Not an Armageddon

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Abstract

We separate the effects of the impact into three periods.

- **Pre-impact** Loss of kinetic energy due to air resistance as the asteroid travels through the atmosphere is less than 0.15%, which is negligible.
- **Short-term**
  - The impact could produce at most 2,940 km^3 of liquid water, which is not sufficient to affect sea level.
  - The maximum volume of ice turned to water vapor would be 383 km^3, insufficient to cause long-term weather changes.
  - We anticipate global seismic effects on the order of 4 to 6 on the Richter scale, depending on the velocity and composition of the asteroid and the distance from the South Pole.
- **Long-term**
  - Even in the worst case, the water vapor introduced to the atmosphere would condense and precipitate quickly, due to the low dewpoint of the polar air and the presence of iron particles to serve as condensation nuclei. We are uncertain as to the effects of iron fallout on the ecology of the Southern Hemisphere.
  - There would be moderate loss of life and property damage in the southern hemisphere. We remain uncertain as to the ecological effects of such an impact but suspect that they would be negligible. We expect that there would be no threats of coastal flooding due to asteroid impact.

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Assumptions

- The asteroid is spherical in shape (this shape maximizes the asteroid's mass, and therefore its kinetic energy and the impact effects).
- The asteroid has an approximate diameter of 1 km.
- The asteroid strikes at the South Pole.
- Since an asteroid that "strikes the earth" does not explode in the atmosphere or rebound off the atmosphere (like a stone skipping on water), we assume that the angle of entry must be greater than 10°.
- The asteroid is primarily composed of iron and nickel. While this assumption is slightly inaccurate (other constituents being varieties of minerals, such as silica and magnesia), it facilitates calculations; because these are the densest materials in an asteroid, this composition results in the greatest mass and thus the greatest energy of impact. The average density of such an asteroid is 5,000 kg/m^3. Moreover, an asteroid composed primarily of iron is significantly less likely to explode before impact.
- The energy of impact of an asteroid is divided between heating the target, heating the asteroid, deformation, and kinetic energy of ejecta. This assumption comes from the 1978 NASA Conference Proceedings on Asteroids [Morrison and Wells 1978, 148].
- The energy of an earthquake is inversely proportional to the square of the distance from the epicenter.
- Seismic waves propagate mainly along the surface of the earth, rather than in a straight line between two points on the surface.
- The depth of ice at the South Pole is approximately 2.5 km.

Model Inputs

- Density of asteroid (depending upon its composition), ρ_{ast}
- Velocity of the asteroid at impact, V_0
- Angle of entry, α
- Initial average temperature of the ice at the South Pole, T_{in}

Other inputs are the percentages of kinetic energy that go into:

- Heating the asteroid, H_{ast}
- Heating the planet (ice), H_{ice}

- Energy of deformation, E_{def}, and
- Kinetic energy of the ejecta, E_{eje}.

Atmospheric Entrance Model

We calculate how much energy is transferred from the kinetic energy of the asteroid to heating the asteroid via air resistance.

$$\begin{aligned} &\text{Mass :} && M_{\text{ast}} = \rho_{\text{ast}} \pi d_{\text{ast}}^3/6 \\ &\text{Kineticenergyofimpact :} && \text{KE} = M_{\text{ast}} V_0^2/2 \end{aligned}$$

The kinetic energy converted to heating the asteroid, due to air resistance, is

$$\text{KE} = \frac{10^5 CAV^2}{6 \ln 10 \sin \alpha},$$

where c is a physical constant based on viscosity and density of air, v is velocity, A is the cross-sectional area of the asteroid, and the rest is a factor corresponding to the changing density of air as the asteroid enters the atmosphere. (We derive this formula in the **Appendix**.)

Entrance Results

The fraction of kinetic energy turned into heat energy by the air resistance would be only 0.02% to 0.15%; therefore, the effect of air resistance would not be significant.

Impact Model

We compute

- the mass of the evaporated water, $M_{\text{H}_2 0}$;
- the size of the impact crater, D_{cra};
- the mass of ejected debris from the impact, M_{eje}; and
- the approximate Richter value of the shock wave generated by the impact and the earthquake intensities felt at certain southern hemisphere cities.

We proceed in the following fashion:

Mass: $M_{\text{ast}} = \rho_{\text{ast}} \pi d_{\text{ast}}^3/6$
Kinetic energy of impact: $\text{KE} = M_{\text{ast}} V_0^2/2$

Crater diameter: $d_{\text{cra}} = (\text{KE}/k)^{2/7}$ [Davies 1986, 103], with $k \approx 10^{15}$. (We estimated this proportionality constant based upon experimental data on size and kinetic energy involved in the formation of craters given in Davies.)

Volume of crater ejecta: Since crater depth is approximately one-tenth of the diameter [Verschuur 1996, 17], we have $\text{Vol}_{\text{cra}} = \pi d_{\text{cra}}^3/40$.

Approximate earthquake forces: These calculations are based on a linear regression (of data gathered from the Cascades Volcanoes Observatory Homepage [1999]) of Joules of energy compared to Richter scale value. For cities distant from the South Pole, we use an inverse-square law to determine how much energy would reach the city and calculate the magnitude of an earthquake with epicenter there to give an approximate "Richter" value. The distance, d, is taken to be the ratio of the distance to the edge of the epicenter (about 1 km) of a quake at the city and the distance from the South Pole to the city. This "Richter" value is an extreme exaggeration and should be taken as the absolute upper bound on the vibration and damage that is done to a given city.

Epicenter Richter value: $R_{\text{epi}} = log_{10}(E_{\text{def}}KE)/1.4995 - 3.2035$.

Distance "Richter" value: $R_d = log_{10}(E_{\text{def}}KE/d^2)/1.4995 - 3.2035$.

Mass and volume of water vapor: We assume that all of the heat that goes toward heating the planet and ice evaporates ice. This assumption gives the worst case in terms of the amount of new water vapor introduced into the atmosphere.

Mass vaporized:

$$M|\text{vap} = \frac{H_{\text{ice}}KE}{T_{\text{in}}S_{\text{ice}} + \text{HF}_{\text{ice}} + 100°C \times S_{\text{H}_2 0} + \text{HV}_{\text{H}_2 0}},$$

where S_x is the specific heat, HF is the heat of fusion, and HV is the heat of vaporization.

Volume vaporized: $\text{Vol}_{\text{vap}} = M_{\text{vap}}/r_{\text{ice}}$.

Mass and volume of liquid water: We suppose that all of the kinetic energy of the asteroid goes into melting the ice.

Mass melted: $M_{\text{mel}} = \dfrac{H_{\text{ice}}KE}{T_{\text{in}}S_{\text{ice}} + \text{HF}_{\text{ice}}}$.

Volume melted: $\text{Vol}_{\text{mel}} = M_{\text{mel}}/\rho_{\text{ice}}$.

Scenarios

We ran a number of scenarios to determine the worst possible global damage, based on unfavorable assumptions about energy distribution upon impact, asteroid densities, and asteroid velocities. We also ran a scenario with relatively more realistic assumptions about the distribution of kinetic energy and with densities and velocities closer to average for an asteroid of the given size.

First we supposed that the impact velocity of the asteroid would be 30 km/s (approximate upper bound for asteroid velocity), with a density of 5,000 kg/m^3, and that all of the energy would go into melting ice near the Pole. Our model calculates that approximately 3.81×10^{14} kg of water vapor would be ejected into the atmosphere. This corresponds to 413 km^3 or 0.0013% of the frozen ice on the Antarctic continent. Even in this exaggerated scenario, we anticipate that there would be no threat to coastal populations from flooding. On the other hand, this amount of water vapor corresponds to a relatively large increase in atmospheric water vapor (0.74%), but mixing with the very cold polar air would lead almost immediately to condensation and then precipitation [Ahrens 1994, 139–141].

If we suppose that all the kinetic energy would merely melt the ice (and leave it at 0° C), we find that 2.94×10^{15} kg of ice would melt, equivalent to 2,940 km^3 of water. But this is only 0.0093% of the ice on Antarctica. This corresponds to an average rise of water level of 7 mm and would not cause any coastal flooding. Moreover, most of this water would remain in the crater, and other water is unlikely to travel the more than 1,200 km to the ocean.

Another extreme scenario is that the kinetic energy would all be converted to deformation energy (and thus earthquakes), that the asteroid has a density of 10,000 kg/m^3, and that the asteroid is traveling at 35 km/s. This seismic worst-case gives an epicenter magnitude of 11.1 on the Richter scale. This is about 230 times(!) as powerful as any recorded earthquake. Vostok Station (about 1,333 km from the South Pole) would feel the shock of a magnitude-7 earthquake, and major Southern Hemisphere cities would feel a shock of magnitude 6. There might be a considerable number of casualties in those cities.

A more reasonable scenario is the energy distribution given by Chapman [Morrison and Wells 1978, 145–160]: An asteroid striking the moon at 5 km/s would contribute 20% of its energy to heating the target, 20% to heating the asteroid, 50% to deformation, and 10% to the kinetic energy of the ejecta.

The 20% of the kinetic energy that would go into heating the asteroid would have the effect of turning part of the asteroid into a super-heated gas. The 20% into heating the ice surrounding the impact site would evaporate 36.8 km^3 of ice and send the resulting water vapor up into the atmosphere. The 10% to ejecta would eject a portion of still-solid ice into the atmosphere and onto Antarctica. A crater 35 km in diameter would be created.

The remaining 50% of the asteroid's kinetic energy would be converted into energy of deformation and produce shock waves, which in turn would cause earthquakes. The earthquake energy at the epicenter would be equivalent to a 10.4-magnitude earthquake, about 20 times as large as any recorded. At Vostok Station, this would feel like a magnitude 6.4 earthquake. Major Southern Hemisphere cities would feel the equivalent of a 5.5-magnitude earthquake.

In any scenario, the net effect of these shocks to Antarctica would probably be severe cracking of ice and the creation of new icebergs all along the coast of Antarctica. Earthquakes would also cause fatalities in polar research stations.

Because the epicenter of the earthquake is at least 1,200 km from the nearest coast, there is no need to worry about the possibility of tsunamis.

Ecology

Since the depth of ice at the south pole is 2.5 km, very little dust from the Earth would be thrown into the atmosphere. Most of the heating would occur in the upper layers of ice, so the rock under the ice would experience fracturing but not vaporize. The air near the impact would be saturated with water vapor [Ahrens 1994, 139–141] and would mix with the very dry and cold polar air. This would produce rapid condensation and formation of clouds. The iron particles thrown into the atmosphere would serve as condensation nuclei, facilitating rain and snow. We can expect the precipitate to settle over much of Antarctica and the Southern Ocean.

Our model does not incorporate the effects of adding up to 2.6×10^{12} kg of iron to the world oceans. Coincidentally, Monastersky [1995] writes that addition of iron to the ocean could be a possible solution to global warming by encouraging the growth of phytoplankton that use carbon dioxide in photosynthesis. But a dramatic increase in phytoplankton could lead to the production of methane. At any rate, the theory is uncertain, as is our knowledge of net ecological effects of the fallout.

Error Analysis

There is no way to verify the accuracy of the model results. While our sources give similar values for the energy imparted to the Earth by asteroid collision, as well as values for the asteroid temperature after impact, the values are not based on observed energy emission at impact but are estimates of the energy released after impact of asteroids millions of years ago. These sources are likely working upon the same assumptions that we are, but we cannot realistically say how accurate such assumptions are.

General Results

Testing our model for various energy distributions leads us to believe that:

- There would be no significant melting of the polar ice cap.
- The seismic effects would be very intense on the Antarctic continent. Nearby major cities should anticipate, at worst, the equivalent shock force of a magnitude-5 earthquake. The force of collision near the impact might cause the ice crust to crack and shift, and ice near the edge of the ice shelves could break off and form icebergs.

- There would be casualties of some polar research scientists, with minimal other casualties elsewhere.
- Water evaporated in the impact would quickly condense and fall out as rain and snow on the Antarctic continent and Southern Ocean. Such condensation would occur relatively quickly, so we do not anticipate a net warming effect such as might occur if another greenhouse gas of the same volume were released into the atmosphere.
- We are uncertain about the effect of iron and nickel fallout on the ecology of the Southern Ocean.

Strengths and Weaknesses

Strengths of the model include a good estimate of an upper bound on physical damage to Earth. It is highly improbable that shock waves or atmospheric effects could be any more severe than we have calculated. The analytic simplicity of the model is another positive feature.

Weaknesses of the model are the lack of long-term weather and ecological analysis, though the first two portions of the model indicate that the net effect in these areas would most likely be relatively small.

Appendix: Derivation of Formula for Air Resistance

The formula for the air resistance force is

$$R = c\rho A V^2,$$

where V is the speed of the object, A is the area of its cross-section, c is a dimensionless constant that depends on the form and the surface structure of the object, and ρ is density of air at sea level. We denote $c\rho$ by C; at sea level, C should about 0.2 to 0.4 kg/m^3 for a spherical asteroid.

We seek an upper bound for the kinetic energy converted into heat due to air resistance. During the fall from a height of 100 km, the speed of the asteroid would increase by only about 1 km/sec, which is only 4 to 7% of its speed at impact; this small increase would not affect much the trajectory. So we can assume that the asteroid would fall in a straight line and that the speed at impact is the greatest speed reached.

The surface level at the Pole is approximately 3 km above sea level, so the air pressure there is somewhat less than that at sea level. Hence the the work done by the air resistance force would be even less than we calculate below.

The density of air changes with height, but according to Davies [1986] , we need consider air resistance only in the lowest 100 km of the Earth's atmosphere.

For 0–100 km, the logarithmic fraction of density of air at sea level [Gamow and Cleveland 1976] is approximated well by a linear function, so we take the density to be 10^{ad+b}, where d is height above sea level.

We identify a and b. The 100-km height of the atmosphere is relatively small compared to the Earth's radius of 6,370 km, so we may disregard the Earth's curvature and consider the Earth's surface to be horizontal. Suppose the asteroid enters the atmosphere at an angle α with the horizontal. Then the asteroid must travel $(10^5/\sin\alpha)$ m from the height of 100 km to sea level, so

- At sea level: $10^0 = 10^{a\cdot 0+b}$, so $0 = a\cdot 0 + b$, that is, $b = 0$.
- At $(10^5/\sin\alpha)$ m from impact, the density of air is 10^{-6} of that at sea level, so $10^{-6} = 10^{a\cdot 10^6/\sin\alpha}$, so $-6 = a\cdot 10^5/\sin\alpha$, thus $a = -6\sin\alpha/10^5$.

Thus, the air density at a distance h from the point of impact is a fraction $10^{-6}h\sin\alpha/10^5$ of the density at sea level. Air resistance there is

$$R = 10 - \frac{6h\sin\alpha}{10^5}\cdot CAV^2.$$

The work of the air resistance force done on this straight line trajectory is

$$\begin{aligned} W &= -\int_{10^5/\sin\alpha}^{0} R\,dh \\ &= -\int_{10^5/\sin\alpha}^{0} 10^{-6h\sin\alpha/10^5} CAV^2\,dh \\ &= \frac{10^5 CAV^2}{6\ln 10\sin\alpha}\, 10^{-6h\sin\alpha/10^5}\Big|_{10^5/\sin\alpha}^{0} \\ &= \frac{10^5 CAV^2}{6\ln 10\sin\alpha}\left(10^0 - 10^{-6}\right) \\ &\approx \frac{10^5 CAV^2}{6\ln 10\sin\alpha}. \end{aligned}$$

We estimate $0.2 < C < 0.4$ and $A \le \pi r^2$, where $r = 500$ m (since the diameter of the asteroid is 1 km). Since both the kinetic energy of asteroid and the work of the air resistance force are proportional to V^2, the percentage of the kinetic energy that is turned into heat by the resistance force does not depend on the speed of the object.

The angle α cannot be very small, or the asteroid would bounce off the atmosphere like a stone off the surface of water. **Table 1** gives the percentage of kinetic energy of the asteroid that is yielded to air resistance for various values of α less than 1% for any entry angle.

Table 1.
Percentage P of kinetic energy changed into heat by air resistance, for $C = 0.4$, $A = 500$ m, and different values of trajectory angle α (in degrees).

α	10	20	30	40	50	60	70	80	90
P	0.163	0.083	0.057	0.044	0.037	0.033	0.030	0.029	0.028

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