Utrecht University

Simulation of Ocean, Atmosphere and Climate
NS-MO501M

# Daisy World (Gaia Hypothesis)

*Authors:*
Timothy van der Duim (5989345)
Freerk Drijfhout (4009509)

*Supervisor:*
Dr. Aarnout van Delden

February 4, 2021

Universiteit Utrecht

# 1 Introduction

In 1969, the English scientist James Lovelock formulated the so-called Gaia Theory (Lovelock and Giffin, 1969). This theory states that the biosphere interacts with its inorganic environment in such a way that it helps maintaining the best possible conditions for life on Earth. The biosphere can be visualized as one huge living organism that can form a self-regulating system. This organism can adapt to changes in global temperature, but can also change the climate itself.

14 years later, James Lovelock and Andrew Watson (another British scientist) published a paper about a model that they had developed in defence of this Gaia Hypothesis (Watson and Lovelock, 1983). This model is called Daisy World.

Daisy World is created as a suitable tool to understand the feedback loop that can control the climate system. It illustrates that a self-regulating planet can exist between a certain range of temperatures. In this model, the luminosity (that has a linear relationship with temperature) is the single variable that defines the environment. There are no other external forcings.

Daisy world is a simple artificial planet that consists of only two different organisms, black and white daisies. Black daisies have a low albedo and induce a temperature increase of the environment, while white daisies have a high albedo which results in a cooling of their surroundings. Because the planet is completely covered by fertile ground (there are no oceans ore ice sheets), these black and white daisies can grow everywhere.

# 2 Methods

Section 2 and 3 of this report will be subdivided in three different subsections that describe three different versions of the Daisy World model. The first one is based on the Classic Lovelock and Watson model, developed in 1983 (Watson and Lovelock, 1983). In the second model, latitude dependence is implemented by creating a meridional temperature gradient. The main changes in version 3 consist of the addition of an ocean and hence a latitude-variant land fraction (per latitude band of 5 degrees) is implemented. In addition to that, albedos are changed to create a larger resemblance with our own planet Earth. In the discussion ( 4), these three model versions will be compared and discussed together.

## 2.1 Classic Model

The classic Daisy world model can be visualised as a flat disk that is always turned to the sun and where every point on this flat earth receives the same amount of radiation. Hence, there are no seasons, latitudes or a daily cycle and the sun is always shining.

Table 1 shows a list of constants, used as input for the basic equations of the classic model. The most important equation probably being the growth rate of daisies as a function of local temperature $T_i$:

$$\beta_i = 1 - 4\frac{(T_{opt} - T_i)^2}{(T_{max} - T_{min})^2}. \tag{1}$$

Figure 1 shows the results of equation 1, in which the growth rate of the daisies $\beta_i$ is assumed to be a parabolic function of local temperature $T_i$. The local temperature is defined as the temperature of the land around a daisy type, which (subscript $i$) can be either black ($b$) or white ($w$). This is a key aspect of the model: the local temperature ($T_i$) differs for the two daisy types because their albedos (Table 1) cause them to absorb different amounts of solar radiation.

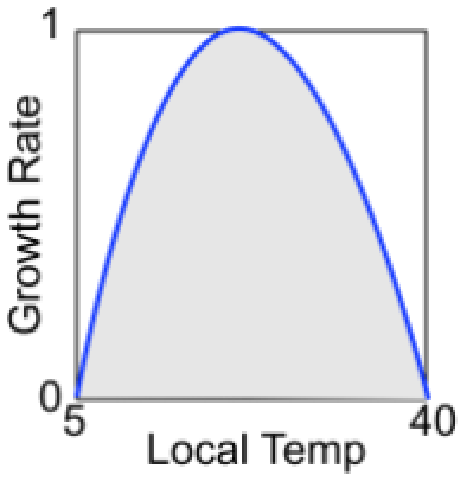


Figure 1: Growth of Daisies $\beta_i$ as a function of local temperature $T_i$

The total amount of incoming solar radiation for Daisy World is defined through the energy balance:

$$T_p = \frac{\frac{1}{4} S_0 L(1-\alpha_p) - I_0}{b}. \tag{2}$$

$T_p$ is the average ground temperature of the planet, $L$ is a dimensionless measure of the luminosity of the sun (a scaling factor for $S_0$) and $\alpha_p$ is the planetary albedo. Assuming a steady state for the local environment of daisy populations, it follows that:

$$\frac{1}{4} S_0 L(1-\alpha_i) - I_0 - bT_i - \beta(T_i - T_p) = 0. \tag{3}$$

$\alpha_i$ stands for the local albedo around a daisy type, which differs for black or white daisies (table 1). $\beta$ (which should not be confused with $\beta_i$, the growth rate) is a so-called relaxation parameter. It represents the redistribution of energy (from warm to cold) between the daisies and environment. From (Budyko, 1968) we take $\beta = 16\ W/m^2/K$.

Table 1: List of constants used for the Classic model

| **Symbol** | **Value** | **Unit** | **Description** |
|---|---|---|---|
| $S_0$ | 1366 | W/$m^2$ | Solar Constant |
| $\alpha_b$ | 0.25 | | Albedo black daisies |
| $\alpha_g$ | 0.50 | | Albedo bare ground |
| $\alpha_w$ | 0.75 | | Albedo white daisies |
| p | 1 | | Proportion of area that is fertile ground |
| $I_0$ | 220 | W/$m^2$ | Constant OLR at 0 degrees Celsius |
| b | 2.2 | W/$m^2$/K | OLR per degree difference |
| $\beta$ | 16 | W/$m^2$/K | Heat transport between daisies and environment |
| $\gamma$ | 0.3 | | Death rate of the Daisies |
| $T_{opt}$ | 22.5 | °C | Optimum temperature for Daisy growth |
| $T_{min}$ | 5.0 | °C | Minimum temperature for Daisy growth |
| $T_{max}$ | 40.0 | °C | Maximum temperature for Daisy growth |

Combining equation 2 and 3, we obtain an equation for the local temperature, which can be used as input for equation 1:

$$T_i = \frac{\frac{1}{4} S_0 L(\alpha_p - \alpha_i)}{b + \beta} + T_p, \tag{4}$$

where $\alpha_p$ (the planetary albedo) is defined as:

$$\alpha_p = \alpha_g A_g + \alpha_b A_b + \alpha_w A_w, \tag{5}$$

i.e. a function of the albedos and areas of black & white daisies and bare ground. As a last step, the equations for those areas are defined:

$$\frac{dA_i}{dt} = A_i(A_g \beta_i - \gamma), \tag{6}$$

$$A_g = p - A_b - A_w. \tag{7}$$

Subscript $i$ in equation 6 can be either black ($b$) or white ($w$). The equation shows that the growth rate ($\beta_i$) is a function of both time and area, while the death rate ($\gamma$) only depends on time. This can be explained by the fact that the available area of fertile ground ($A_g$) has a positive effect on the growth of daisies, whilst they compete with each other for space.

To solve the first order differential equation 6, the fourth-order Runge-Kutta integration scheme with a total amount of 1000 time-steps is used. With this method, steady states for different values of the solar luminosity are calculated. First, the luminosity is slowly increased from 0.8 to 2.8 in steps of 0.05, indicating a warming planet. After that, the same is done for decreasing luminosity, indicating a cooling planet. For every 0.05 step in luminosity, the Runge-Kutta scheme solves for a steady-state, upon which the steady-state solution is used as input for the next step. The results of this method are further discussed in section 3.1.

## 2.2 Latitude Dependence Model

The classic model could be extended to better account for the spherical properties of a planet and its atmosphere. As will be shown, the planet's curvature leads to local growth of daisy populations through spatial variations in solar intensity. Thereby the representation of Daisy World as a flat isothermal disk with a mean solar irradiance of $\frac{1}{4}S_0$, is being omitted.

According to (Pierrehumbert, 2010), the daily mean, non-dimensional solar flux factor $f(\delta, \phi)$ where $\delta$ is the Sun inclination angle and $\phi$ the latitude, both in radians, can be expressed as:

$$f(\delta, \phi) = \frac{1}{\pi}[\cos(\phi)\cos(\delta)\sin(h_t) + \sin(\phi)\sin(\delta)h_t]. \tag{8}$$

This non-dimensional flux number could subsequently be multiplied with the solar constant $S_0$ to obtain the daily average solar irradiance $Q(\delta, \phi)$ (at TOA), i.e.:

$$Q(\delta, \phi) = \frac{S_0}{\pi}[\cos(\phi)\cos(\delta)\sin(h_t) + \sin(\phi)\sin(\delta)h_t]. \tag{9}$$

In equation 9, $h_t$ is the length of the daylight period (in rad). According to (Pierrehumbert, 2010):

$$h_t(\delta, \phi) = \arccos[-\tan(\phi)\tan(\delta)]. \tag{10}$$

For the sake of simplicity, seasonality is not included within the Daisy World model and in order to have symmetry around the equator, the inclination of the Sun $\delta$ is assumed to be zero. From equation 10 follows a daylength of $\frac{\pi}{2}$ (i.e. roughly 12 hours), independent of latitude.

Replacing the mean solar irradiance by a latitude-variant solar irradiance, leads to the following energy balance:

$$C\frac{dT_{lat}}{dt} = QL(1-\alpha_p) - I_0 - bT_{lat}. \tag{11}$$

However, a latitude-variant model where the zonal temperature $T_{lat}$ would merely be a function of 1) solar irradiance $Q$ and 2) daisy growth, leads to unrealistic temperature gradients compared to Earth. Inclusion of a simplistic atmosphere in which meridional heat transport takes place remedies this. This is achieved by adding a relaxation term. (Budyko, 1968):

$$A = \beta(T_{lat} - T_p). \tag{12}$$

Note the similarity between equation 12, which involves a relaxation of the zonal temperature $T_{lat}$ and $T_p$, and the last term of 3 which involves a relaxation of the daisy temperature $T_i$ and the environmental temperature $T_p$. Equation 12 implies a linear relation between the latitude-specific temperature $T_{lat}$ and planetary temperature $T_p$ difference and the meridional heat transport, which was obtained by linearly interpolating meteorological observations (Budyko, 1968). The strength of the relation is controlled by the relaxation parameter $\beta$ as seen in equation 3.

Adding the relaxation term from equation 12 to the energy balance (equation 11), yields for the zonal temperature $T_{lat}$:

$$C\frac{dT_{lat}}{dt} = QL(1-\alpha_p) - I_0 - bT_{lat} - \beta(T_{lat} - T_p). \tag{13}$$

With the implementation of $T_{lat}$ in the model, the physical interpretation of $T_p$ has slightly changed. Where it used to be the physical planetary temperature on an isothermal planet, it should now be seen as the *average* temperature of the planet.

Solving equation 13 for steady state:

$$C\frac{dT_{lat}}{dt} = 0; \tag{14a}$$

$$T_{lat} = \frac{QL(1-\alpha_p) - I_0 + \beta T_p}{b+\beta}. \tag{14b}$$

### 2.3 Ocean Model

The final model adaptation is the inclusion of a latitude-variant (fertile) land fraction based on the geographical location of ocean basins on Earth, an implementation that was not found in any literature. It has two major implications for the model at hand:

a) the low oceanic albedo decreases the albedo of the area not covered by daisies;

b) it restricts daisy population growth as daisy birth rate is coupled with available fertile ground area (see equation 6).

In what is referred to as the Ocean model, there are now four components: an ocean, with albedo $\alpha_o = 0.06$ (NSIDC, 2020); fertile land, with albedo $\alpha_g = 0.17$ (McEvoy, 2011); black and white daisies, with albedos $\alpha_b = 0$ and $\alpha_w = 1$, respectively[1].

[1] Black and white daisies are for the moment assumed to be perfect black and white bodies

Table 2: Land fraction $p$ given for each latitude (in steps of 5°). Retrieved from (Hartmann, 1994).

| *lat* | *p* | *lat* | *p* | *lat* | *p* | *lat* | *p* |
|---|---|---|---|---|---|---|---|
| -90° | 1 | -40° | 0.05 | 10° | 0.25 | 60° | 0.6 |
| -85° | 1 | -35° | 0.1 | 15° | 0.25 | 65° | 0.8 |
| -80° | 0.85 | -30° | 0.2 | 20° | 0.3 | 70° | 0.6 |
| -75° | 0.7 | -25° | 0.25 | 25° | 0.35 | 75° | 0.25 |
| -70° | 0.45 | -20° | 0.25 | 30° | 0.4 | 80° | 0.15 |
| -65° | 0.1 | -15° | 0.2 | 35 | 0.4° | 85 | 0.05 |
| -60° | 0 | -10° | 0.2 | 40° | 0.4 | 90° | 0 |
| -55° | 0 | -5° | 0.25 | 45° | 0.5 | **total** | **0.31** |
| -50° | 0.05 | 0° | 0.2 | 50° | 0.55 | | |
| -45° | 0.05 | 5° | 0.2 | 55° | 0.55 | | |

Attempting to obtain a planetary albedo that better represents Earth, it is assumed that each of the four components are covered for 50% by clouds. Albedo of clouds vary within a wide range, but for the analysis it is assumed that $\alpha_c = 0.5$. The back-emission of long-wave radiation by clouds is neglected for simplicity sake.

The resulting land fraction covered by fertile ground (or daisies), upon subtraction of oceans, is given in table 2.

# 3 Results

## 3.1 Classic Model

Figures 2, 3 & 4 show the results of different runs for the classic model.

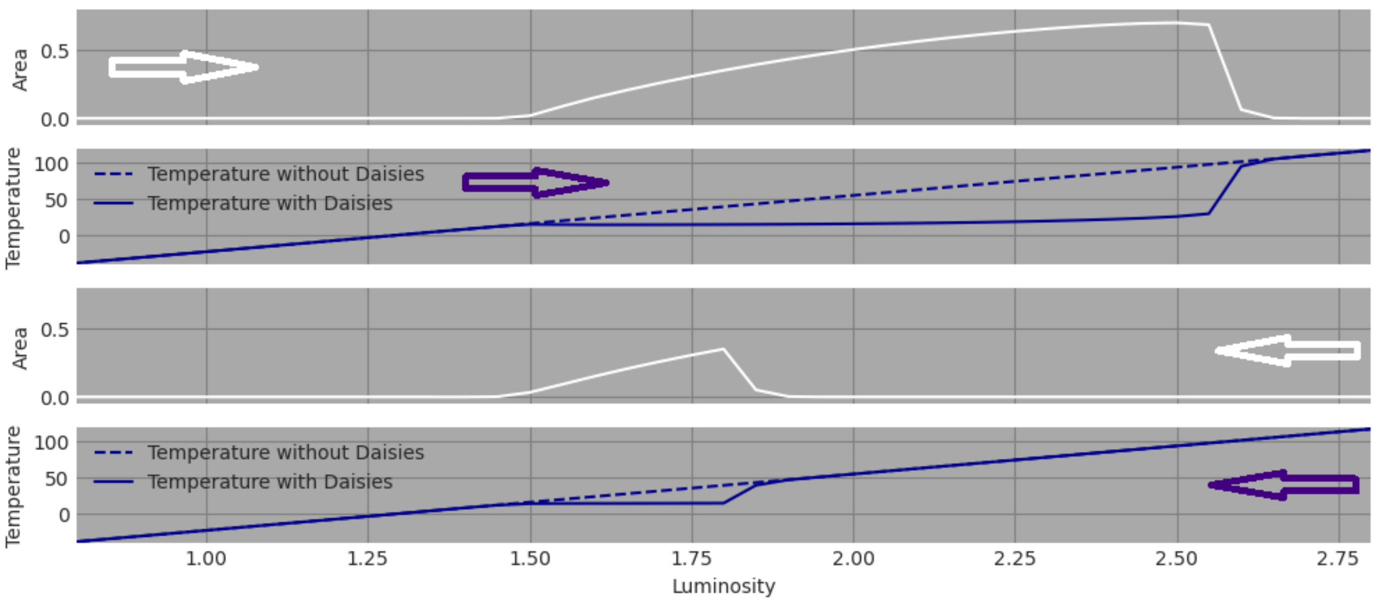


Figure 2: Area (fraction of total area) and temperature (degrees) for a run with only white daisies. The arrows indicate the direction of luminosity, which is increasing for the top two graphs and decreasing for the bottom two.

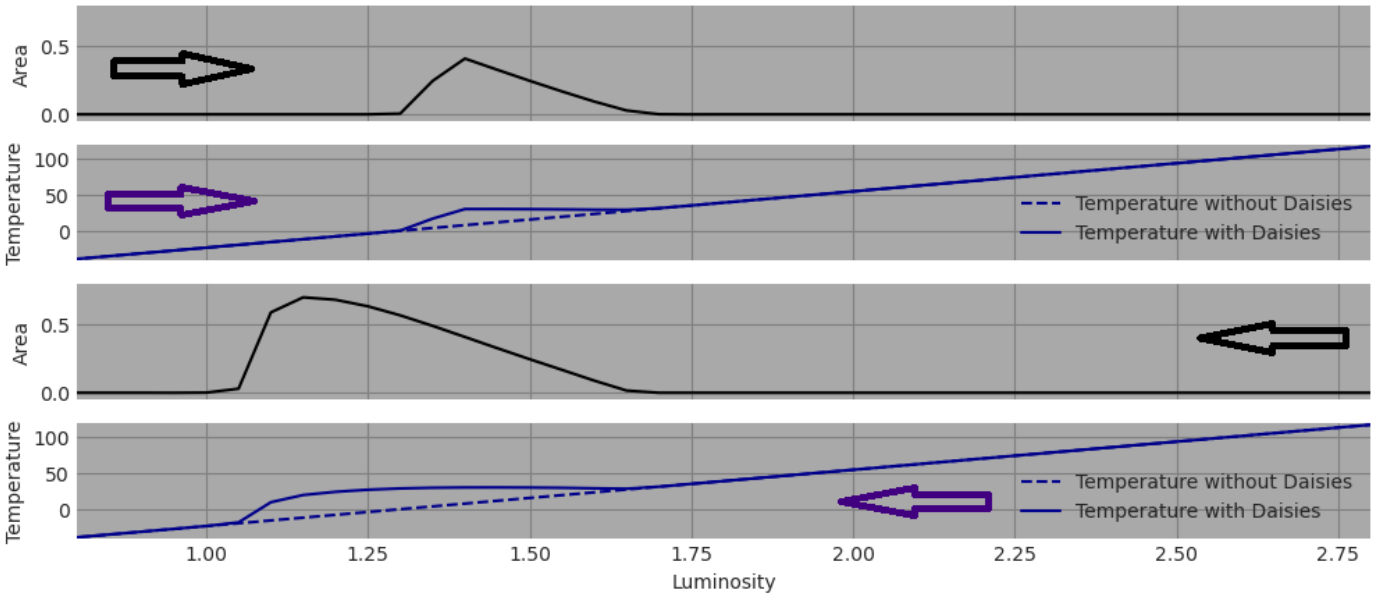


Figure 3: Area (fraction of total area) and temperature (degrees) for a run with only black daisies. The arrows indicate the direction of luminosity, which is increasing for the top two graphs and decreasing for the bottom two.

As explained in section 2.1, both increasing luminosity (indicating a warming climate) and decreasing luminosity (indicating a cooling climate) are analyzed. Figure 2 shows the changes in area and temperature as a function of luminosity for a run with only white daisies.

It becomes immediately clear that white daisies grow a lot better in a warming climate (top two graphs) than in a cooling climate (bottom two graphs). For increasing temperatures there are white daisies between luminosities of 1.5 and 2.6, whilst when temperature decreases they only survive between luminosities of 1.85 and 1.5.

The blue lines indicating temperature, show that there is a linear relationship between luminosity and temperature if there are no daisies (dashed line). However, the white daisies, which have a cooling effect on the temperature because of their high albedo (table 1), can push the temperature down close to their optimum growing temperature of 22.5 °C.

Figure 3 shows the changes in area and temperature as a function of luminosity for a run with only black daisies.

Black daisies show opposite results compared to white daisies and grow a lot better in a cooling climate (bottom two graphs) than in a warming climate (top two graphs). For increasing luminosity, black daisies only grow between values of 1.3 and 1.65, while they grow between values of 1.65 and 1.05 in a cooling environment.

Black daisies have a warming effect on the temperature, because of their high albedo (table 1). Again it becomes visible that when daisies grow, they push the temperature towards values close to their optimum growing temperature of 22.5 °C.

Now, we look at the results from a combined run of black & white daisies, shown in figure 4. The combined run looks like the sum of the two individual runs from figure 2 & 3. However, if one takes a closer look it is clear that for increasing luminosity (top two graphs), the area range of both white & black daisies has expanded towards each other. The white daisies now start growing at luminosities of 1.35, while during the individual run they only started at values of 1.5. For decreasing luminosities (bottom two graphs) the same effect is seen: black daisies started growing in their individual run at a value of 1.65, for the combined run this value has expanded towards 1.8. Figure 4 shows that the combined run creates the largest range of luminosities where white and black daisies can grow, pushing the temperature towards 22.5 °C.

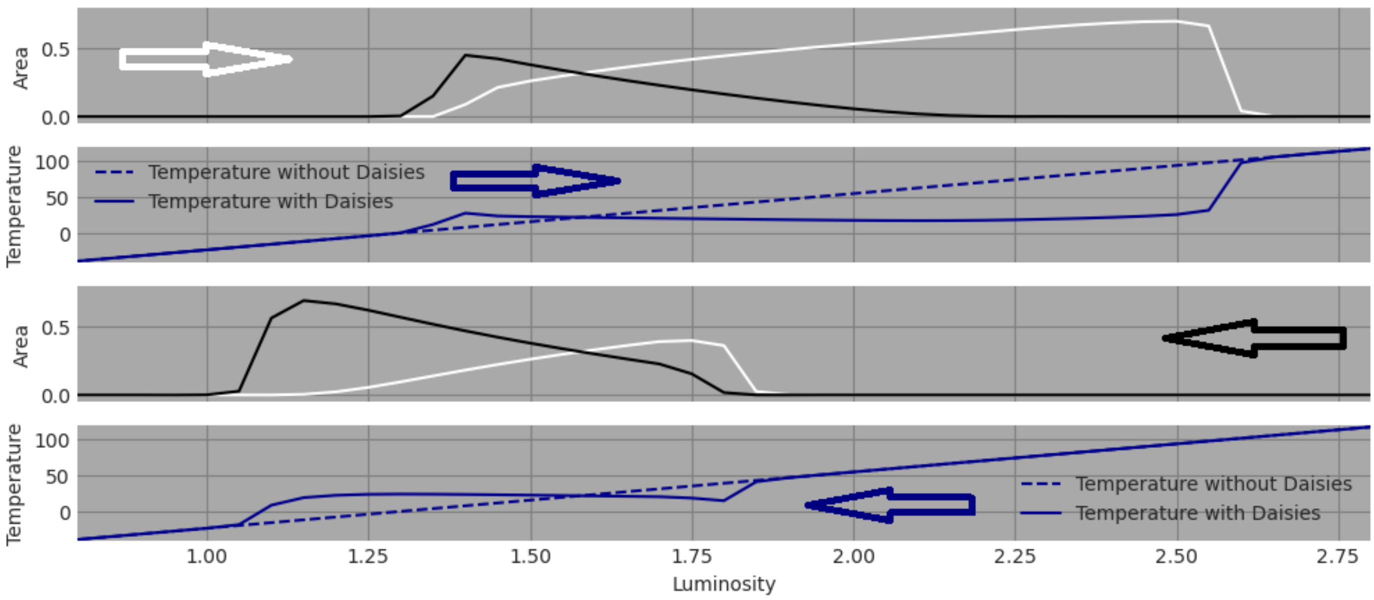


Figure 4: Area (fraction of total area) and temperature (degrees) for a run with black & white daisies. The arrows indicate the direction of luminosity, which is increasing for the top two graphs and decreasing for the bottom two.

## 3.2 Latitude Dependence Model

Figure 5 illustrates the meridional temperature distribution for $\beta = 16$ W m$^{-2}$ K$^{-1}$. Figure 5c represents the temperature difference between the situation with and without meridional transport. Clearly, adding the temperature relaxation term from equation 12 to the energy balance generates a heat flux directed from central latitudes to higher latitudes.

What happens if we allow daisies to grow? The consequent temperature distribution is shown in figure 6d. As a reference, figure 5b is once again repeated in figure 6c, extended to a luminosity of 2.8. In addition, the daisy area as a percentage of the total ground area is shown for white and black daisies separately in figure 6a and 6b, respectively.

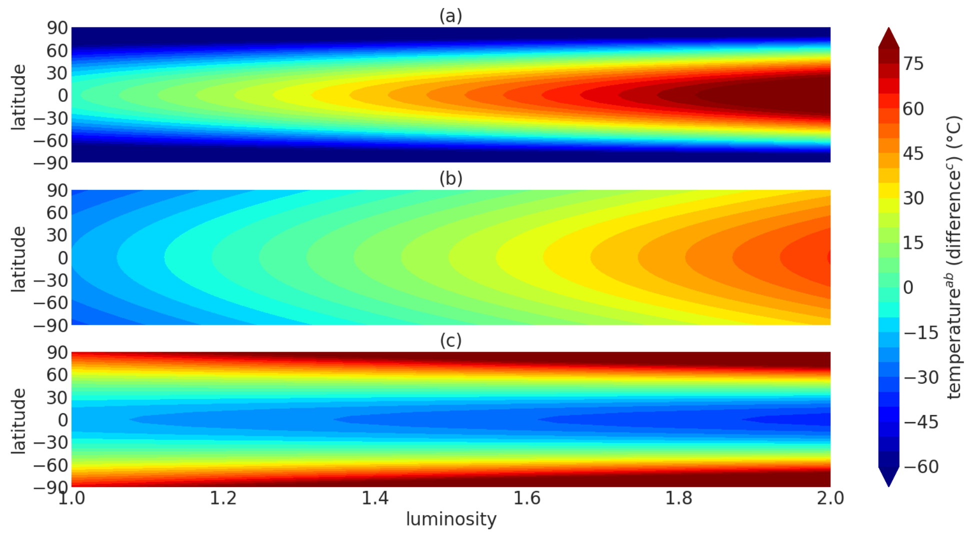


Figure 5: Latitudinal temperature distribution as a function of luminosity for situation (a) excluding and (b) including meridional heat transport. Figure (c) shows the temperature difference between the two ((b) - (a)).

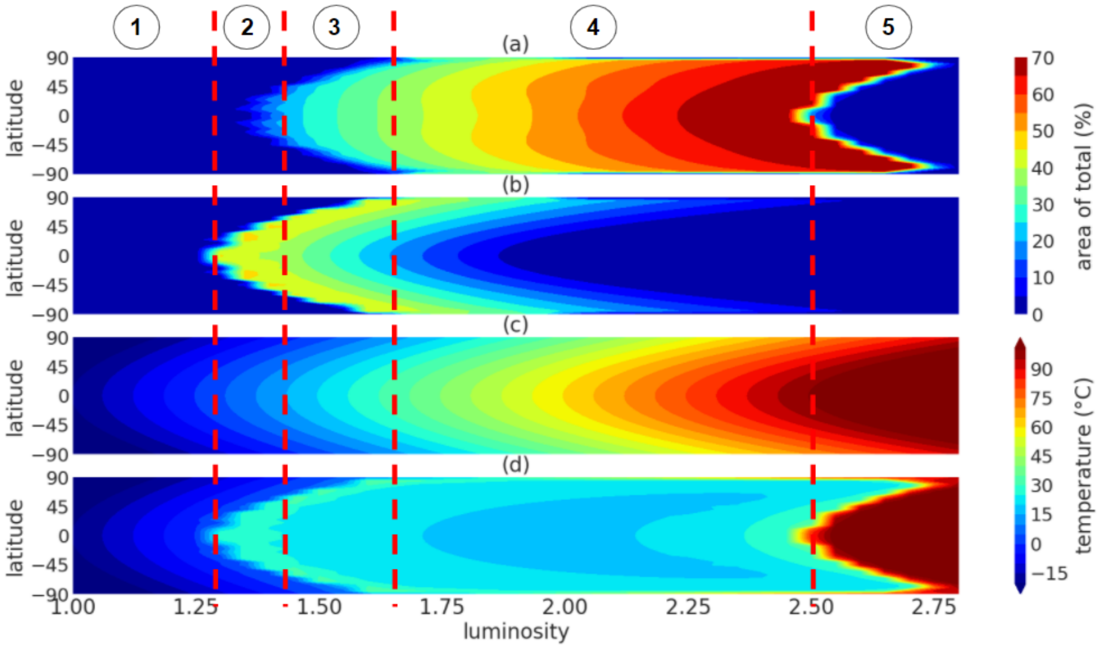


Figure 6: (a) White daisy area, (b) black daisy area, (c) temperature on a planet without daisies and (d) temperature on a planet with daisies as a function of latitude and luminosity. Sections 1-4 represent different phases of Daisy World as explained in the text.

In figure 6 the Daisy World simulation is decomposed into five phases. During phase 1, conditions are still too cold for daisies to grow, and figure 6c is identical to figure 6d.

The transition to phase 2 at $L = 1.3$ is when the black daisy area starts to grow and the temperature profile in figure 6c starts deviating from 6d. The first location at which daisy growth is possible, is at the warmest location: the equator (also see figure 7a). The black daisy population shoots up before the white daisy population does. In this temperature domain, black daisies have a clear physiological advantage over white daisies: black daisies have a higher absorptivity and could thereby raise the local temperature to more bearable life conditions. Comparing figure 6d with figure 6c within phase 2, the black daisy population growth visibly raises the zonal temperature from the equator to mid latitudes on both hemispheres, corresponding to the locations where it is warm enough for them to grow. In this phase, the black daisies locally bridge the gap between low planetary temperatures and (near-)ideal life conditions.

Within phase 3, black daisies are expanding their territory towards the poles, driving the planet towards isothermality. Meanwhile, conditions become favorable for white daisies to grow. The low-albedo black daisy populations are being counteracted by the high-albedo white daisies and a situation is attained in which both daisy types co-exist on a near-isothermal planet with temperatures in between 20°C and 25°C: ideal life conditions. Here the Gaia Hypothesis becomes visible in its full glory.

This ideal situation for both daisy types is not infinitesimally long sustained, as solar power increases. In phase 4, conditions start getting too warm for the black daisy populations, whose aforementioned physiological advantage turned into a disadvantage now. Whereas the white daisy population keeps expanding, the black daisy populations commences to decline, starting at the equator. The white daisy population, however, accomplishes a temperature decline needed for life sustain for a considerable solar power range, up to a luminosity around 2.5.

Finally, at phase 5, the white daisies succumb to the increasing solar power. The drastic decline in daisy population, resulting in a rapid temperature increase, complies with tipping point characteristics. This is also clearly visible in figure 7d.

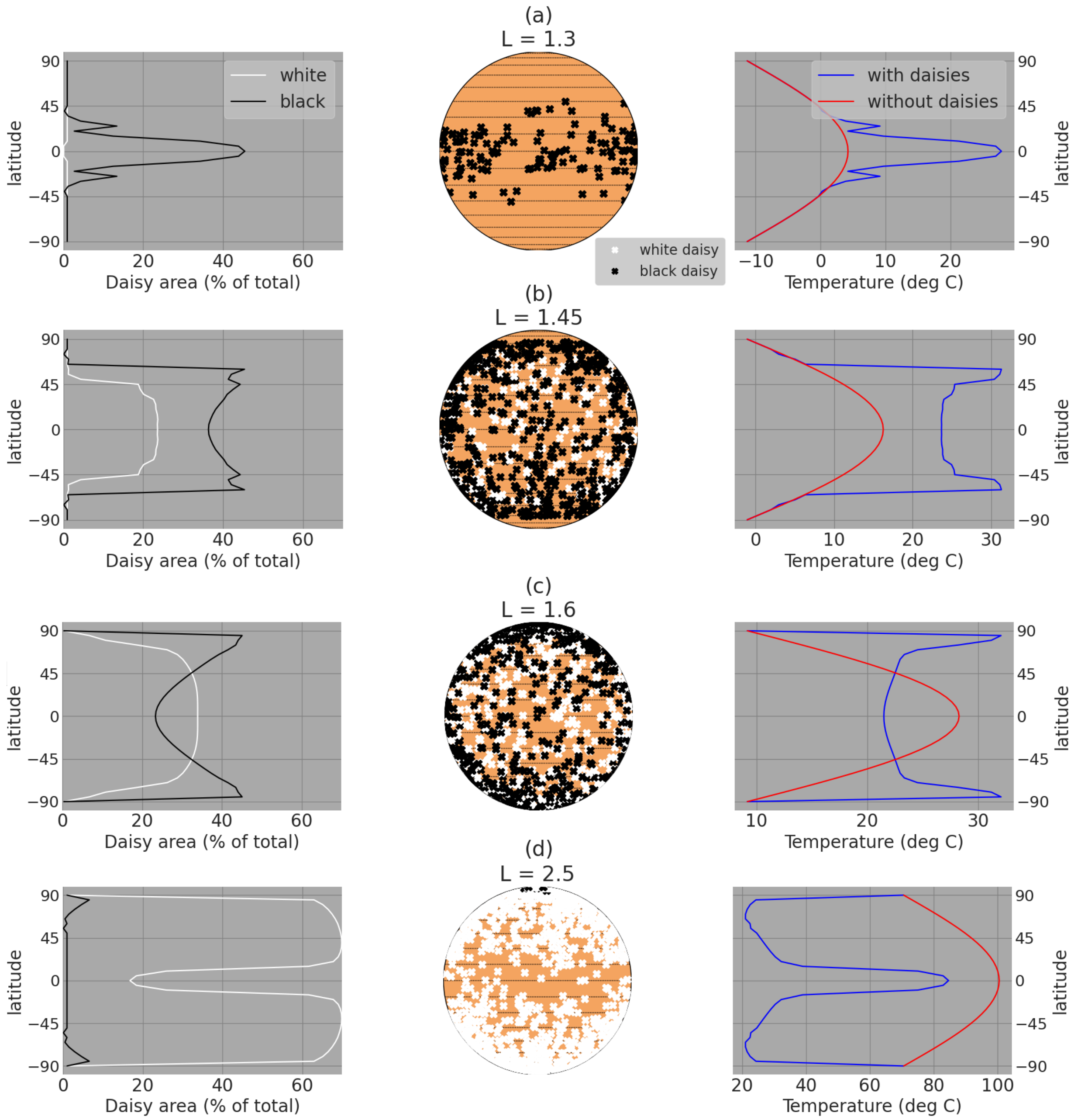


Figure 7: Each subplot shows the daisy area profile with latitude (left), a pro rata projection of the black and white daisy area on Daisy World (center) and the resulting temperature profile with latitude for the situation with and without daisies (right). This is done for a luminosity of (a) 1.3, (b) 1.45, (c) 1.6 and (d) 2.5. Note that those luminosities correspond to the transition location of the different phases shown in figure 6. Hence, this figure could be seen as transects at the red dashed lines from figure 6.

## 3.3 Ocean Model

Running the Daisy World model including oceans, the influence of daisy growth on the temperature is shown in figure 8. First, a subtle asymmetry in the equatorial line is seen in figure 8a (situation without daisies), resulting from a dissimilar land fraction between both hemispheres. Second, in figure 8b the red arrows indicate two small latitude bands where ideal life conditions of 18-25°C are sustained. Surprisingly, the Gaia hypothesis is not being confirmed at most latitudinal positions within the Ocean model.

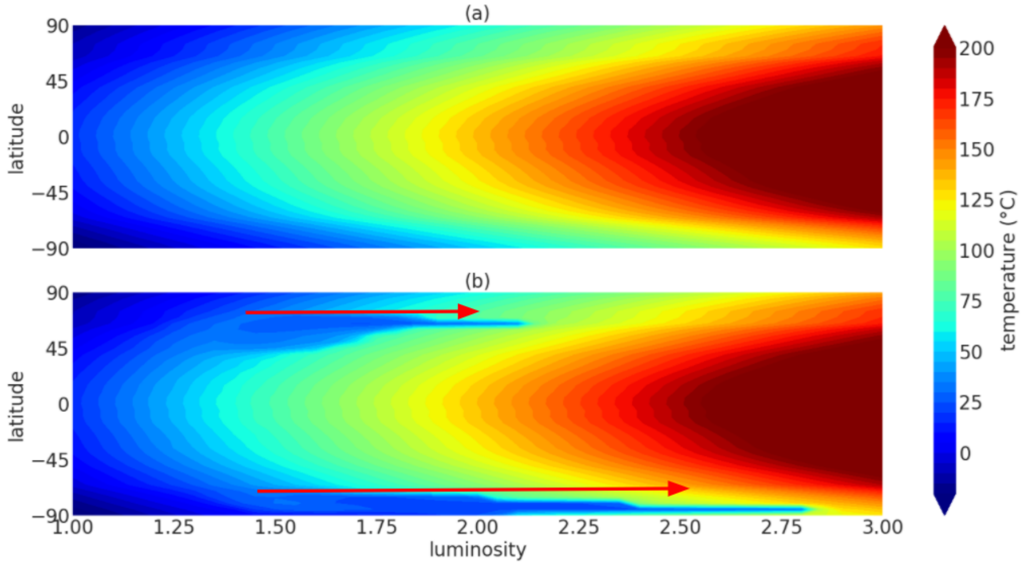


Figure 8: Temperature as a function of latitude and luminosity for the Ocean model for (a) a planet without daisies, and (b) a planet with daisies. (b) differs from (a) due to the presence of two "patches" of low temperature penetrating to higher luminosities.

For the Ocean model the white (left) and black (right) daisy area is shown in figure 9. The land fraction (see table 2) is projected on the $xz$-plane. The generic growth patterns at high latitudes from figure 9 can be clarified. Regarding white daisies, population growth is initiated around a luminosity of 1.6. The growth is most persistent and the daisy area grows largest on Antarctica (-75° - -90°) where temperatures are coldest (see figure 8a). This peak is reached at a luminosity near 2.8, where local temperatures sustained by the white daisies themselves are still bearable. Yet this is prone to change, as upon a slight solar power increase the daisy population collapses, showing the same tipping point behavior as in the Latitude Dependence Model.

The development of the black daisy population is also in accordance with what was observed in the Classic model and the latitude-variant model. Life is initiated with a sharp peak in the daisy population, after which it slowly dies out.

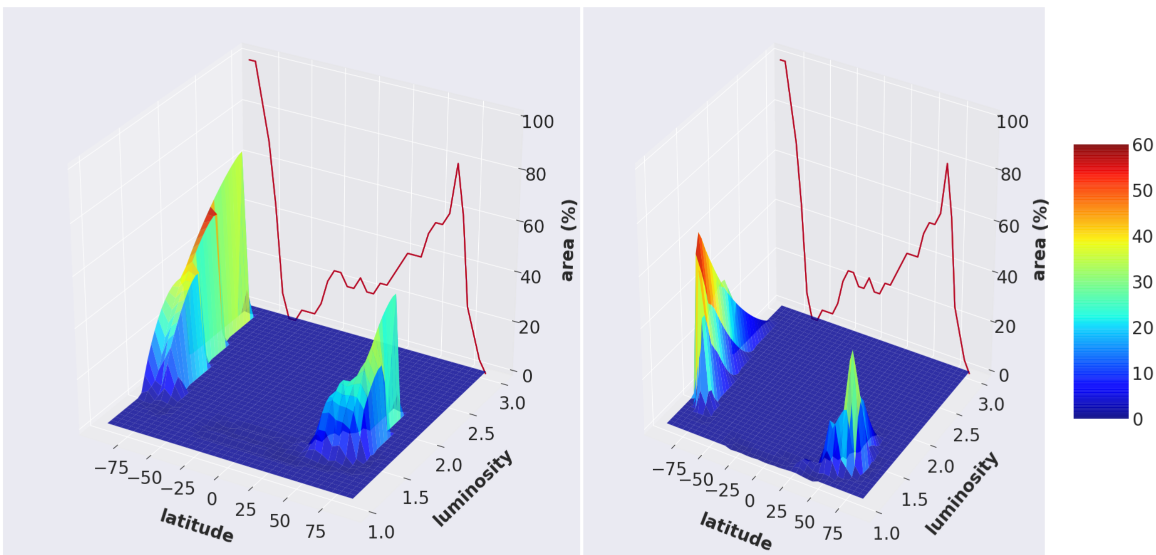


Figure 9: Population area as a function of latitude and luminosity for white daisies (left) and black daisies (right). The projected red line is the available land fraction $p$.

A striking feature that figure 9 illustrates is the apparent restrictive behavior of daisy growth to the given land fraction, as no life is sustained from the equator to mid latitudes, despite life conditions being favorable within some range of luminosities. This occurs non-arbitrarily at locations where $p$ is low, as will be further discussed in section 4.

Figure 10 shows the model output from a 2D perspective, at the moments where the transects are made in figure 6 (transition to different phases). From figure 10, it becomes clear that white daisies have a much stronger influence on the zonal temperature than black daisies. This is a clear albedo-effect. Due to the addition of oceans, the albedo of all but daisy area decreases, and lies much closer to the albedo of black daisies than to the albedo of white daisies. Hence, when both populations are equally large, the white daisies affect the total albedo more than black daisies. This is not observed in the latitude-variant model, as the ground albedo lies exactly in between the white and black daisy albedo (0.5 vs 0.75 and 0.25, respectively).

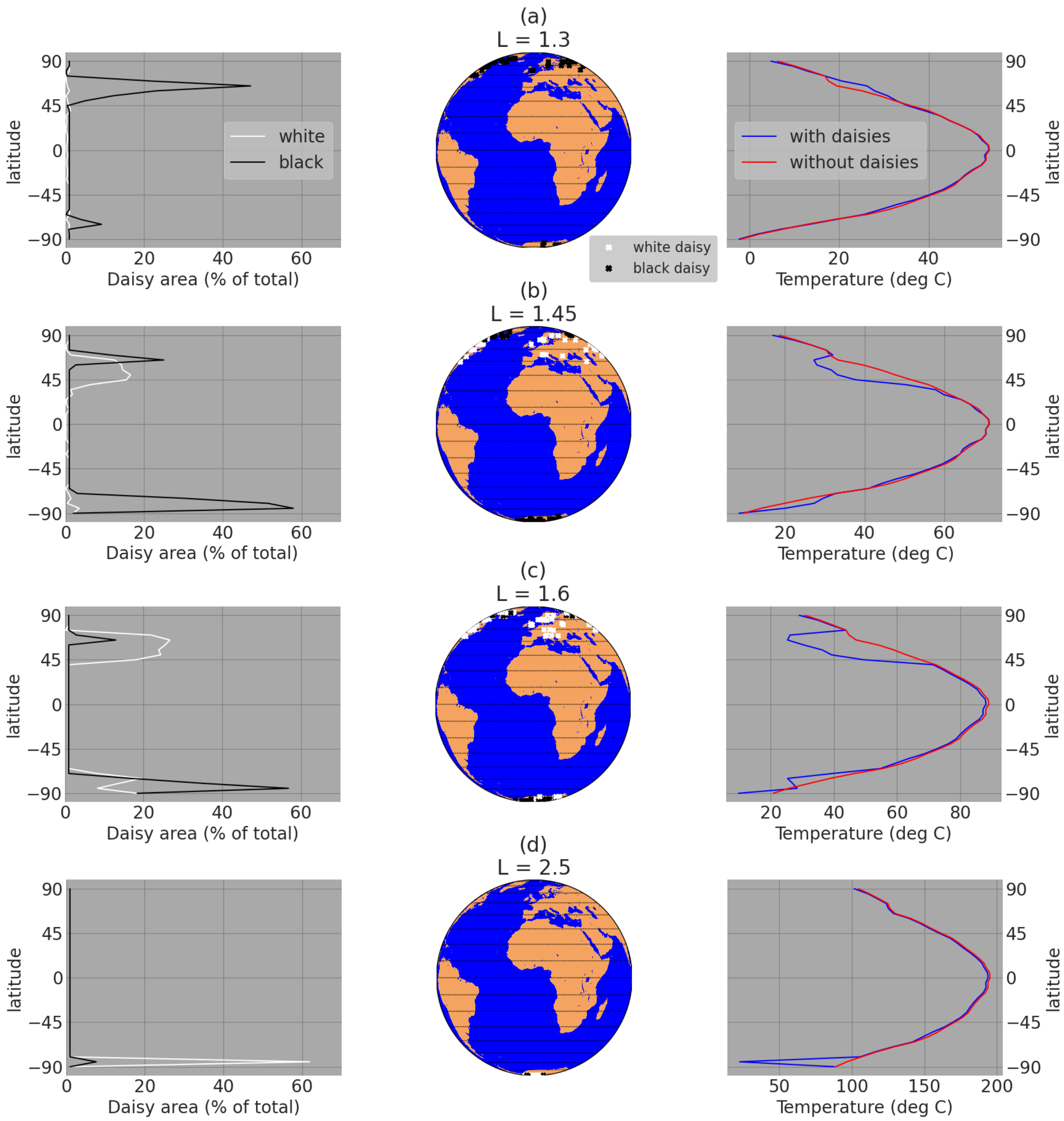


Figure 10: Similar figure as 7, but for the Ocean model. The luminosities are again taken from figure 6, in order to facilitate the comparison with figure 7.

# 4 Discussion

The observed offset in luminosity from 1, corresponding with current climate conditions, might be related to the combination of parameter settings, or to the lack of resemblance of Daisy World to the real world (or both). However, this offset does not change the overall interpretation of the results.

The classic model shows that a combined run of black and white daisies for both increasing and decreasing luminosity is not just the sum of the two individual runs. Black and white daisies do not just have an effect on the environment but on each other as well, creating better climatological circumstances for each other.

White daisies dominate in a warming climate because of their high albedo. Whilst the luminosity increases, the white daisies balance this with their low absorptivity, pushing the temperature down for a large range of luminosities.

Black daisies have the opposite effect, dominating in a cooling climate because of their low albedo. While the luminosity decreases, the black daisies balance this by absorbing a lot of radiation, increasing the temperature.

The effect of white daisies in a cooling climate and black daisies in a warming climate can be visualized as a positive-feedback system. In stead of balancing, they enhance the decrease and increase of luminosity respectively. This enhancing mechanism results in a short peak, where daisies can only survive in a small range of luminosities.

The latitude-variant model facilitates daisy growth at luminosities where life would not be sustained in the classic model. E.g. for a luminosity of 1.3, the planet would be just too cold for daisies to grow in the classic model. In the latitude-variant model, daisies do start growing at the equator where temperatures are above average.

Similarly, the classic model indicates that life terminates when a luminosity of 2.6 is reached. However, the latitude-variant model shows that life is still possible at luminosities up to 2.75 at high latitudes! Hence, adding latitude dependence to the model has confirmed the hypothesis that *the solar power range where life is possible is extended.*

Regarding the Ocean model, it is concluded from the analysis and figure 9 that the expected daisy growth behavior only takes place when $p$ is large (say, above 0.6). The modelled linear relation between daisy growth and available ground area appears to put too much of a strain on the expansion of daisy populations. This might boil down to a model limitation, which immediately forms a recommendation for further research.

# 5 Conclusion

- Daisy World does a good job in visualizing the Gaia Hypothesis. It shows that within a certain range of luminosities, the biosphere can regulate the climate and keep a constant temperature, close to the optimum of 22.5 °.

- Increasing or decreasing the luminosity has different effects on daisy growth and temperature. A combined run of black & white daisies creates the best climate.

- The daisy species that balances the change in luminosity dominates the planet. This causes the negative feedback to dominate over the positive feedback. Without external forcing (manually change the luminosity), daisy world would stay in an infinite negative feedback loop between a certain range of luminosities, always creating the optimal temperature for itself.

- Meridional temperature gradients allow for daisy growth on high latitudes when mean temperatures are high and on low latitudes when mean temperatures are low, extending the range of solar power at which life is possible.

- The Ocean model restricts daisy growth to latitudes below the Antarctic Ocean and above the Mediterranean Sea due to an apparent lack of available fertile ground area. The white daisies have a stronger effect on temperature than black daisies in this setting.

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