Lifetime of the warm climate of Earth-like planets in the habitable zone. 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@eps.s.u-tokyo.ac.jp)

Introduction: Recent studies revealed that, in addition to the insolation, a CO_2 degassing rate is another important factor for the climate of an Earth-like planet because it regulates the amount of atmospheric CO_2 (i.e., pCO_2) through the carbonate-silicate geochemical cycle with the negative feedback against the surface temperature (the Walker feedback) (e.g., [1]): for example, high CO_2 degassing rate results in high pCO_2, hence high surface temperature. The CO_2 degassing rate is supposed to decrease with time owing to the cooling of planetary interior (e.g., [2]), which may result in the cooling of the climate. On the other hand, the insolation is supposed to increase with time owing to the increase in the stellar luminosity (e.g., [3]), which may result in the warming of the climate. Thus, in order to reveal the climatic evolution of an Earth-like planet, it is necessary to consider the combined effects of the evolutions of CO_2 degassing rate and insolation.

In this study, we investigated the evolutionary tracks of Earth-like planets in the habitable zone (HZ) in order to reveal the spatiotemporal conditions for the Earth-like planets to have warm climate.

Models: We apply a one-dimensional energy balance climate model coupled with carbon cycle model in order to estimate a steady state of surface temperature distribution and pCO_2 for various insolation and CO_2 degassing rate. In addition, evolutions of CO_2 degassing rate and insolation are estimated by a parameterized convection model coupled with a CO_2 degassing model and a luminosity evolution model, respectively, in order to estimate an evolutionary track of climate of a planet. For simplicity, we assume the Earth-like planet to have exactly the same physical and chemical properties as those of the present Earth. On the other hand, different mass stars (0.5 M_{sun}, 0.8 M_{sun}, 1 M_{sun}, and 1.4 M_{sun}) are assumed in order to discuss effects of different timescales of the luminosity evolution.

Results & Discussions: In the HZ, the climate of Earth-like planets depend both on the CO_2 degassing rate and insolation. In the HZ, the condition of the insolation required for the planetary climate to be warm is shown to be limited, depending on the CO_2 degassing rate. The climate of the Earth-like planet, in which the Walker feedback is working, like the Earth, is named a "warm climate" mode. In the warm climate mode, high insolation and/or low CO_2 degassing rate result in low pCO_2. The globally-averaged surface temperature is, however, less dependent on the insolation, while it increases with an increase in the CO_2 degassing rate. These features are derived from an effect of the Walker feedback.

When the CO_2 degassing rate is below a critical value, which depends on the insolation, all the planetary surface is covered with ice, even in the HZ. In such a case, a steady state of the climate does not exist, and the climate oscillates between the long-term snowball and short-term warm states. This climate mode is named a "snowball cycle mode".

The evolution of the climate of Earth-like planets should depend on the evolutions of these two factors; the CO_2 degassing rate decreases with time, while the luminosity increases with time. For the first several giga years (Gyr), the climate of the Earth-like planet in the HZ evolves in the warm climate mode owing to the initially high CO_2 degassing rate. If the Earth-like planet orbits in the inner part of the HZ, the climate should evolve warmer; the climate mode changes from the warm climate to runaway greenhouse mode, because of an effect of the luminosity increase of the central star with time. On the other hand, if the planet orbits in the outer part of the HZ, we found that the climate should evolve colder; the climate mode changes from the warm climate to snowball cycle mode, because of an effect of the decrease of the CO_2 degassing rate with time. The timescale for the planet to maintain warm climate is about 4 Gyr in the outer part of the HZ.

We also found that this timescale does not change for the cases of the Earth-like planets around the central stars with different mass, although the luminosity and the timescale of luminosity evolution are different with different star mass. This is because the evolution of the climate depends mainly on the evolution of the planet (the CO_2 degassing rate), rather than the evolution of the central star, in the outer part of the HZ.

It is, therefore, implied that, the age of the planet (i.e., the age of the central star) is one of the very important factors in order to find the Earth-like planets in the HZ of the exoplanetary systems.

References: [1] Kadoya, S. & Tajika, E. (2014) *ApJ*, *790*, 107. [2] Tajika, E. & Matsui, T. (1992) *E&PSL*, *113*, 251. [3] Iben, I., Jr. (1967) *ARA&A*, *5*, 571.