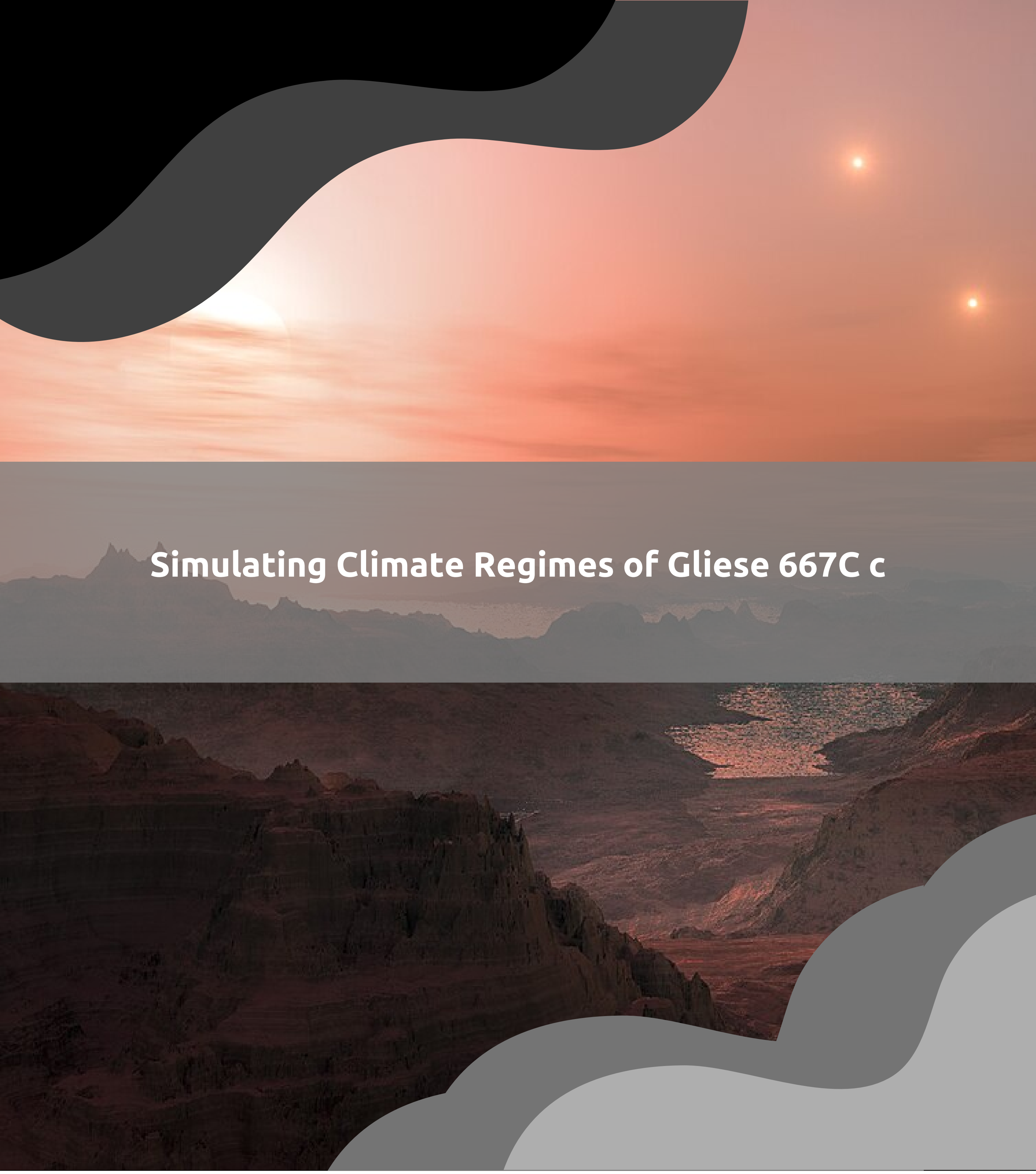

Simulating Climate Regimes of Gliese 667C c

the climate centre

Simulating Climate Regimes of Gliese 667C c

Introduction

- Gliese 667C c is a terrestrial super-Earth orbiting the M-dwarf star Gliese 667C at a distance of ~0.125 AU, with an orbital period of ~28.2 days placing it within the habitable zone (Anglada-Escudé et al 2012, Anglada-Escudé et al 2013). Given its proximity to Earth, being only 23 light years away, it will be important to conduct climate modelling of this exoplanet for the purposes of understanding its potential habitability.
- This requires characterising the sensitivity of its climate to atmospheric composition, surface properties, and orbital configuration. Key unknowns include the atmospheric composition, surface pressure, land-to-water ratio, and spin-orbit resonance state, while its mean radius of ~1.7 Earths, mass being greater than 4.1 Earths, and equilibrium temperature of 277 K, is better established (Sloane, Guinan, & Engle, 2023).
- Despite its importance as a habitability candidate, the climate of Gliese 667C c is not well understood. No direct atmospheric characterisation currently exists, and climate modelling studies remain limited. This work contributes to filling that gap by systematically exploring the sensitivity of surface climate to key physical parameters.
- This study presents a suite of exoplanetary climate simulations spanning atmospheric composition, land fraction, and orbital configuration, with the aim of providing greater understanding on the range of possible climate regimes and potential habitability of Gliese 667C c.

Methods

- ExoPlaSim is a Python-implemented 3D climate model simulation package designed to be fast and flexible with intermediate complexity. Based on the PlaSim model for Earth it has been extended for application to terrestrial exoplanet atmospheres (Paradise et al. 2021).
- Four different configurations were implemented: (1, scenario i) an Earth-like N_2-CO_2 atmosphere with different continental land fractions; (2, scenario ii) a moderate pressure (~15 bars) water world; (3, scenario iii) a high CO_2-rich atmosphere with high surface pressure (~60 bars); and (4, scenario iv) a minimal atmosphere with negligible surface pressure. These span conditions from effectively airless to potentially greenhouse-dominated.
- For the Earth-like atmospheric configuration (scenario i) land fraction was varied across three configurations: 25% (quarter-land), 50% (half-land), and 75% (three-quarter-land), with land distributed using a randomised continental layout applied consistently across all spin-orbit configurations.
- Orbital configurations investigated included: (1) tidally locked (1:1 spin-orbit resonance); (2) 2:1 spin-orbit resonance; and (3) 3:2 spin-orbit resonance.
- Models were run over a 100-year period. Temperatures stabilised within 10-30 years for almost all models, except for all water world configurations (scenario ii), and the Earth-like (scenario i) 50% land configuration in a 3:2 spin orbit state, none of which stabilised during the 100-year period.
- Model performance was evaluated qualitatively by comparing simulated climate behaviour against general expectations, for example the greenhouse effect magnitude for each atmospheric scenario, the day-night contrast under tidal locking, and the precipitation and humidity response.

- Climate variables investigated included surface air temperature, wind speed and direction, cloud cover fraction, precipitation rate, and relative humidity. Spatial and temporal averages were computed for each scenario, with particular attention to dayside-nightside contrasts and latitudinal temperature gradients.

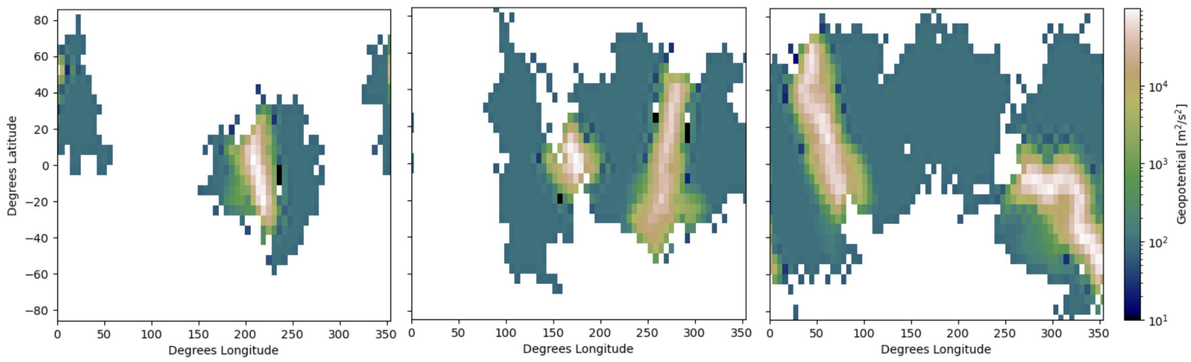

Fig. 1 Randomised continental layouts for different land fractions include quarter-land (left), half-land (middle), and three-quarters land (right), plotted by geopotential.

Results

- The Earth-like N_2-CO_2 atmosphere scenario (i) with different continental land fractions was typically colder than any other scenario. Land fractions of 50% and 75% under a 2:1 configuration were the coldest at -72.25°C and -72.35°C, respectively. The warmest configurations were for a 75% land coverage in a tidally locked configuration, at -2.43°C, and a 3:2 configuration, at -1.18°C. This scenario also experienced moderate wind speeds (2.76 m/s to 6.20 m/s), rainfall (17.41 mm/year to 105.5 mm/year), relative humidity (39.53% to 62.19%), and cloud cover (25.40% to 39.91%).
- While water world scenario (ii) model runs demonstrated the highest temperatures, with 39.53°C for the 2:1 configuration. However, these values did not stabilise at all during the 100-year model run, potentially indicating a runaway greenhouse effect.
- The high CO_2-rich atmosphere scenario (iii) showed elevated temperatures compared to the Earth-like and minimal atmosphere scenarios, but lower than would normally be expected, and lower than the water world scenario. The tidally locked configuration was the coldest at 13.81°C, while the 2:1 was the warmest at 22.76°C. This scenario produced no cloud cover, no precipitation, 0% relative humidity, and gentle wind speeds (0.93 m/s to 1.05 m/s).
- The minimal atmosphere scenario (iv) produced freezing temperatures across all configurations: -21.50°C for 1:1, -13.66°C for 2:1, and -14.44°C for 3:2. There was no cloud cover, no precipitation, 0% relative humidity, and moderate to higher wind speeds (4.67 m/s to 7.48 m/s).
- Day-night differentials for the tidally locked configuration were highest for the minimal atmosphere scenario (iv) with a 64.66°C difference, and moderate for the Earth-like scenario (i) with a 20.79°C difference for the 25% land fraction, a 24.03°C difference for the 50% land fraction, and a 28.71°C difference for the 75% land fraction. Higher rainfall, humidity, wind speeds,

and cloud cover was experienced on the day side compared to the night side for the Earth-like configuration.

- Temperatures conducive to liquid water were experienced across the entire surface for the water world scenario (ii), and the high CO_2-rich atmosphere scenario (iii) for the 2:1 and 3:2 configuration, and the dayside for the tidally locked configuration. For the minimal atmosphere scenario (iv), there was a narrow band of liquid water temperature zone at the equator for the 2:1 and 3:2 configurations, while this zone was limited to the dayside for the tidally locked configuration.
- For the Earth-like scenario (i), liquid water temperature zones could be found on the dayside under the tidally locked configuration for all land fractions. The 75% land fraction under the 3:2 configuration had liquid water temperatures at low to mid latitudes, while the 2:1 configuration the entire planet was below freezing. The 50% land fraction under the 3:2 configuration had liquid water temperatures near low latitude coastlines, oceans, and low elevation zones, while for the 2:1 configuration the entire planet was below freezing. The 25% land fraction model was entirely below freezing.

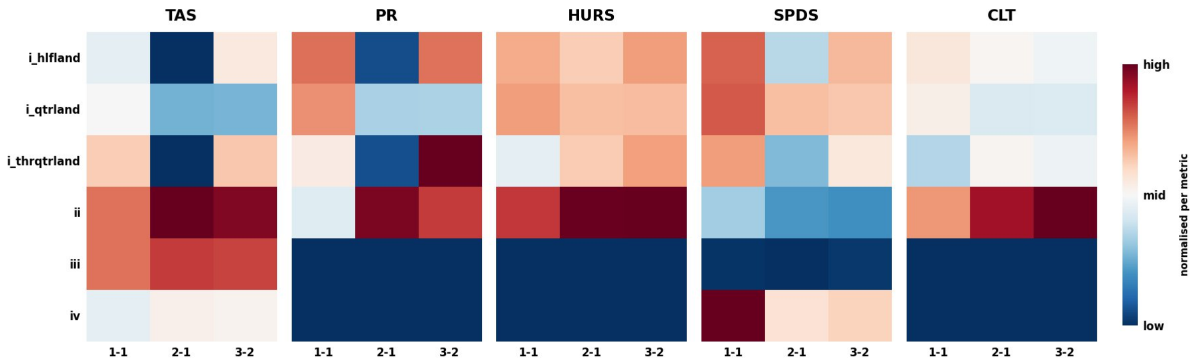

Fig. 2 Normalised comparison of temperature (TAS), rainfall (PR), relative humidity (HURS), wind speed (SPDS), and cloud fraction (CLT) across different model configurations.

Discussion

- These results demonstrate that the climate of Gliese 667C c is highly sensitive to atmospheric composition, land fraction, and orbital configuration. Under Earth-like atmospheric conditions habitability refugia were highly constrained to low latitude areas in a 3:2 configuration, while for a tidally locked configuration this was limited to the dayside, and 2:1 configuration was not deemed habitable due to below freezing temperatures.
- The model successfully reproduced qualitatively expected behaviour in several configurations, including extreme day-night temperature contrasts under tidal locking, but was limited because of its failure to produce a greenhouse warming effect for the dense CO_2-rich atmosphere, which instead produced results similar to a modest temperature increase. This an acknowledged limitation of the model (Paradise et al. 2022), but should be addressed in any future developments of the ExoPlaSim model, otherwise it significantly limits CO_2-dominated habitability assessments using this approach.

- The sensitivity of the liquid water zones under an Earth-like atmosphere to different land fractions, continental land mass configurations and spin-orbit configuration indicates the importance of conducting further observations in order to refine the exact nature of its orbit, and characterising its atmospheric constituents.
- The creation of thermally distinct dayside refugia under higher land fractions suggests surface heterogeneity may sustain localised habitability even where global mean temperatures are marginal.
- Other research has indicated that Gliese 667 Cc maybe subject to extreme tidal heating, meaning the chances of habitability could be much lower than this study indicates. However, this depends on a number of factors relating to its orbital configuration (Makarov & Berghea, 2014).
- This study contributes to the exoplanet climate modelling literature and demonstrates the utility and limitations of using ExoPlaSim for this application, while also indicating the need for follow-up observations to better constrain orbital parameters and atmospheric conditions to better understand the true extent of its potential habitability.

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