CLIMATOLOGICAL EXPLORATIONS USING DAISYWORLD AS AN ENERGY BALANCE MODEL; EXTENDING THE PARABLE TO GEOENGINEERING

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ABSTRACT

Many climate modification studies are being conducted to determine the most effective geoengineering methods to combat global temperature rise. This study uses Daisyworld, a model of a fictional planet, to first look at the climatological implications proposed by Watson and Lovelock (1983) and then extend the parable to explore potential impacts of geoengineering. The planet consists of two types of daisies (black daisies and white daisies) whose individual albedos work to balance the average planetary temperature for an interval of time even though Daisyworld's sun continues to increase energy output that reaches the surface. The interplay between its components makes Daisyworld usable as a basic energy balance model, and was chosen because it is simple in its construction but offers insight into the interconnectedness of biota and the environment. These qualities make it suitable for the simulation of stratospheric seeding by generating a haze covering the modeled planet. This haze lowers the planetary albedo enough to extend the range of suitable temperatures, subsequently allowing the white daisies to last longer on Dasiyworld. While successful at increasing the duration of habitable conditions, increasing the planetary albedo also caused an initial severe temperature drop. Human manipulation of Earth's climate, if done, should be gradual to prevent initial severe changes as well as potential over-correction. Additionally, at the point of conclusion of intervention, the modeled planet's average temperatures drastically increase, indicating once intervention begins it must continue indefinitely.

1. Introduction

It is well understood models aid in simulating processes that are difficult or impossible to replicate in a real-world setting. Several complex energy balance models are used to paint a picture of how Earth's climate might react following a perturbation. The challenge with these models is that they are packed with complicated processes, and it is often difficult to isolate a single process to determine its impact or if it is having the impact one would expect. This study focuses on the use of Daisyworld as a simple energy balance model to observe the climatic effects of geoengineering.

Daisyworld refers to a simple energy balance model introduced by Watson and Lovelock with the purpose of demonstrating the coupling of life and the environment (Watson and Lovelock 1983). Initially it was proposed and linked with Gaia Theory as a justification. Extensively discussed in the Lovelock and Margulis (1974) paper on the Gaia hypothesis, Gaia theory was not widely accepted in the scientific community: scientists viewed the idea that all individuals from Earth's different spheres came together to work towards the same goal unrealistic. Lovelock and Watson implemented Daisyworld to demonstrate the synergy between life and the environment that was described in the Gaia hypothesis. Daisyworld ultimately distanced itself from Gaia to become a popular tool used beyond the ecological regime. In fact, Daisyworld can be used as a simple energy balance model viewed through a climatological lens and further to make important implications for geoengineering. Stratospheric aerosol injection (often refered to as "seeding") is a tactic at the forefront of solar geoengineering research. Stratospheric seeding involves the release of specific particles, such as sulfur dioxide, into the stratosphere to increase reflection of short wave radiation, leading to a decrease in surface temperatures (Feder 2021). This method is being highly consid-

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ered as a way to prevent the increase of global temperatures to unsafe levels that may cause irreparable changes to Earth's systems.

Before using Daisyworld to observe the effects of geoengineering on climate, it is important to consider its structure and functioning. It is a model of a fictional world inhabiting two types of daisies: black daisies and white daisies. Since it is a very simple model, it has features and assumptions to make it useful as such: it is flat, zero-dimensional, insulating, cloudless, and has negligible greenhouse gases (Watson and Lovelock 1983). The indication being solar luminosity and albedo are the only determining factors for surface temperature. This planetary albedo is influenced by the biota on daisyworld. In an effort to ensure the only limiting factor on this biota is temperature, it is assumed that the ground is well watered and complete with plenty of nutrients (Wood et al. 2008).

Much of the allure of Daisyworld comes from the clear interactions between white daisies and black daises with the environment, in this case increasing solar luminosity. While a much simpler scenario than one would see on Earth, it has important implications for climate research. Each daisy type has a different albedo and subsequently the spread of the daisies over Daisyworld's surface drives planetary temperature. The white daisy has a higher albedo and a lower local temperature. The black daisy has a lower albedo, more absorption, and a higher local temperature. The interplay between these two daisy types along with increasing luminosity work to return the planetary temperature to an optimum level. (Kageyama and Yagi 2020).

2. Purpose

The purpose of this study is to use the Daisyworld parable proposed by Watson and Lovelock and to extend it to show the possible impacts of geoengineering. This is alluded to in the original paper on Daisyworld. "Recently, Owen et al. (1979) and Walker et al. (1981) have speculated that the abundance of atmospheric CO_2 may have been dominant in determining the mean temperature of the earth through geological time..." (Watson and Lovelock 1983). While we will not be looking at CO_2 specifically, it supports the idea that this parable is extendable to modeling alterations in a global climate. Additionally, Watson and Lovelock (1983) also state: "We then have the rudiments of a temperature stabilization system for the earth analogous to that on Daisyworld. We can speculate that some such mechanisms may have played a part in regulating the temperature and other environmental variables over the long history of the earth." In this paper, we will test how Daisyworld reacts to the formation of a haze covering the entire planet in an effort to elongate the suitable temperature for daisy survival. This compares analogously to current geoengineering tactics being studied. These studies are largely done via extremely complex modeling. This study takes a step back in order to observe, on a basic level, what the impact geoengineering could have on Daisyworld which will lead to discourse relating the results to Earth's climate. Even considering a drastic shift in global emissions and lifestyle, climate projections are, at the very least, problematic. This has resulted in decision makers taking a closer look at geoengineering as a viable option (Feder 2021).

3. Methods

The models in this study were built with STELLA Architect, a software package developed by isee systems that allows model building using computer simulations. Often used in the business sector, it is also useful in building climate and energy balance models. STELLA Architect is a visual modeling tool with draggable and manipulable icons which makes it an effective tool to build a Daisyworld model. This model is made up of differential equations that can be modified to fit the parameters of STELLA.

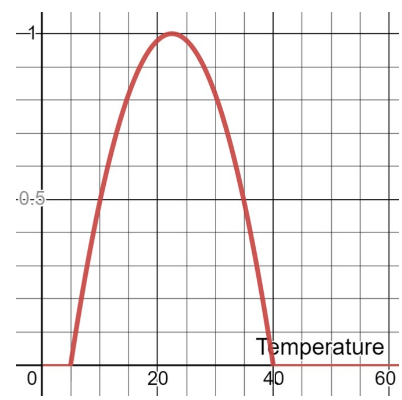

FIG. 1. Parabolic growth rate of each daisy dependent on temperature.

a. *Classic Daisyworld*

The original equations can be found in the Watson and Lovelock (1983) paper introducing Daisyworld. These equations along with Dave Bice's website on using STELLA to model Daisyworld inspired the model created for use in this study (Bice n.d.). In this classic model, daisy growth rates are represented by a parabola (Fig. 1) as a function of temperature (Watson and Lovelock 1983).

$$x = 1 - 0.003265(22.5 - T_1)^2 \quad (1)$$

Where x is the growth rate and T_1 is the local temperature of the daisy. The growth rates of the daisies reach a peak of one at a local temperature of 22.5°C and is zero at 5°C and 40°C (Fig. 1). Each daisy type has a different albedo: $a_w > a_g > a_b$. The white daisy has an albedo of 0.75, bare ground an albedo of 0.5 and the black daisy an albedo of 0.25 (Watson and Lovelock 1983). The variation in albedos causes local temperatures of each daisy to differ from the average planetary temperature. This has implications on which average planetary temperature they will thrive. Another important component of Daisyworld worth mentioning is the maximum area for any daisy is represented by the following equation:

$$A_1 = 1 - DeathRate \tag{2}$$

This study uses a death rate of 0.3, meaning for each time step an area of 0.3 daisies die off, allowing for a maximum coverage area of 0.7 while the rest is comprised of bare ground. It is expected the distributions of those areas change due to some perturbation, in our case changing luminosity. Daisyworld receives more solar luminosity (energy from the sun) over time, similar to that of Earth and Earth's sun. For the sake of this classic model, solar luminosity will increase linearly with a less radiant starting point of 0.6 until the sun's demise at 1.8. This endpoint changes for the geoengineering model (Watson and Lovelock 1983).

b. Daisyworld with Geoengineering Modifications

To model stratospheric aerosol injection in response to global temperatures rising to inhabitable levels, the albedos of each ground cover type was modified, forming a haze over Daisyworld. With increasing luminosity, the goal is to keep the white daisies active as long as possible. The first step was to determine the interval of suitable temperatures before the white daisies reach the temperature threshold. This was done using the classic model, without alterations. The albedo modifications were initiated at the first peak of Fig. 4 which happened to be at a temperature of 26°C. Realistically, once the threshold temperature is reached and white daisies die off, the average planetary temperature should rise up and join the original curve. This led to an initiation of albedo modification at 26°C and conclusion at 40°C. Once the interval was found, the model was then amended to include an increase in albedo for bare ground, white daisies and black daisies within the aforementioned interval, ultimately increasing planetary albedo.

Different albedos could have different impacts on Daisyworld. Perhaps there is an albedo change that is too large, or even too small and the interval is hardly extended. Testing this required the use of a range of albedo increases: from 0.01 to 0.10. The idea being to see how much an albedo modification might impact the climate. For the sake of this model's modifications, the lifespan of Daisyworld's sun was extended to capture the behavior of the average planetary temperature changes once albedo modifications were implemented. Otherwise, there was a risk of the interval of suitable temperatures being extended through to the end of Daisyworld and thusly cutting off the end behavior of the higher albedo curves.

4. Results

To understand how Daisyworld works, the black daisy's isolated growth was plotted along with the growth when both daisies inhabit the same system (Fig. 2). From this plot, the interaction between the two daisy types is evident. When using the parabolic growth rate, once the planetary temperature reaches a suitable level, black daisies grow at a substantial rate. Keeping in mind that luminosity is increasing over time, once conditions are too warm to be suitable for black daisy growth, black daisy population declines also at a rapid rate. Once white daisies are added to the system, the population decline on the right side of the peak (as seen in the figure) is not as steep as it was when the black daisies were isolated. This is the result of the interactions between the two daisy types. The introduction of white daisies with higher albedo helps to balance the planetary temperature, allowing the black daisies to survive longer on Daisyworld.

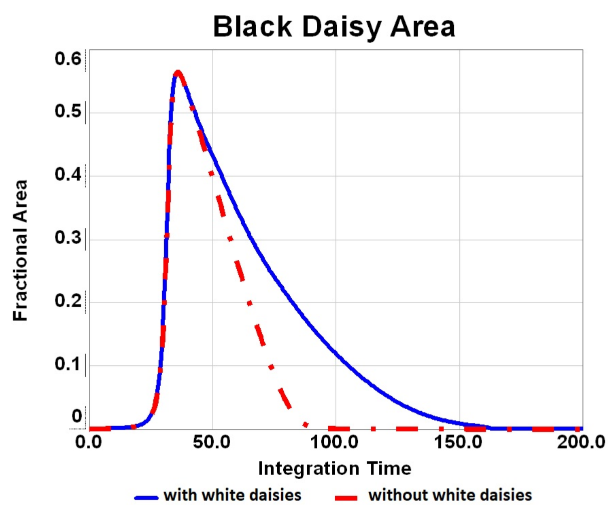

FIG. 2. Fractional area covered by black daisies with increasing luminosity. Red, dashed line shows black daisy growth without influence from white daisies. Blue, solid line shows black daisy growth with interaction between black daisies and white daisies.

This interaction can be seen further when both daisy types are plotted (Fig. 3). Initially, Daisyworld consists of only bare ground; however, once the temperature is suitable for black daisy growth, they increase in area at a rapid rate. The rapidity of black daisy growth is allowed, in part, by the absence of white daisies. Daisyworld's star is similar to earth's in that luminosity increases with time. As such, black daisies begin to grow during earlier time steps when the planetary temperature is cooler

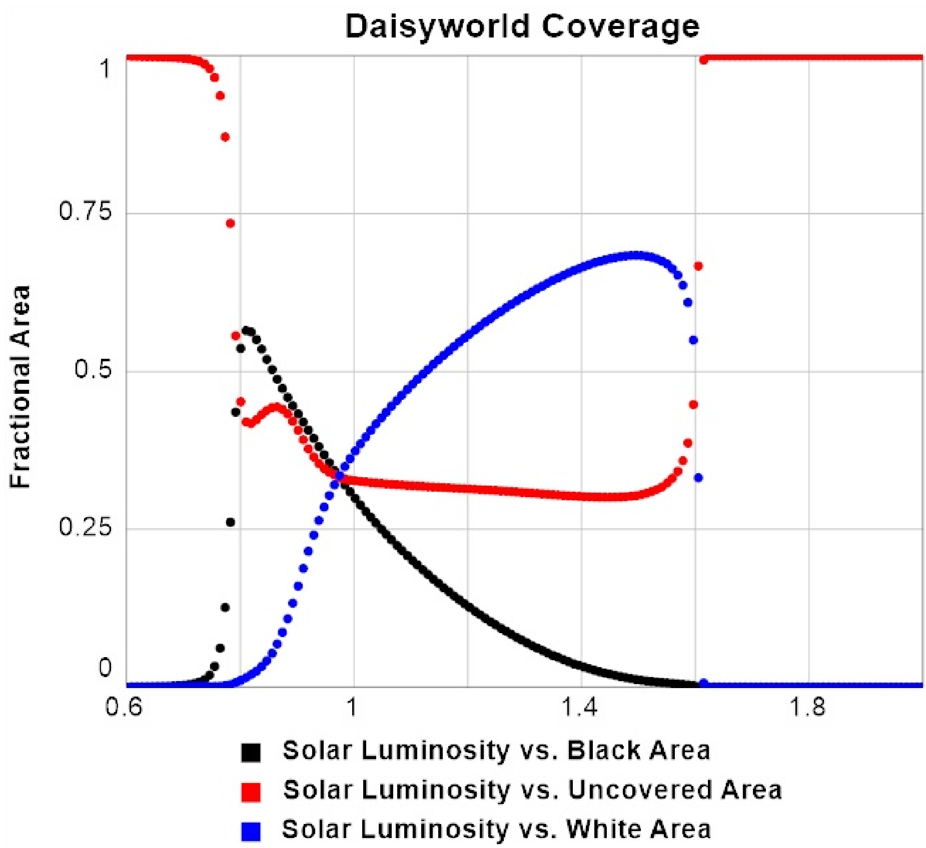

FIG. 3. Fractional area covered by each daisy with increasing luminosity. Within the interval 1 to 1.5 solar luminosity, the interplay between white and black daisies keep the bare ground area relatively constant (just above an area of 0.3) regardless of increasing luminosity.

since their local temperatures are warmer than the environment (Watson and Lovelock 1983). In other words, they (black daisies) can withstand cooler temperatures due to their lower albedo until they self-limit by becoming too warm. While the black daisies are on a decline, the white daisies (with a cooler local temperature) are able to grow. The time at which white daisies grow is due, in part, to the presence of black daisies. The black daisy works to lower the planetary albedo subsequently warming the planet at a faster rate. This allows white daisy growth to commence sooner than would occur without black daisies. The white daisies continue to dominate Daisyworld's surface until it becomes too hot for any Daisyworld biota to survive. Considering the total area cannot exceed one, a way to check the validity of the model is to add up the areas of each daisy type and bare ground along one x value.

In order to determine how the interplay between daisy types impacts the average planetary temperature of Daisyworld, the increasing solar luminosity was plotted along with the average planetary temperature (Fig. 4). As luminosity increases with time, one would expect the planetary temperature to do so; however, the presence of daisies alters the planetary albedo and ultimately the planetary temperature. The curve in Fig. 4 begins a steady increase from the start at 0.6 luminosity up to 0.76 when it deviates from the original path and temperatures increase rapidly. The dramatic increase in temperature at around 0.76 luminosity coincides with the introduction of black daisy growth seen in Fig. 3 (i.e. decreasing the planetary albedo and warming the planet). This occurs until the planet becomes warm enough for white daisies to begin growing. At around 0.85 luminosity we have temperatures now declining which coincides with white daisy growth (i.e. increasing planetary albedo and cooling the planet). This is until luminosity from around 1 to 1.5 where the black daisies and white daisies work together warming and cooling Daisyworld simultaneously, keeping the planetary temperature at a suitable level for life to survive within that interval. Shortly after reaching the end of the interval of stable temperatures, Daisyworld becomes uninhabitably warm and planetary temperature rises at an alarming rate (it is useful to note that the rapid decline of white daisies (Fig. 3) coincides with the substantial jump in planetary temperature), rejoining the trajectory of the solar luminosity curve. From a luminosity of 0.76 to 1.6, the solar luminosity curve is impacted by daisy growth and death and on either side of this interval are the areas of ex-

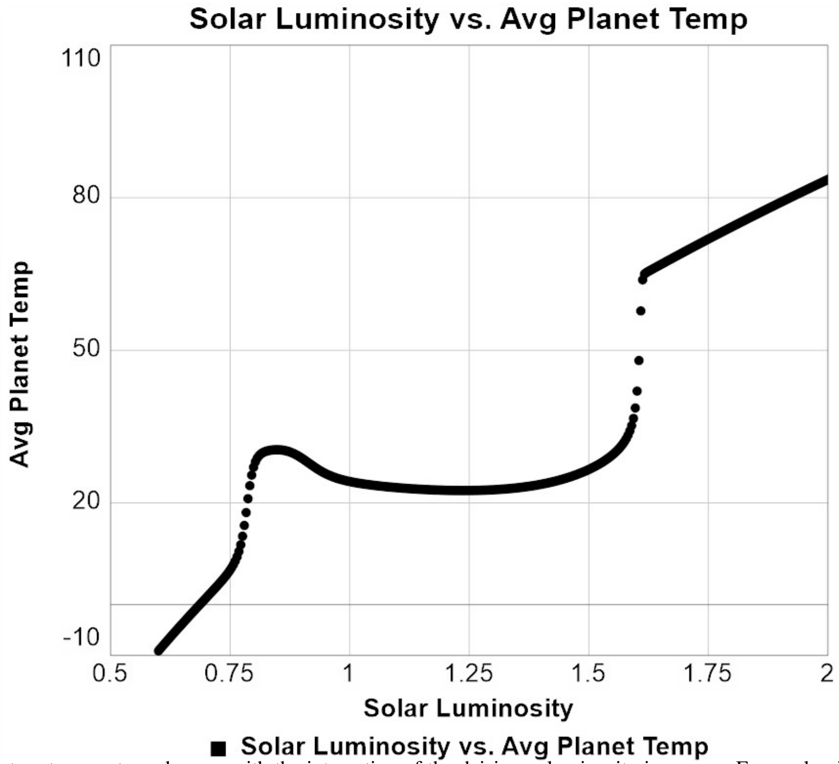

FIG. 4. Average planetary temperature changes with the interaction of the daisies as luminosity increases. From a luminosity of 1 to around 1.5, the average planetary temperature remains somewhat constant and within a range of temperatures conducive for daisy survival.

treme conditions in which the daisies cannot survive so have no impact.

The classic Daisyworld planetary temperature curve was plotted against the same curves but with modified albedos in the attempt to prolong the interval of suitable temperatures. From Fig. 5 it is clear that increasing Daisyworld's albedo did, in fact, extend the range of safe temperatures for daisy survival. When the albedos were increased by 0.01 and 0.02, the interval was not extended a substantial amount. As the change in albedo increased, so did the length of time daisies were able to maintain the range of optimum temperatures. The time at which the plots reached the threshold was different depending on how much the albedo was modified. As mentioned previously, the albedo modification was initialized at 26°C or luminosity of 0.76. When looking at Fig. 5, there is an initial drop in planetary temperature. This drop becomes more severe with increasing albedo.

Another perspective to explore the effects of climate modification is from the point of view of white daisy area coverage. The white daisy area was tracked for each albedo modification because one, it lasts longer in Daisyworld's timeline and two, it shows the behavior of Daisyworld's biota in response to increased planetary albedo (Fig. 6). White daisies are able to survive longer with each increase in planetary albedo. Once again, at a luminosity of 0.76 there is an initial drop in white daisy count, paralleling the initial temperature drops mentioned above. White daisies are limited in cooler planetary temperatures by their high albedo and low local temperature. They do increase in area coverage as the planet continues to warm with the help of black daisies and increasing luminosity. No matter the amount of albedo increase, each curve representing an albedo modification reaches a point of no return where the increasing luminosity can no longer be balanced with daisy presence and planetary temperatures increase dramatically. In fact, the white daisies reach a maximum area of 70% of Daisyworld's total area before dying off, returning Daisyworld to a bare ground planet. In other words, when failure inevitably happens, the change is rapid.

5. Discussion

Watson and Lovelock introduced Daisyworld as a "parable" (Watson and Lovelock 1983), a generalized lesson to support the idea that there is an interconnection between biota and the environment. They did not claim to have perfectly simulated the interplay between all of Earth's systems. This study takes a page from their book (so to speak) and extends the parable to a very highly considered climate change mitigation technique: stratospheric seeding. Even a simple model such as this could suggest

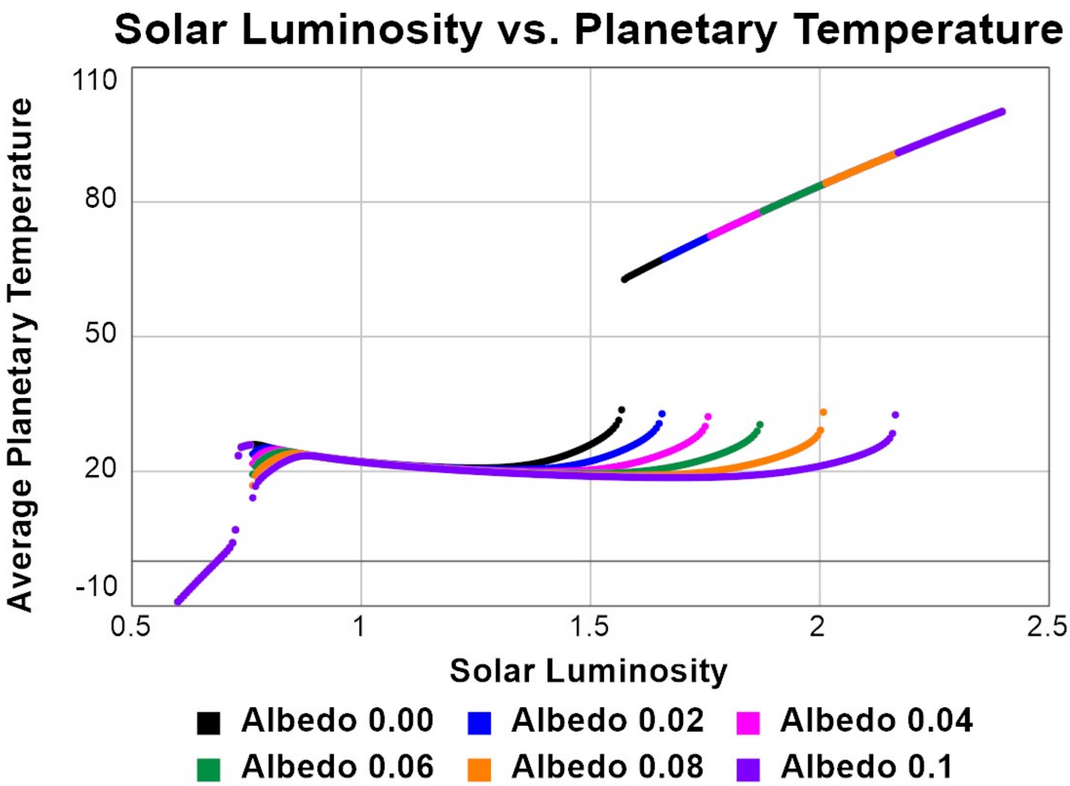

FIG. 5. Daisyworld temperatures with modified albedos. Each curve correlates to a specific increase in albedo. The black curve has an albedo change of 0.00, meaning no change in albedo. The blue curve has an albedo change of 0.02, meaning the white daisy, black daisy and bare ground albedos were increased by 0.02. This addition continued to a maximum albedo increase of 0.1.

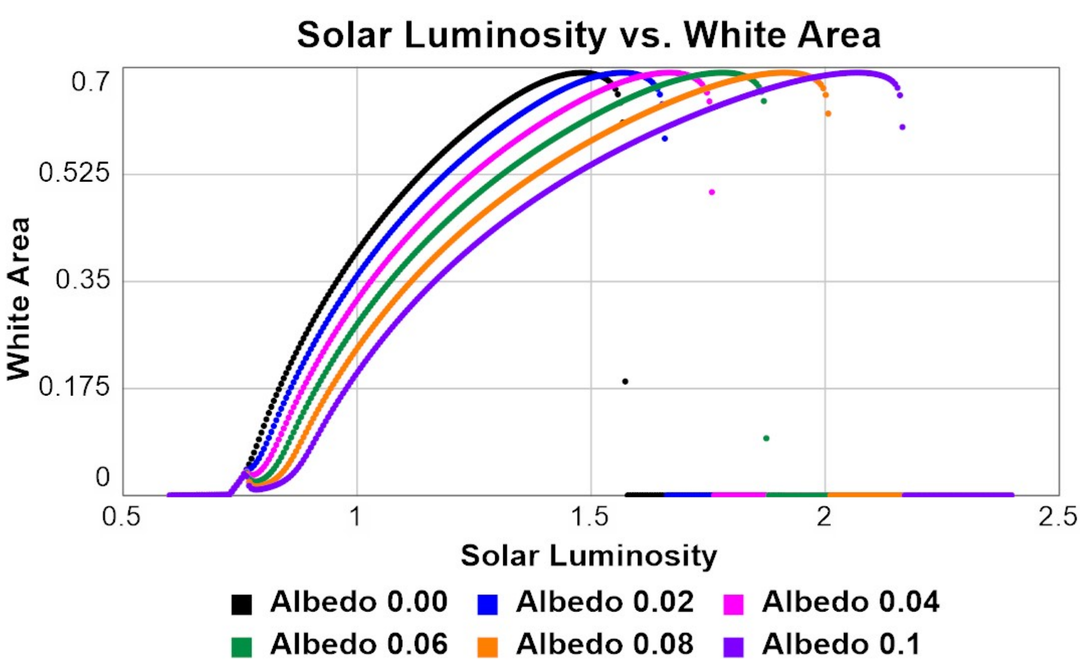

FIG. 6. White daisy area trends with modified albedos. Each curve correlates to a specific increase in albedo. The black curve has an albedo change of 0.00, meaning no change in albedo. The blue curve has an albedo change of 0.02, meaning the white daisy, black daisy and bare ground albedos were increased by 0.02. This addition continued to a maximum albedo increase of 0.1.

adjusting the planetary albedo can offset global temperature rise. However, with each albedo modification run, it always reaches a point where the offset is no longer sustainable and the jump up to the unadulterated solar curve is large and quick. The stress on systems and life would become intense, rapidly. This is also seen in the plot of white daisy area (Fig. 6): in a handful of time steps, the white daisies go from covering the maximum area allowed to nonexistence. While we hesitate to directly relate the time frame of Daisyworld to an earthly time scale due to the simplicity of this model, the lessons learned here can be used as an analogy for Earth's climate modification. This study shows that once an intervention begins, it must continue indefinitely. If or when climate modification begins, it must continue to be modified or, as was shown in Figs. 5 and 6, the global temperatures will increase at an alarming rate. Geoengineering can be compared to mopping up water as it overflows a sink rather than turning off the faucet, although in this case, turning off the faucet may not be a feasible option.

This coincides with the idea that intervention could require an increase in severity over time. For example, in Daisyworld, if we start with an albedo increase of 0.02, we reach a point where that reflectivity will not be enough to combat the increasing luminosity. So the response would be to increase it up to 0.03. Once again, there will be point where 0.03 will not be sufficient and another increase will be needed. So not only will the action of geoengineering need to continue indefinitely, the magnitude may also have to be adjusted over time.

Another potential impact of geoengineering relates to the initial temperature drop after albedo modification initiation. There was a drop to potentially unsafe temperatures before increasing luminosity warmed the planet. This is another response that would be different than that of Earth. Once the albedo modification is initiated, the assumption is the haze over the planet sets in immediately. While this is possible for Daisyworld, it may not be as immediate if implemented in Earth's stratosphere. It could take time to see any cooling effect. Similarly, when modification ceases in Daisyworld, it shuts off immediately. However, particles can stay in Earth's stratosphere for an extended period of time hinting that if albedo modification stops, the temperature change may not be as rapid as it is for Daisyworld. With that being said, it is fair to conclude that while the time frame may be different for Earth and Daisyworld if geoengineering stops, temperatures will increase and even surpass what was originally avoided. Even without being a one-to-one comparison, Daisyworld's model shows it may be helpful to phase in albedo modification to not only prevent an initial drop but also prevent overcorrection. If the modification is implemented all at once, we run the risk of extreme cooling before temperatures are able to rise to safe levels.

Daisyworld is used for a variety of purposes because even though it is simple, it is adaptable and some of the information gathered can be rather helpful and complex. Such is the case for this study. There are active proposals for stratospheric seeding to increase Earth's albedo and that is not the only method being proposed. Any and all geoengineering techniques will have unintended consequences. The idea is to use the results from this study and the simple Daisyworld model to offer an unobstructed view of these consequences that can then be built on in more complex modeling systems.

6. Summary and Conclusions

Daisyworld is a model of a fictional planet and is useful as a basic energy balance model due to the simple biota found on the planet (daisies) and how the biota work to regulate Daisyworld's planetary temperature. Though it started as a justification for Gaia Theory (Watson and Lovelock 1983), it has spread across multiple domains such as climate, ecology and earth system science education. In this study it was used in two parts: one, to explore Daisyworld as a simple energy balance model and two, how Daisyworld responds to climate modification and the potential implications for geoengineering.

STELLA Architect from isee systems was used to build the Daisyworld model. After building the Daisyworld model, several plots were generated to illustrate the way in which Daisyworld regulates its' temperature. The Daisyworld used in this study is based on the classic model described in the Watson and Lovelock (1983) paper and the parabolic growth rates of each type represented by Fig. 1. Fig. 2 demonstrates the application of the parabolic growth rate used for the black daisies and how the introduction of white daisies decreases the slope of the black daisy decline. While the growth rate formulas are the same for black daisies and white daisies, the local temperatures of the daisies differ due to their individual albedos, resulting in different preferred planetary temperatures. Initially Daisyworld consists solely of bare ground until black daisies begin to grow first due to their lower local albedo and subsequent tolerance for lower planetary temperatures (Fig. 3). White daisies begin to grow once the solar luminosity along with the black daisy's lower albedo warm the planet to suitable temperatures. The black daisies self-limit by becoming too warm in the warming climate, even with the help of the cooling white daisies. The white daisies then dominate Daisyworld until the planet reaches temperatures too extreme for survival.

The interactions between the white daisies, black daisies and increasing luminosity can also be seen in Fig. 4. The average planetary temperature increases rather rapidly with only bare ground covering Daisyworld and the only factor impacting planetary temperature in a bare ground scenario is the increasing luminosity. However, the presence of daisies alters the planetary albedo and ultimately the planetary temperature. The dramatic increase in temperature at around 0.76 luminosity coincides with the introduction of black daisy growth and successive decreasing of the planetary albedo and planet warming. Once the temperature is suitable for white daisy growth, the planetary temperature decreases to an optimum temperature around 24°C and maintains that temperature for several time steps. There is an interplay between biota and the environment in order to maintain an optimum planetary temperature. Eventually it reaches a point where the planetary temperature becomes too warm for even the white daisies to survive. Without the reflectivity of the white daisies, Daisyworld's temperature drastically increases. There are rather steady optimum temperatures being maintained by the daisies within the interval 1 to around 1.5 luminosity.

Daisyworld as an energy balance model was then extended to see the effects of geoengineering. When the individual albedos (white daisy, black daisy, bare ground) were increased in the Daisyworld model, it simulated the geoengineering tactic of stratospheric seeding, cooling the planet and the interval of suitable temperatures was lengthened. In other words, global temperature rise was postponed, allowing the daisies to survive longer on the planet. Several albedo modifications were tested ranging from an increase of 0.01 to 0.1, all of which ultimately reached a threshold where the increased albedos were no longer enough to maintain an optimum temperature suitable for daisy survival and the planetary temperature increased.

In this study, a haze was evenly distributed over Daisyworld. However, the distribution of particles in the stratosphere will most likely not be so simple. The initial temperature drop also experienced on Daisyworld may have been the result of the immediate response to the initiation of climate modification. An extension to this study could be to gradually spread out the haze rather than it covering Daisyworld instantaneously. Additionally, since stratospheric aerosol injection is not the only method considered, future studies could look at modeling different geoengineering tactics such as only increasing the albedos of certain areas of Daisyworld to mimic brightening marine cumulus clouds. This could be done by enhancing Daisyworld by adding dimensions and exploring the spatial distribution of daisies. It would be a look into how the complexity of the model impacts the albedo needed to extend the stable temperature range. Other studies have been done, increasing the complexity of Daisyworld by making it one-dimensional with heat transfer patterns more consistent with a spherical planet (Adams et al. 2003). Adams and Carr (2003) found that in terms of model response, there are commonalities between the zero-dimensional and one-dimensional Daisyworlds in regards to stability of the system and conditions favorable for stability versus instability. This lends itself to the idea that while increasing the complexity of Daisyworld may provide more detailed results, the overall lessons provided by the basic Dasiyworld model will show through regardless of complexity. It may be worth further study to see if this idea holds true.

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