EFFECTS OF OCEANS ON ATMOSPHERIC LOSS DURING THE STAGE OF GIANT IMPACTS. H. Genda[1] and Y. Abe[2], [1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology (2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan; genda@geo.titech.ac.jp), [2]Department of Earth and Planetary Science, The University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; ayutaka@eps.s.u-tokyo.ac.jp).

Introduction: The recent works on the planetary formation show that several tens of Mars-sized protoplanets are formed through a successive accretion of planetesimals in the terrestrial planet region [its time scale is ~ 10^5–10^6 years [*e.g.*, 1]]. Then, these protoplanets collide each other as their orbit crosses due to gravitational perturbations among them (its time scale is ~ 10^7–10^8 years [*e.g.*, 2]). Therefore, it is generally thought that several giant impacts of Mars-sized protoplanet occur at the late stage of the terrestrial planet formation.

Protoplanets would have a mixed proto-atmosphere [3] of an impact-induced gas [4] and a gravitationally-attracted solar-type gas [5]. The giant impacts modify such a proto-atmosphere. A large amount of the proto-atmosphere may be blown-off by the globally strong ground motion caused by a giant impact [6–8]. Genda and Abe [9] numerically calculated the loss fraction of the atmosphere (X_{atm}) indued by the global ground motion with various ground velocities (u_g). They showed that the relations between X_{atm} and u_g is insensitive to the initial proto-atmospheric conditions (see Figure 1). According to direct 3-D SPH (smoothed particle hydrodynamics) simulations of the giant impact, the velocity of the ground motion is estimated to be approximately 6 km/s at the antipode of the impact [10] and be smaller elsewhere (4–5 km/s on an average). Therefore, significant fraction of the proto-atmosphere survives a giant impact. This result indicates that the proto-atmospheres formed before the stage of giant impacts play an important role in the present terrestrial atmospheres [11].

In this study, we focus on the effect of an ocean on the planetary surface, which has not been considered in the previous studies[6–9]. We show the presence of an ocean enhances the atmospheric loss by a giant impact.

Numerical Model: We consider a spherically symmetric motion of an atmosphere and ocean induced by the global ground motion. The numerical method and major assumptions used here is the same as those used in Genda and Abe [9]. For the ocean, which is newly introduced here; we use two kinds of the EOSs; the Tillotson EOS [12] and the IAPWS95 EOS [13]. We can exactly treat vaporization of water by using the IAPWS95 EOS.

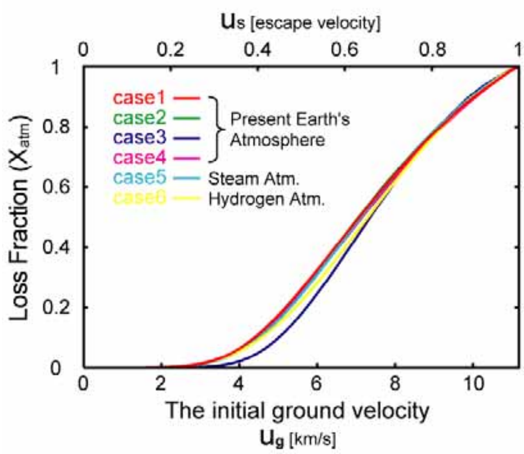

Figure 1. The relations between the initial ground velocity, u_s, and the final loss fraction of the atmosphere, X_{atm}.

As the initial conditions for an atmosphere, we consider a hydrostatically equilibrated polytropic atmosphere with γ_a = 1.4 (polytropic exponent), p_0 = 10 and 100 bar (atmospheric pressure at the sea level), T_0 = 300 K (temperature at the sea level), m_a = 2 g/mol (molecular weight), and γ = 1.4 (specific heat ratio). As the initial conditions for an ocean, we consider a hydrostatically equilibrated ocean with a depth of 3 km on an Earth-sized planet.

We do not solve the motion of the planetary interior induced by a giant impact. Instead, the ground motion is treated as the boundary condition of the bottom of the ocean. As in the cases of the previous studies [8–9], we give the initial ground velocity (u_g), and consider the subsequent ballistic motion of the ground.

Results: Figure 2 shows the temporal evolution of the velocity of the atmosphere and the ocean. In this simulation, the initial ground velocity is 4 km/s. A shock wave is formed in the ocean. When the shock front arrives at the atmosphere-ocean interface (~ 0.3s), the shocked water adiabatically expands and the bottom of the atmosphere accelerates up to ~ 10 km/s. Figure 3 shows the loss fraction of the atmosphere (X_{atm}) and ocean (X_{oce}) as a function of the initial ground velocity (u_g). For a given value of u_g, X_{atm} from an ocean-covered planet is always larger than that

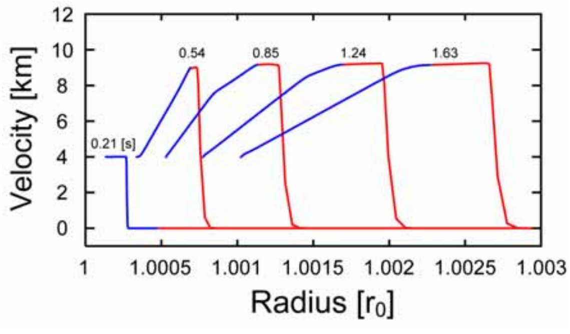

Figure 2. Temporal evolution of the velocity of the atmosphere (red curves) and the ocean (blue curves) for the Tillotson EOS. The value of the horizontal axis is normalized by the initial planetary radius. The numerical values in the figure represent the time (second) from start of the ground motion.

from a planet without an ocean. Thinner atmosphere results in larger X_{atm}.

There are two enhancement mechanisms for atmospheric loss. One is the vaporization of the ocean. The ground motion induces vaporization of the ocean. The vaporized ocean can efficiently push out the atmosphere. The other is the impedance coupling. The shock impedance of the ocean is lower than that of silicate materials and typically higher than that of the atmosphere. Due to such relations of shock impedances, the velocity at the ocean-atmosphere interface becomes larger than that of the ground motion.

Discussion: We discuss the ocean formation on protoplanets. Since the time scale of the dissipation of the surrounding nebula gas is typically 10^6–10^7 years [14], surrounding nebular gas is probably already lost during the stage of giant impacts. According to the calculation of a radiative-convective equilibrium model of an H_2O–CO_2 atmosphere [15], the ocean can be formed when $F_{pl} < \sim 300$ W/m^2, where F_{pl} is the planetary radiation flux, which equals to the energy flux radiated from the planet into the space. Since the energy released by the accretion of planetesimals is negligible after the formation of protoplanets, F_{pl} is almost the net solar radiation flux, that is, $S(1–A)/4$, where S and A are the solar radiation flux and the planetary albedo, respectively. Considering S of the early Sun is about 70% of the present value [16], that is, 960 W/m^2 at 1 AU, F_{pl} is estimated as 168 and 321 W/m^2 for A = 0.3 at the Earth's and Venusian orbits, respectively. This implies that all planets near the Earth's orbit should have oceans during the stage of giant impacts. Thus, the predecessor of the Earth has experience of large-scale atmospheric loss after every giant impact due to existence of an ocean, but almost

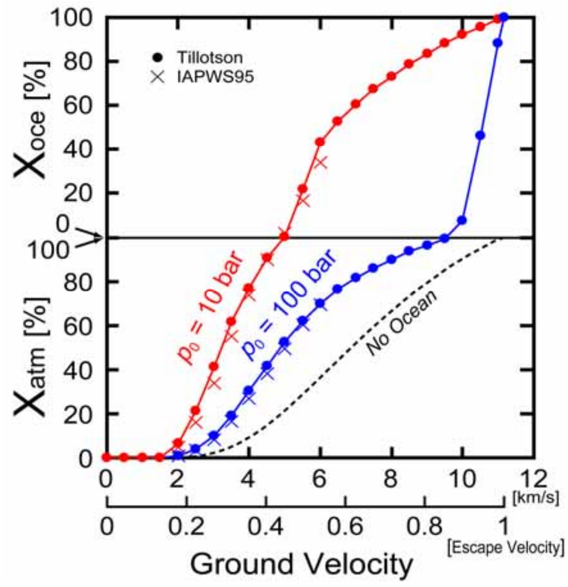

Figure 3 The loss fractions of the atmosphere (X_{atm}) and the ocean (X_{oce}) in the case of ocean-covered planet. Circles and crosses are the results for the Tillotson EOS and IAPWS95 EOS, respectively. The results below X_{atm} = 100% mean the loss of some atmosphere and no loss of the ocean. The results above X_{oce} = 0% mean the complete loss of atmosphere and the loss of some ocean. Dashed curve represents the results without an ocean (Case 1 atmosphere in Figure 1). The existence of an ocean enhances the atmospheric loss.

all ocean survives. Although ocean formation on the planets near the Venusian orbit depends on the planetary albedo, the planets, at least, inside the Venusian orbit cannot have oceans. These atmospheres are in the runaway greenhouse state. Thus, a large amount of the proto-atmosphere survives the giant impacts on Venus.

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