Conditions for oceans on Earth-like planets with carbonate-silicate geochemical cycle. S. Kadoya[1] and E. Tajika[2], [1]The University of Tokyo (kadoya@astrobio.k.u-tokyo.ac.jp), [2]The University of Tokyo (tajika@k.u-tokyo.ac.jp).

Introduction: The habitable zone (HZ) is defined as the cocentric orbital region around a star where Earth-like planets can have warm climates and liquid water (H_2O) on their surface (e.g., [1], [2]). The planets are, however, globally ice-covered when the greenhouse effect of the atmosphere is weak. On the Earth, the carbonate-silicate geochemical cycle has controlled the amount of the atmospheric CO_2 [3], and the negative feedback mechanism of the carbonate-silicate geochemical cycle is thought to maintain the climate of the Earth-like planets warm if the carbonate-silicate geochemical cycle is working on the planet. However, the recent work has revealed that even the present Earth in which the carbonate-silicate geochemical cycle is working could be globally ice-covered if the rate of CO_2 degassing via volcanism is lower than the critical value (e.g., [4]).

In this study, we examine the effect of the CO_2 degassing rate and insolation on the climates of the Earth-like planets which have oceans, continents, and the plate tectonics, i.e., a carbonate-silicate geochemical cycle. In particular, we focused on the conditions under which the ocean can exist on the Earth-like planets.

Model: We apply a one-dimensional energy balance model [5] coupled with a carbon cycle model [3] in order to estimate temperature distribution and atmospheric CO_2 for various insolation and CO_2 degassing rates. For simplicity, we assume the Earth itself as the Earth-like planet considered here, that is, to have exactly the same physical and chemical properties as those of the present Earth (e.g., mass, size, land-sea distribution, plate tectonics, and so on).

Results & Discussion: The climate of the Earth-like planets in the HZ is found to be divided into 3 climate modes: the snowball, warm, and hot climate modes (Figure 1). When the CO_2 degassing rate and/or insolation are high, the liquid water can exists on the Earth-like planet (the warm or hot climate modes). Among the three climate modes, the hot climate mode is characterized by very low pCO_2 level ($<10^{-7}$ bar), and by increased water vapor pressure. The hot climate mode corresponds to the moist greenhouse state as suggested by Kasting (1988) [6]. However, when the CO_2 degassing rate and/or insolation are low, the planet can be globally ice-covered repeatedly (the snowball climate mode) even though the planet is within the HZ and the carbonate-silicate geochemical cycle is working. For example, when the insolation is 0.9 times the present value of the Earth, the planet is in the snowball climate mode even though the CO_2 degassing rate is as much as the present rate of the Earth. We conclude that that the conditions for the existence of liquid water on the Earth-like planets should be largely restricted even when the planet is orbiting within the HZ and the carbonate–silicate geochemical cycle is working.

The Earth-like planet in the snowball climate undergoes the snowball and warm states repeatedly. However, the duration of the globally ice-covered states is much longer than the warm state. Therefore, the snowball planet can be observed statistically especially when the planetary orbit is far from the central star or the age of the planet is very old.

References: [1] Kasting J. F. et al. (1993) *Icarus, 101*, 108-128. [2] Kopparapu R. V. et al. (2013) *ApJ*, *765*, 131. [3] Walker J. C. G. et al. (1981) *J. Geophys.Res.*, *86*, 9776-9782. [4] Tajika E. (2003) *E & PSL*, *214*, 443-453. [5] North G. R. et al. (1981) *Rev. Geophys. Space Phys.*, *19*, 91-121. [6] Kasting, J. F. (1988) *Icarus*, *74*, 472-494. [7] Kadoya, S. and Tajika, E. (2014) *ApJ*, *790*, 107.

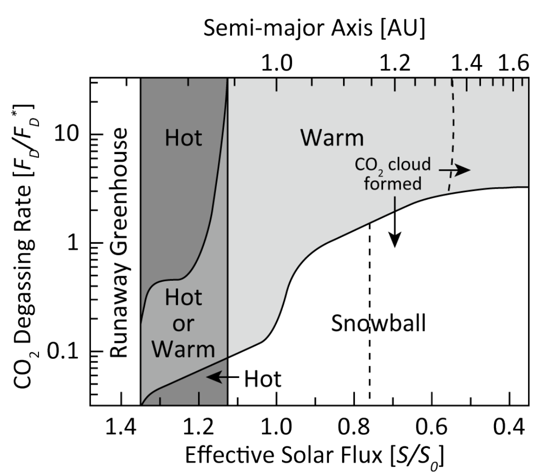

Figure 1: Climate mode diagram as functions of the effective solar flux and CO_2 degassing rate. When the effective solar flux is lower than the present value of the Earth, the planet is globally ice-covered repeatedly even though the CO_2 degassing rate is as much as the present value of the Earth. Modified from [7].