Modelling temperature over varied metrics to determine habitability on exoplanets

Maxine Thembi Khumalo *

Department of Aerospace, Physics and Space Science, Florida Institute of Technology, Melbourne, FL 32901, USA

October 2021

Abstract

Answering, "Are we alone?" is a crucial tenant of Astrobiology. To first know if there is life on faraway exoplanets, modelling them and testing their possibility of life is essential. ExoPlaSim is a Global Climate Model (GCM) based on PlaSim but simulates exoplanets. This paper aims to investigate the impacts of obliquity (the axial tilt of the planet) and synchronicity (tidally locked orbit or not) on the habitability of Earthlike planets. Varying obliquity from 0 to 90 degrees for synchronous and asynchronous planets results in heat maps, average temperature, and habitability percentage data. The paper found that synchronous planets have lower average temperatures and smaller habitable areas than planets with asynchronous orbits. As obliquity increases, the range of temperatures increases for synchronous worlds and decreases for asynchronous planets. Therefore for more moderate climates that are warmer, asynchronous planets with large obliquity are the most suitable.

Keywords: Exoplanets, Habitability, ExoPlasim, GCM, Astrobiology

1 Introduction

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Exoplanet Modeling and Analysis Center (EMAC) website [1] showcases ExoPlaSim as a valuable resource on modelling exoplanets. ExoPlaSim is a modified 3D climate model for exoplanets (expanding on PlaSim which focussed on planets with Earth-like atmospheres) [2]–[4]. This project aims to use the ExoPlaSim software package in python to vary different characteristics (like temperature, pressure, surface gravity and radius of the planet) and compare the resulting simulated planets based on habitability metrics [5]. ExoPlaSim 3D model visualisation allows for an easier understanding of the possibilities for life on exoplanets yet to be discovered [4]. Relationships between characteristics and their effect on metrics will be in the investigation - similar to previous studies of PlaSim [6], [7]. This report also aims to explain the method and process for using this new software to make findings [2].

The conditions studied are obliquity and synchronicity and their effect on temperature. The surface temperature is a metric of habitability using the temperatures with liquid water as a benchmark. The purpose of varying over these conditions is to learn if there are characteristics in exoplanets that we can look for to find life on other planets. The pursuit of habitable exoplanets links to the three fundamental questions of Astrobiology [8]. Modelling obliquity and synchronicity answers how vital these factors were to life flourishing on Earth. Understanding what characteristics to look for in exoplanets helps with finding life. With climate change and resource depletion, humans may need to look for habitable exoplanets and modelling valuable candidates will be crucial in pursuing a new home planet.

2 State of the field

ExoPlaSim improves on Planetary Simulator (PlaSim). PlaSim is a Global Climate Model

*Electronic address: mkhumalo@my.fit.edu

(GCM) focussing on Earth and Mars, while ExoPlaSim allows for the study of exoplanets [3], [9]. PlaSim has a complex atmospheric model with linear models for modelling other characteristics (like oceans, sea-ice and land surface) [9]. These linear models include Newtonian cooling [10] and Rayleigh friction [11] used for modelling atmosphere layers and diabatic processes [12]. PlaSim is an open-source climate model developed in 2003 [12]. It is used primarily in the university environment thus aims to be user-friendly for students [12]. The parameters studied in this paper focus on orbital parameters, and the short radiation equation is one of the equations used in PlaSim dependent on orbital conditions. The downward radiation flux is as follows[12]:

$$F = \mu_0 \cdot E_0 \cdot T_R \cdot T_O \cdot T_W \cdot T_D \cdot T_C \cdot R_S. \quad (1)$$

In equation (1), μ_0 is the cosine of solar zenith (related to synchronicity that is varied in the Section 4), E_0 is the solar flux, R_S is surface albedo and T refers to the transmissivity due to Rayleigh Scattering (R), ozone (O), water vapour (W), dust (D) and clouds (C) [12].

ExoPlaSim extends PlaSim by adding synchronous rotation (studied in this paper), slow rotation, vertical democratisation, radiation and core dynamics [3]. These changes allow for stars to be different from the Sun and planets to orbit in ways that differ from Earth [3]. ExoPlaSim allows for the modelling of tidally locked planets around M dwarfs - a system very plentiful in the universe [3]. ExoPlaSim allows for the adjusting of the solar day and adjusting synchronicity. ExoPlaSim makes changes to the calculation of the surface albedo (R_S) and the transmissivity due to Rayleigh Scattering (T_R) to allow for behaviour that varies from that of the solar system [3]. ExoPlaSim provides multiple physics filters considering different directions on the planet separately as an improvement to the Fast Fourier Transform performed in PlaSim [3].

Other powerful GCM include CAM3 [13], CAM4 [14], ExoCAM [15], PLASIM-GENIE v1.0[16] and PlaSim-ICMMG-1.0[17]. An important part of the study of GCM is testing their performance. ExoPlaSim is claimed to perform better than many others because it is simple while still getting comparable results [3].

2.1 Habitability

With limited candidates for life within the solar system, scientists look to other systems and their planets for candidates. New telescopes have discovered exoplanets in the habitable zones of their stars [18], [19], and this provides an opportunity to model their conditions to test habitability.

One of the ways to test if an exoplanet is habitable is to measure its surface temperature [20]. The temperatures that sustain liquid water act as limits of habitability because of water's hydrogen bonds, polarity and the dielectric effect [21]. Water also acts as an organic solvent essential for cellular processes [21]. This paper uses 273.15K and 373.15K as the limits of habitability. It is important to note that extremophiles can live at temperatures outside the range of liquid water. Some enzymes are active at 263K [22] and a group of archaea that survive temperature at 386K [23].

One of the conditions studied is the effects of obliquity on habitability. In [24], high-frequency obliquity oscillations show an increase in the habitable zone for systems similar to the solar system. According to [25], habitability is possible at all obliquities, and the presence of oceans mitigates extreme climates. The obliquity of Earth is 23.5 degrees while Venus is 180 degrees and Mars has a varying obliquity (from 0 to 60 degrees) [25]. Obliquity is affected by gravitational and atmospheric tides, core-mantle friction and collisions with large bodies [25]. Figure 1 shows the results for high obliquity that were modelled with MITgcm[25]. These graphs show the variation of surface temperature over time and the planet's position. The varieties of obliquities make studying this condition of exoplanets important.

Synchronicity refers to whether or not a planet's orbit is tidally locked [3]. Tidally locked planets have a high contrast between the temperatures at night and in the day [26]. From [26], thin atmospheres allow for planets to stray away from synchronicity over time. [27] shows that after 1Gyr, habitable planets start to lock to their stars tidally. Therefore studying both synchronous and asynchronous Earthlike planets is essential for understanding habitability on exoplanets.

3 Synthesis

Firstly, ExoPlaSim is a new GCM released in 2021 [1], [3] so no papers have been released on its per-

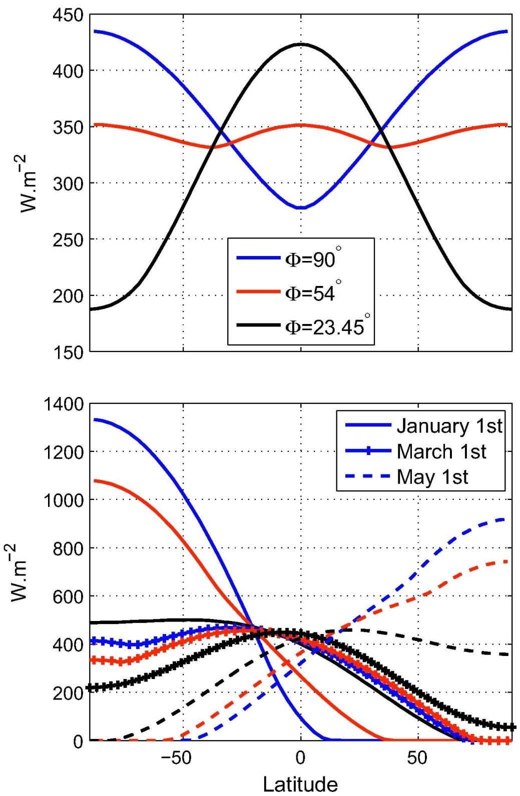


Figure 1: The effects of high obliquity on a planet's habitability

[25]

formance outside of its launch (at time of writing). Obliquity and synchronicity are critical conditions studied regarding the habitable zone but not regarding the percentage of the planet that would be habitable.

Ideally, this paper aims to use the new software to visualise a heat map on a hypothetical planet and make conclusions about the effects of obliquity and synchronicity on habitability. The more understanding of exoplanets surface temperature, the better we can answer if we are alone in the universe. Obliquity and synchronicity are orbital measurements that are easier to identify in planets nearby and can help us identify habitability.

4 Methods

We are analysing Earthlike planets and varying specific characteristics using ExoPlaSim. The code is in `https://exoplasim.readthedocs.io/en/latest/source/exoplasim.html?highlight=earth#exoplasim.Earthlike`.

The benchmark problem in the documentation is discusses TOI-700D[3]. TOI700D is a super-Earth exoplanet that orbits an M-type star[28]. It is in the Habitable zone of a system with three planets. TOI-700 is 102 light-years away [29]. Algorithm 1 shows how the data is generated for Figure 2. Note that one must set stellar, orbit and rotation parameters and bulk and atmospheric properties. The model dynamics determine how many snapshots to take and the physics used. We can mitigate the lack of sharp features using physics filters. These are mathematical filters included in the dynamical core at the spectral transform stage. Here we have told ExoPlaSim to use an exponential filter and to apply it both at the transform from gridpoint space to spectral space, and at the transform from spectral space back to gridpoint, space [3].

After running the benchmark case, the model with all the parameters matching Earth but varying the obliquity. A synchronous Earth is then run. The Algorithm 2 shows the method used with the updated parameters.

5 Results and Discussion

Synchronicity and obliquity are the conditions that varied for this research (that generated results and did not crash the model). Synchronicity refers to

Algorithm 1 Example Model

```
procedure TOI700D MODEL
    toi700d = exoplasim.Model(resolution='T21', ncpus=1)
    toi700d ← model framework
    toi700d.configure(startemp=3480.0, flux=1167.0,                 ▷ Star
eccentricity=0., obliquity=0., fixedorbit=True,                     ▷ Orbit
synchronous=True, rotationperiod=37.426,                            ▷ Rotation
radius=1.19, gravity=11.9, aquaplanet=True,                         ▷ Bulk properties
pN2=1.47*(1-360e-6), pCO2=1.47*360e-6,ozone=False,                  ▷ Atmosphere
timestep=30.0, snapshots=720, physicsfilter="gp—exp—sp");           ▷ Model dynamics
    toi700d.exportcfg();
    toi700d.run(years=1,crashifbroken=True);
```

Algorithm 2 Final method

```
procedure EARTH-LIKE MODELS
    earthlike = exoplasim.Model(resolution='T21', ncpus=1)
    earthlike ← model framework
    earthlike.configure(startemp=5800.0, flux=1367.0,               ▷ Star
eccentricity= 0.016715, obliquity=VARIED, fixedorbit=True,          ▷ Orbit
synchronous=VARIED, rotationperiod=1.0,                             ▷ Rotation
radius=1.0, gravity=9.80665, aquaplanet=True,                       ▷ Bulk properties
pN2=1*(1-360e-6), pCO2=1*360e-6,ozone=True,                         ▷ Atmosphere
timestep=30.0, snapshots=720, physicsfilter="gp—exp—sp");           ▷ Model dynamic
    earthlike.exportcfg();
    earthlike.run(years=1,crashifbroken=True);
```

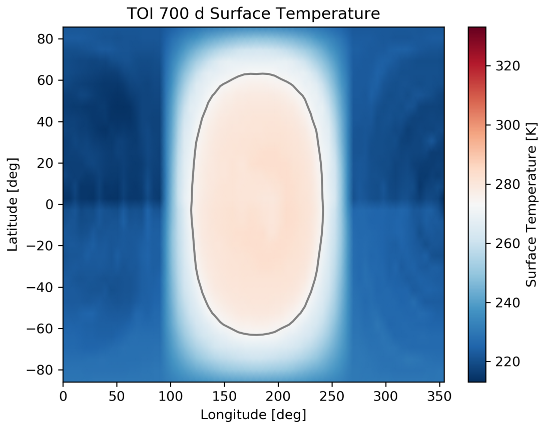


Figure 2: TOI-700D

whether or not the planet is tidally locked. When set to 'True', the Sun stays at 180 degrees longitude into the planet's sky. Therefore synchronicity set to 'False' should show more realistic results for Earth[2]. Obliquity is the axial tilt of a planet. The obliquity of Earth is 23.441 and is responsible for the seasons and thus has an impact on the temperature [30]. This section covers the results of Earth conditions from the software as a benchmark, the asynchronous results over varied obliquity, the synchronous results over the same set of obliquity values and comparing synchronous and asynchronous results. The heat-map images have a grey line where the temperature is 273.15 K - i.e. the beginning of the habitable region. The code for generating the results is at https://github.com/MaxineKhumalo/AstrobiologyProject2021

5.1 Earth conditions

Looking at Figure 3, ExoPlaSim is comparable to the GCMs used at Climate Reanalyzer. This benchmark case gives us confidence that the parameters chosen in Section 4 are accurate and that the model works as intended.

5.2 Asynchronous earthlike planets over varied obliquity

From Figure 4, the plots in Figure 4a, 4b, 4c and 4d look very similar. The plot changes with the larger obliquities of 45 degrees and 90 degrees (note Figures 4e and 4f). There are more islands of inhabitability in the middle of the planet and the habitable area appears larger.

These observations are congruent with Section 2.1 where large obliquity angles change the distribution of the heat on the planet. It also shows the planet is majority habitable for all obliquity angles - another claim from the literature.

5.3 Synchronous earthlike planets over varied obliquity

Figure 5 would show the results if Earth were tidally locked. The increased obliquity shifts the habitable region north and warms the northern regions. Similarly, the southern regions are colder by area and temperature. The islands of no habitability are more significant than in Figure 4. The results end at 45 degrees and not 90 because the model crashes - likely an infeasible scenario.

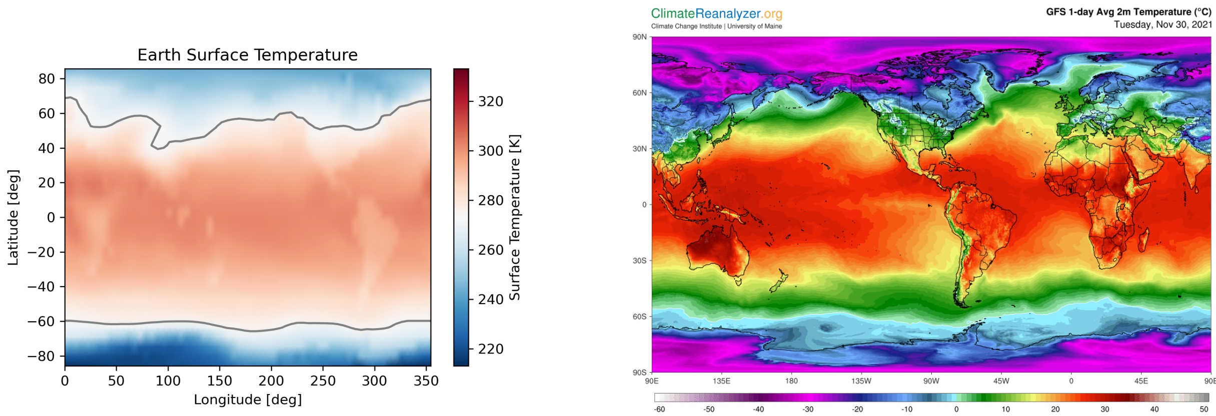
This result supports the high contrast between night and day that synchronous planets experience. It also shows that a tidally locked planet can still be habitable.

5.4 Asynchronous vs synchronous results

From Figure 7, the temperatures become more moderate with increased obliquity if the planet is asynchronous, while the temperatures become more extreme for tidally locked planets. For both, the mean variation is slight compared to the change in min and max over increasing obliquity.

To see the variation in the mean, Figure 8 shows that 23 degrees are a critical obliquity as its the point whether the average temperature is equal for both synchronous and asynchronous Earth temperatures. This critical point is similar to the current obliquity of Earth and might have some exciting implications. The mean temperature increases for increasing obliquity for both synchronous and asynchronous orbits.

The percentage of the planet that is habitable for synchronous and asynchronous orbits is in Figure 9. Asynchronous planets are more habitable than synchronous, except for Earth's obliquity. This observation is interesting since the peak habitability percentage for asynchronous planets is Earth's obliquity. Thus Earth would have a larger habitable area if it was tidally locked.



(a) This is the models surface temperature prediction for Earth

(b) This is the weather forecast for Earth on 30 November 2021.[31]

Figure 3: Comparing results from Exoplasim and ClimateReanalyzer

5.5 Final discussion

Firstly Obliquity vs mean temperature has a positive linear relationship. 0 degrees obliquity shows a unique behaviour when looking at an average temperature. 23 degrees is essential when comparing synchronous and asynchronous in the mean temperature and percentage habitability curves. What these 2 points represent is unclear.

In terms of the performance of the software, ExoPlaSim has fast execution - a couple of hours for all the results displayed using only 1 CPU. ExoPlaSim, however, crashes regularly. Eccentricity and pressure cannot vary in earthlike planets, limiting the conditions varied over for this paper. The number of years and CPUs available are limitations to the quality and speed of the results.

The reasoning for the crashes provided in the ExoPlaSim documentation is as follows. When the model crashes, it is likely ExoPlaSim encountered a numerical instability of some kind. Some are physical (the oceans boiled or the model was too cold, and the physics broke). At the same time, some are not (something happened to violate the CFL condition for the given timestep, or an unphysical oscillation was not damped properly by the dynamical core and grew exponentially). Since exotic exoplanets are the focus of the software, varying over Earthlike properties may not be the best way to understand the performance of ExoPlaSim.

6 Conclusion

Investigating exoplanet habitability is vital to answering the fundamental questions of astrobiology - especially "Are we alone?". Obliquity and synchronicity are essential conditions to investigate habitability, and temperature is a fair measurement. This paper's results show that average temperature increases with obliquity and that asynchronous orbits have a larger habitable area than synchronous ones. The mark of 23 degrees is an exception and where the mean temperatures of synchronous and asynchronous planets cross.

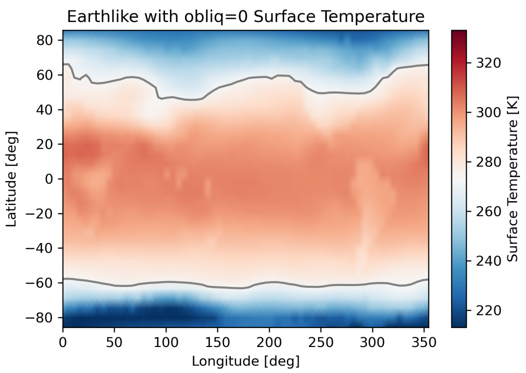
For future work, investigating software and hardware mitigations is an excellent place to start- more CPUs and fewer crashes. Another area is investigating more metrics, simulated over more years. Work should study other base cases other than Earth - maybe model other planets hypothesised as promising candidates for life.

Acknowledgments

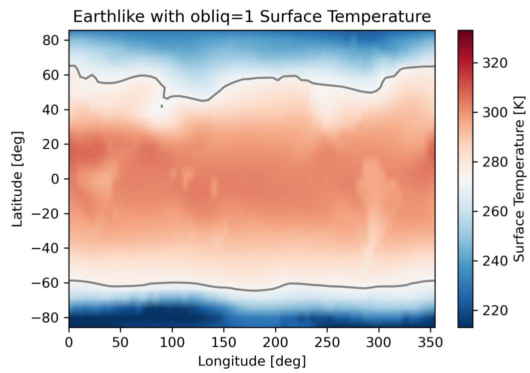
Thanks to Dr Lingam for his guidance and ideas. Hopefully, this work can continue because the software has promise.

References

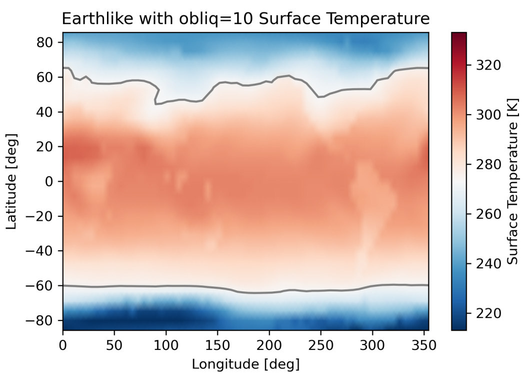
[1] *Exoplanet modeling and analysis center - nasa/gsfc*. [Online]. Available: https://emac.gsfc.nasa.gov/.



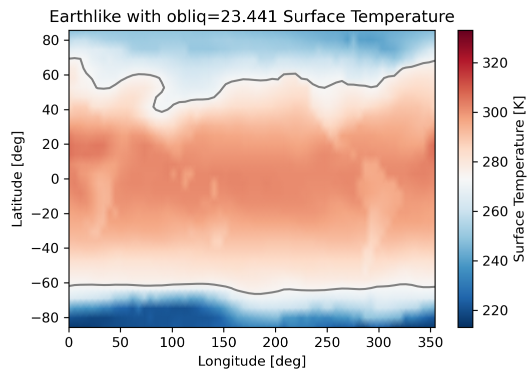
(a)



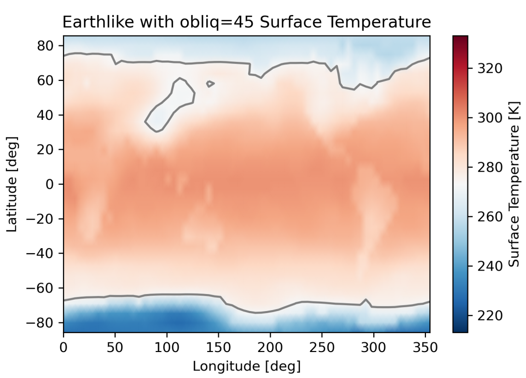
(b)



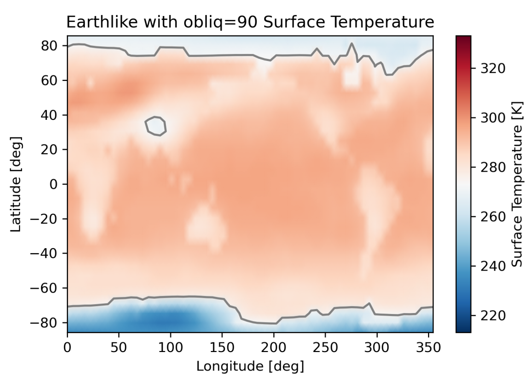
(c)



(d) This is the model's surface temperature prediction for Earth

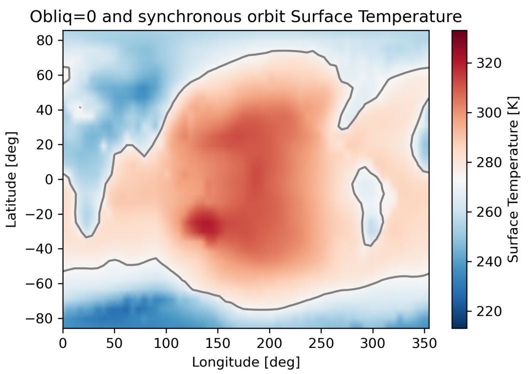


(e)

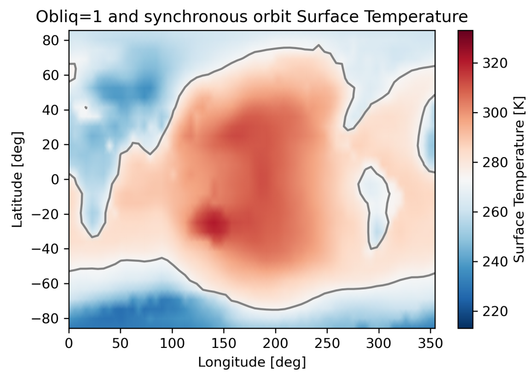


(f)

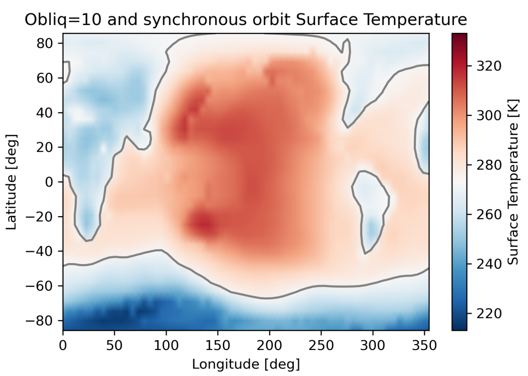
Figure 4: Varying obliquity for a tidally locked Earth.



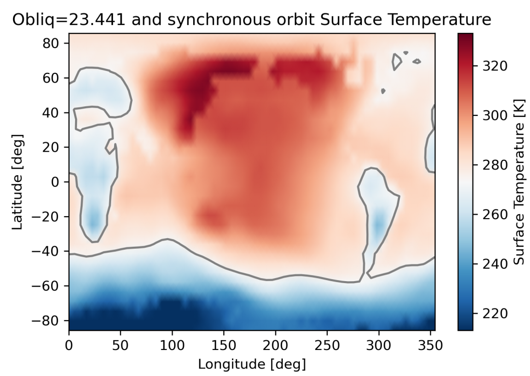
(a)



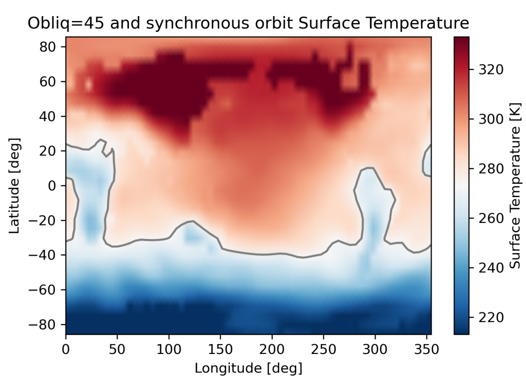
(b)



(c)

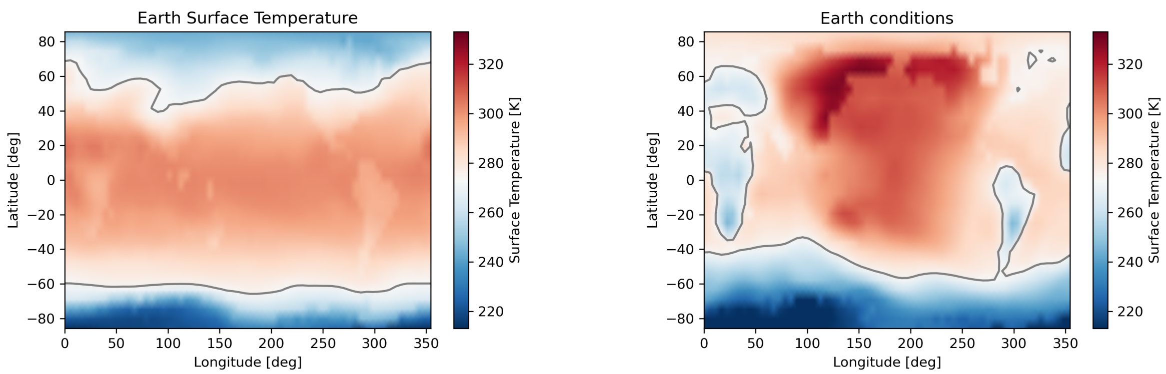


(d)



(e)

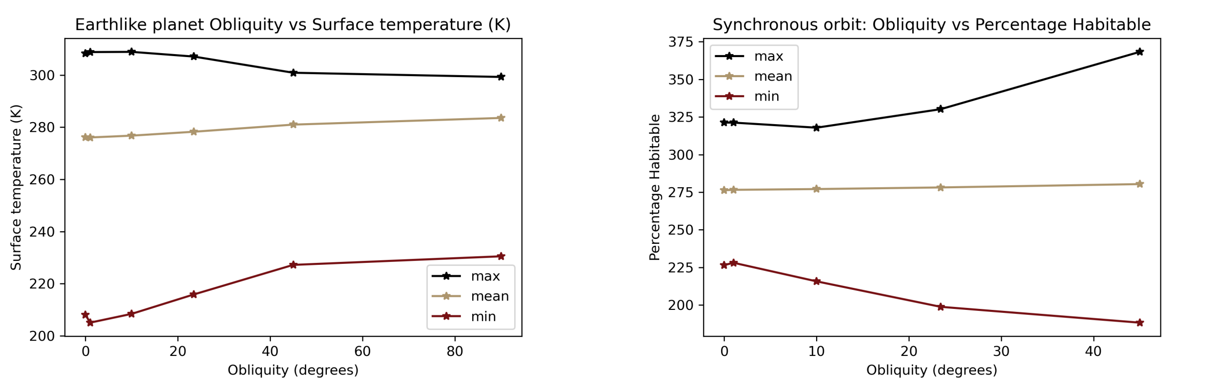
Figure 5: Varying obliquity for a tidally locked Earth.



(a) This is the models surface temperature prediction for Earth

(b) This is the models surface temperature prediction for an Earthlike planet

Figure 6: Comparing Synchronous and Asynchronous orbit of Earth



(a) This shows the temperature statistics of an asynchronous Earth-like planet over varying obliquities.

(b) This shows the temperature statistics of an asynchronous Earth-like planet over varying obliquities.

Figure 7: Comparing Synchronous and Asynchronous temperature statistics over varied obliquity

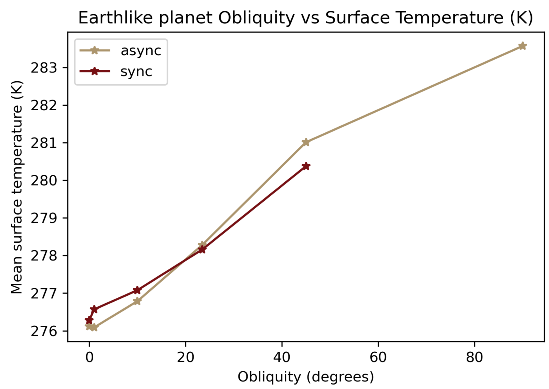


Figure 8: Mean temperature for Earth-like planets over varied obliquity

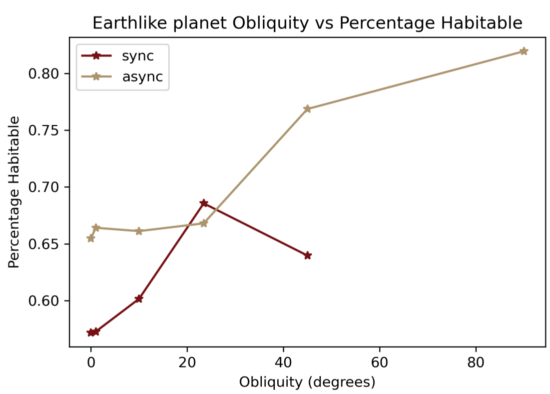


Figure 9: Percentage habitable for Earth-like planets over varied obliquity

[2] A. Paradise, E. Macdonald, C. Lee, K. Menou, B. L. Fan, H. Borth, F. Lunkeit, and Edilbert Kirk, *Alphaparrot/exoplasim: Cross-platform compatibility and pyburn*, 2021. DOI: 10.5281/ZENODO.5500720. [Online]. Available: https://zenodo.org/record/5500720.

[3] A. Paradise, E. Macdonald, K. Menou, C. Lee, and B. L. Fan, *Exoplasim: Extending the planet simulator for exoplanets*, 2021. arXiv: 2107.07685 [astro-ph.EP].

[4] A. Paradise, B. L. Fan, E. Macdonald, K. Menou, and C. Lee, *A large repository of 3d climate model outputs for community analysis and postprocessing*, 2020. arXiv: 2008.02339 [astro-ph.EP].

[5] A. Paradise, K. Menou, D. Valencia, and C. Lee, "Habitable snowballs: Temperate land conditions, liquid water, and implications for co2 weathering," *Journal of Geophysical Research: Planets*, vol. 124, no. 8, pp. 2087–2100, 2019.

[6] P. Nowajewski, M Rojas, P Rojo, and S Kimeswenger, "Atmospheric dynamics and habitability range in earth-like aquaplanets obliquity simulations," *Icarus*, vol. 305, pp. 84–90, 2018.

[7] A. Paradise, B. L. Fan, K. Menou, and C. Lee, "Climate diversity in the solar-like habitable zone due to varying background gas pressure," *Icarus*, vol. 358, p. 114 301, 2021, ISSN: 0019-1035. DOI: 10.1016/j.icarus.2020.114301. [Online]. Available: http://dx.doi.org/10.1016/j.icarus.2020.114301.

[8] P. J. Boston, "Nasa astrobiology institute," 2018.

[9] F. Lunkeit, S. Blessing, K. Friedrich, H. Jansen, E. Kirk, U. Luksch, and F. Sielmann, *PlaSim: Planet Simulator*, Jul. 2021. ascl: 2107.019.

[10] T. J. Dunkerton, "Nonlinear propagation of zonal winds in an atmosphere with newtonian cooling and equatorial wavedriving," *Journal of Atmospheric Sciences*, vol. 48, no. 2, pp. 236–263, 1991.

[11] B. Stevens, J. Duan, J. C. McWilliams, M. Münnich, and J. D. Neelin, "Entrainment, rayleigh friction, and boundary layer winds over the tropical pacific," *Journal of climate*, vol. 15, no. 1, pp. 30–44, 2002.

[12] F. Lunkeit, S. Blessing, K. Fraedrich, H. Jansen, E. Kirk, U. Luksch, and F. Sielmann, "Planet simulator," Reference Manual. Technical Report, University of Hamburg. https://www. mi ..., Tech. Rep., 2011.

[13] W. D. Collins, P. J. Rasch, B. A. Boville, J. J. Hack, J. R. McCaa, D. L. Williamson, B. P. Briegleb, C. M. Bitz, S.-J. Lin, and M. Zhang, "The formulation and atmospheric simulation of the community atmosphere model version 3 (cam3)," *Journal of Climate*, vol. 19, no. 11, pp. 2144–2161, 2006.

[14] R. B. Neale, J. Richter, S. Park, P. H. Lauritzen, S. J. Vavrus, P. J. Rasch, and M. Zhang, "The mean climate of the community atmosphere model (cam4) in forced sst and fully coupled experiments," *Journal of Climate*, vol. 26, no. 14, pp. 5150–5168, 2013.

[15] E. Wolf and O. Toon, "The evolution of habitable climates under the brightening sun," *Journal of Geophysical Research: Atmospheres*, vol. 120, no. 12, pp. 5775–5794, 2015.

[16] P. B. Holden, N. R. Edwards, K. Fraedrich, E. Kirk, F. Lunkeit, and X. Zhu, "PLASIM-GENIE v1.0: a new intermediate complexity AOGCM," *Geoscientific Model Development*, vol. 9, no. 9, pp. 3347–3361, Sep. 2016. DOI: 10.5194/gmd-9-3347-2016.

[17] G Platov, V Krupchatnikov, Y. Martynova, I Borovko, and E Golubeva, "A new earth's climate system model of intermediate complexity, plasim-icmmg-1.0: Description and performance," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, vol. 96, 2017, p. 012 005.

[18] E. A. Petigura, A. W. Howard, and G. W. Marcy, "Prevalence of earth-size planets orbiting sun-like stars," *Proceedings of the National Academy of Sciences*, vol. 110, no. 48, pp. 19 273–19 278, 2013.

[19] G. Anglada-Escudé, P. J. Amado, J. Barnes, Z. M. Berdiñas, R. P. Butler, G. A. Coleman, I. de La Cueva, S. Dreizler, M. Endl, B. Giesers, *et al.*, "A terrestrial planet candidate in a temperate orbit around proxima centauri," *Nature*, vol. 536, no. 7617, pp. 437–440, 2016.

[20] S. Seager, "Exoplanet habitability," *Science*, vol. 340, no. 6132, pp. 577–581, 2013.

[21] A. Brack, "Liquid water and the origin of life," *Origins of Life and Evolution of the Biosphere*, vol. 23, no. 1, pp. 3–10, 1993.

[22] R. Cavicchioli, K. S. Siddiqui, D. Andrews, and K. R. Sowers, "Low-temperature extremophiles and their applications," *Current opinion in biotechnology*, vol. 13, no. 3, pp. 253–261, 2002.

[23] E. Blöchl, R. Rachel, S. Burggraf, D. Hafenbradl, H. W. Jannasch, and K. O. Stetter, "Pyrolobus fumarii, gen. and sp. nov., represents a novel group of archaea, extending the upper temperature limit for life to 113 c," *Extremophiles*, vol. 1, no. 1, pp. 14–21, 1997.

[24] J. Armstrong, R Barnes, S Domagal-Goldman, J Breiner, T. Quinn, and V. Meadows, "Effects of extreme obliquity variations on the habitability of exoplanets," *Astrobiology*, vol. 14, no. 4, pp. 277–291, 2014.

[25] D. Ferreira, J. Marshall, P. A. O'Gorman, and S. Seager, "Climate at high-obliquity," *Icarus*, vol. 243, pp. 236–248, 2014.

[26] J. Leconte, H. Wu, K. Menou, and N. Murray, "Asynchronous rotation of earth-mass planets in the habitable zone of lower-mass stars," *Science*, vol. 347, no. 6222, pp. 632–635, 2015.

[27] R. Barnes, "Tidal locking of habitable exoplanets," *Celestial mechanics and dynamical astronomy*, vol. 129, no. 4, pp. 509–536, 2017.

[28] J. E. Rodriguez, A. Vanderburg, S. Zieba, L. Kreidberg, C. V. Morley, J. D. Eastman, S. R. Kane, A. Spencer, S. N. Quinn, R. Cloutier, *et al.*, "The first habitable-zone earth-sized planet from tess. ii. spitzer confirms toi-700 d," *The Astronomical Journal*, vol. 160, no. 3, p. 117, 2020.

[29] R. Akeson, X Chen, D Ciardi, M Crane, J Good, M Harbut, E Jackson, S. Kane, A. Laity, S Leifer, *et al.*, "The nasa exoplanet archive: Data and tools for exoplanet research," *Publications of the Astronomical Society of the Pacific*, vol. 125, no. 930, p. 989, 2013.

[30] J. J. Lissauer, J. W. Barnes, and J. E. Chambers, "Obliquity variations of a moonless earth," *Icarus*, vol. 217, no. 1, pp. 77–87, 2012.

[31] S BIRKEL, "Climate reanalyzer," *URL: https://climatereanalyzer. org*, vol. 4, no. 6,