How a Near-Earth Object Impact Might Affect Society

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Abstract

The hazard of impacts by meteoroids, asteroids, and comets ranging in size from meters to kilometers should be a matter of practical concern to policy makers in many nations. At worst, the very unlikely case of a 3 km asteroid striking Earth could send civilization into a new Dark Age; this case – with a potential death toll of a billion or more – has an annualized fatality rate comparable to other serious hazards, like earthquakes or airline crashes. At a minimum, the increasing rate of discoveries of Near Earth Asteroids combined with media sensationalism will surely alarm the public and bring the issue of this potentially solvable hazard (e.g. by deflecting an approaching asteroid away from the Earth) to the desks of responsible emergency management officials.

In this report, six representative cases of asteroid impact scenarios are described in practical terms, with implications that vary for nations of different sizes, proximity to ocean coastlines, and other characteristics. Some cases, meriting concern and advance preparation for mitigation, are certain to happen in this century; others are quite unlikely, but sufficiently dangerous that responsibility dictates that they should be evaluated to determine the appropriate priority of preparing for such an event. The six cases are described in terms of the anticipated devastation, the probability of happening, the likely warning time, the opportunities (if any) for post-warning mitigation, the nature of post-impact crisis management, and the opportunities for advance preparation.

Finally, some important issues are discussed: the role of the media and public perception of an inherently non-intuitive but alarming hazard, the unusual scientific uncertainties associated with predicting impacts, international oversight of asteroid deflection technologies, and a post Sept. 11th perspective on the impact hazard. A devastating impact is likely to manifest itself as the compounded effects of various familiar natural hazards, including tsunami, earthquakes, windstorms, fires, and explosions. Therefore, the additional efforts needed to prepare for an unlikely impact may be considered as relatively low-cost, marginal add-ons to existing approaches for managing civil defense against more common natural and man-made dangers.

I. INTRODUCTION

Interplanetary space is not entirely empty. As the Earth orbits the Sun, it encounters particles and objects ranging from microscopic dust to large asteroids and comets. The tiniest particles are very numerous and entirely harmless; they cause the flashes of light, known as meteors or "shooting stars”. The large asteroids and comets are very rare; the chance that one might hit the Earth during our lifetimes is extremely small. Yet some are enormous bodies: those tens of km in size could exterminate most life on our planet. School books tell how the impact of a 10- or 20-km sized asteroid killed off the dinosaurs, and most fossilizable species of life, 65 million years ago. But such once-in-100-million year events are so rare that, despite their apocalyptic horror, they need be of no concern to public officials.

The enormous ranges in impact frequencies and sizes (hence destructive consequences) of cosmic projectiles are summarized in Table 1. (In all entries, I refer to the impact chances for bodies *greater than* the specified size. Because the numbers fall off very rapidly with increasing size, the *typical* size of an impactor is only a little bit bigger than the stated lower bound of the size range. Thus, for example, most objects ">300m" are between 300 and 350 m in size -- and it is for objects of those sizes that I list the destructive energy and damage.)

Projectiles of Practical Concern

Cosmic projectiles in Earth's neighborhood include the tiniest meteoroids (dust grains, pebbles, etc. derived from larger bodies), which burn up harmlessly as "shooting-star" flashes, up to a few giant asteroids -- ten or more km across -- already charted by astronomers. Even larger comets occasionally arrive from the outer reaches of the solar system and briefly penetrate the inner solar system. In Table 1, I label the tiniest bodies as of no practical concern, although they erode and occasionally damage earth-orbiting satellites. I also label the giant asteroids and comets (>10 km diameter) as of no practical concern, since their chances of impact are so exceedingly remote, even though we may muse philosophically about the potential eradication of the human species.

Many objects of in-between sizes are worthy of concern, but we know less about them. For example, bodies meters to hundreds of meters in size are especially difficult to detect and track, and they strike so rarely that skygazers and meteor astronomers hardly ever witness their fiery entry into our atmosphere; until they hit and explode, most are also too small and faintly illuminated by sunlight to be detected astronomically, even with large telescopes -- so one could suddenly appear and strike without warning. Actually, as I discuss below, cosmic objects meters to a few km in size do impact often enough to be relevant to our lives and they constitute an important, if atypical, natural hazard. They can be damaging or even devastating, depending on their size.

Table 1. Frequency of Cosmic Impacts of Various Magnitudes

Asteroid/ Comet Diam.	Energy & Where Deposited	Chance this Century (World)	Potential Damage and Required Response
>10 km	100 million MT global	< 1-in-a-million*	Mass extinction, potential eradication of human species; little can be done about this almost-impossible eventuality.
	^ OF NO PRACTICAL CONCERN ^		
>3 km	1.5 million MT global	< 1-in-50,000*	Worldwide, multi-year climate/ecological disaster; civilization destroyed (a new Dark Age), most people killed in aftermath; chances of having to deal with such a comet impact are extremely remote
>1 km	80,000 MT major regional destruction; some global atmospheric effects	0.02%	Destruction of region or ocean rim; potential worldwide climate shock -- approaches global civilization-destruction level; consider mitigation measures (deflection or planning for unprecedented world catastrophe)
>300 m	2,000 MT local crater, regional destruction	0.2%	Crater ~5 km across & devastation of region the size of a small nation *or* unprecedented tsunami; advance warning or no notice equally likely; internationally coordinated disaster management required
>100 m	80 MT lower atmosphere or surface explosion affecting small region	1%	Low-altitude or ground burst larger than biggest-ever thermonuclear weapon, regionally devastating, shallow crater ~1 km across; after-the-fact national crisis management
>30 m	2 MT stratosphere	40%	Devastating stratospheric explosion; shock wave topples trees, wooden structures and ignites fires within 10 km; many deaths likely if in populated region (Tunguska, in 1908, was several times more energetic); advance warning unlikely, advance planning for after-event local crisis management desirable
>10 m	100 kT upper atmosphere	6 per century	Extraordinary explosion in sky; broken windows, but little major damage on ground
> 3 m	2 kT upper atmosphere	2 per year	Blinding explosion in sky; could be mistaken for atomic bomb
	v OF NO PRACTICAL CONCERN v		
>1 m	100 tons TNT upper atmosphere	40 per year	Bolide explosion approaching brilliance of the Sun for a second or so; harmless
>0.3 m	2 tons TNT upper atmosphere	1000 per year	Dazzling, memorable bolide or "fireball" seen; harmless

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* Frequency from Morrison *et al.* (2002); but no asteroid of this size is in an Earth-intersecting orbit; only comets (a fraction of the cited frequency) contribute to the hazard, hence "<".

The largest, asteroids and comets of practical concern, 1 to a few km across, could destroy life and property across an entire continent or even send civilization back into a Dark Age. They are large enough to be readily discovered by astronomers using modest telescopes in an existing, loosely coordinated, international program known as the Spaceguard Survey. More than half of such Near-Earth Asteroids (NEAs) have already been found and their orbital tracks computed; none of them will strike Earth during this century. Most of the remaining ones will be found during the next decade or so; probably it will be learned that none of them will strike us either, although there is a small chance -- after all, this is the purpose of the Survey -- that one will be found destined to collide during the 21st century. Equally perilous, even the largest long-period comets are very difficult to discover well in advance; though rare (perhaps 10% of the total impact hazard), they will always pose a threat of devastating impact. (The familiar, smaller short-period comets are closer and are handled routinely, like NEAs.)

The smallest harmful projectiles are the sand-grain to pea-sized meteoroids that produce the brightest meteors that people normally see among the constellations. They can damage satellites, spacecraft, and other assets in space, but cannot affect anything on the Earth's surface because they burn up high in the atmosphere. They are common enough so that their statistical frequency of impact can be reliably assessed by astronomers who specialize in studying meteors, including the occasional meteor "showers" or "storms" (like the Leonid showers during recent Novembers), so that potential hazards to space-based equipment can be predicted and preventative measures taken. I consider such small meteoroids to be of "no practical concern" in Table 1.

More worrisome are larger meteoroids, meters to hundreds of meters across, but which are still smaller and more numerous than the km-scale asteroids being searched for by the Spaceguard Survey. As I describe below, impact rates and consequences vary enormously across this broad size range, but such objects share several general traits: (a) whether they explode in the atmosphere, on the ground, or in an ocean, they can have devastating consequences for people proximate to (or occasionally quite far from) the impact site; (b) they are mostly too small to be readily detected or tracked by existing telescopic programs; and (c) their impacts are too infrequent to be witnessed and studied in detail by scientists, so their nature and effects are not yet well characterized. Thus scientific uncertainties are greatest for just those objects whose sizes and impact frequencies should be of greatest practical concern to public officials. Impacts of these cosmic bodies are unfamiliar even to many of those in military agencies whose role is to scan the skies for more familiar military hazards. Impacts of such bodies range, depending on their size, from annual events to extremely devastating potential impacts (a 300 m impactor might cause 1 million deaths, roughly equalling the death tolls of the few largest natural disasters in the last several hundred years); the latter have a few tenths of a percent chance of happening during the 21st century. Impacts of the smaller of these bodies (several meters to 50 m) *will* happen (or at least might well happen) during our lifetimes, so the hazards they pose must be addressed by society's institutions. Even the more unlikely impacts by multi-hundred meter objects have a large enough chance of happening during our lifetimes or our grandchildren's, and conceivably on the "watches" of officials attending this workshop, that it would be prudent to consider how well we are prepared to deal with such an impact if one were predicted to happen in the next few years, or indeed if such a calamity were to occur without warning.

Impacts in the Context of Other Risks

In the 21st century, we must consider the impact hazard in a context in which citizens of many nations are apprehensive about hazards associated with foods, disease, accidents, natural disasters, terrorism, and war. The ways we psychologically respond to such threats to our lives and well being, and the degrees to which we expect our societal institutions (both governmental and private) to respond, are not directly proportional to actuarial percentages of the causes of human mortality nor to forecasts of likely economic consequences. Our concerns about particular hazards are often irrationally exaggerated or belittled, and they vary from year to year, affected by events, media coverage, and hype. Citizens of different nations demonstrate different degrees of concern about risks in the modern world. Yet one would hope that public officials would examine the best information available (uncertainties and all) and base their decisions on that – this is the purpose of this paper. It turns out that objective measures of the potential damage due to asteroid impacts (consequences multiplied by risk) are within the range of other risks that governments often take very seriously. Moreover, public reactions to future impacts of asteroids are predicted to be substantial, given (a) recent responses to somewhat analogous catastrophes, (b) the psychological and sociological vagaries of human risk perception, (c) the increasing rates of discoveries of NEAs and predictions of "near misses", and (d) the high degree of interest in asteroid impacts already demonstrated by the international news media.

Let me characterize the impact hazard in terms recently outlined by the OECD Public Management Committee (OECD, 2001). The *hazard* I discuss here is impacting asteroids and comets from outer space. The *risk* discussed here concerns the *time frame* of the 21st century, during which we, our children, and our grandchildren will shape humanity's response to the evolving natural world. In this paper, I often discuss the *probabilities* of various impact scenarios and I try to characterize the *consequences* of such impacts. As the OECD report emphasizes, scientific uncertainty is at the heart of risk, and that is especially true for the essentially unprecedented potential consequences of cosmic impacts. But that uncertainty,

> while frustrating in its complexity, permits regulators and political decision-makers to make the final choice to intervene or not while having in hand a range of scientific analyses. [OECD, 2001]

This paper's purpose is to present information that will enable decision-makers to adopt a risk management approach toward the impact hazard in a fashion compatible with each nation's particular geography and socio-economic state. In order to frame the impact hazard in recognizable terms, I will describe its consequences in terms of more familiar natural hazards. Thus, while some aspects of the impact hazard (e.g. its predictability) are unusual or unique, most destructive effects resemble those of tsunami, earthquakes, atomic bomb and volcanic explosions, sudden climate change, wildfires, etc. In this way, I describe what to expect in terms of direct physical and environmental damage, but I can only broadly outline the indirect harmful effects on physical and mental health, economic activity, etc., which may differ greatly from one nation to another. Of course, commonly accepted measures of the *costs* of natural disasters far fall short of a full measure of *losses* (NRC, 1999). Costs, as measured by pay-outs by insurance companies and governmental programs, often underestimate the real economic effects (both indirect losses and uninsured direct losses) by factors of many. Less tangible losses (e.g. psychological) are difficult to quantify, but nevertheless may (or may not) be mitigated by advance planning and thus have political consequences. As I discuss toward the end of this paper, such intangible consequences may be enhanced for such an exceptional catastrophe as destruction from the heavens, in ways analogous to how the 9/11 terrorist attacks have had consequences far beyond the ~3000 deaths, destruction of buildings, and temporary economic losses in the affected locales.

I have noted that the impact hazard -- at least the more frequent, lesser magnitude examples -- has many features in common with other natural hazards, for which there is a rough correlation between the number of fatalities and the economic consequences, as measured in conventional ways. One study (Pike, 1991) estimates that total economic costs of disasters average several million dollars times the number of deaths in the disaster. But that amount varies enormously depending on the economic development status of the affected country: disasters are about a factor of ten less costly – in purely economic terms – per death in less developed countries and a factor of ten more costly per death in more developed countries. I commonly speak of deaths as a measure of destruction in the cases discussed below, but we must not forget that there is an associated, often enormous economic toll, however it is measured.

II. CASE STUDIES: EXAMPLES OF IMPACT DISASTER SCENARIOS

In order to make more concrete the nature of the impact hazard, what damage might be done, and what precautionary or after-the-fact measures might be taken to mitigate losses, I present six different impact scenarios in detail. The examples differ greatly in their likelihood of happening, the magnitude of the destruction, the degree of predictability by scientists, and the kinds of prevention or mitigation that might be undertaken. The individual cases discussed here would affect various nations differently (depending, for example, on whether the country is coastal or land-locked). Naturally, there are many other possible cases that could be drawn from within the range of impactors summarized in Table 1; differences in the environmental effects and probable societal responses would also depend on where (or what country) the projectile struck, and on other variables, as well. Readers should be able to interpolate between these six, concrete cases.

As in Table 1, each case scenario involves a body of *approximately* the size stated; for example, the two cases involving a "~200-meter" NEA roughly characterize circumstances for impacts by bodies from ~150 to ~300 meters in size, and the quoted probability of happening refers to impacts of all bodies >200 meters, dominated by those in the range 200 - 250 m.

Case A. Tsunami-Generator: ~200-meter Asteroid Impacts in Ocean

Nature of the Devastation. Imagine a flying "mountain", larger than the Vehicle Assembly Building at NASA's Kennedy Space Center or larger than the world's largest domed stadium (the New Orleans Superdome), crashing to Earth at a speed a hundred times faster than that of a jet airliner. More probable than hitting land, such an asteroid would make a fiery plunge into an ocean and explode with an energy of about 600 MT (MT = million tons of TNT equivalent), about ten times the yield of the largest thermonuclear bomb ever tested. (Although the effects would be very different, the instantaneously released energy would be roughly that of a magnitude 8 earthquake...roughly equal to the annual production of electricity from all nuclear power plants in France and Japan combined.)

The brief atmospheric phase of the impact might disrupt some communications, and any ship near the impact point would be destroyed. Cubic kilometers of water lofted high into the atmosphere would have some short-term, local or regional meteorological consequences. By far the most dangerous outcome of the impact would be the resulting tsunami ("tidal wave"), which would convey maybe 20% of the impact energy toward far-distant coastlines. Specific consequences for coastal cities and lands around the rim of the affected ocean would depend on proximity to the impact point, the specific ocean-bottom topography in the vicinity of the coast, and other attributes of local geography and infrastructure. Typically, the resulting couple-meter high tsunami in the open ocean would be amplified to a wave over 10 m high as it breaks on the coast. Generally, the effects would be much greater in the vicinity of an impact not far off-shore.

Researchers are very uncertain about the overall seriousness of impact-generated tsunami [cf. Ward & Asphaug, 2000; Hills & Mader, 1997]. Estimates of average coastal wave heights vary plus-or-minus fully a factor of ten from what I adopt here, so public officials should be sensitive to the "meta error bars" discussed in a later section. I generally follow Ward & Asphaug in expecting that a tsunami propagated from impact of a 200 m (or somewhat larger) asteroid would reach a height -- over 10 m -- comparable to the biggest ocean-wide (as distinct from purely local) tsunami recorded during recent centuries. Multiple waves might arrive over the course of an hour or so. Local run-ups would vary greatly. Such waves could be inconsequential at some favored locations and in places *very* far removed from the impact point or ocean in question, but they could be locally extreme in places historically damaged by tsunami and along coastlines with tsunami-enhancing cachements, like the Columbia River delta. (Historical tsunami are generally produced by earthquakes, which are mainly centered in narrow zones around the Earth. A tsunami caused by an asteroid impact in a place far removed from earthquake zones might manifest itself rather differently from historical patterns. Since wavelengths of impact tsunami are shorter than those of most earthquake tsunami, tsunami characteristics -- like velocity across the ocean and time intervals between successive waves -- might vary greatly from historical experience.)

Run-ups and breaking waves on coastal plains could range inland as far as kilometers; some low-lying plains near sea-level (e.g. Bangladesh) would be affected in a manner similar to (but more extreme than) the flooding caused by storm surges associated with the greatest hurricanes and typhoons. Other seemingly vulnerable places (e.g. Florida and northern Europe), where shallow continental shelves far off-shore might cause tsunami to break there rather than on the beach, may be comparatively immune to tsunami [Hills & Mader, 1997], although researchers disagree. Even much shorter, lesser run-ups could devastate built infrastructure immediately adjacent to the coast. The human toll would be dramatically affected by the efficacy of tsunami warning systems and established evacuation protocols (see below), but in the worst case millions might die. Consequences for nations without coastlines or on opposite sides of the planet would be restricted to comparatively minor meteorological effects or highly indirect, but possibly major, economic and political repercussions.

Probability of Happening. For a land-locked country, this is not a significant threat (except for the indirect effects just mentioned). For countries with inhabited and/or developed ocean coastlines, this scenario is relevant. Countries that could be affected include all Pacific Rim nations including Australia; American, European, and African nations fronting on the Atlantic where natural tsunami are much rarer; and nations bordering the Indian Ocean. Tsunami propagate around the world, so even if modest-sized bodies of water like the North Sea were not struck, there could be consequences in bays whose geometry enhances tsunami run-ups. Although the Mediterranean is small and unlikely to be struck, ~10% of historic tsunami have occurred within that largely inland sea. A >200 m diameter asteroid impact has one chance in several hundred of happening, worldwide, during this century. (The chances for direct effects to an individual, ocean-fronting nation are generally down by a factor of a few, since the impact might well occur in a different ocean.) Similar but less devastating impact tsunami may be several times more likely -- about a 1% chance of happening this century, but still smaller, even more frequent impactors explode in the lower atmosphere and couple little energy into the ocean.

Warning Time. Currently, it is very unlikely (<20% percent chance) that astronomers will discover such a "small" impactor in advance; if they do, there would likely be years or decades of warning. Most likely, there would be no warning of the impact, but there would be warning before the deadly tsunami effects occurred: it would come from either (a) reports of the impact by military or other marine facilities or (b) by tsunami-warning infrastructures currently in place. It is highly uncertain that source (a) can be relied upon since the event would be unprecedented and reporting channels, if they exist, are untested. Source (b) may be partially effective in those places where the technology and warning infrastructures are deployed (Japan and Hawaii are examples). However, the Pacific Tsunami Warning Center's warnings are triggered mainly by sensors for earthquakes, which might not record or recognize the signature of an oceanic asteroid impact. Many hours of advance warning are possible, as the waves propagate across the ocean at hundreds of km/h, and coastal warning sirens and other protocols could assure evacuation and protection for many. However, if the impact were to occur just offshore, or in a part of the world that has less developed approaches to warning citizens of tsunami (e.g. Atlantic Ocean coasts), then effective evacuation would probably not be achieved under current procedures.

Post-Warning Mitigation Possibilities. In the unlikely event that the approaching NEA were discovered in advance by astronomers, the impact could be prevented by having space-faring nations deflect (or destroy) the asteroid. With several years or more warning time, current technologies could be assembled into an effective project to deflect such an asteroid. While not without challenges, this probably could be reliably accomplished years before the predicted impact so that no mitigation efforts on the ground would be required. The cost would be large, but affordable: perhaps much less costly than the inflation-adjusted cost of the Apollo program.

It is much more likely that, if there is warning at all, it would come only hours before the tsunami arrives. Apart from long-term land-use and building-code regulations that would harden coastal facilities against tsunami in general (possibly providing adequate shelters), the chief short-term action would be to save lives by evacuation to higher ground. In Hawaii, for example, where warning and evacuation procedures are in place and well understood and where the topography near inhabited places generally rises rapidly away from the coast, the chances for successful evacuation are good. In countries where these features do not exist, advance planning for such warnings and evacuations could save lives not only in this unlikely impact scenario but also for other unusually large earthquake-, volcanic-, or landslide-triggered tsunami. The opinion in the natural hazard community (cf. Bryant, 1991) is that many nations are insufficiently prepared for tsunami in general, quite apart from the additional danger of asteroid-induced tsunami.

After-Event Disaster Management. With or without short-term advance warning, the immediate aftermath of such an impact-generated tsunami would resemble other major, localized civil disasters. Of course the "localities" might be distributed around the entire ocean rim, in many countries. To the victims and rescuers, the effects would be those of a tsunami, which they would likely have heard of or even experienced (the fact that an asteroid or comet caused the tsunami would not objectively change the approach to recovery). Many nearby locales, just kilometers inland from the coastline, would not have been affected at all, so they could serve as centers for organizing relief. While there might be minor subsequent ocean waves and adverse weather for several days, resulting from the ocean impact, such lingering effects would be slight compared with the initial tsunami waves and would not unduly hamper rescue and recovery. Preliminary considerations have been given to the acutedisaster and rehabilitative phases of managing an asteroid impact tsunami disaster (Garshnek *et al.*, 2000).

Advance Preparation. (Also see comments about preparing for post-warning evacuation above.) The most effective preparations would be the same ones that would protect coastlines from the effects of tsunami generally, with enhanced recognition that much larger tsunami than those remembered by people now alive are possible: impacts could, very rarely, generate a larger tsunami than are ever produced by natural geological processes. Mitigation efforts might include hardening necessary coastline infrastructures, limiting and/or hardening developments within several hundred meters or kilometers of the coast, and developing civil defense procedures that would be effective in evacuating endangered populations -- perhaps to distances or elevations not normally contemplated. While the impact hazard might not, by itself, justify major new development of tsunami mitigation measures, awareness of the asteroid impact scenario can broaden our appreciation for the possible magnitudes of tsunami and the variety of their causes and effects.

Officials and personnel responsible for national and international tsunami-warning systems should be apprised of some of the differences between impact- and earthquake-generated tsunami, should be linked into astronomical/military/maritime organizations that might report immediate information about an impact, and should be aware of the possibility of a tsunami of unprecedented magnitude, with different initial signature, or generated in an unusual locality. National geologists and ocean scientists could research local circumstances, like bathymetric modelling of the effects on tsunami run-up of underwater, near-coastal topography. Currently, such studies, even for normal tsunami, are poorly developed in most countries, but are needed if officials are to plan for possible contingencies.

Case B. ~200-meter Asteroid Strikes Land

Nature of the Devastation (cf. Toon *et al.*, 1997). As in Case A, imagine an enormous rock larger than any of the world's largest buildings crashing through the Earth's atmosphere in a few seconds, but striking land instead of an ocean. The 600 MT explosion would be as though we took the world's largest thermonuclear bomb ever tested and exploded ten of them at once. An enormous crater would be created within seconds, 3 to 4 km across and deeper than the Grand Canyon. Anything within several km of the crater rim would be smashed and totally buried by flying material excavated from the crater a fraction of a minute beforehand. All things would be destroyed and all people killed immediately within this city-sized zone.

While less than total, devastation and death due to the blast and associated phenomena would be very serious out at least 50 km in all directions: trees would be toppled by the atmospheric shock wave; wooden and unreinforced structures might implode from the overpressure pulse and their debris would then be blown about by a brief spell of super-hurricane-force winds. Fires, ignited by the object's blazing entry and surface explosion, might threaten much of the same area. A simultaneous, damaging, local earthquake would add to the calamity. People living even hundreds of km from ground zero would not be immune to rocks falling from the skies, choking smoke and dust downwind from the crater, and lesser effects of the seismic and atmospheric shock waves spreading away from the explosion. In short, such an impact would substantially destroy a region the size of a small nation or a modest-sized American state.

The death toll could be enormous, in the range of thousands to hundreds of thousands, depending on population density. However, unless the impact occurred in an urbanized or otherwise densely populated area like Bangladesh, deaths would not likely exceed those caused by the worst natural disasters of the twentieth century. It is also conceivable, but unlikely, that an isolated part of the world would be hit so that few or none at all might be killed. There is a small chance of immediate consequences other than those discussed here (e.g. flooding if the crater diverts a river, radiation concerns if a nuclear power plant is near ground zero, etc.), but these would be unexpected complications on top of an already highly unlikely event.

Probability of Happening. The chance of a >200 m asteroid striking land during the 21st century is about 1-in-a-thousand. Cosmic impacts are not selective, so one of the world's largest countries (Russia, Canada, China, the United States, Australia, and Brazil) would be the most likely target. While there is a negligible chance that a very small country would be directly struck, it would be affected if ground zero were closer than several hundred km away.

Warning Time. As noted in Case A, there is <20% chance (given the current telescopic survey efforts) that such an asteroid would be discovered before impact. In case of such a discovery, warning times would likely be decades or longer. If it struck without any warning, the devastation would be immediate, unlike the hours of possible warning in Case A. Individuals who witness the terrifying plunge of the asteroid to Earth might have seconds to tens of seconds to take cover (e.g. hiding behind a strong wall or in an underground shelter) and lessen somewhat their personal risk from the blast, if they are at least 10 km away from ground zero; if closer, they have no time to react and minimal chance of survival.

Post-Warning Mitigation Possibilities. If, by luck or design, the object were discovered long before impact, then it would be possible to divert it so that it would miss the Earth (see Case A and later discussion of asteroid deflection issues).

After-Event Disaster Management. The destruction would be total within and near the enormous crater formed by this impact and the severity would diminish with distance, out to several hundred km. The causes of death, injury, and destruction would mainly be the same as those of some other natural disasters -- earthquake, volcanic explosion, typhoon, firestorm -- except that the effects of all four would be compounded in this case. The extent of the disaster zone would resemble that for the greatest localized natural disasters, like the explosion of Krakatoa in 1883, where some 36,000 people perished. The disaster zone would not be widely distributed across many nations, as for the tsunami case, but the interior of the zone would be much more difficult to reach and service because of its breadth. Unlike earthquakes or storms, there would be no lingering threats from additional asteroids after the event; fires and environmental toxicity might be the longest lasting aftereffects. The kinds of emergency management issues facing society in the aftermath of such an impact (public health issues, panic, etc.) are described by Garshnek *et al.* (2000).

Advance Preparation. Unlike Case A, for which vulnerable zones (coasts) are already mapped, there is no spot on Earth more likely to suffer direct blast damage from an asteroid impact than any other. Normal mitigation and emergency management procedures designed to protect lives and infrastructure from extreme windstorms, fires, and earthquakes, which are much more likely to occur as normal terrestrial events than because of an asteroid impact, would also serve in the case of an impact. Unless an incoming asteroid is discovered before it hits, there is little justification for mounting asteroid-specific mitigation measures (except at the margins) in the face of the 1-in-a-thousand chance of this scenario playing out on some continent during this century.

Case C. Mini-Tunguska: Once-a-Century Atmospheric Explosion

Nature of the Devastation. In this case, a massive rock the size of an office building (say 30-40 m across) streaks down through the atmosphere, starting with a velocity a hundred times that of a jet airliner. Just as a high-dive "belly-flop" into water can be very painful, impact into a layer of air at 20 km/sec is almost like running into a wall: unless this small asteroid were made of solid metal, it would be torn apart, exploding with the force of several megatons well before reaching the ground, perhaps 15 km up (near the bottom of the stratosphere). Unlike Cases A and B, which have never been witnessed in recorded human history, this case is to some degree a known quantity: what was probably an even larger airburst occurred in 1908 when a stony asteroid exploded over the Tunguska region of Siberia with a yield of ~15 MT. Also, in the middle of the last century there were atmospheric bomb tests of comparable energies that were approximately analogous to impacts, so the effects for this Case are fairly well understood. (Nevertheless, Boslough & Crawford [1997] offer arguments that Tunguska itself was caused by only a 3 MT impact, in which case the 2,000 sq. km of flattened Siberian forest may be representative of once-a-century damage rather than of 1,000 yr 10-15 MT impacts, as generally expected; however, it is possible that the Tunguska forest was already dying and weakened prior to the impact and was toppled by overpressures and winds that would be minimally damaging to houses and buildings.)

Case C represents roughly the minimum sized impact (except for rare iron projectiles) that can do significant damage on the ground (Chyba, 1993). (Of course, three-quarters of these impacts occur over the ocean and do negligible damage.) Rocks 30 m and smaller explode too high in the atmosphere and with too little force to do much damage at the Earth’s surface. Those 50 m and somewhat bigger, the nominal assumption concerning the Tunguska impactor, can devastate thousands of square km of forest and destroy structures over a similar area. Certainly it would be dangerous to be within several tens of km of a lower-stratospheric, small asteroid explosion. Fires might well be ignited beneath the brilliant explosion, unless it were cloudy. Weak structures might be damaged or even destroyed within a 20 km radius by the shock wave and subsequent hurricane-force wind gusts. Exposed people and animals could be struck by flying objects. While Tunguska killed few people if any, the once-a-century class of asteroid airburst would be very frightening to witnesses and very deadly in a susceptible locality.

Probability of Happening. Such an impact explosion happens once a century, but the probability is that the next one would occur over an ocean or desolate desert where its effects would be minor. No locality is favored or disfavored by the random targeting of asteroidal projectiles.

Warning Time. While not impossible, it is quite unlikely that such a small asteroid would be discovered by astronomers or military surveillance prior to impact – unless survey efforts are augmented in a dramatic way. The brilliant explosion would happen without warning. Whatever damage ensued, it would likely be over within seconds to minutes, except for lingering fires and a stratospheric pall.

Mitigation Issues. In general, nothing practical can be done about this modest hazard other than to clean up after the event. It would be very costly to build a search system that could find most 30 m bodies before one strikes, although the Spacewatch Telescope in Arizona has found several representative examples. Once an atmospheric impact occurs, the usual disaster management protocols should be able to handle trauma and damage in the affected locality. It makes no sense to plan ahead for such a modest disaster, which could occur anywhere, other than educating the public about the possibility.

Case D. Annual Multi-Kiloton Blinding Flash in the Sky

Dangerous Consequences. A rocky meteoroid the size of a bus explodes 20 km up in the stratosphere with the energy of a small A-bomb (2 to 10 kT), producing a brief, blinding flash much brighter than the Sun. While such an event could do no damage on the ground, there is concern that military commanders in a region of tension -- unable to immediately verify the true cause of the explosion -- might regard it as the hostile act of an enemy and retaliate dangerously. Indeed, a 25 kT airburst occurred on 6 June 2002 over the Mediterranean, leading to speculation that if the event had happened instead in the vicinity of Kashmir, where tensions between India and Pakistan were elevated at the time, unfortunate reactions might have occurred. The nature of meteoritic fireballs is presumably generally understood within the military establishments of nuclear powers, but the degree to which adequate command and control procedures are in place to handle such rare and frightening events is not known.

Probability of Happening. Impacts of 3 m bodies happen annually, somewhere on Earth. But, from a fixed location on our planet, such an event is unlikely to happen throughout a human lifetime. Smaller, but still brilliant, fireballs happen much more frequently and can be seen occasionally, day or night, anywhere on Earth.

Warning Time. Objects of these sizes strike without warning.

Mitigation Issues. Currently, the U.S. Departments of Energy and Defense regularly observe such events worldwide from geostationary surveillance satellites designed for other purposes. The signatures of such events are recognized as distinct from hostile military phenomena, so an inappropriate reaction by the United States is unlikely. Normally, information about these events is released to the public days or weeks afterwards. I am not aware of whether capabilities exist to analyze the data and distribute it to other countries rapidly enough to address the potential for inappropriate military retaliation. Obviously, it would be beneficial to develop such procedures, if possible. Beyond that, raising public consciousness worldwide about rare, brilliant fireballs could only help.

Case E. Civilization Destroyer: 2-3 km Asteroid or Comet Impact

Nature of the Devastation. Much has already been written about this case. Despite the rarity of such large impacts, they statistically dominate the impact hazard, in the sense that the small probability of such an event happening each year multiplied by the enormous number of expected fatalities yields an annual rate of fatalities similar to that of hurricanes, earthquakes, or airliner crashes. While the other cases treated here (as well as species extinction by an even larger impact) are terrible disasters, an individual’s chances of dying are considerably less in all those cases than for the 2-3 km impact (Morrison *et al.*, 1994). Here I largely follow Toon *et al.* (1997).

A 3 km diameter asteroid, or somewhat smaller but higher speed comet, would explode with the almost inconceivable yield of a million megatons of TNT. It would be as though more than 1,000 of the Case A or B impacts hit the same place simultaneously. The crater alone would engulf an area comparable to one of the world’s largest cities. An impact into the ocean would penetrate into the seafloor, ejecting enormous quantities of oceanic crustal rocks in addition to tens of thousands of cubic kilometers of ocean water; the resulting tsunami would be of a scale unprecedented in recorded history. The localized devastation due to the immediate effects of an impact on land would be similar to those described in Case B, except that all effects would extend outward at least ten times as far, thus qualifying as a "regional" rather than "local" disaster (as I describe below, other aspects transform this event into a "global" disaster). In addition, new effects would add to the magnified, compound effects already discussed. Material thrown out of the Earth’s atmosphere would rain back toward the ground, filling the sky with blazing fireballs and incinerating an area perhaps as large as India or twice the size of Western Europe. The Earth’s ozone layer would be severely depleted or destroyed for a period of several years, subjecting everyone to the dangers of direct ultraviolet sunlight. And so on.

Such apocalyptic devastation nevertheless pales compared with the worldwide death and economic calamity that would be produced by sudden (taking hold within a couple of weeks), worldwide, climate change due to stratospheric contamination. Enormous quantities of dust, water vapor, sulfate aerosols, and nitric oxide would not only dramatically change stratospheric chemistry but would block out most sunlight worldwide for months. It is expected that an "impact winter" would ensue, encompassing the whole globe and probably ruining one growing season worldwide before sufficient recovery of the climate could occur. Without advance preparation, mass starvation might result in the deaths of a large fraction of the world's population. No nation would be spared the dramatic climate change, but some -- with abundant food stores -- would be better equipped than others to weather the temporary cessation of agriculture.

One can only speculate about secondary repercussions, such as disease, disruption of global economic interdependencies, perturbation of military equilibria, social disorganization, and so on. Depending on the robustness vs. fragility of modern civilization, the world might well be jolted into a new Dark Age by such a horrific global calamity. Chapman & Morrison (1994) defined a civilization threatening impact as one that would kill more than one-quarter of the world's population. There are great scientific uncertainties about whether it might take only a 1 km asteroid or instead would require a >5 km asteroid to wreak the environmental disruption described in this Case and whether that would, in fact, kill more than 1.5 billion people and, beyond that, whether such devastation would destroy modern civilization as we know it. But there can be little doubt that the calamity would be the most catastrophic in recorded human history.

Probability of Happening. An >2 km asteroid has a probability of striking Earth about once every 2 million years. However, most asteroids of such sizes have already been discovered, largely by the telescopic Spaceguard Survey during the past decade, and none of those will hit during the 21st century. Much of the remaining threat of civilization-threatening impacts is thus posed by long-period or "new" comets, whose numbers are poorly known and many of which are not discovered until a year or so before they enter the inner solar system. My best estimate is that the chance of a million MT impact happening in the 21st century is between 1 in 50,000 and 1 in 100,000. Beyond that, the meta error bars discussed in a later section are particularly relevant for this unwitnessed case.

Warning Time. There is an excellent chance that an asteroid of this size would be discovered long before it would strike the Earth, giving decades of warning. Comets, however, are found only months to a few years at most before entering the inner Solar System where one could conceivably strike Earth. There is a very small chance that such an impact would happen with little or no warning.

Post-Warning Mitigation Possibilities. If an incoming object of this size were discovered decades before impact, it could perhaps be diverted using advanced space-based technologies. Unlike Case A, moving an object this large would be technically very challenging. But the motivation would be high so the challenge could probably be met, at Apollo Program costs or more, especially if design work had already begun to deflect smaller asteroids.

If diversion of the asteroid could not be accomplished, or if the warning time were only months or years rather than decades (as would almost certainly be true for a comet), then mitigation would turn to (a) evacuation of the entire sector of the Earth where the impact's effects would be greatest, (b) optimal advance production and storage of food, and (c) "hardening" of those susceptible elements of civilization's infrastructure (communications, transportation, medical services, etc.) that would be most vital to have in place during and after the disaster. I will not amplify on these complex issues, which would surely engage all the nations of the planet and would be extraordinarily challenging; if the warning time were only months, it is unlikely that such efforts could be effectively mobilized in time.

After-Event Disaster Management. These issues have been briefly considered by Garshnek *et al.* (2000). In view of the wholly unprecedented nature of such a holocaust, one might gain as much insight from historical and even fictional accounts of past or imagined wars, disasters, and breakdowns of civilizations (cf. "Lucifer's Hammer", Niven & Pournelle, 1977). It is not useful for me to expand here.

Advance Preparation. Since human beings are psychologically accustomed to imagining that the future will be rather like the recent past, thus leaving themselves vulnerable to the sudden shocks and dislocations of the unexpected, it would probably be useful for disaster management agencies to consider a catastrophe like the one discussed in this case, if only to encourage "out-of-the-box" thinking. However, the chance of such an impact happening is very remote, and its probable consequences are too enormous and widespread to be substantially addressed by affordable, practical efforts (in the absence of a predicted, impending impact). Therefore, I would not recommend making advance preparations to mitigate the extraordinary consequences of a large asteroid- or comet-impact, with a couple of modest exceptions.

Because of the unimaginably enormous downside consequences of such an impact and the technological possibility of preventing one from happening, some level of strategic and systems planning should be done to understand the technological challenges of diverting large asteroids or comets, including taking first steps toward moving much smaller NEAs. Second, there are presumably various measures that can be taken inexpensively, at the margins, in the course of generic disaster and emergency planning, to incorporate features that would be relevant to the impact threat. One example is that, as part of their normal networking and coordination, national and international disaster management entities should develop communications channels with the astronomical and military projects that detect and track asteroids. In view of (a) the fact that any nation or ocean can be struck and (b) the planetwide consequences of such an impact, a truly global effort would be in order, except that technologically developed and space-faring nations would bear the major responsibility for asteroid diversion programs. All nations, in proportion to their capabilities, have responsibilities for protecting their citizens in the face of potential catastrophes.

Case F. Prediction (or Media Report) of Near-Term Impact Possibility

Nature of the Problem. As asteroid detection programs improve and "near misses" are more frequently reported, the most likely aspect of the impact hazard that a public official will encounter is not the actual impact by a dangerous asteroid but (a) the prediction of a *possibility* of an impact or threatening near miss or (b) a serious mistake by professional scientists or, more probably, by the purveyors of scientific information in the media. In general, human foibles are more likely than a rare asteroid impact, but they can have *real* social and political consequences. Examples of such very real possibilities include:

* The actual "near miss" by a bigger-than-Tunguska, >100 m asteroid, say "just" 60,000 km from Earth. A similar event probably *will* happen during this century. The passing projectile would be visible to ordinary people with their naked eyes. Will people believe scientists or military officials who say it will miss? (The near-miss might well be predicted in advance of its happening, but perhaps with only a few days notice.)

* The prediction by a reputable, but mistaken, scientist that an impact by a devastating asteroid or comet will occur, say, on 1 April, 2017, in a particular country. Such a report could be published in reputable news media and might not be effectively analyzed by other scientists and withdrawn for several days. In the meantime, people in the affected country might become quite frightened, particularly if rumors or sloppy journalism (see below) lead people to think that the disaster is imminent.

* The official prediction by astronomers, coordinated by the International Astronomical Union, that a dangerous, multi-hundred meter asteroid has an unusually large *possibility* (say 1 chance in several hundred) of impacting Earth on one or more specific dates later in the century. This would rate an extremely unusual "2" (in the yellow zone) of the Torino Impact Hazard Scale (Binzel, 2000). It might take months for astronomers to obtain data that would change (probably reduce) the predicted risk.

* An unusually grotesque example of media hype in which, perhaps, one of the above already worrisome examples is badly misreported (with accompanying, even more exaggerated page-one banner headlines) by one or more mainstream wire services or cable TV news networks. At least three cases of prominent mis-reporting about NEAs by much of the worldwide news media happened in the year 2002 alone; one can imagine that more egregious cases, leading to mass panic, could readily occur during the next decade.

Concerns by an agitated public about predicted impacts might well be presented to national elected leaders, emergency management agencies, and military and space departments; few governments have anyone in authority who can answer such questions. Health agencies, school officials, and police might have to deal locally with associated panic and anti-social behaviors by frightened people, especially children.

Probability of Happening. Several of the examples just cited have already happened since the reality of the impact hazard reached public awareness in the late 1980s. All of them probably *will* happen during the next century, some of them (especially the news media hype) many times.

Warning Time. It is the nature of modern life, fueled by the internet, that many of the examples cited could suddenly reach page-one status around the world within hours and catch officials totally by surprise.

Mitigation Issues. An uninformed, apprehensive, risk-averse public combined with media hype are elements of the modern world. The mix confounds many issues at the interface of science and society. The business goals and/or political agendas of the informational and entertainment media -- whether print, TV, or internet -- often run counter to dispassionate purposes of educating and informing the public. One might hope that continuing dialog among scientists, journalists, and public officials could change things for the better, but my view is that the problem is still getting worse. Better information exchange and coordination among relevant entities (astronomers, fledgling NEA information organizations [e.g. the Spaceguard Foundation, the British Near Earth Object Information Centre, and NASA's Near-Earth Object Program Office], national and international disaster management agencies, etc.) might serve to prevent some official mistakes and miscommunications. Adoption and further refinement of the Torino Scale could help to ensure that impact predictions are interpreted by science journalists and the interested public within an increasingly familiar context. Generally, improvements in education (chiefly involving science and rational thinking) can serve the long-term goal of minimizing irrational and exaggerated responses to technology in general and to the impact hazard, in particular.

III. ISSUES THAT AFFECT SOCIETAL RESPONSE

Public Perception/News Media (Subjectivity vs Objectivity)

The impact hazard has captured public imagination, thanks to blockbuster motion pictures and frequent news reports of predicted "near misses," and it is now regularly used as an often humorous metaphor for the risks of modern life. Yet an impact disaster has not been experienced by anyone now alive nor are there compelling examples of such a calamity in human history. (Indeed, most people in the world remain wholly oblivious to this hazard and its potential manifestations.) Thus, at best, it retains a fictional, out-of-this-world character for people aware of it. However, there have been instances during the past decade -- thanks to media hyperbole or mistakes -- when the impact threat has become real for some people. Brief "mass panic" in China in December 1989 was ascribed to a mistaken, nationally televised news story. The headline-producing but mistaken predictions in March 1999 of a close encounter, and non-negligible chances for impact three decades hence, by the mile-wide asteroid 1998 XF11 (Chapman, 2000) frightened some susceptible individuals (e.g. schoolchildren) around the world. Thus there is every expectation that, as risk perception experts have forecast, a predicted or actual impact event might elicit the often exaggerated reactions evoked by the subset of risks classified as uncontrollable, involuntary, fatal, catastrophic, and "dreadful" in the risk perception literature (Slovic, 1987); other features of the impact hazard that predict exaggerated public concern are that it is a newly recognized hazard, due to unobservable agents, as well as a perception that the risk is increasing (the latter isn't actually true, but the augmented telescopic discovery programs are finding "near miss" objects ever more frequently, and the news media are reporting them).

We may hope that such widespread apprehension as when the Earth passed harmlessly through the tail of Halley's Comet in 1910 may not recur in our enlightened, modern times. However, momentous cosmic events often evoke religious or superstitious connections for many people (the titles of two science fiction novels dealing with cosmic impacts exemplify such themes: Niven and Pournelle's "Lucifer's Hammer" and Arthur C. Clarke's "The Hammer of God"). The predicted fiery, but almost certainly harmless, atmospheric re-entry of the Skylab space module in 1979 caused public concern in many nations; efforts at public education may have helped lessen similar fears prior to the re-entry of the larger Mir space station in 2001. However, these real space-related events may be less relevant as analogs for public reaction to many of the more substantial impact scenarios discussed here than such larger natural disasters as the ten-or-so that have each killed more than 10,000 people (a few over 100,000) in the last three decades, or than the horrors of mass terrorism, war, genocide, or epidemic.

In cases where there are advance warnings, public communicators may be able to couch the impending disaster in familiar terms, such as protocols that prepare people to evacuate from approaching hurricanes. Many imagined frightening features of impacts, such as predecessor or after-the-fact subsequent impacts as depicted in movies, are not plausible features of a cosmic impact. So education about the objective character of impacts might reduce dysfunctional reactions. If a destructive impact were to occur without warning, the management of the disaster could proceed much as though it were caused by one or more prosaic natural disasters (earthquakes or floods). The victims need not fear more esoteric after-effects, analogous to earthquake aftershocks or the lingering radiation/infection following a nuclear/biological attack.

The role of the news media in handling the impact hazard has generally not improved as scientific knowledge about the impact hazard has become more robust. During the year 2002, there were several widely broadcast but erroneous concerns about NEAs. Public commentators suggested that the Spaceguard Survey is inadequate because asteroid 2002 EM7 emerged unseen from the direction of the Sun (called a "blind spot" by those unfamiliar with search strategies) and was found only after passing by the Earth. There was extraordinary hype and hyperbole about asteroid 2002 NT7 (the BBC reported, falsely, that it "is on an impact course with Earth"). Also, in late November, headlines around the world proclaimed that the impact hazard is now less than had been thought based on an article in *Nature* (Brown *et al.*, 2002) that demonstrated nothing of the sort, being restricted to data concerning objects 1 - 10 m across that we have described above as essentially harmless. Different governments and societies have varied approaches to disseminating reliable information to citizens. It is not too early to consider ways to prepare citizens and emergency response organizations to respond appropriately to what might well be badly distorted information in the world news media about an impending impact. One element of such an approach is to develop a consistent protocol for placing predictions or warnings of potential impacts into context by utilizing the 10-point Torino Scale (Binzel, 2000).

The Role of Scientific Uncertainties

I have already quoted last year’s OECD document "Identify Risk" in explaining the central role of scientific uncertainty. Uncertainty is a fundamental attribute of the forecasting sciences. But it is notoriously difficult for technical experts to communicate uncertainty to public officials in ways that can be translated into practical measures (numerous examples are discussed in the "Prediction..." book, Sarewitz *et al.*, 2000).

The impact hazard involves its own peculiar suite of uncertainties. In some ways, asteroid impacts are more reliably predictable than any other natural disaster. In the same way that astronomers have long forecast when solar eclipses will occur, or that modern space engineers can guide a spacecraft to orbit a distant planet, it is possible to calculate precisely when and where an asteroid will hit, perhaps many years or decades in advance. But that is true only once its orbit has been precisely determined, which may take months or even many years after it is first discovered. In the interim, an arcane suite of uncertainties clouds the reliability of predictions, and the ongoing highly technical work is difficult for science journalists to understand or translate to the public. Simplified analogies, like throwing darts at a target, do not generally apply.

Above and beyond the formal, statistical uncertainties that affect all scientific predictions, the impact hazard is particularly prone to "meta errors." These are the errors due to perceptual mistakes, computer programming errors, inadequate modelling or extrapolations, miscommunications, and other confusions that are amplified by the fact that impact disasters are unprecedented, and the hazard itself is a rather new and unfamiliar concern. There aren’t legions of trained, practiced impact forecasters as there are weather forecasters in bureaus around the world. More significantly, and potentially subject to remedy, protocols for forecasting and communicating about impact events of potential concern are rudimentary at best, increasing the chances for error or miscommunication. Even once astronomers become adept at translating Spaceguard discoveries into calculations of impact probabilities, an *actual impact* will present itself as a unique case, with exceptional characteristics never previously encountered...thus ripe for confusion.

Even more uncertainty clouds predictions of the physical, environmental, social, and economic consequences of a potential or actual impact. I have sketched our best guesses about potential consequences for six different scenarios, but for the more serious among them we have never experienced anything remotely similar. "Experts" in tsunami, weather, and other specialties might be called on to make predictions about consequences of a predicted asteroid impact, but all would be operating in unchartered waters. Thus decision-makers in the public sphere must be prepared for a wider range of contingencies than would be true for more common scientific hazard predictions (e.g. for maximum river levels in a flood).

Civil Defense: Synergy with Other Hazards and Emergencies

As exhibited in the six cases, impact hazards can be divided into three categories of warning: (a) no warning at all; (b) very short warning (hours, primarily in the case of some impact-induced tsunami); and (c) very long warning (years, or more probably, decades). The long-warning case, of course, has no practical analog -- when in the past has a war, earthquake, or other calamity been reliably forecasted decades in the future? The long warning time plus the nature of the problem permit not only the development of well considered mitigation scenarios for people on Earth but also the possibility of deflecting the asteroid so that the impact simply will not happen (see below).

The other two cases, of zero or short warning, have ample analogs with other disasters that mobilize warning and recovery efforts. If prediction is possible, the location/s likely to be affected should be known as reliably as for such other predictable disasters as hurricanes or earthquake-generated tsunami, in which case more-or-less routine evacuation procedures could be implemented. A downside, however, is that there may well be significant differences from historical experience. An impact-generated tsunami might have different characteristics (e.g. wave frequency, direction of propagation) from previously experienced tsunami because of the location and manner (asteroid impact) in which it was generated. Also, an impact occurs in a random location on Earth, not necessarily near the restricted localities where earthquakes and many weather-related disasters are common and emergency warning-and-response procedures are well practiced; potentially relevant civil defense strategies against military attack are mature in some nations but not in others.

If an impact occurs with no warning, then the recovery procedures would resemble those applicable to most other hazards, emergencies, and wars of comparable magnitude.

(The only exception would be in the case of an extremely unlikely, unprecedented, global disaster occasioned by impact of an asteroid or comet 2 or 3 km in size.) As mentioned above, it is unlikely that a cosmic impact would involve such complicating after-effects as additional impacts or the lingering features of a military attack (e.g. enemy soldiers, persisting radiation). Of course, rescuers would have to deal with irrational fears of after-effects. But, basically, the direct physical damage of the impact explosion would be over in a matter of minutes, any indirect physical consequences such as a wildfire would play out in familiar ways, and the longer-term medical, social, and economic consequences would not be dominated by impact-hazard-specific features. That is not to say that there would be none, however; for example, legal and insurance-related consequences would have no precedent, perhaps complicating restitution.

Deflecting a Dangerous Asteroid

While the concept of stopping a natural disaster from happening is not unknown (e.g. avalanche control), most natural disasters are marginally or not at all preventable. The impact hazard is unique in this respect. A literature has developed in the past decade about potentially available space-based technologies that could divert an asteroid, causing it to miss the Earth, given a long enough lead time (years to decades). While early discussion emphasized the use of powerful bombs to disrupt or abruptly change the velocity vector of an asteroid, recent analyses have focussed on slower acting, low-thrust options (Mitigation Workshop, 2002). One motivation is to minimize the possibility of rapidly stressing the body and disrupting it into multiple dangerous, uncontrollable pieces. There are several associated policy issues, which I touch on briefly here.

While the generic elements of asteroid deflection technology are known (e.g. there has already been a spacecraft landing on one Earth-approaching asteroid, Eros), no integrated system has been designed, let alone implemented. It may be prudent or cost-effective to develop such technologies, perhaps as comparatively inexpensive add-ons to space missions conducted for other purposes (e.g. scientific or resource utilization). The community of space-faring nations will need to determine what level of priority should be given to budgeting such mitigation-oriented activities before any asteroid is known to be headed for Earth. In this context, consideration should be given to the "deflection dilemma" (Sagan & Ostro, 1994) prior to full development of an asteroid deflection technology in the absence of an impending impact; the fundamental argument is that the risk of the technology being misused could be greater than the risk of an asteroid impact.

In the unlikely case that an asteroid is found to be on an Earth-collision course, then there would be a sudden, high-priority justification for exploratory and developmental space missions motivated by the need to study the asteroid that needs to be deflected. Such a program should be conducted in an open, international forum in order to fully take into account potentially sensitive issues, such as options of using controversial weapons-based technologies. An issue being studied by the B612 Foundation (Schweickart, 2002) concerns the politically sensitive issue of how a long-term, low-thrust deflection operation is carried out. Presumably prior to any deflection, a specific time and geographical location for "ground zero" will be known with high precision. However, during the course of a long-term deflection operation (perhaps taking months or years of applied low thrust), the nominal ground-zero point will be controllably moved toward, and eventually beyond, the limb of the Earth. By accident or malicious design, the deflection operation could be halted with the ground-zero point located over a different country from the one where nature first placed it. No nation would feel wholly comfortable about having the devastating risk moved, however temporarily, from another country to itself. It is obvious that this scenario requires broad international involvement in the development of a trustworthy system to accomplish the deflection.

Conclusions in a Post-Sept. 11th Context

Especially in the United States, but throughout much of the world, the terrorist attacks on New York City and Washington D.C. on Sept. 11, 2001 (9/11), have had a major effect on the public's perception of their personal safety and security in the face of unexpected disasters. Even in the seemingly disconnected professional world of natural hazard research, 9/11 has served as a touchstone for contemplating future social consequences of all manner of hazards.

One feature of 9/11 is distinct from the impact hazard: its proximal cause resulted from the malicious intentions of human beings rather than an amoral natural contingency. On the other hand, there are obvious (and potential) similarities. The airliner attacks on buildings occurred with no (or at least wholly inadequate) warning, as would be expected for any cosmic impactor likely to kill similar numbers of people. The resulting deaths (~3000) and direct physical damage to Lower Manhattan and the Pentagon were magnified enormously (in both social and economic terms) as the United States government and American citizens responded in countless different ways (e.g. minimizing travel, changing national budgetary priorities, attacking the Taliban regime in Afghanistan, becoming fearful of the future). Obviously, it was not the deaths or direct destruction (modest in terms of historical disasters) that caused such additional disruptions to the American economy and way of life. It was the particular, unexpected, and horrifying nature of the attack.

Reactions to much more deadly disasters around the world are often characterized by a subdued fatalism -- especially in an international context, but even in the affected nation -- if the cause is the usual "act of God": an earthquake, typhoon, or flood. While such disasters encompass countless personal tragedies and may engender massive international relief efforts, they lack the amplified and reverberating repercussions witnessed after 9/11. Where on this scale of concern might an asteroid impact lie? Research in risk perception suggests that a large, unexpected asteroid impact could have an effect more like that following 9/11, even if the actual mortality and damage were comparatively modest. Connected viscerally to the event by TV news coverage, many people would fear that they could be the next random casualties. Victims would seek scapegoats, just as the U.S. is now engaged in a massive search for pre-9/11 failures of its intelligence agencies. Inasmuch as a known, incoming impactor can, in principle, be diverted using existing space technology, many victims may well ask, "Why wasn't something done?" Of course, the technology that could discover all potential ~100 m projectiles, and that would reliably divert or destroy an incoming one, would be enormously expensive. But it is technologically feasible, hence the reason it is not being implemented is at least an implicit political decision, so far, concerning priorities on the part of the governments of the world's space-faring nations.

As the OECD (2001) document "Identify Risk" notes, despite much individual, personal risk-taking behavior, "collective risks are barely tolerated, regardless of the anticipated degree of risk." Thus, it would be wise for "governments and other standard-setting organizations...to define a rational level of acceptable or tolerable risk" for the impact hazard and to do so, not by benign neglect, but rather by examining "scientific and socio-economic information in a *public forum open to free communication* and debate by all concerned parties." [Quotes, including emphasis, from OECD, 2001.] In this way, the development of an appropriate level of approaches toward responding to the impact hazard would have a rational legitimacy. It is toward that end that I offer this preliminary examination of the practical consequences of, and mitigation requirements for, several asteroid impact hazard scenarios. Much additional effort is required to provide a thoroughly sound foundation for decision making.

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