A NEW METRIC FOR ASSESSING PLANETARY SURFACE HABITABILITY

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Background

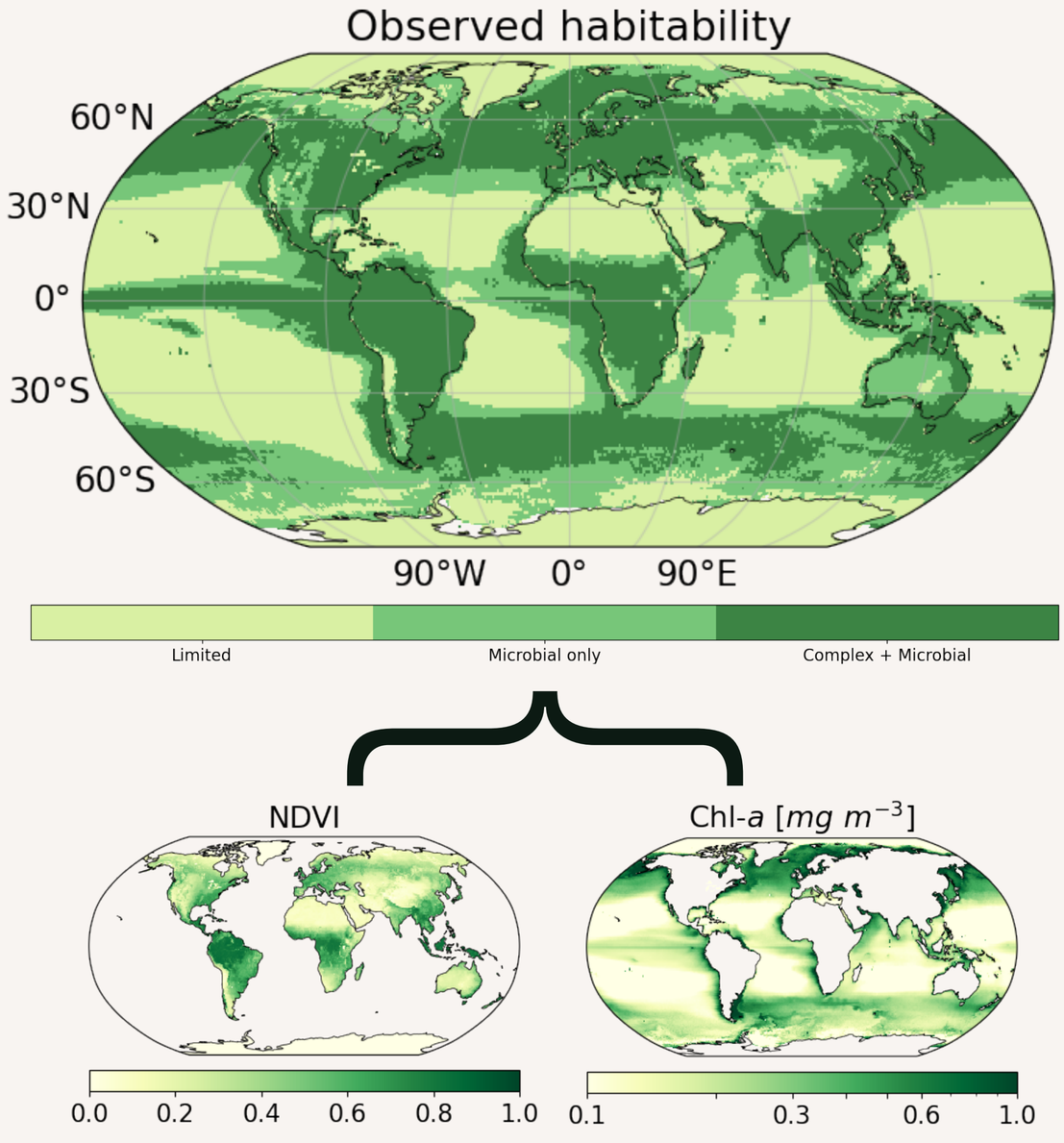
- Considering habitable area of planetary surface is important for potential emergence and evolution of life, with implications for generation and subsequent detection of biosignatures and/or technosignatures.
- Variety of climate-based metrics defined so far, based upon various variables including ‘habitable’ surface temperature ranges, ice-free fraction, aridity:
  - How do patterns of habitability compare?
  - How do metrics compare to how we see life spatially distributed on Earth?
  - Can we improve on these metrics?
  - Can we extend out of a ‘binary’ habitability? e.g. consider conditions optimal for ‘complex’ as well as ‘microbial’ life

Earth 'observed' habitability

- **Satellite-derived data**: MODIS NDVI (terrestrial) + OC-CCI Chlorophyll-a concentration (marine) across 2003–2018
- Discretise into habitability categories:

$$H^{obs} = \begin{cases} \text{complex} & \text{if} \quad NDVI_{mean} > 0.3 \,|\, Chl\text{-}a_{min} > 0.15 \text{ mg m}^{-3}, \\ \text{microbial} & \text{if} \quad NDVI_{mean} > 0.15 \,|\, Chl\text{-}a_{mean} > 0.15 \text{ mg m}^{-3}, \\ \text{limited} & \text{otherwise} \end{cases}$$

- NDVI thresholds based on annual mean biomes:
  - Complex: annual mean value across vegetated biomes
  - Microbial: maximum value of bare ground, soil, sand, rock
- Chla-a thresholds based on annual mean and minimum due to short phytoplankton turnover time (~2-6 days) & value corresponds to a shift from abundance in picoplankton to nano- and microplankton as well as from phytoplankton to mesozooplankton.
  - Complex: annual minimum applies ability to continually support higher trophic states
  - Microbial: annual mean recognises seasonal abundance of phytoplankton



Initial metric comparison

- **Data source**: ERA5 reanalysis across 2003–2018
- Unless otherwise specified, 'microbial' is default habitable category for where metric criteria is satisfied
- **Validation**:
  - **Accuracy**: the weighted fraction of grid cells correctly assigned
  - **Heidke Skill Score (HSS)**: accuracy to predictive skill vs random chance
  - **Chi-squared (χ^2)**: statistical significance of relationship with observed
  - **Fractional habitability (f_H):** proportion of the planet that satisfies the habitability criteria as defined by metric

Metric	Domain	Definition	Valid for:
H^{S08}	Global	$0 \leq T_s \leq 100°C$	Microbial
H^{S16}	Global	$0 \leq T_s \leq 50°C$	Complex
H^{S19}	Global	$5 < T_{bio} < 30°C$	Complex
H^{IF}	Marine	$SIC < 0.15$	Microbial
H^{DG19NA}	Terrestrial	$AI \geq 0.17$	Microbial
H^{DG19H}	Terrestrial	$AI > 0.39$	Microbial

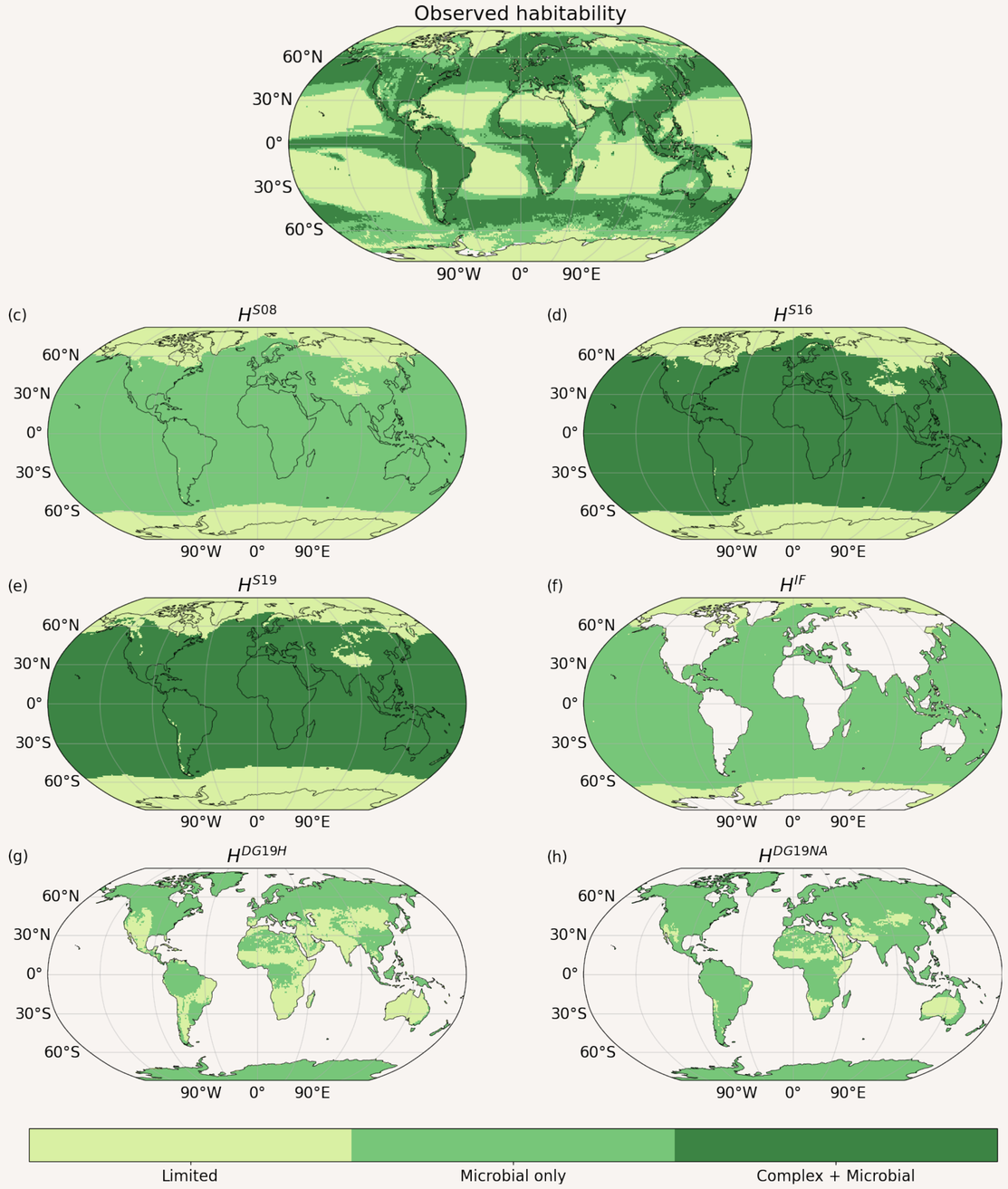
- Biotemperature

$$T_{bio} = \begin{cases} 30 & \text{if} \quad T_s \geq 30°C \\ 0 & \text{if} \quad T_s \leq 0°C \\ T_s & \text{otherwise} \end{cases}$$

- Surface air temperature T_s
- Sea ice concentration SIC
- Aridity index $AI = \frac{P}{P + PET}$

Initial Metric comparison

- Metrics able to partially capture patterns of habitability, with T_s-based metrics showing different patterns to AI-based metrics
  - New metric definition should incorporate **both** temperature and ‘water availability’
- AI definition uses PET, which makes it only applicable to land, as well as including transpiration which may introduce bias wrt exoplanet habitability.
  - Can similar habitability patterns be captured using variables that can be applied globally?



New metric definition

Combining the complex life habitability metric with the observed temperature limits of microbial life, we define $H_T = H_T(T_s)$ describing the thermal habitability:

$$H_T(T_s) = \begin{cases} \text{complex} & \text{if} \quad 0 \leq T_s \leq 50\ ^\circ\text{C}, \\ \text{microbial} & \text{if} \quad -20 \leq T_s \leq 122\ ^\circ\text{C}, \\ \text{limited} & \text{otherwise} \end{cases}$$

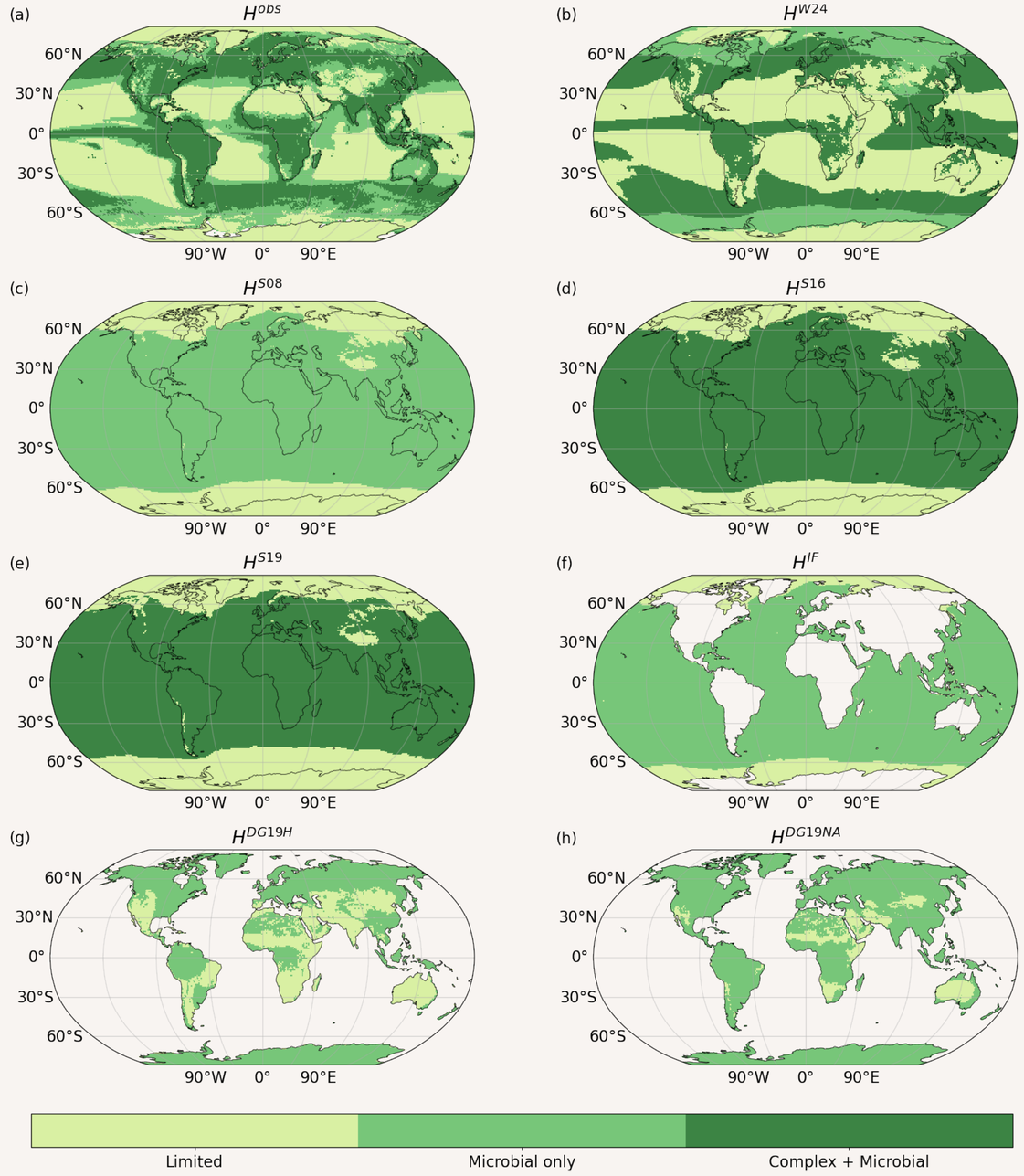
for surface air temperature $T_s = T_s(\phi, \lambda)$, latitude ϕ, and longitude λ. The climatological surface habitability $H = H(T_s, P, E)$ is then defined as the category as described by H_T with an additional condition which uses surface water fluxes to represent 'water availability':

$$H(T_s, P, E) = \begin{cases} H_T & \text{if} \quad P - E \geq 0\ \&\ P \geq 250\ \text{mm year}_\oplus^{-1}, \\ \text{limited} & \text{otherwise} \end{cases}$$

for precipitation $P = P(\phi, \lambda)$ and evaporation $E = E(\phi, \lambda)$.

Metric comparison & validation

- **Qualitative improvement**: captures high latitude shift to microbial habitability as well as lower latitude regions of limited habitability
- Surface habitability constraints:
  - High latitude + altitudes: mixture of temperature and water limitation
  - Low latitude: water limitation



Metric comparison & validation

- **Quantitative improvement** across all domains. Higher HSS indicates of increase in predictive skill:
  - Particularly for 'complex' habitability + in the marine domain
  - **Marine**: greatest improvement relative to other metrics
  - **Terrestrial**: metric performs best
  - f_H: H^{W24} closer to observed for all metrics except for H^{SO8} in microbial terrestrial, but H^{W24} has higher accuracy + HSS

Microbial

Domain & Metric	Acc	HSS	χ^2	f_H
Global				**0.59**
H^{W24}	**67%**	**0.34**	**4906**	**0.53**
H^{SO8}	59%	0.05	135	0.85
Marine				**0.55**
H^{W24}	**64%**	**0.28**	**2550**	**0.49**
H^{SO8}	52%	-0.03	83	0.89
H^{IF}	53%	-0.02	31	0.90
Terrestrial				**0.71**
H^{W24}	**77%**	**0.48**	**2881**	0.62
H^{SO8}	75%	0.36	1566	**0.75**
H^{DG19NA}	70%	0.15	326	0.60
H^{DG19H}	52%	-0.04	22	0.60

Complex

Domain & Metric	Acc	HSS	χ^2	f_H
Global				**0.36**
H^{W24}	**70%**	**0.36**	**5455**	**0.41**
H^{S16}	46%	0.10	1333	0.85
H^{S19}	47%	0.10	990	0.82
Marine				**0.29**
H^{W24}	**66%**	**0.25**	**1898**	**0.40**
H^{S16}	38%	0.06	671	0.89
H^{S19}	37%	0.02	31	0.84
Terrestrial				**0.53**
H^{W24}	**80%**	**0.60**	**4287**	**0.45**
H^{S16}	68%	0.33	1615	0.75
H^{S19}	71%	0.40	2523	0.78

Conclusions + future work

Preprint!

- Presented 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 on Earth.
  - Qualitatively captures patterns of observed habitability (e.g. ‘limited’ habitability 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 best performance seen on land — 77% (microbial) & 80% (complex)
- Future work:
  - Apply metric to other worlds — tidally-locked exoplanets, but also past Mars or Earth?
  - Investigate incorporation of other sources of water, e.g. surface runoff, glacial melt, rivers, groundwater
  - Repeat validation using other datasets representative of Earth-based life, e.g. biodiversity or species richness