Asteroid Impact at the South Pole: A Model-Based Risk Assessment

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Introduction

We consider approximate upper bounds for the magnitude of various environmental consequences of a spherical iron asteroid with a diameter of 1,000 m impacting at the South Pole.

The increase in worldwide ocean levels would be on the order of a millimeter, except for the possibility of an unstable ice sheet being dislodged into the ocean. There would be global warming effects, though they would not be much greater than those caused by human-based industrial emissions. Significant amounts of acidic water vapor would likely be produced, and the subsequent precipitation of this acid rain in nearby fishing areas would disrupt ecosystems and lead to decreased fish harvests.

Simplifying Assumptions and Modeling

A Worst-Case Scenario

The possible consequences of the impact of a comparatively large asteroid on the Earth are immense in number and in potential impact. A practical model would treat quantitatively only those effects that can be characterized by well-understood physical processes. For each effect, we consider the upper limit of potential environmental impact. This method estimates the "worst-case scenario."

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The Size and Composition of the Asteroid

We assume that the asteroid is spherical and made of iron. Although many near-Earth asteroids are composed of other materials [Kieffer 1980], an iron asteroid would pose the gravest threat, due to its high density, which implies a higher kinetic energy and hence a greater capacity to induce seismic shocks.

Velocities and Energies

We offer a celestial mechanics model to estimate the incident velocity of an asteroid on the Earth's outer atmosphere. To consider the descent of the asteroid, we present a detailed dynamical model to calculate impact velocities as well as to estimate the energy transferred to the atmosphere.

Ice Melting, Vaporization, and Ejection

The asteroid would impact in the heart of the largest reservoir of frozen water on the planet. How much ice would be liberated from the continent? We consider three likely routes by which ice may be affected directly:

- direct heating from the impact kinetic energy,
- melting and vaporization from the pressure wave released, and
- ice fragments breaking off the continent and entering the ocean.

To place upper bounds on these effects, we consider the cases of maximum possible energy transfer to each of these reservoirs. For the pressure wave and the ice fracturing, the bounds are less exact, since empirical estimates must be made of quantities such as the seismic efficiency.

Seismic Shocks and Ice

There is potential for the unstable western ice sheet to become dislodged, partially slip into the ocean, and melt, possibly having dramatic consequences for ocean levels. The calculation is accomplished using a simple wave-equation model for the shock wave and is sensitive to the empirically determined proportion of kinetic energy that goes into the pressure wave.

Climatic Changes from Atmospheric Water Vapor

A large asteroid impact into the ice would transfer much water vapor into the atmosphere, possibly creating an effect similar to the increased greenhouse gases that have raised the mean surface temperature of the Earth. We analyze these potentialities, treating the Earth as a blackbody radiator with a varying albedo.

Chemical Effects and Acid Rain

A final consideration is the production of chemicals in the atmosphere such as nitrous oxides, which can undergo later reactions to produce nitric acids and result in acid rain. Using empirical data for the rate of production of these compounds and the modeled atmospheric energy transfer, we estimate upper bounds on the acidity of rain in the region and for its effects.

Celestial Dynamics of the Asteroid

Gravity

By Newton's Law of Gravitation, the force of attraction between the asteroid and any body is

$$F = -\frac{Gm_a M}{r^2}\,\hat{r},$$

where G is the gravitational constant, m_a is the mass of the asteroid, M is the mass of the other body, and *r* is a vector directed from the other body to the asteroid. Being a central force, *F* may be written as the gradient of a scalar function ϕ:

$$F = -\nabla\phi = -\nabla\left(-\frac{Gm_a M}{r}\right).$$

An integral of *F* over a path depends only on the endpoints of integration and not on the path itself. Because of this feature, ϕ is known as the *gravitational potential energy*. The work-energy theorem of classical mechanics implies the following relationship between the change in the kinetic energy T of the asteroid and the changes in gravitational potential energy for any physical process [Marion and Thornton 1995]:

$$\Delta T = \Delta\left(\frac{1}{2}m_a v^2\right) = \sum_i \Delta\left(\phi_i\right),$$

where the sum is over all bodies with which the asteroid is interacting.

A Lower Estimate of Asteroid Velocity

To obtain a lower estimate of the asteroid's impact velocity, we follow the approach of Melosh in using Earth's escape velocity [Melosh 1989]. The *escape velocity* for a planet is the velocity required for a body to escape completely from the planet's gravitational field. That is, the escape velocity corresponds to the change in gravitational potential energy in bringing an object from infinity to the surface of the planet. We have

$$\frac{1}{2} m_a v^2 = \lim_{R \to \infty} G m_a m_{\mathrm{e}} \left(\frac{1}{r_{\mathrm{e}}} - \frac{1}{R} \right),$$

where m_{e} and r_{e} are the mass and radius of the Earth. The asteroid does not come from infinity but more plausibly from the asteroid belt, perhaps 3 au from the Sun (1 au ["astronomical unit"] = mean radius of the orbit of the Earth).

This is a lower bound because we neglect both the previous kinetic energy of the asteroid in its orbit and its gravitational interaction with the Sun. We obtain 11.2 km/s for the speed of the asteroid (terminal velocity) upon impacting the outer atmosphere, using $32{,}000$ m as the height of the atmosphere. This result is independent of the mass of the asteroid.

A More Realistic Estimate of Asteroid Velocity

A more realistic model of the asteroid's incident velocity would include its interaction with the Sun and the kinetic energy of its orbit. We assume that the asteroid occupies a pre-collision orbit that is totally determined by its interaction with the Sun.

The Virial Theorem

The total energy of the asteroid's orbit may be determined from the geometry of its orbit and the classical virial theorem. A result of the general equations of motion, the virial theorem states [Marion and Thornton 1995]:

$$T = -\frac{1}{2} \langle F \cdot r \rangle .$$

The right-hand side of the equation, called the *virial*, reduces in the case of a circular orbit in a central gravitational field to

$$-\frac{1}{2} \langle F \cdot r \rangle = -\frac{1}{2} \left(\frac{G m_a m_{\mathrm{Sun}}}{r^2} \hat{r} \cdot r \right) = -\frac{1}{2} \frac{G m_a m_{\mathrm{Sun}}}{r} = -\frac{1}{2} \phi.$$

Though the asteroid's orbit is almost certainly not circular if it is to collide with Earth, we make the approximation of circularity to obtain a simple velocity estimate.

Total Energy of the Asteroid's Orbit

Using the virial, we can write the total energy as

$$E = T + \phi = \frac{1}{2} \phi.$$

When the asteroid reaches the Earth, it is at a distance 1 au from the Sun. In this model, conservation of energy requires that the change in potential must be absorbed as kinetic energy of the asteroid.

$$\frac{1}{2} m_a v^2 = \frac{1}{2}\phi - \phi_{\text{at Earth}}$$

Again, the mass of the asteroid cancels out, since it appears in both ϕ and ϕ_{atEarth}. If the asteroid is from the midst of the asteroid belt, so that the average radius in the circular-orbit approximation is, say, 2.6 au [Gehrels 1979], we get a velocity of $v = 23.5$ km/s.

We have neglected the interaction with the gravitational field of the Earth. To obtain a total estimate, we add on the energy from the calculation of the Earth's terminal velocity. Our best estimate for the incident velocity is $v = 26$ km/s, in good agreement with impact data [Gehrels 1994; Kieffer 1980].

From Atmosphere to Impact

What would happen to the asteroid as it descended through the atmosphere? This question is of interest in determining both the kinetic energy on impact and the energy transferred to the atmosphere during the descent. This latter aspect is important because energy transfer plays a significant role in atmospheric chemistry [Melosh 1989].

Dynamical Equations

In describing the dynamics of the asteroid descent, we follow the approach of Melosh [1989]. By considering the physics of the descent, we acquire a simplified model consisting of four coupled nonlinear differential equations. We begin by introducing coordinates to specify the state of the system:

$v(t)$ is the speed of the asteroid;

$\theta(t)$ is the instantaneous angle that the trajectory makes with the horizon;

$m(t)$ is the mass of the asteroid, which changes in time due to ablation caused by heat generated by friction with the atmosphere; and

$Z(t)$ is the vertical altitude of the asteroid.

We also consider the following functions of the state variables:

$\rho_g(Z)$ is the density of air at the altitude of the asteroid, and

$A(m)$ is the cross-sectional area of the asteroid.

The $v(t)$ Equation

The only forces that change the speed of the asteroid act along the line of motion. There is a component of gravity $g \sin \theta$ acting in the direction of motion, as well as a drag force retarding the motion. To calculate the drag force, we assume with Melosh that the air immediately behind the asteroid is at effectively zero pressure and that the air immediately in front is at the *stagnation pressure* $\rho_g v^2$ [Melosh 1989]. This pressure differential produces a force equal to $A\rho_g v^2$, where A is the cross-sectional area of the asteroid. Combining these forces with Newton's Second Law, we obtain the differential equation for $v(t)$:

$$v' = -\frac{A\rho_g v^2}{m} + g \sin \theta.$$

The $\theta(t)$ Equation

We approximate the surface of the Earth as flat. This assumption does not have significant consequences as long as θ is not particularly small, since the horizontal displacement is thus smaller than the curvature scale of the Earth's surface.

We assume that the only force acting perpendicular to the direction of motion is gravity. This neglects possible lift forces, but Melosh's analysis suggests that lift is small compared to the force of gravity [1989]. Suppose that the velocity vector of the asteroid undergoes a small perpendicular displacement denoted $\Delta v_\perp$. Then the change in the angle made with the horizontal $\Delta\theta$ is

$$\Delta\theta = \tan\left(\frac{\Delta v_\perp}{v}\right).$$

As we allow the size of the displacements to become infinitesimally small, we can neglect all but the first term in the Taylor series expansion of this function:

$$\Delta\theta \approx \frac{\Delta v_\perp}{v}.$$

But $\Delta v_\perp$ for small changes is just the acceleration of the asteroid perpendicular to its motion times Δt. Since we assume that gravity is the only significant component to this acceleration, we obtain

$$\frac{\Delta\theta}{\Delta t} \approx \frac{g \cos \theta}{v}.$$

In the limit, we obtain the differential equation for θ

$$\theta' = \frac{g \cos \theta}{v}.$$

The $m(t)$ Equation

The issue of ablation due to heating is less straightforward. Our approach follows that of Melosh [1989]. A calculation of the available energy due to the pressurized heating of the atmosphere tells us how much ablation could occur. Two dimensionless empirical parameters are involved: C_h, which is an *ablation efficiency*, and a term involving the velocity squared, $1 - (v_{\text{cr}}/v)^2$, which accounts for a critical speed v_{cr} below which ablation does not occur. The resulting differential equation is

$$m' = -\frac{C_h \rho_g A v}{2\zeta}\left(1 - \left(\frac{v_{\text{cr}}}{v}\right)^2\right),$$

where ζ is the heat of ablation for the material. For reasonable values of C_h and v_{cr}, Melosh gives empirically determined values of about 0.02 and $3{,}000$ m/s.

The $Z(t)$ Equation

The equation for $Z(t)$ is particularly simple, resulting from purely kinematic considerations. We need only project the total speed v into its velocity component in the vertical direction. Since we approximate the surface of the Earth as a plane, this component is simply

$$Z' = -v \sin\theta.$$

Air Density and Cross-Sectional Area

To obtain $A(m)$, the cross-sectional area, we must presume a shape for the asteroid. Though many asteroids have large eccentricities [Gehrels 1979], modeling the impactor as a solid uniform ball has the advantage of being mathematically tractable as well as not too far from reality. From the geometric formula for the volume of a ball, the expression for the asteroid radius R in terms of its mass m and its density ρ is

$$R = \left(\frac{3}{4\pi}\frac{m}{\rho}\right)^{1/3}.$$

From this, the cross-sectional area $A = \pi R^2$ becomes

$$A = \left(\frac{9\pi}{16}\right)^{1/3}\left(\frac{m}{\rho}\right)^{2/3}.$$

To find an expression for $\rho_g(Z)$, we use a simple model in which the density decreases exponentially as altitude increases. A good value for the characteristic height scale of the atmosphere is 10 km [Melosh 1989]. Thus, we have

$$\rho_g = \rho_0 e^{Z/10},$$

where ρ_0 is the atmospheric density at sea level and Z is measured in kilometers.

Numerical Solution

As promised, we have obtained a coupled set of nonlinear ordinary differential equations. Substituting the algebraic relations from the previous section removes dependence on A and ρ_g. With a given set of initial values for the height, angle, speed, and mass, we have an initial-value problem that completely specifies the physics of the asteroid descent.

Though some of the equations have simple cascade relationships to the other state variables, the nonlinearities make an analytic approach intractable. We solved the system using the fourth-order Runge-Kutta integration method in the software package ODE Architect, published by Intellipro.

Results

To obtain numerical results, we must take another step away from the world of theory toward empiricism, imposing additional constraints on the composition of the asteroid. We presume that the asteroid is composed of iron with approximate density $\rho = 2{,}600\,\mathrm{kg/m^3}$. Many asteroids are largely iron [Gehrels 1979]; impacting on ice, iron creates some of the most severe pressure effects of any common asteroid composition [Kieffer 1980].

A solid iron ball of radius $R = 500$ m has a mass of approximately 1.4×10^{12} kg. We use the estimated velocity of 26 km/s for an asteroid at a distance of $Z = 32{,}000$ km away from the Earth's surface.

Impact Velocity

Using the above parameter values, we consider the dynamics of an asteroid with initial angles of 30°, 45°, 60°, and 90° from the horizontal. Because the mass of the asteroid is comparatively large, we do not expect a large fraction of the asteroid's energy to be given up during the descent.

For all four trajectories, the final velocity decreases to 2.58×10^4 m/s and the mass to 1.38×10^{12} kg, though, as shown in **Figures 1** and **2**, the incident angle has a significant effect on the flight time.

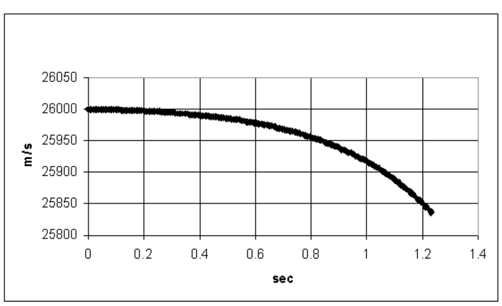

Figure 1. Initial angle of $90°$.

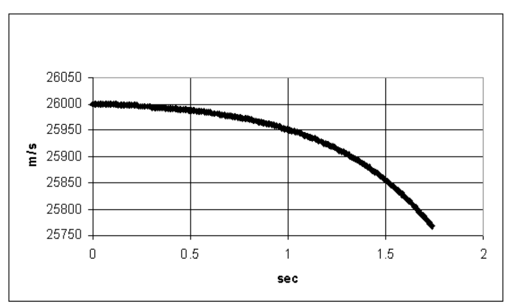

Figure 2. Initial angle of $45°$.

Atmospheric Energy Transfer

To obtain an upper bound on the energy transfer to the atmosphere, we again appeal to the tools of energy conservation. Neglecting the energy retained by ablated asteroid material, we obtain

$$E_{\text{to atm}} = \Delta T - mgZ = \frac{1}{2}m_f v_f^2 - \frac{1}{2}mv^2 - mgZ.$$

That is, whatever kinetic energy is lost by the asteroid must go somewhere, so that gravity, the only conservative force in effect, can be accounted for. Since Melosh finds $45°$ to be the most probable incident angle [1989], we take our calculations for $45°$ as representative.

With these data, we obtain an energy transfer of $E = 1.57 \times 10^{19}$ J, a figure which later has relevance to the treatment of environmental effects.

Effects on the Earth's Oceans

Introduction

Since the global-warming crisis came to the forefront of environmental thought in the mid-1980s, scientists have warned of the possibility of melting an Antarctic ice sheet and the inevitable catastrophic consequences. With regard to ice melting, the impact of a high-velocity asteroid with Antarctica could have two potentially disastrous results:

- the sheer amount of kinetic energy could vaporize a large amount of ice, which would eventually rain down into the ocean; or
- the collision could act as a pseudo-earthquake, generating seismic waves strong enough to break apart and move above-ground ice sheets, forcing large amounts of ice into the ocean.

Either of these events could potentially raise the water level by a significant amount. In addition, whenever there is a large seismic event, there is the possibility of a tsunami, which could have deadly consequences.

Vaporization of Ice

If we assume that all of the asteroid's kinetic energy is converted directly into thermal energy that is used solely for melting and vaporizing the ice, we can estimate an upper bound — however unrealistic — on the amount of water deposited into the Earth's atmosphere.

For ease of calculation, we first calculate the number of moles of H_2O vaporized by the impact. We assume that the ice is initially at $-40°$ C. The amount of energy needed to vaporize the ice is

$$\Delta H = \Delta H_{\mathrm{H_2O\ at\ -40^\circ \to H_2O\ at\ 0^\circ}} + \Delta H_{\text{fusion}} + \Delta H_{\mathrm{H_2O\ at\ 0^\circ \to H_2O\ at\ 100^\circ}} + \Delta H_{\text{vaporization}}.$$

Using the values [Atkins and Jones 1997] specific heat of ice $= 2.03$ J$\cdot^\circ$C$^{-1}\cdot$g^{-1}, latent heat of fusion $= 6.01$ KJ$\cdot$mol^{-1}, specific heat of water $= 4.18$ J$\cdot^\circ$C$^{-1}\cdot$g^{-1}, and the latent heat of vaporization $= 40.7$ KJ$\cdot$mol^{-1}, we calculate the most that could be vaporized would be 5.03×10^{15} moles, or 9.05×10^{13} kg, of water. If this water were spread around the water-covered surface of the Earth—given that the radius of the Earth is approximately 6.4×10^6 m and the surface area covered by water is approximately 3.6×10^{14} m^2—it would change the water level by only $\Delta h \approx 0.4$ mm. This amount is insignificant in comparison with seasonal changes, so we conclude that melting of the ice would have almost no effect on sea level.

Breaking Up of Ice Sheets

Given the very complex nature of the ice sheets on Antarctica, it is beyond the scope of this paper to give a detailed model of the amount of damage that a seismic wave generated by the impact could bring about. Melosh claims that based on geological evidence from previously studied asteroid impacts, the seismic efficiency, or fraction of impact energy converted into seismic energy, is on the order of 10^{-4} [1989]. Given an impact energy of 4×10^{20} J, the approximate seismic energy, as measured on the Richter scale, is $M \approx 7.9$. This is a significant earthquake, but Melosh also points out that this would produce mainly p-waves, while s-waves—the transverse waves created by the slipping of plates in an earthquake—are far more destructive. Therefore, he suggests that the damage of the pseudo-earthquake would be comparable to an actual earthquake of an order of magnitude less, in this case, an earthquake of magnitude 6.9.

Although a magnitude 6.9 earthquake is very large, we must consider that the nearest floating ice sheet to the South Pole, the Ross Ice Shelf, is nearly 400 km away. If we assume that all of the seismic energy radiates in a hemispherical pattern, then from the point of view of conservation of energy, we can say that at a distance r from the South Pole, the energy density, J, is

$$J = \frac{E_{\text{initial}}}{2\pi r^2}.$$

For $r = 400$ m and the initial seismic energy of a magnitude 6.9 earthquake, we find an energy density of 1.5 KJ/m^2. This amount is equivalent to a large man falling five or six feet to the ground, which, considering the density of the ice, should not be that significant. This rough estimate is in agreement with observed impacts with the moon. Melosh claims that "few surface features on the moon or other planets can be directly attributed to impact-induced seismic shaking"[1989]. Still, the possibility that large chunks of ice could fall into the ocean is not negligible but is beyond the scope of this model.

Tsunami Generation

The generation of tsunamis by underground seismological events is poorly understood; their generation by land-based seismological events is even less understood. Many people have attempted to calculate the size of the water wave that would be created by a near-shore nuclear blast, yet the strength of the tsunami is always overestimated [Murty 1977]. If we also consider that by the time the shock wave would reach the ocean, over $1{,}000$ km away, the energy density would be around 250 J/m^2, then the chances of a dangerous oceanic shock wave are negligible.

Potential Impact on the Earth's Climate

Introduction/General Modeling Concept

Many models of asteroid impact on land masses predict that a large dust cloud would be released into the atmosphere, causing massive global warming due to greenhouse effects. An asteroid's impact on Antarctica would be substantially different in this respect. Antarctica is covered by an average of 2 km of ice, so little or no dust would be released. However, the rapid release of a large amount of water vapor into the Earth's atmosphere has the potential to significantly alter climate, much as the release of greenhouse gases has stimulated global warming. We present here a simple climatic model of the Earth based on the assumption that the Sun and the Earth behave as blackbody radiators. This model allows us to determine a reasonable upper bound on potential global warming due to vapor injection.

The two defining characteristics of a blackbody radiator are:

- All radiation incident upon it is absorbed.
- Energy is re-radiated over the entire spectrum of wavelengths.

Through quantization of the radiation field, quantum theory tells us that the *radiancy*, or power per area, radiated by a blackbody is given by Stefan's law:

$$R_T = \sigma T^4 \qquad \text{[Eisberg and Resnick 1985]},$$

where σ is experimentally determined to be 5.67×10^{-8} W/m^2·K^4. We treat both the Sun and the Earth as ideal blackbody radiators; this treatment is commonly accepted as an accurate assumption for the purposes of global climate studies [Toon and Pollack 1980]. The majority of the light incident upon the Earth from the Sun is in the visible spectrum, while the light radiated from the Earth is mostly in the infrared. For this reason, we model the atmosphere as a shell of particles with two distinct albedos: one for visible light, the other for infrared light. We denote the percentage of the Sun's light that is transmitted through to the Earth by K_{visible} and the percentage of the Earth's light transmitted out into space by K_{IR}. For the Earth to be in thermal equilibrium, the power entering the atmosphere must equal the power leaving, that is,

$$P_{\text{from Sun}} = P_{\text{reflected sunlight}} + P_{\text{transmitted from Earth}}.$$

The power that reaches the atmosphere from the Sun is just

$$\sigma T_{\text{Sun}}^4 \pi R_{\text{atm}}^2 R_{\text{Sun}}^2 / d^2,$$

where d is the distance from the Sun to the Earth's atmosphere and R_{atm} represents the radius of the Earth's atmosphere. The R_{Sun}^2/d^2 term in the equation accounts for the fact that the power from the Sun that actually reaches the Earth is determined by the solid angle subtended by the Earth. The πR_{atm}^2 term accounts for the effective area of the atmosphere that is exposed to the radiation, characterized by the cross section of the Earth. Using Stefan's law, we have the following relation for thermal equilibrium:

$$\sigma K_{\text{visible}} T_{\text{Sun}}^4 \pi R_{\text{atm}}^2 \frac{R_{\text{Sun}}^2}{d^2} = \sigma K_{\text{IR}} T_{\text{Earth}}^4.$$

Worst-Case Heating of the Atmosphere

Upon injection of water vapor into the upper atmosphere, the values of K_{visible} and K_{IR} can be expected to change significantly. We first concern ourselves with the worst-case heating of the atmosphere due to water vapor. In this case, the vapor would act to reflect the Earth's infrared radiation back to the surface, causing a greenhouse effect corresponding to a decrease in K_{IR} and/or an increase in K_{visible}. From our general equation for equilibrium, we see that

$$T_{\text{Earth}} \propto \left(\frac{K_{\text{visible}}}{K_{\text{IR}}} \right)^{1/4},$$

which follows from the fact that all other quantities of interest would remain constant. To place an upper bound on potential global heating, we make the simplifying assumption that $K_{\text{visible}}/K_{\text{IR}}$ is directly proportional to the amount of water vapor in the atmosphere. This is not a completely unreasonable assumption; Toon and Pollack note that "the radiation budget of the Earth is dominated by water vapor and clouds" [1980]. For an upper bound on the effects, we take the vapor released to be the maximal amount, roughly 9×10^{13} kg, calculated in the previous section. According to Trewartha, the average moisture in the atmosphere is about 1.31×10^{16} kg, yielding an increase of about 0.69% [1954]. Using Trewartha's value for the mean global blackbody temperature of 287 K, we find that the equilibrium value for the temperature of the

Earth after water injection is 287.50 K, an increase of half a degree. Such climatic changes are roughly equivalent to the already observed increase in global mean temperature due to global warming [Oppenheimer 1998]; and while it not a totally insignificant consequence of impact, the effects would merely accelerate the global warming that is already under way.

Worst-Case Cooling of the Atmosphere

Although it is less likely that the injection of water into the atmosphere could exhibit a cooling effect, it has been suggested by some sources that, below a certain threshold droplet size, and high enough in the atmosphere, water could act to reflect the Sun's light, thus causing a trend of overall cooling [Toon and Pollack 1980]. We can show, using our simple atmospheric model, that the worst-case cooling effect is negligible. Returning to our general equilibrium expression, we see that

$$T_{\text{Earth}} \propto \left(\frac{K_{\text{visible}}}{K_{\text{IR}}} \right)^{1/4} .$$

Using the simplifying assumption this time that $K_{\text{visible}}/K_{\text{IR}}$ is *inversely* proportional to the amount of vapor in the atmosphere, we find once again, that there is roughly a decrease of half a degree in global mean temperature. Not only would such an effect be negligible, but it would actually work to counteract the global warming process underway.

Conclusions/Limitations of Climatic Model

The predictions of our model suggest that the worst-case climatic changes to the atmosphere would be a change in global mean temperature of roughly $\pm 1/2$ K. We state a few limitations of this simple model.

- First, the calculations are based on water that is vaporized by the energy of the asteroid. In actuality, there would likely be some ice ejecta mechanically propelled into the atmosphere by the impact. However, this effect should fit within our upper bound, because the ratio of energy to mass of water required to overcome the Earth's gravity, in addition to the energy expended by the damping effect of traversing the atmosphere itself (which would likely vaporize the ice particles), is substantially higher than the ratio for merely vaporizing the water. In addition, somewhat less than the maximum possible amount of water would be vaporized, since much of the asteroid's energy would be dissipated elsewhere.

- The model offers only an equilibrium value for the temperature of the Earth; the climatic changes are gradual, not sudden. Due to the large thermal mass of the Earth's oceans, temperature effects on the scale of global warming could take more than a decade to reach equilibrium [Toon and Pollack 1980].

- Finally, the model assumes that the percentages of light transmitted are proportional to the amount of water vapor in the atmosphere. Ignoring other particles in the atmosphere has the effect of making the predicted climatic changes worse than they might be in reality, which is acceptable, given the modest climatic changes predicted. The assumption that the percentages are merely proportional, however, is somewhat simplistic, given the complex nature of the atmosphere. This assumption is the most severe limitation on the model.

Nitric Acid Contamination

Generation of Nitrous Oxide

As the asteroid passes through the atmosphere, it is likely that the heat generated would cause nitric oxide to be generated. The nitric oxide would subsequently form nitric acid, possibly leading to severe acid rain in the vicinity of the impact.

A reaction that forms nitric oxide in the air is

$$N_2 + O_2 \longrightarrow 2NO.$$

The energy required for this reaction is 173.1 kJ per mole of NO generated [Atkins and Jones 1997]. The theoretical maximum amount of NO that can be generated is therefore about 1.73×10^{-7} kg/J. However, according to Melosh, the actual amount generated is closer to 7×10^{-9} kg/J [1989]. Using the amount of energy released into the atmosphere calculated previously, we find that 1.1×10^{11} kg, or 3.66×10^{13} moles, of NO would be produced. This NO would react in the atmosphere to produce nitric acid, HNO_3.

A Simple Lower Bound on Acid Rain Damage

We can get an idea of the minimum amount of damage that this nitric oxide production could cause by assuming that each mole of NO produced becomes a mole of nitric acid and that the nitric acid is homogeneously distributed into five years' worth of rain throughout the globe. The estimate of five years is based on Toon's assertion that it would take about five years to remove the nitric acid generated by a large impact from the atmosphere [Gehrels 1994]. The average yearly rainfall over the Earth is 5×10^{20} g of H_2O/year [Gehrels 1994]. This corresponds to 5×10^{17} L of water, yielding a molarity of 14.6 micromolar. Toon notes that many regions in Europe and the eastern United States receive acid rain at more than 100 micromolar [Toon and Pollack 1980]. Therefore, the effects of such a minimum damage scenario would be negligible.

Upper Bound on Acidification of the Earth's Oceans

If we assume that the nitric acid would find its way into the surface layers of the Earth's oceans, we can predict what percentage of the world's oceans would be rendered corrosively acidic. We define "corrosively acidic" as a 600 micromolar solution of nitric acid in water; this is the nitric-acid concentration necessary to dissolve calcite [Gehrels 1994]. We take the depth of "surface layers" to be 75 m, as suggested by Toon [Gehrels 1994]. Using the surface area of the Earth covered by water, we find the total volume of surface layer water to be 2.7×10^{16} m^3. The density of water is 5.5×10^4 mol/m^3; so 0.23% of the Earth's oceans could, in principle, be rendered corrosively acidic, corresponding to an area of about 8.2×10^{11} m^2 of ocean, or a cylinder of water with a radius of about 510 km. For a relatively strong acid such as HNO_3, we expect the pH of the water to be close to the negative log of the molarity, which yields a pH value of 3.2. The actual value, however, is likely to be higher because of the buffering effect of the salt in ocean water. According to Howells, a pH of 3.5 to 4.0 will kill almost any fish [1995].

Conclusions

A large quantity of nitric acid would likely be released into the oceans surrounding Antarctica. This release would likely devastate the fish population of the region, including Australia and the southernmost parts of South America. It is difficult to determine the exact effects because of the lack of data regarding acid rain pollution of seawater environments.

Conclusions and Limitations of the Models

The models that we developed are focused on placing an upper-bound estimate on the damage that could occur if a $1{,}000$ m-diameter asteroid were to impact the South Pole. Using Newtonian mechanics, we estimated the probable impact velocity of the asteroid and the energy released from the asteroid onto the Earth. These estimates allow us to place an upper bound on many of the possible destructive consequences of the impact.

The primary concern associated with impact is the potential raising of the water levels of the Earth's oceans. A simple argument based on energy conservation demonstrates that the water vapor created by the impact would not substantially raise the level of the Earth's oceans. Another argument demonstrates that the seismic shock waves generated would likely have little effect on the ice sheets near the Antarctic coast, although there is always the possibility of instabilities in the ice sheet structure, which is not accounted for by the model.

Another significant cause for concern is the long-term climatic impact of the asteroid. While very little dust is expected to be released into the atmosphere, a large quantity of water vapor almost certainly would be. Calculations show, however, that the upper bound on climatic changes amounts to, at most, the same climatic changes of about 0.5 K that are a consequence of current global warming. Therefore, while global warming would be accelerated somewhat, it is not a primary concern. The model implicitly assumes that the albedo of the Earth's atmosphere is simply proportional to the amount of water vapor it holds.

The major cause for concern, according to our model, is the large quantities of nitric acid that would be released on the oceans surrounding Antarctica. These waters would be contaminated with enough nitric acid to completely destroy their food-production capabilities.

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