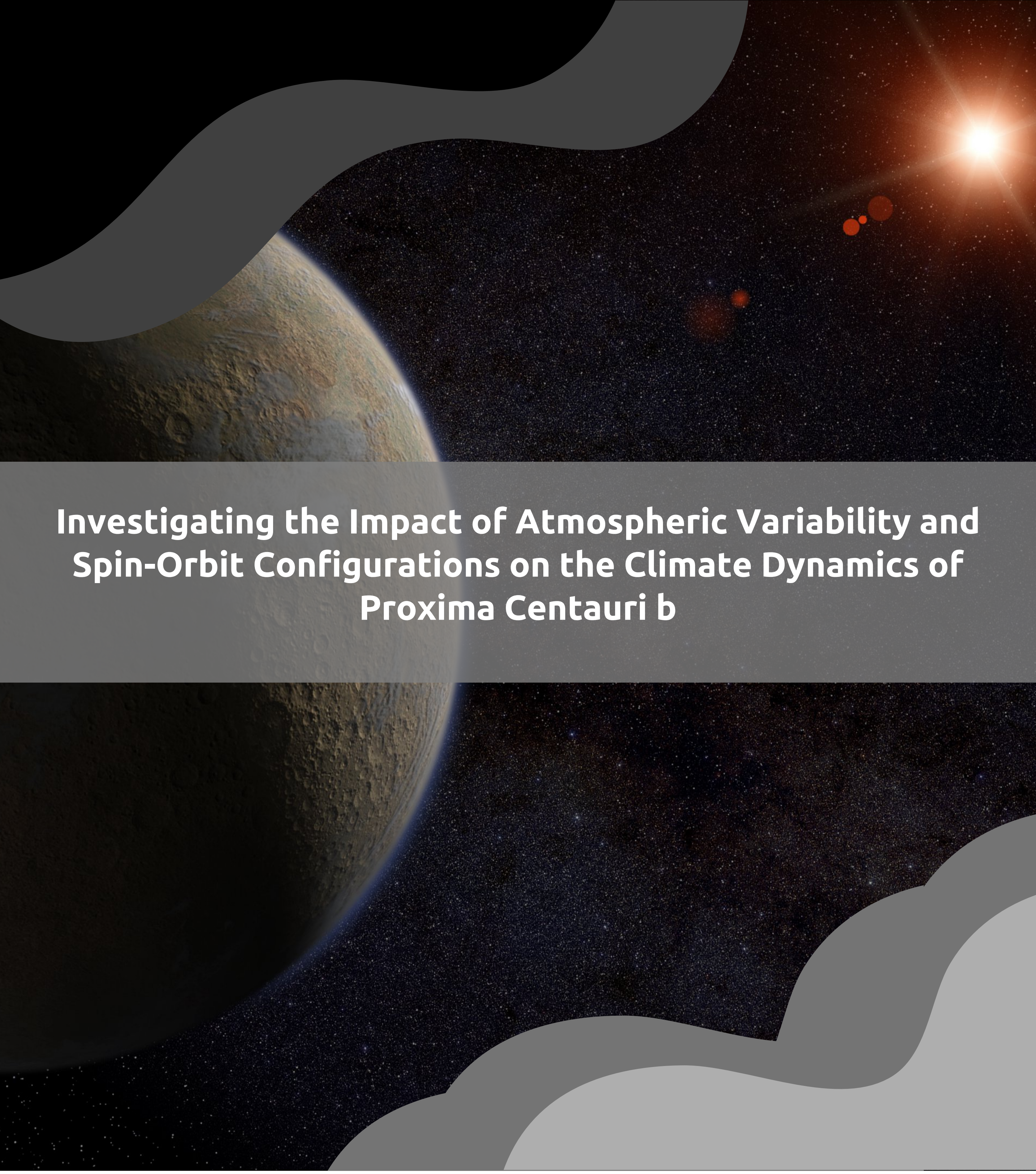

Investigating the Impact of Atmospheric Variability and Spin-Orbit Configurations on the Climate Dynamics of Proxima Centauri b

the climate centre

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Introduction

- Proxima Centauri b is a terrestrial planet candidate orbiting Proxima Centauri, an M-type red dwarf star, with an orbital period of ~11.2 days at a distance of ~0.05 AU, placing it within the habitable zone (Anglada-Escudé et al., 2016). It is the closest known exoplanet to Earth, making it an important target for both observation and climate modelling.
- Understanding habitability on Proxima Centauri b requires characterising the sensitivity of its climate to atmospheric composition, surface properties, and orbital configuration. Its mean radius is between 0.9 and 1.4 Earth radii, and its mass is greater than 1.05 Earth masses (Brugger et al 2016; Suárez Mascareño et al. 2025). Key unknowns include its atmospheric composition, surface pressure, land-to-water ratio, and spin-orbit resonance state (Ribas et al., 2016; Turbet et al 2016).
- Despite its importance as a habitability candidate, the climate of Proxima Centauri b is poorly constrained. No direct atmospheric characterisation currently exists, and climate modelling studies remain hypothetical. 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 general climate model simulations spanning atmospheric composition, land fraction, and orbital configuration, with the aim of assessing model performance and providing constraints on the range of possible climate regimes and potential habitability of Proxima Centauri b.

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 atmospheric configurations were implemented: (1) a minimal atmosphere (near-vacuum, Scenario i) with negligible surface pressure; (2) a moderate-pressure (~6.5 bars) $N_2/CO_2/H_2O$ atmosphere (Scenario ii); (3) a dense CO_2-rich atmosphere (Scenario iii) with high surface pressure (~50 bars); and (4) an Earth-like N_2/O_2-dominated atmosphere (Scenario iv).
- Land fraction was varied across three configurations for the Earth-like N_2/O_2 atmosphere: 25% (quarter-land), 50% (half-land), and 75% (three-quarters land), with land distributed using a randomised continental layout applied consistently across all 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 time period. Stable temperatures were reached within ~15 years for most model configurations, with the water world configuration taking longer (~30 years). The water world configuration for 2:1 and 3:2 resonance did not stabilise, but the rate of temperature increase slowed after ~30 years.
- Model performance was evaluated qualitatively by comparing simulated climate behaviour against theoretical expectations: the greenhouse effect

magnitude for each atmospheric scenario, the day-night contrast under tidal locking, and the precipitation and humidity response to land fraction and orbital configuration changes.

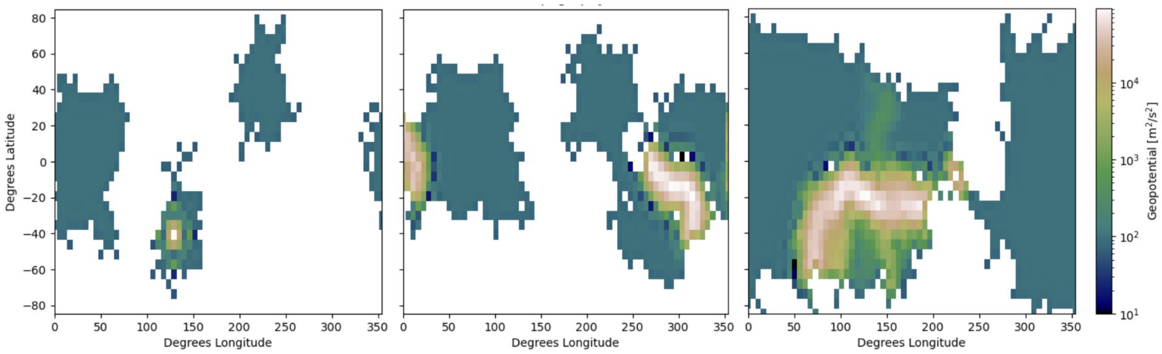

Fig. 1 Randomised continental layouts for different land fractions include quarter-land (left), half-land (middle), and three-quarters land (right), plotted by geopotential.

Results

- Mean global surface temperature in the minimal atmosphere (Scenario i) was −47.23°C under tidal locking, with a pronounced day-night contrast of 81.75°C (dayside: −6.36°C; nightside: −88.11°C). No precipitation or cloud formation occurred in this scenario, and wind speeds were the highest of any configuration, reaching a mean of 10.67 m/s.
- The high-pressure water world (Scenario ii) produced a greenhouse effect, with mean temperatures reaching 10.37°C under tidal locking, 49.12°C under 2:1 resonance, and 30.88°C under 3:2 resonance; the warmest values of any scenario. This is the only configuration in which the model produced a strong positive greenhouse feedback. This scenario also produced the highest relative humidity (86-89%) and the highest cloud fractions (44-54%).
- The dense CO_2-rich atmosphere (Scenario iii) did not produce the expected greenhouse warming, yielding a mean global temperature of 2.65°C under tidal locking, 11.12°C for the 2:1 configuration and 10.98°C for the 3:2 configuration. No moisture feedback occurred, with 0% relative humidity, zero precipitation and no cloud coverage across all orbital configurations. This scenario produced the lowest wind speeds (0.87-1.12 m/s).
- The Earth-like N_2/O_2 atmosphere (Scenario iv) produced varied temperature outcomes. Tidal-locked (1:1) configurations showed day-night contrasts of 22.72–38.66°C across land fraction variants, with dayside temperatures reaching −4.53°C for the 75% land configuration. The 2:1 resonance configurations produced warmer global averages (e.g. −4.18°C for 25% land), while 3:2 resonance yielded intermediate results (e.g. −9.89°C for 25% land), and tidally locked configuration produced the coldest average (e.g. -22.11°C for 25% land).
- In the Earth-like N_2/O_2 atmosphere under tidal locking, increasing land fraction showed limited effect on mean temperature (ranging from −22.11°C at 25% land to −23.96°C at 50% land and −23.86°C at 75% land). However, relative humidity decreased substantially from 64.19% at 25% land to 30.49% at 75% land for 1:1 configurations, with a reduced decrease at 3:2 configuration from 68.18% at 25% land to 52.15% at 75% land.

- Proxy habitable conditions, i.e. those where temperatures allowed liquid water, were seen across all scenarios. The minimal atmosphere scenario allowed liquid water on the daytime side under tidal locking, but was otherwise below zero for 2:1 and 3:2 configurations. The high-pressure water world experienced favorable temperatures across the entire planet under 2:1 and 3:2 configurations and all locations other than the poles under a tidal locked configuration. The dense CO_2-rich configuration experienced liquid water temperatures at all locations other than the poles, while the tidally locked configuration only allowed liquid water on the daytime side. The Earth-like N_2/O_2 configuration was more restrictive, only allowing liquid water temperatures are low and mid latitudes under 3:2 and 2:1 configurations, or on the dayside for tidally locked configuration.
- Despite showing surface air temperatures supportive of liquid water, the minimal atmosphere and the dense CO_2-rich configurations indicate no precipitation or cloud cover and 0% relative humidity, meaning such circumstances would be inhospitable to life.

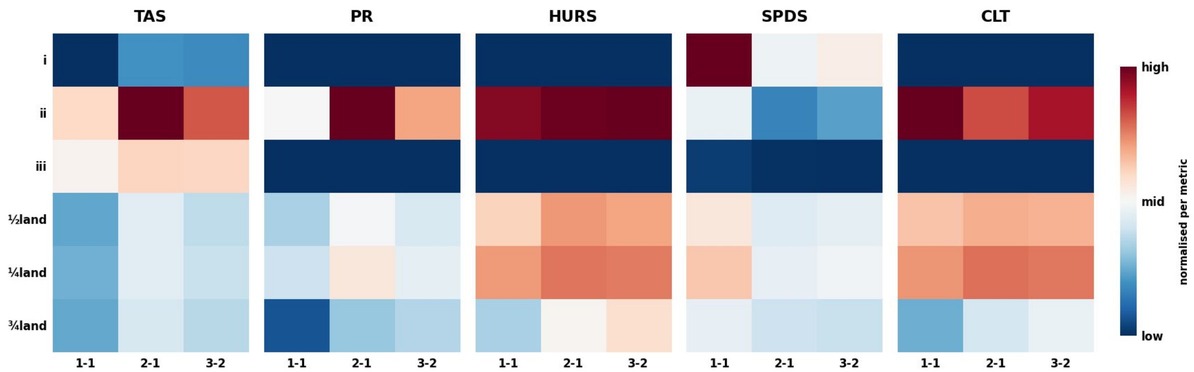

Fig. 2 Normalised comparison of temperature (TAS), rainfall (PR), relative humidity (HURS), wind speed (SPDS), and cloud fraction (CLT) across different model configurations.

Discussion

- These results demonstrate that the climate of Proxima Centauri b is highly sensitive to atmospheric composition, land fraction, and orbital configuration. No single scenario produces unambiguously habitable global conditions; however, the Earth-like N_2/O_2 atmosphere with quarter-land fraction under tidal locking represents a favourable case among those assessed.
- The model successfully reproduced qualitatively expected behaviour in several configurations, including extreme day-night temperature contrasts of 81.75°C under tidal locking in the minimal atmosphere scenario, but showed limitations through its failure to produce a greenhouse warming effect for the dense CO_2-rich atmosphere. This is a noted limitation of ExoPlaSim (Paradise et al. 2022), meaning its utility in modelling terrestrial exoplanetary climates is limited.
- Benchmarking against established exoplanet GCMs such as ExoCAM (Wolf et al., 2022) or ROCKE-3D (Way et al., 2017) would help confirm whether this behaviour is realistic or a consequence of the simplified physics in the current implementation.

- Spin-orbit configuration emerged as an important control on climate in the Earth-like N_2/O_2 scenario (Turbet et al., 2016). Transitions from tidal locking to non-synchronous rotation generally increased global mean temperatures. This highlights the importance of considering non-tidally-locked orbital states.
- Under tidal locking, the quarter-land configuration produced the warmest conditions and highest relative humidity, while increasing land fraction reduced humidity and precipitation. The creation of thermally distinct dayside refugia under lower land fractions suggests surface heterogeneity may sustain localised habitability even where global mean temperatures remain marginal.
- This study contributes to the exoplanet climate modelling literature and demonstrates the utility and limitations of moderate complexity climate models applied to terrestrial exoplanets. Future work should address the CO_2 greenhouse parameterisation, incorporate M-dwarf stellar spectrum effects (particularly enhanced UV and flare activity from Proxima Centauri; Ribas et al., 2016), and extend the orbital parameter sweep to eccentric configurations and non-zero obliquity.

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