From Surface to Spectra: Characterising TRAPPIST-1e's Atmosphere and Climate

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INTRODUCTION

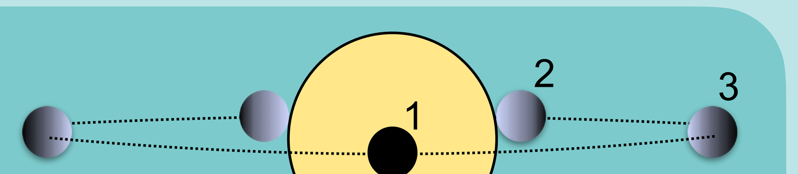
TRAPPIST-1e, a rocky **exoplanet** in the habitable zone, is a prime candidate for **habitability studies** due to its Earth-like mass, radius, and gravity. Its **tidally locked** orbit creates stark day–night contrasts. Characterising such atmospheres remains difficult due to observational and modelling limitations. This study uses data from the **ROCKE-3D** climate model to **characterise possible atmospheric scenarios** for TRAPPIST-1e and assess the **observational precision** needed to distinguish between them with current and future instruments.

METHODS

Instruments:
- JWST MIRI (Space-based)
- VLT CRIRES+ (Ground-based)
- ELT ANDES (Ground-based)

Modelling:
- ROCKE-3D [1]

Tools:
- Planetary Spectrum Generator
- Panoply



1. **Transmission spectrum** - primary transit
2. **Emission spectrum** - planet's thermal radiation
3. **Reflection spectrum** - starlight reflected by the planet's atmosphere or surface

Planet Radius	Planet Mass	Density	Orbital Period	Inclination	Semi-major Axis	Surface Gravity	Irradiation
0.92 R⊕ [2]	0.69 M⊕ [2]	0.89 ρ⊕ [2]	6.1 days [2]	89.79° [2]	0.03 AU [2]	0.93 g [3]	0.66 S⊕ [4]

Name	Description of Atmospheric Scenario [5]
A	Arid Venus: Venus-like topography, minimal to no surface water, N_2-dominated atmosphere + 400 ppmv CO_2
B	10-meter ocean in the lowest parts of Venus topography, N_2-dominated atmosphere + 400 ppmv CO_2
C	310-meter ocean in the lowest parts of Venus topography, N_2-dominated atmosphere + 400 ppmv CO_2
D	Aqua planet: completely ocean-covered planet, N_2-dominated atmosphere + 400 ppmv CO_2
E	Aqua planet: completely ocean-covered planet, N_2-dominated atmosphere + 1% CO_2. 25x more CO_2 than in previous scenarios
F	Aqua planet: completely ocean-covered planet, 100% CO_2 atmosphere

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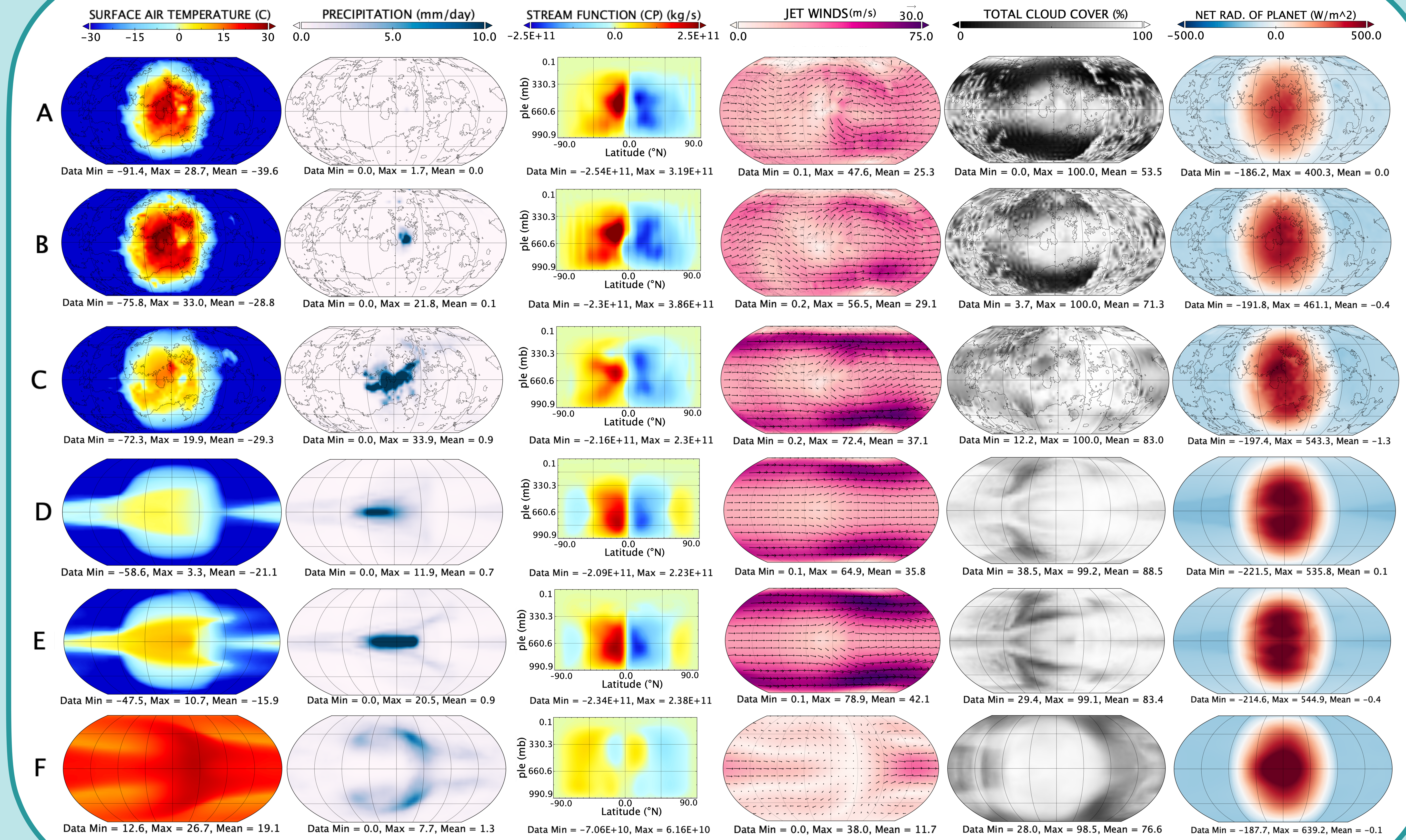

RESULTS

Atmospheric Characterisation:
- **Surface Temperature:** Most cases show "eyeball" patterns with heat concentrated at the substellar point; aqua planets have smoother gradients, arid planets stronger day–night contrasts.
- **Precipitation:** Mostly dry with substellar rainfall peaks, except in the 100% CO_2 case, which forms a horseshoe-shaped precipitation pattern.
- **Global Circulation:** Dominated by two Hadley-like cells; aqua planets show additional Ferrel-like cells, and CO_2 dominated scenarios exhibit reversed upper-level flow and subsidence.
- **Cloud Cover and Net Radiation:** Cloudiest in aqua planets; low-level clouds near the substellar point reduce reflection. Most cases experience slight net energy loss at the top of the atmosphere.
- **Jet Streams:** Strong Rossby waves appear in arid Venus cases; Scenario D best matches Earth-like jets; CO_2 rich cases show broken jet structure and strong asymmetry.

Spectra:
- **Transmission** spectra are **similar across scenarios**, except for the distinct CO_2 dominated case.
- **Emission** spectra (phase angle 3°) show **growing differences** at longer wavelengths.
- **Reflection** spectra (phase angle 30°) reveal the **clearest distinctions** between scenarios.

CONCLUSION

I. **Tidal locking** induces extreme day-night contrasts and atmospheric dynamics, often creating **"eyeball worlds"** with distinct profiles compared to Earth.
II. **CO_2 rich atmospheres stand out** most with atmospheric dynamics and transmission spectra.
III. **Spectral differences between scenarios are least visible in transmission spectra, more apparent in emission spectra, and most evident in reflection spectra.**

Future work:
I. Analysing **JWST NIRSpec**, ELT ANDES and VLT CRIRES (H & K bands), data to identifying key diagnostic wavelengths.
II. Constructing a **climate diagram**, similar to Koppen's climate classification, to assess the potential habitability based on climate zones.
III. Using **broadband filters** (F1500W and F1280W), for measuring precise points on the spectra.