Simple Climate Models: Daisyworld and Potential For Classroom Instruction

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ABSTRACT

In the 1980s, Watson and Lovelock demonstrated using Daisyworld that biota may have strong impacts on the environment in which they live. Through investigations with simple models such as this, the behavior of more complex, big picture models becomes easier to understand. This gives simple models an important place in education as a way to explore aspects of the world around us. This study uses Stella modeling software to create simple variations on Daisyworld, explain them, and explore how modeling could have uses in the classroom and specific instances where models might be useful. A case is made for using hypothetical models like Daisyworld instead of simplified models of the Earth. Conclusions include potential ways to further exploration of classroom applications and pedagogy since few studies were found that specifically addressed that aspect of modeling.

1. Introduction

As climate change has come to the forefront of scientific and political platforms in recent years, climate modeling has become an important part of research. Simple energy models are integral in looking at how aspects of the Earth can change (Chua 2013). Simple representations of the Earth can facilitate analytical and numerical studies of various phenomena that bridge the gap between more realistic (but also much more complex) models and theoretical understanding (Lohmann 2019). Once a basic model has been created specific variables can be added to look at impacts of man-made or natural changes to the planet. Even systems that only have one independent variable can help piece together how larger dynamic systems work. A working model is not useful unless it is understood (Spiegelman 1997).

Energy Balance Models (EBMs) are the simplest of climate models. These models' only dependent variable is the temperature of the Earth's surface. Zero-dimensional EBMs assume the Earth is only a point in space. Energy comes in at a rate consistent with the solar constant, some is reflected back to space based on the surface albedo, then energy that reaches the surface is reflected out to space or into the atmosphere. EBMs can also be one-dimensional. In these 1st degree models the same principles apply, but Earth is broken up into *m* latitude zones and energy flows from high to low concentrations (Chua 2013).

These simple EBMs cut down to the essential information that is needed to attempt to solve a specific problem—a solution that might be lost in a larger, more complicated model. In rough parallel, Dewdney (1989) discusses the development of a Tinkertoy computer by students at MIT. He says that this device reveals something incredible about digital computation that can also be pointed out about these simple climate models: "…at the very root of a computation lies merely an essential flow of information."

Simple models also allow the creation of non-Earth, conceptual illustrations. One of these is the Daisyworld model developed and introduced by Andrew Watson and James Lovelock in the 1980s (Watson and Lovelock 1983). They propose that life on a planet has a profound impact on the environment, but that the system on Earth was too complex to be able to prove that outright. The original Daisyworld is made up of only two daisies with different albedos and is meant to demonstrate how the daisies changes the world on which they live.

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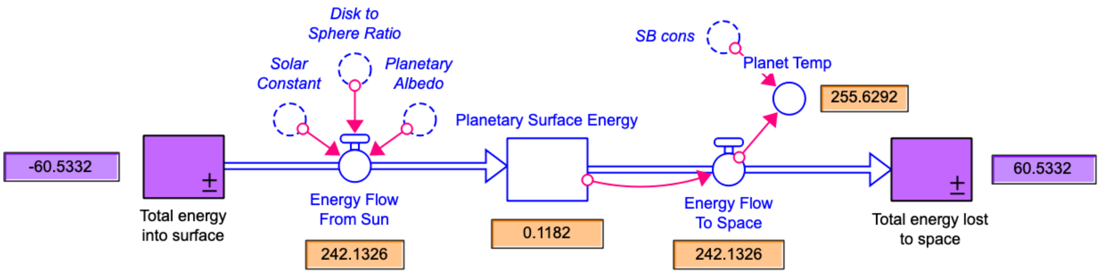

FIG. 1. A simple zero-dimensional EBM constructed in the Stella modeling software. This model shows the energy transfer into and out of the Earth if there were no atmosphere and no greenhouse effect.

The primary goals of this paper are (1) to analyze different variations of Daisyworld and suggest how these analyses might be translated to a better understanding of concepts important to the environment on Earth and (2) to suggest how instructors might use these basic models to give their students more digestible pieces of information and a more secure base level understanding that provides a foundation for more complex ideas.

2. Methods

The models built in this paper were constructed using Stella (“Systems Thinking for Education and Research”), a commercial software developed by Richmond in 1985, and today produced by isee systems (isee Systems 2015). Stella is a drag-and-drop programming interface that provides the fundamentals of system building (stocks, flows, converters, and connectors) as well as basic graphing and animation features. The modeling process in Stella is built on quantities changing over time represented by either differential or difference equations that the software then solves as difference equations. The Stella resources manual mentions specifically that Stella can be used to make models that have fewer computations and more understandable presentation and uses climate models as an example.

Fig. 1 is a simple, introductory Stella model. In this model there is no atmosphere and no greenhouse effect, only the flow of energy into the Earth and back out of it. Fig. 1 an example of a zero-dimensional EBM, since it imagines the Earth as a single point in space with no latitudinal divisions. The boxes in the model are called stocks, and in this model they act as a quantified source and sink for energy. The energy into the system and the energy lost to space in the purple stocks at the beginning and end of the model add to 0. This makes it obvious that the model is balanced and energy conserving. The EBM’s dependent variable of planetary temperature can also be seen in this model coming off of the flow representing the energy lost back to space. The calculated temperature of $\approx 255°\mathrm{C}$ matches observed temperatures of the Earth from space. When working with models of the Earth, knowing what the goal temperature is makes an effective way of checking the performance of the model.

As mentioned previously, in the 1980s Watson and Lovelock developed a model to demonstrate biota impact on the overall environment. The original Daisyworld is a zero-dimensional EBM, described by Watson and Lovelock as a flat disk, and at best a cylinder. However, Daisyworld can be expanded into a 1^{st} degree EBM. Certain colors of daisy grow better at certain planetary temperatures, and in a spherical Daisyworld with latitude bands the result would be a gradient of daisies with the lightest at the equator, and then darkening as they move closer to the poles.

All the equations needed to recreate Daisyworld are found in the original paper, and they can all be solved to be compatible with Stella (Menking cited 2020). In Daisyworld there are several variable combinations that can be changed to see different applications of the model beyond Watson and Lovelock’s original goal. The basic graphing capabilities combined with the ability to export data at each time-step allows for endless potential analyses of Daisyworld. The studies presented in the results section focus on runs of the model with different numbers of daisies with varying albedos, different luminosity inputs, and sudden unexpected changes to the system’s equilibrium midway through the model.

3. Results

a. *Daisyworld*

The more daisies introduced to Daisyworld, the more complex their interactions become. These interactions are explored first by looking at the paired daisies from Watson and Lovelock’s original model and comparing them to how each daisy grows as the only population on the planet.

The original Daisyworld starts at 50% luminosity with a 2% increase every year ($Luminosity = 0.5 + (0.02 * Time)$. This means there is a time at which it becomes too hot for any daisy to grow. The original model specifies that the black daisies have an albedo of 0.25, the white daisies

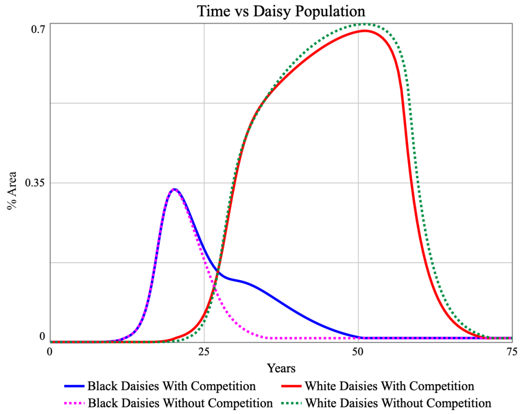

FIG. 2. Plot showing the growth in black daisies (α=0.25) and white daisies (α=0.75) as a percentage of available area both as single species on the planet (dotted lines) and then as a pair on the planet (solid lines). Run SPECS: Range: 0-75, DT: 0.5 years.

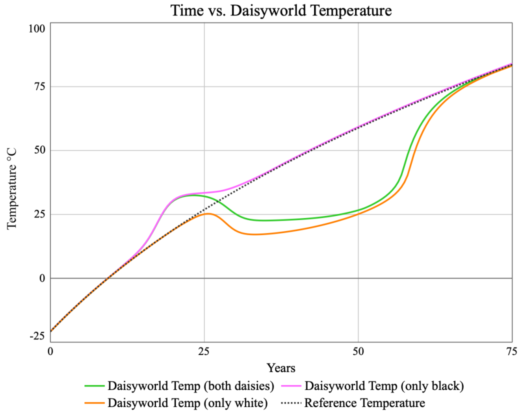

FIG. 3. Plot showing the temperature vs. time for a world with increasing luminosity when 2 daisies are growing (green line) compared to what it would be without daisies (dotted line), as well as the lines for only black daisies (pink line) and white daisies (orange line). Run SPECS: Range: 0-75, DT: 0.5 years.

have an albedo of 0.75, and the bare ground albedo is 0.5. The increasing luminosity allows observation of how the albdeo affects the growth patterns, and how the growth has a steadying effect on the planetary temperature.

Fig. 2 shows the daisy growth as a percentage of the available area. The black daisies grow first because they absorb more of the sun's energy and reach a growth temperature more quickly. As the temperature of the world continues to increase the white daisies reach their growth temperature and outpace black daisies in the fight for available surface area.

Also shown in Fig. 2 is the the difference in the growth patterns when the daisies are competing and when they are the only daisy on the planet. The black daisy curve is identical until the white daisies begin to grow, but the pattern changes as the black daisies decline. The white daisies decrease the temperature of the planet as their surface area increases, since the white daisies increase the planetary albedo, calculated using

$$\alpha_P = A_g\alpha_g + A_b\alpha_b + A_w\alpha_w. \tag{1}$$

This is a weighted average where A_x is the area of the bare ground, black daisies, or white daisies, and α_x is the corresponding albedo. The planetary temperature is negatively correlated with the albedo of the planet. The white daisies enable the black daisies to maintain a temperature in their growth range, meaning the black daisies survive until the white daisy growth rate outpaces theirs and they cannot compete for land effectively. Fig. 2 also illustrates that the white daisies can begin to grow slightly sooner with the help of the black daisies because they are able to reach their growth range a few years earlier.

Fig. 3 shows how the daisies cause temperature changes on the planet. See that the time period where the black daisies are dominant pushes the Daisyworld temperature above what it would be without the daisies, and that the white daisies push the temperature below. This is because the black daisy albedo is lower than the bare planet albedo. Using equation 1, this brings down the overall albedo and causes the planet to absorb more energy. The opposite happens when the white daisies start to increase.

Fig. 2 and Fig. 3 both show what happens when the luminosity heats the planet beyond what the daisies are able to regulate. Eventually the sun also becomes too strong for the white daisies (see the increase in temperature that corresponds to the white daisy population beginning to decrease) and the temperature of Daisyworld continues to rise as if daisies had never existed at all.

Before continuing, an explanation of the concept of growth temperatures. This ideal growth range is a reference back to the original model from Watson and Lovelock (1983). The growth equation for the daisies is shown in here in Equation (2).

$$\beta_n = 1 - 0.003265(22.5 - T_n)^2. \tag{2}$$

β_n is the growth rate of the daisies and T_n is the corresponding local temperature of the daisy population. This parabolic function gives the daisies positive growth values between 5°C and 40°C, with their maximum growth happening when the local temperature is 22.5°C.

Table 1 shows the temperatures in Celsius at which the daisies of various albedos begin to grow in a 5-daisy model. Notice that all of the values are just over 5. Since data was being reviewed by hand in all the exercises in this paper, the differential (DT) value in Stella is not very small (1/16 for this particular model run). The smaller the DT is the closer the integration is to continuous, and the closer these values will get to 5.

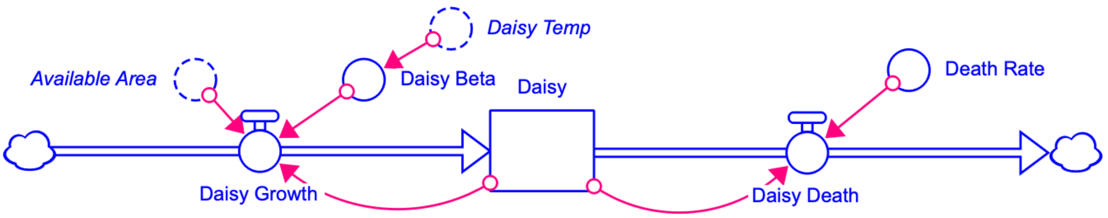

FIG. 4. The daisy population monitoring component of a 1-daisy Stella model. One of the building blocks of all larger *n*-daisy models. Here the clouds serve as sources and sinks for the population, rather than having a numerical monitoring component.

Albedo	Starting Growth Temp.
0.1	5.011937512
0.3	5.000354911
0.5	5.031263599
0.7	5.263937642
0.9	5.224976683

TABLE 1. A table showing the initial growth temperatures of each daisy in a 5-daisy model in °C with DT=1/16.

Now some of the broader modifications of Daisyworld are introduced. The original 2-daisy model shows some leveling out of the temperature, but this phenomenon becomes more apparent when more daisies are added to the model. Throughout this research daisies with varying numbers of models were made, but at this point the focus will be on a 5-daisy model. This larger variation works in the same way as the 2-daisy model, but with a larger system of equations. In Stella this is achieved by duplicating components (referred to as ”building blocks”) from the original model and adding new pieces into other equations as needed. Fig. 4 shows the population component of a 1-daisy model. This is an example of a building block that would be copy-pasted into an expanded model. In other words, a new model does not mean starting from scratch.

The more daisies that are included in the model the flatter the curve is between when the lowest albedo daisy peaks and the highest albedo daisy begins to die. Fig. 5 shows the temperature curve of the 5-daisy model. Notice the low albedo daisies still grow first and raise the temperature above the reference temperature, and as the higher albedo daisies grow they keep the temperature below the reference. Then the luminosity becomes too high for the daisies to regulate the temperature, they die off, and the temperature curve once again reverts to what it would be without daisies. In this model the albedos are equally distributed around the bare ground albedo, but further study could be conducted to look at what would happen if there

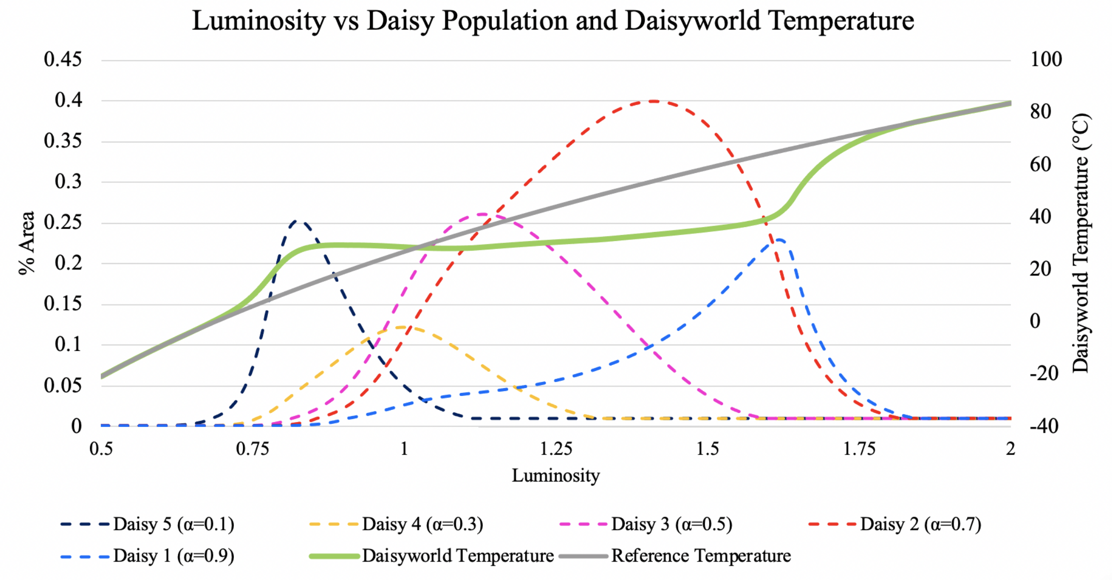

FIG. 5. Graph showing the temperature of the planet with the 5 daisies and the baseline temperature compared to when and how the daisies are growing. Run SPECS: Range: 0-75, DT: 1/16 years.

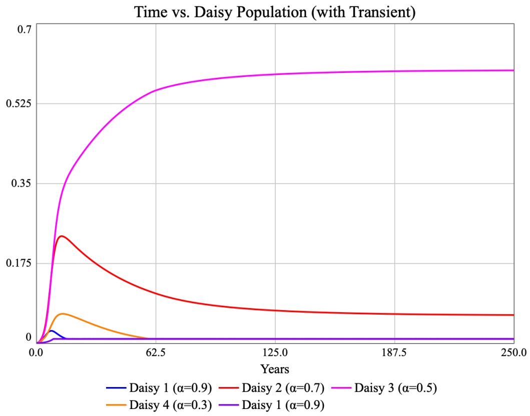

FIG. 6. Graph showing the daisy population in a 5-daisy model with constant luminosity. Includes population as a % of available land. Note the time it takes for the daisy populations to approach equilibrium.

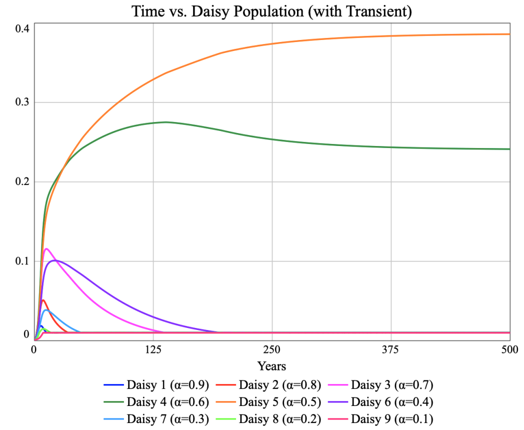

FIG. 7. Graph showing the daisy population in a 9-daisy model with constant luminosity. Includes population as a % of available land. Note the time it takes for the daisy populations to approach equilibrium.

were uneven albedo distributions. For example, all the albedos above or below the bare ground, one daisy whose albedo is an outlier, tighter distribution around the bare ground albedo, or changing the bare ground albedo itself.

Another variation on Daisyworld is changing the luminosity to a constant value instead of increasing. This allows the daisies to reach an equilibrium where they maintain the same area distribution. Fig. 6 and Fig. 7 show 5- and 9-daisy models, respectively, where the luminosity value has been set to 1, or 100% of the solar constant. In these models the albedos are continue to be spaced evenly between 0 and 1. Note the different x- and y-axis values. The graphs go to different times because the time to reach equilibrium increases as more daisies are added, and they have different maximum y-values because as more daisies are added the maximum area any one daisy can occupy decreases. (This can be observed in the different y-axis values in Fig. 2 versus Fig. 5 as well.) Both of these models include a starting transient which shows the time it takes for the model to find balance with each daisy value.

Once these equilibrium values are found a different pair of graphs could be created which eliminate the starting transient. This is accomplished by setting the initial value of each population to the equilibrium value found in the model runs of Fig 6 and Fig. 7. These graphs might be a more realistic view of Daisyworld if it could be physically observed.

Notice which albedo values become dominant in the systems with constant luminosity. This goes back to the concept of ideal growth temperature. The dominant daisies are the ones with local temperatures that give them the highest growth rate. A deeper mathematical analysis could be done on the equations provided by Watson and Lovelock (1983) to figure out exactly which albedo values would dominate. Something else to consider in a system with constant luminosity is which daisies would thrive if the albedo of the bare ground changed? In these Daisyworld models the bare ground is about 30% of the planet at any given time, giving it a significant impact on the overall temperature of the planet.

The final modification of Daisyworld explored here involves sudden changes during the course of the model. What if a disaster strikes Daisyworld? First assume a meteor hits the planet. Since Daisyworld is flat let each daisy type be uniformly spread across the surface so the disaster affects all daisies equally. How does the system respond and recover?

To accomplish a disaster simulation in Stella an extra outflow is added to each population stock in the model which drops the daisy populations suddenly at 50 years. The disaster simulation drops each population by approximately 40%. When a disaster happens in a world with constant luminosity (Fig. 8), the system is able to resume the equilibrium balance within approximately 10 years of the disaster. This is because the luminosity is not changing, allowing the daisies maintain their pre-disaster growth rates. This is not the case in a world where the luminosity increases.

The disaster has increased long term effects when it interferes with the delicate temperature balance the daisies achieve when the luminosity is increasing, as shown in Fig. 10. When compared to the 5-daisy model under normal conditions (Fig. 5) it is easy to see that this significantly impacts the model. The disaster interrupts the temperature balance in such a way that the daisy growth is unable to recover. The daisies die off suddenly and the Daisyworld temperature continues to rise unregulated.

What if the disaster is a plague that targets only daisies of certain colors, or albedos? See in Fig. 9 another version of the 5-daisy model with constant luminosity. Daisy 3 is now the only daisy to be affected at 50 years. This time the pre-plague equilibrium is not regained as quickly. Daisy 3

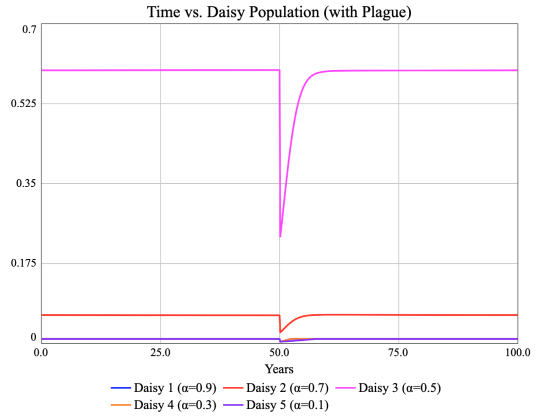

FIG. 8. A plot showing the effects of a sudden disaster at 50 years in a 5-daisy simulation of Daisyworld with constant luminosity. The impact of the disaster affects each of daisy population in the same way.

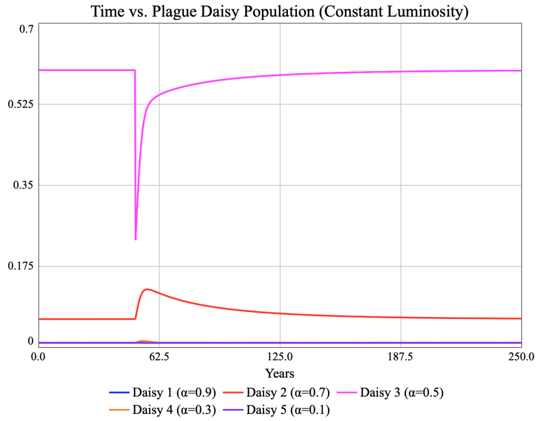

FIG. 9. Plot for constant luminosity showing the response of the daisy populations to a disturbance that sharply reduces a single daisy. While the reduced population shows a quick partial recovery, this is followed by long slow return toward equilibrium.

not only has to repopulate the land it lost, it has to fight for it, as seen by the increase in the other daisy populations. Now refer to Fig. 11, where the plague strikes a Daisyworld with increasing luminosity. Daisy 3 dies off only slightly sooner than it would otherwise, but this causes a noticeable lengthening of the model. The lighter albedo daisies are able to grab onto that bit of extra land and continue to drop the temperature and fight the increasing luminosity for a longer period of time.

All of these simulations and modifications are only a sample of what Daisyworld can offer in terms of simulations. From more modifications involving only the daisies, to adding mammals to the model, the possibilities are endless.

b. Classroom Applications

A clear example of Daisyworld in the classroom is the lab that was the starting point for the Daisyworld models used in this paper (Menking cited 2020). From a curriculum standpoint the exercise encourages critical thinking. An understanding of the original paper by Watson and Lovelock (1983) is required to be able to answer the questions asked in the course of formulating the model. Then, using Stella to translate equations into stocks, flows, and converters requires interpreting, deconstructing, and reconstructing each piece of information (quantitative and qualitative) in the original source material to make sure all the variables are interacting correctly and efficiently. Once the model is built it requires continued interpretation of the results in the form of graphs help to illustrate how different variables work together and demonstrate simple concepts like feedback loops. These types of models allow for a lot of independent thinking as well, especially in the lab style this document is presented in.

From the perspective of the student author who spent time learning about modeling and coming from a math background instead of an environmental science or meteorology background, Daisyworld was incredibly helpful in getting a base level knowledge of all the concepts used throughout the summer in REU and in this paper. Concepts like albedo, luminosity, and systems of differential equations like the ones used in Daisyworld are base level information that apply across disciplines like physics, biology, and meteorology. Theoretical models are also very helpful as a precursor to simulations of Earth. Theoretical models have set equations, and there is a general understanding of what they are supposed to look like. The same can not always be said of Earth models.

Watson and Lovelock (1983) say in their original paper than any direct connection between Daisyworld and Earth is tenuous at best. Daisyworld has no rotation, no seasons, and perhaps most importantly: no humans. Its purpose at its inception was simply to show that ecosystems can significantly impact the environment. This does not diminish Daisyworld's value as a useful tool for teaching the concepts that exist within it. As mentioned previously and as seen in Fig. 12, feedback loops are a principle that Daisyworld is built upon. One condition changes the next, and the change moves through a series of variables until it comes back to the first condition. Fig. 12 is a general feedback loop meant for illustrative purposes. More specific versions could be developed to explain different types of feedback loops. Another specific example of a phenomenon that Daisyworld could be used to draw parallels between is the concept of the urban heat island effect (Chua 2013). Seeing the black daisies raising the temperature as a function of their albedo is an effective analogy to cities with high amounts of concrete and fewer plants tending to have higher local temperatures.

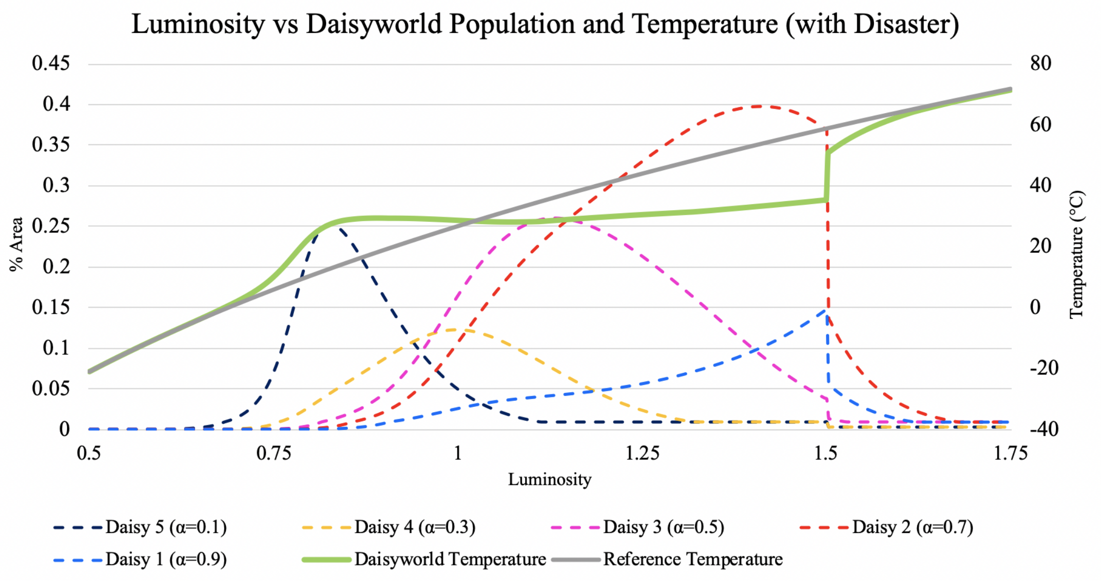

FIG. 10. Graph showing the effects of a sudden disaster at 50 years/150% luminosity in a 5-daisy simulation of Daisyworld with increasing luminosity, as structured in the original 5-daisy model.

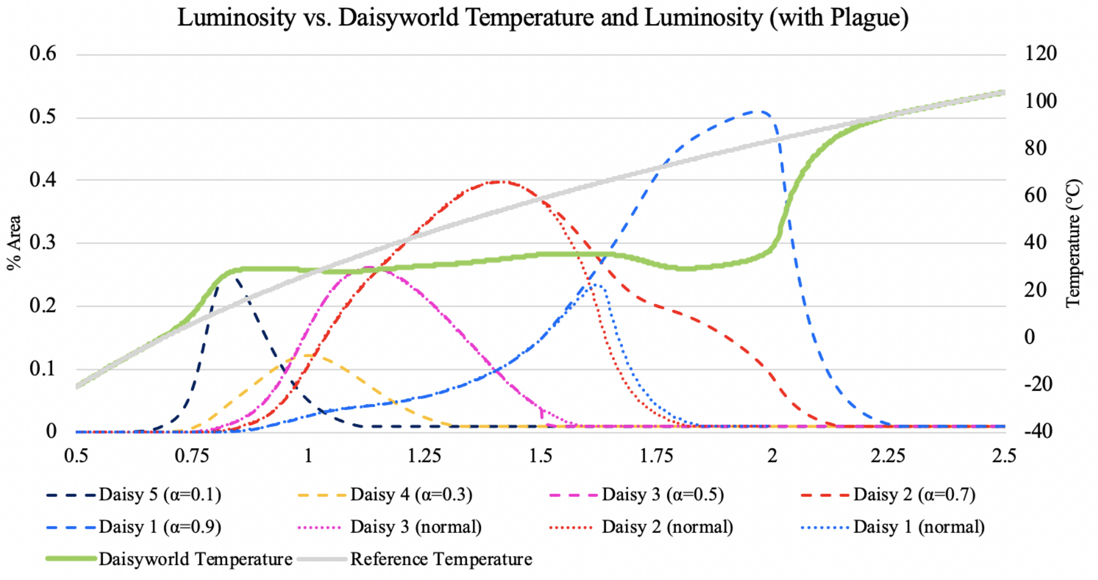

FIG. 11. A plot for increasing luminosity showing the impact of a plague killing off most of Daisy 3 at luminosity 1.5. The dotted lines represent the behavior of daisies 3, 2, and 1 without the plague, shown for comparison.

The EBMs that have been referenced throughout this paper are a subset of dynamic systems, or a system of equations that discuss how variables change over time (Spiegelman 1997). Daisyworld is only a small subset of all climate models, let alone all dynamic systems. Spiegelman (1997) also says, however, that while these systems might be different on the surface, they are all able to be investigated in similar ways, using similar tools. In other words, these models are incredibly versatile teaching tools with a lot of room for specialization.

4. Conclusions

Despite the lack of exact parallels between Earth and basic models such as Daisyworld, there are many ways to use these ideas in insightful, educational ways. EBMs serve as a bridge between large, complex models, and theoretical concepts. This systems thinking allows a deeper awareness of the world and how seemingly unrelated variables could be connected.

Simple models are effective illustrations. Daisyworld itself is an example which includes concepts such as albedo, solar constant, luminosity, and feedback loops. Because there is a set of equations that Daisyworld is strictly based off of, it can be a less confusing first modeling exercise than a model of the Earth. Learning to understand Daisyworld is also a good introduction to critically reading and thinking through a scientific paper. Watson and Lovelock (1983) very clearly states their goal and explain their reasoning and results in a way that is easy to follow and recreate.

a. Potential Future Applications

There are many other applications of Daisyworld that are not touched on in this paper. There are variations and applications of Daisyworld that can serve as an illustration for many other concepts. How does the effect of the biota change when predators and prey are added to Daisyworld? In its original form Daisyworld has no clouds. How could a model be changed to represent how the temperature would change with that added variable? Wood et al. (2008) goes through many of the modifications that Daisyworld has undergone since its inception, some more complicated than others, as well as reiterating that a more general model of life-environment interaction would need to be quite different from Daisyworld. Wood et al. (2008) shows that the literature on Daisyworld generally takes the basic concept and adds more complicated layers to more closely represent processes that happen on Earth. This paper tries to break down Daisyworld, not draw any direct parallels.

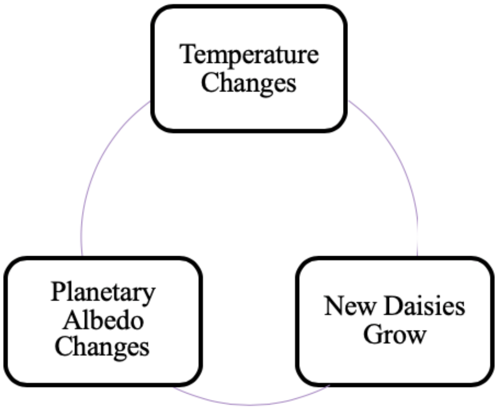

FIG. 12. A graphic created to show one of the possible feedback loops in Daisyworld.

Throughout discussion of this study with other scientists it became apparent that Daisyworld is used with some frequency in atmospheric science and meteorological education, but there is a lack of peer-reviewed literature in regards to it and other models as to their specific benefits as a learning tool. An practical next step would be researchers going into the classroom at different levels from high school through graduate school, in various disciplines, to explore how modeling affects understanding of basic concepts such as the ones discussed in this paper.

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Thank you to Dr. Susan Boyle of Rhodes College who provided me with some online resources used in her own class to help familiarize myself with potential uses of Daisyworld in the classroom.

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