Habitability in 4-D

A. Adams, C. Colose, S. Kane, A. Merelli, M. Turnbull

How does climate-based habitability on Earth-like worlds vary with rotation and orbital state?

Key Points

- Rotation period is the primary influence on habitability

  ➡ Obliquity influences habitability at "faster" rotations ($\lesssim 20$ days); beyond this there's a break in habitability where obliquity isn't as important

  ➡ Orbital eccentricity has the weakest effect of all (up to our limit of $e = 0.225$)

- A Gaussian process regression does a reasonable job of predicting a global+orbit-averaged climate habitability metric

Defining Habitability

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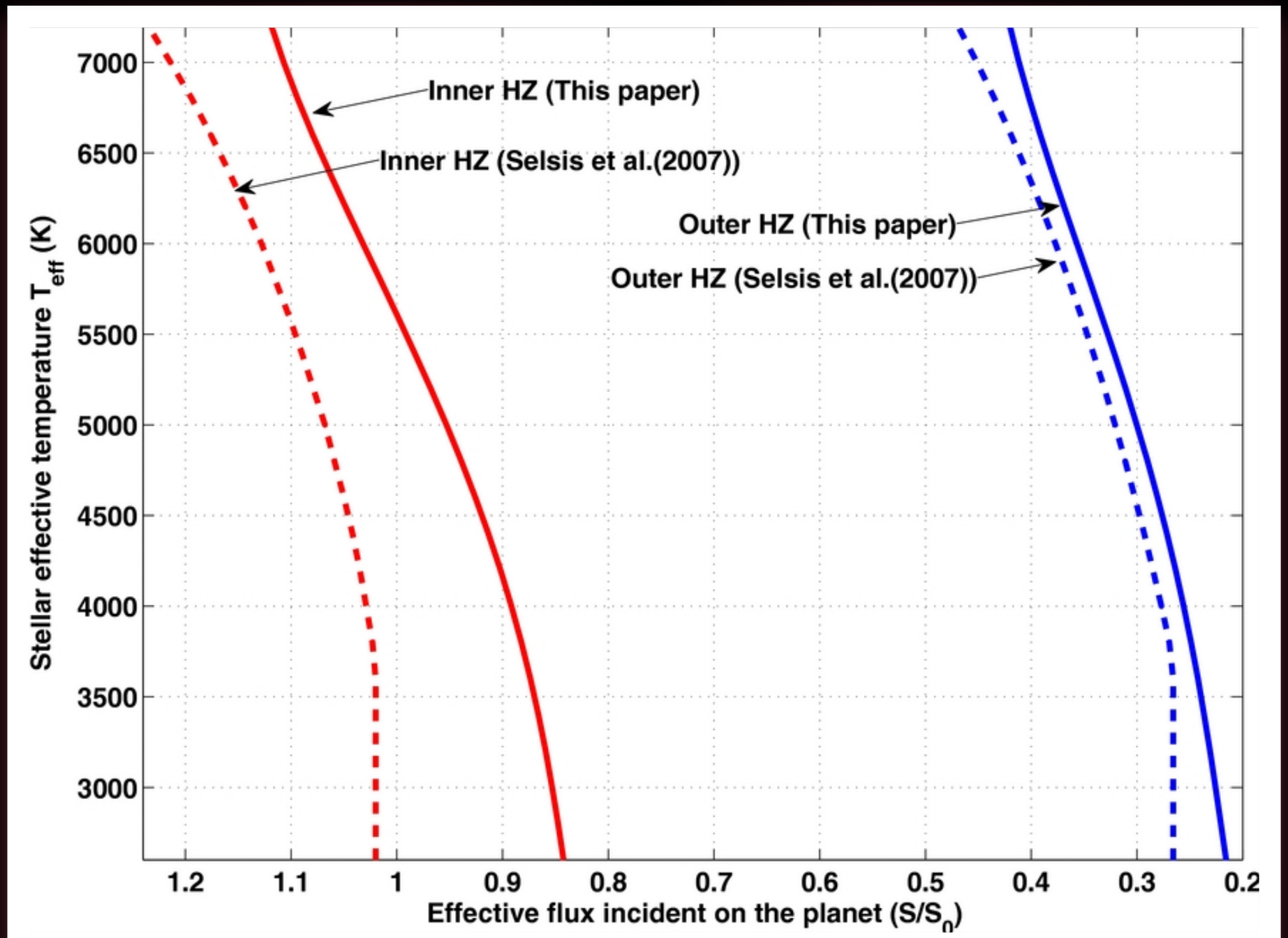
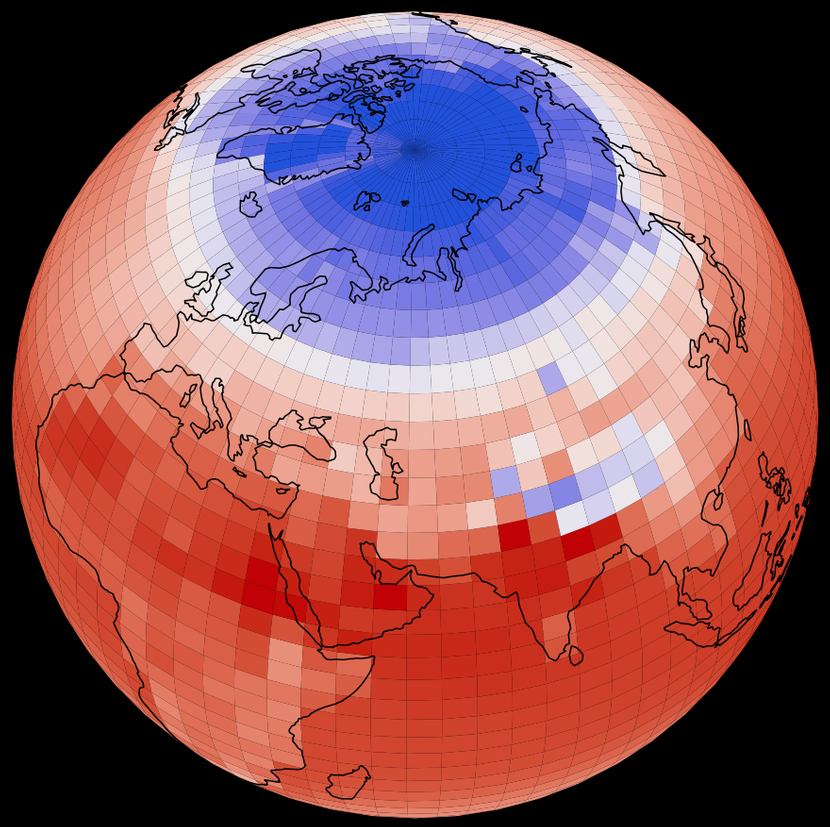


Kopparapu et. al. (2013)

“Climate” Habitability



$0 \leq T_{\text{surf}} \leq 100^{\circ}\,\text{C}$

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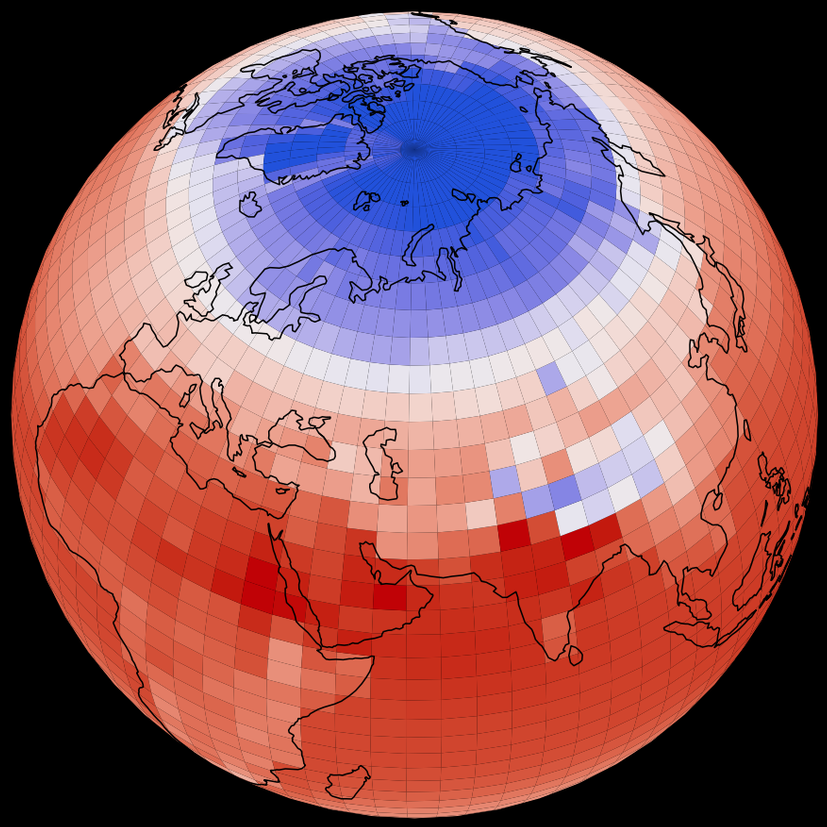

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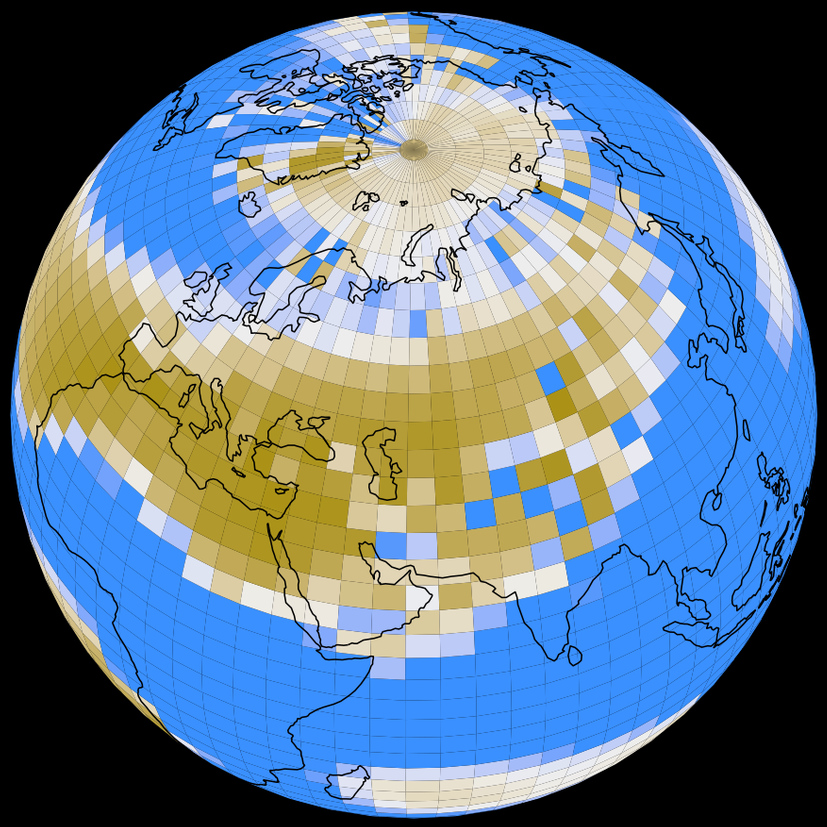
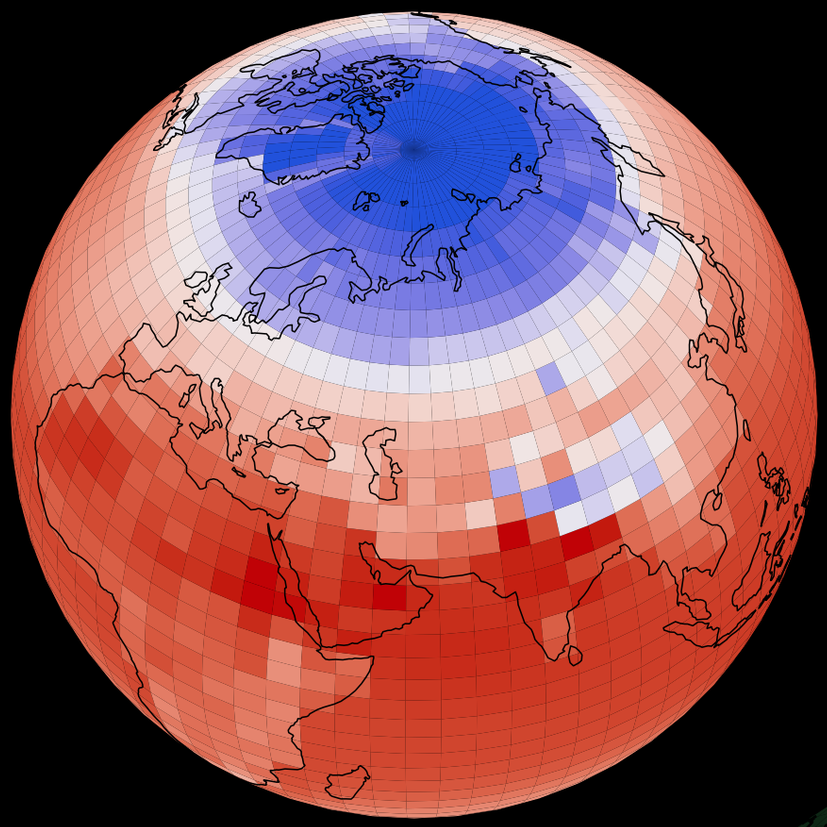


Precipitation $\geq$ 300 mm/year

“Climate” Habitability



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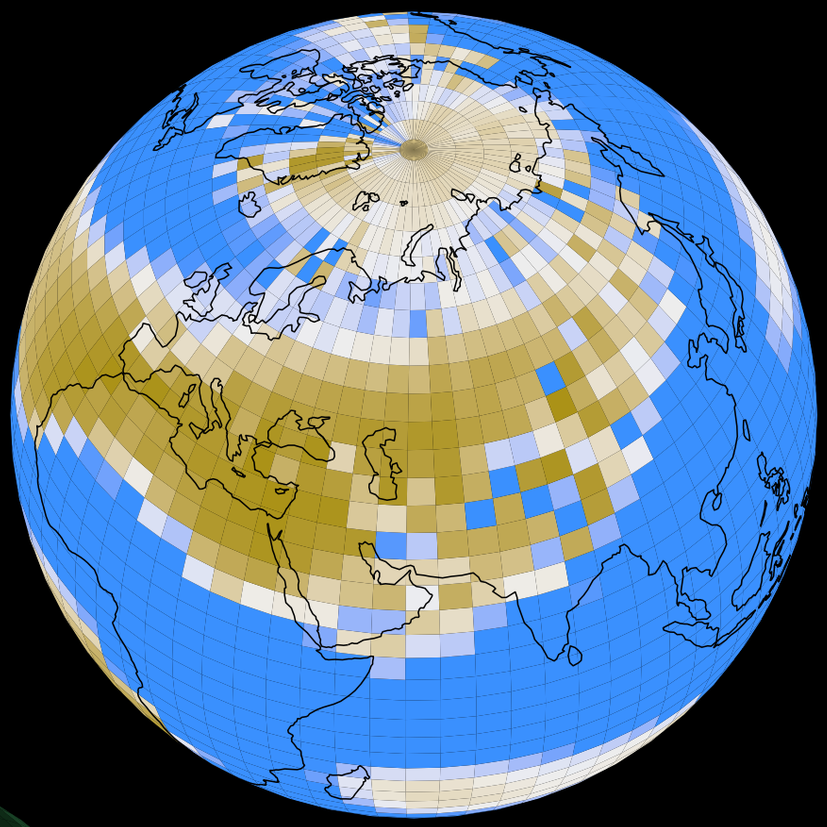

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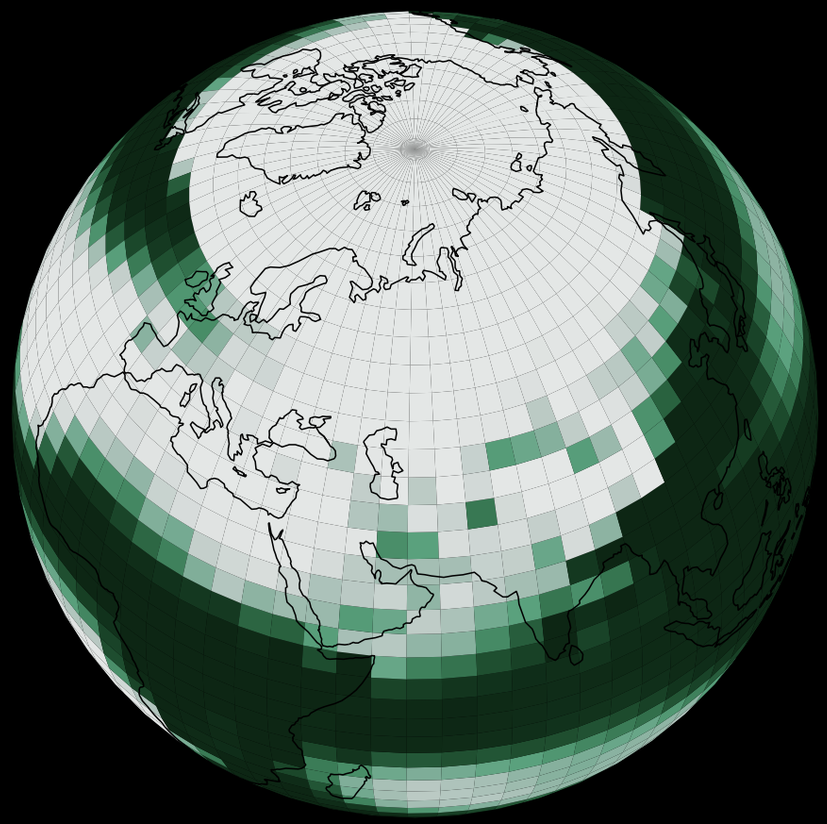
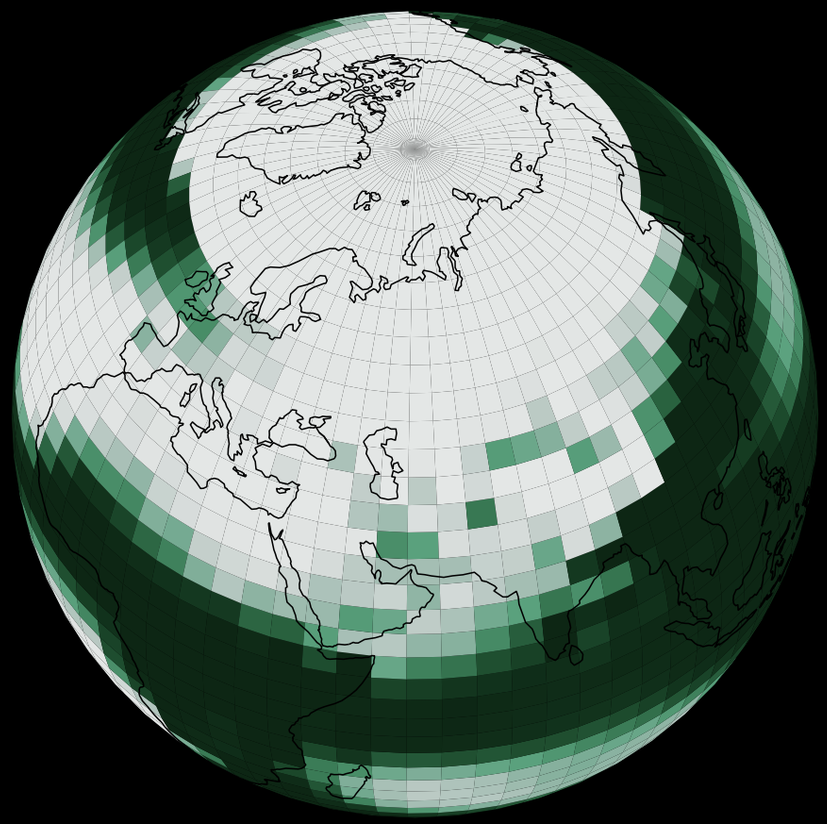


$$f_{\mathrm{X}}\left(P_{\mathrm{rot}}, \psi, e, \phi_{\mathrm{peri}}\right) \equiv \frac{1}{A_{\mathrm{terr}}} \sum_{i=1}^{n_\lambda} \sum_{j=1}^{n_\phi} \frac{1}{n_{\mathrm{orb}} P_{\mathrm{orb}}} \sum_{k=1}^{12 n_{\mathrm{orb}}} I_X\left(\lambda_i, \phi_j, t_k; P_{\mathrm{rot}}, \psi, e, \phi_{\mathrm{peri}}\right) f_{\mathrm{terr}} A_{ij} \tau_k(e)$$



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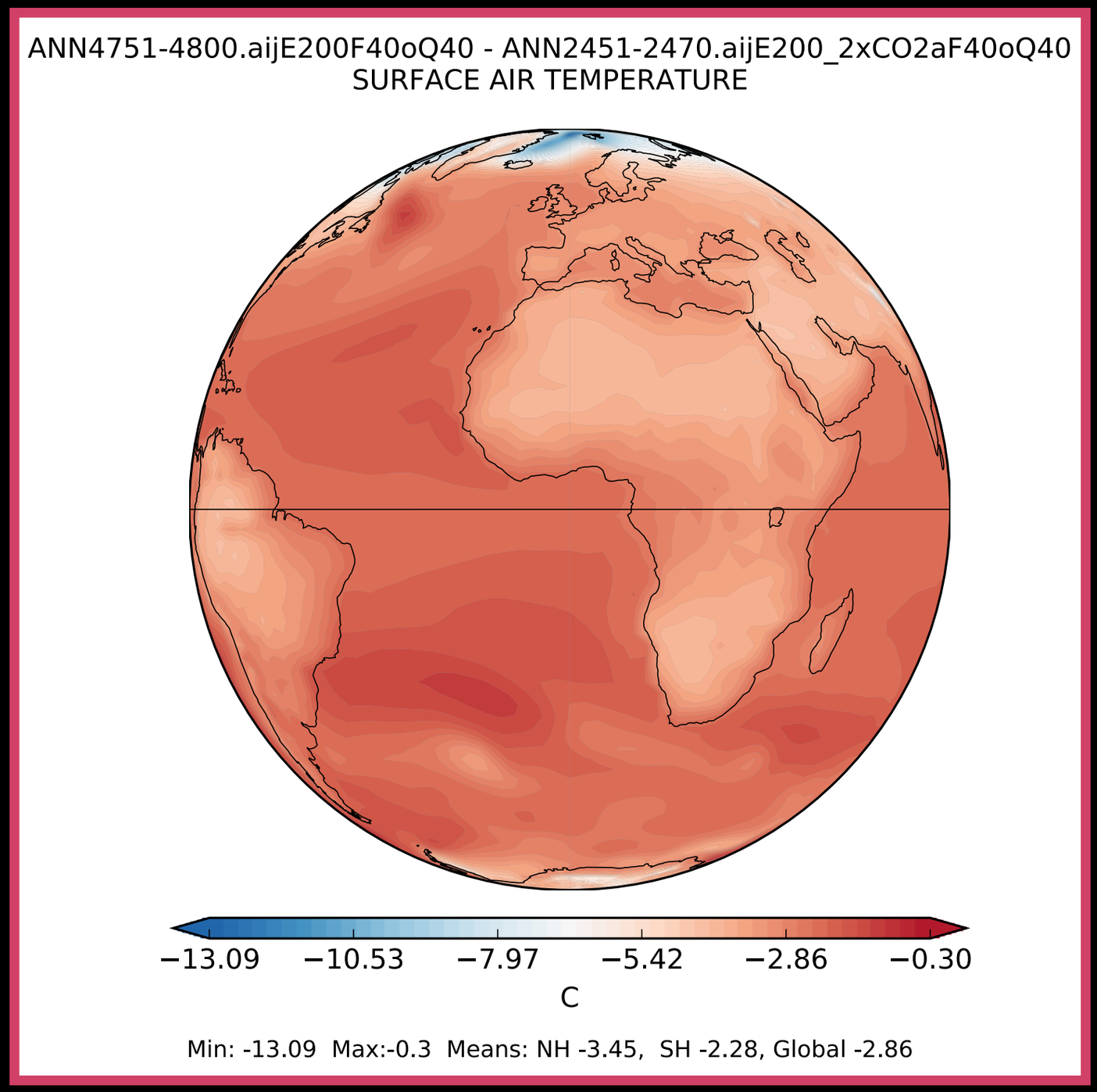
- Each cell gets 0 or 1 per month (temperate and wet)
- Weight by surface area in land, then take land average
- Weight by month length, then take time average

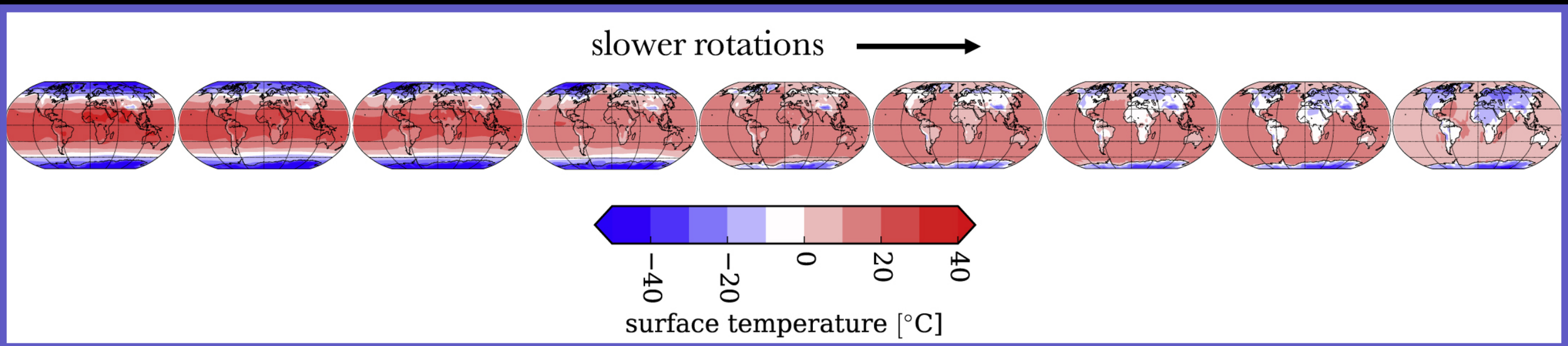
ROCKE-3D

Way et. al. (2017)



- $4^\circ \times 5^\circ$ latitude-longitude resolution
- 40 vertical layers (10^{-4} to 1 bar)
- Dynamic ocean (uniform 1360 m depth)
- Bare soil, ocean, ice (no vegetation)

Jansen et. al. (2019):
Rotational "Goldilocks" Zone



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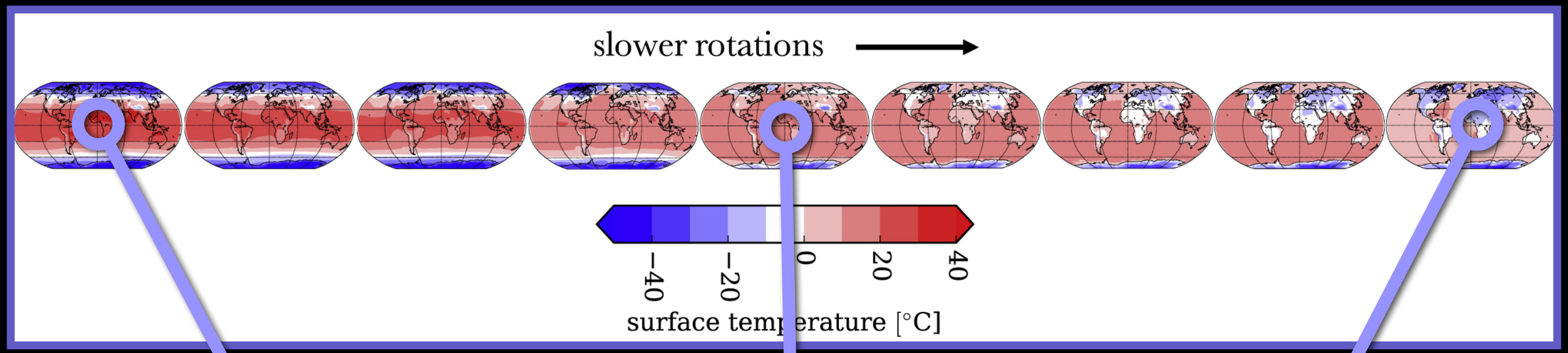
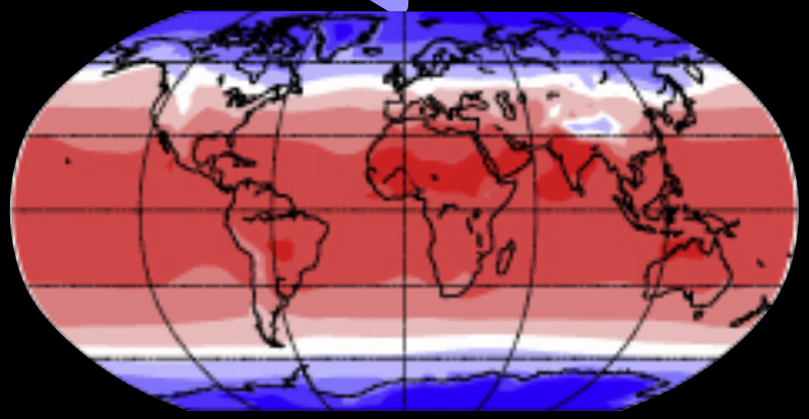
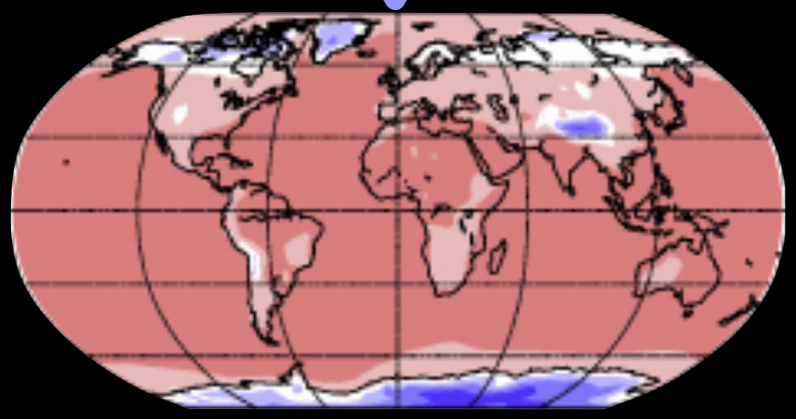
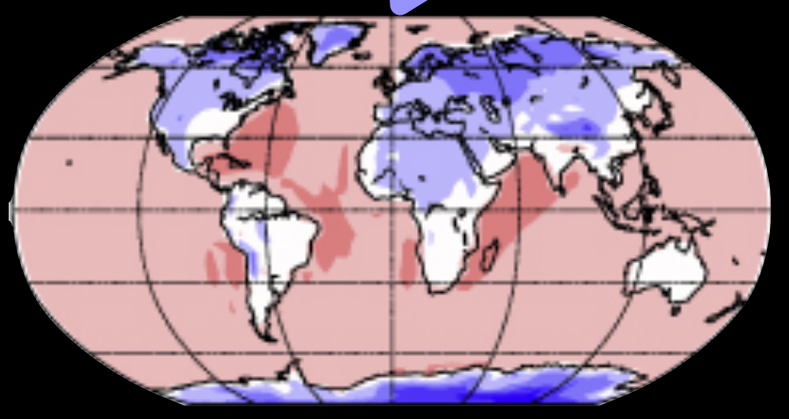




1 day



16 days

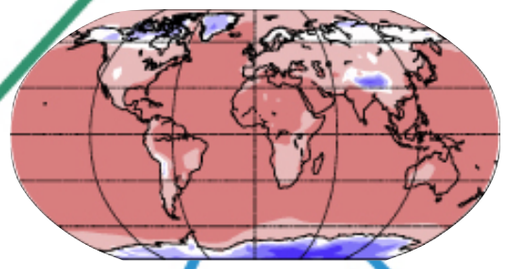


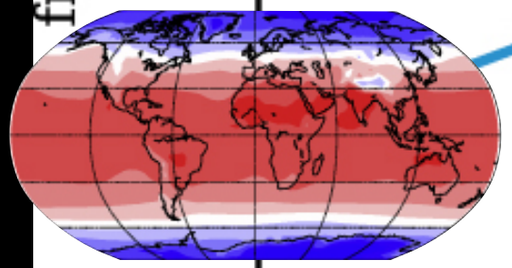
256 days

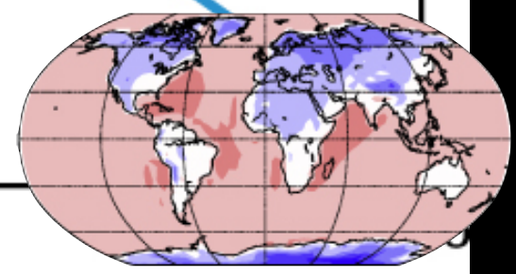
1.00
0.95
0.90
0.85
0.80
0.70

fractional habitability $f(t_{rot})$

1.2S0
1.1S0
1.0S0







Jansen et. al. (2019)

1
2
4
8
16
32
64

rotation period [days]

He et. al. (2022): Obliquity Matters at Fast Rotations

0° 45° 90°

1 day

16 days

256 days

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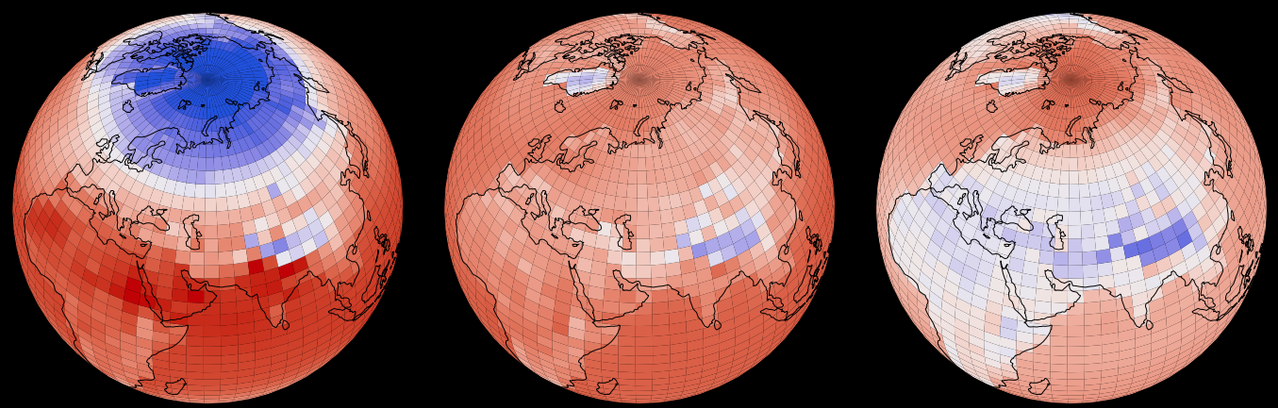

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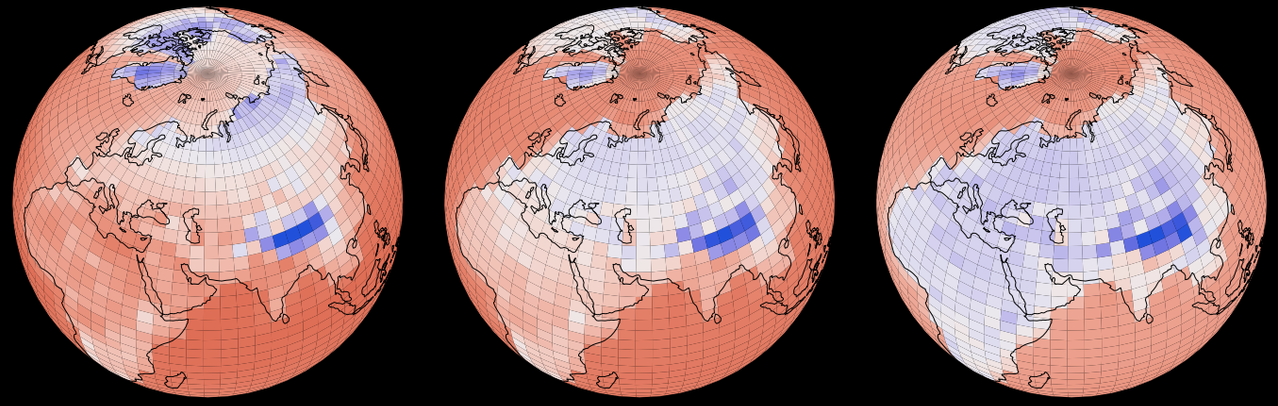
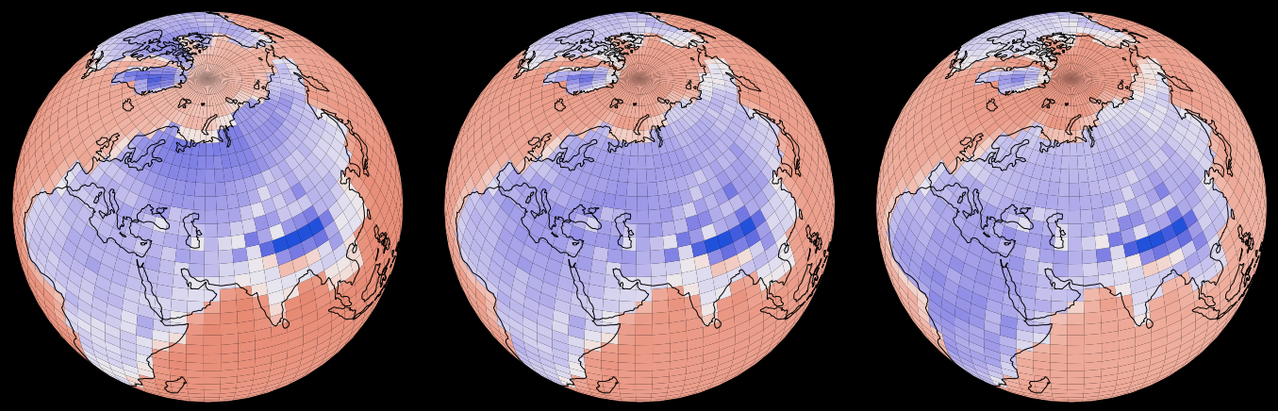


256 days



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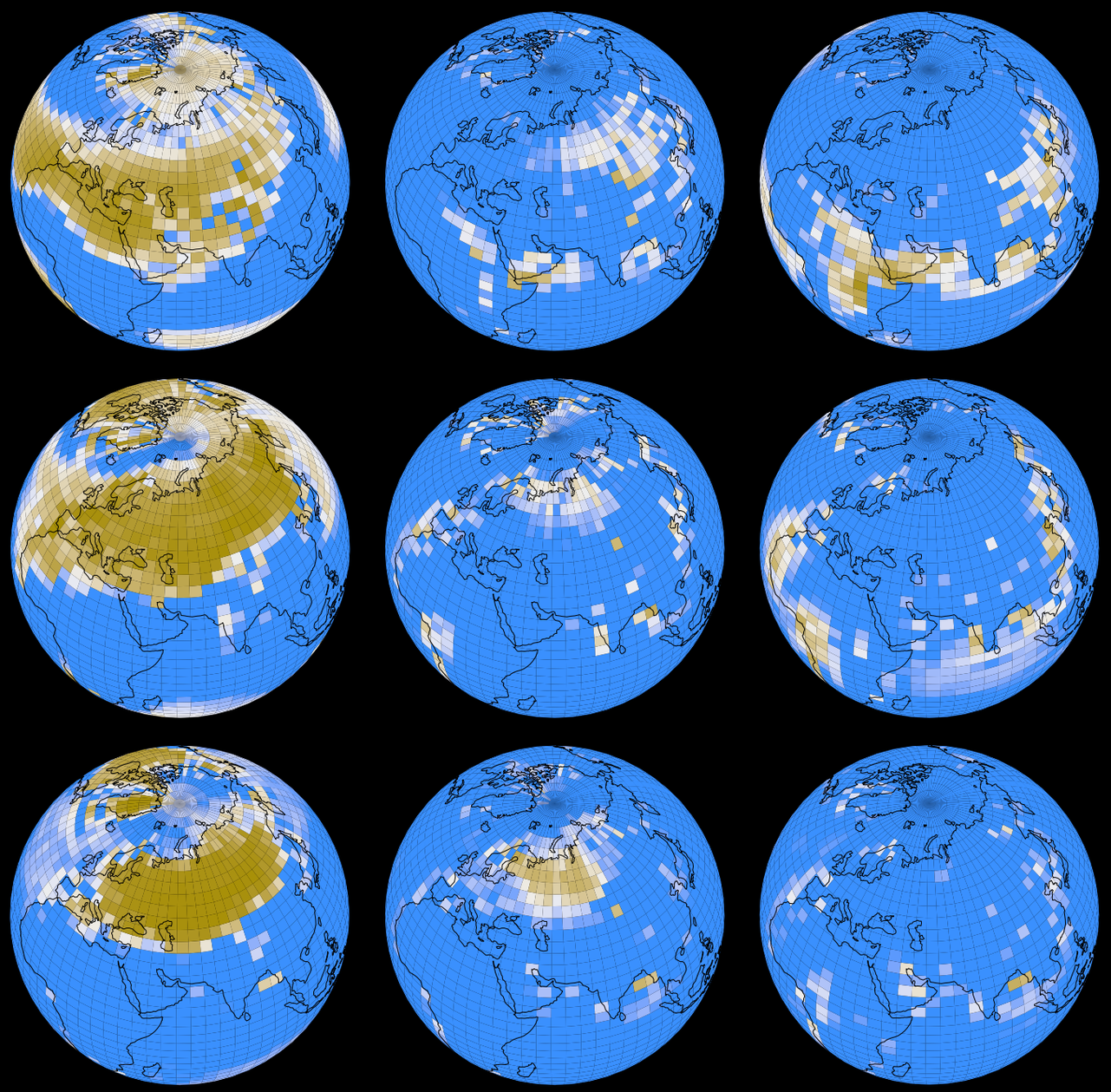

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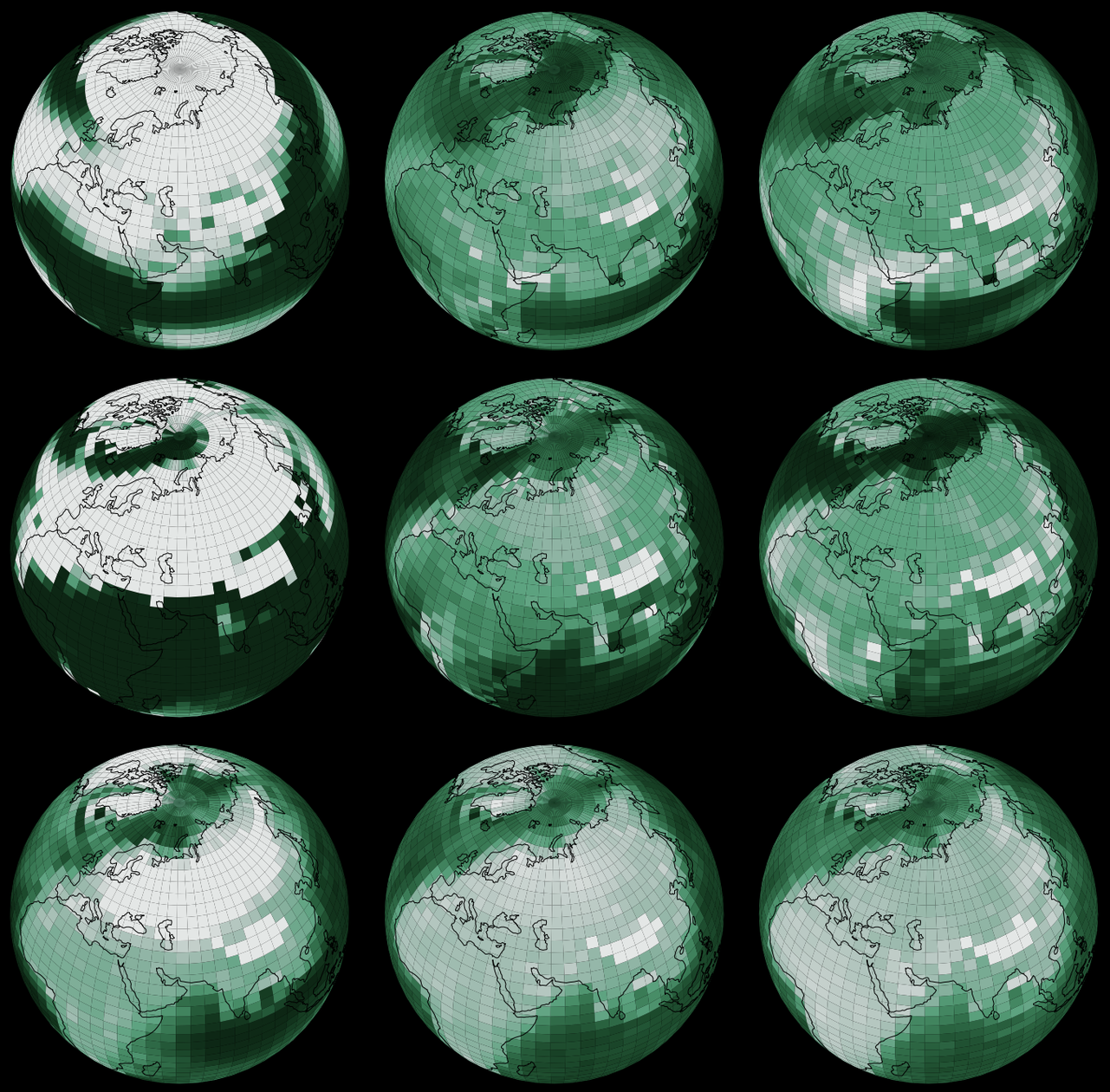

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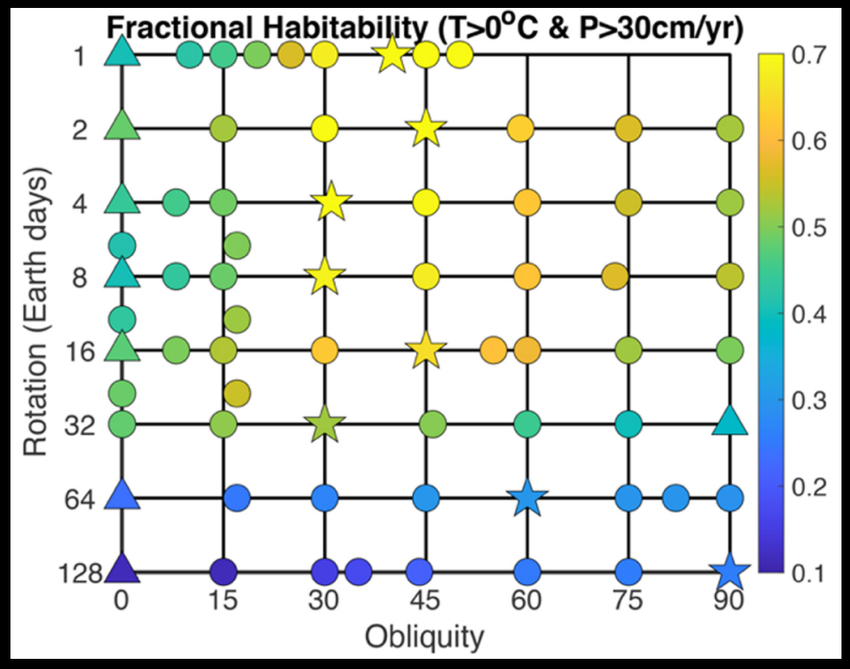
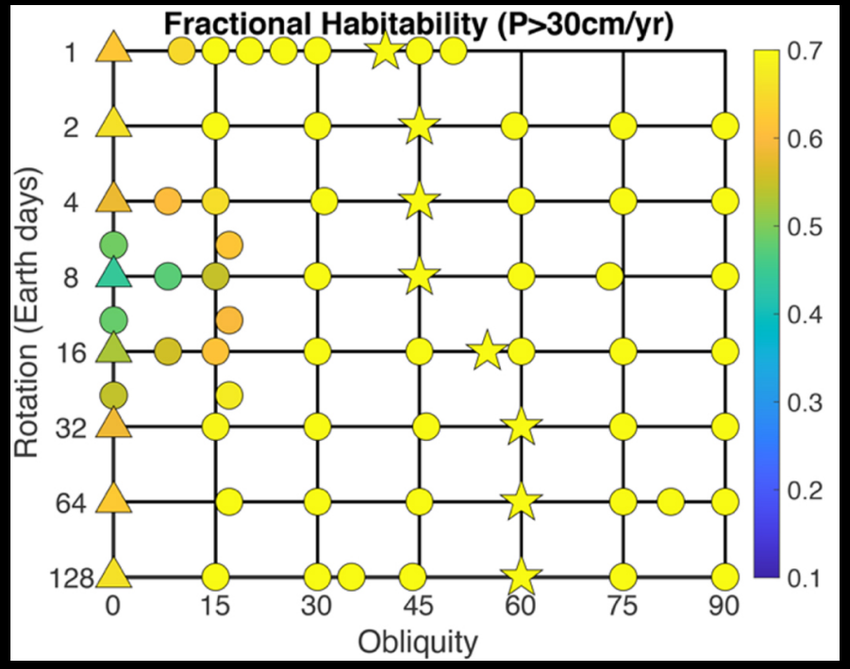
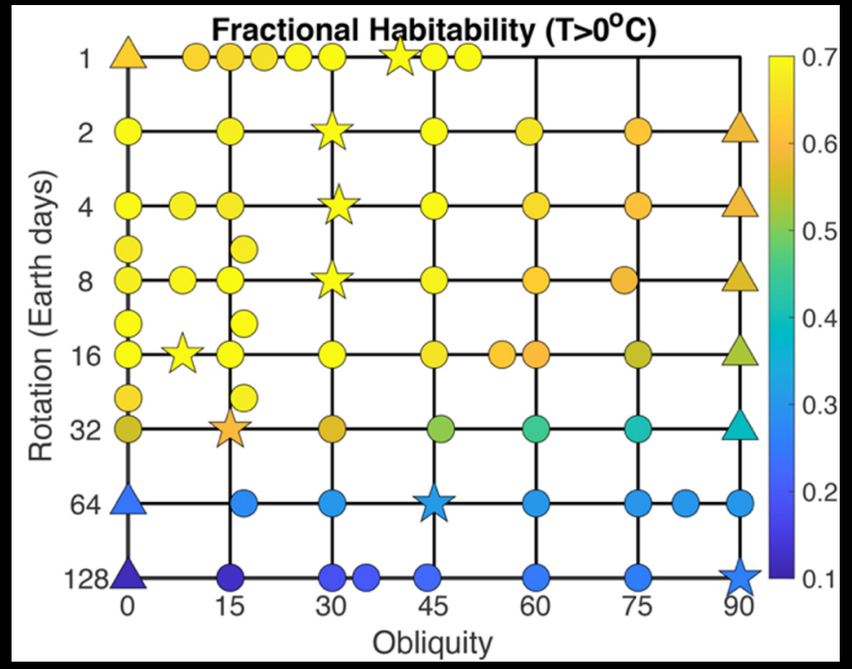
Precipitation $\geq$ 300 mm/year

Both







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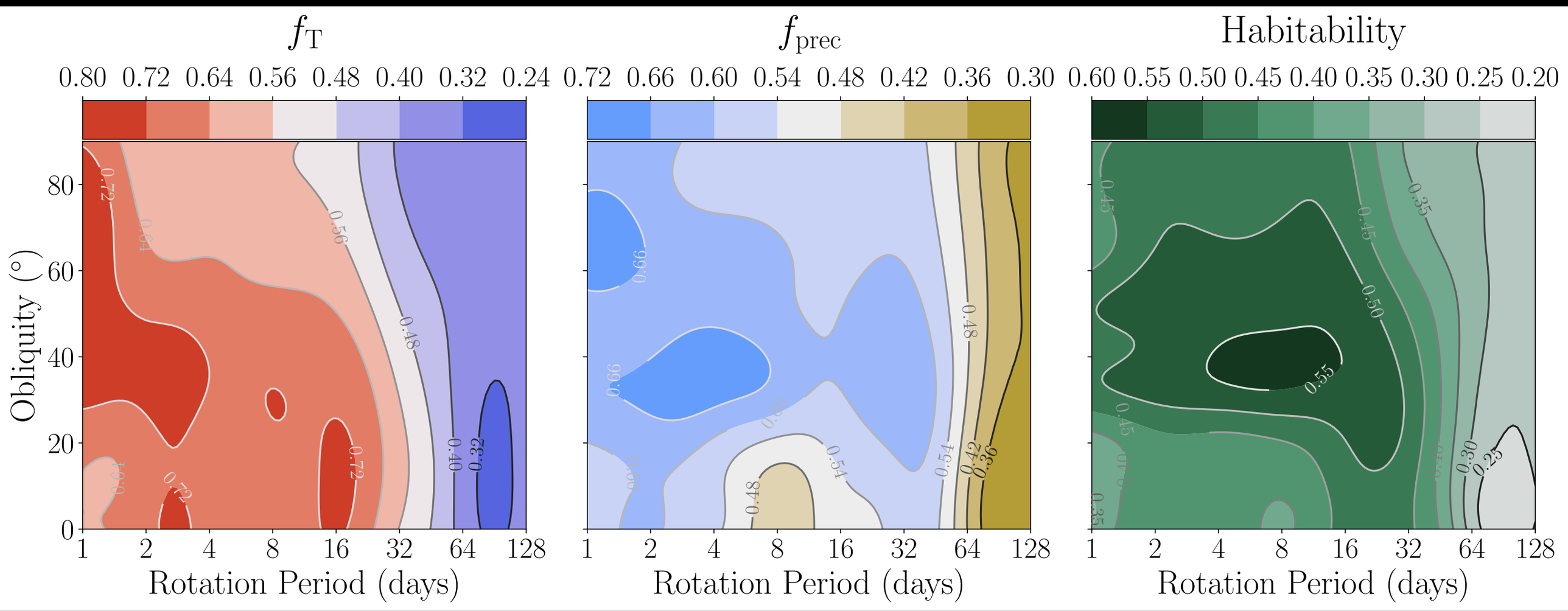
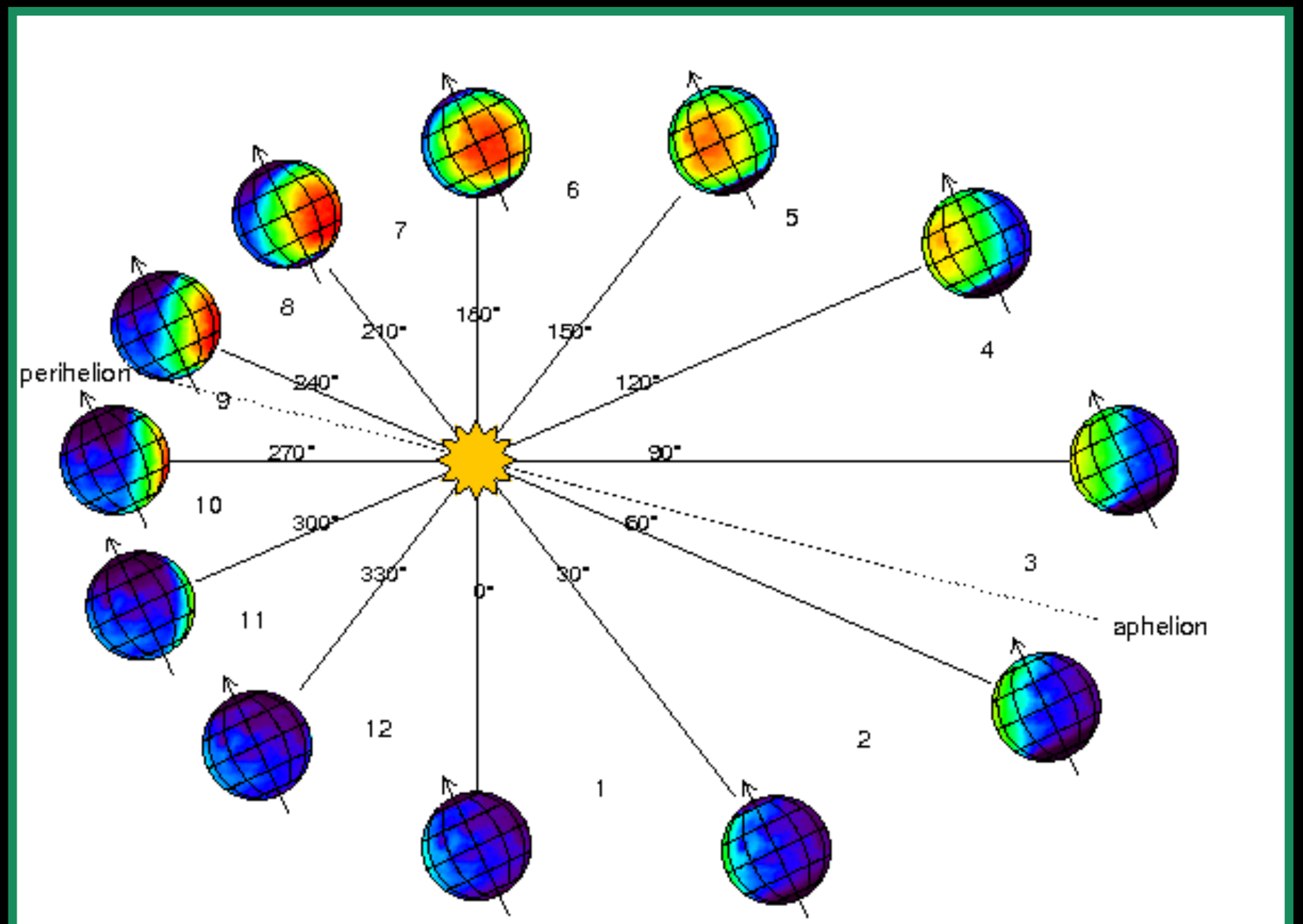


Adding Eccentricity



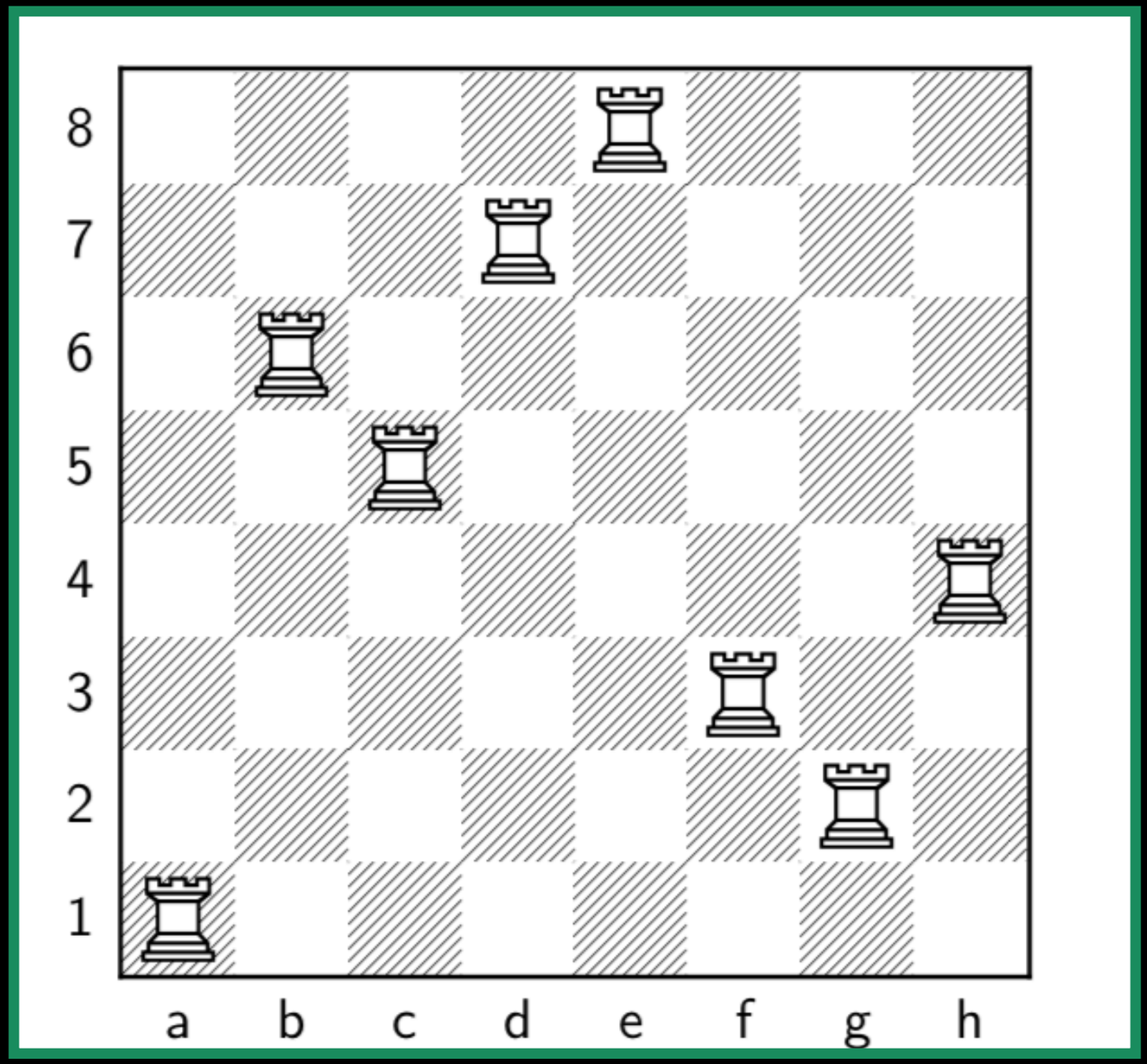
https://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html

$\sin \Phi > 0$: northern summers get more intense sunlight

$\sin \Phi < 0$: southern summers get more intense sunlight

How do we probe a 4-D parameter space when computation is limited?

Latin Hypercubes!



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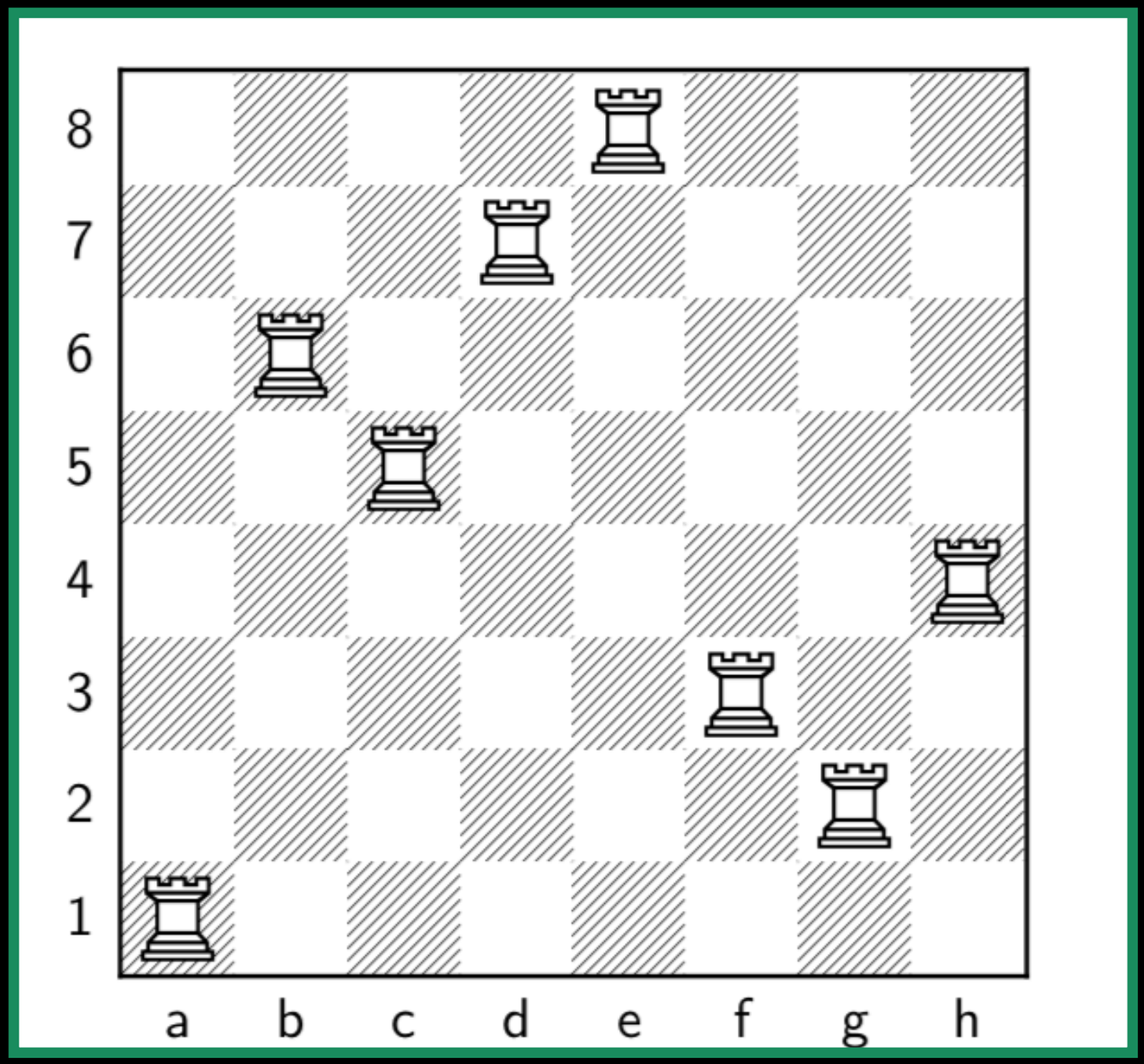
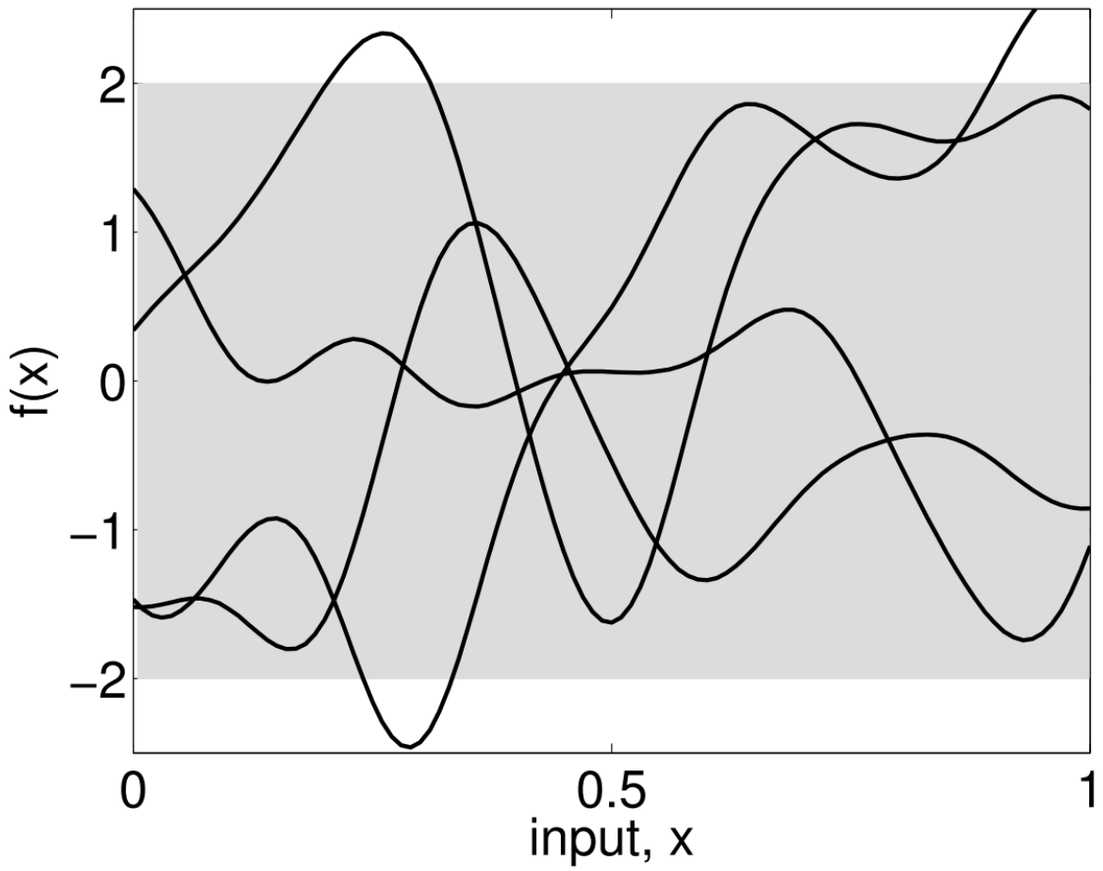
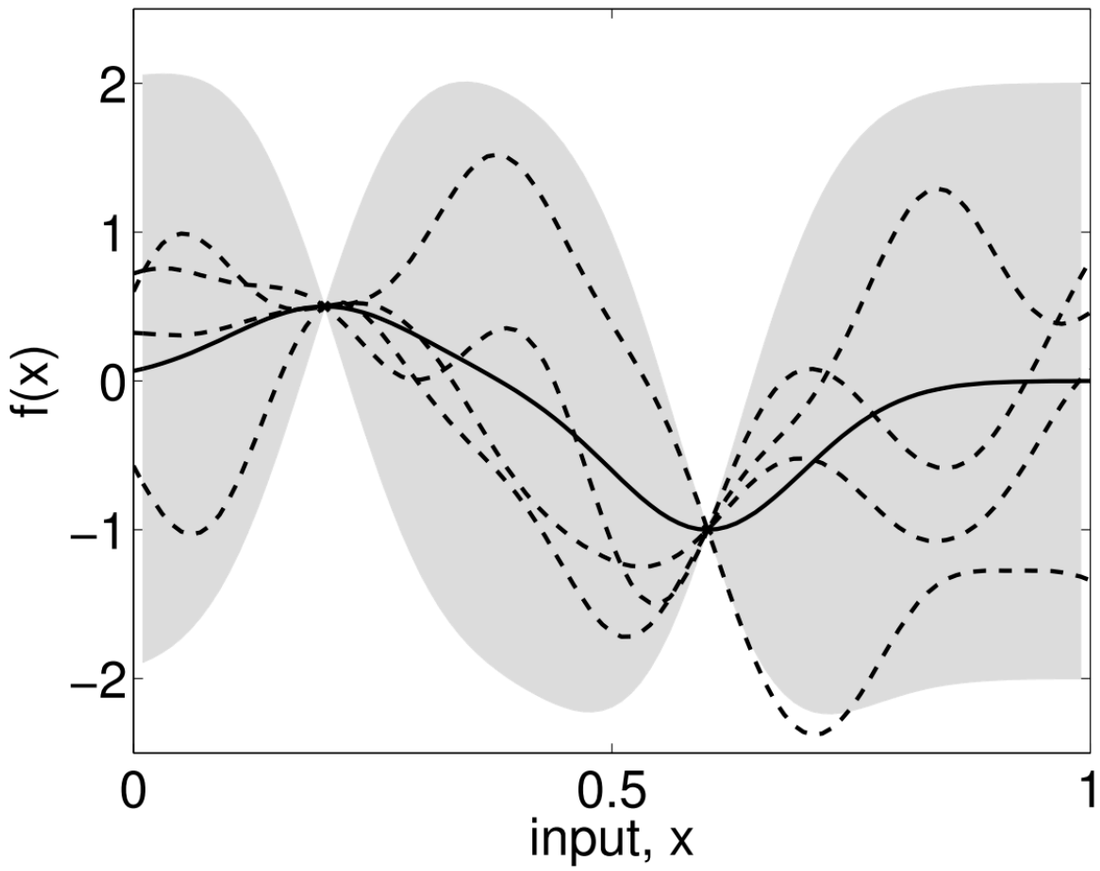


Emulating Habitability



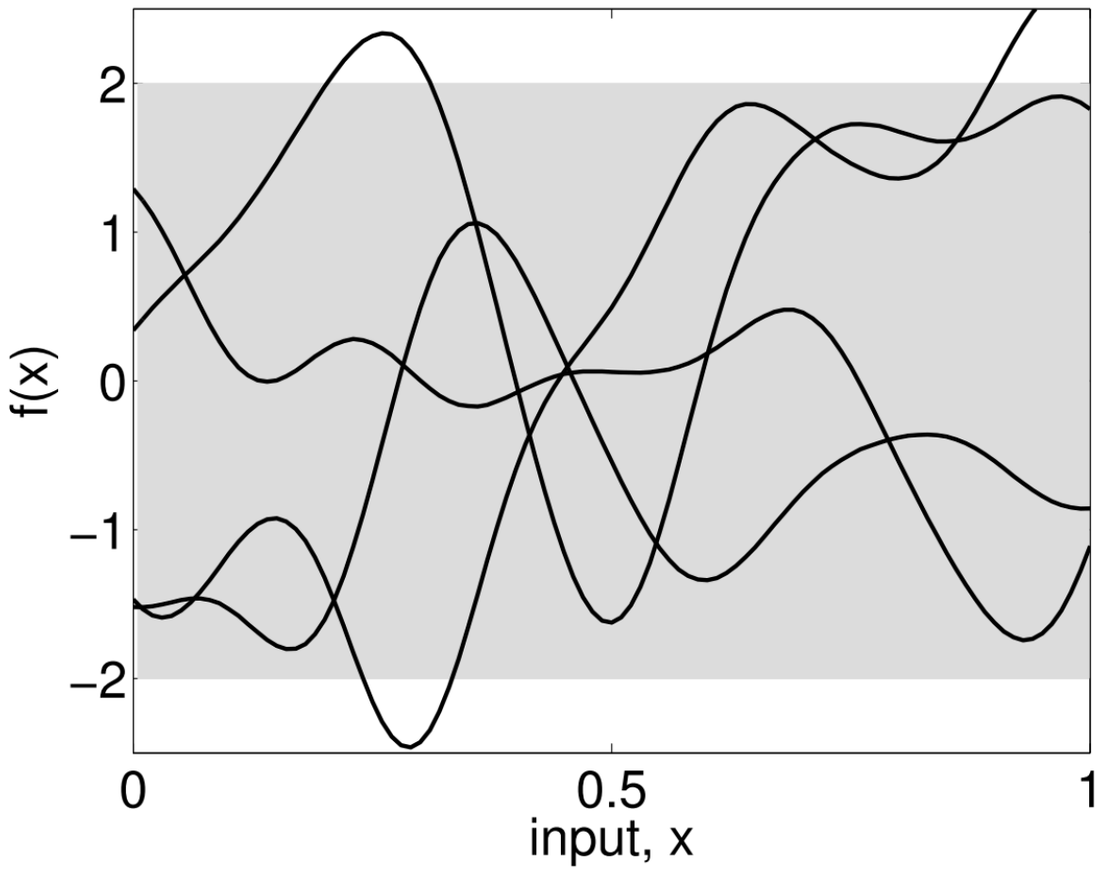
(a), prior



(b), posterior

Emulating Habitability

Non-parametric?



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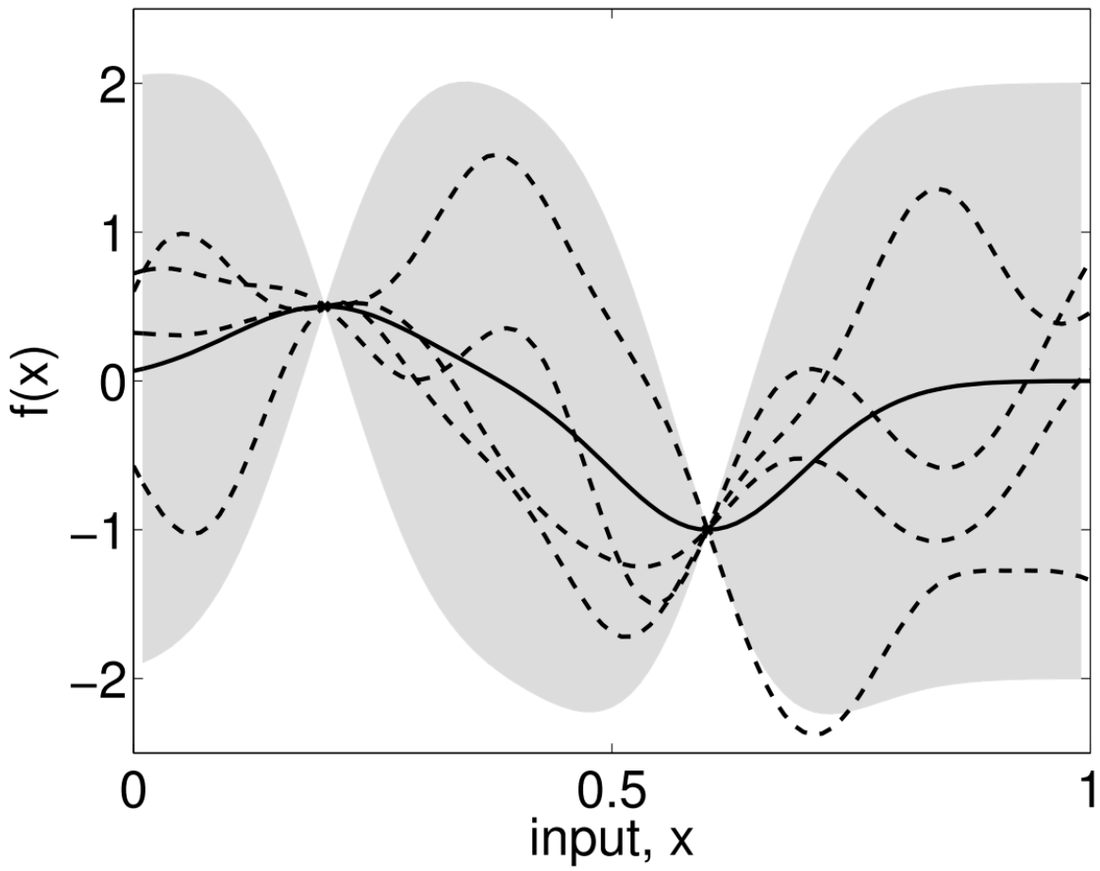

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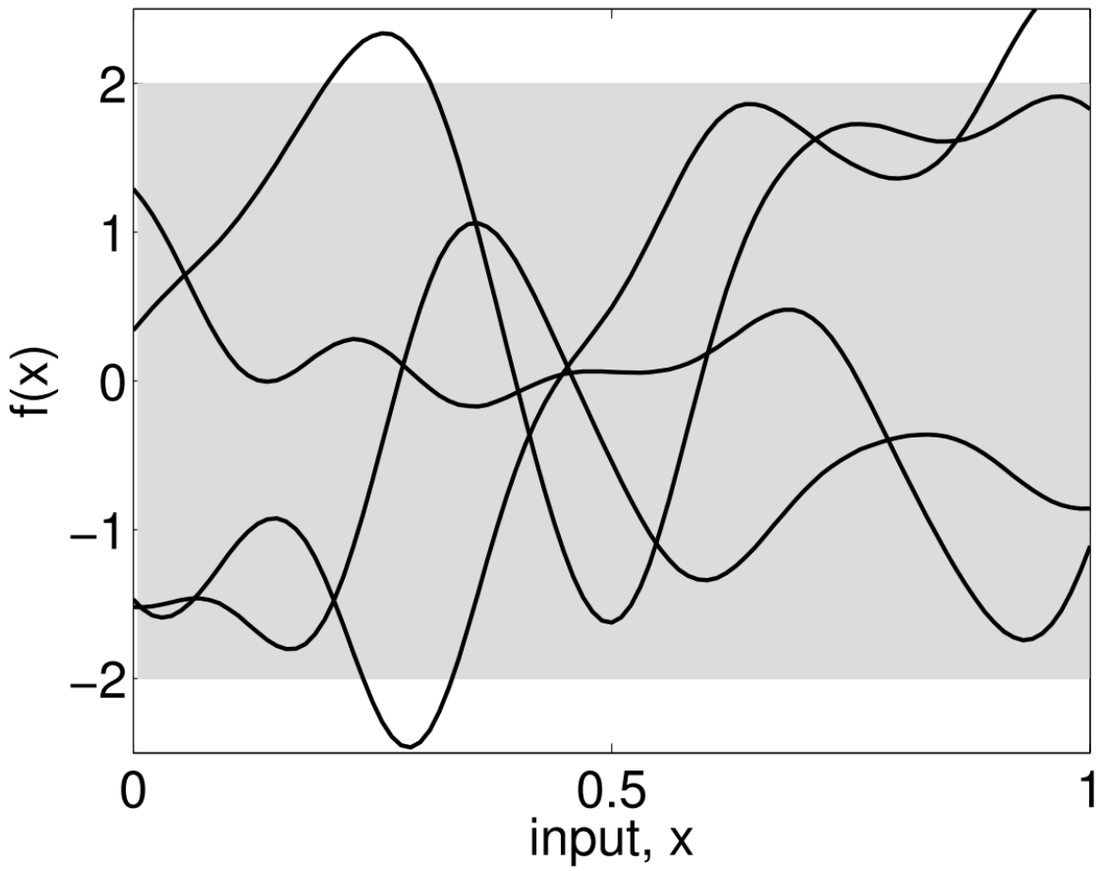
Emulating Habitability

Non-parametric? Bayesian?



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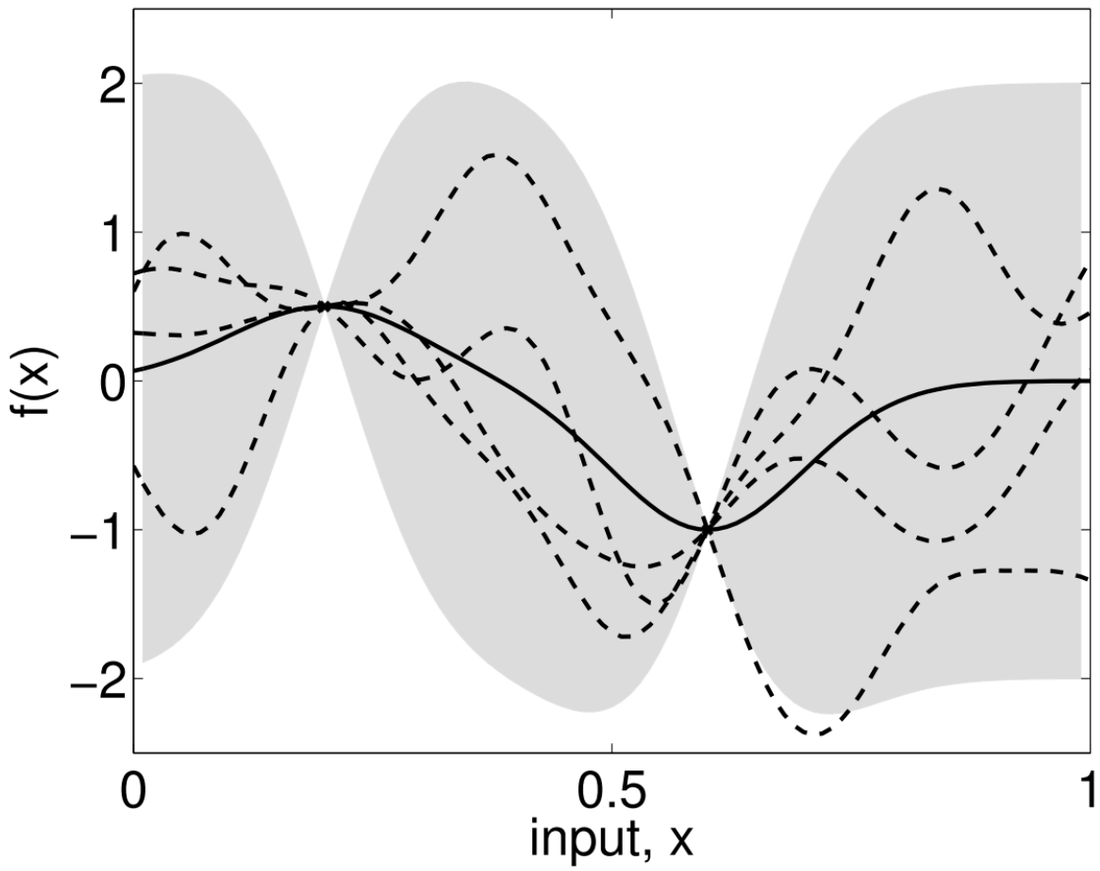
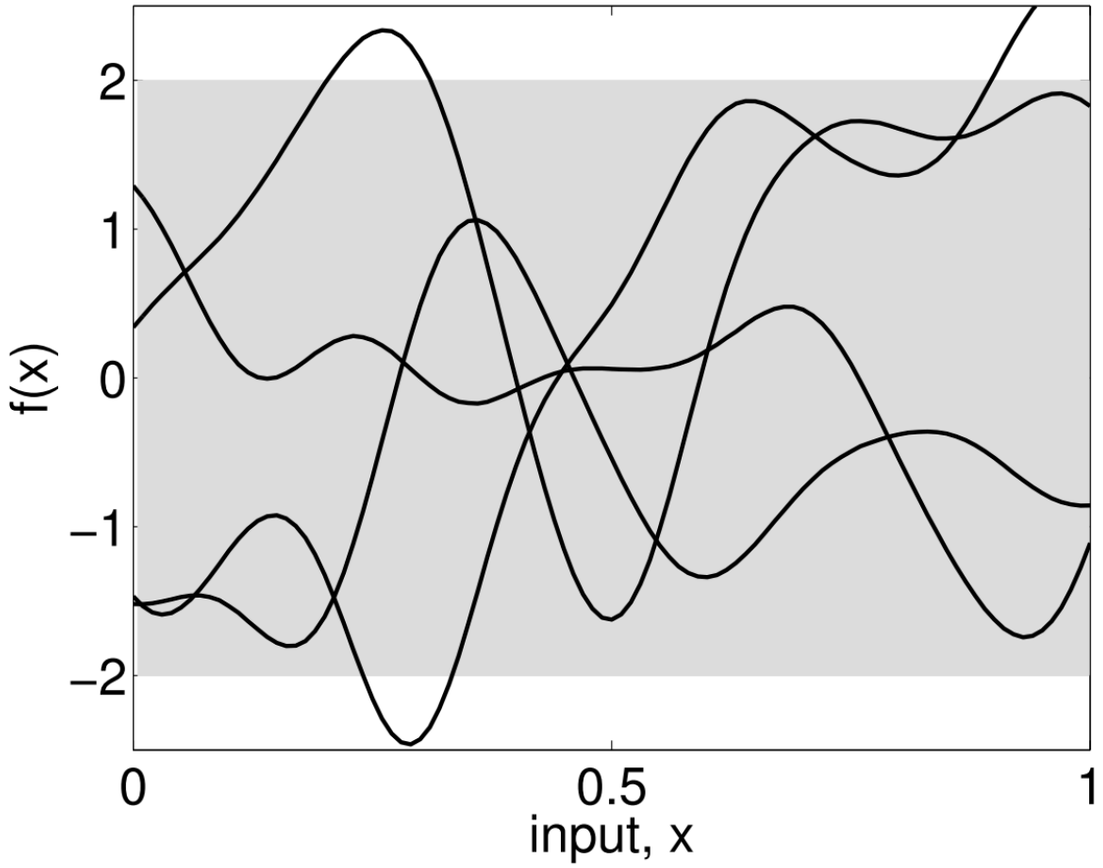


(b), posterior

Emulating Habitability

Non-parametric? Bayesian? Gaussian processes!?



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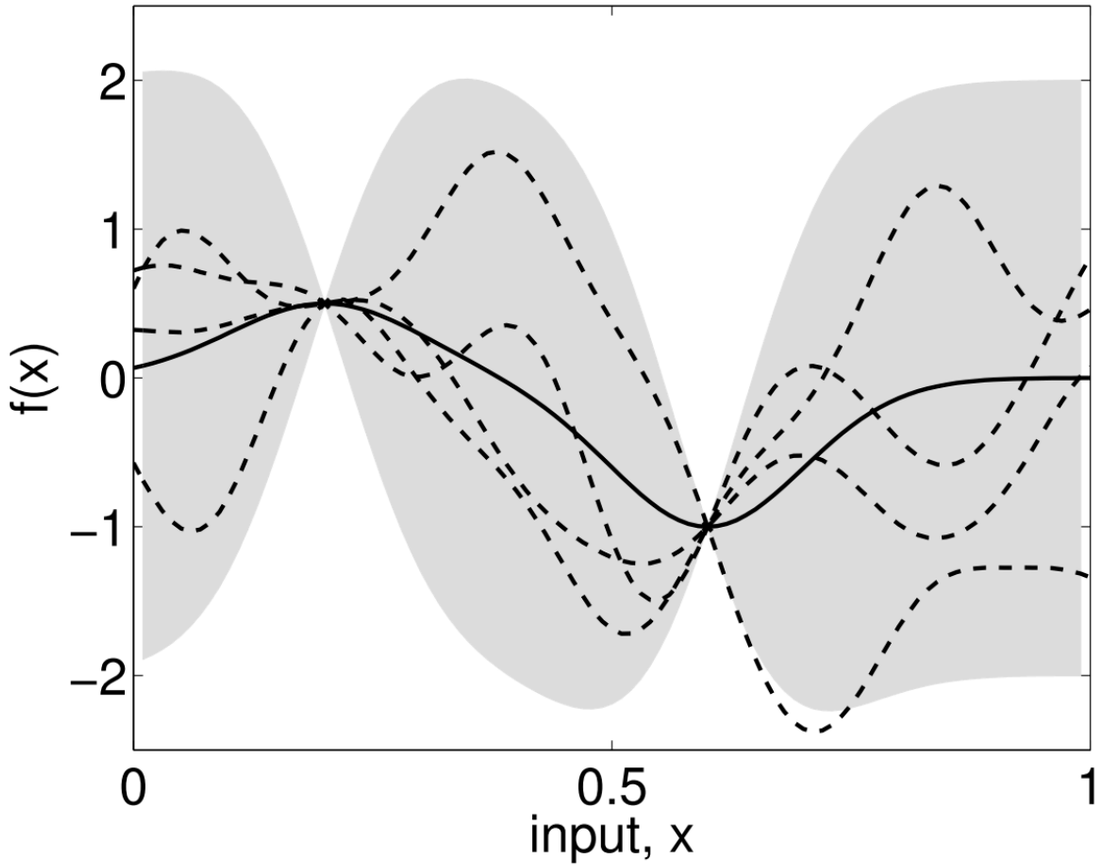


(b), posterior

$e \cos \phi_{\text{peri}} = -0.225$ -0.1125 0 0.1125 0.225

$e \sin \phi_{\text{peri}} = -0.225$ -0.1125 0 0.1125 0.225

Obliquity (°)

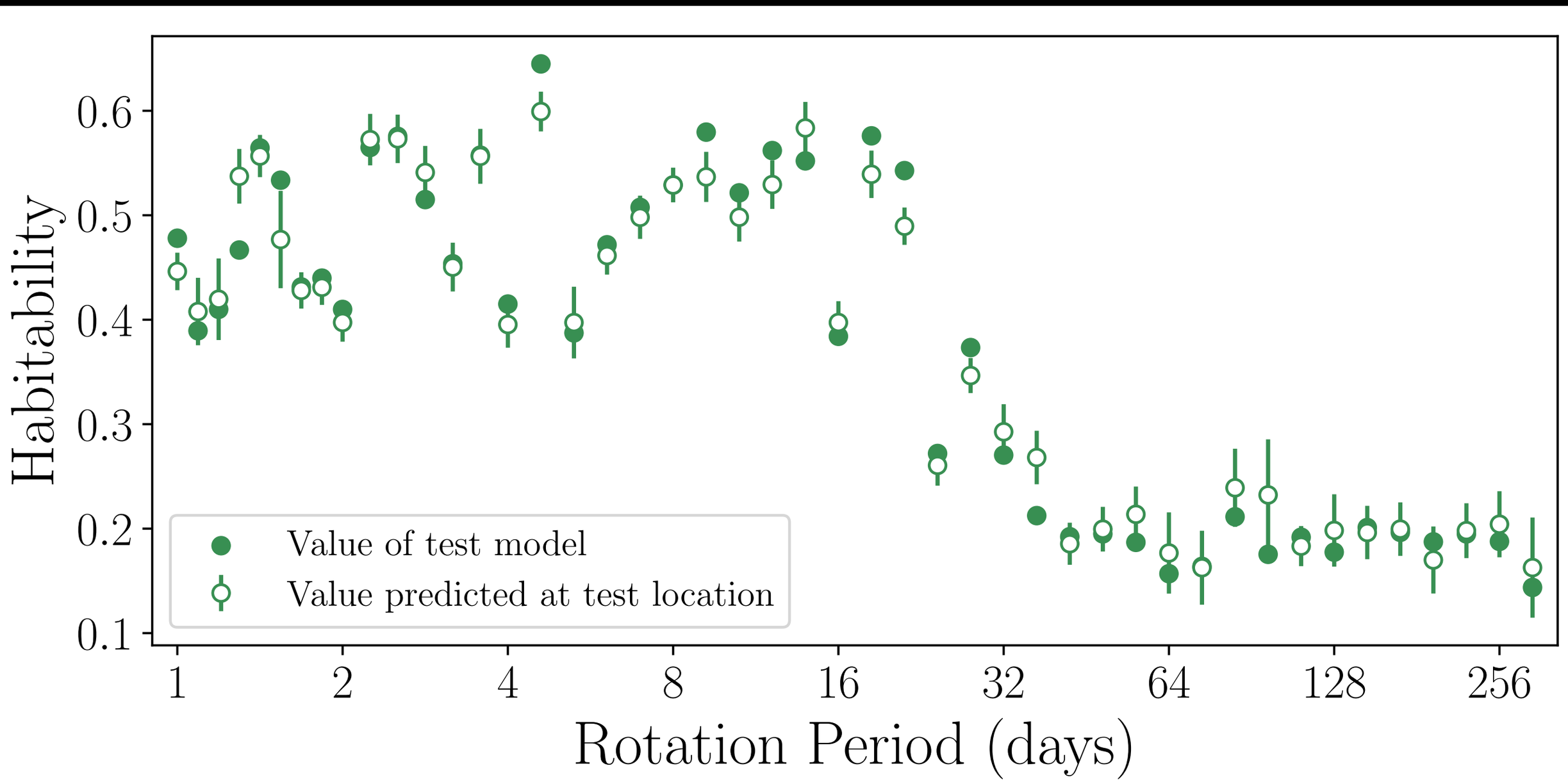
Rotation Period (days)

Habitability

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

$\sin \Phi$

Emulator does a pretty good job



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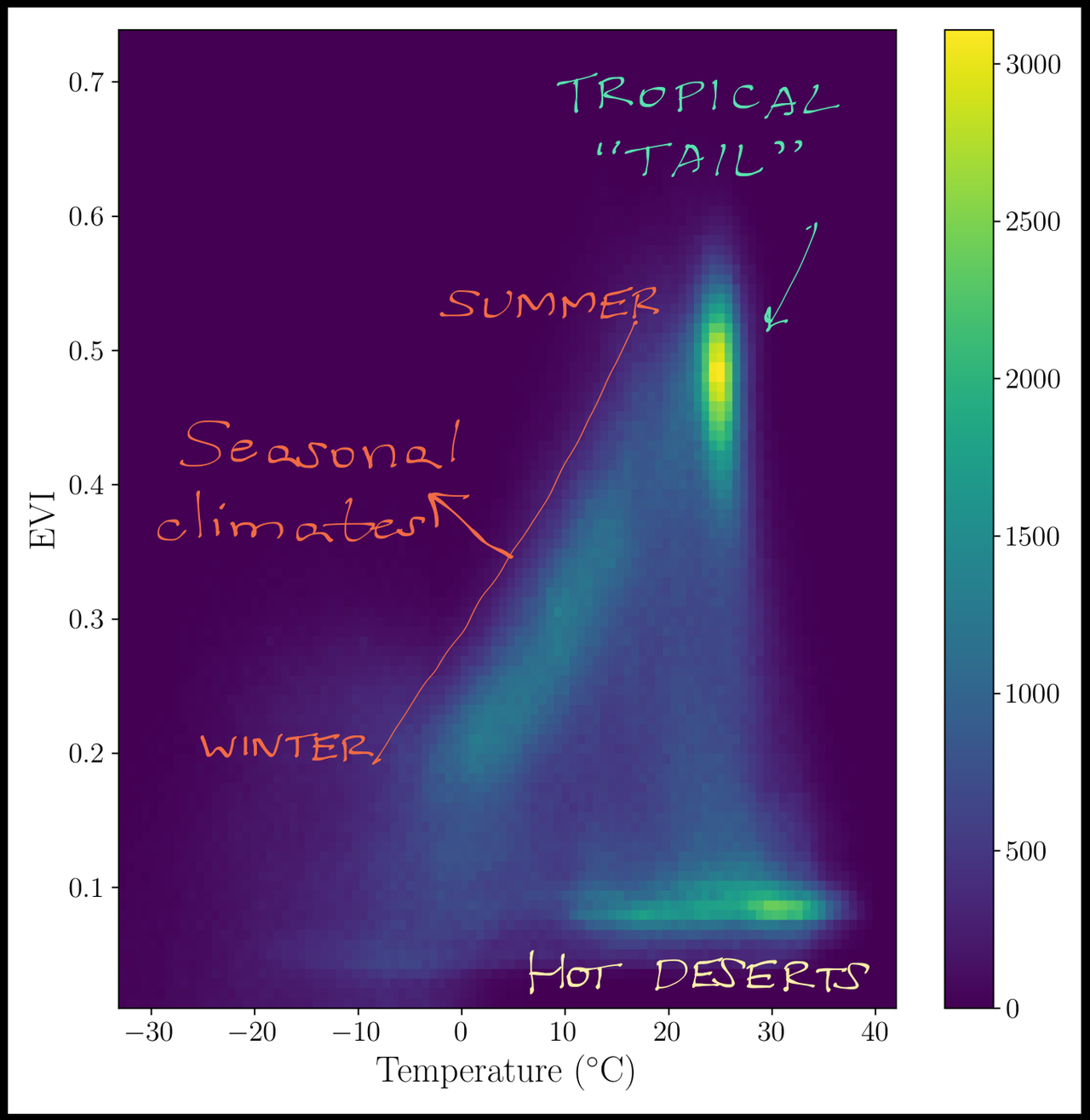
Future/Parallel Directions:

Vegetation index as a habitability metric?



Annie Shelton

(former undergrad at UCR, now at Cornell)

$e \cos \phi_{\rm peri} = -0.225$ -0.1125 0 0.1125 0.225

$e \sin \phi_{\rm peri}$ = −0.225 −0.1125 0 0.1125 0.225

Obliquity (°)

Rotation Period (days)

$f_{\rm T}$

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

sin Φ

$e\cos\phi_{\rm peri} = -0.225$ -0.1125 0 0.1125 0.225

$e\sin\phi_{\rm peri}$ = 0.225 0.1125 0 −0.1125 −0.225

Obliquity (°)

Rotation Period (days)

$f_{\rm prec}$

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

sin Φ