# A new metric for planetary surface habitability

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## Introduction

- Considering the habitable area of a planetary surface is important for the potential emergence and evolution of life, with implications for the subsequent generation and detection of biosignatures or technosignatures.
- A variety of habitability metrics have been defined so far, based upon habitable surface temperature ranges, open ocean (or equivalently ice free) fraction, and aridity[1-6]. Some of these have been used to calculate the 'fractional habitability' of a planet for comparisons of broad parameter sweeps or to explore spatial patterns of surface habitability[1-6].
- We build upon these previous studies to introduce a **new climatological metric** which is defined using the known thermal limits of life on Earth, along with a consideration of surface water fluxes. It is the **first of its kind** to consider both **microbial** and **macroscopic complex** life, as well as being validated against datasets representing surface life on Earth.

## Methods

- **Metric definition:** Combining the complex life habitability metric[6] with the observed temperature limits of microbial life[7], we define $H_T = H_T(\phi, \lambda)$ describing the thermal habitability:

$$H_T = \begin{cases} \text{complex} & \text{if } \quad 273.15 \leq T_s \leq 323.15, \\ \text{microbial} & \text{if } \quad 253.15 \leq T_s \leq 395.15, \\ \text{limited} & \text{otherwise} \end{cases}$$

  for latitude $\phi$, longitude $\lambda$, and surface air temperature $T_s = T_s(\phi, \lambda)$ [K]. The climatological surface habitability $H = H(\phi, \lambda)$ is then defined as the result of $H_T$ with an additional condition representing water availability:

$$H = \begin{cases} H_T & \text{if } \quad P - E \geq 0 \;\&\; P \geq 250, \\ \text{limited} & \text{otherwise} \end{cases}$$

  for precipitation P and evaporation E [mm year$^{-1}$]. The minimum P condition is based on the definition of a desert on Earth[8].
- **Fractional habitability:** Each category is calculated as the weighted fraction of all grid cells which satisfy the respective conditions defined above.
- **'Predicted' climatological habitability:** Calculated from ERA5 reanalysis[9] annual means across 2003–2018.
- **'Observed' habitability:** $H_O = H_O(\phi, \lambda)$ is calculated from satellite derived data — normalised difference vegetation index (NDVI) on land[10], and gap-filled Chlorophyll-*a* concentration (Chl-*a*, mg m$^{-3}$) in the ocean[11] — with the following conditions:

$$H_O = \begin{cases} \text{complex} & \text{if } \quad NDVI > 0.3 \,|\, Chl\text{-}a_{min} > 0.15, \\ \text{microbial} & \text{if } \quad NDVI > 0.15 \,|\, Chl\text{-}a_{mean} > 0.15, \\ \text{limited} & \text{otherwise} \end{cases}$$

  where non-subscripted and subscripted *min* denote annual mean and minimum values, respectively. Thresholds are based upon values of different biomes (NDVI)[12,13] and phytoplankton size class (Chl-*a*)[14].
- **Validation tests**: Accuracy as weighted fraction of grid cells correct, Heidke Skill Score (HSS)[15] for attributing accuracy to predictive skill vs random chance, and $\chi^2$ for statistical significance of relationship with observed.
- **Aquaplanet simulations:** ExoCAM[16] (slab ocean) and ROCKE-3D[17] (slab + dynamic ocean) used to simulate an 'aquaplanet' Earth orbiting a solar-type (G2V) star.
- **Aquaplanet config:** $\varepsilon = 23.4°$, solar flux = 1360 W m$^{-2}$, 2003–2018 atmospheric composition: ~1 bar $N_2$ + 390ppm $CO_2$ + 1810ppb $CH_4$[18,19].

### References

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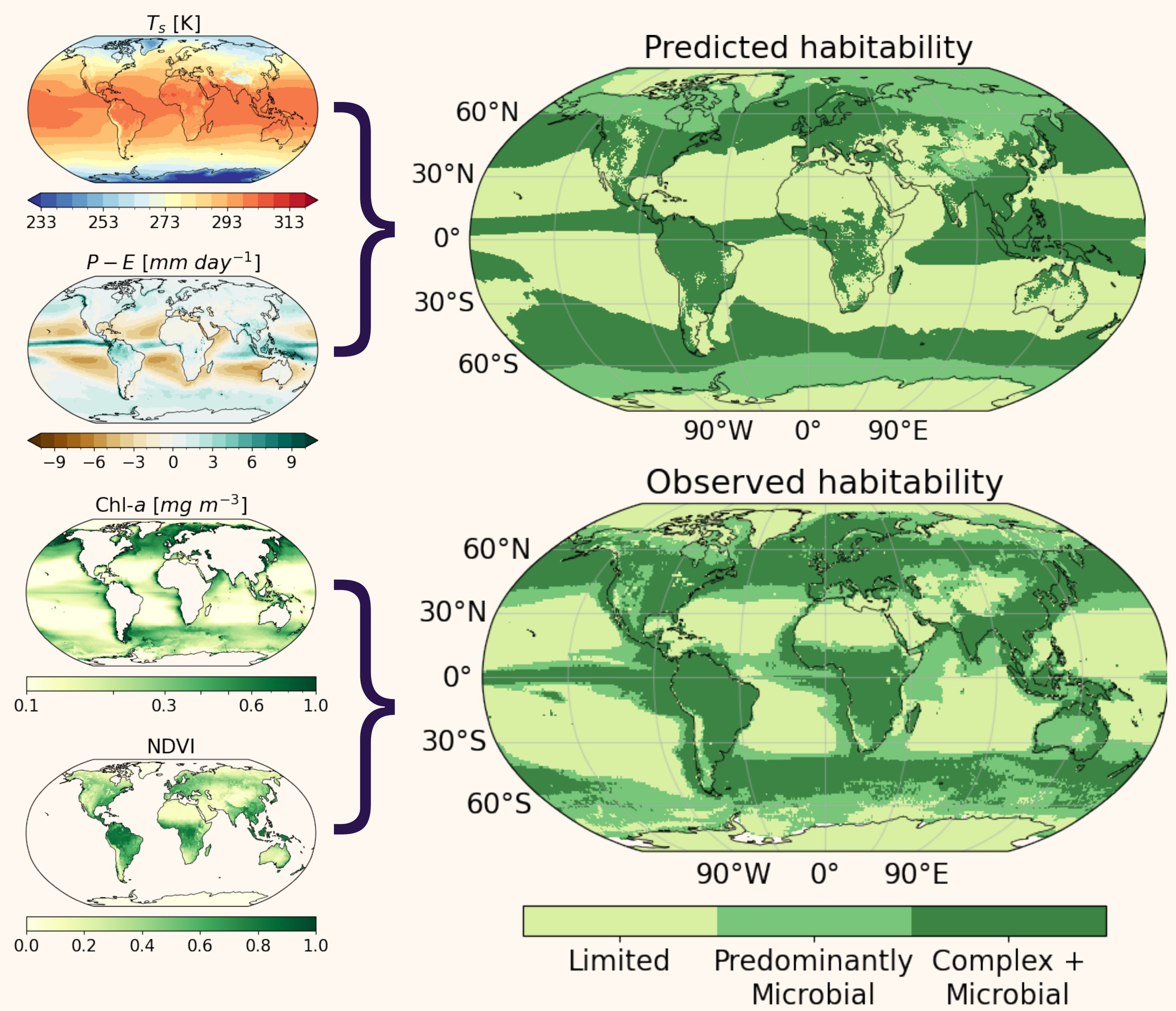
## Key Findings

- Presented a new surface habitability metric based on surface temperature, precipitation, and evaporation.
- Metric **qualitatively** captures patterns of observed habitability (e.g. 'limited' deserts, mountains, oligotrophic sub-tropical gyres; 'complex' equator & mid-latitudes; 'microbial' high-latitudes).
- Metric is validated against satellite-derived data of photosynthetic life with a **statistically significant relationship** across marine and terrestrial domains that can be attributed to **predictive skill** vs random chance.
- Overall accuracy of 67% (microbial) & 69% (complex), higher accuracy and skill found in terrestrial domain.
- Observed marine habitability (and validation results) may be impacted by Chl-*a* data issues: high latitude gaps during wintertime and positive bias at low values.
- **Aquaplanets:** similar habitable patterns & fractions, but differences between models and configuration highlight importance of intercomparisons.
- **Future work**: compare to other defined metrics of surface habitability; apply metric to other planets!

## Results: Metric validation




- Metric indicates water limitation at low latitudes and a mixture of temperature/water limitation at high latitudes & altitudes.

### Fractional habitability

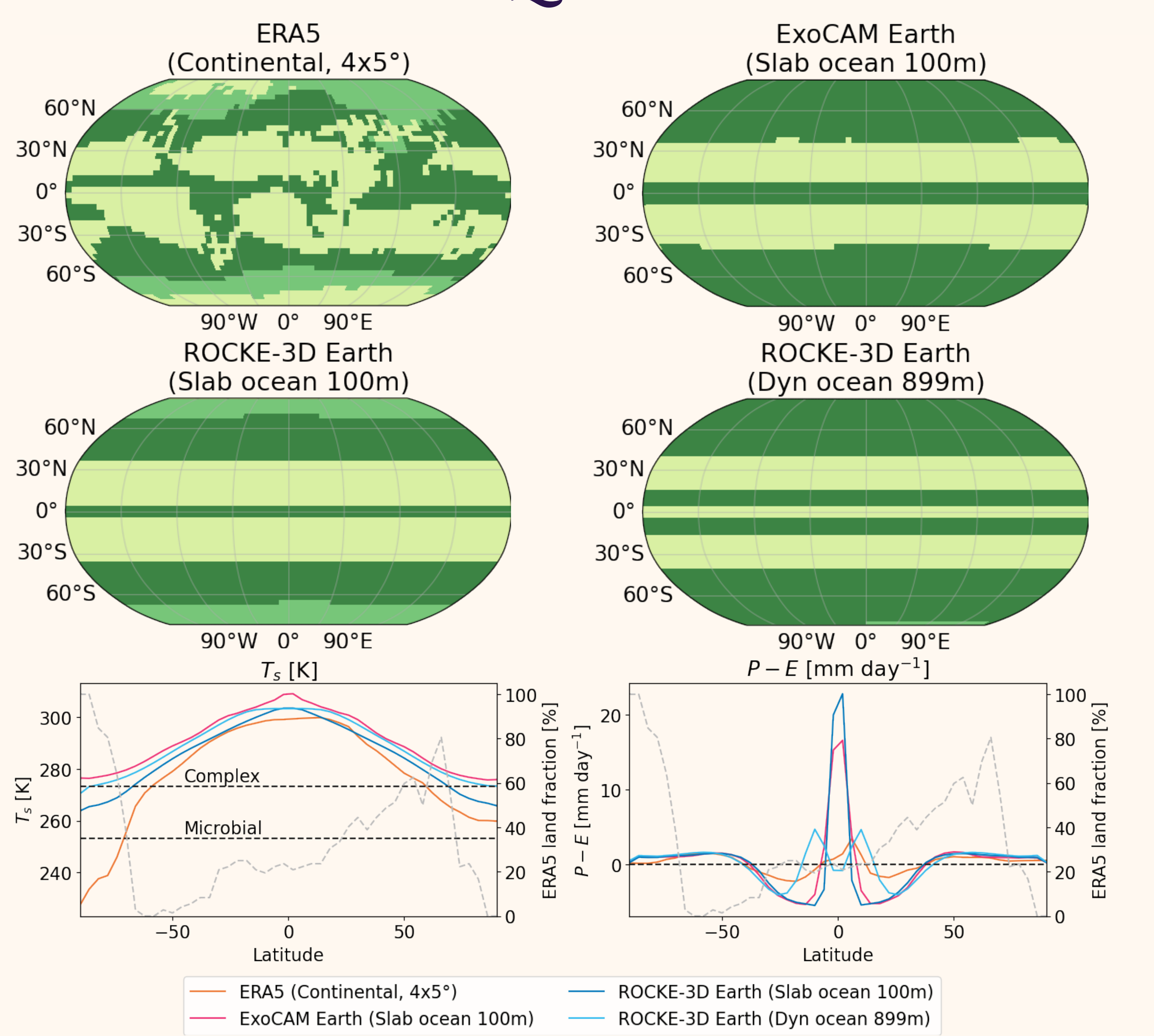
| | Microbial | Complex |
|---|---|---|
| Predicted | 0.53 | 0.41 |
| Observed | 0.59 | 0.36 |

### Validation statistics

| | Accuracy | | $\chi^2$ | | HSS | |
|---|---|---|---|---|---|---|
| Domain | M | C | M | C | M | C |
| Terrestrial | 0.80 | 0.77 | 2992 | 4247 | 0.50 | 0.60 |
| Marine | 0.63 | 0.65 | 2044 | 1781 | 0.26 | 0.24 |
| Global | 0.67 | 0.69 | 4817 | 5313 | 0.34 | 0.36 |

M: Microbial, C: Complex, HSS: Heidke Skill Score
$\chi^2$: chi-squared statistic with p=0.0, dof=1

## Results: Aquaplanet comparison




- Presence of land primarily affects water availability at low latitudes and temperature at high latitudes.
- Ocean configuration affects meridional heat transport & ITCZ 'mode'. Model choice also affects $T_s$ globally and P — E at lower latitudes.

### Validation & Fractional habitability

| | Accuracy | | $\chi^2$ | | HSS | | $f_H$ | |
|---|---|---|---|---|---|---|---|---|
| | M | C | M | C | M | C | M | C |
| ERA5 (4x5°) | 0.67 | 0.69 | 229 | 255 | 0.33 | 0.35 | 0.53 | 0.41 |
| ExoCAM (Slab) | 0.68 | 0.61 | 266 | 121 | 0.36 | 0.23 | 0.53 | 0.53 |
| ROCKE-3D (Slab) | 0.67 | 0.69 | 248 | 241 | 0.34 | 0.34 | 0.48 | 0.41 |
| ROCKE-3D (Dynamic) | 0.62 | 0.55 | 100 | 44 | 0.22 | 0.14 | 0.56 | 0.56 |

M: Microbial, C: Complex, HSS: Heidke Skill Score, $f_H$: fractional habitability, $\chi^2$: chi-squared statistic with $p < 10^{-11}$, dof=1