD

Whereas a great deal of study has been devoted to defining and characterizing the impact hazard, little effort has thus far been spent to understand how laypeople perceive this threat. Public perceptions of impact risks are important for several reasons. First, our general understanding of human response to risk will undoubtedly benefit from studies of people's response to this hazard, which is unique in its combination of very low probability and very great consequence. Second, public attitudes and perceptions influence government policies toward risk management. Third, understanding how the hazard is perceived is essential for effective education and communication efforts.

History of Risk-Perception Research

Social scientists have been studying risk perception extensively during the past 15 years, examining the opinions that people express when they are asked to evaluate various natural and technological hazards. In these studies, researchers have sought to discover what people mean when they say that something is (or is not) "risky" and to determine what factors underlie these perceptions.

This research has demonstrated that the concept of risk means different things to different people. When technical experts judge risk, their responses correlate highly with expected annual fatalities or with probabilities of mortality, such as those discussed in the previous section of this chapter. However, the risk perceptions of laypeople are sensitive to factors other than fatalities, such as catastrophic potential, dread, controllability, and threat to future generations (Slovic 1987). As a result, public perceptions often differ considerably from judgments made by experts.

Research has compared public perceptions of risk and benefit from a great

many activities, but most instructive for our purposes are the perceptions associated with radiation and chemical technologies. Nuclear power has a very high perceived risk and low perceived benefit, whereas diagnostic x-rays have the opposite pattern. Similarly, non-medical sources of exposure to chemicals suspected of being toxic (pesticides, food-additives, alcohol, cigarettes) are seen as very low benefit and high risk, while medical chemicals (prescription drugs, antibiotics, vaccines) are generally perceived as high benefit and low risk, despite the fact that they can be very toxic substances. The favorable attitudes and acceptance of risks from x-rays and medicines demonstrate that perception of risk is conditioned by the context in which exposure occurs and the degree of trust in those responsible for managing the hazard; e.g., the medical profession vs. industry.

Will the Public be Concerned About the Impact Hazard?

If a credible prediction of a catastrophic impact were made, the public would undoubtedly be quite frightened. Absent such a specific prediction, how might we expect people to respond to the statistical threat of impact, as it is reported in the news media? Will their level of concern be great enough to induce them to support expenditure of public funds to detect threatening asteroids or comets? In the absence of data on public perceptions regarding this specific hazard, we can find reasons from previous experience to predict both lack of concern and a high degree of concern.

Reasons for expecting lack of concern and possible opposition to large expenditures are the following:

- Natural hazards such as impacts tend to be less frightening than technological hazards (Erickson, 1990). People perceive nature as benign and react rather apathetically to the threat from natural hazards (Burton, Kates, and White 1978).

Personal experience of a natural disaster is usually necessary to motivate action to reduce future risks.

- Probabilities are typically more important than consequences in triggering protective actions (Slovic *et al.* 1977; Kunreuther *et al.* 1978); hence the impact probabilities may be too low and the risk apparently too remote in time to trigger concern, in spite of their high consequences.
- People are often insensitive to very large losses of life. We will expend great effort to save an individual life, but in a context of impersonal numbers or statistics, the lives of individuals lose meaning. A threat that puts 100 people at risk is likely to be seen as quite serious, but we will probably respond identically to a hazard that threatens 2200 people and one that threatens 2300 (Kahneman and Tversky 1979).
- People tend to prefer 100% insurance against a threat (Slovic *et al.* 1977; Kahneman and Tversky 1979). If impact defense systems cannot provide 100% protection, they may be undervalued.

On the other hand, there are also reasons to expect the public to be concerned enough about impact hazards to support action:

- The risk is demonstrable (it happened to the dinosaurs) and is endorsed by credible scientists.
- The potential consequences of large impacts are uniquely catastrophic and are qualitatively different from other natural hazards.
- The probabilities of catastrophic impacts, while small, are not trivial. Considerable public funds are already being spent to deal with risks of even lower

probability, such as death or injury from tornadoes or terrorist attacks.

- Unless action is taken, the risk is unknown and uncontrollable. Lack of control, dread, and catastrophic potential are all qualities associated with high risk perception and strong desire for action to reduce risk (Slovic 1987).

In addition, we can expect increased public awareness of the hazard as the media report discoveries of new asteroids and comets and more frequent "near misses". The collision of Comet Shoemaker-Levy 9 with Jupiter in July 1994 is sure to draw public attention to the general impact issue (Chapman 1993). This awareness may lead to diverse reactions, ranging from incredulity that anyone could be concerned about such unlikely events to calls for public action to avert or reduce the risks.

Exploratory Research on Public Attitudes and Perceptions

Just as astronomers need observational data to determine the probability of asteroidal impact, social scientists need data to improve their understanding of risk perception and to forecast public attitudes toward impact detection and defense policies. Fortunately, data on public perceptions are relatively easy to acquire, by means of survey techniques. We now summarize the results from a two-part survey of attitudes and perceptions of the impact hazard (Slovic and Peterson, 1993), carried out with a sample of 200 college students shortly after the *Newsweek* cover story on the impact hazard (November 1992). The participants were students at the University of Oregon with a median age of 20. Before answering, each respondent was asked to read a seven-page briefing consisting of media articles on the impact threat. Despite the extensive recent media coverage of this topic, only about 25% of the respondents said they had heard about this hazard prior to participating in this study.

Part A of the survey asked people to rate 24 hazards on each of 11 scales. The hazards included cigarette smoking, motor vehicle accidents, AIDS, floods, earthquakes, nuclear power plant accidents, and an asteroid hitting the Earth. The scales include perception of risk to the American public, immediacy of risk, severity of consequences, ability of scientists to control the risk, threat to future generations, and potential for global catastrophe. Part B asked respondents to agree or disagree with a wide range of statements about the impact hazard dealing with such items as perceived risk, immediacy of the threat, support for establishing a tracking network, and attitudes toward development of a defense system.

The results of this survey showed that the impact risk ranks 14th out of 24 with regard to mean rating of risk to the American public. The impact risk was judged higher than risks from prescription drugs, medical x rays, bacteria in food, floods, and air travel, but lower than risks from earthquakes and hurricanes. Impact risks were rated as extreme with regard to being unknown to scientists and the public, distant in time (non-immediate), uncontrollable, and catastrophic. There was modest support for detection efforts but considerable opposition to use of weapons in space, even to deflect a threatening asteroid. The survey respondents indicated a strong preference for collecting more data on the risk before developing a defense system. Support for asteroid tracking and defense systems was greatest among those who tended to trust both the scientific community and the government, and it was lowest among those concerned about militarization of space and those who felt that the next major impact is likely to occur very far in the future.

It is of interest to look at the attitudes of the respondents toward the immediacy of the impact threat. Only 6% believed that a catastrophic impact would occur in the next 50 years; 35% believed that one would occur more than 1000 years from now, and 34% denied that a threatening asteroid "could appear

within the next 20 years." When asked to interpret the statement that "scientists say that a civilization-threatening asteroid impact can be expected every 300,000 to 1,000,000 years", 56% felt that "we don't really have to worry about this threat in our own lifetimes", 38% agreed with the assertion that "no such asteroid will appear for thousands of years", and 33% agreed with the assertion that "this statement is not believable because no one can predict the future for hundreds of thousands of years".

While these results must be interpreted with caution because of the small and nonrepresentative sample used, they appear to demonstrate at least two interesting results. First is the perhaps surprising degree of credibility of the scientists who are expressing concern about this threat. Apparently the media have treated these activities in a positive light and have not interpreted these public statements as particularly ill-founded or self-serving. Second is the general problem of interpreting the immediacy of low-probability events. Considering the number of our scientific colleagues who have interpreted long average spacing between impacts to mean that this is a problem for future generations rather than the present, it should not surprise us that a sample of laypersons, most of whom are being exposed to this discussion for the first time, should be similarly confused.

PROPOSED SPACEGUARD SURVEY

A number of options exist for dealing with the impact hazard, ranging from doing nothing (a reaction consistent with dismissal of the risk as negligible) to the development of elaborate planetary defense systems, such as the Spaceguard System envisioned in the science fiction novel *Rendezvous with Rama* (Clarke 1973) or the *ad hoc* defense against a fictitious impact from asteroid Icarus studied 25 years ago at MIT (Kleiman 1968). Many of the chapters in this book

are devoted to various aspects of possible defenses against asteroidal or cometary impacts. One of the unique aspects of this particular natural hazard is that it is possible to defend against incoming projectiles and, at least in principle, to avoid disaster entirely by deflecting any threatening object before it can strike the Earth.

Effective defense against asteroids and comets requires advanced knowledge of their orbits; the greater the warning time, the smaller the velocity change that must be imparted to render a threatening object harmless (Ahrens and Harris 1992; Ahrens *et al.*, this book). Even if orbital deflection is impracticable, advanced warning would permit efforts to mitigate the damage of an impact, for example by evacuating population from the probable target area. The essential first step in any program to deal with the impact hazard is a system to discover and track Earth-crossing asteroids and comets.

One approach to such a survey requirement was developed by the NASA Spaceguard Survey Working Group (Morrison 1992) at the request of the U.S. Congress. The Spaceguard System discussed in that report is an international survey network of ground-based telescopes equipped with arrays of CCD detectors and sophisticated real-time data analysis systems (Gehrels 1991; Rabinowitz 1991). Such a network could increase the monthly discovery rate of Earth-crossing asteroids from a few to as many as a thousand (Bowell and Muinonen, this book). Implementation of this or a similar system would reduce the time-scale required for a nearly complete census of large (> 1 km diameter) Earth-crossers from several centuries (at the current discovery rate) to about 25 years.

The proposed Spaceguard Survey is optimized for the detection of Earth-crossing asteroids with diameters > 1 km, because these are the smallest asteroids that might threaten a global catastrophe (taking the range of uncertainty to be 5×10^4 to 5×10^6 MT of energy). As shown by the hazard analysis presented in this paper and its antecedents, the greatest risk is associated with objects above

the global threshold. In addition, it is only these larger impacts that threaten society or, in extreme cases, the survival of the species. In practice, such a magnitude-limited survey would also discover many more smaller objects, but it would not attempt completeness for diameters < 1 km within 25 years. If the survey were continued, however, it would eventually catalogue virtually all asteroids above the atmospheric cutoff (10 MT). The limitations of surveys of this sort are discussed in detail in this book by *Bowell and Muinonen*.

The survey approach typically leads to discovery of an Earth-crossing asteroid many orbits in advance of any actual impact threat. Thus a warning of a decade or more would be provided, independent of the size of the asteroid (*Ostro et al. 1991; Yeomans et al. 1992*). Such a program could deal effectively with the threat of asteroidal collision. Only in the unlikely event that an object is predicted to strike the Earth is it necessary to take additional steps toward interception or deflection. However, no survey of this sort can provide similar long-term warning of cometary impact. Roughly 25% of the total impact risk is associated with previously unknown comets that descend into the inner solar system with little warning. Even the most elaborate telescopic system, either ground-based or orbital, cannot guarantee detection of such an incoming comet with more than about a year's warning (*Morrison 1992; Bowell and Muinonen, this book*). In practice, the great majority of the objects discovered by Spaceguard will be NEOs with diameter less than 1 km, which will be acquired at a rate of several hundred per month.

Search programs such as Spaceguard, which are based on current technology, represent efforts at risk reduction. They can provide advanced warning of most potentially catastrophic impacts, but not of all. We are unlikely to reduce the level of risk close to zero without the commitment of immense resources, a commitment that is surely inconsistent with the level of additional security that is achieved.

CONCLUSIONS

While there is no longer any question that cosmic impacts have been important in the history of life on Earth, calculations of the contemporary hazard remain uncertain. While the average flux of incoming bodies is known to within a factor of two over a range of some 8 orders of magnitude in energy, there remain substantial uncertainties about possible "comet showers" or other non-random clustering of events. As a result of recent work we now have a good understanding of the degree of protection against smaller impacts offered by the Earth's atmosphere, but our understanding of the physical implications of impact becomes weaker as we move toward the largest (and most dangerous) cases. The greatest uncertainties, however, concern the ecological effects of large impacts (for example on agricultural production), and the possible implications for human society.

In the analysis presented here we have adopted a nominal energy threshold of 5×10^5 MT (Toon *et al.* this book) for transition to large-scale global effects, where a globally catastrophic impact is defined as one that leads to mass starvation and mortality of >25% of the world's human population. For purposes of calculation, we have carried uncertainties of a factor of ten in this threshold energy. Similar but slightly larger threshold uncertainties were used by Chapman and Morrison (1993). While we cannot demonstrate that this energy range encompasses the full spectrum of possibilities, we assert that it conforms to common sense: no mechanisms have been suggested that would produce significant climate perturbations for impacts of less than 10^5 MT (1 km diameter for typical asteroids), while an energy of 10^7 MT (4 km asteroid) is only one order of magnitude less than some estimates of the K/T impact energy, which certainly represented major "overkill" with respect to the phenomena that lead to what we define as a global catastrophe. Our adopted range in threshold energies corresponds to average intervals between globally catastrophic events of 100,000

to several million years.

Even with the present uncertainties of the risk analysis, it is possible to derive several robust conclusions of a qualitative or semi-quantitative nature. We conclude this overview with a summary of these conclusions.

- Impacting objects with energy of less than about 10 MT pose little danger; only metallic bodies in this size range can penetrate to the surface, and history demonstrates the rarity of significant mortality from iron meteorite falls. Only in the case of possible misidentification of a megaton-range atmospheric explosion with a nuclear attack should such impacts concern us.

- Over a range of several orders of magnitude in energy, from the threshold for atmospheric penetration to the threshold for global catastrophe, the impact hazard to humans is smaller than the hazards associated with many other natural risks, such as those of earthquakes, floods, volcanic eruptions, and severe storms. Because of the concentration of human population near coastlines, the greatest danger is associated with tsunamis generated by large impacts in deep ocean.

- Above some threshold energy (probably between 5×10^4 and 5×10^6 MT), impacts produce global environmental degradation sufficient to lead to massive crop failures and widespread mortality. Impacts just above this threshold dominate the hazard, with risks that are probably an order of magnitude higher than the cumulative effects of all smaller impacts. These impacts are also qualitatively different from other natural hazards, in that they have the potential to disrupt society as well as kill billions of people. However, such globally catastrophic impacts are rare, perhaps occurring only about twice per million years.

- As an extreme example of low-probability/high-consequence disasters,

large impacts are without precedent in terms of public perception and public policy. Issues associated with cosmic impacts and possible defenses against them are receiving public attention for the first time. With increasing public awareness, demands may grow for action to deal with the impact hazard.

- Over the entire range of impact energies considered, the risk level increases with the energy (size) of the impact. Therefore the most prudent and cost-effective strategies deal first with the largest projectiles.
- Any program to mitigate the impact hazard should begin with a comprehensive survey of Earth-crossing asteroids (such as the proposed Spaceguard Survey). Such a survey would provide decades of warning for asteroidal impacts. Better understanding of the numbers, orbital distributions, and physical properties of asteroids and comets are required in order to define an effective defense system.

ACKNOWLEDGEMENTS

We are grateful to our colleagues on the Spaceguard Survey Working Group and to others with whom we have discussed various aspects of the impact hazard over the past three years; we have benefitted greatly from these exchanges of views. We especially thank Richard Binzel, Edward Bowell, Alan Harris, Steven Ostro, Gene Shoemaker, Brian Toon, and Kevin Zahnle for their insightful comments and critiques of previous versions of this work, and Gregory Canavan, Jack Hills, and John Pike for sharing their results with us in advance of publication. This research was supported in part by

BIBLIOGRAPHY

Ahrens, T.J. and W.A. Harris (1992). Deflection and fragmentation of near-Earth asteroids. *Nature* 360: 429-443.

Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel (1980). Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208: 1095-1108.

Anonymous (1988). *World Map of Natural Hazards*. Munchener Ackversicherungs Gesellschaft, Munich.

Anonymous (1989). *Accident Facts*. National Safety Council, Chicago.

Anonymous (1991). *Statistical Abstract of the United States 1991*. U.S. Bureau of the Census, Washington.

Burton, I., R.W. Kates, and G.F. White (1978). *The Environment as Hazard*. Oxford University Press, Oxford.

Cepplecha, Z. (1992). Earth influx of interplanetary bodies. *Astron. Astrophys.* 263: 361-366.

Chapman, C.R. (1993). Comet on target for Jupiter. *Nature* 363: 492-493.

Chapman, C.R. and D. Morrison (1989). *Cosmic Catastrophes*. pp302. Plenum Press, New York.

Chapman, C.R. and D. Morrison (1993). Hazard of impacts on Earth by asteroids and comets. Submitted to *Nature*.

Chinnery, M.A. and R.G. North (1975). The frequency of very large earthquakes. *Science* 190, 1197-1198.

Chyba, C.F. (1993). Explosions of small Spacewatch asteroids in the Earth's atmosphere. *Nature* 363: 701-703.

Chyba, C.F., P.J. Thomas, and K.J. Zahnle (1993). The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid. *Nature* 361: 40-44.

Clarke, A.C. (1973). *Rendezvous with Rama*. Ballantine Books, New York.

Clube, V. and B. Napier (1990). *The Cosmic Winter*. pp307. Blackwells, Oxford.

Cornell, J. (1982). *The Great International Disaster Book, 3rd edition*. Scribners, New York.

Covey, C., S.J. Ghan, J.J. Walton, and P.R. Weissman (1990). Global environmental effects of impact-generated aerosols: Results from a general circulation model. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 263-270.

Erickson, K. (1990). Toxic reckoning: business faces a new kind of fear. *Harvard Business Review* (Jan-Feb issue), 118-126.

Gehrels, T. (1991). Scanning with charge coupled devices. *Space Sci Rev.* 58: 347-375.

Gilmore, I., W.S. Wolbach, and E. Anders (1990). Early environmental effects of the terminal Cretaceous impact. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 383-390.

Glasstone, S. and P.J. Dolan (1977). *The Effects of Nuclear Weapons, 3rd edition*. U.S. Government Printing Office, Washington.

Grieve, R.A.F. (1987). Terrestrial impact structures. *Annual Rev. Earth Planet. Sci.* 15: 245-270.

Harwell, M.A. and T.C. Hutchinson (1989). *Environmental Consequences of Nuclear War II: Ecological and Agricultural Effects, 2nd edition*. Wiley and Sons, New York.

Hildebrand, A.R. *et al.* (1991). ----- *Geology* 19: 867-871.

Hills, J.G. and M.P. Goda (1993). The fragmentation of small asteroids in the atmosphere. *Astron. J.* 105: 1114-1144.

Hoffman, M.S. editor (1990). *World Almanac*. Pharos Books, New York.

Kahneman, D. and A. Tversky (1979). Prospect theory: An analysis of decision under risk. *Econometrica* 47: 263-291.

Kleiman, L.A., editor (1968). *Project Icarus*. pp162. MIT Press, Cambridge.

Kopec, R. (1971). Global climate change and the impact of a maximum sea level on coastal settlement. *J. Geography* xx: 541-550.

- Krinov, E.E. (1963). The Tunguska and Sikhote-Alin meteorites. In *The Moon, Meteorites, and Comets* (B.M. Middlehurst and G.P. Kuiper editors): 208-234. University of Chicago Press, Chicago.
- Krinov, E. (1966). *Giant Meteorites* (translated by J. Romankiewicz). Pergamon Press, Oxford.
- Kunreuther, H. et al. (1978). *Disaster Insurance Protection: Public Policy Lessons*. Wiley, New York.
- Lewis, J.S. et al. (1982). Chemical consequences of major impact events on the Earth. In *Geological Implications of Impacts of Large Asteroids and Comets with the Earth* (L.T. Silver and P.H. Schultz editors), Geological Society of America Special Paper 190: 215-222.
- McFadden, L., D.J. Tholen, and G.J. Veeder (1989). Physical properties of Apollo, Aten, and Amor asteroids. In *Asteroids II* (R.P. Binzel, T. Gehrels, and M.S. Matthews editors): 442-467. University of Arizona Press, Tucson.
- Melosh, H.J. (1981). Atmospheric break-up of terrestrial impactors. In *Multi-Ring Basins* (P.H. Schultz and R.B. Merrill, editors). *Geochem. Cosmochim. Acta, Suppl. 15*: 29-35.
- Melosh, H.J. (1989). *Impact Cratering: A Geologic Process*. pp245. Oxford University Press, New York.
- Morrison, D., editor (1992). *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop*. Unpublished NASA report.
- Morrison, D. (1993a). An international program to protect the Earth from impact catastrophe: Initial steps (IAA-92-0226). *Acta Astronautica* 30: 11-16.
- Morrison, D. (1993b). The impact hazard. In *Proceedings of the Near-Earth Object Interception Workshop* (G.H. Canavan, J.C. Solem, and J.D.G. Rather editors): 49-61. Los Alamos National Laboratory LA-12476-C.
- Morrison, D. and C.R. Chapman (1992). Impact hazard and the international spaceguard survey. In *Observations and Physical Properties of Small Solar System Bodies* (A. Brahic, J.-C. Gerard, and J. Surdej editors): 223-229. Institut d'Astrophysique, Universite de Liege, Belgium.
- Ostro, S.J. et al. (1990). Radar images of asteroid 1989PB. *Science* 248: 1523-1528.

- Ostro, S.J. *et al.* (1991). Asteroid radar astrometry. *Astron. J.* 102: 1490-1502.
- Ostro, S.J. *et al.* (1993) ----- *Bul. American Astron. Soc.* ??
- Pike, J. (1991a). The asteroid and comet impact hazard in the context of other natural and manmade disasters. Presented to the International Conference on Near-Earth Asteroids, San Juan Capistrano, 29 June 1991.
- Pike, J. (1991b). The sky is falling: The hazard of near-Earth asteroids. *The Planetary Report* 11: 16-19.
- Pike, J. (1993). The big splash. Unpublished manuscript.
- Rabinowitz, D.L. (1991). Detection of Earth-approaching asteroids in near real time. *Astron. J.* 101: 1518-1529.
- Rabinowitz, D.L. (1993). The size distribution of the Earth-approaching asteroids. *Astrophys. J.* 407: 412-427.
- Rabinowitz, D.L. *et al.* (1993). Evidence for a near-Earth asteroid belt. *Nature* 363: 704-706.
- Rampino, M.R. *et al.* (1985). ----- *Ann. Rev. Earth Planet. Sci.* 16: 73-99.
- Rampino, M.R., S. Sell, and R.B. Stothers (1988). Volcanic winters. *Annual Rev. Earth Planet. Sci.* 19: 383-422.
- Reynolds, D.A. (1993). Fireball observation via satellite. In *Proceedings of the Near-Earth-Object Interception Workshop* (G.H. Canavan, J.C. Solem, and J.D.G. Rather, editors), Los Alamos National Laboratory LA-12476-C: 221-225.
- Sekanina, Z. (1983). The Tunguska event: No cometary signature in evidence. *Astron. J.* 88: 1382-1414.
- Sharpton, V.L. and R.A.F. Grieve (1990). Meteorite impact, cryptoexplosion, and shock metamorphism: A perspective on the evidence at the K/T boundary. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 301-318.
- Sharpton, V.L. *et al.* (1992). New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary. *Nature* 359: 819-821.

Shoemaker, E.M., editor (1982). *Collision of Asteroids and Comets with the Earth: Physical and Human Consequences*. Unpublished draft NASA conference report.

Shoemaker, E.M. (1983). Asteroid and comet bombardment of the Earth. *Annual Rev. Earth Planet. Sci.* 11: 461-494.

Shoemaker, E.M., J.G. Williams, E.F. Helin, and R.F. Wolfe (1979). Earth-crossing asteroids: Orbital classes, collision rates with the Earth, and Origin. In *Asteroids* (T. Gehrels, editor), University of Arizona Press, Tucson.

Shoemaker, E.M. and R.F. Wolfe (1982). Cratering time-scales for the galilean satellites. In *Satellites of Jupiter* (D. Morrison, editor): 277-339. University of Arizona Press, Tucson.

Shoemaker, E.M., R.F. Wolff, and C.S. Shoemaker (1990). Asteroid and comet flux in the neighborhood of the Earth. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 155-170.

Sigurdsson, H. (1990). Assessment of the atmospheric impact of volcanic eruptions. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247, 99-110.

Slovic, P. (1987). Perception of risk. *Science* 236: 280-285.

Slovic, P., J.H. Flynn, and M. Layman (1991). Perceived risk, trust, and the politics of nuclear waste. *Science* 254: 1603-1607.

Slovic, P., B. Fischhoff, S. Lichtenstein, B. Corrigan, and B. Combs (1977). Preference for insuring against probable small losses: Insurance implications. *Journal of Risk and Insurance* 44: 237-258.

Slovic, P. and K. Peterson (1993). Perceived risk of asteroid impact. Unpublished manuscript.

Stothers, R.B. (1984). The great Tambora eruption of 1815 and its aftermath. *Science* 224: 1191-1198.

Swisher, C.C. et al. (1992). Coeval $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65 million years ago from Chicxulub crater melt rock and Cretaceous-Tertiary boundary tektites. *Science* 257: 954-958.

- Toon, O.B. *et al.* (1982). Evolution of an impact-generated dust cloud and its effects on the atmosphere. In *Geological Implications of Impacts of Large Asteroids and Comets with the Earth* (L.T. Silver and P.H. Schultz editors), Geological Society of America Special Paper 190: 187-200.
- Turco, R.P. *et al.* (1983). Nuclear winter: Global consequences of multiple nuclear explosions. *Science* 222: 1283-1292.
- Turco, R.P. *et al.* (1991). Nuclear winter: Physics and physical mechanisms. *Annual Rev. Earth Planet. Sci.* 19: 383-422.
- Weissman, P.R. (1982). Terrestrial impact rates for long and short-period comets. In *Geological Implications of Impacts of Large Asteroids and Comets with the Earth* (L.T. Silver and P.H. Schultz editors), Geological Society of America Special Paper 190: 15-24.
- Weissman, P.R. (1991). The cometary impactor flux at the Earth. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 171-180.
- Wetherill, G.W. (1989). Cratering of the terrestrial planets by Apollo objects. *Meteoritics* 24: 15-22.
- Wetherill, G.W. and Shoemaker, E.M. (1982). Collisions of astronomically observable bodies with the Earth. In *Geological Implications of Impacts of Large Asteroids and Comets with the Earth* (L.T. Silver and P.H. Schultz editors), Geological Society of America Special Paper 190: 1-14.
- Wolbach, W.S. R.S. Lewis, and E. Anders (1985). Cretaceous extinctions: Evidence for wildfires and search for meteoritic material. *Science* 230: 167-170.
- Yeomans, D.K. *et al.* (1992). Asteroid and comet orbits using radar data. *Astron. J.* 103: 303-317.
- Zahnle, K. (1990). Atmospheric chemistry by large impacts. In *Global Catastrophes in Earth History* (V.L. Sharpton and P.D. Ward, editors) Geological Society of America Special Paper 247: 271-288.

Table 1. Fatality Rates (Equivalent Annual Average Deaths) as a Function of Impact Energy

Type of Event	Energy (MT)	Diameter	World Deaths/yr
High atmosphere break-up	<10	<50m	<1
Tunguska-like events	10 - 2×10^3	50m - 300m	20
Sub-global land impacts	2×10^3 - 5×10^5	300m - 2km	30
Sub-global ocean impacts	2×10^3 - 5×10^5	300m - 2km	300 (?)
Threshold global catastrophes	5×10^5 - 10^7	2km-4km	3000
Mass extinction events	$> 10^7$	>4km	<300

Table 2. Summary of Impact Effects as a Function of Energy

Yield Y (MT)	Interval log T	NEO diam.	Crater D (km)	Consequences
<10				Upper atmosphere detonation of stones and comets; Only irons (<3%) penetrate to surface
10 ¹ -10 ²	3.0	75 m	1.5	Irons make craters (Meteor Crater); Stones produce airbursts (Tunguska). Land impacts destroy area size of city (Washington, Paris, Moscow)
10 ² -10 ³	3.6	160 m	3	Irons and stones produce groundbursts; Comets produce airbursts Land impacts destroy area size of large urban area (New York, Tokyo)
10 ³ -10 ⁴	4.2	350 m	6	Impacts on land produce craters; Ocean tsunamis becoming significant Land impacts destroy area size of small state (Delaware, Estonia)
10 ⁴ -10 ⁵	4.8	0.7 km	12	Tsunamis reach oceanic scales, exceed damage from land impacts. Land impacts destroy area size of moderate state (Virginia, Taiwan)
10 ⁵ -10 ⁶	5.4	1.6 km	30	Land impacts raise enough dust to affect climate, freeze crops. Ocean impacts generate hemispheric scale tsunamis. Global destruction of ozone. Land impacts destroy area size of large state (California, France, Japan)
10 ⁶ -10 ⁷	6.0	3 km	60	Both land and ocean impacts raise dust, impact climate. Impact ejecta are global, triggering widespread fires. Land impacts destroy area size of large nation (Mexico, India)
10 ⁷ -10 ⁸	6.6	7 km	125	Prolonged climate effects, global conflagration, probable mass extinction. Direct destruction approaches continental scale (Australia, Brazil, U.S.)
10 ⁸ -10 ⁹	7.2	16 km	250	Large mass extinction (K/T)
>10 ⁹				Survival of most lifeforms at risk.

Table 3. Ranked Selected Causes of Mortality (World)

- (1) Major Diseases (e.g. heart disease, cancer)
 - (2) War and genocide
 - (3) Epidemics
 - (4) Famine
 - (5) Other diseases (pulmonary, pneumonia, influenza)
 - (6) Major accidents (motor vehicle, falls)
 - (7) Suicide and homicide
 - (8) Cyclones and floods
 - (9) Lesser accidents (poisoning, fires/burns, suffocation)
 - (10) Earthquakes
 - (11) Rare accidents (falling object, railway accident, airliner crash)
 - (12) Globally catastrophic asteroid/comet impact
 - (13) Rare natural disasters (thunderstorms, volcanoes)
 - (14) Venomous bite or sting
 - (15) Tunguska-like locally catastrophic impact
 - (16) Airline hijacking aftermath
 - (17) Drinking water with EPA limit on TCE
-

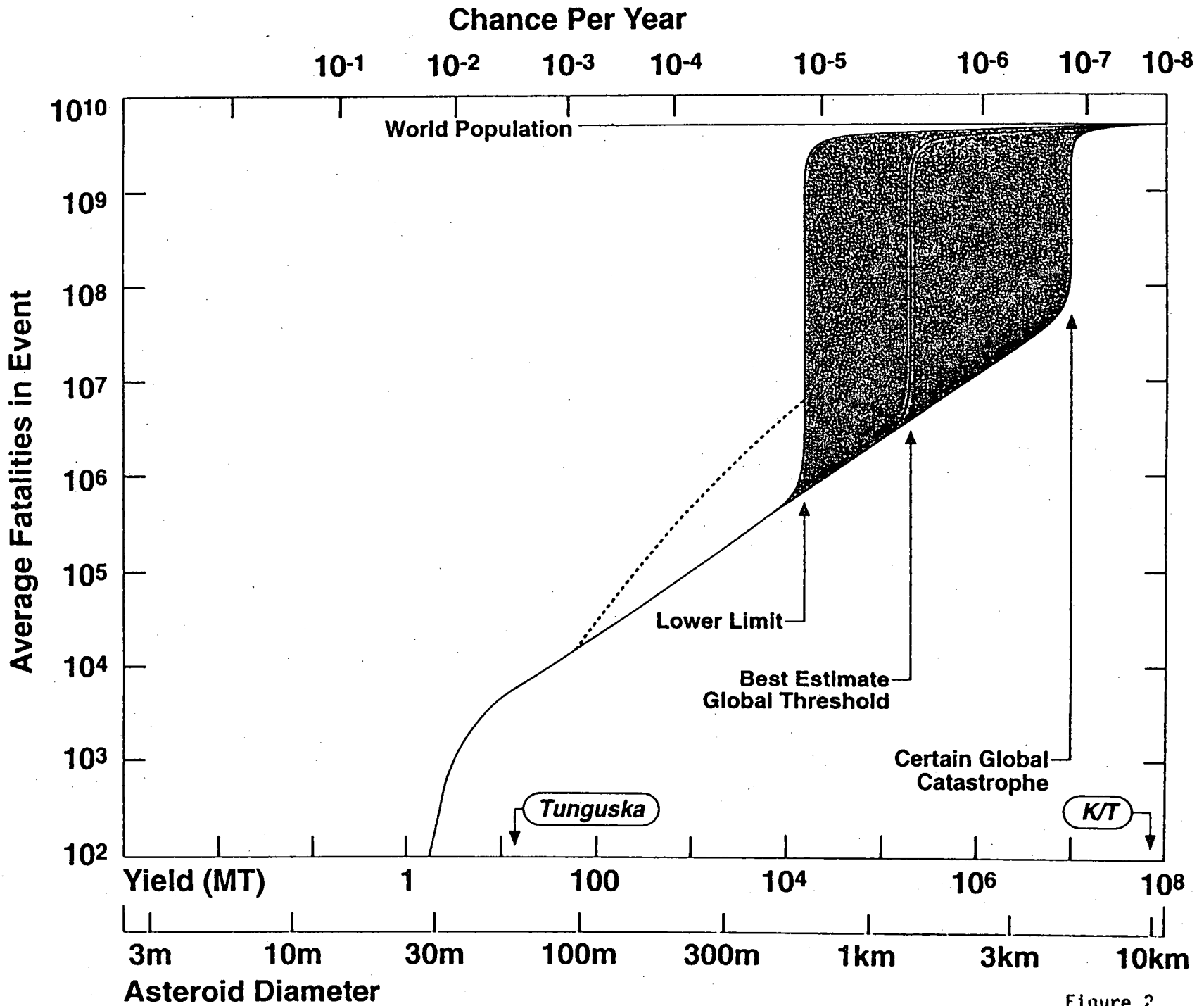


Figure 2

Note: Will be revised for this chapter.

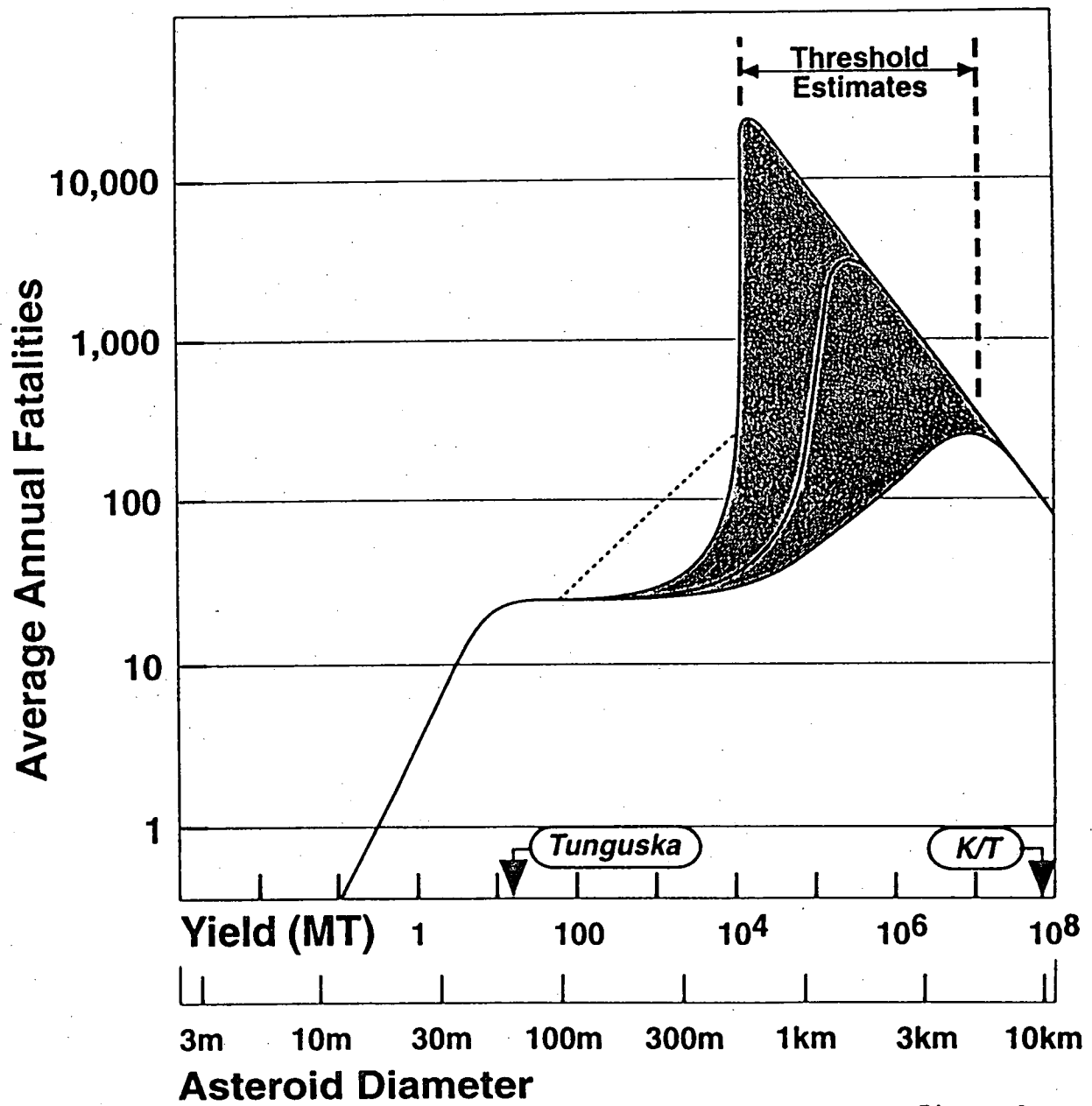


Figure 3

Note: Will be revised for this chapter.

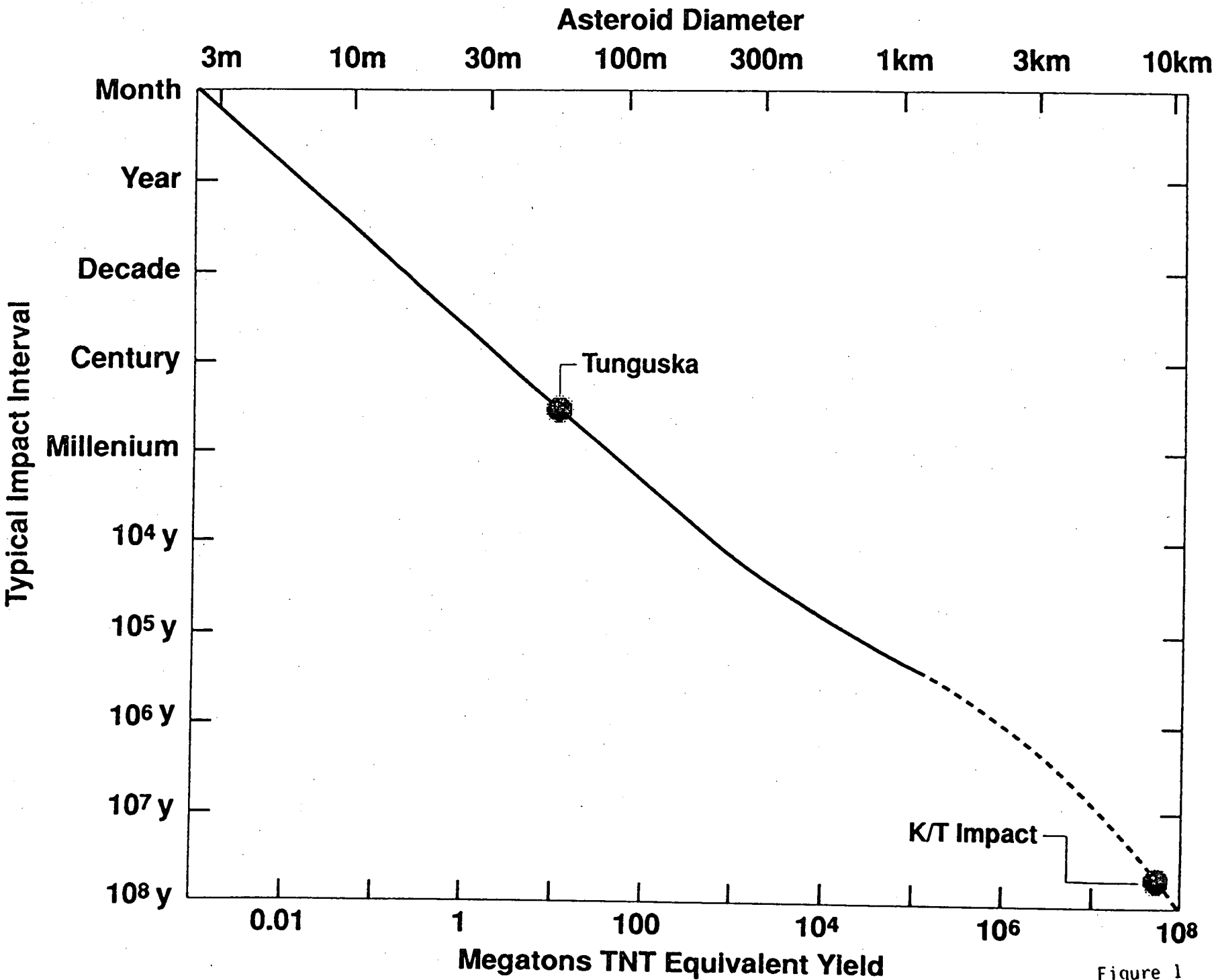
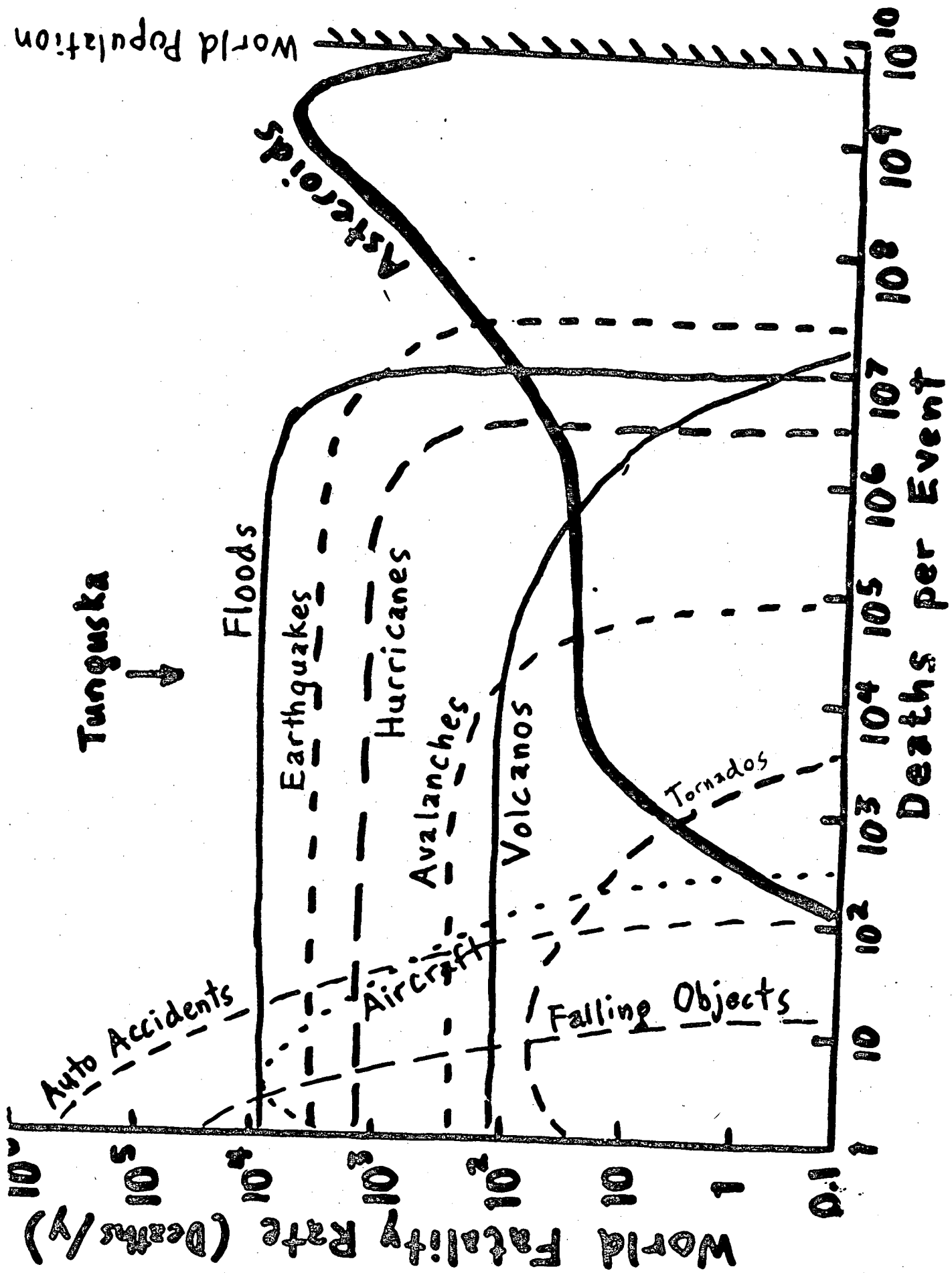


Figure 1



Note: Will be properly drawn.

Fig 4