A new metric for planetary surface habitability

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Introduction

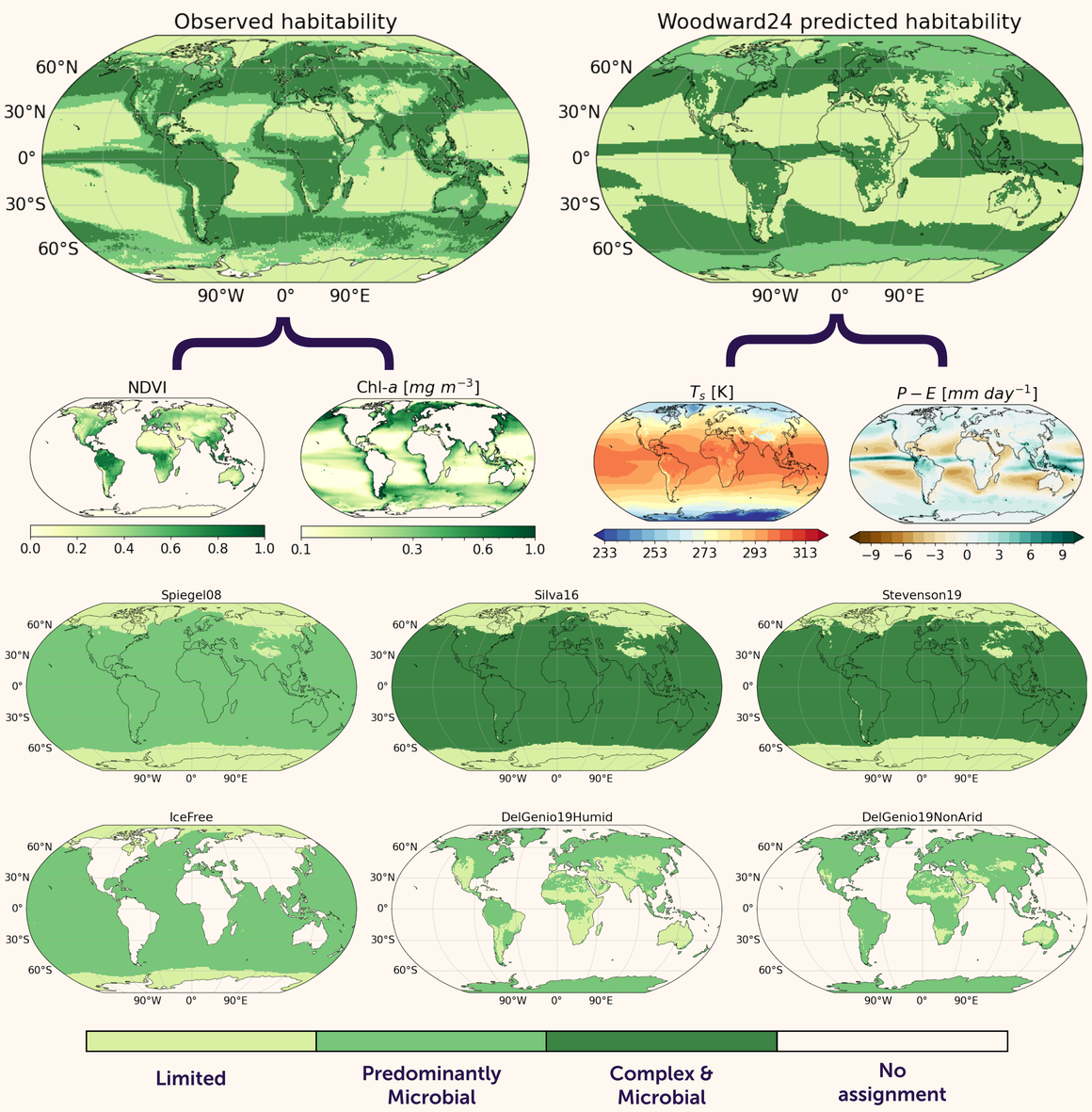
- Considering the habitable area of a planetary surface is important for the potential emergence and evolution of life, with implications for the generation and subsequent detection of biosignatures or technosignatures.
- A variety of habitability metrics have been defined so far, based upon different '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

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

- Indicates water limitation at low 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) & 69% (complex) with better performance seen on land — 76% (microbial) & 79% (complex).

Earth habitability: metric comparison & validation



Complex

Domain & Metric	PC	HSS	χ^2	f_H
Global				**0.36**
Woodward24	**0.69**	**0.36**	**5313**	**0.41**
Silva16	0.46	0.10	1312	0.85
Stevenson19	0.46	0.10	971	0.82
Marine				**0.29**
Woodward24	**0.66**	**0.25**	**1898**	**0.40**
Silva16	0.38	0.06	671	0.89
Stevenson19	0.37	0.02	31	0.84
Terrestrial				**0.52**
Woodward24	**0.79**	**0.58**	**4024**	**0.46**
Silva16	0.66	0.31	1484	0.75
Stevenson19	0.70	0.38	2410	0.78

Microbial

Domain & Metric	PC	HSS	χ^2	f_H
Global				**0.59**
Woodward24	**0.67**	**0.34**	**4817**	**0.53**
Spiegel08	0.58	0.05	133	0.85
Marine				**0.55**
Woodward24	**0.64**	**0.28**	**2550**	**0.49**
Spiegel08	0.52	-0.03	69	0.90
Ice-free Fraction	0.53	-0.02	31	0.90
Terrestrial				**0.69**
Woodward24	**0.76**	**0.47**	**2756**	0.62
Spiegel08	0.73	0.34	1359	**0.75**
DelGenio19NonAri	0.68	0.14	268	0.85
DelGenio19Humid	0.53	-0.01	1.59 (p=0.2075)	0.60

Validation statistics and global habitable fraction f_H for each metric and domain against the observed habitability. Optimal metric values have been highlighted in bold. The observed f_H for each domain is listed in bold in the row of each respective domain label. PC: proportion correct, HSS: Heidke Skill Score, $\chi 2$: chi-squared statistic (p=0.0 dof=1 unless otherwise stated).

Methods

- **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 the 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[8].

- **'Observed' habitability:** $H_O = H_O(\phi, \lambda)$ is calculated from satellite derived data — normalised difference vegetation index (NDVI) on land[12], and gap-filled Chlorophyll-*a* concentration (Chl-*a*, mg m^{-3}) in the ocean[13] — 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)[14,15] and phytoplankton size class (Chl-*a*)[16].

- **'Predicted' climatological habitability:** Calculated from ERA5[11] annual means across 2003–2018.
- **Fractional habitability:** Each category is calculated as the weighted fraction of all grid cells which satisfy the respective conditions defined above (or as per other metrics).
- **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.
- **Metric comparison:** Validation is performed for our new metric & repeated for other popular metrics used in habitability studies[1-8]:

Metric	Domain	Definition	Valid for:
Spiegel08[8]	Global	$0 \le Ts \le 100$	Microbial
Silva16[6]	Global	$0 \le Ts \le 50$	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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