IMPACT TSUNAMI: A PROBABILISTIC HAZARD ASSESSMENT S. N. Ward and E. Asphaug, Institute of Tectonics, University of California, Santa Cruz CA 95064

We investigate the generation, propagation, and hazard of tsunami spawned by oceanic asteroid impacts. Linear tsunami theory dictates that radially symmetric, initial impact cavities $u_z^{impact}(\mathbf{r}_0)$, evolve into vertical sea surface waveforms at position $\mathbf{r}$ and time t as

$$u_z^{surf}(\mathbf{r},t) = \int_0^\infty k\, dk\, J_0(kr)\cos(w(k)t) \int_{r_0} r_0 dr_0\; u_z^{impact}(r_0)\; J_0(kr_0) \quad (1)$$

with r=|**r**|; $\omega(k)=kc(k)=kv_t[\tanh(kh)/kh]^{1/2}$; $v_t=(gh)^{1/2}$; h, a constant ocean depth; and J_0, a cylindrical Bessel function. By being valid in both shallow and deep water, and by properly accounting for losses due to geometrical spreading and frequency dispersion[1], formula (1) can determine maximum tsunami amplitude expected at distance r from cavities created by any diameter impactor. Coupling this information with the statistics of such falls, we assess the probabilistic hazard of impact tsunami shoaling upon global coastlines.

Our research is motivated by the fact that 2/3 of all objects striking Earth impact the ocean[2]. Geological evidence[3] for oceanic impacts include mesosiderite fragments from the Eltanin meteorite that struck the Southern Ocean of the Pliocene (~2.15Ma), and tsunami deposits discovered from Texas to Haiti[4] that date to the K/T impact (~66 Ma). Moderate size impactors 30 to 300 m diameter are thought to strike Earth's oceans every 100 to 10,000 years. Impactors of moderate scale draw our attention because they may produce a perceptible safety hazard within historical contexts, or within the life span of a human being.

The initial stage of cratering by moderate size impactors may be characterized[5] by the excavation of a paraboloid transient cavity with a depth(d_C)/diameter ratio ~1:3. Accordingly, we model 1:3 initial cavities that include an outer lip such that there is no net water loss:

$$u_z^{impact}(r) = d_C(1 - 4r^2/9d_C^2); r \le R_D = 3\sqrt{2}d_C/2$$

This initial cavity is transient, transforming to propagating tsunami waves

$$u_z^{surf}(\mathbf{r},t) = 4d_C\int_0^\infty dk \frac{F(k,d_C)J_0(kr)\cos(w(k)t)}{k} \quad (2)$$

[1] Ward, S.N. (1982), *Phys. Earth Planetary Interiors* **27**, 273-285.
[2] *e.g.* Toon, O.B. *et al.* (1994), in *Hazards due to Comets and Asteroids* (T. Gehrels, Ed.), U. of Arizona Press, pp. 791-826; Hills, J.G. and C. Mader (1995), in *Proc. Planetary Defense Workshop*, LLNL.
[3] Gersonde, R. *et al*. (1997), *Nature* **390**, 357-363
[4] Maurrasse, F.J.-M. and G. Sen (1991), *Science* **252**, 1690-1693; Bourgeois, J. *et al.* (1988), *Science* **241**, 567-570.
[5] Grieve, R.A.F. *et al.* (1989), *Meteoritics* 24, 83-88.

where $F(k,d_C) = J_2(kR_D) - kR_D J_1(kR_D)/4$. Figure 1 shows a cross section of the birth and development of an impact tsunami as computed from (2).

By equating tsunami energy to some fraction ε, of the impactor kinetic energy, crater depth d_c is tied to impactor radius R_I, velocity V_I, and density ρ_I by

$$d_C = (8\varepsilon\rho_I R_I^3 V_I^2/9\rho_w g)^{1/4} \quad (3)$$

For ε=0.135, equation (3) reproduces traditional crater diameter predictions[6] to within 5% for impactor radii 25m<R_I<500m. Repeated evaluation of (2) with (3), exposed an empirical law for maximum tsunami amplitude versus distance r, and impactor radius as:

$$u_z^{max}(r,R_I) = d_C\left[1 + 2r/3d_C\right]^{-(1.07+0.03d_C/h)} \quad (4)$$

Figure 2 plots (4) for V_I =20 km/s and ρ_I =3 gm/cm^3. Note that attenuation losses in maximum tsunami amplitude are nearly (1/r) for R_I<500m and ocean depths h>1000m. Given a particular tsunami hazard threshold u_z^{crit}, and impact-site/coast-site distance r, (4) can be used to find $R_I^{crit}(r,u_z^{crit})$, the critical impactor radius. Any impact at distance r from a body $R_I > R_I^{crit}(r,u_z^{crit})$ will produce tsunami heights exceeding u_z^{crit}. Given the annual impact flux $n(R_I)$ for all R_I, the annual rate of falls exceeding the threshold is

$$N(r,u_z^{crit}) = \int_{R_I^{crit}(r,u_z^{crit})}^{\infty} n(R_I)dR_I \quad (5)$$

For impact rate density we consider

$$n(R_I) = a\, R_I^{-2}$$

where *a* is fixed to generate one Earth-striking impactor R_I>1km per 100,000 years – a conservative estimate of the flux of small Near Earth Objects[7].

Work in progress includes the production of a global coastline map of impact tsunami hazard from (4) and (5) based on the fluxes of stony, iron, and cometary bolides, and the incorporation of atmospheric filtering and tsunami shoaling effects.

[6] Housen, K.R., R.M. Schmidt and K.A. Holsapple (1983), *J. Geophys Res.* **88**, 2485-2499.
[7] Rabinowitz, D. *et al.* (1994), in *Hazards due to Comets and Asteroids* (T. Gehrels, Ed.), U. of Arizona Press, 285-312.

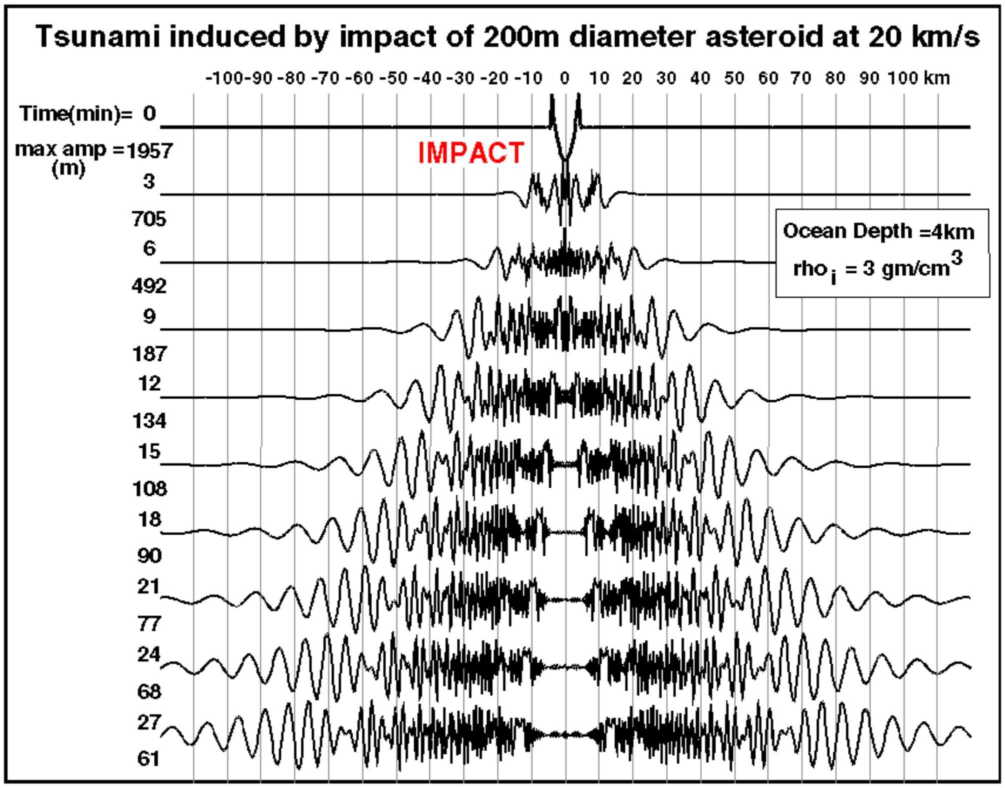

Figure 1. Tsunami induced by the impact of 200 m diameter asteroid at 20 km/s as computed by equations (2) and (3). Waveforms are shown at 3 minute intervals. Maximum amplitude is listed to the left. Note the strong effects of frequency dispersion in "pulling apart" the initial impact cavity. Peak amplitude is found at the wavelength corresponding to the cavity diameter. Maximum tsunami amplitude versus distance read from many plots like this are capsulized in Figure 2.

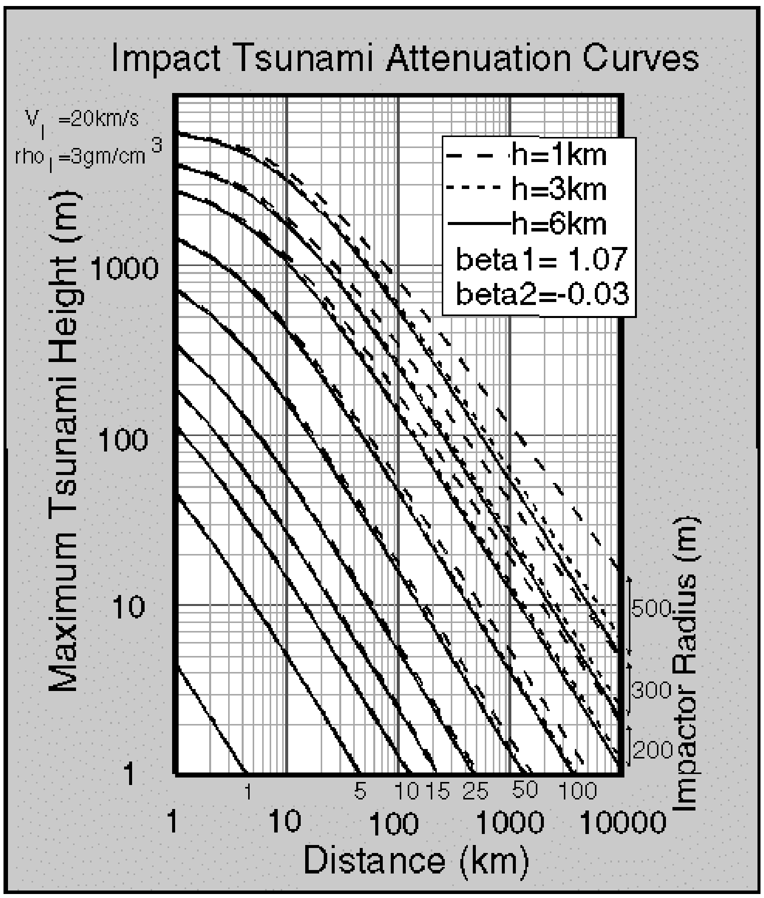

Figure 2. Tsunami attenuation from equation (4). The curves trace maximum tsunami height versus distance for asteroid radii between 1 and 500 meters. Note that there is little dependence of attenuation on ocean depth for impactors of this size range. Asteroids smaller than ~15 m radius typically airburst rather than impact.