Antarctic Asteroid Effects

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Motivation for the Model

The only type of energy expansion relatively similar in scale to an asteroid impact is a nuclear explosion. The National Research Council (NRC) assessed the impacts of nuclear war on the atmosphere [Press et al. 1985], and their report details the potential for major atmospheric effects for blasts of various sizes. Our model extrapolates these effects for much higher yields.

We calculate the energy yield of the asteroid impact using Newtonian mechanics. We then use the NRC findings to estimate the impacts of such a yield. Finally, we assess human casualties from the impact in terms of food production, rising sea levels, and atmospheric fluctuations.

Initial Assumptions

- The asteroid is 1 km in diameter at impact.
- The asteroid is approximately spherical. A different shape would affect air drag and thus impact velocity but little else. Hence, a nonspherical asteroid is equivalent to a spherical asteroid with a different velocity.
- The asteroid has a density of between 2 and 8 g/cm^3, typical of a stony meteorite or asteroid [Wasson 1974].
- The asteroid's velocity when striking the earth is between 11 and 70 km/s [Wasson 1974].
- The Earth-asteroid collision is inelastic.

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- The crater produced by the impact has a parabolic shape. This is consistent with models in King [1976].
- There is no great difference in effect due to the angle of impact. We assume that pieces of the asteroid burnt away during descent are significantly less important than the impact itself; an asteroid reduced in this way should be equivalent to a spherical asteroid of a different velocity.
- The explosion of impact is similar to a nuclear blast.

Table 1.
Symbols used in equations.

Symbol	Description	Units
α	Nitric oxide constant	0.8×10^{32}(molecules NO)/MT
C	Initial amount of nitric oxide post-impact	mol
D	Diameter of crater	m
d	Density of asteroid	kg/m^3
ΔT	Change in temperature	°C/yr
G	Greenhouse constant	0.007°C/yr
k	Joule–kiloton proportion constant	4.2×10^{12} J/kT
KE	Kinetic energy of asteroid at impact	Joules (= kg·m^2/s^2)
M	Mass of asteroid	kg
ω	Percentage of ozone lost	—
ρ	Ratio of diameter to depth	—
V_{asteroid}	Volume of asteroid	m^3
V_{crater}	Volume of crater	m^3
v	Velocity of asteroid at impact	m/s
w	Ejecta of H_2O into atmosphere	mol

Impact

Diameter of the Crater

The diameter of the crater depends on the kinetic energy of the asteroid. A basic Newtonian formula gives the kinetic energy of the asteroid as

$$\text{KE} = \frac{1}{2}\,Mv^2.$$

The mass is simply the volume multiplied by the density, giving

$$\text{KE} = \frac{1}{2}\,V_{\text{asteroid}} d v^2.$$

For a spherical asteroid, the volume is

$$V_{\text{asteroid}} = \frac{4}{3}\,\pi r^3.$$

The diameter of the crater, according to Wasson [1974], is

$$D = 49W^{0.294},$$

where W is the total work done by the asteroid on the Earth, in kilotons of TNT. Thus, to find the diameter, we substitute kinetic energy for total work:

$$D = 49\left(\frac{1}{2}Vdv^2k\right)^{0.294},$$

where k is a proportionality constant that converts Joules to kilotons of TNT:

$$k = \frac{1}{4.2 \times 10^{12}}\,\frac{\text{kT}}{\text{J}}.$$

Thus, the diameter depends on the volume of the asteroid, its density, and the velocity at which it impacts the South Pole. See **Table 2** for different scenarios for varying densities (2, 3, 5, and 8 g/cm^3) and velocities.

Table 2.
Scenarios.

Scenario	Asteroid			Crater			
	Velocity v	Mass M	Energy	Diameter	ρ	Volume	Depth
	km/s	$\times 10^{12}$ kg	$\times 10^4$ MT	$\times 10^3$ m		$\times 10^{10}$ m^3	$\times 10^3$ m
A	11	1.05	1.51	8.27	5	4.44	1.67
		2.62	3.76				
		4.14	6.02				
	20	2.62	7.48				
B	20	1.57	12.5	10.1	7	9.22	1.44
	30	1.57	16.8				
C	30	2.62	28.1	11.8	7	18.6	1.69
	50	1.57	46.7				
D	50	2.62	78.1	20.2	8	12.9	2.53

Volume of the Crater

Let the crater have a diameter-to-depth ratio of ρ; according to King [1976], $5 \leq \rho \leq 8$. Thus the crater has radius of $D/2$ and depth D/ρ.

We assume that the crater is a paraboloidal cap with cross-sectional parabola

$$y = Ax^2.$$

Algebraic manipulation gives

$$y = \frac{4}{\rho D}x^2.$$

We rotate the parabola around the y-axis and use circular disks to find the volume of the paraboloidal cap:

$$V_{\text{crater}} = \int_0^{D/\rho} \pi x^2 y\, dy = \int_0^{D/\rho} \frac{\pi \rho D}{4} y\, dy = \frac{\pi D^3}{8\rho}.$$

For a density of 3.0 g/cm^3 and an impact velocity of 20 km/sec, we find that the crater has volume 9.22×10^{10} m^3.

Effects of Impact

We first look at how much water would be ejected by the impact and then consider the effects of the shock wave created by impact.

Ejecta

We assume that due to the depth of the ice at the South Pole, the amount of dust ejected from the crater would be minimal. However, the amount of ice ejected is a different matter. For this, we look at the effects of nuclear blasts and ejections of dust with diameter less than one micrometer.

In nuclear blasts, about 1% of the volume of the crater is ejected into the stratosphere [Press et al. 1985]. We assume that ice would eject at a higher rate than dust because instead of rock, this asteroid would vaporize ice—a much easier task. So we use 5% of the volume of the crater as the total amount of ejecta (water as vapor, water, and ice) into the stratosphere.

The amount of dust vapor from a nuclear blast of 1 MT or less is between 0.2 and 0.5×10^{12} g/MT [Press et al. 1985]. For Scenario B (an average case), with energy 7.5×10^4 megatons, a yield of 5% of volume gives 0.06×10^{12} g/MT.

Some dust would be ejected into the atmosphere, some would come from the asteroid itself, and some could even from Antarctic soil if the depth of the crater exceeds the depth of the ice (2,800 m)—but this last does not occur in any of our scenarios (see last column of **Table 2**).

Shock Waves

At impact, a spherical shock wave would be emitted, affecting both land and air but at different rates. Most effects of the impact would come from the shock wave rather than from the ejecta. We discuss the effects of the shock wave in terms of overpressurization, a thermal radiation contour, and the making of nitric oxide.

Overpressurization

According to Press et al. [1985], an area is "overpressurized" if the shock wave creates a 5 psi (pounds per square inch) increase over normal atmospheric pressure.

Table 3 provides sample radii of overpressurization, given certain energy levels. The Ross Ice Shelf is 600 km, and the West Ice Shelf is 2600 km, from the impact site. Overpressurization past these points would overstress the respective ice shelves, possibly causing massive volumes of ice to break off and float into the ocean.

In addition to the ice shelves, there are more massive ice sheets that hold the vast majority of water in the continent. The Western Ice Sheet may be unstable [Glacier ... 1999; Is Global Warming ... 1999], and overpressurization of the sheet could cause much of it to break off from the continent.

Table 3.

Shock wave effect radii in km, from regression on the yield x in kilotons.

Scenario	Overpressure radius $r_o = 8.62010 + 0.132189x$ ($\times 10^3$ km)	Incineration radius $r_i = 2.50300 + 0.247767x$ ($\times 10^3$ km)
A	1.26	1.72
B	1.77	2.43
C	3.44	4.71
D	5.73	7.85

Thermal radiation contour

The shock wave also would create a 30 cal/cm^2 thermal radiation contour. This is essentially a heat wave; there is little on the Antarctic plain that would incinerate, but the heat would instantaneously melt the surface ice. Much of the water would refreeze as quickly as it melted, but water that doesn't refreeze quickly could account for additional water vapor in the air.

At higher energy levels, the incineration radius encompasses large portions of South America and could lead to forest fires (see **Table 3**).

Nitric Oxide Emission

From Press et al. [1985], we know that large blasts create and release large volumes of nitric oxide (NO) into the stratosphere. The chemical reaction is

$$\mathrm{O_2 + N_2 \rightarrow 2NO},$$

and NO is produced at a rate of

$$\alpha = 0.8 \times 10^{32} \text{ molecules NO/MT}.$$

Table 4 uses this rate to give the amounts of NO that would result from explosions of various megatonnage.

Table 4.
Quantities of H_2O and NO (in moles) lofted by explosion.

Scenario	H_2O	NO
A	1.22×10^{14}	$5.0\ \times10^{12}$
B	2.56×10^{14}	9.93×10^{12}
C	5.16×10^{14}	3.74×10^{13}
D	3.58×10^{14}	1.04×10^{14}

Atmospheric Effects

The impact would have major consequences in the upper levels of the atmosphere, including a significant decline in stratospheric ozone. Also, some nitric oxide would convert into nitric acid and cause acid rain.

Ozone

The atmosphere currently contains 3.3×10^{15} g of ozone. With the emission of nitric oxide caused by the heat created by the impact, a significant amount of stratospheric ozone would decompose into nitrogen dioxide and oxygen, according to the reaction

$$\mathrm{NO} + \mathrm{O}_3 \rightarrow \mathrm{NO}_2 + \mathrm{O}_2.$$

From how much nitric oxide is put into the air and the rate at which it reacts with ozone, we can find how much ozone would decompose and how fast.

The amount of nitric oxide emitted by the shockwave is αE, where E is the energy of the explosion given in megatons.

Normally in the atmosphere, 99% of the nitric oxide reacts with ozone to form nitrogen dioxide and oxygen. However, given the substantial amount of water displaced into the stratosphere by the asteroid, we predict that only 97% of the NO would react with O_3. Thus, the rate at which NO is lost over time due to reaction is given by

$$\frac{d(\mathrm{NO})}{dt} = -0.03(\mathrm{NO}). \qquad \textbf{(1)}$$

The nitrogen dioxide produced by the reaction is reconverted into nitric oxide (NO) according to

$$\mathrm{NO}_2 + \mathrm{O} \rightarrow \mathrm{NO} + \mathrm{O}_2.$$

Thus, nitric oxide is replenished naturally after reacting with ozone.

Solving **(1)**, we get

$$\mathrm{NO} = Ce^{-0.03t}, \qquad \textbf{(2)}$$

where C is the initial amount of nitric oxide after the explosion. The normal amount of NO in the atmosphere is 10^{10} moles. To judge the effects of additional

NO in the atmosphere, we need the time for the NO levels to return to normal (see **Table 5**).

Table 5.
NO normalization time.

Scenario	Time (days)
A	207
B	230
C	274
D	308

Since ozone reacts with NO in a one-to-one ratio of molecules, the area under the curve of **(2)** yields the mass of ozone (in moles) that is decomposed:

$$\int_0^t Ce^{-0.03t}\,dt.$$

Solving, we find that all of the ozone would be depleted long before NO levels return to normal. **Table 6** shows estimates of ozone depletion from nuclear blasts. Regression on **Table 6** gives a fairly linear fit, which produces results similar to our own.

Table 6.
Nuclear war ozone depletion estimates, from Press et al. [1985].

Scenario	Yield (MT)	Maximum Ozone Depletion (%)
Baseline	6,500	17
Excursion	8,500	43
Chang Case A	10,600	51
Chang Case B	5,300	32
Chang Case C	5,670	42
Chang Case D	4,930	16
Chang Case E	6,720	39
Chang Case F	3,890	20
Ambio excursion	10,000	65
Turco et al. (1983)	10,000	50

Acid Rain

The other 3% of NO reacts in the stratosphere first to form NO_2 and then with water to form nitric acid:

$$NO_2 + 2H_2O \rightarrow HNO_3 + H_2. \quad \textbf{(3)}$$

Only 3% of NO converts to HNO_3, and only 3.8% of HNO_3 turns into a cloud form [Walker 1977]. Therefore, only 0.114% of the NO turns into acid rain.

However, this concentration is much higher than that of normal acid rain. The usual concentration of HNO_3 in water vapor is 30 ppb [Walker 1977]. **Table 7** shows the different concentrations of HNO_3 in water vapor after varying scenarios.

Table 7.
Acid rain; the usual HNO_3/H_2O is 30 parts per *billion*.

Scenario	HNO_3/H_2O (ppm)
A	46
B	44
C	83
D	330

Environmental Impacts

Global Warming

With the complete loss of the ozone, it is safe to say that catastrophic events would occur, especially with respect to global climate. Let ω stand for the percentage loss of ozone. Let G stand for the "greenhouse constant," which is the amount of temperature increase given no ozone depletion. Thus, our model equation is given by

$$\Delta T = G + \zeta\omega,$$

where ζ is a proportionality constant. By experimentation (of others), we find that $G \approx 0.007^\circ$ C/yr. Earth's climate has increased approximately 4° C over a twenty-year period. In that time, the ozone level decreased by 4%, giving $\omega \approx 0.04$. Solving for ζ gives $\zeta \approx 4.83$. Thus, our equation for the change in temperature in °C/year given ω is

$$\Delta T = 0.007 + 4.83\omega.$$

This model works nicely but only for small values of ω. When $\omega \geq 0.2$, as in our scenarios, the model loses most of its usefulness. The temperature increase due to a lack of ozone would be large and pose a threat to human existence.

Sea Levels

One of the major concerns of global warming theorists is the effect of polar melting and a change in sea level. A rise of 1 cm in sea level would salinate coastal rivers up to 1 km inland [Glacier ... 1999]. The melting of the Western Ice Sheet of Antarctica would cause a 6 m rise. Having no ozone would eventually lead to these events. Besides the Western Ice Sheet, there are many other ice formations in Antarctica that could be affected by global warming. If all of Antarctica's ice melted, sea level would rise 60 m. Other possible causes of a rise in sea level are the overpressurization of Antarctic ice and the thermal radiation contour created by the blast. The thermal radiation contour might weaken the ice, and the overpressurization would then break the ice off the continent.

Our model predicts that the oceans would rise 7 to 10 m within 10 years. This would cause most small island countries to become uninhabitable. Coastal seaports would be flooded all over the world. With no ozone in the atmosphere, this rise would surely continue over the following years.

Food Supplies

The impact would significantly decrease crop yields, because of the rise in sea level, the rise in temperature, and the overabundance of ultraviolet radiation.

The rise in the sea level would wipe out all crops in coastal regions, especially in Brazil, southeastern China, the Mediterranean, and India. Salinization of coastal rivers would significantly reduce the amount of irrigation that can be done, thus affecting the midwestern United States along with interior Africa.

The desalinization of the ocean due to the melting to polar ice caps would significantly affect the South Atlantic, South Pacific, and Indian Oceans. This desalinization would pose serious health risks to shallow-water fish and other sea life that relies on salt water. Thus, fishing would significantly decrease off the coasts of South America, Africa, the Indian Peninsula, and Southeast Asia.

The rise in temperature and the overabundance of UV would also greatly affect all plant and animal life. Since this change is so rapid, the threat of extinction of multiple species would be imminent.

Impacts to Humans

Crops highly affected would be ones requiring lots of fresh water, such as rice, corn, grain, bananas, coffee, sugar, and other staples. The regions most affected would be those that grow enough just to support their own nations, not those that export these staples. Nations such as Brazil, China, India, and much of the non-industrialized world would find a severe lack of food. Countries like the United States, which have enough grain and corn to export, would barely be able to sustain themselves, much less export food to other countries. Much of North Africa, the Middle East, Central Asia, and central South America, which have little natural arable land, would indubitably starve. The impact of this alone could cause the population in those areas to suffer tremendous losses.

For example, "soybean yield may drop one percent for each one percent drop in ozone" [Hidore 1996]. By extrapolation, a complete loss of the ozone layer would result in the complete loss of soybean crops. The same holds true for many other crops. Even if the loss were not this drastic, most of the world's crop production would be lost.

The severe increase in ultraviolet radiation would significantly impact the entire planet. According to Hidore [1996], "models show that a 16% reduction in ozone will result in a 44% increase in UVB radiation. A 30% global reduction in ozone will produce a doubling of surface UVB radiation." A 100% loss of ozone would more than sextuple the amount of radiation, given a linear model. "The EPA forecasts that for every 1% decrease in the ozone layer, there will be a 3% increase in non-melanoma skin cancer." Hence non-melanoma skin cancer cases would triple under our scenario.

A rise of sea levels of 7 to 10 m would displace the half of the world's population that resides near coastlines. Most of this would occur in India and Southeast Asia. Other major seaports such as New York, Tampa, Rio, Bangladesh, Cape Town, and Cairo would also be affected. This major relocation of people would lead to massive overcrowding in the rest of the world and impose on land designated for the growing of crops and the raising of livestock.

Although less likely, a very serious threat that could threaten the population of southern Chile and Argentina is a large-scale earthquake. The shock wave, if large enough (Scenario D), would overpressurize the Tierra del Fuego and surrounding areas. This could also create tsunamis that would ravage the coasts in this area.

Other Effects

Our model concentrates mostly on atmospheric effects of the asteroid's impact, but focuses little on two areas of possible importance: severe cloud cover and tsunami. Severe cloud cover caused by the tremendous amount of water vapor and/or dust ejected into the stratosphere could cover the earth for several months. However, since the average water cloud lasts for only an hour, the probability of long-term cloud cover is minimal. The force of the impact itself and the shockwaves from the explosion, or even ice shelves falling into the ocean, might cause enough seismic disturbance to create a tsunami. Such a tsunami could immediately threaten coastal areas in the Southern Hemisphere, resulting in severe flooding along the coasts of South America, Southern Africa, India, and Southeast Asia.

Strengths and Weakness of the Analysis

Strengths

The greatest strength of the model is the ease with which the equations are derived and can be recalculated given different scenarios, such as a smaller or larger asteroid. The model also incorporates the significant parameters of the impact, including velocity and density of the asteroid.

Weaknesses

The greatest weakness is the model's simplicity. Our model does not take into account carbon dioxide effects in terms of global warming, deal with desalinization of the ocean currents, nor calculate the pH difference due to a significant amount of HNO_3 being displaced due to acid rain.

In basing our modeling on smaller-scale detonations, we extrapolate into uncharted territory, which could very easily lead us to overestimate or underestimate the impacts of the asteroid.

Conclusions

Since our model suggests that the environment would be ravaged by such an impact, that sea levels would rise due to global warming and the breaking off of Antarctic ice sheets, and that a severe loss of food due to flooding and salinization of previously freshwater coastal river would occur, the probability of a substantial number of deaths is quite high.

Our model shows significant damage done to staple crops (such as soybeans) and a significant increase in ocean temperature, along with desalinization due to ice melting and rain. In the short term, we predict a 7 to 10 m rise in sea level, with a long term forecast of a 60 m rise with the complete melting of the Antarctic ice sheets.

Human deaths would result from multiple factors:

- Flooding would destroy much of the coastal regions of the earth. Half of the Earth's population would be displaced to higher and less arable ground.
- The tripling of UV-B radiation would certainly shorten the life expectancy of humankind.
- There would be an intense increase in the world's mean temperature, which has not happened since the dawn of man.

It is hard to picture the drastic conclusions that we have reached because we have no experience with events of this nature. We certainly hope that science can find a way to prevent such an event.

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