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 generation and subsequent detection of biosignatures or technosignatures.
- A variety of habitability metrics have been defined so far, based upon different 'habitable' surface temperature ranges, open ocean (or equivalently ice-free) fraction, and aridity[1-8]. Some of these have been used to calculate the **'fractional habitability'** for comparisons of broad parameter sweeps or to explore spatial patterns of surface habitability[1-8].
- 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.

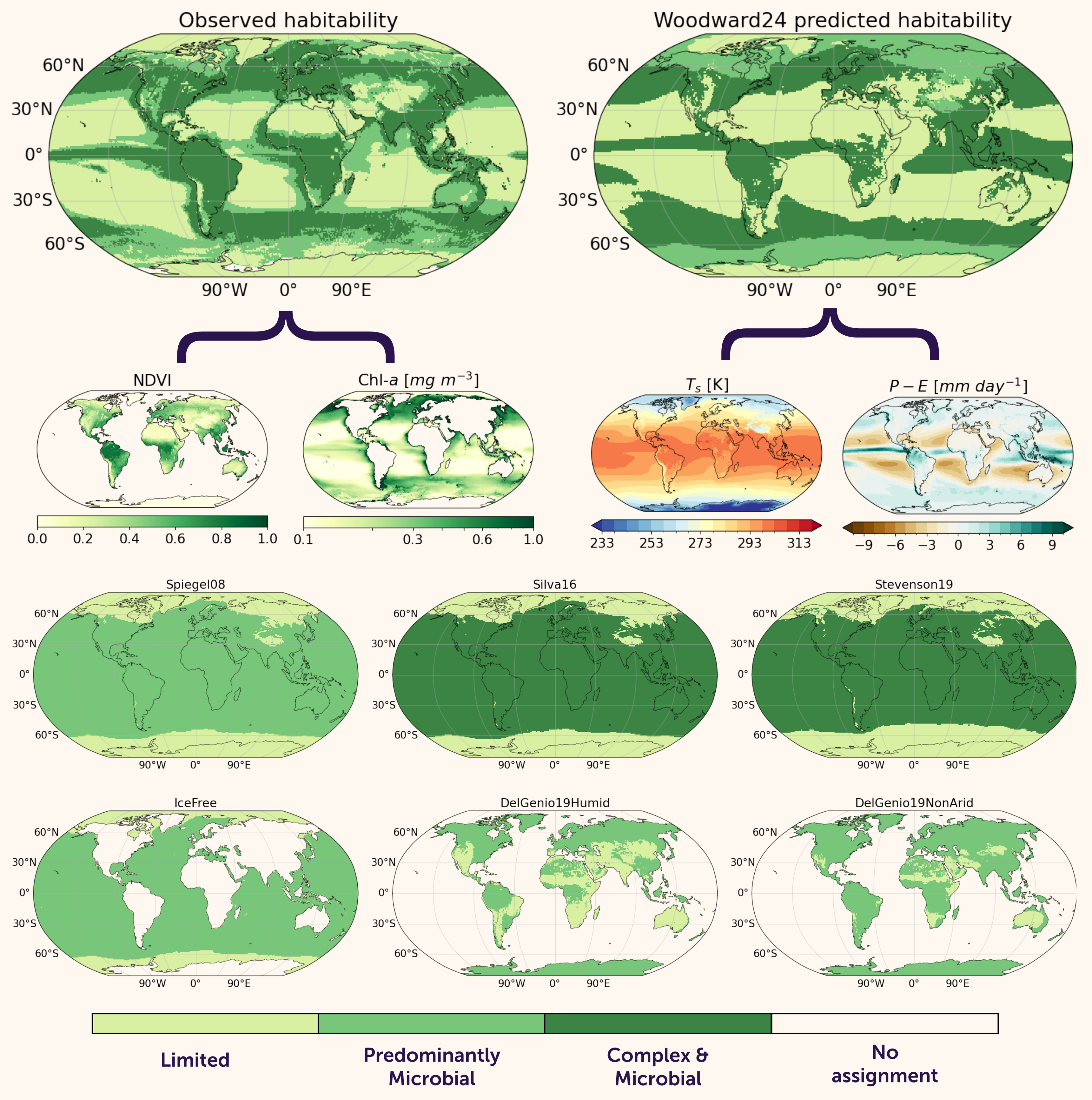
Key Findings

Preprint!

We present a new metric of surface habitability based on surface air temperature, precipitation, and evaporation, which:

- Indicates water limitation at lower latitudes and a mixture of temperature & water limitation at high latitudes & elevations.
- *Qualitatively* captures patterns of observed habitability (e.g. 'limited' ice sheets, deserts, mountains, sub-tropical ocean gyres; 'complex' equator & mid-latitudes; 'microbial' high-latitudes).
- 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.
- Performed best in comparison against other popular metrics: overall accuracy of 67% (microbial) & 70% (complex) with better performance seen on land — 77% (microbial) & 80% (complex).

Earth Habitability: Metric Comparison



- **Validation statistics and fractional habitability can be viewed in the preprint!**

Metric Definition

- Combining the complex life habitability metric[6] with the observed temperature limits of microbial life[9], we define $H_T = H_T(\phi, \lambda)$ describing thermal habitability:

$$H_T = \begin{cases} \text{complex} & \text{if} \quad 0 \le T_s \le 50, \\ \text{microbial} & \text{if} \quad -20 \le T_s \le 122, \\ \text{limited} & \text{otherwise} \end{cases}$$

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

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

for precipitation P and evaporation E [mm year⁻¹]. The minimum P condition is based on the definition of a desert on Earth[10].

Future Work

Metric application:

- Explore habitability of other worlds — tidally-locked exoplanets, but also past Mars or Earth?
- Repeat validation using other datasets representative of Earth-based surface life, e.g. biodiversity or species richness.

Metric development:

- Investigate incorporation of other sources of water, e.g. surface runoff, glacial melt, rivers, groundwater.
- Improve consideration of nutrient availability, e.g. coastal weathering or wind-driven upwelling (Ekman pumping) in the surface ocean.

Methods

- **'Observed' habitability:** $H_O = H_O(\phi, \lambda)$ is calculated from satellite derived data — normalised difference vegetation index (NDVI) on land[11], and gap-filled Chlorophyll-*a* concentration (Chl-*a*, mg m⁻³) in the ocean[12] — with the following conditions:

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

where non-subscripted and subscripted *min* denote annual mean and minimum values, respectively. Thresholds are based upon values of different biomes (NDVI)[13,14] and phytoplankton size class (Chl-*a*)[15].

- **Metric comparison:** Validation is performed for our new metric & repeated for other popular metrics used in habitability studies[1-8].
- **'Predicted' climatological habitability:** Calculated from ERA5[16] annual means across 2003–2018.
- **Validation tests:** Accuracy defined as the weighted fraction of grid cells correct, Heidke Skill Score (HSS)[17] attributes accuracy to predictive skill vs random chance, and χ^2 gives the statistical significance of relationship with observed.
- **Fractional habitability:** Each category is calculated as the weighted fraction of all grid cells which satisfy the respective conditions for habitability.

Metric	Domain	Definition	Valid for:
Spiegel08[8]	Global	$0 \le T_s \le 100$	Microbial
Silva16[6]	Global	$0 \le T_s \le 50$	Complex
Stevenson19[7]	Global	$5 < T_{bio} < 30$	Complex
IceFree[2,3,5]	Marine	$SIC < 0.15$	Microbial
DelGenio19NonArid[1]	Terrestrial	$AI \ge 0.17$	Microbial
DelGenio19Humid[1]	Terrestrial	$AI > 0.39$	Microbial

T_{bio}: annual mean T_s where all $T_s < 0 = 0$ and $T_s > 30 = 30$; SIC: Sea ice concentration; AI: Aridity Index = P/(P + PET) for precipitation P and potential evapotranspiration PET.

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