Comparative Climates of the Trappist-1 Planetary System: Results from a Simple Climate-vegetation Model

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Abstract

The recent discovery of the planetary system hosted by the ultracool dwarf star TRAPPIST-1 could open new paths for investigations of the planetary climates of Earth-sized exoplanets, their atmospheres, and their possible habitability. In this paper, we use a simple climate-vegetation-energy-balance model to study the climate of the seven TRAPPIST-1 planets and the climate dependence on various factors: the global albedo, the fraction of vegetation that could cover their surfaces, and the different greenhouse conditions. The model allows us to investigate whether liquid water could be maintained on the planetary surfaces (i.e., by defining a “surface water zone (SWZ)”) in different planetary conditions, with or without the presence of a greenhouse effect. It is shown that planet TRAPPIST-1d seems to be the most stable from an Earth-like perspective, since it resides in the SWZ for a wide range of reasonable values of the model parameters. Moreover, according to the model, outer planets (f, g, and h) cannot host liquid water on their surfaces, even with Earth-like conditions, entering a snowball state. Although very simple, the model allows us to extract the main features of the TRAPPIST-1 planetary climates.

Key words: planets and satellites: general – radiative transfer

1. Introduction

The sharp acceleration of exoplanet discoveries in recent years (Mayor & Queloz 1995; Marcy & Butler 1996; Petigura et al. 2013; Gillon et al. 2016, 2017; NASA Exoplanet Archive 2017), and their presumed habitability (Kasting et al. 1993; Scharf 2009; Spiegel et al. 2008; Kopparapu et al. 2013; Gillon et al. 2017), are changing our point of view on planetary science.

According to the usual definition (Kasting et al. 1993; Kopparapu et al. 2013), a planet resides in the so-called circumstellar habitable zone (HZ) if, being a terrestrial-mass planet with a CO₂–H₂O–N₂ atmosphere, it can sustain liquid water on its surface (Kasting et al. 1993; Kopparapu et al. 2013). The above requirements, coupled with the assumption of an Earth-like geology for the resulting greenhouse effect and carbon-silicate weathering cycle, imply that the surface temperature must be in the range 0°C–100°C. Typically, apart from orbital features (e.g., eccentricity, period, transit time, inclination) and rough estimates of mass and radius, little information is directly known about exoplanets. For instance, the planetary surface temperature can be roughly estimated using equilibrium conditions from energy-balance climate models depending on the distance of the planet from the hosting star and planetary outgoing energy. However, in such cases these estimates could be incorrect, since no information about the planetary atmosphere is included in these models (for instance, Venus has an estimated temperature of ~300 K, while the true surface temperature is about 737 K). Nevertheless, more complex energy-balance climate models, including the greenhouse effect and/or heat diffusion, provide insight into the climate on a planet (Alberti et al. 2015, and references therein).

Despite some recent comments on the metrics used to define the HZ in relation to public interest in scientific results (Moore et al. 2017; Tasker et al. 2017), the recently discovered TRAPPIST-1 system (Gillon et al. 2016, 2017), formed by seven temperate (with equilibrium temperatures ≤400 K) Earth-sized planets orbiting around a nearby ultracool dwarf, increased interest in studying the climate conditions of terrestrial exoplanets (Bolmont et al. 2017; Bourrier et al. 2017; O’Malley-James & Kaltenegger 2017; Wolf 2017). Since, as pointed out above, estimates of equilibrium temperatures that do not take into account the greenhouse effect and the albedo feedback (so-called null Bond albedo hypothesis) cannot be sufficiently reliable, improved and advanced climate models that consider the planetary albedo and the atmospheric composition are required (Gillon et al. 2017; Wolf 2017). Using both a 1D radiative-convective climate model and a more sophisticated 3D model, Gillon et al. (2017) found that inner planets, T-b, T-c, and T-d (in the following we indicate as T-x the xth TRAPPIST-1 planet), show a runaway greenhouse scenario, while outer planets, T-e, T-f, and T-g, could host water oceans on their surfaces, assuming an Earth-like atmosphere. The seventh planet, T-h, on the other hand, cannot sustain surface liquid water oceans, due to the low stellar irradiance received. However, since little is known about the planetary system, several approaches and hypotheses can be helpful for investigating both planetary climates and atmospheric compositions (De Wit et al. 2016; Bolmont et al. 2017; O’Malley-James & Kaltenegger 2017; Wolf 2017).

One of the drawbacks of the more detailed climate models is the necessary large pool of assumptions of atmospheric and surface conditions. In this paper we investigate the possible climates of the TRAPPIST-1 planetary system using a simple zero-dimensional energy-balance model (Rombouts & Giguère 2015), which allows extraction of global information on the climate evolution using actual knowledge of the planetary system. This model has the advantage of transparency through minimal assumptions, allowing comparative sets of models to be studied. We study several situations, from completely rocky planets to Earth-like conditions, both neglecting and considering the greenhouse effect, to explore
different possible climates and make a comparative study of TRAPPIST-1 planetary system climates.

### 2. The Climate Model

The main features of the climate dynamics of Earth-like planets can be recovered through a zero-dimensional model based on two equations describing the time evolution of the global average temperature \( T \) and the time evolution of the fraction of land \( A \) covered by vegetation:

\[
C_T \frac{dT}{dt} = [1 - \alpha(T, A)] S(a, L_s) - R(T),
\]

\[
\frac{dA}{dt} = A[\beta(T)(1 - A) - \gamma].
\]

Here, \( C_T \) is the planet heat capacity, \( \alpha(T, A) \) is the planetary albedo, \( S(a, L_s) = L_s/(4\pi a^2) \) is the mean incoming radiation that depends on the star–planet distance \( a \) (in au) and on the star luminosity \( L_s \), \( R(T) \) is the outgoing energy from the planet, and \( \beta \) and \( \gamma \) are the vegetation growth and death rates, respectively (Watson & Lovelock 1983; Alberti et al. 2015; Rombouts & Ghil 2015). The albedo of the planet depends on the fraction of land \( p \), namely \( \alpha(T, A) = (1 - p) \alpha_o(T) + p[\alpha_o + \alpha_g(1 - A)] \), where \( \alpha_o \), \( \alpha_g \), and \( \alpha_v \) represent the albedos of ocean, vegetation, and bare-ground, respectively. The albedo of the ocean is assumed to be linearly dependent on temperature as

\[
\alpha_o(T) = \alpha_{\text{max}} \left[ \frac{T - T_{\text{low}}}{T_{\text{up}} - T_{\text{low}}} \right]
\]

in a range of temperatures \( T \in [T_{\text{low}}, T_{\text{up}}] \), resulting in \( \alpha_o(T) = \alpha_{\text{max}} \) for an ocean completely covered by ice \( (T \leq T_{\text{low}}) \) and \( \alpha_o(T) = \alpha_{\min} \) for an ice-free ocean \( (T \geq T_{\text{up}}) \).

The outgoing energy is described by a blackbody radiation process, modulated by a grayness function, in order to take into account the greenhouse effect

\[
R(T) = \left[ 1 - m \tanh \left( \frac{T}{T_0} \right)^6 \right] \sigma T^4,
\]

where \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \) is the Stefan–Boltzmann constant, \( m \in [0, 1] \) is a grayness parameter \( (m = 0.5 \sim 0.6 \text{ for an Earth-like planet (Sellers 1969; Alberti et al. 2015)}) \), and \( T_0 \) represents the mean global planetary temperature. The growth-rate \( \beta(T) \) of vegetation is a quadratic function of temperature, \( \beta(T) = \max \{0; 1 - k(T - T_{\text{opt}})^2\} \) (\( k \) being a parameter for the growth curve width and \( T_{\text{opt}} \) being an optimal temperature), while the death-rate \( \gamma \) is assumed to be constant (Watson & Lovelock 1983; Alberti et al. 2015).

The new parameters \( k, T_{\text{opt}}, \gamma, \) and \( \alpha_v \) are related to vegetation (as in Rombouts & Ghil 2015; Alberti et al. 2015). In the following, since we assume an Earth-like vegetation, these parameters are set to Earth’s conditions. A complete list of the used parameters and their corresponding values is shown in Table 1.

| Symbol | Value | Units  |
|--------|-------|--------|
| \( C_T \) | 500 | W yr K^{-1} m^{-2} |
| \( \alpha_v \) | 0.1 | ... |
| \( \alpha_g \) | 0.4 | ... |
| \( \alpha_{\text{max}} \) | 0.85 | ... |
| \( \alpha_{\min} \) | 0.25 | ... |
| \( T_{\text{low}} \) | 263 | K |
| \( T_{\text{up}} \) | 300 | K |
| \( T_{\text{opt}} \) | 283 | K |
| \( k \) | 0.004 | yr^{-1} K^{-2} |
| \( \gamma \) | 0.1 | yr^{-1} |

As shown in previous studies (Sellers 1969; Watson & Lovelock 1983; Alberti et al. 2015; Rombouts & Ghil 2015, and references therein), this set of parameters produces results in agreement with the observed surface temperature of Earth. In particular, the model also shows oscillatory solutions that can reproduce the observed sawtooth-like behavior of palaeoclimate changes (see Rombouts & Ghil 2015 for more details).

Using the above set of parameters, we perform a parametric study of the solutions as functions of the initial fraction \( A_0 \) of land covered by vegetation and of the bare-ground albedo \( \alpha_v \). Moreover, we use different values of \( p \) and \( m \) in order to investigate the effect of land/ocean distribution and the role of the greenhouse effect on planetary climates. We define a “surface water zone (SWZ)” as the circumstellar region where the planetary surface temperature ranges between 273 and 373 K. It depends on the set \{\( \theta \)\} of the variable parameters of the model and can be expressed as a step-wise function

\[
\text{SWZ}(\{\theta\}) = \begin{cases} 1 & \text{if } 273 \text{ K} \leq T \leq 373 \text{ K,} \\ 0 & \text{otherwise.} \end{cases}
\]

Note that SWZ(\{\theta\}) in the parameter space \{\theta\}, generally defines a range where equilibrium temperatures calculated from the model are compatible with the presence of liquid water on a planetary surface, independently from their atmospheric composition.

### 3. TRAPPIST-1 Planetary Climates

The possible climates of the TRAPPIST-1 planetary system are investigated by numerically solving Equations (1)–(2) through a second-order Runge–Kutta scheme for time integration and looking at the stationary equilibrium solutions.
The luminosity of the star is set to

\[ S(a, L_a) = \frac{0.0005}{a^2} S_\odot, \]

where, based on the stellar properties of TRAPPIST-1 (Gillon et al. 2016, 2017), we assumed that \( L_a = 0.0005 \, L_\odot \), \( d_p = a \ast d_\odot \) (\( d_\odot = 1 \, \text{au} \), the Sun-Earth distance), and \( S_\odot / 4\pi d_\odot^2 = 342.5 \, \text{W} \, \text{m}^{-2} \) is the mean solar radiation observed at the top of the Earth’s atmosphere. The initial temperatures are set equal to the equilibrium temperatures obtained by assuming a null Bond albedo (see Table 1 in Gillon et al. 2017) and the scale parameter \( a \) is chosen as the mean distance of each T-x planet to the TRAPPIST-1 star (Gillon et al. 2017).

First, we consider the case of rocky planets (\( p = 1 \)) with no vegetation (\( A = 0 \)) and no greenhouse effect (\( m = 0 \)). In Figure 1 we show the stationary solutions for the temperature of the planets, obtained from Equations (1)–(2), as functions of the star–planet distance, for different values of the bare-ground albedo \( \alpha_g \).

When \( \alpha_g \) is set to zero (i.e., for black dots in Figure 1), solutions reported in Table 1 of Gillon et al. (2017) are obtained, since they are equilibrium solutions of an energy-balance climate model with a null Bond albedo hypothesis. Moreover, in this case only T-c and T-d reside in the SWZ. However, as the bare-ground albedo \( \alpha_g \) is changed, different conditions can be observed, that is, as \( \alpha_g \) increases some T-x planets can enter or exit the SWZ. For example, T-b could host surface liquid water on its surface only for a range of \( \alpha_g \) close to \( \alpha_g \approx 0.5 \). This suggests that in the simple case when planets are mainly rocky and without atmospheres, their residence in the SWZ is dependent on their surface albedo. This consequently implies that the vegetation coverage is the main feedback acting as a thermal regulator for planetary temperature.

For the above reasons, in the following we investigate the climate properties of the planetary system when planetary conditions, related to different surface vegetation coverage and bare-ground albedo, are considered. We will show, in detail, T-x temperatures for three different situations: (i) rocky planets without oceans or ice (\( p = 1 \)) and without the greenhouse effect (\( m = 0 \)); (ii) Earth-like land distributions (\( p = 0.3 \)) without the greenhouse effect (\( m = 0 \)); and (iii) Earth-like land distributions (\( p = 0.3 \)) with a greenhouse effect similar to that observed on Earth (\( m = 0.6 \)). This gradual approach is useful for investigating planetary climates starting from different conditions, in order to make a comparative study on the possible climates of TRAPPIST-1 planets by considering several possible situations.

The stationary solutions for temperatures in the plane \((\alpha_g, A_0)\) are shown in Figure 2 for the case of rocky planets (\( p = 1 \)).
This indicates that vegetation acts as feedback that maintains conditions for which SWZ\( (\theta) = 1 \). A similar behavior is recovered for T-d, but only for higher values of \( A_0 \) (\( A_0 > 0.8 \)), suggesting that this exoplanet should be almost completely covered by vegetation to reside in the SWZ. Conversely, due to its lower distance from the star, T-b shows an opposite behavior, entering the SWZ for lower values of \( A_0 \), namely \( A_0 \approx 0.5 \). For the planets T-e, T-f, T-g, and T-h, even using the Earth’s value of \( m \), outer exoplanets cannot reach global surface temperatures in the range \([273 \text{ K}, 373 \text{ K}]\). This implies that these planets need a different greenhouse effect with respect to the Earth, and consequently a different atmospheric composition, to enter the SWZ. These results are quite different from those by Gillon et al. (2017), who showed that outer planets, with Earth-like atmospheres, could host water oceans on their surfaces. This could be related to the main difference between our model and that used in Gillon et al. (2017). While in our model the greenhouse effect is included using a parametric approach (Sellers 1969; Alberti et al. 2015), Gillon et al. (2017) utilized a 1D radiative-convective cloud-free model in which the greenhouse effect is taken into account by considering the contribution of several types of greenhouse gases (e.g., CO\(_2\), H\(_2\)O, N\(_2\)) with...
different partial pressures (Wordsworth et al. 2010). However, our results are quite in agreement with that reported by Wolf (2017), who showed, using a 3D climate model, that outer planets (i.e., T-f, T-g, and T-h) are not warmed enough, falling beyond the HZ and entering a snowball state. On the other hand, inner planets T-b and T-c show higher surface temperatures, so to reside in the SWZ their greenhouse effect should be similar or less efficient than that on the Earth. In particular, T-b cannot be in the SWZ for an Earth-like greenhouse effect, while, when low values of $A_0$ and high value of $\alpha_g$ are considered, T-c is in the SWZ for a narrow range of the model parameters. These results for inner planets are also in agreement with Wolf (2017), who reported that the inner three planets (T-b, T-c, and T-d) could reside in the traditional liquid water HZ but only with runaway greenhouse conditions.

The SWZ changes significantly with the planetary atmospheric composition, such that, for instance, the first three planets can reside in the SWZ for a wide range of the parameters, or, in some cases, even none of them can be there. In particular, it is interesting to see whether T-e, which is at the center of the system, could enter the SWZ, since previous studies by Wolf (2017) have suggested this planet has the best chance to have water oceans on its surface. For this reason, we investigate changes in the SWZ, keeping $\alpha_g = 0.4$ fixed and varying both $p$ and $m$.

In Figure 5 we show the stationary solutions for temperatures in the plane $(p, m)$. As expected, the planetary surface temperature strongly depends on the greenhouse effect conditions. In particular, T-b has a very narrow range of surface liquid water for very low values of $m$, while planets T-c and T-d have a wide range of parameters for which SWZ ($\{\theta\} = 1$). Interestingly, for high values of $p$ and $m$, T-e enters the SWZ. In an Earth-like situation this planet cannot have surface liquid water for lower values of $m$, suggesting that its atmosphere must have higher levels of greenhouse gases, such as CO$_2$ or N$_2$, with respect to those observed on Earth. This result is quite different from that obtained by Wolf (2017), who claimed T-e has the best chance to be a habitable ocean-covered planet. This discrepancy could be related to the fact that our model considers the greenhouse effect in a parametric way, while the 3D model used in Wolf (2017) directly uses the contribution of several types of greenhouse gases, such as N$_2$ and CO$_2$ (similarly to Wordsworth et al. 2010). Indeed, a zero-dimensional climate model can determine the effective planetary emissivity of long-wave radiation emitted to space, while a radiative-convective model considers different processes of energy transport, from radiative transfer through atmospheric layers, to heat transport by convection. This allows a direct investigation of the effects of varying greenhouse gas concentrations on thermal energy balance. However, although the results are different, the number of unknowns makes it not

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**Figure 4.** Equilibrium solutions for temperatures in the plane $(\alpha_g, A_0)$, for planets with an Earth-like fraction of land and oceans and a greenhouse effect $(p = 0.3, m = 0.6)$. The surface water zone, when present, is shown through dashed lines.
possible to know which climate model is more likely. Finally, outer planets (T-f, T-g, and T-h) seem to not be in the SWZ, entering a snowball state (Wolf 2017), even if the greenhouse effect increases to higher levels than those observed on Earth.

4. Conclusions

In this paper we investigated the climate of the TRAPPIST-1 planetary system using a zeroth order energy-balance model that allows us to outline the main features of the different planets. We found that the SWZ, defined as the circumstellar region where a planet can host liquid water on its surface, is strongly dependent on the different parameters of the model, particularly the initial fraction of vegetation coverage, the bare-ground albedo, and the presence of oceans. More specifically, the “inner” three planets T-b, T-c, and T-d seem to be located in the SWZ for several values of the parameters, as described before, while planet T-e, at variance with what has been reported in Gillon et al. (2017), can present water oceans only for greenhouse effect conditions different from those of Earth. The climate of planet T-d seems to be the most stable from an Earth-like perspective because this planet resides in the range of SWZ(θ) = 1 for a wide interval of reasonable values of the different parameters. This result is not in agreement with that reported by Wolf (2017), for whom the best candidate for a habitable ocean-covered surface is the planet T-e. This difference could be related to the different models employed: in our energy-balance model a parametric description of the greenhouse effect is used, while in the 3D climate model by Wolf (2017) the contributions of several types of greenhouse gases are taken into account. However, since the number of unknowns makes it difficult to choose one model with respect to another, different approaches, based either on simple or more complex climate models, can be useful. In this framework, our model has the advantage of transparency through minimal assumptions, allowing comparative sets of cases to be studied.

Here, we showed that the TRAPPIST-1 system can have different climates and that equilibrium temperatures depend on the global albedo, that is, on the mean physical conditions of the planetary surface. However, this parameter is strongly variable, since the vegetation could cover only a fraction of the surface, such as, for example, the case of Earth. Moreover, the greenhouse effect also needs to be properly considered since it is one of the main feedback mechanisms for regulating thermal energy balance. Investigating these features requires more sophisticated models, extended to space variables, at least with a description of the atmospheric heat diffusion. The model is actually under investigation and results will be reported in a forthcoming paper.

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