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Abstract English

The ultracool M dwarf TRAPPIST-1 hosts seven terrestrial exoplanetes. These exoplanets have orbits within 1 AU around the red dwarf and three of them are located in the system's habitable zone. These planets are excellent candidates for investigating different planetary climates at different distances from the central star. The aim of this thesis is to investigate the evolution of the pre-main sequence climates of these planets under varying CO_2 mixing ratios. The habitability of exoplanets during the PMS phase has not yet been investigated and is therefore an important aspect for habitability evolution of these planets. My thesis focuses on the outer planets of this system, from TRAPPIST-1e to TRAPPIST-1h, neglecting the innermost planets due to the high stellar irradiation they receive. The four TRAPPIST-1 planets atmospheres are simulated using the open source planet simulator PlaSim from the University of Hamburg. This 3D global circulation model of intermediate complexity allows me to investigate the climates of exoplanets in various aspects. I use a stellar luminosity model with a stellar mass of 0.09 $M_\odot$ and zero metallicity for these simulations. The simulations are done at 7 distinct times during TRAPPIST-1's first billion years of evolution. For these times the corresponding stellar model luminosities are recalculated into stellar constants for each of the seven four studied exoplanets. The simulation show that TRAPPIST-1e can have clement temperature spots even today at its equatorial region, if the atmosphere has at least a CO_2 mixing ratio of 100.000 ppm. During the PMS evolution all four investigated TRAPPIST-1 planets exhibit early habitability windows.

Abstract Deutsch

Der kühle Zwergstern TRAPPIST-1 beherbergt 7 terrestrische Exoplaneten. Diese Planeten umkreisen den roten Zwergstern innerhalb von 1 AE. Drei dieser Planeten befinden sich in der Habitablen Zone des Sterns. Die TRAPPIST-1 Planeten sind exzellente Kandidaten, um das Klima von Exoplaneten in verschiedenen Abständen vom Zentralgestirn zu untersuchen. Diese Arbeit verfolgt das Ziel, die Entwicklung des exoplanetaren Klimas während der Vor-Hauptreihe Phase mit verschiedenen CO_2 Werten der Atmosphäre zu untersuchen. Die Habitabilität von Exoplaneten während der Vor-Hauptreihe Phase wurde bisher noch nicht untersucht, sollte jedoch nicht vergessen werden, wenn es um Betrachtungen bezüglich der Habitabilität von Exoplaneten geht. Die Entwicklungen dieser Planeten in der frühen und heißen Phase des Systems, tragen maßgeblich dazu bei, ob es ein lebensfreundliches Klima geben kann. In dieser Arbeit liegt der Fokus auf den vier äußeren Planeten, angefangen bei TRAPPIST-1e bis zu TRAPPIST-1h. Die innersten Planeten dieses Systems wurden nicht in die Untersuchungen miteinbezogen, da sie heute noch sehr viel stellare Strahlung erhalten und für die hier durchgeführten Habitabilitätsbetrachtungen daher nicht infrage kommen. Um Klimatdaten der TRAPPIST-1 Exoplaneten zu simulieren, benutze ich den Planetensimulator *PlaSim*. Ein Open Source Projekt der Universität Hamburg. Mithilfe dieses 3D globalen Klimamodells, von mittlerer Komplexität, kann ich verschiedene Aspekte des Klimas auf den Planeten untersuchen. Um die Leuchtkraft von TRAPPIST-1 während der Vor-Hauptreihe in die Simulationen mit einfließen zu lassen, benutze ich ein Sternen-Leuchtkraft-Modell in Anlehnung an TRAPPIST-1. Die stellare Masse dieses Modells beträgt 0.09 $M_\odot$ und weist keine Metallizität auf. Die Simulationen wurden an sieben bestimmten Zeitpunkten während der ersten Milliarde Jahre der stellaren Entwicklung durchgeführt. Für diese Zeitpunkte wurde die Leuchtkraft von TRAPPIST-1 in stellare Konstanten der jeweiligen Planeten umgerechnet. Die Ergebnisse zeigen, dass auf TRAPPIST-1e, der in der Habitablen Zone liegt, auch heute noch im äquatorialen Bereich Gebiete mit gemäßigteren Temperaturen zu finden wären, sofern der atmosphärische CO_2 Gehalt mindestens 100.000 ppm beträgt. Meine Arbeit zeigt, dass während der Vor-Hauptreihe Phase alle vier TRAPPIST-1 Exoplaneten ein frühes Habitabilitäts-Fenster aufweisen und damit für einen bestimmten Zeitpunkt lebensfreundliche Temperaturen auf der Oberfläche vorhanden waren.

Chapter 1

Introduction

The aim of this thesis is to model the climates of the four outer TRAPPIST-1 exoplanets, TRAPPIST-1e , TRAPPIST-1f , TRAPPIST-1g and TRAPPIST-1h by using the planet simulator 'PlaSim'. In this thesis I am focusing on the pre-main sequence (PMS) evolution phase of the host star. During that time the habitable zone of TRAPPIST-1 was further away from the star compared to the present state of the system. The decreasing stellar luminosity during that time had major impacts on the climates of TRAPPIST-1 planets and consequently on their possibility to maintain surface conditions that allow the presence of liquid water. Cool M dwarfs are interesting hosts for habitable planets, but have an evolution different from solar-like stars. They have a very long PMS phase, during which the stellar luminosity decreases by up to two orders of magnitude. During that time the habitable zone (HZ) moves inwards, so that the outer planets that are outside the HZ during the main-sequence time, can have an early habitability window that has never been studied before. If life could have originated during this time, it could potentially be preserved under the ice shell once the planets leave the habitable zone. The pre-main sequence climates on exoplanets have not been studied before.
It is a difficult task to find an exoplanet with conditions similar to those of Earth. In Chapter 1 a brief look into exoplanet detection methods is given in Section 1.1. The properties and evolution of low mass M dwarfs and their pre-main-sequence evolution is discussed in Section 1.2. Section 1.3 describes the atmospheric properties and insights into exoplanetary climate research. Concluding this chapter the targets of this work, the TRAPPIST-1 star and its exoplanets are discussed in Section 1.4.

Chapter 2 describes the methods and models used in this thesis. Section 2.1 introduces the general circulation model, PlaSim. Hereinafter in Section 2.2 I present the stellar luminosity model used as an input for the climate simulations. I finish this chapter in Section 2.3 where the simulation specifications and the set-up are shown.

The results of the climate simulations for all four exoplanets are given in Chapter 3. Followed by a discussion on the reliability of these results as well as atmospheric escape estimates for these planets in Chapter 4. Concluding my whole work in Chapter 5 where I summarize and point out the major outcomes and further implications.

1.1 Exoplanets

An extrasolar planet, or exoplanet, is a planet which orbits a star other than the Sun. Finding other worlds where life could exist is a fascinating but challenging task. In 1992, Aleksander Wolszczan and Dale Frail (Wolszczan & Frail, 1992) discovered the first rocky exoplanet around the pulsar PSR B1 257+12 (in Virgo). Since then, more than 4000 planets orbiting different stars have been found. Today the *NASA Exoplanet Archive*[1] contains 4296 confirmed exoplanets (28th of November 2020). The catalog at *Exoplanet.eu*[2] contains 4371 exoplanets (28th of November 2020). Figure 1.1 shows a mass-radius distribution of all confirmed exoplanets. The radius-mass diagram of the found exoplanets contains a group of around 51 rocky exoplantes. The majority of known exoplanets have all been found within the last decade owing to the increased technical possibilities. Amongst the 4296 NASA planets, 2392 have been discovered by the Kepler Space Telescope [3] and so far 81 exoplanets have been discovered by Kepler's successor TESS [4]. These exoplanets range from Jupiter-sized to small Earth-sized planets. This work focuses on the planets in the TRAPPIST-1 system that are all rocky and similar in size and density to Earth or Mars.
Certain detection methods to find these far away, and compared to the central star tiny, object have been proven to be important tools in today's astronomy. The most common methods of detecting exoplanets are [5]:

- transit method (3269 exoplanets)
- radial velocity method (821 exoplanets)
- gravitational microlensing (101 exoplanets)
- direct imaging (51 exoplanets)

The most efficient and widely used detection method is the **transit method**, which by now found 3269 planets outside of our solar system. These planets got detected through small dips in the stellar light curve, caused by the decreased light shadowed by the planet's transit in front of the star. Figure 1.2 shows an example of these light curves for the TRAPPIST-1 planets from Delrez et al. (2018).

[1] exoplanetarchive.ipac.caltech.edu
[2] exoplanet.eu
[3] The Kepler Space Telescope was launched on 7.3.2009 and retired on 30.10.2018. One major task was to survey the Milky Way for Earth-sized exoplanets within or nearby the (mainly dwarf) stars habitable zones.
[4] The Transiting Exoplanet Survey Satellite, TESS, was launched on 18.4.2018 and is supposed to observe the sky for two years. It is using the transit method like Kepler, with an emphasis on much brighter and nearby stars.
[5] date: 28.11.2020, source: exoplanets.nasa.gov

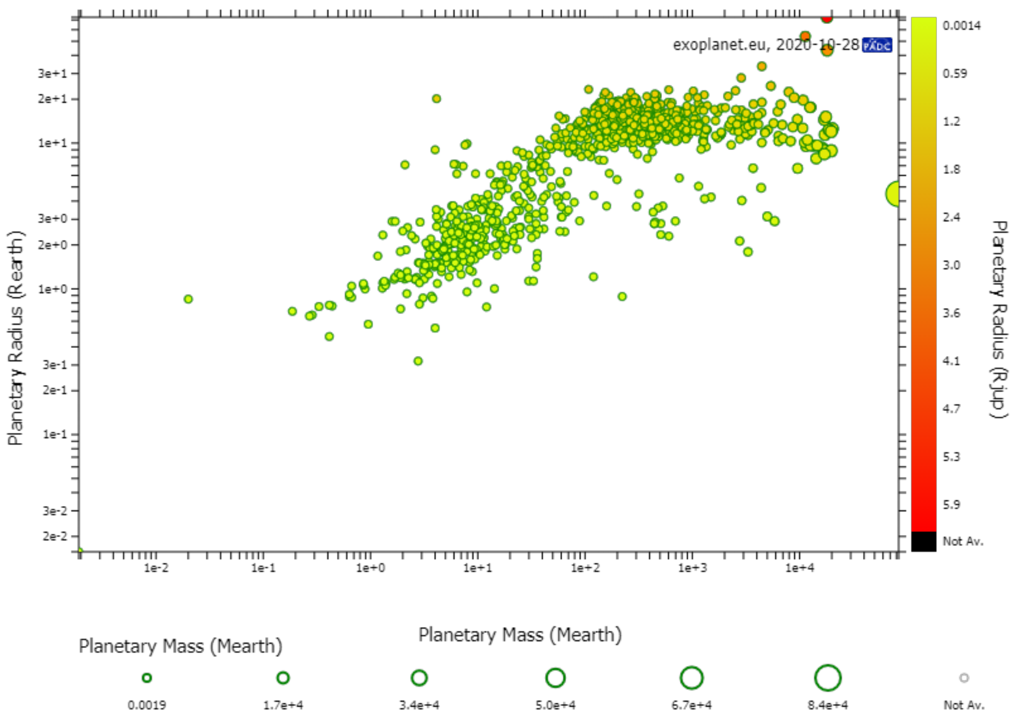

Figure 1.1: The mass-radius diagram of the found exoplanets, according to `exoplanet.eu`. The left lower tail is populated by rocky exoplanets.

Finding exoplanets using the **radial velocity method** (or Doppler spectroscopy) is also a profiting discovery method. The star and the planet are moving around the systems's common center of mass. This motion manifests as a Doppler shift in the stellar spectrum that is caused by the planet's motion. When the star is moving towards the observer the spectrum is blue shifted, and when the star is moving away a the spectrum is red shifted. A stellar companion (exoplanet or brown dwarf) causes a periodic shift in the spectra of stars. This method can further be used to determine the masses of planets.

The **gravitational microlensing effect** uses a background source (star) in alignment with some foreground object (planet) that is bending the light from the source due to its gravitational field while passing between the source and the Earth. In this way it leads to two distorted magnified images of the same source.

Making an **image** of an exoplanet can be done by shadowing or removing the overall dazzling of the star light to reveal the nearby planet(s). Usually this can just be done for planets far away from the star.

Last but not least the **transit timing variation** method. Here the variation of the timing of the exoplantes transit is measured. In systems with more than one planet, the planets

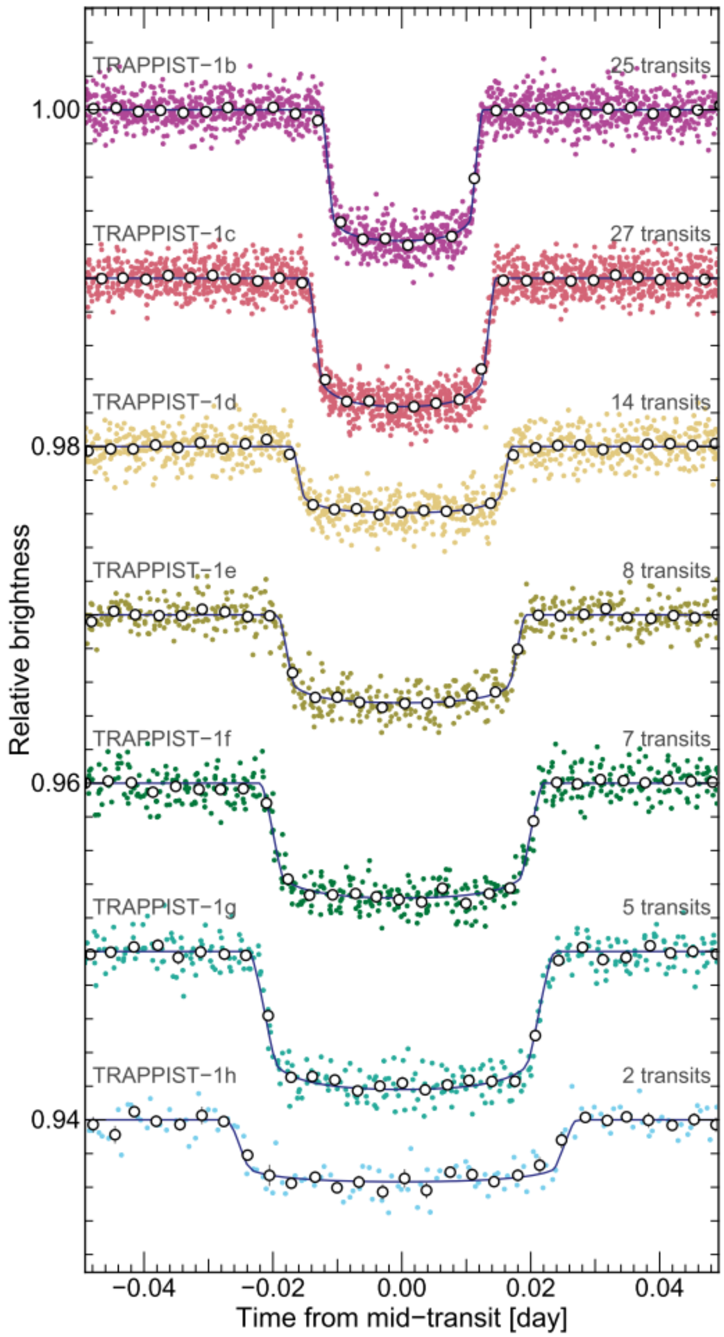

Figure 1.2: The light curves presented here are obtained by *Spitzer* at 4.5 μm. The lines are the best-fit transit models and the dots are the observations done. For further information see Delrez et al. (2018). One can see that during the transit the stellar light slightly decreases, caused by the shadowing of the transiting exoplanet in the line of sight.

exert a gravitational pull onto each other, causing deceleration or acceleration of their orbital motion. This causes a change in the planets orbital period. This method was used to determine the masses of TRAPPIST-1 planets (Grimm et al., 2018).

1.1.1 Habitability of terrestrial exoplanets

The growing number of discovered exoplanets and the improving technological progress makes target selection for further characterization and detailed studies of potential habitable worlds essential. It is crucial to refine the selection criterion of potential habitable worlds.

Habitable zone - The first and most easily applied characterization on exoplanets habitability is to define the "Habitable Zone" or "Goldylocks Zone". It is defined as the circumstellar orbital region in which the temperature on the planet's surface and pressure allow liquid water to exist on the surface of the planet (Kopparapu et al. 2013 & Kasting et al. 1993).

Orbital motion - In compact systems, where the planets are near the central star and thus the center of gravity, gravitational forcing of the planets orbiting the star might occur, leading the planets into 1:1 spin-orbit resonances and leading to planets being tidally locked. This means, that there is always the same side of the planet facing the star. The presence of multiple planets in near mean-motion resonance though can influence the mean-motion of a planets spin state through induced oscillations. In this way the spin state gets excited and the spin amplitude can be increased, which might lead to a increase of the illuminated area and therefore have major implications for the climate and the habitability of the planet Vinson & Hansen (2017). Vinson et al. (2019) examined the spin states of the TRAPPIST-1 exoplanets and showed that mutual interactions of the planets can cause non-synchronous planetary spin states. Hence the TRAPPIST-1 exoplanets are not necessarily tidally locked.

One can estimate the time TRAPPIST-1 planets needs to become tidally locked, τ_{sync}, according to the calculations done by Grießmeier et al. (2009):

$$\tau_{sync} \approx \frac{4}{9}\alpha Q'_p \left(\frac{R_p^3}{GM_p}\right)(\Omega_i - \Omega_f)\left(\frac{M_p}{M_*}\right)^2\left(\frac{d}{R_p}\right)^6 \quad (1.1)$$

In Eq. 1.1 τ_{sync} is the time a planet needs to be tidally locked, Q'_p is the tidal dissipation factor, Ω_i and Ω_f are the initial and final rotation rates, α is the structure parameter, R_p and M_p are the planet's radius and mass, R_* and M_* are the star's radius and mass, d is the semi-major axis, G is the gravitational constant and finally α is the structure parameter.

The parameter α describes the internal mass distribution within the planet, for Earth's it is given by $\alpha = 1/3$ (Goldreich & Soter, 1966). The tidal dissipation factor is assumed to equal 500 that is typical for small super-Earths and ocean planets (Grießmeier et al., 2009), like for the TRAPPIST-1 planets, which might be covered by oceans (Grimm et al., 2018). Although the initial rotation rates (Ω_i) are unknown, Grießmeier et al. (2009) are assuming an initial rotation rate according to early Earth of 4 hr ($\Omega_i = 5.86\Omega_\oplus$) and the final rotation rate (Ω_f) can be neglected according to (Grießmeier, 2006). The corresponding stellar and planetary physical values can be found in Sec. 1.4. The approximated time for the TRAPPIST-1 planets to become tidally locked ranges from 200 yr up to around 5 Myr. The approximations according to Eq. **??** can be found in Table 1.1.

TRAPPIST-1	b	c	d	e	f	g	h
τ_{sync} [yr]	2.04×10^2	1.65×10^3	8.97×10^3	7.67×10^4	3.17×10^5	9.60×10^5	4.82×10^6

Table 1.1: The approximated time the TRAPPIST-1 planets need to become tidally locked are listed here in years.

Due to interactions with other planets, in compact systems not only 1:1 resonance is possible Vinson et al. (2019), also other resonance such as 3:2 might occur for the TRAPPIST-1 exoplanets. The 3:2 resonance can be stable for some time and is more favorable for habitability.

Orbital eccentricity and tidal heating - In a circular orbit with no eccentricity (e=0) a more or less constant gravitational power is exerted onto the planet by the central star. In the case of more eccentric orbits the tidal forcings vary which causes tidal heating of the planets interior Luger et al. (2017). In this case, the orbital energy dissipates in the planets interior. In a two body system (star and planet) the orbital eccentricity decreases through the tidal dissipation and dissolve when the orbital motion is circular. In multiple planetary systems, where the planets are in mean motion resonances the periodic gravitational influence onto each other preserves non-zero eccentricities (Barr et al., 2018). In this way the interior of the TRAPPIST-1 planets can be tidally heated. This might trigger volcanic activity on the planets and thus refill their atmospheres.

Axial tilt or planetary obliquity - The tilt of a planets rotation axis can also have implications on the climate of a planet. On Earth the axial tilt causes seasoning through varying the solar insolation angle onto the surface. At the moment, it is not possible to determine the obliquities of exoplanets. Heller et al. (2011) modeled the obliquity evolution of terrestrial planets in the habitable zone of low-mass stars, concluding that the obliquity of these planets will be damped within 0.1 Gyr and that during this time, tidal heating due to obliquity tides plays a role. Due to the fact that we do not have information on the obliquities of the TRAPPIST-1 planets, zero obliquities for all of them are assumed in this study.

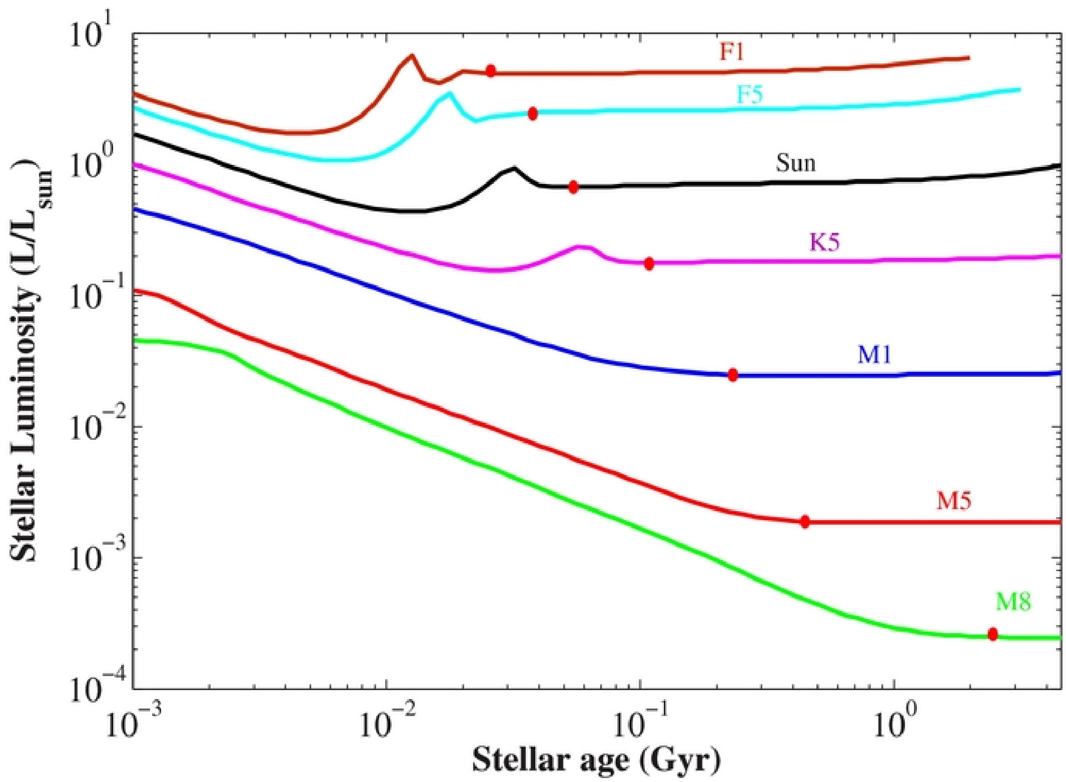

Figure 1.3: Evolution of the bolometric luminosity for stars of different spectral classes (Ramirez & Kaltenegger, 2014).

1.2 Habitability of planets orbiting M dwarfs

1.2.1 The pre-main sequence evolution phase of the host star

The pre-main-sequence evolution phase of a very low mass red dwarf star (such as TRAPPIST-1) lasts around 1 Gyr. During the PMS phase, the star is contracting and the luminosity is steadily decreasing before the full ignition of the nuclear burning process. Figure 1.3 shows the different evolutionary tracks for various stellar types. The red dot marks the entry onto the main sequence. One can see that solar-type stars (black line) have a very short PMS phase, while stars like TRAPPIST-1 (green line) evolve slowly (Ramirez & Kaltenegger, 2014). In the case of a low mass M dwarf such as TRAPPIST-1 of class M8, the decrease in the luminosity can be up to two orders of magnitude which has tremendous implications for the climates of planets orbiting such stars. This leads to a shrinking of the habitable zone around the star. The evolution of the stellar luminosity and the habitable zone have tremendous implications for the habitability of planets orbiting low-mass M dwarfs. Figure 1.4 shows the time dependent distance of the habitable zone of the model. The habitable zone boundaries are calculated after Kopparapu et al. (2013). The inner edge is assumed to be the Venus boundary and the outer edge the Early Mars boundary.

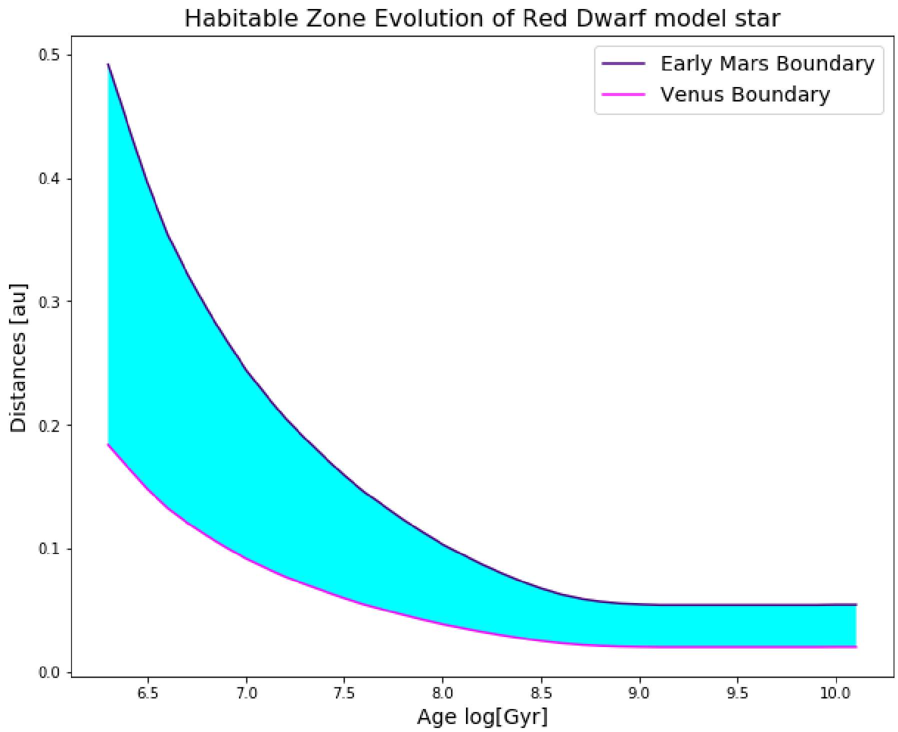

Figure 1.4: The evolution of the habitable zone according to Kopparapu et al. (2013). The inner and outer limits of the habitable zone are calculated by using Venus and Early Mars as reference values, marked with a solid line, respectively.

1.3 Planetary atmospheres

In our solar system we find promising targets for examining planetary atmospheres. Having a look on Venus's very dense atmosphere reveals a composition dominated by 96% Carbon dioxide (CO_2) and 3% nitrogen (N_2) . The surface pressure on Venus is 9.3 MPa. On the other hand there is Mars atmosphere, which is tenuous compared to Venus and Earth. Mars atmosphere is also dominated by a huge amount (95%) of CO_2. In addition there is also 3% N_2 and 2% Argon (Ar) present. Unlike Venus, Mars surface pressure is with 610 Pa (around 1% of Earth pressure) very low. Both planets do not support the presence of liquid water on the surface, but offering a range to examine different atmospheres (Unsöld & Baschek, 2004).

By now the best studied planetary atmosphere is the Earth's atmosphere. Its layered composition can be seen in Figure 1.5 [6]. The here illustrated layers contribute to an Earth that is supporting life as we know it. The composition of the whole atmosphere is influencing the planetary climate. Earth's atmosphere is composed of 78% N_2, 21% oxygen

[6] https://planetary.s3.amazonaws.com/assets/images/charts-diagrams/2016/20160412_5_atmospherestatic.png, date: 9.3.2020

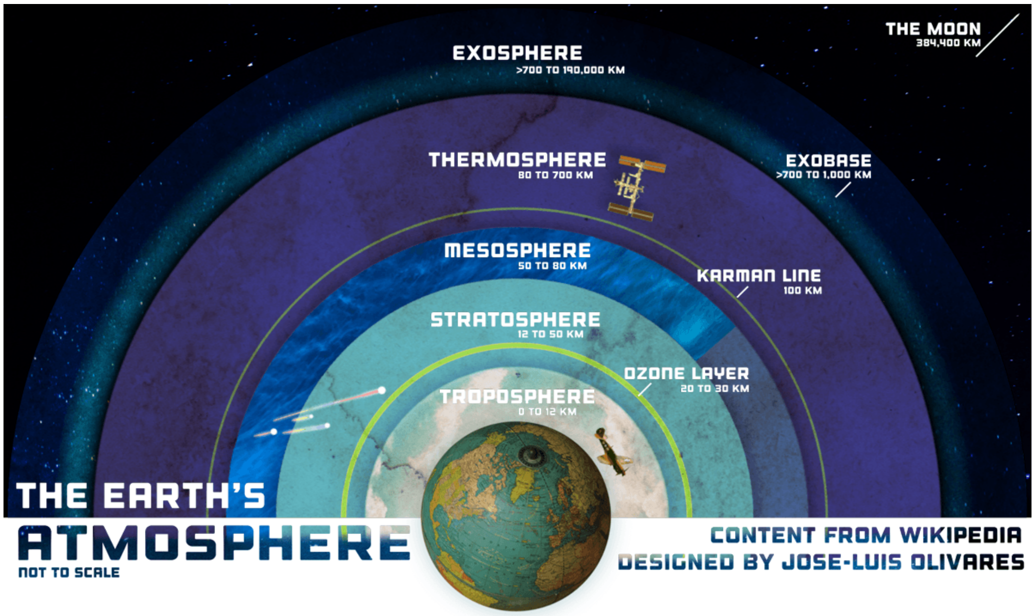

Figure 1.5: The schematic view on the layers of Earth's atmosphere.

(O_2) and 0.9% Ar, also some aerosols and trace gases (Unsöld & Baschek, 2004). CO_2 is an important greenhouse gas, supporting the favourable temperatures on Earth for living organisms. Currently [7] the CO_2 mixing ratio of Earth is 415 ppm according to the World Meteorological Organization. The weather is mainly produced in the bottom layer, the Troposphere. Here the opacity of the atmosphere and consequently the amount of stellar radiation reaching through, are important to know, as well as the water vapour content and the occurrence of seasons, when examining a plant's habitability. The simulations done in this thesis are focusing on this layer of the TRAPPIST-1 exoplanets.

1.3.1 Atmospheres and climates on TRAPPIST-1 planets

Not much is known about the presence or nature of the atmospheres of the TRAPPIST-1 planets so far. Several studies have tried to simulate their present day's atmospheres. Hori & Ogihara (2020) say it is unlikely that the TRAPPIST-1 planets have hydorgen-dominated atmospheres. Lincowski et al. (2018a) and Lincowski et al. (2018b) simulated the climate of the TRAPPIST-1 exoplanets assuming various climate scenarios. They tested water-depleted O_2- and CO_2 -dominated atmospheres, Venus-like scenarios, and moist Earht-like environments. Lincowski et al. (2018a,b) have shown that the climate is sensitive to the presence and amount of trace species in the atmospheres, even if the amount of stellar radiation is kept the same. The atmospheric conditions are mainly determining the planet's climate. The orbital distance also takes part in shaping a planet's climate. The atmospheric escape of H_2O is found to be a function of the stellar irradiation and the time spend within the inner edge of the HZ. The extensive loss of water

[7] date: 25.11.2019

(even beyond the outer boundary of the HZ) leads to an accumulation of dense O_2 atmospheres due to water photodissociation. According to (Turbet et al., 2018) an atmosphere, composed of O_2, N_2 or CO, might be resistant against atmospheric collapse. Hu et al. (2020) says that TRAPPIST-1 planets could have O_2 and CO_2-dominated atmospheres.

The studies from Peacock et al. (2019) simulated the impact of the M8 star's radiation on the atmospheres of the habitable zone planets around it. They found that the simulated XUV flux is high enough to erode oceans as well as atmospheres in a time-span of a few billion years. Also their simulated EUV and the observed Xray fluxes indicated high mass loss rates, which makes it unlikely that the exoplantes in the HZ around TRAPPIST-1 are still harbouring liquid water. Observations done by Bourrier et al. (2017) indicate a lack of liquid water on TRAPPIST-1 exoplanets. They observed the star's Ly-α line during a transit of TRAPPIST-1c which leads to the conclusion that the planets b to g could have lost up to 20 Earth oceans caused by hydrodynamic loss. The innermost planets b, c and eventually d might be still in a runaway phase. Some planets of the system could have potentially retained some water (Menou, 2013). However, X-ray and UV observations of TRAPPIST-1 indicate that even outer planets receive an XUV flux much larger than that of the Earth (Wheatley et al., 2017; Fleming et al., 2020). This makes the studies on the PMS climates especially important. One can speculate that once the life has originated on the outer planets, it can survive underneath an ice shell once the planets leave the habitable zone. A tick ice shell can also protect the life from strong UV radiation of TRAPPIST-1 (O'Malley-James & Kaltenegger, 2017).

1.4 TRAPPIST-1

The ultracool M8 star TRAPPIST-1 (2MASS J23062928-0502285) is around 12 pc away from the sun (Gillon et al., 2016, 2017; Kirkpatrick et al., 1995). This M dwarf has a radius of approxiately 0.121 $R_\odot$ and a mass of 0.089 $M_\odot$ (Delrez et al., 2018; de Wit et al., 2016). The inferred age of the M dwarf is approximated to be between 3 and 8 Gyr (Luger et al., 2017; Burgasser & Mamajek, 2017). Simulations on the interior structure and compositional models for the seven TRAPPIST-1 exoplanets carried out by Barr et al. (2018) and Dobos et al. (2019) indicate that very likely the interior structures found include a significant amount of H_2O in the planetary composition. The TRAPPIST-1 system is very compact, which implies that the tidal interactions are strong. Gillon et al. (2016) reasons, that these planets are probably tidally locked, so their rotations are synchronized to their orbits (see discussion in Sec. 1.1 about possible rotation periods of the planets). The most up-to-date data of the TRAPPIST-1 planets are collected in Table 1.2.

TRAPPIST-1b

The innermost planet of the TRAPPIST-1 system shows an interior structure containing at least 0.2% of H_2O by volume and these simulations further show, that up to 70%

	b	c	d	e	f	g	h
Mass	1.017 $M_\oplus$	1.156 $M_\oplus$	0.297 $M_\oplus$	0.772 $M_\oplus$	0.934 $M_\oplus$	0.148 $M_\oplus$	0.331 $M_\oplus$
Radius	1.127 $R_\oplus$	1.1 $R_\oplus$	0.788 $R_\oplus$	0.91 $R_\oplus$	1.052 $R_\oplus$	1.154 $R_\oplus$	0.777 $R_\oplus$
Density	0.726 $\rho_\oplus$	0.883 $\rho_\oplus$	0.616 $\rho_\oplus$	1.024 $\rho_\oplus$	0.816 $\rho_\oplus$	0.759 $\rho_\oplus$	0.719 $\rho_\oplus$
Period	1.51 d	2.42 d	4.05 d	6.10 d	9.21 d	12.36 d	18.77 d
T_{eff}	391.8 K	334.8 K	282.1 K	246.1 K	214.5 K	194.5 K	169.2 K
Surface gravity	0.812 $g_\oplus$	0.966 $g_\oplus$	0.483 $g_\oplus$	0.93 $g_\oplus$	0.853 $g_\oplus$	0.871 $g_\oplus$	0.555 $g_\oplus$
Irradiation	3.88 $S_\oplus$	2.07 $S_\oplus$	1.043 $S_\oplus$	0.604 $S_\oplus$	0.349 $S_\oplus$	0.236 $S_\oplus$	0.135 $S_\oplus$
Semi-major axis [10^{-3} AU]	11.548 AU	15.815 AU	22.280 AU	29.283 AU	38.534 AU	46.877 AU	61.935 AU

Table 1.2: The masses, densities, surface gravities and semi-major axes are taken from Grimm et al. (2018). The radii, orbital periods, effective temperatures and the irradiation are from Delrez et al. (2018).

of water might be present despite its proximity to the central star (Dobos et al., 2019). Kislyakova et al. (2017) shows that the densities are in agreement with a rocky composition. Grimm et al. (2018) show with their improved mass and density calculations, that TRAPPIST-1b needs to have a volatile envelope (thick atmospheres, oceans or ice). Further they found that TRAPPIST-1b is the only planet of the system, that is above the runaway greenhouse limit.

TRAPPIST-1c

It is likely that TRAPPIST-1c has a large rocky interior according to simulation done by Grimm et al. (2018). Bourrier et al. (2017) conclude through their Ly-α observations, that TRAPPIST-1c does not have an hydrogen-dominated atmosphere. Spectroscopic observations show no hints of hydrogen dominated atmospheres for TRAPPIST-1c and TRAPPIST-1b (de Wit et al., 2016).

TRAPPIST-1d

The interior structure simulations done by Dobos et al. (2019) show a volume fraction of water of at least 0.25 for TRAPPIST-1d. This result was obtained assuming a Bond albedo $\geqslant 0.3$ (also used for the simulations done by de Wit et al. (2018)) [8], which might be caused by a thick reflective cloudy atmosphere. In this case, the calculated total heat flux from tidal heating and insolation is below its runaway greenhouse limit of $\sim 273.2\ W/m^2$, and the planet could avoid getting in a runaway greenhouse state and be harbouring liquid water at the substellar point, assuming it is tidally locked in a 1:1 spin-orbit resonance (Turbet et al., 2018). As well as TRAPPIST-1b also TRAPPIST-1d needs a volatile envelope to avoid a runaway greenhouse effect (Grimm et al., 2018) and further more, Grimm et al. (2018) conclude that it is not likely that the planet has an atmosphere enriched in volatiles. de Wit et al. (2016)'s spectroscopic observations on the TRAPPIST-1 exoplanets excludes the presence of cloud free, hydrogen dominated atmospheres for TRAPPIST-1d

[8] Bond albedo of Earth = 0.306 for comparison

to TRAPPIST-1f.

TRAPPIST-1e

TRAPPIST-1e is the innermost planet in today's habitable zone of TRAPPIST-1. A habitable atmosphere for TRAPPIST-1e might be possible, according to the simulations carried out by Lincowski et al. (2018b), in an aqua-planet setting with an Earth-like geological outgassing and CO_2 content. Grimm et al. (2018) obtained updated mass and density measurements of the TRAPPIST-1 planets. They conclude that TRAPPIST-1e likely has a rocky interior and that it is very unlikely that the planet has a CO_2 enriched atmosphere above the bare core. According to modeling done by Barr et al. (2018), TRAPPIST-1e's surface might be covered in a solid ice layer. They further conclude that the density of TRAPPIST-1e would allow the presence of H_2O.
Simulations done by Turbet et al. (2018) show that although a large fraction of the planet's surface is frozen, liquid water is still possible at the substellar point. Greenhouse warming can take place through H_2O gas and no other gas is necessary to sustain liquid water on the surface (Turbet et al., 2018). The stellar irradiation at the orbit of TRAPPIST-1e should be sufficient to have substellar water in the so-called "eyeball regime"[9]. Amongst all TRAPPIST-1 exoplanets and through various simulation settings they where modelling, TRAPPIST-1e is the only one potentially having liquid water. They also show through there N-body simulations, that for the inner planets up to TRAPPIST-1e , tidal heating is the main process of internal heating. Furthermore, if there is a stable CO_2 atmosphere existing on TRAPPIST-1e , it has to be very thick. According to Bolmont et al. (2016) TRAPPIST-1e has lost several Earth oceans during the PMS phase, but if the initial water reservoir exceeded than of current Earth water might still be abundant today.

TRAPPIST-1f

TRAPPIST-1f lies within the habitable zone of the TRAPPIST-1 system, although its effective temperature (see Table 1.2) is already cooled below the freezing point of water. It might be that on TRAPPIST-1f as well as on the two farther outer planets TRAPPIST-1g and TRAPPIST-1h an ice layer covers the planets surface on top of an underneath ocean, similar to the Galilean moon Europa. Active volcanism and plate tectonics are contributing to the habitability of such ocean worlds Noack et al. (2014). The comparable planetary mass of around Earth mass might be in favor for geological processes and therefore its habitability, according to Noack et al. (2016), who found, that the geological activity ceases with increasing planetary mass and water layer thickness. Despite the current cool temperature, life could have originated while the planet's temperature have been warmer. It could have sustained below a the froozen surface. Simulations from Lincowski et al. (2018b) show that TRAPPIST-1f's atmosphere has not an Earth-like composition and that it would require an atmosphere dominated by CO_2 (Turbet et al., 2018) for liquid surface water.

[9]the substellar point, that is receiving the most energy

TRAPPIST-1g

The least massive of the TRAPPIST-1 planets is TRAPPIST-1g. Already at the outer cooler edge of the habitable zone, the current surface is very likely frozen by now. This might on the one hand be in favor for the water amount preserved on the surface. According to (Lincowski et al., 2018b) loss of planetary water is a function of instellation and time spend beyond the inner edge of the habitable zone. After planets entered the habitable zone, the loss of water decreased. This might be in favor for the outer planets, to help preserve their H_2O. On the other hand, Noack et al. (2016) conclude that a frozen surface might not be in favor for habitability than a liquid surface ocean would. As for TRAPPIST-1f also TRAPPIST-1g is unlikely to have an Earth-like atmosphere and is supposed to have a CO_2 dominated atmosphere (Lincowski et al., 2018b).

TRAPPIST-1h

The outermost and coolest planet of the TRAPPIST-1 system is also the one, that suffered the least on water loss through impacts, according to Kral et al. (2018). They found that the further away the planet was from the center of the system, the smaller amount of water is lost due to impacts. Which might also be in favor for TRAPPIST-1g and TRAPPIST-1f. The volatiles delivered through impacts on TRAPPIST-1h would condense to ice on the surface. Lincowski et al. (2018b) show that if a dense CO_2 atmosphere does form subsequent to an early runaway greenhouse phase, habitable or hotter surface temperatures might occur even outside of the habitable zone's outer edge.

Despite the fact that the outer TRAPPIST-1 exoplanets today are too cool to be considered habitable, they have experienced warmer periods during the PMS phase. This improves their chances for habitability then and now and makes them unique targets for the study of pre-main sequence climates and their evolutions.

Chapter 2

Methods

This chapter presents the methods used for this work starting with an overview on the Planet Simulator, PlaSim in Section 2.1. Section 2.2 presents the model of the PMS luminosity adopted for TRAPPIST-1. In Section 2.3 all necessary setups are shown. Plasim allows the user to modify the physical as well as the numerical parameters. At the end of this section, I summarize the paramteres selected for the Planet Simulator.

2.1 The climate model

The open source "Planet Simulator" PlaSim is a global circulation model (GCM) published by the University of Hamburg in 2005[1]. PlaSim is a 3D model of intermediate complexity designed to run climate simulations for Earth, Mars and earth-like exoplanets. Through coupling interfaces the user can add further models, such as ocean models, ice models and vegetation (Fraedrich et al., 2005a).

PlaSim's dynamical core is adopted from PUMA, *the Portable University Model of the Atmosphere*, presented in Fraedrich et al. (2005b). The dynamical core is based on the moist primitive equations, like the conservation of momentum, mass and energy. A few dimensionless equations like the prognostic equations for the vertical component of the vorticity and the horizontal divergence, the first law of thermodynamics, the equation of state (with hydrostatic approximation), the continuity equation and the prognostic equation for water vapour (specific humidity) are also used in PlaSim.

Next to the medium complex general circulation model of the atmosphere, the Planet Simulator incorporates different parts that interact with the climate system, as the ocean with sea ice or a land surface including a biosphere. These additional modules are simplified to linear systems, which parameterise for example the ocean module given in

[1] https://www.mi.uni-hamburg.de/en/arbeitsgruppen/theoretische-meteorologie/modelle/plasim.html

terms of a mixed layer energy balance. For my simulations I used the mixed layer ocean module, which consists of a prognostic equation as well as sea ice layer model both described in Fraedrich et al. (2005a).

2.2 The model of the star's luminosity

To approximate the early evolution of TRAPPIST-1 luminosity, I have used a model by Baraffe et al. (1998) [2] for the stellar mass of 0.09 $M_\odot$ and zero metallicity. The measured mass and metallicity of TRAPPIST-1 are 0.089 $M_\odot$ and 0.04 $\pm$0.08 (Gillon et al., 2017), respectively, but the chosen model closely approximates the evolution of TRAPPIST-1. Table 2.1 summarizes the evolution of the effective temperature and the absolute magnitude of TRAPPIST-1 as well as the calculated luminosity. I calculated the luminosities from the absolute magnitudes using the following relation:

$$L_* = L_0 \times 10^{-0.4Mbol} \tag{2.1}$$

Here the stellar luminosity (L_*) is in units [W] and is calculated based on the zero-point luminosity (L_0). [3] The corresponding evolution track for the 0.09 $M_\odot$ dwarf star can be seen in Fig. 2.1.

PlaSim uses the stellar flux on top of the atmosphere, the so-called 'stellar constants' for the climate simulations as an input parameter. These stellar constants are in units of [W/m^2]. The stellar constants for each planet can be found from the luminosity as

$$I_* = \frac{L_*}{4\pi k d^2} \tag{2.2}$$

Here, I_* is the stellar constant on top of the atmosphere in [W/m^2], d is the orbital distance of a planet, and k is a constant that is used to account for the eccentricity of the orbit. In my simulations, I set k=1 [4] which corresponds to an orbit with zero eccentricity.

2.3 Simulations setup

2.3.1 Choice of simulation parameters and specific setups

For all the Trappist-1 planets I assume zero eccentricity and obliquity in all simulations (Turbet et al., 2018). The obliquities of the TRAPPIST-1 exoplanets are unknown. The most up-to-date physical parameters of the planets were adopted from Grimm et al. (2018) and Delrez et al. (2018) and were presented in Sec. 1.4.

[2] http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/337/403 ViziR is a library containing published astronomical catalogues and data tables.

[3] Zero-point luminosity is the luminosity of a star with $M_{bol} = 0$.

[4] k is a constant and it should allow for the orbit to be not exactly circular and that there is some distant variation. For simplicity k is set to exactly 1

Age [Gyr]	T_{eff} [K]	M_{bol} [mag]	Luminosity [W]
0.002	2974	7.98	$1.9363*10^{25}$
0.00253	2991	8.21	$1.5666*10^{25}$
0.00317	3006	8.45	$1.2559*10^{25}$
0.00402	3021	8.69	$1.0069*10^{25}$
0.00505	3042	8.89	$8.3747*10^{24}$
0.00636	3055	9.09	$6.9658*10^{24}$
0.00803	3058	9.29	$5.7939*10^{24}$
0.01007	3059	9.49	$4.8191*10^{24}$
0.01272	3058	9.68	$4.0455*10^{24}$
0.01596	3058	9.87	$3.3960*10^{24}$
0.02012	3058	10.05	$2.8772*10^{24}$
0.02548	3054	10.24	$2.4153*10^{24}$
0.03193	3043	10.43	$2.0275*10^{24}$
0.04022	3030	10.62	$1.7020*10^{24}$
0.05012	3015	10.79	$1.4554*10^{24}$
0.06367	2996	10.99	$1.2105*10^{24}$
0.07992	2971	11.18	$1.0162*10^{24}$
0.10086	2946	11.38	$8.4522*10^{23}$
0.1279	2919	11.57	$7.0953*10^{23}$
0.16004	2890	11.76	$5.9562*10^{23}$
0.20189	2853	11.95	$5.0000*10^{23}$
0.25334	2814	12.14	$4.1973*10^{23}$
0.31783	2773	12.32	$3.5561*10^{23}$
0.40455	2730	12.49	$3.0407*10^{23}$
0.51504	2695	12.62	$2.6976*10^{23}$
0.63374	2672	12.7	$2.5059*10^{23}$
0.80397	2654	12.76	$2.3712*10^{23}$
1.02137	2645	12.79	$2.3066*10^{23}$
1.27488	2641	12.81	$2.2645*10^{23}$
1.59176	2640	12.81	$2.2645*10^{23}$
2.0037	2639	12.81	$2.2645*10^{23}$
2.5424	2640	12.81	$2.2645*10^{23}$
3.17616	2640	12.81	$2.2645*10^{23}$
4.00005	2640	12.81	$2.2645*10^{23}$
5.01407	2641	12.81	$2.2645*10^{23}$
6.31328	2641	12.81	$2.2645*10^{23}$
7.96106	2642	12.81	$2.2645*10^{23}$
10.0208	2642	12.8	$2.2854*10^{23}$
12.6192	2643	12.8	$2.2854*10^{23}$

Table 2.1: Parameters of TRAPPIST-1 adopted for simulations following the model by Baraffe et al. (1998).

Age [Gyr]	TRAPPIST-1e [W/m^2]	TRAPPIST-1f [W/m^2]	TRAPPIST-1g [W/m^2]	Trappist-1h [W/m^2]
0.002	80294.0	46369.3	31332.2	17948.9
0.00253	64965.5	37517.2	25350.8	14522.4
0.00317	52081.4	30076.7	20323.2	11642.3
0.00402	41752.5	24111.8	16292.6	9333.4
0.00505	34728.3	20055.3	13551.6	7763.2
0.00636	28885.7	16681.3	11271.8	6457.1
0.00803	24026.1	13874.9	9375.4	5370.8
0.01007	19984.0	11540.6	7798.1	4467.2
0.01272	16775.8	9687.9	6546.2	3750.1
0.01596	14082.6	8132.6	5495.3	3148.0
0.02012	11931.2	6890.2	4655.8	2667.1
0.02548	10015.7	5784.0	3908.3	2238.9
0.03193	8407.8	4855.5	3280.9	1879.5
0.04022	7058.0	4076.0	2754.2	1577.8
0.05012	6035.1	3485.2	2355.0	**1349.1**
0.06367	5019.8	2898.9	1958.8	**1122.1**
0.07992	4213.9	2433.5	**1644.3**	**942.0**
0.10086	3505.0	2024.1	**1367.7**	**783.5**
0.1279	2942.3	**1699.1**	**1148.1**	657.7
0.16004	2469.9	**1426.4**	963.8	**552.1**
0.20189	2073.4	1197.4	**809.1**	463.5
0.25334	**1740.5**	**1005.1**	679.2	**389.1**
0.31783	**1474.6**	851.6	**575.4**	329.6
0.40455	**1260.9**	**728.2**	492.0	281.9
0.51504	**1118.6**	646.0	**436.5**	250.1
0.63374	1039.2	**600.1**	405.5	232.3
0.80397	**983.3**	567.8	383.7	219.8
1.02137	956.5	552.4	373.2	213.8
1.27488	939.0	542.3	366.4	209.9
1.59176	939.0	542.3	366.4	209.9
2.0037	939.0	542.3	366.4	209.9
2.5424	939.0	542.3	366.4	209.9
3.17616	939.0	542.3	366.4	209.9
4.00005	939.0	542.3	366.4	209.9
5.01407	939.0	542.3	366.4	209.9
6.31328	939.0	542.3	366.4	209.9
7.96106	**939.0**	**542.3**	**366.4**	**209.9**
10.0208	947.7	547.3	369.8	211.9
12.6192	947.7	547.3	369.8	211.9

Table 2.2: Stellar constants for the TRAPPIST-1 planets. Decreasing stellar luminosity leads to decreases in the incident fluxes on top of the atmospheres.

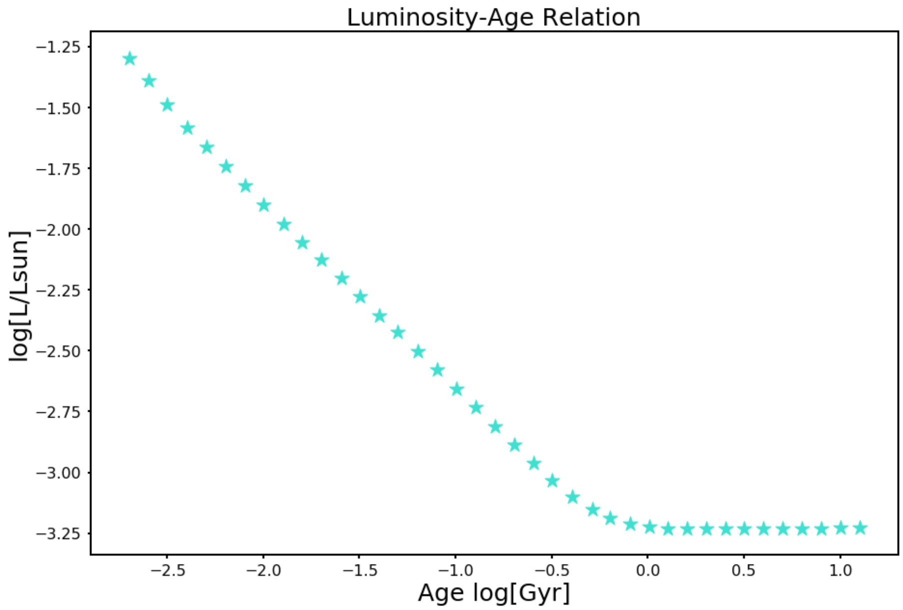

Figure 2.1: The evolution of the luminosity of a 0.09 $M_\odot$dwarf scaled to the luminosity of today's Sun . After approximately one gigayear the star reaches the main sequence and the decrease in luminosity stops. Model is taken from Baraffe et al. (1998).

The length of the stellar and sidereal days for the TRAPPIST-1 planets are calculated assuming a 3:2 spin-orbit resonance[5]. Although the TRAPPIST-1 planets are likely tidally locked, due to the model limitations we assumed the periods corresponding to 3:2 orbital resonances. Such an assumption seems reasonable since the planets are not locked into 1:1 resonance immediately after their formation. Instead, they can be locked in a sequence of meta-stable resonances such as 5:2, 3:2, 1:2, etc. Besides that, in multi-planet systems, other planets might support other resonances than 1:1 as is the case for Mercury in the solar system. Detailed numerical simulations confirm that the spin states of TRAPPIST-1 planets may be chaotic and variable in time (Vinson et al., 2019).

The stellar constants used in my simulations are summarized in Table 2.2. I have marked the cases I have chosen for detailed simulations with bold font. Since PlaSim was designed to model moderate planets, I could only simulate the cases with stellar constants similar to the one of the Earth and lower, which is appropriate for studying the habitability of these planets. It can be seen in Table 2.2 that the time span analyzed in this work starts at an age of around 500 million years and ends at around 1 billion years (around the end of the PMS lifetime). I have chosen the simulation times to cover a large range of stellar constants.

For each age, I have simulated several CO_2 mixing ratios: 360 ppm, 10.000 ppm

[5]In a 3:2 spin-orbit resonance the planet rotates three times around its axis while orbiting two times around the central star.

	orbital period *[days]*	spin (3:2) *[days]*	Duration of the simulations *[Trappist-1 years]*
TRAPPIST-1e	6.1	9.2	$\approx$ 2950
TRAPPIST-1f	9.2	13.8	$\approx$ 1957
TRAPPIST-1g	12.4	18.4	$\approx$ 1452
TRAPPIST-1h	18.8	28.2	$\approx$ 958

Table 2.3: Assumed planetary rotation period given in Earth's days used for the simulations, according to the selected 3:2 spin-orbit resonance. The third column shows the number of years of a specific planet corresponding to 50 years of the Earth.

(1% of the atmosphere) and finally 100.000 ppm CO_2 (10% of the atmosphere). Apart from the CO_2 mixing ratios the assumed compositions of the atmospheres have been identical to the Earth's atmosphere. The atmospheric pressure in all these simulations has been set to 1 bar (100.000 Pa). I have simulated the climates for 50 Earth years, which corresponds to values ranging from several hundred to several thousand years of TRAPPIST-1 planets (see Table 2.3). The day corresponded to the solar day, which is given by the orbital period (assumed in the 3:2 resonance) of each Trappist-1 exoplanet. The adopted planetary orbital periods corresponding to the 3:2 spin-orbit resonance can be found in Table 2.3.

Chapter 3

Results

3.1 Evolution of surface temperatures of TRAPPIST-1 planets during the pre-main-sequence evolution phase

Since I was primarily interested in the pre-MS habitability of the TRAPPIST-1 planets, I calculated the surface average temperatures for the ages and CO_2 mixing ratios described above in 2.1. The surface temperatures are given for each monthly time step (50 years simulation) at 32 latitudes and 64 longitudes around the globe. All temperatures referred hereinafter are the global weighted average surface temperatures, unless explicitly mentioned. The averages were calculated taking into account the coverage area of every latitude [1]. Equation 3.1 describes the calculation of the average temperature. The y is assigned to be the latitude (in radiant) and x is the longitude (in radian). All temperature results are averaged following:

$$\cos y = \frac{\sum_{x,y} T(x,y)\cos y}{\sum_{x,y} \cos y} \tag{3.1}$$

For TRAPPIST-1e and TRAPPIST-1f I chose six distinct ages during their PMS evolution. The two outer planets TRAPPIST-1g and TRAPPIST-1h have been simulated for seven different ages, respectively. In Figure 3.1 I show the surface temperature plot for TRAPPIST-1e in a setting with 360 ppm CO_2 as an example. This shows the whole 50 years of simulation time and the evolution to a stable temperature. Each coloured line marks a different stellar constant, which denotes a certain age of TRAPPIST-1 . One can easily see that the simulations reach a steady state after approximately 50 month of simulation. These initial parts of the simulations are therefore not feasible for averaging over to whole time span to get a global temperature, because it would inappropriately alter the temperature results. Therefore, all figures starting from Figure 3.3, respectively

[1] the weighting factors account for the latitude circles covering different areas at the poles than at the equator

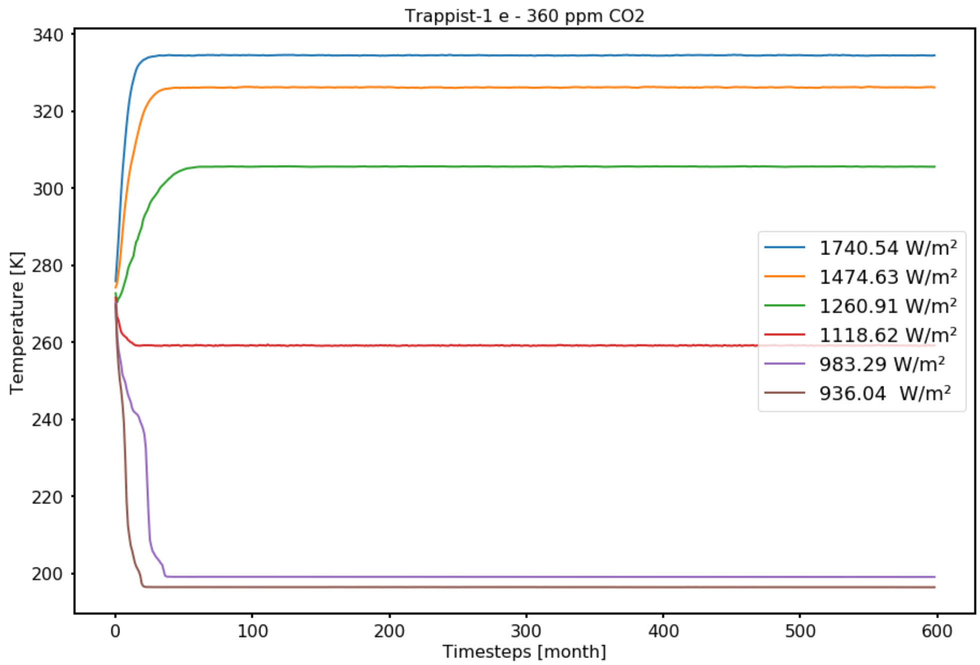

Figure 3.1: Averaged surface temperatures for TRAPPIST-1e assuming 360 ppm CO_2 for different stellar constants.

for the other planets, show the simulations after they have reached the steady state. For each PMS time step (colored lines) the surface temperature, averaged over the remaining simulation time is shown, as well as the corresponding ages taken from the model (Table 3.1).

For a better visualisation of the results, the surface temperature maps shown in Figures 3.4, 3.7, 3.10 and 3.13 are plotted at the end of the simulations at 600 month (after 50 years in a stable state). The trend towards cooler temperatures can be easily seen, from the upper left map to the lower right one image, starting at 0.25 Gyr up to 1.27 Gyr. Notice that each column denotes a different CO_2 mixing ratio.

3.1.1 Comparing the evolution of all four planets

In Figure 3.2 I compare the temperature evolution of all four exoplanets. The solid lines mark the 360 ppm CO_2 , the dashed lines the 10.000 ppm CO_2 and the dotted lines the 100.000 ppm CO_2 mixing ratio, respectively. It is not surprising that the surface temperatures are warmer for higher CO_2 mixing ratios. The simulations of TRAPPIST-1e (green) show the warmest temperatures and also the largest surface temperature variations between the different CO_2 contents. TRAPPIST-1e is also more sensitive to variations in the irradiation than the other three exoplanets. This plot shows clearly that the difference between different atmospheric composition is larger for the planets orbiting closest to the central star.

3.2 Evolution of the surface temperature of TRAPPIST-1e

According to my simulations, at present TRAPPIST-1e is the most likely planet to host surface liquid water. The evolution of the surface temperature can be seen in Table 3.1. The first two columns show the assumed stellar constants and the corresponding stellar ages. Notice that in the last row the solar constant used is valid for the ages from 1.27 Gyr up to 7.96 Gyr. This means that at the end of the PMS stage, when the star enters the main sequence, the luminosity is not decreasing anymore and stays constant over the next few billion years. This is the same as in Table 3.3, 3.5 and 3.7.

Solar Constant [W/m^2]	Age [Gyr]	360 ppm CO_2 [K]	10.000 ppm CO_2 [K]	100.000 ppm CO_2 [K]
1740.54	0.25	334	336	340
1474.63	0.32	326	329	332
1260.91	0.41	306	319	321
1118.62	0.52	259	301	307
983.29	0.80	199	256	268
939.04	1.27 - 7.96	196	202	258

Table 3.1: Stellar constants of TRAPPIST-1e at a given age and the resulting surface temperatures assuming different CO_2 mixing ratios.

In Figure 3.3 the x-axis shows the time steps of the simulation in (Earth-) month, while the colored lines correspond to the decreasing luminosity of TRAPPIST-1e during the PMS phase. The bottom line in these plots gives the results for the zero-age-main-sequence (ZAMS). Due to a very slow evolution of M dwarfs, the luminosity of TRAPPIST-1 has not significantly changed since then, so that this temperature can also be used as an estimate of the present temperature on this planet for a given CO_2 mixing ratio. When looking at Figure 2.1 in Section 1.2.1 it is clear that at an age of around 1 Gyr, at the turning point where the red dwarf enters the main sequence, the luminosity stays nearly constant for the rest of the red dwarfs lifetime.

For a CO_2 abundance of 360 ppm in the planet's atmosphere the global averaged surface temperature drops from 334 K to 196 K within around 1 Gyr (between the ages from 0.25 Gyr to 1.27 Gyr). Raising the CO_2 levels to 10.000 ppm raises the temperatures insignificantly when just comparing the highest and lowest stellar constant simulations. The largest temperature difference of 57 K can be seen between the simulations with the 983.29 W/m^2 stellar constant. My results show that in the case of higher solar irradiation the temperature variations is comparably small as it is for the weaker solar constants, which seem to be more affected by the CO_2 mixing ratio. The temperature changes due to the different CO_2 mixing ratios are presented in Table 3.2.

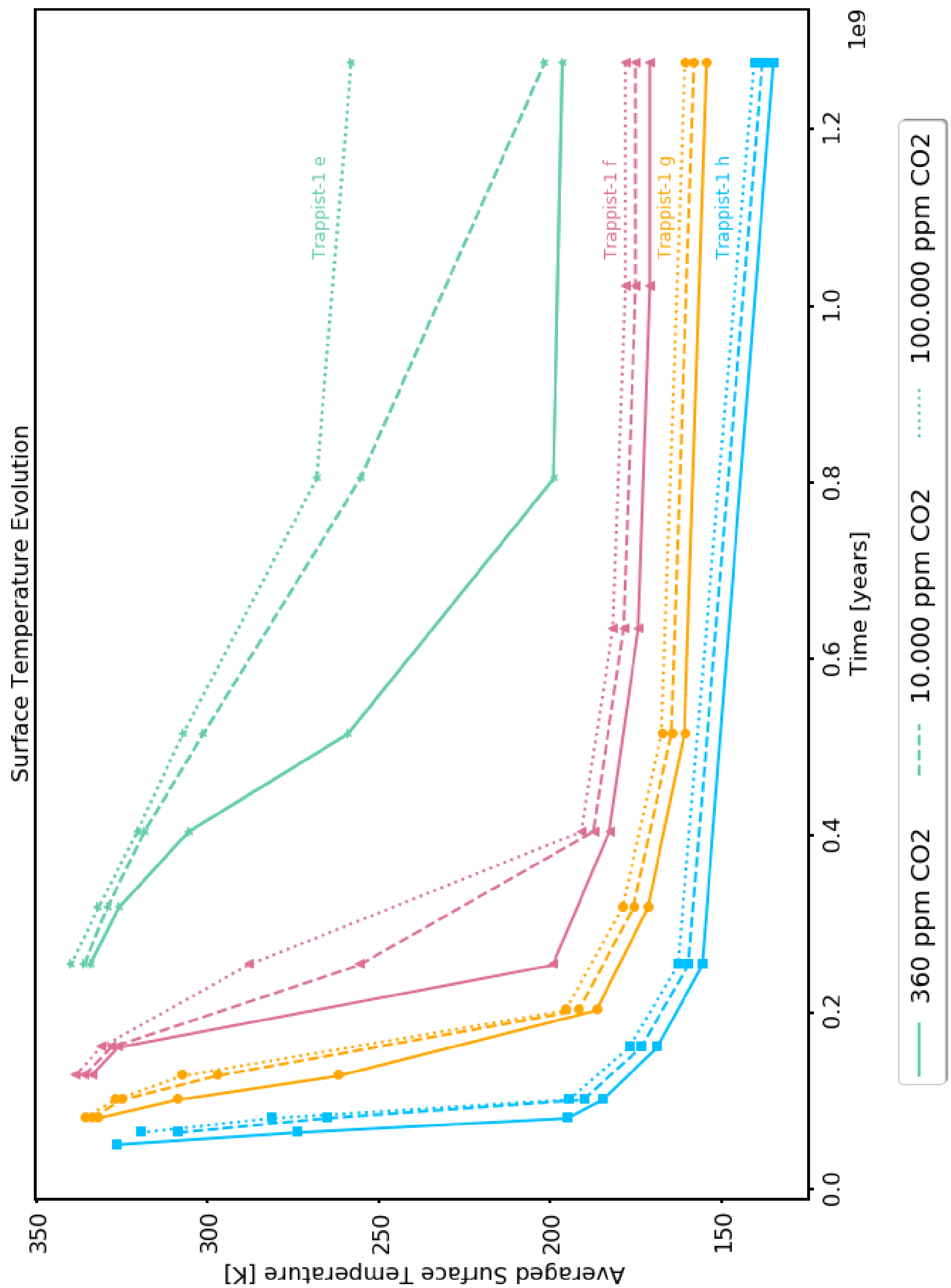

Figure 3.2: Temperature evolution during the PMS stage for all four TRAPPIST-1 planets.

stellar constant [W/m^2]	Δ_1 [K]	Δ_2 [K]	Δ_3 [K]
1740.54	1.7	3.8	5.6
1474.63	3.3	2.6	5.9
1260.91	12.9	2.1	15.0
1118.62	42.2	5.9	48.2
983.29	56.5	12.7	69.2
936.04	5.2	56.5	61.7

Table 3.2: The difference in temperature for TRAPPIST-1e simulations. The temperature differences are given for three cases, when raising the CO_2 mixing ratio from 360 to 10.000 ppm CO_2 simulations (Δ_1), 10.000 to 100.000 ppm CO_2 (Δ_2) and from 360 to 100.000 ppm CO_2 (Δ_3).

Although the global temperatures for TRAPPIST-1e always stay below the freezing point, the temperature maps (Fig. 3.4) show that there are equatorial regions which are warm enough for liquid water to exist. For a better visibility, Figure 3.5 presents the surface temperatures at different latitudes. Fig 3.5 illustrates the latitudinal temperature distribution for three CO_2 mixing ratios at different evolutionary stages. The liquid water range is indicated by the blue area between 273.15 K (freezing point) and 373.15 K (boiling point). One can see that even for the lowest CO_2 level, the peak temperatures in the equatorial region are above the freezing point of water (273.15 K) for all stellar constants exceeding 1118.62 W/m^2. Equatorial liquid water can be present also in the case of 10.000 ppm CO_2 down to a solar constant of 983.29 W/m^2. For 100.000 ppm CO_2, a region with the temperature above freezing point of water is present for all stellar constants, including the amount of irradiation the planet receives today.

3.3 Evolution of the surface temperatures of TRAPPIST-1f

The second habitable zone planet of the system TRAPPIST-1f does not show a wide range of surface temperature variations over 40 years of simulation (see Fig. 3.6). Starting at the highest irradiated case with 334 K and cooling down through the PMS evolution to 171 K with an atmosphere containing 360 ppm CO_2. The two cases with a higher CO_2 mixing ratio exhibit a similar behavior.

My simulations show that the biggest temperature difference between different atmospheric compositions is achieved at a stellar constant of 1005.1 W/m^2 (see Table 3.3). The temperatures differ by around 90 K when comparing the 360 ppm CO_2 with the 100.000 ppm CO_2 case. The other simulations done with higher and as well lower solar constants than 1005.1 W/m^2, the CO_2 dependent temperature variations does not exceed above 10 K between the applied CO_2 mixing ratios. The temperature differences between the different CO_2 contents are listed in Table 3.4.

The temperature maps I present (see Fig. 3.7) show a warm surface temperature, more or less homogeneously spread over the whole globe for the youngest planetary ages.

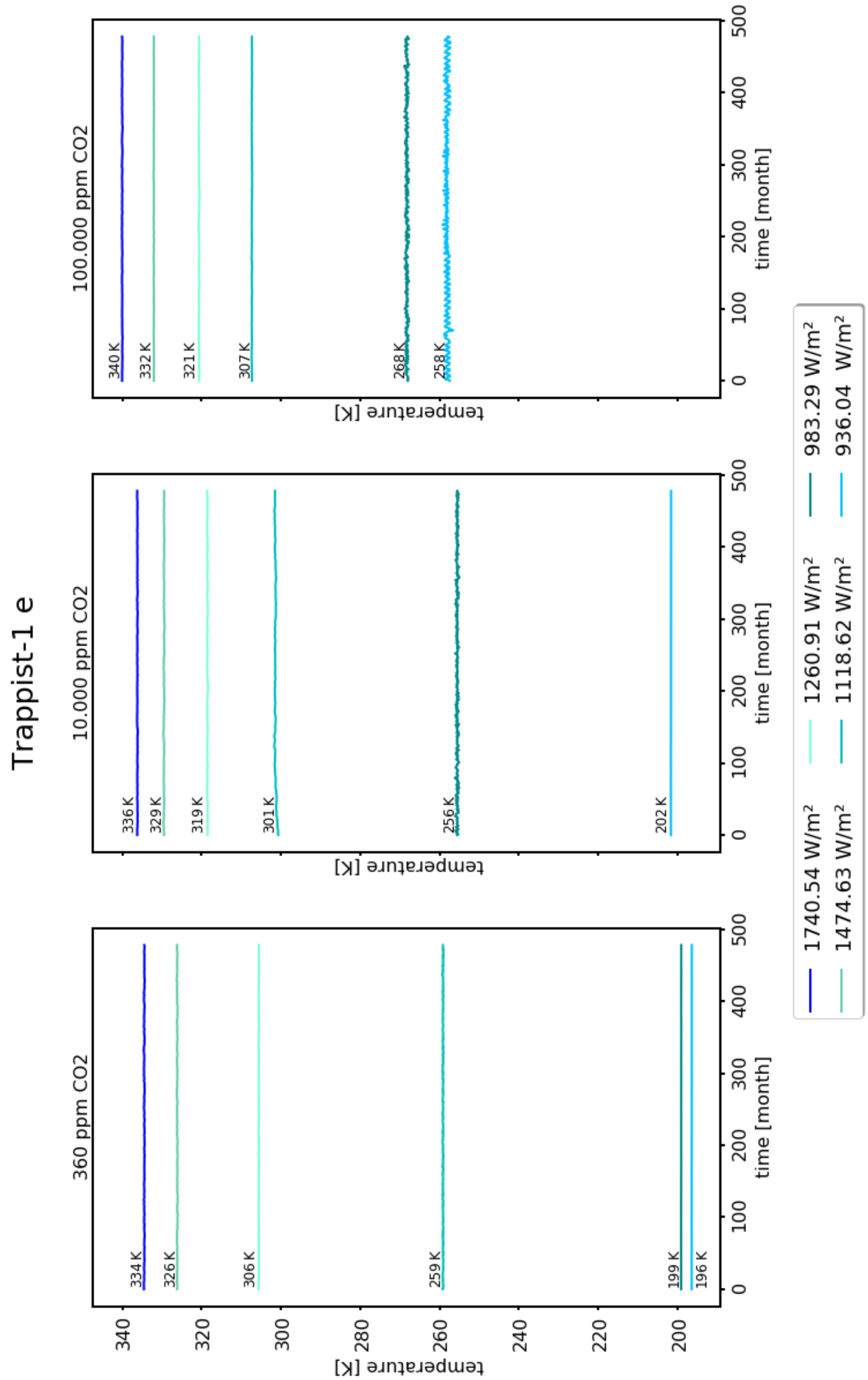

Figure 3.3: The resulting average temperatures for TRAPPIST-1e. Three different CO_2 mixing ratios (360, 10.000 and 100.000 ppm) and the changing stellar constants are shown.

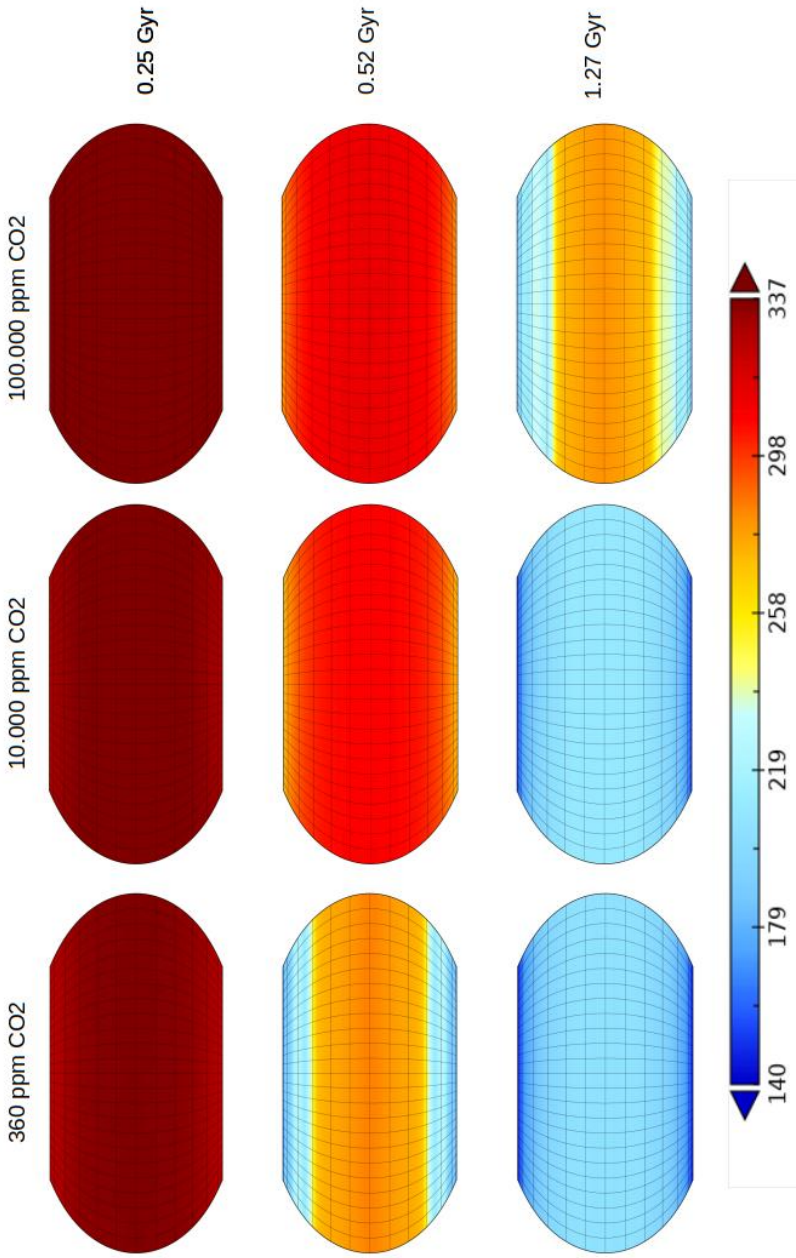

Figure 3.4: TRAPPIST-1e global temperature map at 1 bar atmospheric pressure for 306, 10.000 and 100.000 ppm CO_2. The temperature range chosen for the maps spans from 140 K up to 337 K.

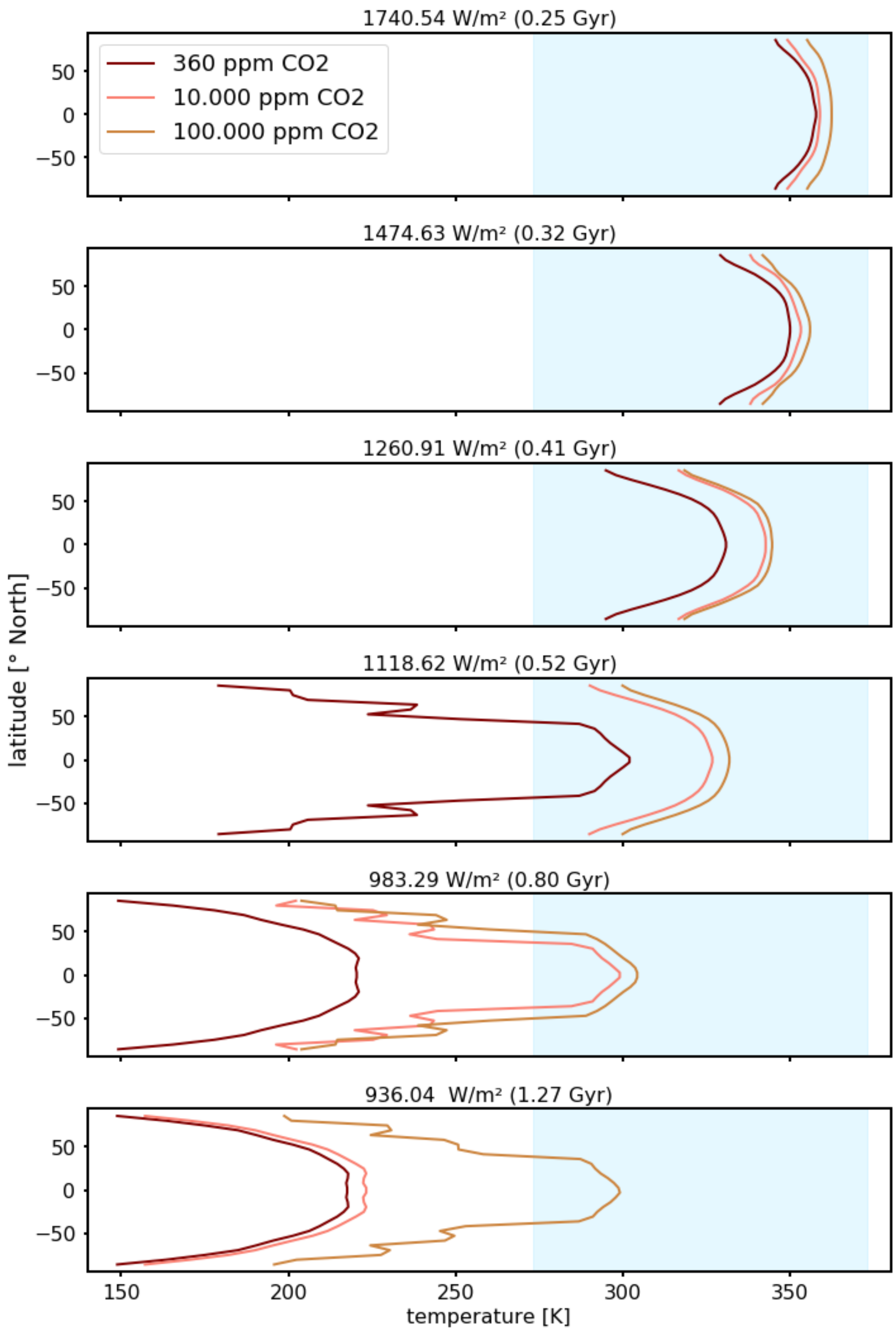

Figure 3.5: The zonal average temperatures for TRAPPIST-1e . The region where the temperature allows liquid water to exist is marked with blue shading. The latitude range spans from 85.76° North to -85.76° South. From top to the bottom the decreasing stellar luminosity (PMS evolution) can be compared.

Stellar Constant [W/m^2]	Age [Gyr]	360 ppm CO_2 [K]	10.000 ppm CO_2 [K]	100.000 ppm CO_2 [K]
1699.1	0.13	334	336	339
1426.4	0.16	326	328	331
1005.1	0.25	199	256	296
728.2	0.41	183	187	191
600.1	0.63	174	179	182
542.3	1.27 - 7.96	171	175	178

Table 3.3: Same Table as 3.1 but for TRAPPIST-1f.

stellar constant [W/m^2]	Δ_1 [K]	Δ_2 [K]	Δ_3 [K]
1699.14	2.1	2.6	4.7
1426.36	2.0	3.0	5.0
1005.15	56.5	32.5	89.0
728.17	4.7	3.5	8.2
600.11	4.3	3.1	7.4
552.37	4.1	3.0	7.1

Table 3.4: Same as Table 3.2 but for TRAPPIST-1f.

Proceeding further with the PMS phase (from top to bottom) the temperature gradually decreases, especially in the polar areas. By the end of the PMS phase the temperature decreases on the whole planet, with an exception of a slightly warmer (higher than the melting point of water) equatorial region in the 100.000 ppm CO_2 scenario for the present day case.

Figure 3.8 presents the latitudinal maps of the surface temperature on TRAPPIST-1f. One can see that the surface temperatures exceed the melting point of water only in the first three panels which corresponds to the youngest stellar age. At the end of the pre-main sequence phase, the global surface temperature is around 90 K, which is below the water's freezing point.

For all three atmospheric CO_2 mixing ratios the first two solar constants (corresponding to the youngest stellar ages) show that the liquid water can exist on the surface almost at all latitudes. In the case of the 1005.15 W/m^2 simulation the 10.000 ppm and 100.000 ppm cases have clearly higher temperatures compared to the 360 ppm CO_2 simulation. In these cases the surface temperatures at the equatorial regions exceeds the freezing point and would allow liquid surface water at the age of 0.25 Gyr.

3.4 Evolution of the surface temperatures of TRAPPIST-1g

Table 3.5 lists average temperatures in climate simulations between the age of 0.08 Gyr and 7.96 Gyr. Figure 3.9 shows that the surface temperatures for stellar constants lower than 1118 W/m^2 are not very sensitive to the CO_2 mixing ratio. In the later stages of the

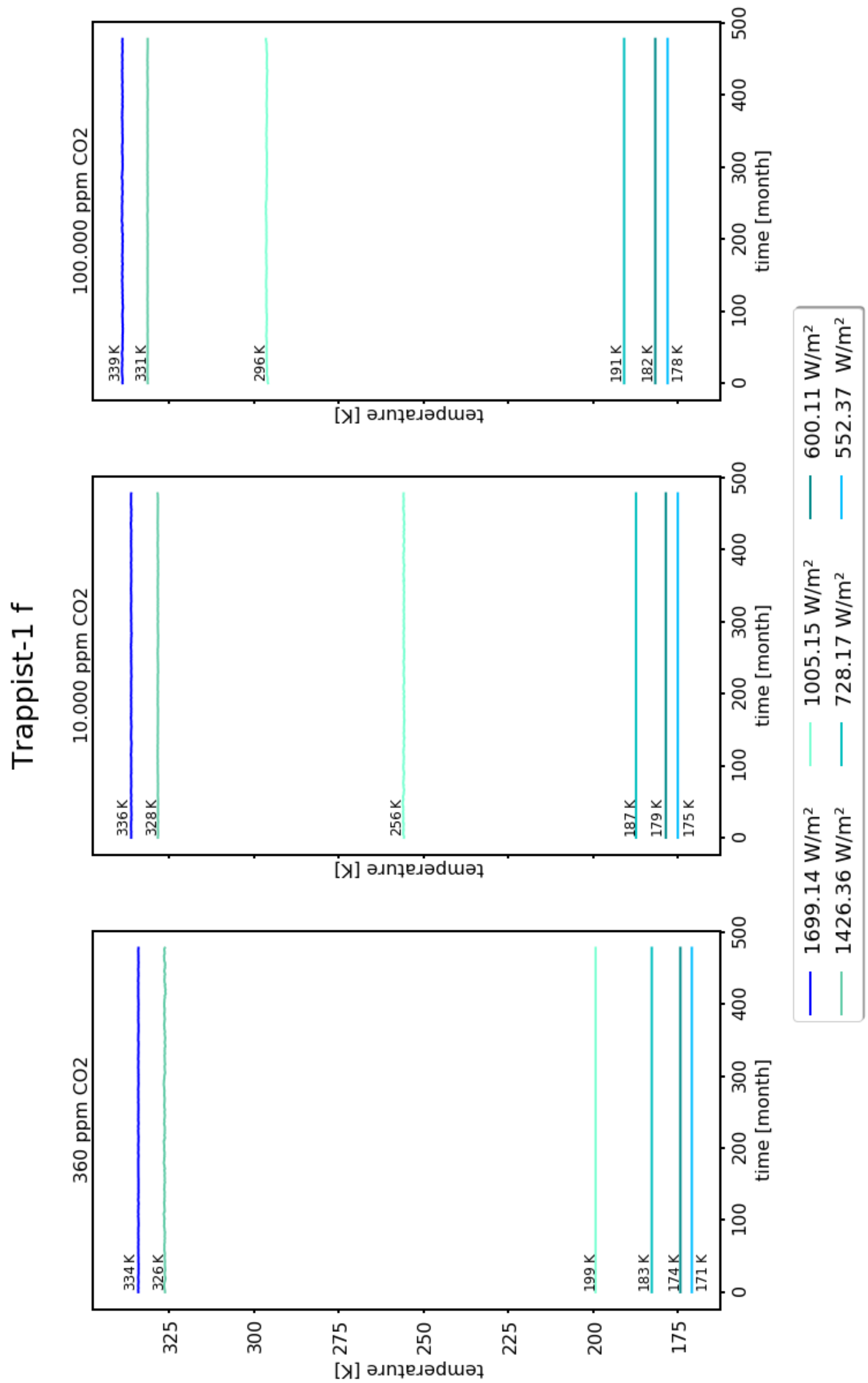

Figure 3.6: Same as Figure 3.3 but for TRAPPIST-1f.

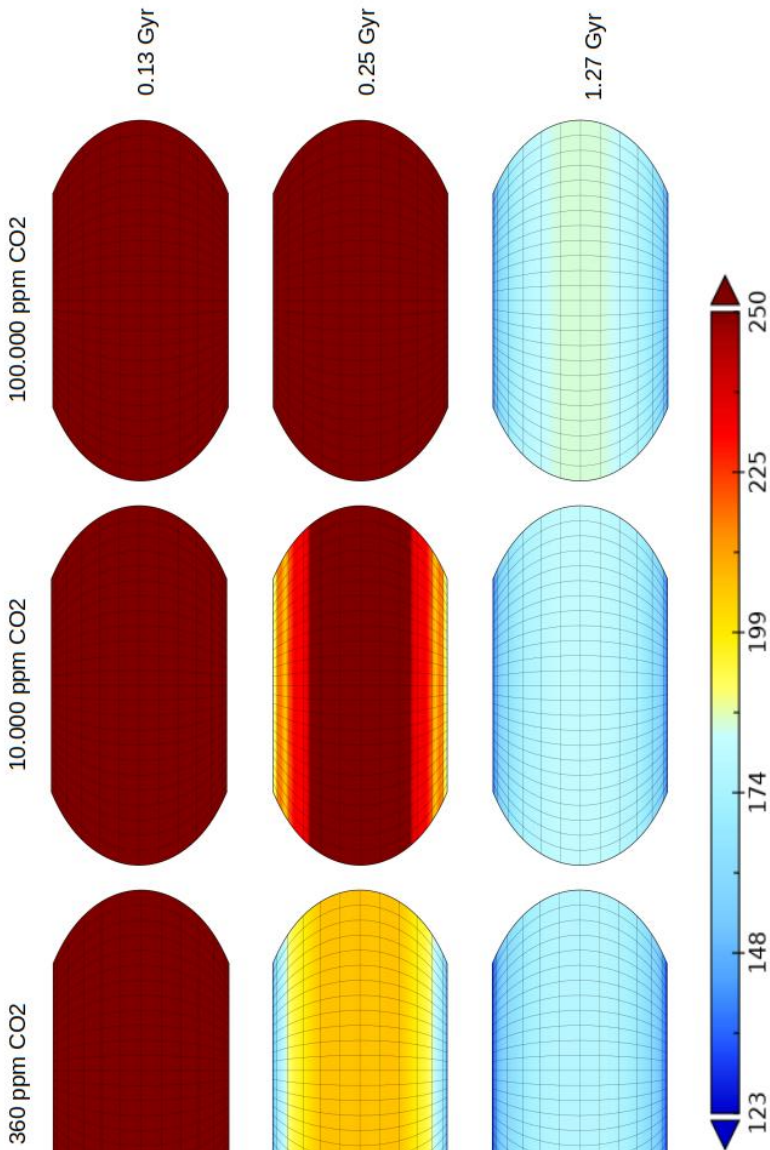

Figure 3.7: Same as Figure 3.4 but for TRAPPIST-1f. The temperature range spans from 123 K up to 250 K.

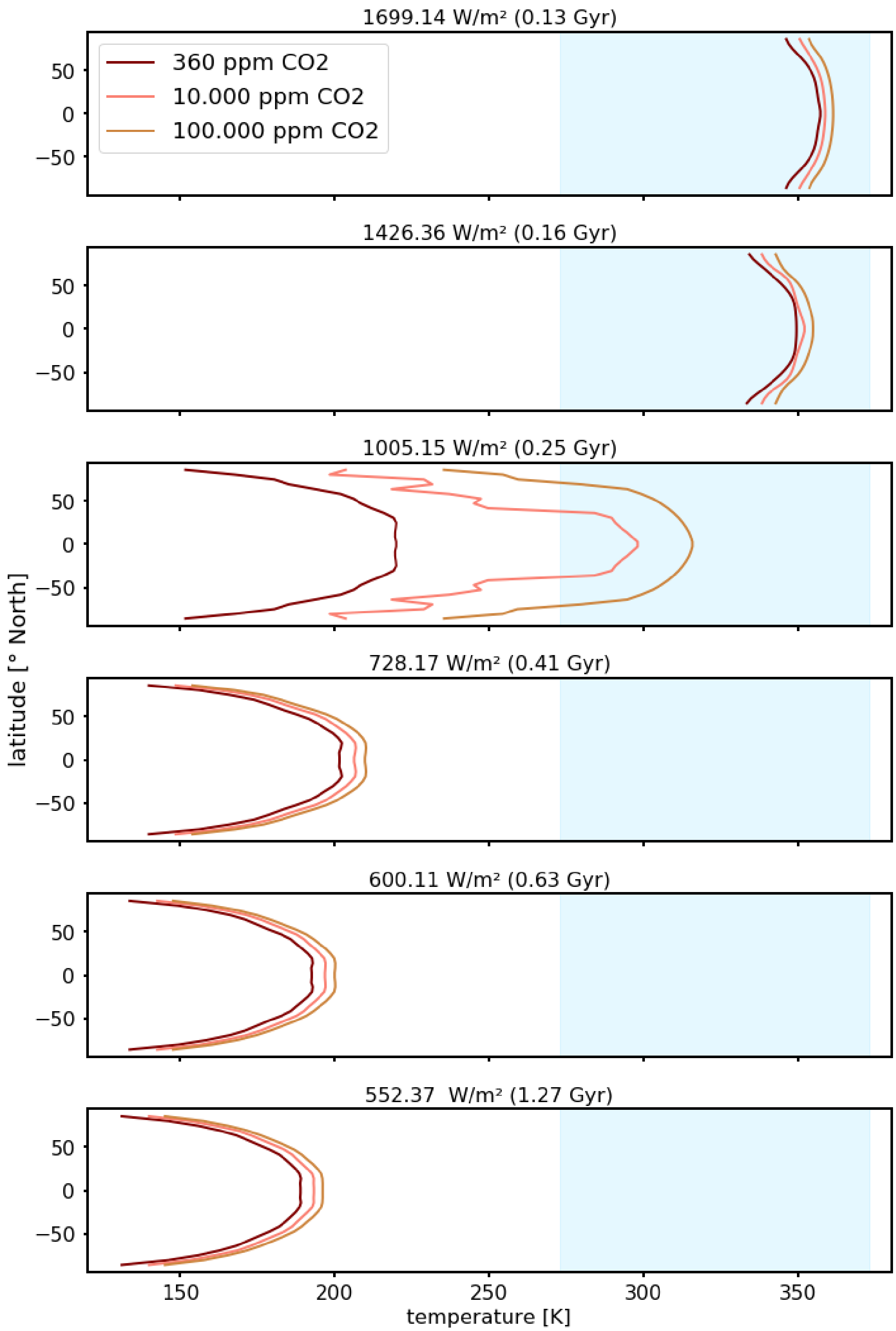

Figure 3.8: Same as Figure 3.5 but for TRAPPIST-1f.

PMS evolution, the temperature differences between different stellar constants are only of the order of several Kelvin. Whereas in the earlier stages the temperatures show more CO_2-dependent variations. The surface temperatures for the 1148.13 W/m^2 simulations are influenced the most by the increase in CO_2 abundance. In the 1367.70 W/m^2 case the temperature increases by around 16 K when the atmospheric CO_2 content increases from 360 ppm up to 10.000 ppm (Δ_1) and from 360 ppm to 100.000 ppm (Δ_3). The increase from 10.000 ppm up to 100.000 ppm is comparably small (see Tab. 3.6).

Stellar Constant [W/m^2]	Age [Gyr]	360 ppm CO_2 [K]	10.000 ppm CO_2 [K]	100.000 ppm CO_2 [K]
1644.3	0.08	332	334	336
1367.7	0.10	309	325	327
1148.1	0.13	262	297	307
809.1	0.20	187	192	196
575.4	0.32	172	176	179
436.5	0.52	161	165	167
366.4	1.27 - 7.96	154	158	161

Table 3.5: Same Table as 3.1 but for TRAPPIST-1g.

Due to a large orbital distance to the central star, the cooling of TRAPPIST-1g during the PMS phase is quite strong (see Fig. 3.10). Although initially warmer, due to the decreasing luminosity the global temperature drops already after 0.13 Gyr into a cold state, regardless of the CO_2 mixing ratio (see Fig. 3.11). Therefore no liquid water can be sustained on the surface of TRAPPIST-1g after the age of 0.13 Gyr.

stellar constant [W/m^2]	Δ_1 [K]	Δ_2 [K]	Δ_3 [K]
1644.34	1.6	2.2	3.9
1367.70	16.4	1.9	18.3
1148.13	35.5	10.0	45.5
809.08	5.1	3.9	9.0
575.43	4.3	3.2	7.4
436.51	3.8	2.9	6.7
366.43	3.6	2.7	6.3

Table 3.6: Same as for Table 3.2 but for TRAPPIST-1g.

3.5 Evolution of the surface temperature of TRAPPIST-1h

The results for TRAPPIST-1h, the coolest and outermost TRAPPIST exoplanet are listed in Table 3.7. Notice here, that for the simulation at the age of 0.05 Gyr (1349.1 W/m^2) only the 360 ppm CO_2 case could be modeled, since the simulations with higher levels of CO_2 could not be completed due to limitations of the PlaSim model. Comparing the results for the three different mixing ratios (see Fig. 3.12) shows not much variation in the

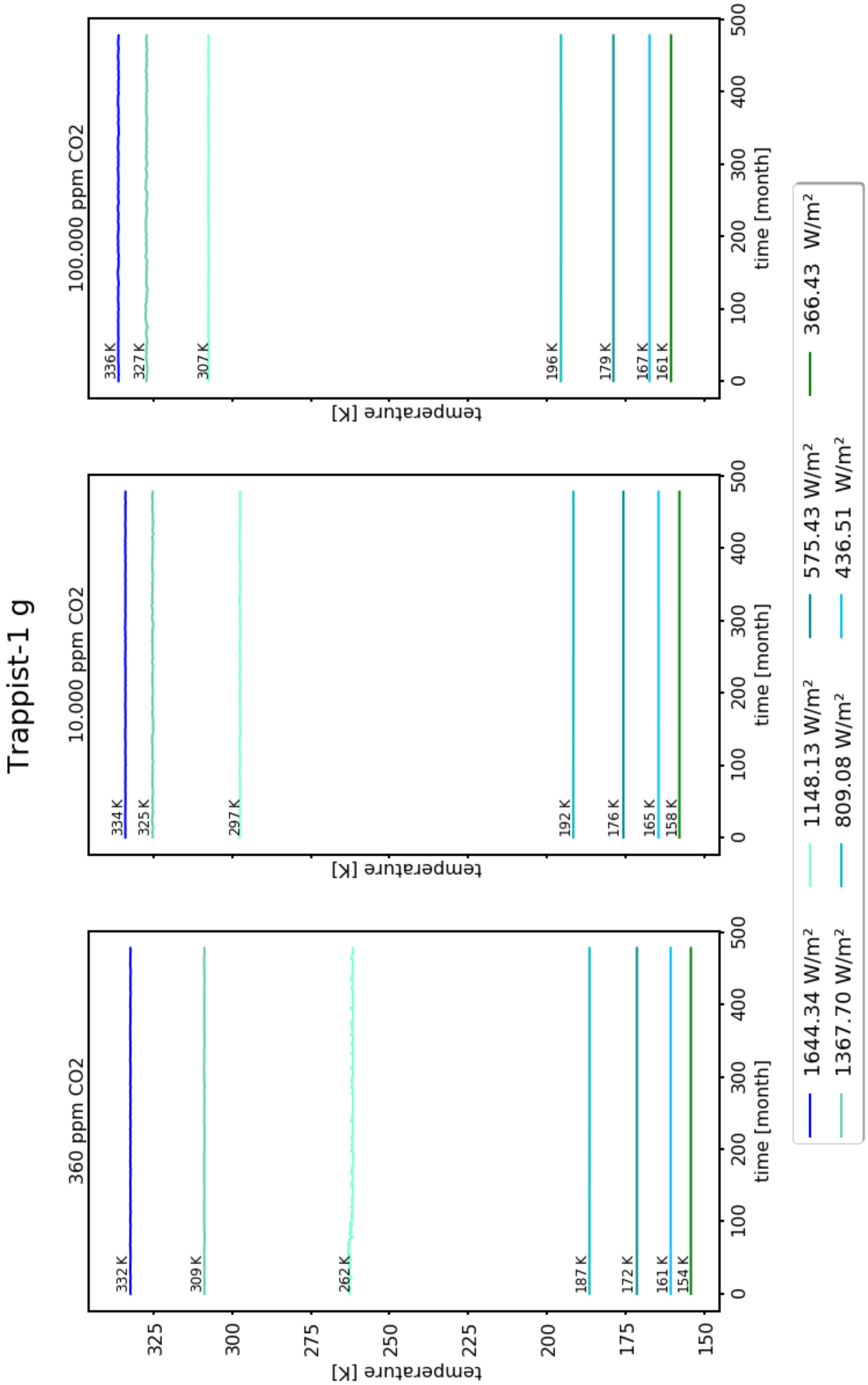

Figure 3.9: Same as Figure 3.3 but for TRAPPIST-1g.

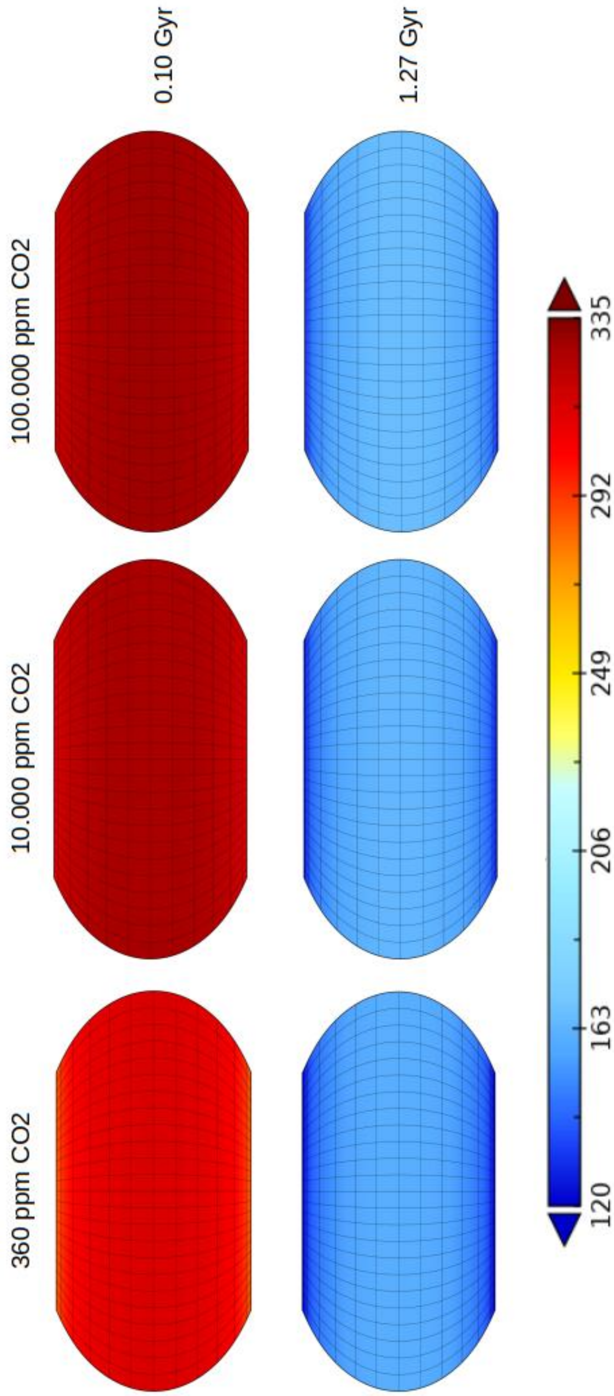

Figure 3.10: Same as Figure 3.4 but for TRAPPIST-1g. The temperature range spans from 120 K up to 335 K.

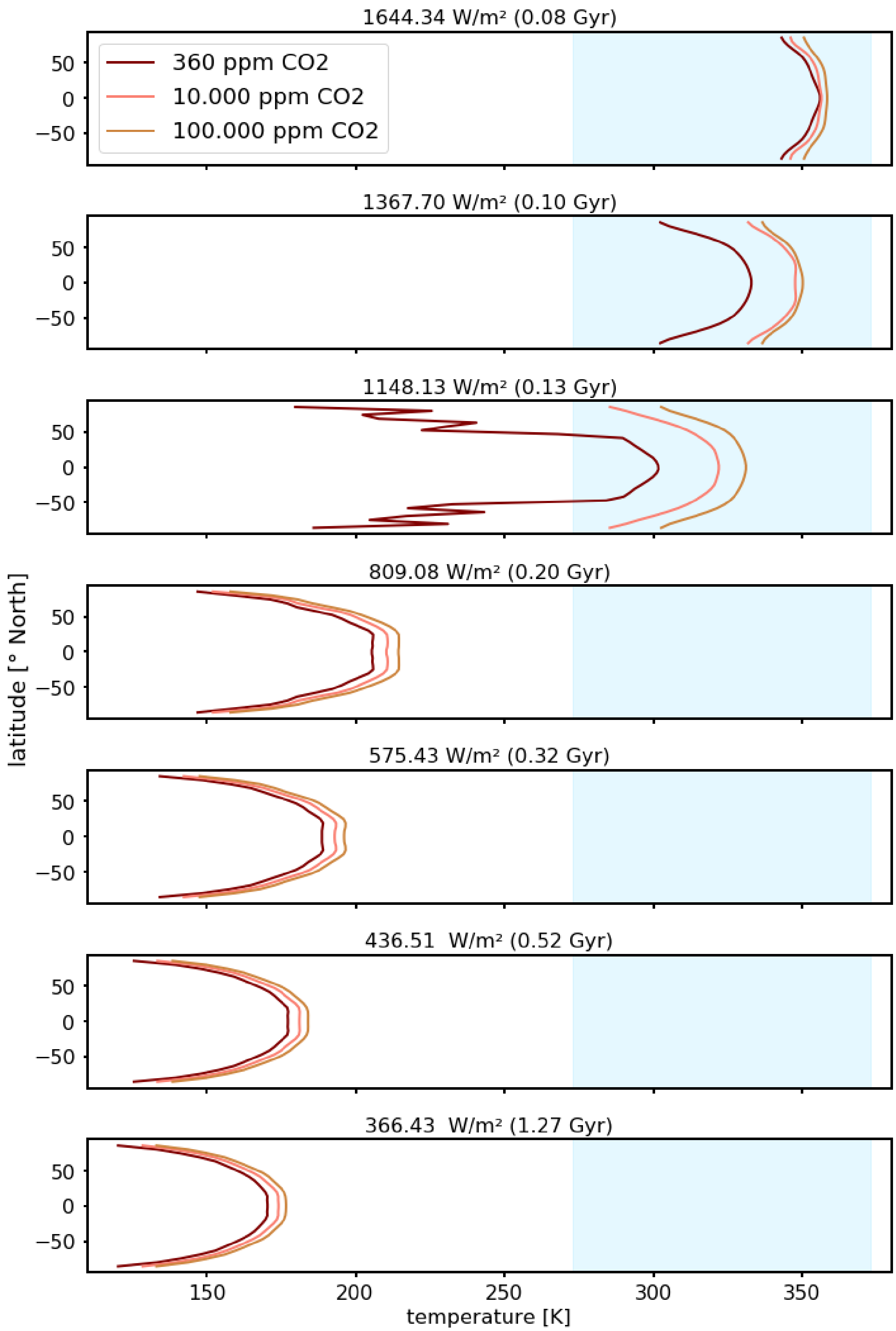

Figure 3.11: Same as Figure 3.5 but for TRAPPIST-1g.

temperature below a stellar constant of 783.5 W/m^2. Above this value, the temperatures are more sensitive to the CO_2 content in the atmosphere than to the stellar constant. This effect can be seen in Table 3.8.

Stellar Constant [W/m^2]	Age [Gyr]	360 ppm CO_2 [K]	10.000 ppm CO_2 [K]	100.000 ppm CO_2 [K]
1349.1	0.05	327	-	-
1122.1	0.06	274	309	320
942.0	0.07	195	266	282
783.5	0.10	185	190	195
552.1	0.16	169	174	177
389.1	0.25	156	160	163
209.9	1.27 - 7.96	135	138	140

Table 3.7: Same Table as 3.1 but for TRAPPIST-1h.

The temperature maps in Figure 3.13 show an initially warm planetary surface, at an age of 0.06 Gyr. At the end of the PMS phase, which corresponds to the current state of the planet, the surface is fully frozen. This is confirmed by the latitudinal temperature maps shown in Figure 3.14. As you can see in the second panel, at an age of 0.06 Gyr, the planet could potentially have habitable conditions, at least the equatorial regions. Very quickly, within 0.01 Gyrs to 0.04 Gyrs the surface temperatures decreases below the freezing point of water, making TRAPPIST-1h unlikely to sustain liquid water till today.

stellar constant [W/m^2]	Δ_1 [K]	Δ_2 [K]	Δ_3 [K]
1122.12	34.6	11.0	45.6
941.97	70.5	16.2	86.7
783.50	5.7	4.3	10.0
552.13	4.7	3.4	8.2
389.08	4.1	3.0	7.1
209.91	3.2	2.4	5.7

Table 3.8: Same as for Table 3.2 but for TRAPPIST-1h.

The results in Table 3.2, 3.4, 3.6 and 3.8 are indicating a sensitivity to certain stellar luminosities of the climate model. This so called *specific equilibrium climate sensitivity* is known but not completely explained. Ice albedo feedback, water vapor or clouds might contribute to this climate sensitivity (Friedrich et al., 2016; Pfister & Stocker, 2017).

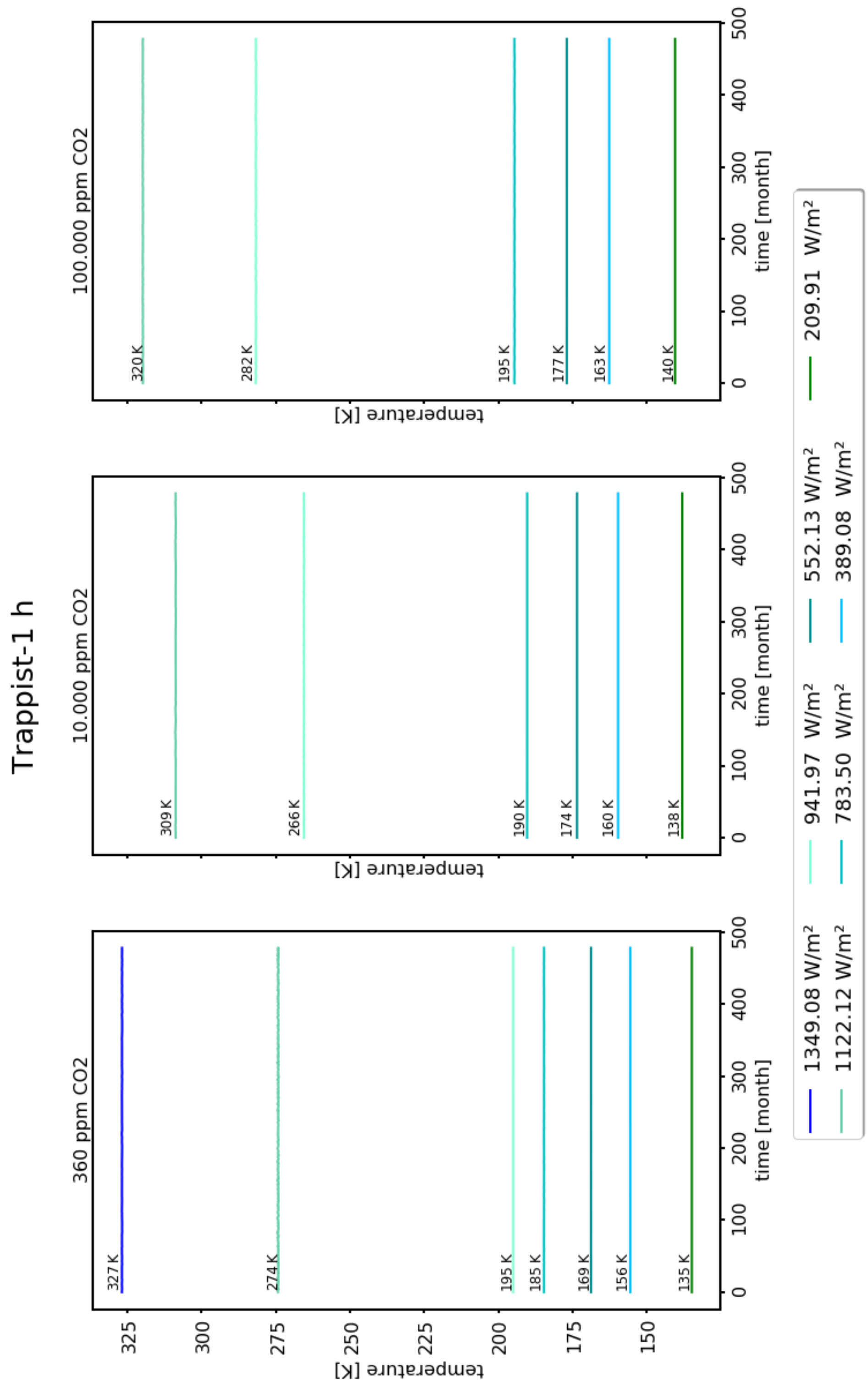

Figure 3.12: Same as Figure 3.3 but for TRAPPIST-1h.

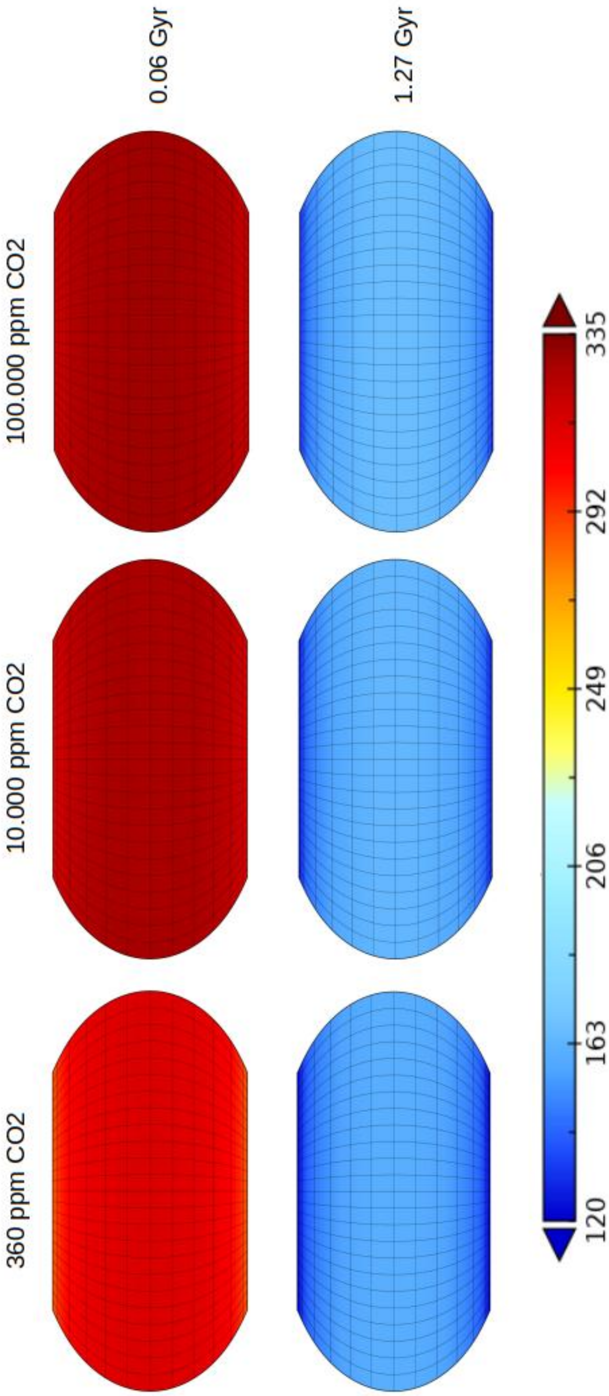

Figure 3.13: Same as Figure 3.4 but for TRAPPIST-1h. The temperature range from 150 K to 300 K.

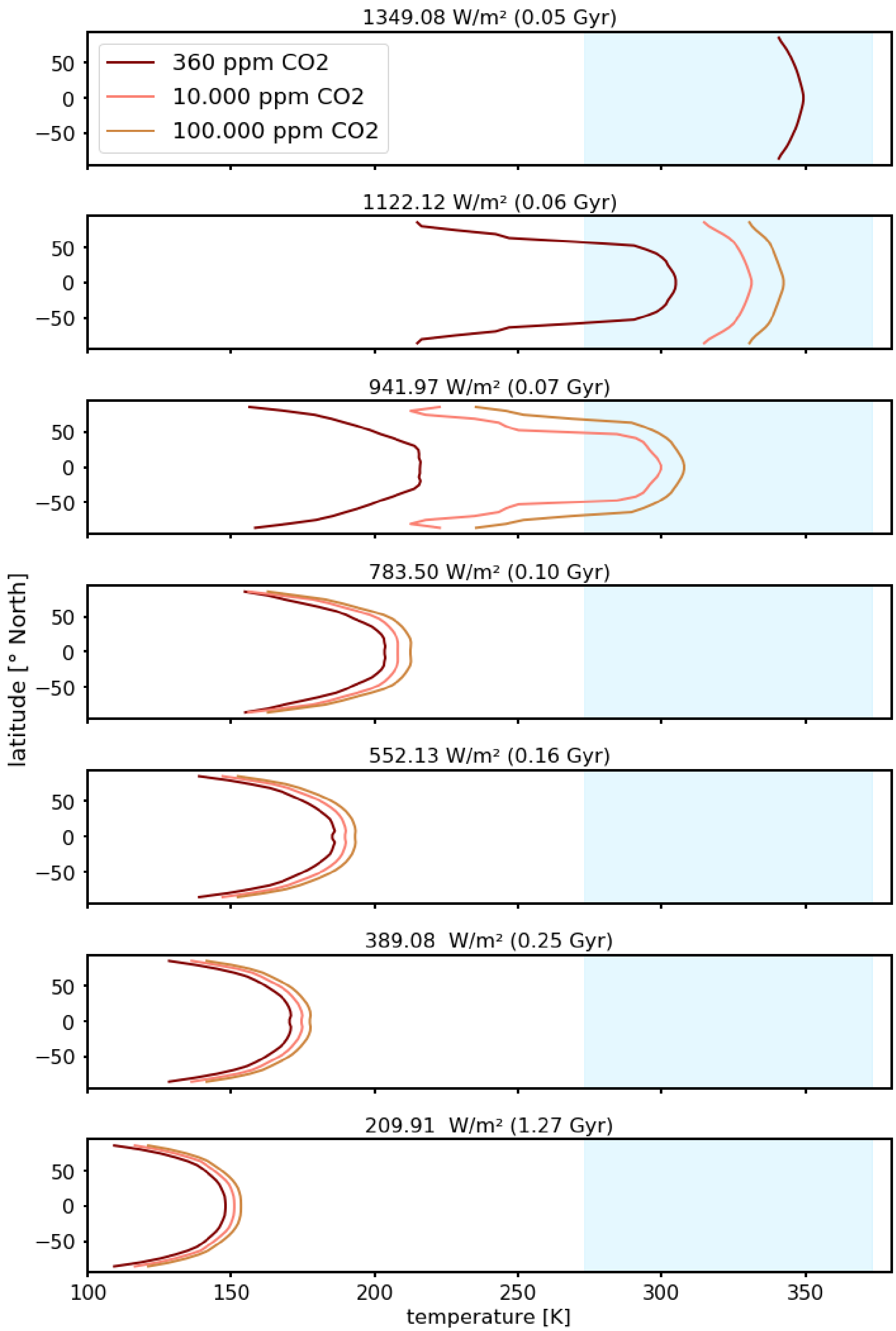

Figure 3.14: Same as Figure 3.5 but for TRAPPIST-1h.

Chapter 4

Discussion

4.1 The ocean world habitability

Different types of exoplanets and the need to classify them as habitats is described by Lammer (2013). Class 1 describes planetary bodies that are more or less Earth-like. Class 2 planets evolve to Venus- or Mars-like worlds. The Class 3 planets, the icy moons, are ocean worlds where the ocean is interacting with the silicate-rich core below an ice layer. This classification matches with Europa in our solar system. The Class 4 planets have liquid water layer between ice layers or even liquids above the ice. The solar system ambassador for this class would be Ganymed. Last but not least, Class 5 comprises planetary bodies with rocky cores and huge amounts of water and no solid surface. The ice-covered worlds (Class 4) are considered interesting targets for habitability, in the solar system and beyond.

In this thesis, I assumed that the TRAPPIST-1 planets were ocean planets with no continents. Habitability of water-worlds with deep oceans faces many challenges. The depth of the ocean might determine if life can arise or be prevented. Noack et al. (2014) pointed out that the bigger the planet is the more likely a high-pressure ice layer can form at the ocean's bottom. Such an ice layer can prevent the material exchange between the surface of the planet and the ocean. In this way no nutrients could be supplied to the ocean. The TRAPPIST-1 exoplanets are more or less of similar sizes and masses as Earth, which hopefully prevents them from having such a high-pressure bottom ice layer. Only in shallow oceans sufficient nutrients could be present (Maruyama et al., 2013), which might be the case on the TRAPPIST-1 planets depending on the initial amount of water delivered to them (Tian & Ida, 2015).

Kaltenegger (2019) showed, that the depth of light penetrating into the water on these planets could be limited to just 2 m and therefore photosynthesis might be different than known from Earth and would be restricted to a small area near the surface. The existence of life on such planets could also be prevented from the lack in atmospheric O_2 or a sufficiently warm ocean temperature that prevents the existence of phytoplancton-like biota (Lingam & Loeb, 2020). Another limiting factor on the habitability is the existence of plate tectonics and volcanic activity, which are known to have been supporting life on Earth through an ongoing CO_2 cycle (Dehant et al., 2019). Currently, the existence and magnitude of volcanism on TRAPPIST-1 planets is debated, but volcanic activity in the past or present day cryovolcanic activity like on Titan or Enceladus can not be excluded. The TRAPPIST-1 system is old enough for complex life to develop, if life emerged on these planets earlier.

4.2 Atmospheric escape

Observations show that TRAPPIST-1 is a bright X-ray source, which also implies a high flux of extreme ultraviolet, or EUV, radiation (Wheatley et al., 2017). X-ray and EUV radiation (together XUV) drives atmospheric escape (Johnstone et al., 2018, 2019). Therefore, an increased level of short wavelength radiation can mean that the atmospheres of TRAPPIST-1 planets have been lost. However, these planets could have still retained their atmospheres in the early phases of evolution, maybe due to stronger volcanic activity that helped to replenish gases lost due to escape to space or due to an increased CO_2 mixing ratio, as CO_2-dominated atmospheres are less prone to atmospheric escape than nitrogen-dominated atmospheres (Johnstone et al., 2018). My results show that during this time the outer planets also could have had clement climates that potentially could allow the life to originate, especially taking into acocunt that excess UV radiation might not limit this process (O′Malley-James & Kaltenegger, 2017). Potentially, this life might have survived to present day under the ice shells on the surfaces of these planets (Taubner et al., 2018, 2020).

Chapter 5

Conclusions

Habitable conditions on a planet's surface can be achieved for different atmospheric compositions and stellar constants. Through my simulations these criteria are met by all target planets at a certain time during there pre-main-sequence phase. All four outer TRAPPIST-1 planets exhibit an early habitability window, assuming that their secondary atmospheres are not eroded by the stellar short wavelength radiation.

The first and most promising target of my study is **TRAPPIST-1e**. Starting the simulations at an early age of 0.25 Gyr (corresponds to a stellar constant of 1740.54 W/m^2) the planet's global surface temperature is warm with approx. 340 K. An early habitability window could have started as early as 0.25 Gyr after the system's formation. Before that, the surface temperature was too hot. During the next 160 Myr, the surface temperature gradually decreases, but still stays within limits suitable for the existence of the liquid water. During that time, the temperature of the 360 ppm CO_2 simulation decreases and leaves only the equatorial region habitable, while the poles have cooled down below the freezing point of water. At present, a warm state at the equatorial region of the planet is achievable only for atmospheric CO_2 concentration of 10.000 and 100.000 ppm. At an age of 0.80 Gyr also for these two cases only the equatorial area show temperatures that can sustain liquid water on the surface. This doesn't exclude the presence of liquid water under the ice sheet. An example are the icy moons orbiting the solar system giants that have the surface temperatures between approx. 30 K and 150 K. However, indirect methods indicate the presence of large oceans on these bodies (Sohl et al., 2010). In addition to that, warmer ponds, geysers or in a subsurface ocean to have organic compounds or maybe even some organisms to survive under harsher conditions are possible (Taubner et al., 2016, 2018). A large time span of about 500 Myrs could be enough for life to arise and adapt to the continuous decreasing temperatures. As on Earth, the emergence of life took several hundred million years (Pearce et al., 2018), which is a comparably long time span. Later in the Earth's history, life has survived the periods of full glaciations (Hoffman, 2013), which indicates that once it originates, life can survive low surface temperatures at least for some time. If there is sufficient atmospheric CO_2 in the planets atmosphere, that means more than 100.000 ppm, the simulations show, that at the end of the PMS phase the equatorial region of TRAPPIST-1e is still suitable for liquid surface water. This condition might persist even up till today. This makes TRAPPIST-1e a promising target for further observations by the upcoming James Webb telescope. In summary, TRAPPIST-1e is the most promising planet of the TRAPPIST-1 system for habitability studies.

The habitability window of **TRAPPIST-1f** is somewhat shorter than for its neighbour TRAPPIST-1e. At the age of 0.13 Gyr (stellar constant of 1699.14 W/m^2) all three CO_2 mixing ratios show that the planets surface is in a very warm state of approx. 340 K. This state lasts for 30 Myr till a distinct decrease of the surface temperature occurs. At the age of 0.25 Gyr, after 120 Myr, just a small area of the planet's surface stays habitable for the two higher CO_2 concentrations. At this stage of the planet's evolution, the global temperature is below the freezing point of water with solely 360 ppm CO_2 in the atmosphere. A higher CO_2 content in the atmosphere leads to a prolonged early habitability window, therefore raising chances for the producing of organic molecules in TRAPPIST-1f's oceans. These simulations indicate a 120 Myr long habitability window in the planet's history. In later simulations of the PMS phase, the temperatures have dropped to around 180 K already at an age of 0.41 Gyr and lingered at this cool state from that time on. TRAPPIST-1f also might still show spots where live could have took shelter from the freezing surface conditions.

For **TRAPPIST-1g** my simulations starting at an age of 0.08 Gyr. The simulations show a similar behavior as for TRAPPIST-1f, but with a faster decreasing surface temperature. In the simulations for the stellar constant of 1644.34 W/m^2, all three CO_2 mixing ratios lead to surface temperatures within the habitability window. These surface temperatures are around 336 K. Good conditions for liquid water and potential life evolution. Within 20 Myr the planet's surface temperature drops to around 20 K for the 306 ppm CO_2 simulations, while two scenarios with higher CO_2 abundances do not show a huge temperature drop. The habitable conditions on (at least certain parts of) the surface could have lasted for 50 Myr. In the case of 360 ppm CO_2 just the equatorial region is warm enough for liquid water to exist assuming some stellar constant, the poles have cool temperatures even at an early age of 0.13 Gyr. On the other hand, the whole surface area can have liquid water in 10.000 ppm and 100.000 ppm CO_2 simulations. After 120 Myr, all scenarios produce surface temperatures well below the freezing point and the planet evolves to a icy planet with a surface temperature of around 160 K. The time span of 50 Myr is possibly still long enough to build organic compounds such as amino acids.

We see a similar behavior for **TRAPPIST-1h**. The simulations done for stellar constant of 1349.08 W/m^2 (at an age of 0.05 Gyr), show an early habitability window for the whole planet with an atmospheric CO_2 mixing ratio of 360 ppm. For this stellar constant no simulations could be done with higher amounts of CO_2. Other simulations show that the surface cooling proceeds very quickly and takes only 10 Myr. Just the equatorial region is capable of hosting liquid water on the surface in these simulations. Assuming more CO_2 in the atmosphere's composition at the age of 0.06 Gyr allows the whole planet to be warm enough to be called habitable, even on the polar regions. Another 10 Myr later, also these cases noticeably cooled down, so that here the equator area can be seen as habitable. But not for the case of the 360 ppm CO_2, which is already below the freezing point. This planet clearly shows, that at outer planets, a vast amount of CO_2 has to be present in the planet's atmosphere to keep the surface temperatures favorable for liquid water over a longer period of time. In the best case this planet could have been habitable for around 10 Myr before it started freezing down to todays 140 K.

At present these exoplanets do not show surface conditions that allow liquid water to exist (except TRAPPIST-1e). The habitability window of TRAPPIST-1e is still open, if at least 100.000 ppm CO_2 is present in the planet's atmosphere. TRAPPIST-1f could harbour liquid water till an age of 0.25 Gyrs, so the temperature window for water lasted at least for 120 Myr. Shorter but still mentionable is the 50 Myr lasting PMS habitability window of TRAPPIST-1g. The very short habitability window of TRAPPIST-1h of only 10 Myr might also bear interesting planetary features below the frozen surface. Various scenarios might still be in favor of today's habitability for these planets. If life had enough time to originate during the early habitability windows of these four exoplanets, then it might have evolved and adapted to the decreasing temperatures. It might be possible that the TRAPPIST-1 planets harbour subsurface oceans under a frozen surface, where temperatures might still be suitable for life, like on icy moons. Hydrothermal vents at the ocean floor (black or white smokers) could serve as oceanic oasis for living organisms, if no high-pressure bottom ice layer is present at the oceanic floor (Noack et al., 2014). The planet's interior might be heated up through tidal heating, raising the overall temperature through volcanic activity and CO_2 enriched atmosphere. Also cryovolcanism might occur as on certain icy moons. Even though the TRAPPIST-1 planets are not habitable when looking at them today, except TRAPPIST-1e, their might be still the chance for life under the surface. The time might have been enough for organisms to evolve into a psychrophiles or cryophiles, which are also present at Earth today. These psychrophiles could survive in oceans that became covered by an ice layer following the cooling of the surface. Even on Earth we find oligotrophs, that can survive with very little nutrients. If after the PMS phase the surface of the planet is frozen and a high-pressure ice layer has formed on the ocean ground, what might be the case for planets these sizes, these organisms could still persist. Also piezophiles, which can sustain up to a pressure of a few MPa would fit in these conditions. Many scenarios are possible and can be determined or further refined by ongoing observations and further simulations of the planet's current state and the evolution it has already gone through. The search for life on icy moons like Saturn's moons Titan or Enceladus or Jupiter's moons Europa or Ganymed, which all show even harsher surface conditions today and likely during their evolution, we might also understand better the conditions on the TRAPPIST-1 planets, that are promising targets for the searching of life outside the solar system.

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