Day-night water cycle dynamics on TRAPPIST-1e using an integrated global climate, hydrological, and glaciological model

*Arihiro Kamada[1], Takeshi Kuroda[1], Takanori Kodama[2], Mirai Kobayashi[1], Ralf Greve[3,4]

1. Graduate School of Science, Tohoku University, 2. Earth-Life Science Institute, Tokyo Institute of Technology, 3. Institute of Low Temperature Science, Hokkaido University, 4. Arctic Research Center, Hokkaido University

To date, more than 5,500 exoplanets have been discovered in our neighborhood (see NASA Exoplanet Archive), many of them orbiting M-dwarf stars. Their reduced luminosity compared to the Sun results in a habitable zone that is only ~0.1 AU away from the star. Over the past decade, many of the most promising candidate systems for habitability have been discovered, such as TRAPPIST-1, Proxima Centauri, and TOI-700. In general, exoplanets around M-dwarfs are subject to rapid tidal locking and are likely to rotate synchronously, so that they have a permanent day side, and a permanent night side, accumulating very large amounts of volatiles. In the TRAPPIST-1 system, TRAPPIST-1e would be a habitable environment without any warming gas, with a solar luminosity of about 900 W m^{-2} (~66 % compared to the Earth). For water-limited tidally locked planets, it is possible to maintain a temperate climate in the terminator region, but how the water circulates from the night side back to the day side is not fully understood.

Here we performed simulations to elucidate the self-consistent water cycle on exoplanets by coupling global climate model (PMGCM), global river model (CRIS), and global ice sheet models (ALICE), with a particular focus on the role of geothermal and tidal heating in maintaining liquid water in the terminator region. The generated geothermal heat flux at the base of the ice sheet induces subglacial melting, creating rivers that transport water to the day side, where it evaporates and returns to the night side. We ran climate simulations with a horizontal resolution of ~2.8° in longitude and latitude, 15 σ-level layers reaching an altitude of about 50 km. For the radiative transfer scheme, we used the TRAPPIST-1 radiation spectrum and performed calculations in atmospheric conditions composed of N_2 or CO_2 with a surface pressure of 1 bar. We assumed the initial water source of the nightside up to a several kilometers high. Prior to this study, we validated our model by performing simulations based on the THAI protocol benchmarks for both dry (Ben 1 and Ben 2, see THAI part 1) and ocean (Hab 1 and Hab 2, see THAI part 2) planetary conditions. These preliminary simulations confirmed the consistency of our models for dry and ocean planets in comparison with previous studies.

We found that the evening side of the terminator region is consistently warmer than the morning side due to the inflow of warm air from the subsolar point, promoting active subglacial melting in the evening side, and forming rivers that flow toward the day side. The day side rivers gradually warm, leading to evaporation. This process culminates in the complete dissipation of the rivers, with the water vapor eventually precipitating as rain or snow and returning to the terminator and nightside regions. Furthermore, ice sheets on the nightside flow toward the dayside. As the ice sheets approach terminator region, surface melting of the ice sheets also occurs, further contributing to the dynamics of the global water cycle. The active supraglacial and subglacial melting, and river flow patterns are indicative of a complex climate system of the TRAPPIST-1e in which the terminator behaves as a transition zone, facilitating significant water exchange between the night and day sides.

Keywords: Exoplanet, TRAPPIST-1e, Global climate model, Global river model, Global ice sheet model