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Determining and Identifying Stable and Habitable Climates of Exoplanet Gliese 581g

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Abstract

This research attempts to determine the atmospheric conditions needed to create a stable, habitable climate on Gliese 581g and other exoplanets, and to determine whether that climate is uniquely identifiable with the James Webb Space Telescope (JWST). Exoplanets like Gliese 581g are tidally locked, meaning its rotational period equals its orbital period; one hemisphere is always facing its star, making permanent day and night sides. This makes the day side very hot and the night side very cold. Adding an atmosphere allows for heat to be distributed, cooling the day side and warming the night side. Our model assumes that the ground temperature depends only on zenith angle, the air temperature is constant over the entire exoplanet, and the incoming solar energy is constant. Our energy balance model (EBM) equates incoming and outgoing energy, leaving the exoplanet in equilibrium. We require energy balance both on Gliese 581's surface and at the top of the atmosphere (TOA). The surface EBM finds the ground temperature, for each zenith angle, for a given air temperature. The Ice/Water albedo feedback loop then updates the surface albedo, allowing for a liquid ocean or ice sheets, depending on the current ground temperature. Those temperatures determine the thermal energy Gliese 581g emits. The TOA EBM balances this energy to incident solar energy and returns an updated air temperature. This new air temperature is used to solve for new ground temperatures. This process is iterated multiple times until it approaches a stable atmospheric state. Using this model, we can find what atmospheric conditions allow for stable day side temperatures that are high enough to be detected by the JWST, yet cool enough to have Earth-like temperatures.
keywords Habitable Climate; Gliese 581g; Energy Balance Model.

Keywords: Climates, Exoplanet, Gliese 581g

1 Introduction

Exoplanets have been fascinating the world for decades. The first exoplanet, HD 114762, was discovered in 1989[1]. Since then, more than 3000 exoplanets have been confirmed using techniques, such as planetary transits[2,3] and radial velocity measurements[4,5,6,7], which can be used to understand the exoplanet's mass, radius, orbital distance, and atmosphere. Using this information, we can create models that will simulate the climate of the exoplanet. Even if a planet exists in their star's Habitable Zone (HZ), the range of orbital distances where liquid water could exist on the plant's surface, that does not imply that there is liquid water only the possibility that it could exist. For example, Mars is thought to be inside the sun's HZ[8,9], but it lacks the atmosphere necessary to maintain liquid water. Modeling the planet's atmosphere allow us to estimate the planet's possible climate states. One such model is a Global Climate Models (GCMs). These are descriptive atmospheric models that are typically used when investigating exoplanetary atmospheres[10,11,12,13,14]. As the model becomes more representative simulation of a planet's atmosphere, its complexity grows. Due to a CGM's complexity, they require days of running on supercomputers to produce results. Instead of a CGM, an Energy Balance model provides a broad understanding of the planet's atmosphere. What they lose in complexity, they gain in short run times while still providing a decent overview of the planet's climate.

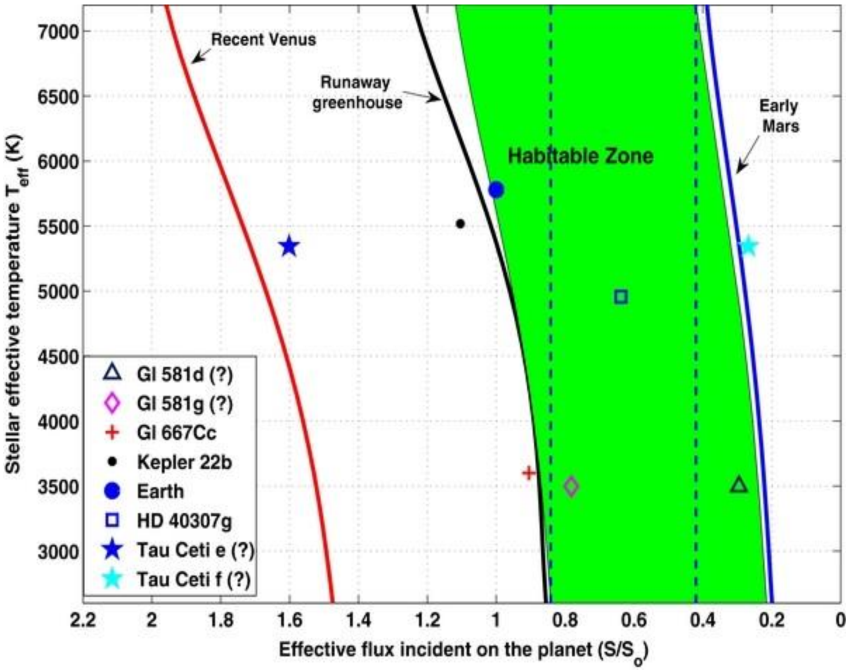

Figure 1: Image from Kopparapu[9]. This graph describes the amount of incoming stellar energy (relative to the solar flux received from the Sun) compared to the star's effective temperature. Planets within the green band are likely to support liquid water, like Earth or Gliese 581g.

Pierrehumbert[15] developed an Energy Balance model to understand the climate states of Gliese 581g (GJ 581g), an exoplanet located within the HZ (Figure 1)[7]. They define a simple energy balance called the Weak Temperature Gradient (WTG) Energy Balance Model. At GJ 581g's orbital distance, the planet is likely to be tidally locked to its star. Tidally locked planets have rotation rates which are equal to their orbital period. This slow rotation rate leads to a very weak Coriolis Effect which causes the atmosphere to transport heat very efficiently or a small temperature difference between any two locations. From the WTG assumption, it can be approximated that the planet's atmosphere has a constant temperature at any point on the planet. We have modified their model to incorporate a greenhouse effect and an ice-albedo feedback. The greenhouse effect will allow the atmosphere to absorb and re-emit energy, increasing the energy received by the surface. The ice-albedo feedback allows for ice to melt/freeze depending on the surface temperature, allowing for oceans, like an "Eyeball Earth" state[15].

GJ 581g will be used a test case due to its location in the habitable zone, similarity to Earth's mass and likelihood to be tidally locked. Even though we will be comparing this model to Pierrehumbert's WTG Energy Balance model, this model is general enough to be applied to any terrestrial planet with a relatively thin atmosphere. This model will not work for planets with thick atmospheres, like Jupiter or Venus.

2 Weak Temperature Gradient Energy Balance Model

An energy balance model finds which climates where the amount of incoming and outgoing energies are equal. The conditions where these energies are balanced means that the planet's climate is in equilibrium (or a steady state). It's like a mug of coffee left out to cool. After some time, the coffee has cooled. The amount of energy the coffee releases into the room is the same as the incoming energy, leaving it in a steady state. In addition to being in equilibrium, they climate must be stable. When in a stable state, after a small disturbance from equilibrium will return the planet to its original state. For the current day Earth, receiving too much energy causes the surface to warm, increasing the outgoing energy from the planet. This increased radiation reduces the temperature back to equilibrium. However, the Earth has multiple possible equilibrium states one of which is unstable. When at an unstable equilibrium, this slight disturbance will lead to a climate that "runs" away from the original state, like the difference between balancing a cone on its base versus on its tip. If the Earth was in an unstable state, any slight temperature increase leads the system to increase the incoming energy, increasing the temperature even more. This continues until the climate settles into the next equilibrium, see section 4. Since these climates will move away from these states quickly, they will rarely be observed. Thus, we only need to focus on the planet's stable equilibrium.

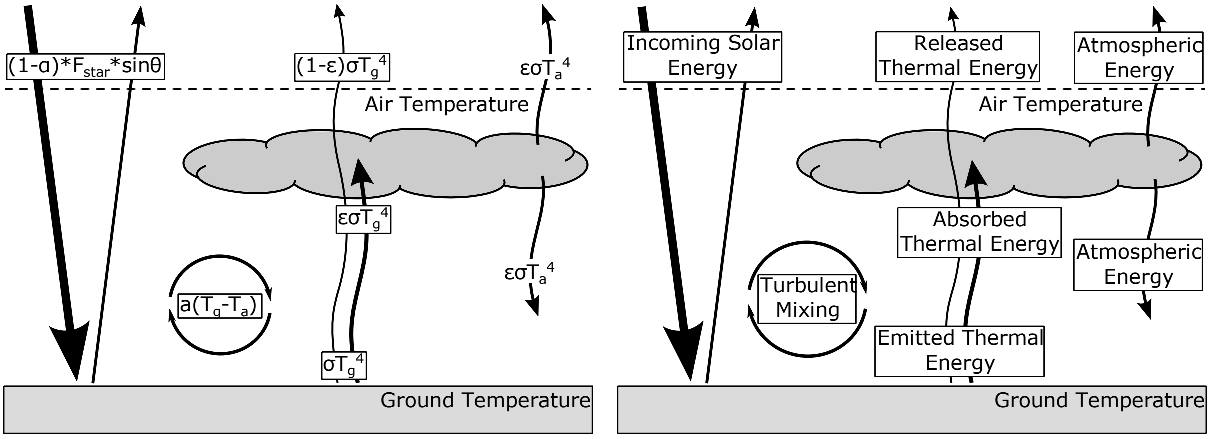

Figure 2: (Left) The flow of energy is described using the arrows. Passing through the surface or ToA boundary adds that term to the respective equation. (Right) This diagram depicts the same energy flows but with labels that represent the energy that that arrow is describing.

From Pierrehumbert's WTG Energy Balance model[15], we can define energy balance from Equations (1) and (2). Equation (1) is a surface energy balance, making sure that the incoming and outgoing energies are equal at each point on the planet's surface. Equation (2) is a top of atmosphere (ToA) energy balance, making sure the total amount of energy coming in and out of the planet are equal.

$$(1-\alpha)F_{star}\sin\theta + \varepsilon\sigma T_a^4 = \sigma T_g(\theta)^4 + a(T_g(\theta) - T_a) \tag{1}$$

$$\int_{-90}^{+90}(1-\alpha)F_{star}\sin\theta\cos\theta\, d\theta = \int_{-90}^{+90}\varepsilon\sigma T_a^4\cos\theta\, d\theta + \int_{-90}^{+90}(1-\varepsilon)\sigma T_g^4\cos\theta\, d\theta \tag{2}$$

When both are satisfied, then each position (θ) and the entire planet are in equilibrium. But what do these equations even mean? Written out, how the energy flows may be confusing, but Figure 2 depicts how the energy flows and why these terms are what they are. For each equation, the incoming energies are to the left of the equals sign. The ToA energy balance has incoming solar energy which depends on the reflectivity of the surface (α) and received stellar flux from the star (F_{star}). The surface is receiving energy from both the star ($F_{star}\sin\theta$) and the atmosphere, described by the Stefan-Boltzmann law. The amount of received solar energy changes depending on location on the planet and is proportional to the sine of the position (θ) (Figure 2, Right). It must be noted that if $\theta < 0$ then the location is on the dark side of the planet so ($F_{star}\sin\theta$) drops to zero. To be expected, the outgoing energies are to the right of the equals sign. The surface emits some amount of energy, described by the Stefan Boltzmann Law, and from a turbulent mixing term, which is proportional to the difference in temperature between the surface (T_g) and the atmosphere (T_a). The proportionality constant (a) depends on the atmospheric temperature and the atmospheric pressure (P_s)[15]. The ToA energy balance has some released energy from the emitted atmosphere energy and the emitted surface energy, also described by the Stefan-Boltzmann Law, that was not absorbed ($1-\varepsilon$) by the atmosphere, due to the greenhouse effect.

However, these equations only work for a tidally locked planet, as described above. To allow for a rotating planet, we can re-frame how we defined θ. For a rotating planet, like Earth, it would be better to use latitude to define your location (Figure 3).

$$\frac{1}{\pi}(1-\alpha)F_{star}\sin\theta + \varepsilon\sigma T_a^4 = \sigma T_g(\theta)^4 + a(T_g(\theta) - T_a) \tag{3}$$

$$\int_{-90}^{+90}\frac{1}{\pi}(1-\alpha)F_{star}\cos\theta\cos\theta\, d\theta = \int_{-90}^{+90}\varepsilon\sigma T_a^4\cos\theta\, d\theta + \int_{-90}^{+90}(1-\varepsilon)\sigma T_g^4\cos\theta\, d\theta \tag{4}$$

The cosine term came from the 90° rotation so the model can use latitude for position. It may seem that we are forgetting Longitude, but that is taken care of from the new $\frac{1}{\pi}$ term. At noon, the sun reaches its highest point in the sky. Currently, for a tilt less planet, the sun has an altitude equal to 90°-the latitude. However, at sunrise/sunset the sun's altitude is much lower, reducing much energy is being received. When accounting for these decreases, it comes out to a reduction of exactly $\frac{1}{\pi}$.

This model relies on the Weak Temperature Gradient (WTG) approximation states that a region that has a weak Coriolis Effect has a very efficient heat transport, leading to the atmospheric temperature to be nearly constant over the region. Since tidally locked planets have slow rotational periods, the Coriolis Effect is weak across the entire planet's surface so we assume that the atmospheric temperature is constant over the entire planet. The rotating planet's rotational period is no longer slow enough for the WTG to be a valid assumption. To keep this model simple, the WTG approximation is applied to the rotating planet scenario. This approximation will over estimate the amount of heat transport performed by the atmosphere, which will lead to warmer poles and cooler tropic regions.

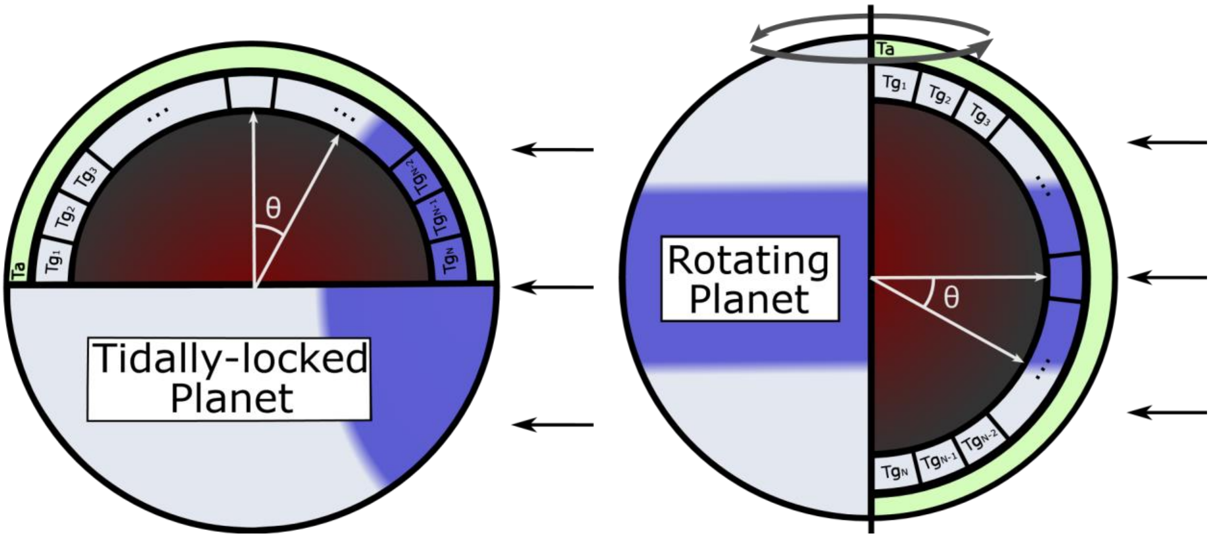

Figure 3: The tidally locked planet (Left) has positions θ that depend on the angle between the terminator and your location on the surface. +90° is the sub-solar point and −90° is the anti-solar point. The rotating planet (Right) has positions θ that depend on your latitude, like Earth, as your location on the surface. +90° is the North Pole and −90° is the South Pole.

3 Methods

The Surface Pressure (P_s), Stellar Flux (F_{star}), and Emissivity (ε) are the parameters for this model. Surface Pressure affects thickness of the atmosphere and the efficiency of the turbulent mixing term. Stellar Flux dictates how much stellar energy the planet receives which is affected by the brightness of the star and the orbital distance of the planet. Finally, Emissivity affects the strength of the greenhouse effect. There is an additional parameter that decides if the planet is tidally locked, Equations (1) and (2), or rotating, Equations (3) and (4).

For a given set of parameters, how to find the values of T_a and T_g? Since the surface and ToA energy balances depend on each other, they cannot be solved conventionally. They must be numerically approximated. An initial value of T_a is approximated allowing us to solve for T_g using a root finding method. Root finding methods approximate the roots of some function or in other words they find the value of x when $F(x) = 0$ (Figure 5). Using a Newton's root finding method, the value of T_g is found at a position θ. This process this then repeated for each potion between −90° and +90°. The surface energy balance is satisfied at each position, but the ToA energy has yet to be satisfied. With each ground temperature, the total amount of incoming/outgoing energy is calculated using the ToA energy balance. it is unlikely that the ToA energy balance will be satisfied given the initial approximate atmospheric temperature that was chosen. Using another root finding method, a secant method, the value of T_a is updated. Using this new atmospheric temperature, the ground temperatures are again calculated, same as before. This process is iterated and will quickly approach the temperatures that satisfy both equations. This cyclical, iterative process can be seen on model flowchart (Figure 4). It should be noted that the surface albedo (reflectivity) depends on the whether the surface is water or ice, thus the ground temperature. It is due to this that allows us to determine if there is liquid water on the planet (Figure 4).

The previously mentioned process finds a single balanced climate state. As previously stated, a planet may have in multiple equilibrium states. The current day Earth has three. To find all the possible equilibrium states, this entire process must run multiple times, with varying initial values of T_a.

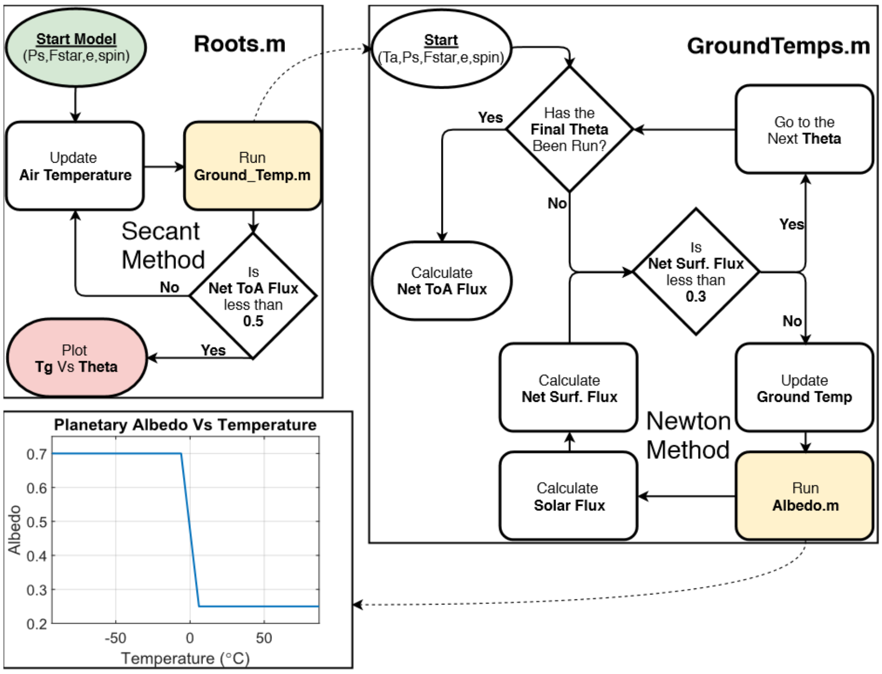

Figure 4: The right figure describes how the code find these roots. For a certain set of parameters, this model returns a temperature profile for those conditions. Notice that the cyclical nature of updating the temperatures until the surface and ToA energy balances are satisfied. The graph in the lower left describes the albedo as a function of ground temperature. Around 0°C the albedo drops due to the highly reflective ice melting into less reflective oceans.

4 Results

The model outputs a series of graphs based on the given parameters (surface pressure (P_s), stellar flux (F_{star}), emissivity (ε) and the rotation). The first graph plots ground temperature vs position (e.g. Figure 7). Additionally, the model produces an Atmospheric Temperature vs Net_ToA_Flux graph (referred to as a NetFlux diagram). It is this function whose roots are found using the secant method. At root 1 (Figure 5), a small increase in air temperature leads to a rise in ground temperatures and thus an increase in the amount of energy emitted from the planet more outgoing energy causes temperatures to decrease, returning the planet back to equilibrium, so root 1 must be stable. The same argument shows that root 3 is stable too. Root 2 is where things change. As the air temperature increases, the planet, paradoxically, has an increase in Net_ToA_Flux. This increase then leads to more energy coming into the planet, rising temperatures even more. When the planet is in this state, the climate is not stabilizing, like it was for roots 1 and 3. Thus the root in this region must be unstable. The cause for the instability in this region is the ice-feedback loop. When temperature increases in this region, it causes some ice to melt. Since water has a reduced albedo, it absorbs more energy, increasing the incoming energy.

Using this model, three different scenarios were tested, varying only one parameter (rotation, stellar flux, and surface pressure) in each case. Emissivity was keep constant for each experiment. A fourth experiment was run, based off the previous results, to compare the differences between a planet with no atmosphere (Like Mercury) and a planet with a thin atmosphere (like Mars).

4.1 Tidally locked vs Rotating planet

Tidally locked planets are much more sensitive to changes in stellar flux than rotating planets are. The tidally locked planet has a range of about 40 W/m^2 where multiple climate states could exist. These climate states occur within a range of about 200 W/m^2, between 1250 and 1450 W/m^2 (Figure 6, Top Left). The rotating planet has a range of 200W/m^2, which is over quadruple that of the tidally locked planet. The range of stellar fluxes is between 1500 and 2500 W/m^2 (Figure 6, Top Right), about 5 times larger than that of the tidally locked planet. The tidally locked planet is much more sensitive to the value of F_{star} than the rotating planet is. The tidally locked planets are more sensitive to changes in surface pressure as well. At a pressure of 1E+05 Pa (Blue for Figure 6, Bottom Left; Yellow for Figure 6, Bottom Right), there is a significant difference. The tidally locked planet begins melting at much lower air temperatures, about 185 K compared to 245 K for the rotating planet. The melting region is much narrower for the rotating planet, showing that the rotating planet is better at averaging out the surface temperatures than the tidally locked case.

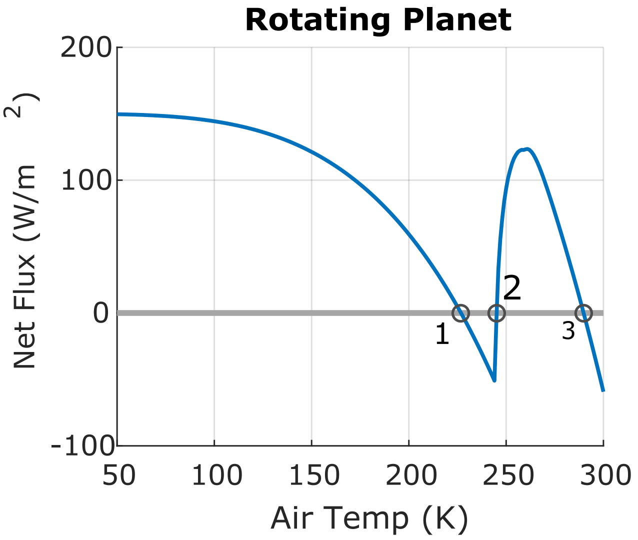

Figure 5: The left figure describes the net energy flow in/out of the planet as function of the planet's atmospheric temperature. When NetFlux is positive then the amount of incoming energy is greater than the outgoing energy.

4.2 What Happens as Stellar Flux is Varied?

Increasing stellar flux causes more incoming stellar energy. The surface receives more energy, heating up the ground and the atmosphere. This leads to a larger thermal output from the planet, returning the climate back to equilibrium (Figure 7, Any Row). This result is also seen from the NetFlux diagrams. As stellar flux is increased, each position on the planet receives more solar energy, incrementally rising Net_ToA_Flux at each temperature (Figure 6, Top). The stable roots of this function occur at higher air temperatures, as expected. The graphs also show a slight left shift of the turn off point into the ice melting region. This is caused by ice melting at lower air temperatures due to the increased absorption of stellar energy

4.3 What Happens as Surface Pressure is Varied?

A greater surface pressure makes the atmosphere better at transferring energy between positions on the planet. The hot sub-solar region gives away energy making the colder night side region rise in temperature. For low pressures, the lack of heat transport allows the sub-solar/equatorial region to maintain high temperatures while the cold regions stay cold. When the atmosphere is thick, the increase in heat transport takes energy from the hot regions and warms up the colder regions (Figure 7, Any Column).

Changing the surface pressure did not cause a shift on the Netflux diagram. It only changes when the turning point on the NetFlux diagrams occurred (Figure 6, Bottom). As the pressure increased, the turn off point occurs at higher atmospheric temperatures. The increase in heat transport means that the sub-solar region requires higher air temperatures before ice begins melting. When the atmosphere get thicker, the ice melting region becomes narrower and focuses in around the ice's melting temperature. This signifies that this feature is caused by the ice-feedback loop. At low pressures, the sub-solar region can melt, and melting occurs gradually as atmospheric temperature is increased, making a wider ice melting region. At high pressures, the surface temperatures are averaged out. The air temperature must be close to the melting temperature before any melting can occur. Since the temperatures are well averaged, if one-part melts, the rest of the planet is close to melting as well. A small change in atmospheric temperature causes a large amount of ice to melt, which explains why the ice melting region becomes narrower at higher pressures and why low surface pressure allows parts of the surface to start melting (sub-solar region) at substantially lower atmospheric temperatures.

4.4 No Atmosphere Vs Thin Atmosphere

When an atmosphere that is 100 times thinner than Earth is introduced, the temperature difference decreased by 76°C. The sub-solar point only decreased by 3°C while the night side increased by 73°C (Figure 8). The large increase in the night side temperature demonstrates that the atmosphere is redistributing heat between the day and night side. The introduced atmosphere has a surface pressure similar to Mars' atmosphere[17]. Even with such a thin atmosphere, there was a significant decrease in the temperature difference between the day and night sides of the tidally locked planet.

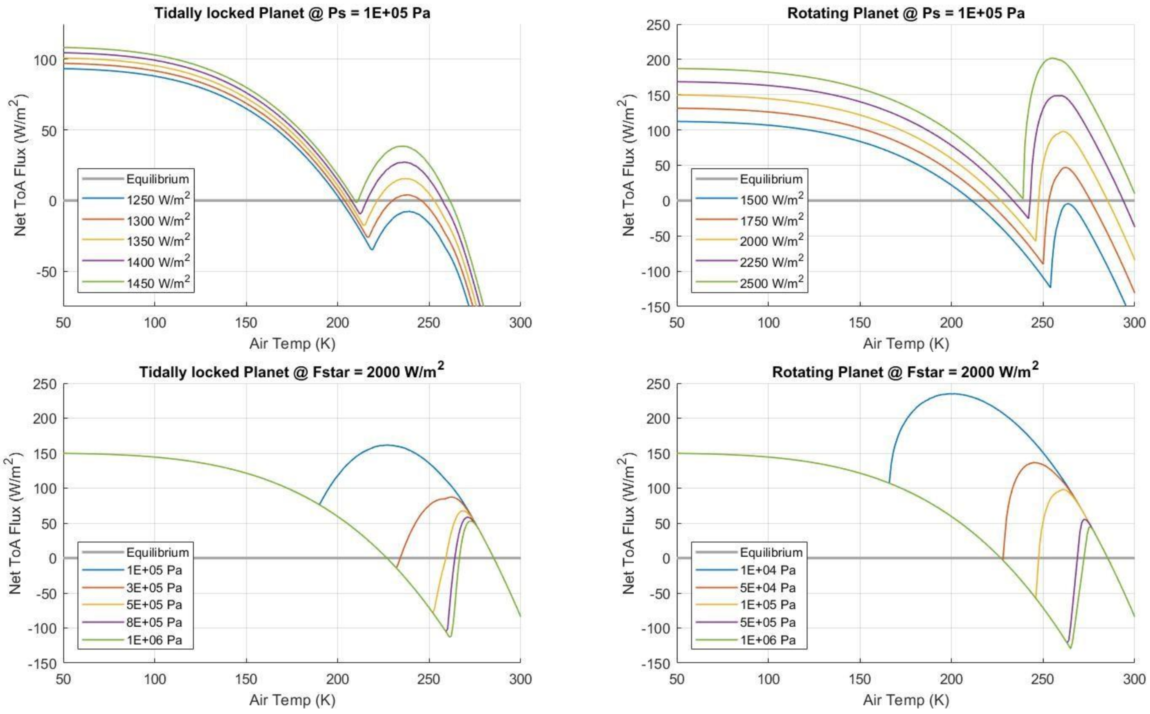

Figure 6: These Netflux diagrams show how changing stellar flux (Top) and changing surface pressure (Bottom) affect the equilibrium climates for tidally locked (Left) and rotating (Right) planets. Note that the ranges used between tidally locked and rotating planets are not the same. The emissivity was constant across all these trails and equal to 1.

5. Conclusion

Changing the parameters has a large impact on the planet's temperatures. The stellar flux changes how much energy the planet receives from its star, causing the temperatures needed to maintain equilibrium to increase or decrease. A planet with a large stellar flux receives more energy so the planet became hotter, thus emits more energy to balance the climate. Surface pressure affected how efficient the heat transport within the atmosphere is. For a thick atmosphere, the planet's surface temperatures are almost uniform over the planet's surface. Emissivity changes how much the atmosphere absorbed and emitted back toward the surface. As the atmosphere absorbed more energy, the emitted energy was able to keep the surface much warmer than if the greenhouse was not present or very strong. The rotating planet shows the same trends as the tidally locked planet, but the tidally locked planet is much more sensitive to the parameters than the rotating planet, having a small range of parameters that can support multiple climate states.

This model shows that tidally locked planets can support multiple equilibrium. Under certain parameters the tidally locked planet had no multiple equilibrium while rotating planet always had multiple equilibrium[14]. However, for planets that are efficient at transporting heat between the day and night side, the plant could have multiple equilibrium states. Due to the Weak Temperature Gradient (WTG) approximation, the atmosphere is incredibly efficient at energy transportation. The presence of multiple equilibrium is also related to weak sub-solar cloud coverage, which is another assumption thus model makes. Thus, this model matches what has previously been found regarding tidally locked planets supporting multiple equilibrium states.

The atmospheric pressure plays an important role in the planet's ability to support water. When the planet has a low pressure, the surface's temperatures are non-uniform. In this case, the sub-solar region gets hot causing ice to melt at low air temperatures. When the stellar flux is low, then only the sub-solar region will support liquid water (Figure 7, Top Left). If the pressure is increased, then the ground temperatures become uniform and the sub-solar region cannot get hot enough to start melting (Figure 7, Bottom Left). If instead the planet closer at a low pressure (Figure 7, Top Right), the planet is receiving too much energy from the star, keeping the night side just above melting. However, if this hot sea world had a thick atmosphere, it would average the hot sub-solar region, warming the relatively cool night side, returning to a habitable climate (Figure 7, Bottom Right). Thus planets with thin atmospheres, like Mars, are able to support liquid water at further orbital distances than planets with thick atmospheres.

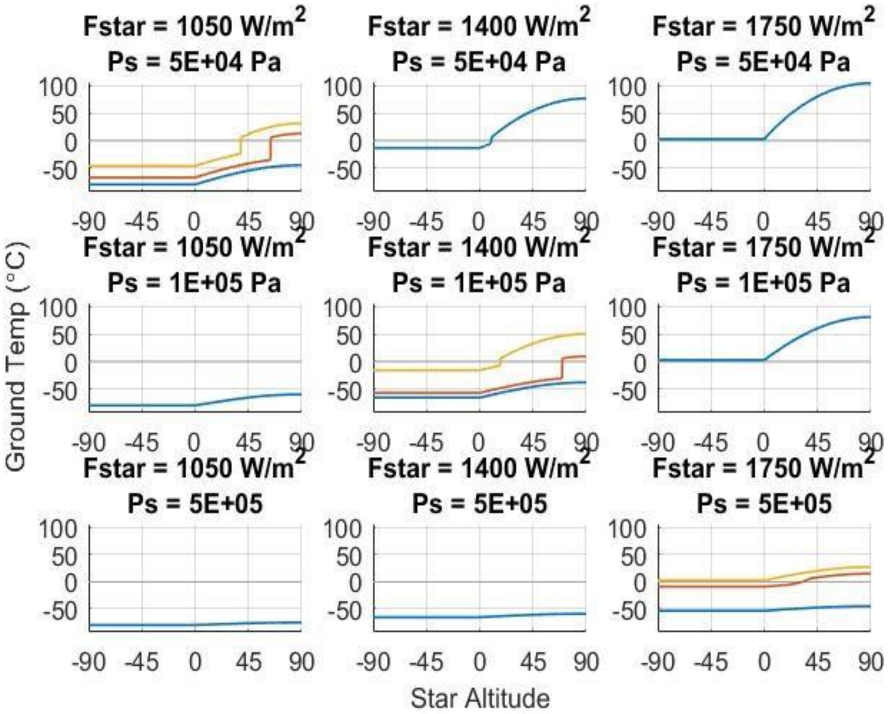

Figure 7: Each row has a constant surface pressure while each column has a constant stellar flux. Each diagram depicts the ground temperatures over the planet's surface (θ) for a tidally locked planet (where $\varepsilon = 1$). Sharp jumps in these graphs indicate that there is a water/ice boundary at that location.

To understand how well the model is working, we applied both Earth-like and Gliese 581g-like (GJ 581g) parameters[14,15]. Pierrehumbert's Global Climate Model (GCM) conditions are not as clearly stated but we will assume that they used these approximate values, F_{star} = 866 W/m^2, P_s = 1e5 Pa, and ε = 0.77. Under these conditions, the effect from the emissivity was near negligible, so we have assumed an Earth-like emissivity. For GJ 581g-like conditions, there were no stable states that allowed for liquid water on the planet's surface, regardless of whether the planet was rotating or not.

Under these Earth-like conditions, (F_{star} = 1360 W/m^2, P_s = 1e5 Pa, and ε = 0.77) the model showed no liquid water for the rotating planet. To assess the accuracy of the model, conditions matching the current day Earth were found. The Earth is near the inside edge of the Sun's habitable zone (Figure 1), so to match this state, the model planet must be close to the HZ as well. By changing only stellar flux, the model matches Earth-like conditions at

1710 W/m^2. This gives the model a percent error of 25%, which is a fair given the purpose of this model and the approximations that were made.

The percent error from the model is due to the approximations that were made while setting the model up. The biggest factor was making the Weak Temperature Gradient (WTG) approximation for both tidally locked and rotating planets. The WTG approximation is valid for tidally locked planets[15,16] and over estimates the amount of atmospheric temperature averaging on the rotating planet. Another approximation was the ocean's albedo of 0.25 rather than 0.1. This was to account for scattered cloud coverage over the ocean. However, the amount of clouds could depend on the surface pressure, air temperature and humidity (which is not being accounted for either). We have also assumed an atmospheric composition composed of only Nitrogen molecules. The Earth's atmosphere is mostly nitrogen, so this assumption is only marginally invalid in these cases. The addition of other elements would just affect the surface pressure and the atmosphere's emissivity, which are already parameters of the model. Unlike Earth, this model assumes that the planet has no continents. The addition of landmasses, with lower albedos, would affect how much solar energy is absorbed. A landmass in the sub-solar region would not absorb as much stellar energy making it so the amount of incoming radiation is not great enough to keep the ice melted, keeping the planet completely ice covered[15].

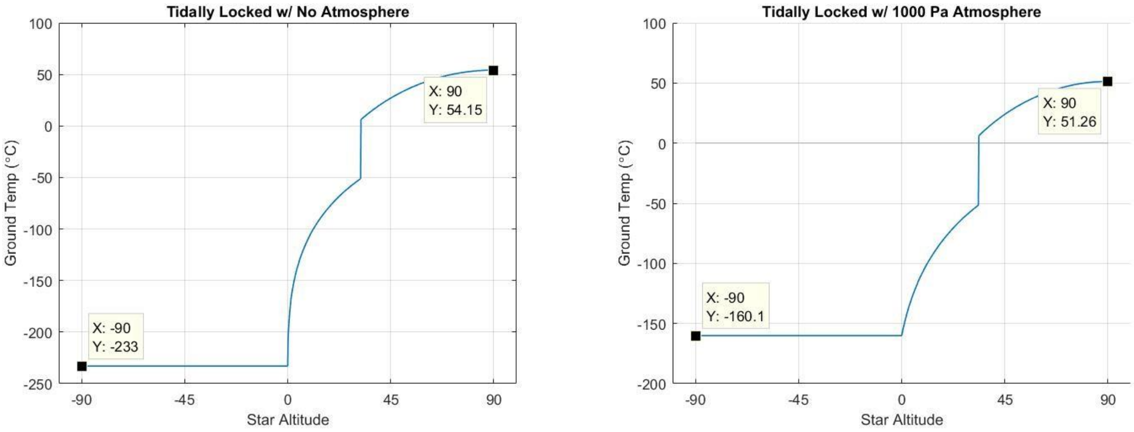

Figure 8: When the model is given a planet without an atmosphere (Left), there is temperature difference of 287.15°C between the sub-solar point and anti-solar point. (It must be stated that these results are approximate, as it appears as if there would be liquid water on this planet's surface while any water would have boiled off leaving a Mercury like planet behind) With a Mars like atmosphere, the temperature difference was reduced to 211.36°C.

Another factor is that this model finds steady states using a simplified atmospheric model. Pierrehumbert's work used a more detailed GCM which took into account more factors than our model could. Using this simplified model, the result was not going to be as representative as a GCM could have been[16]. From these findings, it is concluded that this energy balance model is useful for qualitative findings rather than replicating real world observations[14,15,16]. They are useful for understanding the rough idea of a stable climate, rather than the detailed results produced by a GCM.

6. References

1. D.W. Latham *et al.*, Nature. 339 (6219), 38 (1989).
2. D. Charbonneau, T.M. Brown, D.W. Latham and M. Mayor, Astrophys. J. Lett. 529 (1), L45 (1999).
3. H.A. Knutson *et al.*, Nature. 447 (7141), 183 (2007).
4. X. Bonfils *et al.*, Astron. Astrophys. 443 (3), L15 (2005).
5. S. Urdy *et al.*, Astron. Astrophys. 469 (3), L43 (2007).
6. M. Mayor *et al.*, Astron. Astrophys. 507 (1), 487 (2009).
7. S.S. Vogt *et al.*, Astrophys. J. 723 (1), 954 (2010).
8. F. Forget and R.T Pierrehumbert, Science. 278 (5341), 1273 (1997).
9. R.K. Kopparapu *et al.*, Astrophys. J. 765 (2), 131 (2013).
10. M.M. Joshi, R.M. Haberle and R.T. Reynolds, Icarus. 129 (2), 450 (1997).
11. T.M. Merlis and T. Schneider, J. Adv. Model. Earth. Sys. 2 (13), 17 (2010).
12. F. Selsis, R.D. Wordsworth and F. Forget, Astron. Astrophys. 532, A1 (2011).

13. Y. Kaspi and A.P. Showman, Astrophys. J. 804 (1), 60 (2015).
14. J. Checlair, K. Menou and D.S. Abbot, Astrophys. J. Lett. 845 (2), 132 (2017).
15. R.T. Pierrehumbert, Astrophys. J. Lett. 726 (1), L8 (2010).
16. S.M Mills and D.S. Abbot, Astrophys. J. Lett. 774 (2), L17 (2013).
17. T. Owen, Astrophys. J. 146, 257 (1966).