Deep Impact

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Abstract

We consider the impact of a 1,000 m-diameter asteroid with the South Pole. Impacts of this magnitude can have substantial effects, including earthquakes and tsunamis on a regional scale and the possibilities of global climatic change and catastrophic agricultural damage from dust ejected into the atmosphere.

Luckily, an Antarctic collision would result in a far less disastrous scenario. By modeling the possible trajectories of the asteroid, we determined that the angle of incidence would be relatively small, resulting in a smaller, more shallow crater. Since Antarctica is covered by a thick ice cap, very little dust would be ejected into the atmosphere. The heat of the collision would melt an insignificant amount of ice. The worst scenario would be if the shock wave created by the impact resulted in a large tsunami, so we predict which coastal areas would be flooded.

Initial Assumptions

1. The asteroid is spherical, is 1,000 m in diameter, has a typical composition and density, and strikes the Earth at the South Pole.

2. The asteroid originated in our solar system and so before the collision was orbiting the Sun in the same plane as the Earth [Transcript—Plane of the Solar System 1996].

3. The only bodies significantly affecting the trajectory of the asteroid are the Sun, the Earth, and the Moon. The trajectories of the four bodies can be predicted using a Newtonian model of gravitation.

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4. Near the South Pole, the Antarctic ice cap is uniformly 2 km deep, has roughly constant density, and is at $-76°$ C everywhere.

Properties of the Asteroid

Location, Angle, and Velocity of Impact

We investigate the relative probability of impacting at the South Pole vs. elsewhere. So we simulate the motions of the Sun, Earth, Moon, and asteroid, based on the Newtonian model of gravitation, in which

$$F = \frac{Gm_1 m_2}{d^2}$$

describes the magnitude of the force F exerted on two masses, m_1 and m_2 separated by a distance d. The direction of the force is along a straight line connecting the center of mass of each object. The universal gravitational constant G has the value 6.67259×10^{-20} km^3 s^{-2} kg^{-1}. Gravitational force accelerates a body according to $\vec{a} = \vec{F}/m$. This acceleration changes the body's velocity $\vec{v}$, which in turn affects the body's position $\vec{x}$.

We use a time-discretized numerical simulation. The location $\vec{x}_{i,t+\Delta t}$ of a body i at time $t + \Delta t$ is calculated using the locations and masses of the other planetary bodies in addition to the location, velocity, and mass of body i at time t. In particular, we perform the following calculations on each body in the system:

$$\begin{aligned}
\vec{F} &= \sum_{j,j\neq i} \frac{Gm_i m_j}{|\vec{x}_{i,t} - \vec{x}_{j,t}|^2} \times \frac{\vec{x}_{i,t} - \vec{x}_{j,t}}{|\vec{x}_{i,t} - \vec{x}_{j,t}|} \\
\vec{a}_{i,t+\Delta t} &= \frac{\vec{F}}{m_i} \\
\vec{v}_{i,t+\Delta t} &= \vec{v}_{i,t} + \vec{a}_{i,t+\Delta t} \times \Delta t \\
\vec{x}_{i,t+\Delta t} &= \vec{x}_{i,t} + \vec{v}_{i,t+\Delta t} \times \Delta t + \frac{1}{2}\,\vec{a}_{i,t+\Delta t} \times (\Delta t)^2.
\end{aligned}$$

The Sun, Earth, and Moon initially have the characteristics in **Table 1** [Lide 1992, 14–26, 14–27].

We choose our coordinate system with the Sun at the origin and both the Earth and the Moon in the xy-plane. By Assumption 1, the asteroid is spherical with diameter 1,000 m. Thus, it has volume of $V_{\text{ast}} = \frac{4}{3}\pi(0.5\,\text{km})^3$, or $0.524\,\text{km}^3$. A typical asteroid has density $\rho_{\text{ast}} = 2.5 \times 10^{12}$ kg km^{-3} [Toon et al. 1997, 44]. Thus, the asteroid has mass of $m_{\text{ast}} = 1.31 \times 10^{12}$ kg.

We distinguish between asteroids that approach the Earth from within the solar system plane (such as ones from the asteroid belt of the solar system) and those that approach from outside that plane. Would an asteroid approaching

Table 1.

Mass, radius, position, and speed of the Sun, Earth, and Moon.

	Sun	Earth	Moon
m_i	1.99×10^{30} kg	5.97×10^{24} kg	7.35×10^{23} kg
r_i	6.96×10^{5} km	6.38×10^{3} km	1.74×10^{3} km
$\vec{x}$	$(0, 0, 0)$ km	$\vec{x}_{\text{Sun}} + (1.50 \times 10^8, 0, 0)$ km	$\vec{x}_{\text{Earth}} + (0, 3.84 \times 10^5, 0)$ km
$\vec{v}$	$(0, 0, 0)$ km s^{-1}	$\vec{v}_{\text{Sun}} + (0, 29.8, 0)$ km s^{-1}	$\vec{v}_{\text{Earth}} + (-1.02, 0, 0)$ km s^{-1}

from outside the plane be more likely to hit the South Pole? To find out, we simulate both kinds of asteroids.

We place the asteroid at a random location 1.54×10^6 km (about four lunar distances away) from the Earth. We give the asteroid the same velocity that the Earth has relative to the Sun, as though the asteroid were falling through an orbit that coincides with that of the Earth. We put the asteroid on a collision course with the Earth by adding 10 km s^{-1} to the asteroid's velocity in a direction towards a random point no more that 9.57×10^3 km from the center of the Earth (i.e., the asteroid is approaching a point contained within a sphere centered on the Earth with a radius 1.5 times that of the Earth).

We ran the simulation with $\Delta t = 10$ s. A collision occurred if the distance between the asteroid and the Earth was less than the sum of their radii. We calculate the latitude of the impact from the vector. The angle that the vector $\vec{x}_{\text{ast}} - \vec{x}_{\text{Earth}}$ makes with the xy-plane determines the latitude of the impact:

$$\begin{aligned} \Delta\vec{x} &= \vec{x}_{\text{ast}} - \vec{x}_{\text{Earth}} \\ \text{latitude} &= \arctan\left(\frac{\Delta\vec{x} \times (0,0,1)}{\sqrt{(\Delta\vec{x} \times (1,0,0))^2 + (\Delta\vec{x} \times (0,1,0))^2}}\right). \end{aligned}$$

Similarly, we calculate the angle of incidence and the velocity of the impact from the vectors $\vec{x}_{\text{ast}} - \vec{x}_{\text{Earth}}$ and $\vec{v}_{\text{ast}} - \vec{v}_{\text{Earth}}$, since the angle that the vector makes with the tangent plane of the Earth's surface at the point of impact is the angle of the impact, and the magnitude of this vector is the speed of impact:

$$\begin{aligned} \Delta\vec{x} &= \vec{x}_{\text{ast}} - \vec{x}_{\text{Earth}} \\ \Delta\vec{v} &= \vec{v}_{\text{ast}} - \vec{v}_{\text{Earth}} \\ \text{angle} &= -\arcsin\left(\frac{\Delta\vec{x}}{|\Delta\vec{x}|} \times \frac{\Delta\vec{v}}{|\Delta\vec{v}|}\right) \\ \text{speed} &= |\Delta\vec{v}| \end{aligned}$$

We ran 20,000 simulations of the asteroid, half for an asteroid approaching from within the solar system plane and half for an asteroid approaching from outside the plane. In both cases, slightly under one-fourth of the asteroids avoided colliding with the Earth. **Figure 1** shows the distribution by latitude of those hitting the Earth. For either approach, there is about a 1% chance of an asteroid impacting above 80° S.

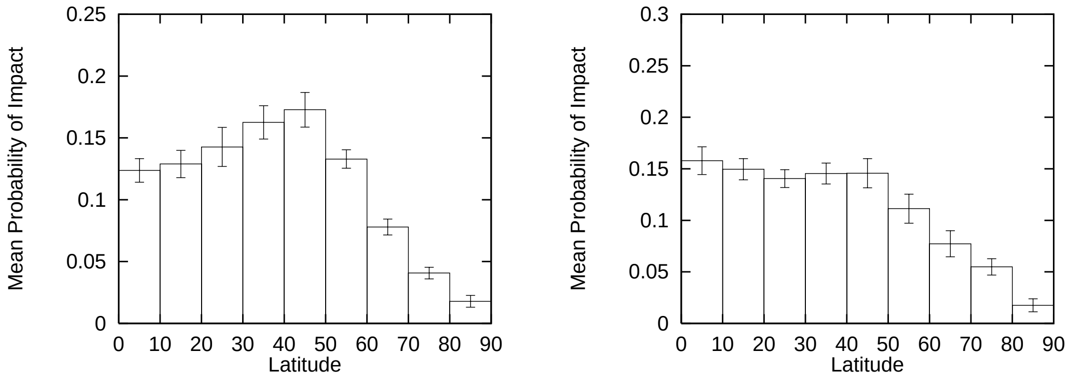


Figure 1. Probability of impact for asteroid from within the solar system plane (left) and from outside (right).

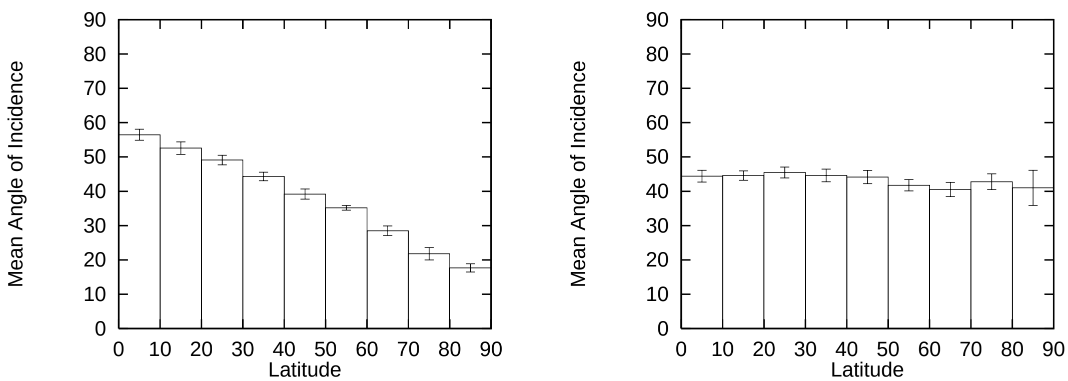


Figure 2. Angle of incidence for asteroid from within the solar system plane (left) and from outside (right).

However, an asteroid from within the solar system plane impacting in the highest latitude ranges is more likely to impact at a shallower angle: $18° \pm 1°$ vs. $41° \pm 5°$ (see **Figure 2**).

For asteroids with radii exceeding 100 m, air resistance is negligible; such asteroids hit the ground with most of their original kinetic energy [Hills and Mader 1995]. Our simulations show impact at a relative speed of 15 km/s, consistent with the literature [Chapman and Morrison 1994, 34].

The calculations do not take into account the Earth's tilt relative to the xy-plane (about 22°), since we have no information about the time of year of the collision. Hence, the probability of impact at the South Pole cannot be taken simply by reading the height of the bar in **Figure 1**, nor can the expected angle of incidence be read directly from **Figure 2**.

Dynamics of Collision

Using the calculated mass of 1.31×10^{12} kg and the velocity of 15 km/s, we find that the energy of the asteroid reaching the Earth's atmosphere is

$$E = \frac{mv^2}{2} = \frac{(1.31 \times 10^{12}\text{ kg})(15\text{ km/s})^2}{2} = 1.5 \times 10^{20}\text{ Joules.}$$

This is equivalent to 3.5×10^4 megatons (MT) of TNT. (If the collision were with a comet rather than an asteroid, the speed of impact would be 50 km/s; but because of the comet's lesser density of 1 g/cm, the energy of impact would be slightly less [Toon et al. 1997, 44].)

The ice cover over Antarctica makes predicting the size of the crater problematic. For impacts on land, Toon gives the following two formulas for the expected value of the diameter of the crater (km):

$$D = 0.64 \left(\frac{Y}{\rho_t}\right)^{1/3.4} \left(\frac{20000}{v_i}\right)^{0.1} (\cos\theta)^{0.5} \left(\frac{\rho_i}{\rho_t}\right)^{0.083},$$

$$D = 0.53 c_f \left(\frac{Y}{\rho_t}\right)^{1/3.4} (\cos\theta)^{2/3},$$

where

Y is the energy in megatons,

ρ_t is the density of the target,

ρ_i is the density of the impactor,

v_i is the speed of the impactor,

c_f is a correction factor with value approximately 1.37, and

θ is the angle of impact [1997, 45].

The value $\theta = 18°$ from our model for an asteroid from within the plane of the solar system is probably a little low, because asteroids are likely to have some perturbation from the plane. Hence we use $\theta = 30°$. With a density of 0.9 g/cm^3 for ice, both formulas give a crater diameter of about 15 km.

Since a crater for a "typical" asteroid has a depth-to-diameter ratio of about 1:5 or 1:7 [Terrestrial Impact Craters 1999], a crater of this diameter would have a depth of 2.5 to 3 km. However, a "typical" asteroid does not hit at as shallow an angle as the asteroid of our model, which plows through a large swath of the ice to create a crater that is wider but not as deep. If, despite its reduced downward momentum, the asteroid were to break through the ice, it would encounter a much denser bedrock 2 to 2.5 km deep; so we do not expect the crater to be much deeper than 2 km.

Since ice melts more readily than the rock, we could be underestimating the size of the crater. Ice around the South Pole has a depth of 2 km and an average temperature of $-76°$ C. A crater of diameter 15 km and average depth just 1 km would displace about 175 km^3 of ice. However, melting so much ice is unlikely. Also, the collision would send a large amount of ice/water, and some bedrock, into the atmosphere, but less rock than if the asteroid hit another continent.

Effects on Antarctica

The effects of an asteroid hitting Antarctica would be profoundly different from those of a collision elsewhere. Although Antarctica is far from most centers of population, the melting of the ice cap is a concern. Our calculations use the data of **Table 2**.

Table 2.

Data on the Antarctic ice cap.

Feature	Size	Source
Volume	30×10^6 km^3	Virtual Antarctica [1999]
Area	14×10^6 km^2	World Factbook [1998]
Avg. thickness	2 km	Computerworld Antarctica [1999]
Avg. temperature	$-76°$ C	Assumption 4

In theory, a large-enough collision could melt the entire ice cap, raising the water level of the world's oceans by 70 m [Computerworld Antarctica 1999]. Assume for the moment that all of the energy produced in the collision were converted to heat. To calculate the volume of ice that could be melted by the collision, we need some thermal properties of water (see **Table 3**).

Table 3.

Thermal properties of water, from Lide [1992, 6–172, 6–174].

Phase	Conductivity ($\mathrm{Wm^{-1}K^{-1}}$)	Specific Heat c ($\mathrm{J\,K^{-1}kg^{-1}}$)	$k/c\rho$ ($\mathrm{m^2s^{-1}}$)
Ice	1.88	2030	9.26×10^{-7}
Water	0.61	4810	1.27×10^{-7}
Vapor	0.027	2020	1.34×10^{-8}
Enthalpy of Fusion		3.33×10^5 J kg^{-1}	
Enthalpy of Vaporization		2.26×10^6 J kg^{-1}	

Let us suppose that all of the 1.5×10^{20} J of collision energy raised the temperature of mass M_{ice} of ice to $0°$ C and melted the ice, without heating the resulting water. Then we have:

$$1.5\times10^{20}\,\mathrm{J} = (273.2\ \mathrm{K} - 197.2\ \mathrm{K})\times 2030\,\mathrm{J\,K^{-1}\,kg}\times \mathrm{M_{ice}} + 3.33\times10^5\,\mathrm{J\,kg^{-1}}\times\mathrm{M_{ice}}.$$

Solving gives $M_{\text{ice}} = 3.1 \times 10^{14}$ kg of ice. Using a density of 0.9 g/cm^3 for ice, the impact would melt 340 km^3 of ice, slightly more than $1/100{,}000$ of the total volume of the Antarctic ice cap! If all of the water could reach the ocean, it would raise the levels of the oceans by less than 1 mm. However, since the South Pole is over 500 km from the nearest Antarctic coast, it is unlikely that *any* of the water would reach the ocean.

For a more accurate model of the heat in the Antarctic ice cap, let us suppose that all 1.5×10^{20} J of the energy raises the temperature of the ice beneath the asteroid, which we approximate by a cylinder of diameter 1 km. The mass of ice under a circle 1 km in diameter would be 1.5×10^{12} kg.

- The energy to heat the ice by 76° C (to its melting point) would be the mass times the temperature change times the specific heat of ice, giving 2.31×10^{17} J.
- The enthalpy of fusion of ice is 3.33×10^5 J/kg, so the energy to melt the ice would be 5.00×10^{17} J.
- Raising the ice another 100° C would expend 7.2×10^{17} J.
- Vaporizing the water at boiling point would expend 3.39×10^{18} J (the enthalpy of vaporization is 2.26×10^6 J/kg).

Subtracting these four numbers from the initial energy still would leave 1.46×10^{20} J. If we assume that all of the remaining energy would be used to heat the water vapor, we find (by applying the specific heat of water vapor) that the water vapor could be raised to 48,000° C.

It is unlikely that all of the energy of the impact would go into heating the ice, and some of the water vapor would escape before passing on its heat to the surrounding ice, so this model gives a huge overestimate of the effects of the collision.

The Heat Equation

We model the spread of the temperature distribution by using the heat equation. Since the ice sheet is an average of only 2 km thick but more than 6,000 km wide, we model it using just two dimensions. Let $u(x, y, t)$ represent the temperature (°C) of the ice sheet at position (x, y) (meters) at time t (seconds). Set the coordinate system so that $u(0, 0, 0)$ is the temperature of the center of the impact location at the time of impact. In the heat equation

$$\frac{\partial u}{\partial t} = \frac{k}{c\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right),$$

the constant k is the thermal conductivity of the substance, c is the specific heat, and ρ is the density. Because all three values change as the ice turns to water and then to vapor, the only way to solve this equation is numerically. We use a method based on an algorithm given in Burden and Faires [1997]. Let the time step between successive iterations be Δt and let the physical distances between temperature readings be Δx and Δy. To derive the method of finite differences, first consider the Taylor series approximations of u in t, x, and y:

$$\begin{aligned}
\frac{\partial}{\partial t}u(x,y,t) &= \frac{u(x,y,t+\Delta t)-u(x,y,t)}{\Delta t} - \frac{\Delta t}{2}\frac{\partial^2}{\partial t^2}u(x,y,\tau),\\
\frac{\partial^2}{\partial x^2}u(x,y,t) &= \frac{u(x+\Delta x,y,t)-2u(x,y,t)+u(x-\Delta x,y,t)}{(\Delta x)^2} - \frac{(\Delta x)^2}{12}\frac{\partial^4}{\partial x^4}u(\chi,y,t),\\
\frac{\partial^2}{\partial y^2}u(x,y,t) &= \frac{u(x,y+\Delta y,t)-2u(x,y,t)+u(x,y-\Delta y,t)}{(\Delta y)^2} - \frac{(\Delta y)^2}{12}\frac{\partial^4}{\partial y^4}u(x,\psi,t),
\end{aligned}$$

for some $\tau \in (t, t+\Delta t)$, $\chi \in (x-\Delta x, x+\Delta x)$, and $\psi \in (y-\Delta y, y+\Delta y)$. Let us assume that $\Delta x = \Delta y$, so that we can combine more terms. Substituting these into the partial differential equation, and separating out the error terms as $E(x,y,t)$, yields the following relations:

$$\frac{u(x,y,t+\Delta t)-u(x,y,t)}{\Delta t} =$$
$$\frac{k}{c\rho}\left(\frac{u(x+\Delta x,y,t)+u(x-\Delta x,y,t)+u(x,y+\Delta y,t)+u(x,y-\Delta y,t)-4u(x,y,t)}{(\Delta x)^2}\right),$$

$$E(x,y,t) = \frac{\Delta t}{2}\frac{\partial^2}{\partial t^2}u(x,y,\tau) - \frac{k}{c\rho}\frac{(\Delta x)^2}{12}\left(\frac{\partial^4}{\partial x^4}u(\chi,y,t)+\frac{\partial^4}{\partial y^4}u(x,\psi,t)\right).$$

The constants can be grouped into a single term K:

$$K = \frac{k}{c\rho}\frac{\Delta t}{(\Delta x)^2}.$$

Then solving the first equation for $u(x,y,t+\Delta t)$ yields the following equation, which allows us to solve for the temperature distribution at time $t+\Delta t$ given the distribution at time t:

$$\begin{aligned}
u(x,y,t+\Delta t) = u(x,y,t)\,(1-4K) + K\,(&u(x+\Delta x,y,t)+u(x-\Delta x,y,t)\\
&+\; u(x,y+\Delta y,t)+u(x,y-\Delta y,t)-4u(x,y,t)).
\end{aligned}$$

Simulation Results

We wrote a computer program in C to solve this equation for an initial temperature distribution of $-76°$ C everywhere except for a circular region of diameter 1 km, to which we gave an initial temperature of 48,000° C. We discovered that if all of the hot water vapor remained in place (instead of rising into the atmosphere, as we would expect), it could at most melt 5.7×10^7 m^3 of ice (enough to raise the ocean level by 2×10^{-7} m), and melting this much would take more than 10 days! Long before then, one would expect everything to cool off. Even the water that would melt would have a difficult time reaching the ocean, because much of the surface of Antarctica has been pushed below sea level by the enormous weight of the ice [Virtual Antarctica 1999].

The results of the simulation are not too surprising once one considers the order of magnitude difference in the thermal conductivities of ice and water. The initial heat melts a large amount of ice fairly quickly, but the rate of temperature increase slows rapidly as the temperature rises, reaching almost an equilibrium at less than 100° C. The process provides a layer of insulation between the hot vapor that was supposed to transfer the heat and the surrounding ice, which is now adjacent to just very warm water. As that ice melts, it does not transmit much heat to the next layer of ice.

Conclusion: The last thing that we need to worry about is any significant amount of ice melting.

Antarctic Ecosystem

The waters around Antarctica are inhabited by small crustaceans called krill, which are central to the food chain in this region. Small differences in water temperature, or any natural disaster that upsets the balance of nature, could affect their population, with global repercussions. However, since little ice would melt and there would be no other significant long-term effects of the collision, our best estimate is that nature would repair itself over time.

Effects on a Global Scale

Tsunami

One of the most significant things we need to worry about is the possibility that the collision would cause an earthquake large enough to start a tsunami (tidal wave), which tends to be more severe if caused by a disturbance near the surface. Tsunamis can measure 10 to 30 m in height but extend 4 to 5 km from front to back [Monastersky 1998b], and they typically travel at about 800 km/hr [Monastersky 1998a]. (Technically, the word "tsunami" refers to a large wave that has slowed down and increased in height as it hits a continental shelf before a coastline, but we use the term in a broader sense to refer to any large wave with the potential of becoming a tsunami.)

Tsunamis are extremely hard to forecast. It is not the magnitude of the earthquake that determines the height of the wave, but rather the frequency; in particular, the cause is long-period vibrations over time that drive the wave up higher and higher [Monastersky 1998a]. When the waves hit the coastline, they rise up even higher and flood the land with a wall of water, causing mass destruction. Between 1992 and 1997, 1,200 lives were lost as a result of tsunamis in the Pacific; and the July 1998 tsunami in Papua New Guinea claimed at least

2,500 more. A primary reason for loss of life is little to no warning of the tsunami's approach.

A tsunami caused by an asteroid impact in Antarctica would take more an hour to reach the southernmost tip of South America, and we would know far in advance of the approach of an asteroid of that size (within 10 years, 90% of Earth-orbit-crossing asteroids of this size should be identified and their orbits should be plotted [Asteroid Comet Impact Hazards 1999].) Therefore, human casualties could be almost completely avoided by evacuating coastal areas.

The maximum distance that a tsunami travels inland can be determined from its height when it hits the shore, the depth of the water at the shoreline, the roughness of the terrain, and the slope of the shore away from the coast. As an example, for a terrain corresponding to a typical developed area, a 40-m tsunami could travel inland about 9 km, and a 100-m one could travel inland about 100 km [Hills and Mader 1995].

An accurate simulation of a tsunami on a global scale would require complicated fluid-dynamics equations, but these simulations would be meaningless without extremely good initial data. Instead, we created a much simpler model. Assume that the shock wave caused by the asteroid collision would travel through the Antarctic continent quickly enough that it would reach the coastline at all places at approximately the same time. Then the initial wavefront would take on the shape of Antarctica and travel north. Consider a two-dimensional grid of lattice points representing the surface of the Earth. Label each point initially as either water or land. Points that represent water are given two variables: a height (a scalar) and a direction of wave motion (a vector). Initially, all points representing water are given zero height and no direction, except for a wavefront at the border of Antarctica directed away from the continent at all points. Each time step, the waves propagate in the direction of motion and interfere constructively or destructively with other parts of the wave. Unless acted upon by another wavefront, water above sea level falls back towards the ocean.

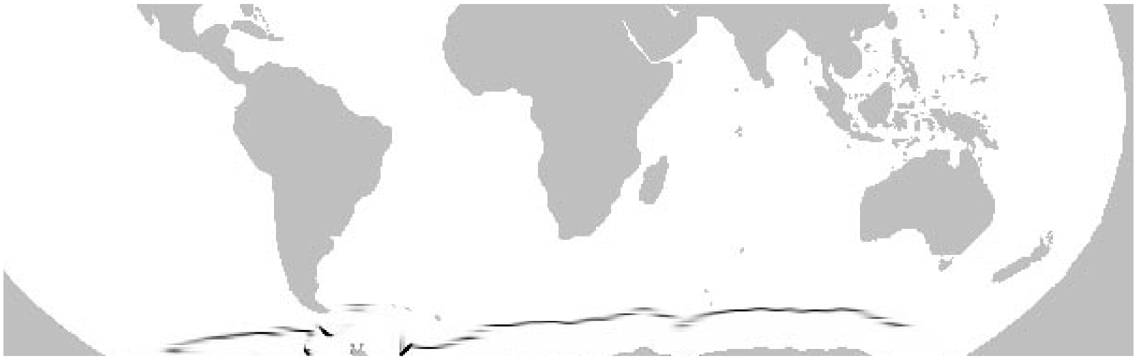
This model of a tsunami is limited, but it is about as much as can be expected without more information on the type of earthquake that might cause the tsunami to start. **Figure 3** shows the output of our computer simulation of the tsunami at various moments in time.

While the exact locations of coastal flooding are unpredictable, some general trends can be observed:

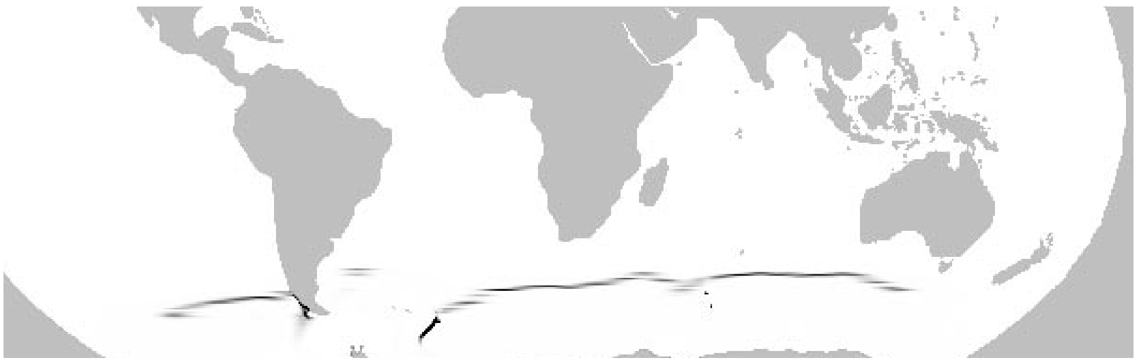
- The west coast of South America is more likely to be flooded than the east coast, mostly because of the shape of the Antarctic Peninsula.

- The southern-facing borders of Africa, Madagascar, India, and Australia have nothing in their way, so they are likely to be flooded.

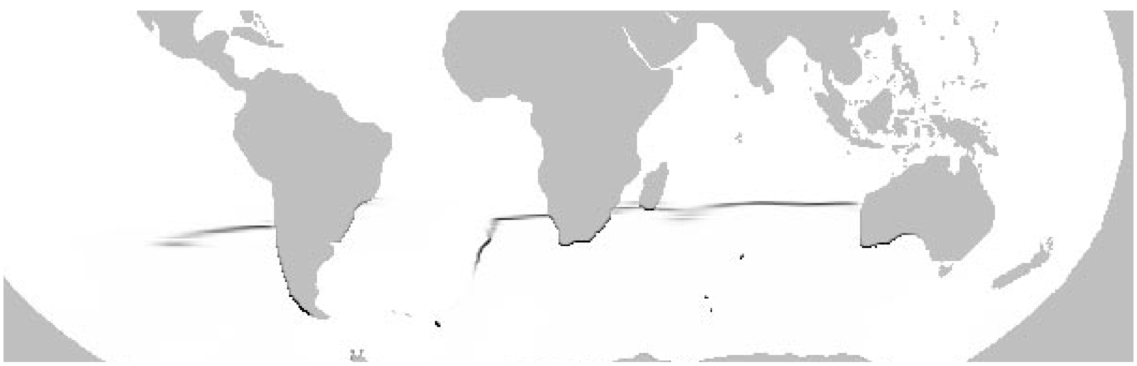
- Both the east coast of North America and most of Europe are shielded from the tsunami and need not evacuate.



One hour after impact. The shape of the Antarctic Peninsula has caused the wave to avoid hitting the southeastern coast of South America.



One hour later. The tsunami has struck South America.



Hours later. The tsunami has flooded parts of Africa and Australia.

Final image, showing all flooded coastlines in black.

Figure 3. Computer-generated model of tsunami wavefront.

Dust and Ice Loading

To the person living in Tibet, a tsunami doesn't much matter. But if huge amounts of dust were released into the atmosphere, Tibetans would find the weather unusually cold, and the plants that they depend on for food would stop photosynthesizing and die. This effect worldwide could destroy all traces of civilization.

We can see from volcanic activity what dust can do. On 15 June 1993, Mt. Pinatubo in the Philippines erupted. It had the largest effect on the particulate levels in the atmosphere of any event this century [McCormick et al. 1995, 399]. An asteroid hitting land with energy of 10^4 MT of TNT would send up about the same amount of dust; with energy of 10^5 MT of TNT, it would produce results similar to the eruption in Tambora in 1815 [Toon et al. 1992, 59]. Pinatubo lowered global temperatures by about 0.5° C [McCormick et al. 1995] and Tambora by 0.75° C [Tambora, Indonesia, 1815 1999].

This gives us a rough bracketing of what to expect from our asteroid with energy 3.4×10^4 MT of TNT, though hitting the thick ice sheet at a shallow angle should produce less dust than striking another continent.

The dust put into the atmosphere would not have sufficient energy to go into orbit and so would spread around through the atmosphere [Toon et al. 1992, 57]. We expect the spread of dust to be restricted by the prevailing winds, which create bands blowing in opposing directions. To cross from the South Pole to the Northern Hemisphere by following prevailing winds, the dust would have to change altitude significantly several times. It took 2 to 3 months for the dust from the Pinatubo eruption to spread from the equator to the Northern and Southern Hemispheres. We would expect a similar (if not greater) time lag for transporting dust from the South Pole to the Northern Hemisphere.

While the dust from the impact would have consequences to the global climate, it is unlikely to be of a magnitude to damage civilization significantly. It would have moderate and temporary effects on agriculture, particularly in the Southern Hemisphere.

In addition to the dust, a significant amount of ice would be put into the atmosphere. A substantial part of this would become rain or snow and fall back to Earth, possibly removing some of the dust from the atmosphere. Increased water vapor would lower the temperature in the upper atmosphere, because water is a strong infrared radiator, causing more water vapor to condense and precipitate out [Toon et al. 1992, 68–69].

An impact in the ocean with energy of 10^4 MT of TNT would about double the amount of water in the ambient upper atmosphere. This would have a minor greenhouse effect that would be somewhat canceled by ice clouds blocking the sun. It would not have any significant impact unless it lasted longer than the 10-year response time of the oceans to temperature change [Toon et al. 1992, 69].

Conclusions

An asteroid 1000 m in diameter could cause a serious global disaster. An impact near a heavily populated area could cause mass destruction and loss of life, and an ocean collision could create a tremendous tsunami. If an asteroid were to strike a continent not near the poles, it could send up enough dust into the atmosphere to cause long-term environmental damage. Compared to any of these scenarios, an Antarctic collision would be far less disastrous.

The angle of incidence would likely be small for an asteroid originating in our solar system, creating a wider, shallower crater than if it hit perpendicularly. Because the ice cap is 2 km thick at the South Pole, most of what would get thrown into the atmosphere is shards of ice, not dust. Escaping dust would not travel north to more populated areas, because of the prevailing wind currents. The ice that would reach the atmosphere could cause a greenhouse effect, but only if it remained for many years; it is likely that much of it would fall in the form of rain.

The possibility of a tsunami is real but impossible to predict. Our model predicts the possible flood locations, but these simulations would need to be done in greater detail with a more accurate model of the world and a more sophisticated model of a tsunami. In any event, because of advance warning, coastal areas could be evacuated. Serious flooding could damage millions of square kilometers of food production regions, but these effects would be short-term.

One would hope for enough warning to evacuate the 4,000 people on Antarctica doing exploration and scientific research.

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