Kilometer-scale Climate Modeling of TRAPPIST-1e Using ICON-Sapphire: Advancing Exoplanet Habitability Studies

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Recent advances in kilometer-scale modeling and exascale computing have made it possible to simulate Earth's climate with unprecedented detail. Alongside this, breakthroughs from the James Webb Space Telescope (JWST) present new opportunities for characterizing Earth-like exoplanets and helped create a growing catalog of over 5,000 confirmed exoplanets. In this work, we focus on one such exoplanet, TRAPPIST-1e, a rocky planet slightly smaller than Earth orbiting in the habitable zone of an ultra-cool dwarf star 40 light-years away from our solar system.

Until now, prior climate simulations of exoplanets have relied on coarse-resolution models (grid spacings >100 km), which require explicit parameterizations for convection and clouds, introducing large uncertainties. We carry out the first global climate simulations of TRAPPIST-1e's atmosphere at 5 km horizontal resolution using ICON-Sapphire, a kilometer-scale model previously applied only to Earth's climate. The model is specifically adapted to Trappist-1e, accounting for its size, rotation rate, surface properties, and stellar radiation, offering a groundbreaking look at Earth-like exoplanet atmospheres.

We aim to explore whether ICON-Sapphire can perform stable and physically consistent simulations of Trappist-1e's climate over long timescales. We also seek to understand how high-resolution simulations differ from previous coarse-resolution models, with a particular focus on the representation of clouds and water vapor. Lastly, we will investigate whether the improved resolution enhances our ability to detect and characterize the atmospheres of Earth-like exoplanets through synthetic spectral observations. This could offer critical insights into the detectability of key atmospheric features and the overall feasibility of confirming habitability via remote sensing. Initial simulations will follow the "Hab 1" protocol of the THAI model intercomparison project [1], assuming a static ocean, and a 1-bar N_2-dominated atmosphere with 400 ppm of CO_2. Development and test runs are carried out on the Vienna Scientific Cluster, and production runs will be conducted on the LUMI supercomputer.

This work makes use of new HPC capabilities to pioneer the use of kilometer-scale climate modeling for exoplanet research, bridging advancements in Earth system science and exoplanetary studies. By critically re-evaluating earlier coarse-resolution models and incorporating detailed physical processes, it provides a robust framework to understand the climates of Earth-like exoplanets and their potential habitability.

References

[1] Fauchez T, et al. TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI): motivations and protocol version 1.0, Geoscientific Model Development, 13, 707–716, (2020).