From: Hazards Due to Comets and Asteroids, Tom Gehrels, editor, Tucson: University of Arizona Press, 1994.

THE IMPACT HAZARD

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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. For impacts below 10 MT (equivalent TNT) energy there is virtually no risk because 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. (see their Chapter) we estimate that this threshold lies between 10^5 and 10^6MT, with a nominal value of 3×10^5MT, corresponding to an average interval between events of about a third of one 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. Simple arguments suggest that expenditure of up to several hundred million dollars per year might be appropriate in dealing with such disasters. 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.

I. 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 yr 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 diameters of about 10 km, are not capable of significant geological or geophysical modification to the Earth. It is only because the biosphere is sensitive to relatively small impact perturbations that objects a few kilometers in diameter pose a substantial hazard.

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 (derived from the quantity of extraterrestrial material identified in the K/T boundary layer) of 10^{15} to 10^{16}kg. In this instance a relatively modest cratering event (produced by an object roughly the size of comet Halley) 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. 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 and Chapman 1992; Morrison 1993*a*, *b*; Chapman and Morrison 1994).

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.

II. 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^{-1}. 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^{-1} (McFadden et al. 1989; Chapters by Chapman et al., by Shoemaker et al., and by Rahe et al.).

The implied range in projectile density spans an order of magnitude, and the range in physical properties (e.g., strength) is likely to be greater yet. At smaller sizes (diameters less than a few hundred meters), 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, because the threat from larger impacts is related to the kinetic energy of the objects, which is typically nearly 2 orders of magnitude greater than an equivalent mass of TNT. In this chapter, we adopt this kinetic energy (expressed in megatons (MT) of TNT, where 1 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 (Chapter by Rabinowitz et al.); the largest is 1627 Ivar (diameter about 8 km, mass presumably about 10^{15}kg). Other still larger objects (up to 1036 Ganymed, with mass 2 orders 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 the size of Ivar or greater; for 1-km objects the completeness is less than 10% (Chapter by Bowell and Muinonen). From their large-amplitude variations in brightness, we know that many of these asteroids are irregular in shape (Chapters by Chapman et al. and by Ostro); at least two, 4769 Castalia (Ostro et al. 1990) and 4179 Toutatis (Ostro et al. 1993) appear to resemble contact binaries, consisting of two or more pieces in approximately a dumbbell configuration.

The integrated or average flux of meteoroids over the past 3 Gyr 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 the following references: Shoemaker et al. (1979, 1990); Shoemaker and Wolfe (1982); Weissman (1982); Wetherill and Shoemaker (1982); Shoemaker (1983); Wetherill (1989); Weissman (1991); Ceplecha (1992); and Chapters by Rabinowitz et al. and by Shoemaker et al.] For this discussion we adopt the size-frequency distribution for impactors with energies between 1 KT (kiloton) and 10^8MT published by Shoemaker (1983) and reproduced in the Spaceguard Survey Report (Morrison 1992). Recent observations of small (<10 MT energy) asteroids (Rabinowitz 1993; Rabinowitz et al. 1993) suggest a modest enhancement in the asteroid fluxes in this size range, but these objects (with the exception of rare irons) do not penetrate the atmosphere (Chyba 1993). Thus it is sufficient for our purposes to use the smooth curve (Fig. 1) based primarily on lunar crater data for estimations of impact hazard, which is in any case 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 than 25% of the asteroid flux at the same energy (Shoemaker and Wolfe 1982; Weissman 1982,1991; Chapter by Shoemaker et al.). 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; Chapter by Steel et al.), but for purposes of this chapter it is adequate, given other uncertainties, to treat impacts as occurring randomly in time.

III. 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 energy at which impacts begin to produce significant global environmental stress in addition to their direct blast damage.

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

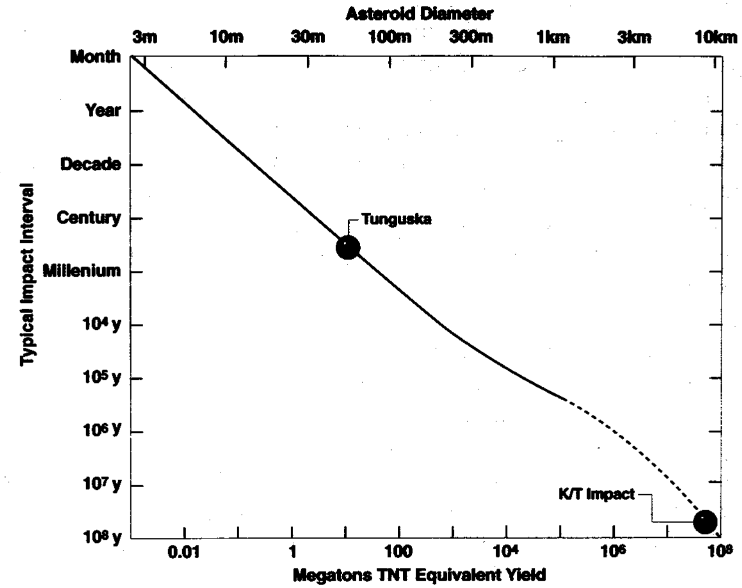

Figure 1. Cumulative energy-frequency curve for impacts on the Earth. The line is the "best estimate" from Shoemaker (1983) for the average interval between impacts equal to or greater than the indicated energy yield. Equivalent asteroid diameters are also shown, calculated assuming impact speed of 20 km s^{-1} and density of 3 g cm^{-3}. This is the same size distribution used in the Spaceguard Survey Report (Morrison 1992) and in our previous hazard discussion (Chapman and Morrison 1994).

the location of the impact. However, a threshold is useful for discussing the impact energies at which one class of physical effects gives way to another.

A. Penetration Through the Atmosphere

The atmosphere protects us from small impacts. The flux curve of Fig. 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; Chyba 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 30 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; Chyba 1993).

If a large meteoroid penetrates to the troposphere or actually strikes the surface at velocities of tens of km s^{-1}, the 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 topple trees over an area of nearly 10^5 hectares and a fireball that ignited fires over a smaller area near ground zero (Krinov 1966; Sekanina 1983; Pike 1991*a*, *b*; Chyba et al. 1993; Hills and Goda 1993). The yield of the Tunguska blast has been estimated at 10 to 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

$$A = 10^4 Y^{2/3} \quad (1)$$

where Y is the yield in MT and A is in hectares. 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 10^5MT, 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.

B. 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 (Chapters by Hills et al. and Toon et al.), 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 an oceanic impact has a substantial probability of reaching land and producing large-scale destruction. For yields greater than about 10^3MT, tsunamis associated with oceanic impacts contribute more to the hazard than the direct blast damage of impacts on land or in the continental margins.

C. Globally Catastrophic Impacts

At sufficiently great energies, an impact has global consequences. An obvious if extreme example is the K/T event 65 Myr ago. This impact released $>10^8$MT of energy and excavated a crater (Chicxulub in Mexico) at least 200 km in diameter (Sharpton and Grieve 1990; Hildebrand et al. 1991; Sharpton et al. 1992; Swisher et al. 1992; Chapter by Grieve and Shoemaker). 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 et al. 1985; Covey et al. 1990; Gilmore et al. 1990; Sharpton and Grieve 1990; Chapter by Toon et al.).

The K/T impact darkened the entire planet for many months and precipitated a general destruction of terrestrial ecosystems. Fortunately, events of this magnitude are exceedingly rare. 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 (1994) define a globally catastrophic impact as one that *results in 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; Sagan and Turco 1990), leading to widespread loss of agricultural production and resulting in mass starvation. 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 might 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.

D. 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 (Harwell and Hutchinson 1989; 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 in the Chapter by Toon et al. They identify 10^5MT 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 at least a regional scale and lead to significant crop loss. Effects of the Tambora explosion on climate and agriculture are discussed in some detail by Sagan and Turco (1990, pp. 99–101). At ten times larger enegy (10^6MT), for either land or ocean impacts, approximately 2×10^{-4}g cm^{-2} of submicrometer dust is injected into the atmosphere. The optical depth is about 10 with an atmospheric transmission of less than 1%, certainly sufficient to induce global freezing and large-scale crop loss. Toon et al. refer to the energy region between 10^5 and 10^6MT 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^{-1}, 10^6MT corresponds to diameter of about 2 km.

For purposes of this discussion, we adopt an energy of $10^{5.5\pm0.5}$MT (or about 3×10^5MT), in the middle of the "grey area" of Toon et al., as the nominal threshold for global catastrophe. For an asteroid with density 3 g cm^{-3} and an impact velocity of 20 km s^{-1}, the corresponding diameter is approximately 1.7 km. The average interval between impacts of this size or larger is 300,000 yr from Fig. 1.

It is important to recognize that the threshold for global catastrophe as we have defined it is uncertain by an order of magnitude in energy, and hence a factor of 2 in projectile diameter (from about 1 km to somewhat more than 2 km for a stony asteroid striking at 20 km s^{-1}). Our discussion attempts to be consistent with the chapter by Toon et al., but we cannot exclude more extreme values of the threshold. Chapman and Morrison (1994), who took a more conservative approach in their error analysis, considered a range from 1.5×10^4MT (about 0.6 km diameter for an asteroid) to 10^7MT (about 5 km diameter).

E. Misidentification of a Bolide

One additional source of hazard has frequently been discussed: the misidentification of a natural impact event with a nuclear attack (see, e.g., Shoemaker 1982 and Chapter by Tagliaferri et al.; see also "Erice Statement" quoted in Chapter by Morrison and Teller). 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 once or twice per century, but most such explosions take place at high altitude and have no significant 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; Beatty 1994; Chapter by Tagliaferri et al.). 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.

IV. 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.

A. 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:

$$N = 1 \times 10^3 Y^{2/3} \tag{2}$$

Thus an event with the energy of the Tunguska blast, occurring on land only once or twice per millenium, would on average cause about 14,000 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 millenium span of human history. (It is therefore not surprising that there is no historical record of such a catastrophe.)

B. 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; Chapter by Hills et al.). 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. The idea that the Mosaic Flood might have represented an impact-induced tsunami can be traced back as far as Laplace and even Halley (see the discussion of Sagan and Druyan [1985, pp. 276–279]).

To estimate the potential mortality from tsunamis, we use the expressions for wave height and depth of penetration into coastal plains given in the Chapter by Hills et al. 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 distance inland 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 10^5km. The associated area of coastal plains at risk from tsunamis, to a nominal width of 20 km, is 2×10^6km^2 or 2×10^8hectares. 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 a rough upper limit to the mortality that might be associated with impacts having energy in the gigaton range (10^3 to 10^5MT). 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, perhaps 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 10^4MT land impact is of order 10^6. In a similar analysis, Pike (1993) concluded that the hazard from open ocean impacts is 4 to 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.

C. Globally Catastrophic Impacts

Above the threshold energy for global catastrophe (3×10^5MT), the number of fatalities is (by definition) >1.5 billion. For example, for a land impact near 10^6MT, 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) at least 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 10^5MT 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; Chapter by Toon et al.). However, because such events are extremely rare, they constitute a smaller numerical risk than do impacts near the global threshold.

D. 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.

We can illustrate our approach with a simplified estimate of the total casualties in the regime of local or regional impacts on land by using a single power-law fit to the data of Fig. 1. Our reference is an "average Tunguska" impact by a 60-m diameter projectile with an energy yield of 15 MT and a resulting mortality of 14,000; an equal or larger event occurs on land about once every 600 to 700 yr. Over the impact range of interest (from the 10 MT atmospheric cut-off up to the globally catastrophic case), the differential impact frequency can be represented approximately by

$$f(D) = 10D^{-2} \tag{3}$$

where the frequency is in yr^{-1} and the asteroid diameter D is in meters. Using the expression given previously for the average deaths as a function of impact yield, we find that the mortality is related to the asteroid diameter by the expression

$$N(D) = 4D^2 \tag{4}$$

where N is the number killed and D is in meters.

With these approximations, the total mortality is found by integrating from the minimum diameter for penetration through the atmosphere (50 m) up to the size of interest (D_{max}).

$$N = \int_{50}^{D_{max}} N(D) f(D)\, dD = 40 \ln (D_{max}/50). \tag{5}$$

TABLE I

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

Type of Event	Energy (MT)	Diameter	World Deaths yr^{-1}
High atmosphere break-up	<10	<50 m	<1
Tunguska-like events	10–2×10^3	50 m–300 m	55
Sub-global land impacts	2×10^3–5×10^5	300 m–2 km	30
Sub-global ocean impacts	2×10^3–5×10^5	300 m–2 km	300 (?)
Threshold global catastrophes	10^5–10^6	1 km–2 km	3000
Mass extinction events	$>10^7$	>4 km	<300

From this expression, the total mortality for impacts on land from the 50-m atmospheric cut-off to the global threshold at 1.7 km is about 140 deaths per year.

To obtain a more accurate assessment of 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, each segment represented by a best-fitting power law (Chapman and Morrison 1994; Chapter by Harris et al.). The results are summarized in Table I. If the effects of tsunamis from ocean impacts is added, the equivalent annual casualties may rise to several hundred. All of these calculated values are long-term averages, and they all have substantial uncertainties. However, it is possible to draw some semi-quantitative conclusions from this analysis, as follows.

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^{-1} 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. 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 60 yr^{-1} for the world's present population (6 billion people killed per 10^8yr). 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 3×10^5MT, such events occur roughly three times per million years, implying a fatality rate of a few thousand per year. The annual risk per individual is thus somewhat smaller than one in a million. For comparison, the fatality rate for all impacts below the threshold is a few hundred per year, yielding an annual risk of the order of 10^{-7}.

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 (Chapman and Morrison 1994). For

TABLE II
Summary of Impact Effects as a Function of Energy

Yield Y (MT)	Interval log T	NEO diameter	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 the size of a 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 the size of a 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 the size of a moderate state (Virginia, Taiwan).
10^5–10^6	5.4	1.7 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 the size of a large state (California, France, Japan).
10^6–10^7	6.0	3 km	60	Both land and ocean impacts raise dust, change climate. Impact ejecta are global, triggering widespread fires. Land impacts destroy area the size of a 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				Threatens survival of all advanced forms of life.

our nominal range in threshold energies (10^5 to 10^6MT), the probability of death from impact ranges from about 1:10,000 to 1:40,000. 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 may be greater than that from earthquake, flood, or severe storm, as is discussed in the next section.

Table II summarizes the effects of impacts as a function of energy from <10MT 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 Fig. 2 (adapted from Chapman and Morrison 1994), which displays schematically the dependence of risk on impact energy. The lower panel 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 10^5 to 10^6MT 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. The upper panel illustrates the expected annual fatality rate as a function of impact energy.

E. Estimate of Economic Losses from Impacts

The primary concern about impacts is derived from their unique potential to kill a substantial fraction of the Earth's population and destabilize the global civilization. The hazard can also be analyzed in terms of its economic impact, however, and this approach may be useful in comparing it with other hazards. (Similar but more detailed economic arguments are given in the Chapter by Canavan.)

A simple estimate can be made of the economic cost of impacts in the regime between the atmospheric cut-off and the threshold for global catastrophe, if we assume that average economic loss, like average mortality, is proportional to the area of devastation. Only the multiplier is different. We assume that the total value of the world's developed property and economic infrastructure is $\$4\times10^{14}$ (Canavan 1993; Chapter by Canavan), to yield a total world value of approximately $\$1.5\times10^5$ per person.

For impacts with energies less than the global impact threshold, the approximate economic loss from impacts (in millions of dollars) is:

$$V = 6\ln(D_{\max}/50). \qquad (6)$$

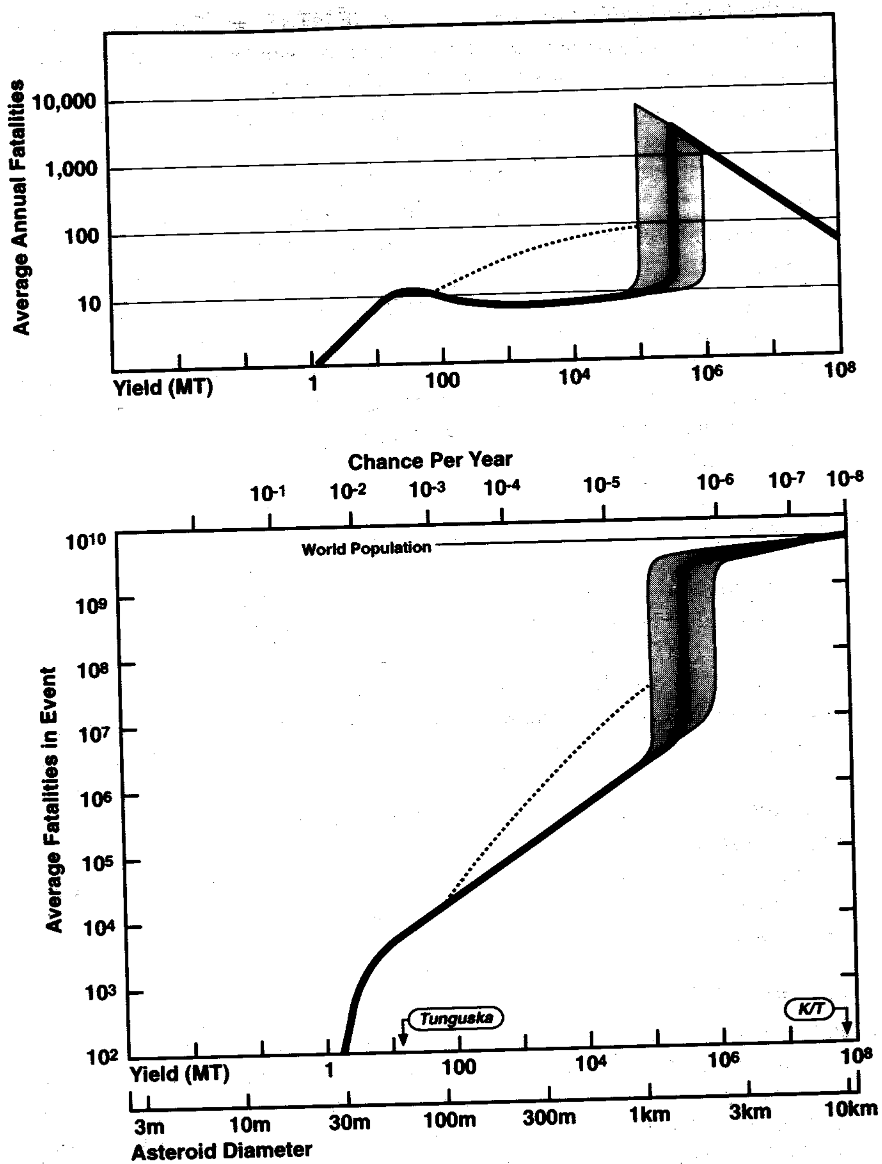

Figure 2. *Bottom*: Average mortality from impacts as a function of energy, for the current population of the Earth. The solid line from 10 to 10^5MT is for impacts on land or the continental shelves; the dashed line indicates enhanced mortality from tsunamis that result from deep ocean impacts. The shaded region shows the range of values associated with the choice of the threshold for global catastrophe (between 10^5 and 10^6MT). *Top*: Schematic representation of the average mortality (worldwide deaths per year) from impacts over the same range of energies, showing that the total hazard increases as the size of the impactor ranges from ordinary meteorites up to the global threshold at a nominal energy of 3×10^5MT. Scales for associated impact probabilites and asteroid diameters from Fig. 1 are also shown (figure is adapted from Chapman and Morrison 1994).

For the nominal global threshold of 3×10^5 MT ($D = 1.7$ km), this value is about \$20 million per year. If the effects of tsunamis are included, this number will rise to perhaps \$100 million. This number (which is, we stress, very approximate) could be interpreted as a justifiable amount to spend in defending against impacts below the global threshold.

At and above the global threshold, the equivalent annual casualties are in the thousands. Application of a similar factor to convert from mortality to economic destruction then leads to a value for development of mitigation or defense systems (in advance of a specific threat) of several hundred million dollars per year. This simply says that most of the total economic "value" of the world—currently some $\$4 \times 10^{14}$—might be lost from a large impact once every million years or so, for an annual equivalent loss of hundreds of millions of dollars—a very crude way of assessing such a global catastrophe, but one that may be of some interest in considering the justification for possible mitigation schemes.

V. 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 analogs—natural disasters.

A. 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 (National Safety Council 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^{-1} in the United States (half are motor-vehicle related), but they pale in comparison with cardiovascular and malignant diseases as a cause of mortality (U. S. Bureau of the Census 1991).

Table III illustrates some selected causes of mortality for the world population. The closest analogs 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 1991*a*), 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 analogs to the impact hazard.

TABLE III

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, airline crash)
12.	Globally catastrophic 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

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 (U. S. Bureau of the Census 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) (*World Map of Natural Hazards* 1988). This average 10-yr interval between huge natural disasters may be compared with the thousands of years between asteroid impacts large enough to cause comparable fatalities.

B. 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 geologic record was the Toba, Sumatra, event 75,000 yr ago, with eruptive volumes at least a thousand times greater than Mt. St. Helens (Rampino et al. 1988; 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 time scales 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.

C. Comparative Risk Summary

This discussion of comparative risk can be summarized by the schematic illustration in Fig. 3. For three representative classes of disasters and accidents, Fig. 3 presents the world fatality rate (deaths/yr) as a function of the number of deaths per catastrophic event. At one to a few deaths per event, automobile and other transportation accidents dominate the mortality. These are also the dominant forms of accidental death overall. Other human-caused accidents (chemical spills, 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.

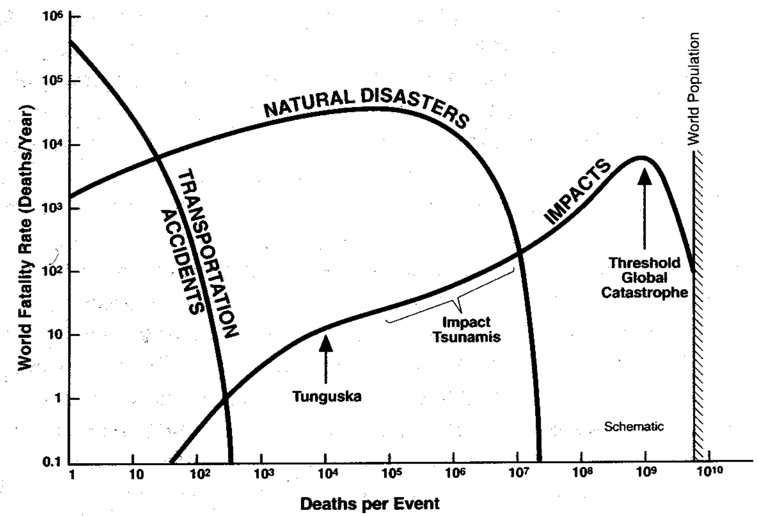

Figure 3. Schematic indication of the fatality rate from accidents and disasters (worldwide deaths per year per factor of 10 in the abscissa) as a function of the number of deaths per event. The primary cause of accidental deaths is transportation accidents (including auto, train, and plane), which typically involve the deaths of fewer than 100 persons per incident. Large-scale natural disasters (floods, earthquakes, hurricanes, volcanic eruptions) cause deaths over a wide range of scales, up to rare but statistically important events that can kill millions. Only impacts, however, are capable of killing more than 100 million persons per event, and they dominate the hazard in the right-hand side of the figure.

As natural disasters approach their upper limits (at several million fatalities per event), cosmic impacts, occurring only once every 100,000 yr, 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.

VI. 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.

A. History of Risk-Perception Research

Social scientists have been studying risk perception extensively during the past 15 yr, 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, nonmedical 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.

B. 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:

1. 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 et al. 1978). Personal experience of a natural disaster is usually necessary to motivate action to reduce future risks.
2. 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.
3. 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).
4. 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:

5. The risk is demonstrable (it happened to the dinosaurs) and is endorsed by credible scientists.
6. The potential consequences of large impacts are uniquely catastrophic and are qualitatively different from other natural hazards.
7. 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.
8. 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 drew great 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.

C. 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. This sample of students has been shown in previous studies to respond rather similarly to broader demographic samples of American adults. 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 include 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 yr; 35% believed that one would occur more than 1000 yr from now, and 34% denied that at a threatening asteroid "could appear within the next 20 yr." 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.

VII. 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 Survey 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 yr 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; Chapter by Ahrens and Harris). 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 Survey discussed in that report is an international survey network of groundbased 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 (Chapter by Bowell and Muinonen). 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 yr.

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 10^5 to 10^6MT of energy). As shown by the hazard analysis presented in this chapter 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 yr. If the survey were continued, however, it would eventually catalog virtually all asteroids above the atmospheric cut-off (10 MT). The limitations of surveys of this sort are discussed in detail in the Chapter 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 groundbased or orbital, cannot guarantee detection of such an incoming comet with more than about a year's warning (Morrison 1992; Chapter by Bowell and Muinonen). 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 would be achieved.

VIII. 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 2 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 consequences 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 3×10^5 MT (Chapter by Toon et al.) for transition to large-scale global effects, where a globally catastrophic impact is defined as one that leads to mass starvation and mortality of $\geq$25% of the world's human population. For purposes of calculation, we have carried uncertainties of a factor of 10 in this threshold energy. Our adopted range in threshold energies corresponds to average intervals between globally catastrophic events of approximately 0.2 to 1 Myr.

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 end this overview with a summary of these conclusions.

1. Impacting objects with energy of less than about 10 MT pose little danger; only rare 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.
2. 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.
3. Above some threshold energy (probably between 10^5 and 10^6MT), 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 three times per million years.

4. 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.
5. 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.
6. 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.

Acknowledgments. 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 R. Binzel, E. Bowell, A. Harris, S. Ostro, E. M. Shoemaker, B. Toon, and K. Zahnle for their insightful comments and critiques of previous versions of this work, and G. Canavan, J. Hills, J. Pike, C. Sagan, and P. Weissman for sharing their results with us in advance of publication. This research was supported in part by grants from the NASA Planetary Astronomy Program.

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