COMPUTER METHODS AND MODELING IN GEOLOGY
DAISYWORLD

The parts of this exercise for students are in normal text, whereas answers and explanations for faculty are italicized.

In the 1970s scientist James Lovelock introduced the Gaia hypothesis, in which he proposed that the Earth is a self-regulating system governed by the interactions of myriad organisms with the atmosphere, hydrosphere, rocks, and soils. This hypothesis has been largely misinterpreted, with many understanding Lovelock to mean that the Earth acts as a single organism, with a sort of built-in consciousness that maintains the conditions necessary for life. This was not Lovelock's meaning. Instead, he recognized that in order for life to persist and thrive, it had to optimize the environment for itself, accessing nutrients and getting rid of wastes. This optimization is not a conscious act, but instead comprises the evolutionary responses of individual organisms to the conditions in which they find themselves. One organism's waste is another's food supply, and both rely on the cycling of nutrients throughout the Earth system, brought about by biological, hydrological, and plate tectonic processes. To lend evidence to his idea that life optimizes its environment, Lovelock pointed to the fact that Earth's atmosphere is a highly improbable mix of gases. It contains far too much methane gas (CH_4) given the abundant oxygen that oxidizes methane to carbon dioxide. The fact that methane is found in abundance requires that life is maintaining it at an elevated level.

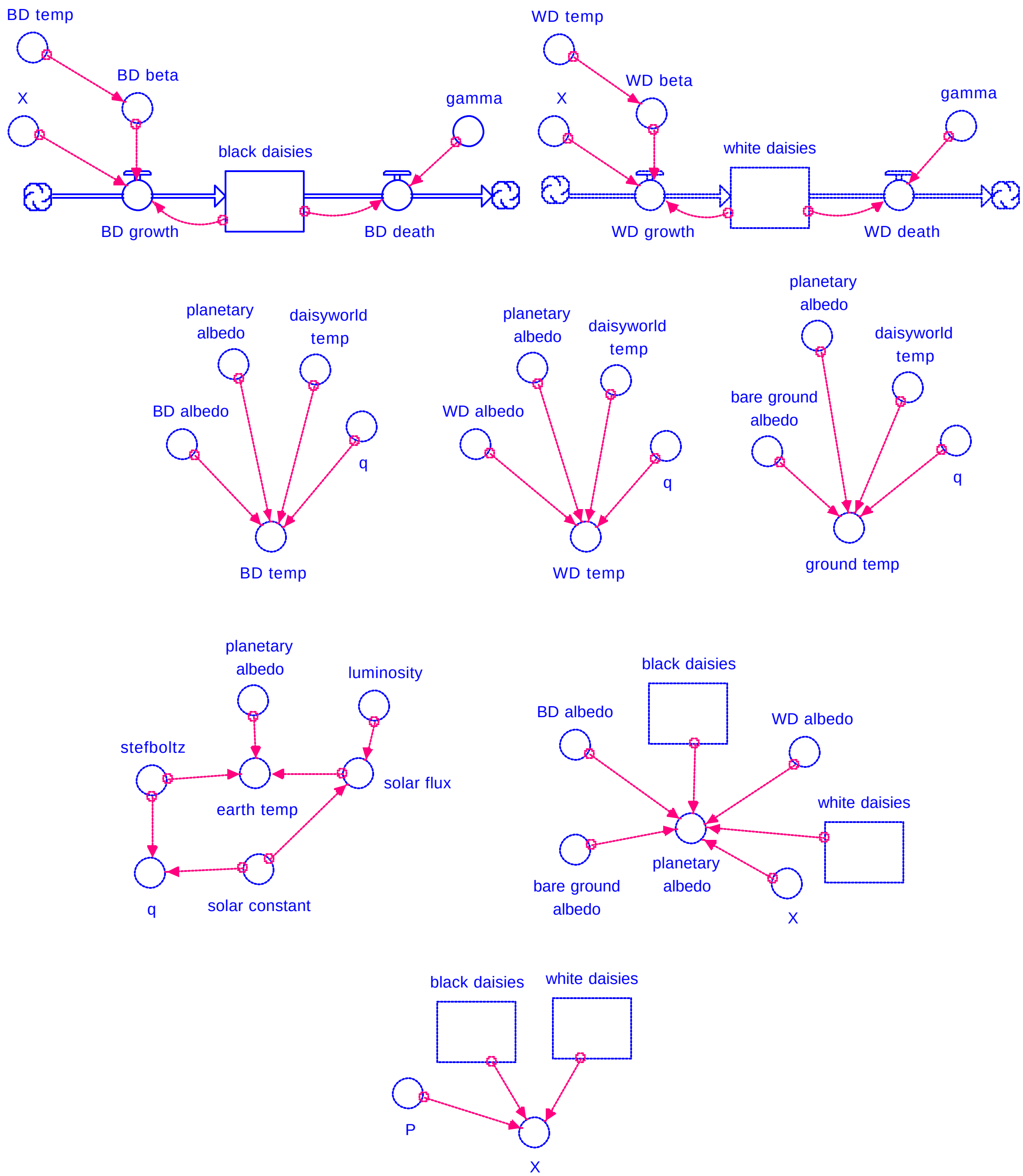
Lovelock also pointed to Earth's temperature history to lend evidence to his idea. According to well-accepted models of stellar evolution, stars, such as our sun, increase in luminosity over time. However, geologic evidence suggests that Earth has been cooling, at least since the early Cenozoic. Somehow life has been able to control its environment to keep the planet habitable despite ever increasing inflows of solar radiation. Lovelock's ideas met with great criticism from biologists, so he and Andrew Watson designed a simple experiment to show that self-regulating systems of organisms can exist and can optimize the environment to themselves simply by responding to external conditions that cause increases or decreases in birth and death rates. The experiment, called Daisyworld, consists of a planet in which only 2 species exist, white and black daisies. The planet has no atmosphere to speak of, no plate tectonic cycle, and no hydrologic cycle, yet despite these deficiencies, daisies grow and interact with a sun of ever increasing luminosity to maintain the planet at a remarkably uniform temperature for many years. If such a simple system can be shown to be self-regulating, argued Watson and Lovelock, shouldn't the Earth, with its much richer array of organisms, also be capable of self-regulation? Today we'll recreate Watson and Lovelock's Daisyworld to explore this fascinating idea, building on the understanding of Earth's climate system gained last week.

Readings

Watson, A.J., and Lovelock, J.E., 1983, Biological homeostasis of the global environment: the parable of Daisyworld, Tellus, v. 35B, p. 284-289.

STELLA Model and Code

Daisyworld STELLA Model



Daisyworld STELLA Model Code

```
black_daisies(t) = black_daisies(t - dt) + (BD_growth - BD_death) * dt
INIT black_daisies = 0.001

INFLOWS:
BD_growth = black_daisies*BD_beta*X
OUTFLOWS:
BD_death = if(black_daisies>0.01)then(black_daisies*gamma)else(0)
white_daisies(t) = white_daisies(t - dt) + (WD_growth - WD_death) * dt
INIT white_daisies = 0.001

INFLOWS:
WD_growth = white_daisies*WD_beta*X
OUTFLOWS:
WD_death = if(white_daisies>0.01)then(white_daisies*gamma)else(0)
bare_ground_albedo = 0.5
BD_albedo = 0.25
BD_beta = if(BD_temp>5)and(BD_temp<40)then(1-0.003265*((22.5-
    BD_temp)^2))else(0)
BD_temp = ((q*(planetary_albedo-BD_albedo)+((daisyworld__temp+273)^4))^(0.25))-
    273
daisyworld__temp = ((solar_flux*(1-planetary_albedo)/stefboltz)^(0.25))-273
gamma = 0.3
ground_temp = ((q*(planetary_albedo-
    bare_ground_albedo)+((daisyworld__temp+273)^4))^(0.25))-273
luminosity = 0.5+(0.02*time)
P = 1.0
planetary_albedo =
    (white_daisies*WD_albedo)+(black_daisies*BD_albedo)+(X*bare_ground_albedo)
q = 0.2*solar_constant/stefboltz
solar_constant = 917.0
solar_flux = luminosity*solar_constant
stefboltz = 5.67e-8
WD_albedo = 0.75
WD_beta = if(WD_temp>5)and(WD_temp<40)then(1-0.003265*((22.5-
    WD_temp)^2))else(0)
WD_temp = ((q*(planetary_albedo-WD_albedo)+((daisyworld__temp+273)^4))^(0.25))-
    273
X = P-white_daisies-black_daisies
```

Exercises

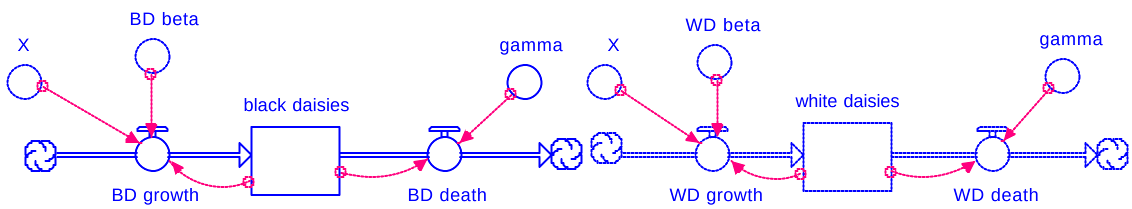
1) In Stella, create two stock and flow diagrams to govern the population of white and black daisies over time. Use Watson and Lovelock's equation 1 to

specify the growth and death of the daisies. We'll worry about the input values in a minute. For now, just set up the relationships governing growth and death. You will be making extensive use of Stella's ghost tool today - so you may want to think ahead at each step in your modeling to whether you want to put in the original or a ghosted variable.

Watson and Lovelock's equation 1 states the following:

$$da_b/dt = a_b (x\mathbf{b} - g)$$
$$da_w/dt = a_w (x\mathbf{b} - g)$$

where a_b *and* a_w *are areas covered by black and white daisies,* x *is the area of fertile ground not yet covered by daisies,* $\mathbf{b}$ *is the growth rate, and* g *is the death rate. By this point in the modeling course, students should be able to understand this simple differential equation and cast it in STELLA terms. Its meaning can be stated verbally as the change in the population of daisies over time is equal to the inflow of daisies via population growth minus the outflow of daisies via death. In STELLA, these 2 equations look like the graphics below:*



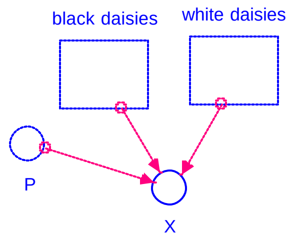
As set up by Watson and Lovelock, the growth flows for black and white daisies (BD growth and WD growth) are dependent on how many daisies exist at any time period (black daisies and white daisies reservoirs), how much fertile ground is available for colonization (X), and on the growth rate for each population (BD beta and WD beta). The death flows (BD death and WD death) are dependent on the populations of black and white daisies and on their death rates (gamma).

Note that both black and white daisies depend on the values X, γ, and β. X and γ are identical for both sets of daisies - is β?

No, $\mathbf{b}$ *(the growth rate) is not identical for both sets of daisies.* $\mathbf{b}$ *depends on local temperature, so it has to be specified for each daisy type. For this reason, the model contains both BD beta and WD beta as variables.*

2) Next, keep track of the amount of ground available for daisy growth (X). Available ground is ground that is fertile and not yet covered by white or

black daisies. Assume that P, the proportion of the ground that is fertile, is 1. This means that the entire planet is covered in fertile ground.



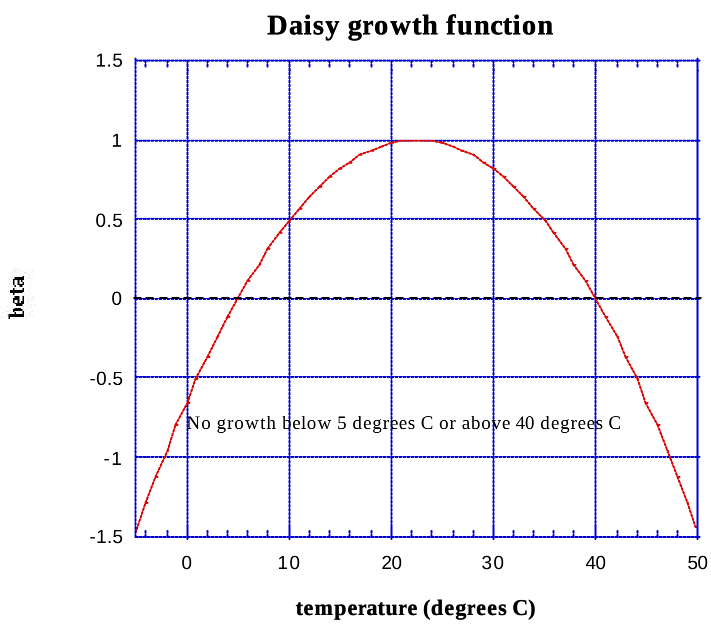
X, the amount of fertile ground remaining, is equal to P-white_daisies-black_daisies.

3) Watson and Lovelock designed their system such that the daisies, like most Earth species, have very specific ecological tolerances. Daisies cannot grow at temperatures colder than 5 degrees C or warmer than 40 degrees C. Their growth is maximized at 22.5 degrees. The growth function,

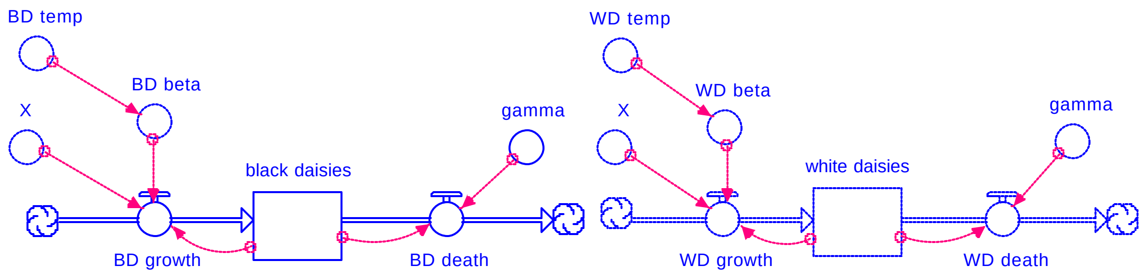
$$\beta = 1 - 0.003265*(22.5 - T)^2$$

describes the ecological constraints on daisy growth.

In Kaleidagraph or Excel create a graph of beta as a function of temperature so that you can see what this function looks like. Paste it into your word file.



4) Create new converters on your model page to specify the values of the β functions. Don't worry that you don't know what the daisy temperatures are yet – we'll get to that.



In this graphic, the dependency of BD beta and WD beta on the local temperature has been specified through the addition of the BD temp and WD temp converters.

Now, we have a little bit of a problem. If you look at the growth function equation you'll see that we can put any temperature into it. If we put in temperatures greater than 40 or lower than 5, however, we will get out negative values of growth. Obviously we don't want negative values of growth. How can we tell Stella to make growth values be zero except for temperatures between 5 and 40 degrees?

This can be accomplished by using a conditional statement in the equation:

BD_beta = IF(BD_temp>5)AND(BD_temp<40)THEN(1-0.003265((22.5-BD_temp)^2))ELSE(0.)*

WD_beta = IF(WD_temp>5)AND(WD_temp<40)THEN(1-0.003265((22.5-WD_temp)^2))ELSE(0.)*

5) The next thing we need to do is examine the inflow and outflow equations that govern the growth and death of the daisies. Here we again encounter a little issue. We have to be careful never to drop the number of daisies all the way to zero or there won't be a sufficient population to grow new daisies with. How can we ensure that the population of daisies never falls below a certain threshold?

We can ensure that the daisy population always remains above zero by changing the death flow to zero if the population falls below a particular threshold:

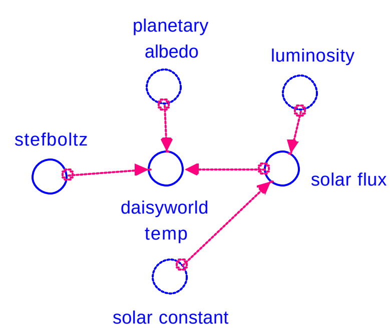
*BD_death = IF(black_daisies>0.001)THEN(black_daisies*gamma)ELSE(0.)*
*WD_death = IF(white_daisies>0.001)THEN(white_daisies*gamma)ELSE(0.)*

Here, as long as the proportion of the ground covered by white and black daisies is above 0.1% (0.001), daisies are allowed to die during each time step. As soon as the proportion falls to 0.1% or lower, daisies no longer die, thereby ensuring a small surviving stock from which to grow new populations.

Use 0.001 for your threshold. What value do you need to put in for the initial number of daisies?

0.001 is the initial value for the stocks of both black and white daisies. Note that if we were to start with 0 in these reservoirs, the daisies would never be able to start growing since the growth flow is dependent on daisy population.

6) Now we're ready to determine the temperatures of the white and black daisies so that we can determine the β values. Equation 6 in Watson and Lovelock describes the relationship between the temperature of each type of ground cover (white daisies, black daisies, and bare ground) and the average temperature of Daisyworld. The average temperature of Daisyworld is in turn specified in equation 4, which you should recognize from last week's lab. Let's first work on the average temperature of Daisyworld. Create the necessary converters and connectors to determine the average Daisyworld temperature.



*The average temperature of Daisyworld is determined from the Stefan-Boltzmann equation, assuming that the planet is a perfect black body. The solar constant used by Watson and Lovelock measures 917 W/m². This value is modulated by a luminosity function, measuring 0.5+(0.02*time), which allows the flux of solar energy to ramp up slowly over time, from a starting value equal to half of 917 W/m², or 458.5 W/m². Students are asked to come up with this equation and the value for the solar constant in problem 10 below.*

According to Watson and Lovelock's equation 4, the temperature of Daisyworld is determined from:

$$s(T_d+273)^4 = SL(1-A)$$

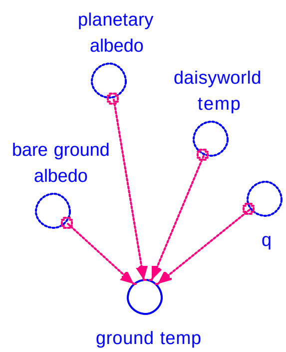
where s is the Stefan Boltzmann constant ($5.67*10^{-8}$ $W/(m^2K^4)$), T_d is the temperature of Daisyworld, SL is the solar flux, and A is the albedo.

Casting this equation in terms of the variables names used in the STELLA model and rearranging to solve for the temperature of Daisyworld gives the following equation:

daisyworld temp =((solar_flux(1-planetary_albedo)/stefboltz)^(0.25))-273*

where stefboltz is the Stefan Boltzmann constant.

7) Let's next determine the temperature of bare ground using equation 6. Don't worry about specifying q yet. We'll put it in later.



According to Watson and Lovelock's equation 6, local temperature of white and black daisies or of bare ground (T_1) is a function of planetary temperature (T_d), the difference in albedo between the local area (A_1, i.e., white or black daisy or ground albedo) and the planetary albedo (A), and a factor q that determines whether heat can be conducted from areas of high heating to low heating:

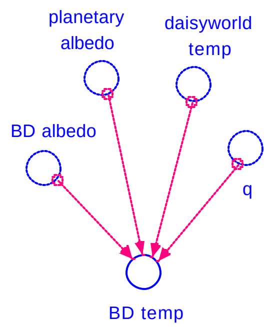
$$(T_1+273)^4=q(A-A_1)+(T_d+273)^4$$

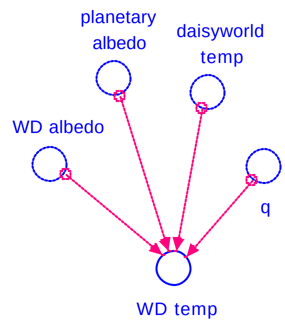
Rearranging this equation to solve for T_1 and casting it in the terms of the STELLA variables shown above gives:

ground temperature = ((q(planetary_albedo - bare_ground_albedo) + ((daisyworld__temp + 273)^4))^(0.25))-273*

8) Now determine the temperature of the white daisies and black daisies.

These temperatures are also determined using Watson and Lovelock's equation 6 and by simply substituting in black and white daisy variables where the bare ground variables were in the previous equation.

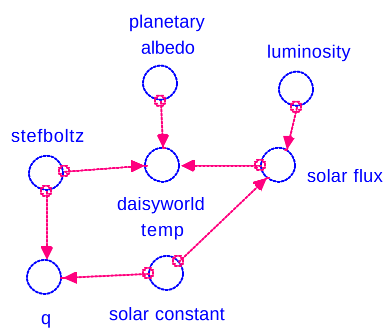




BD temp = ((q*(planetary_albedo-BD_albedo)+((daisyworld__temp+273)^4))^(0.25))-273

WD temp = ((q*(planetary_albedo-WD_albedo)+((daisyworld__temp+273)^4))^(0.25))-273

9) We're almost ready to run the model. Just a few things remain. First, we need to specify what q is. Use the value that Watson and Lovelock suggest, $q=0.2*(SL/\sigma)$.



q can be added to the part of the model graphic in which the planetary temperature is calculated. Students are asked to explain the meaning of this q value and to experiment with it in part 19 below.

10) Lastly, we need to specify the luminosity, solar constant, and Stefan-Boltzman constant. The Stefan-Boltzman constant is the same as last week. For the solar constant, Watson and Lovelock use a value of $9.17*10^5$ ergs/cm^2s. Daisyworld is their creation, and it doesn't represent reality, so we'll use this number also. We must convert it to W/m^2 though in order to be consistent with the Stefan-Boltzman constant. Use the following conversion to determine what the value is in W/m^2:

1 Joule = 10^7 ergs

1 Watt = 1 Joule / sec

What is the value?

917 W/m^2

For the luminosity we want to create an equation that will ramp up the solar energy given off by the sun over time. Make up an equation that will start the sun off at half its current brightness and that will then ramp up the insolation by 2% a year.

What is your equation?

*0.5+0.02*TIME*

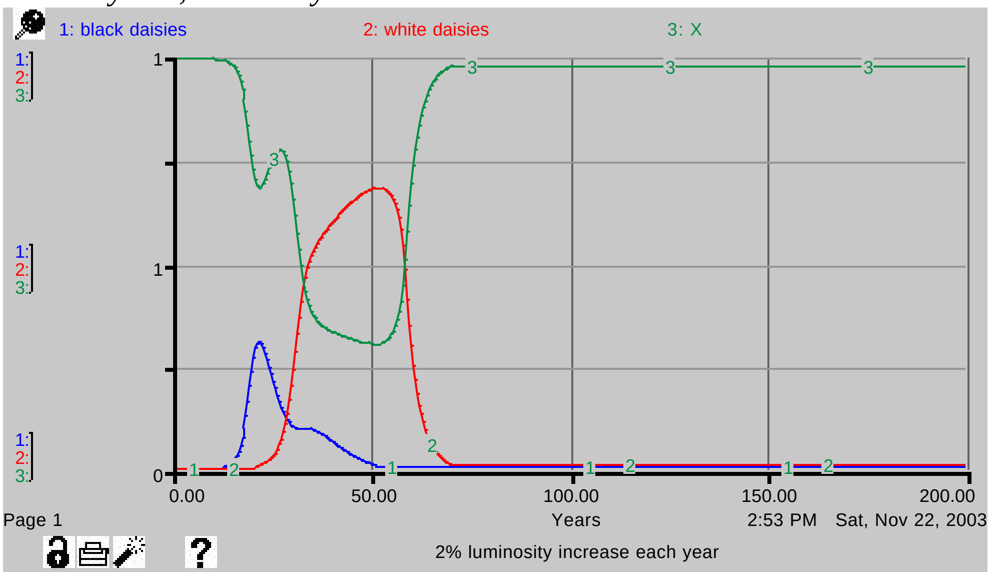
11) Fill in the remaining values of constants you have not yet specified and initial conditions.

Here students should fill in the values for albedo of white and black daisies and of bare ground. According to Watson and Lovelock, white daisy albedo is 0.75, bare ground albedo is 0.5, and black daisy albedo is 0.25.

12) Run your model, keeping track of the population of white daisies, black daisies, and percent bare ground on one graph, noting the insolation and planetary temperature on a second graph, and the growth flows for black and white daisies on a third graph. If you have a constant population of white and black daisies you have a problem. See me and we'll discuss how to fix it.

13) **Describe and explain** what you see in your graphs. How do the daisies act to moderate the planetary temperature while the solar luminosity increases?

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year

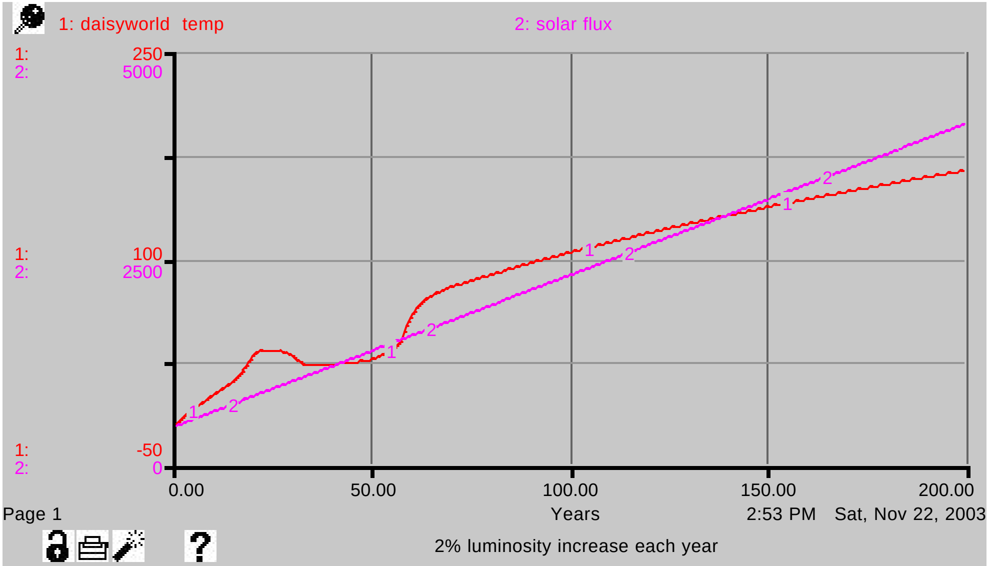


Note: the middle value on the y-axis should be 0.5, rather than 1. This is a bug in the STELLA vs. 7 software. The y-axis values range from 0 at the bottom to 1 at the top.

In this graph, the black daisies are the first to increase in quantity, but they peak very quickly and then decline. As the black daisies decline, the white daisies increase in quantity. The number of white daisies ultimately declines as well. The available ground cover decreases and increases with an inverse relationship to the abundance of flowers, as expected.

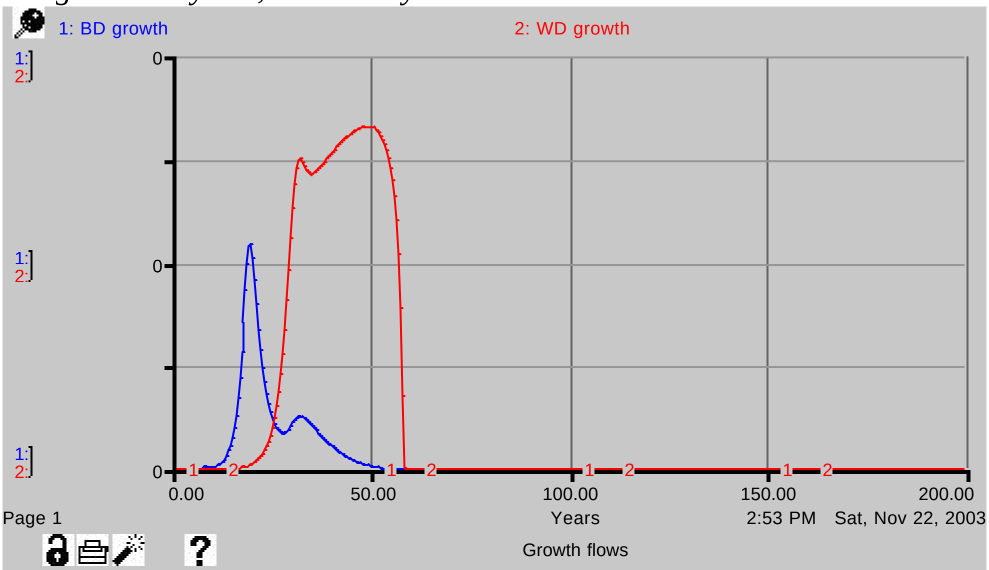
Comparison of this graph of daisy population to a graph of solar flux and planetary temperature (below) reveals that the black daisies begin to grow once their local temperature rises above 5 degrees. Their growth rate then increases until such time as their low albedo makes conditions too warm for them. In the meantime, the warming of the planet by the growth of the black daisies makes local conditions warm enough to allow the white daisies to start to grow. As the black daisies become too hot to continue flourishing, the white daisies take off, causing the planetary temperature to drop as more ground is covered by these high albedo flowers. This drop in temperature leads to a momentary reprieve for the black daisies, which stop their precipitous population decline and stabilize for some time. Eventually, however, the incoming solar flux proves too powerful and the black daisies and then eventually, the white daisies, die out. During the time that the daisies are alive, the planetary temperature remains fairly steady despite a continuously increasing solar flux.

This graph was created by running the model with the following Run SPECS:
Range: 1-200 years, DT: 0.5 year



A graph of the growth flows of black and white daisies shows the behavior of the daisies explicitly:

Range: 0-200 years, DT = 0.5 years

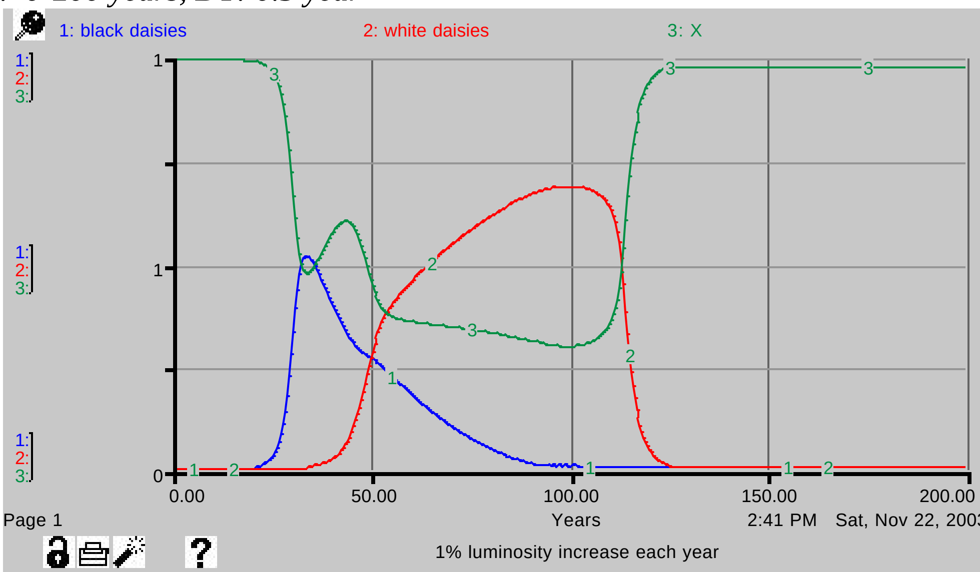


In this graph, the top value along the y-axis is 0.25 daisies/year. For some reason, STELLA vs. 7 does not allow decimal values on the y-axis of graphs.

14) Run some experiments in which you change the luminosity by different amounts each year - say by 1% and by 5%. What impacts do these changes have on the daisy population curves and on the planetary temperature?

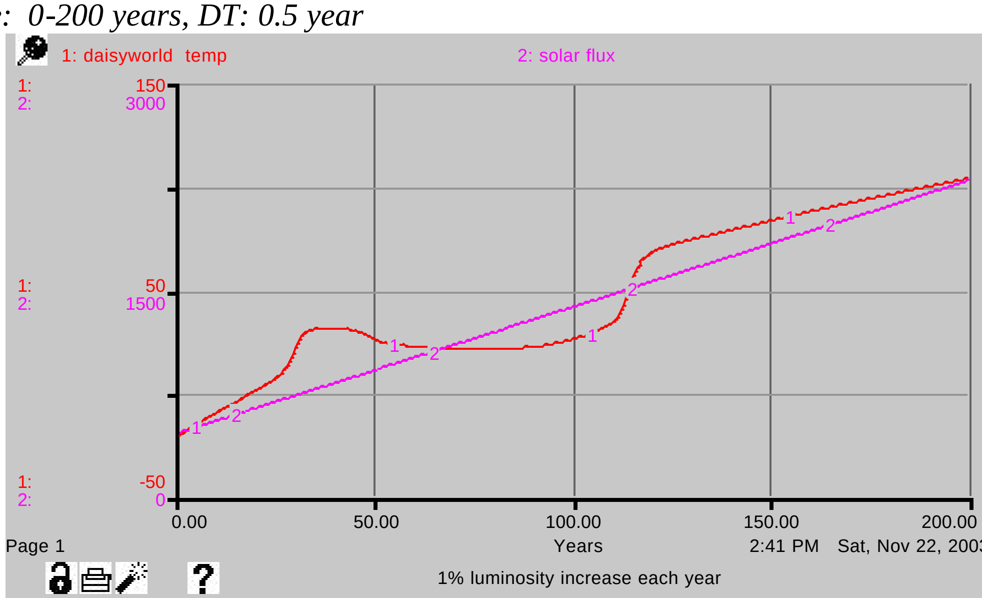
1% per year luminosity increase

*luminosity=0.5+(0.01*time)*
Range: 0-200 years, DT: 0.5 year



Changing the luminosity function to reflect a 1% increase each year results in an increase in the number of both black and white daisy populations, as well as an increase in the amount of time that the daisy populations can survive on the planet before it gets too hot.

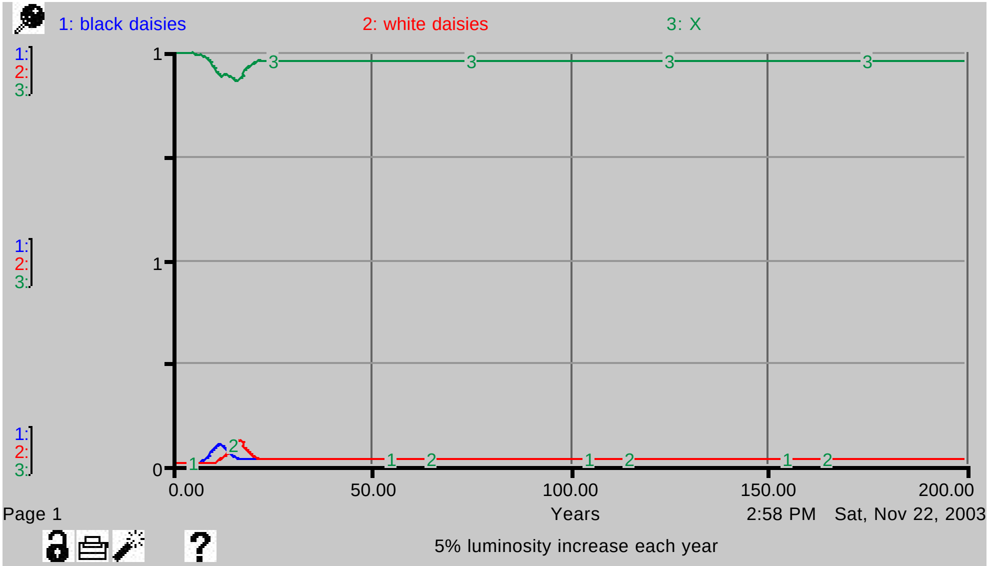
Range: 0-200 years, DT: 0.5 year



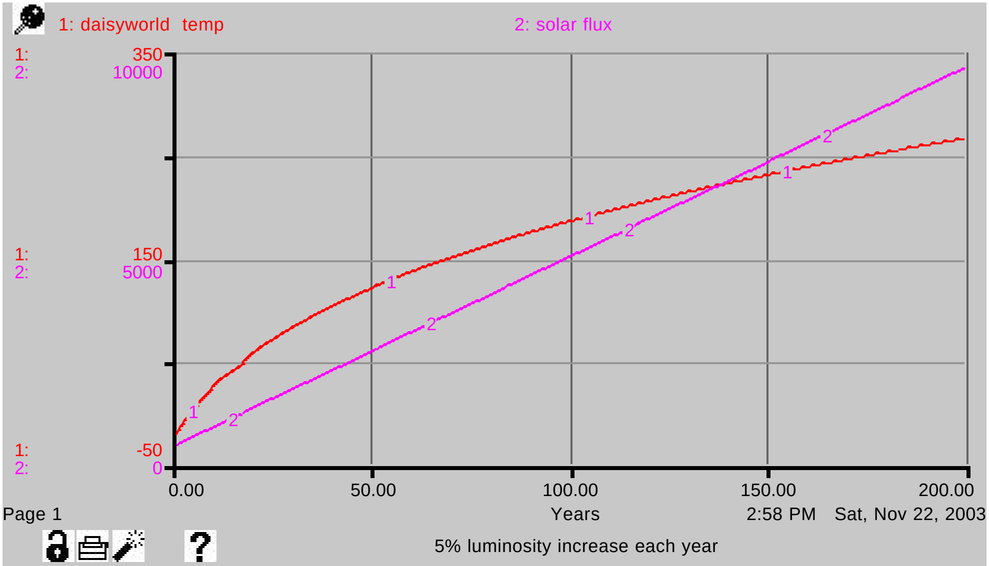
The change to a 1% luminosity increase per year also allows the daisies to modulate the planet's temperature for a longer period of time, as seen in the graph above.

5% per year luminosity increase

*luminosity=0.5+(0.05*time)*
Range: 0-200 years, DT: 0.5 year



Range: 0-200 years, DT: 0.5 year

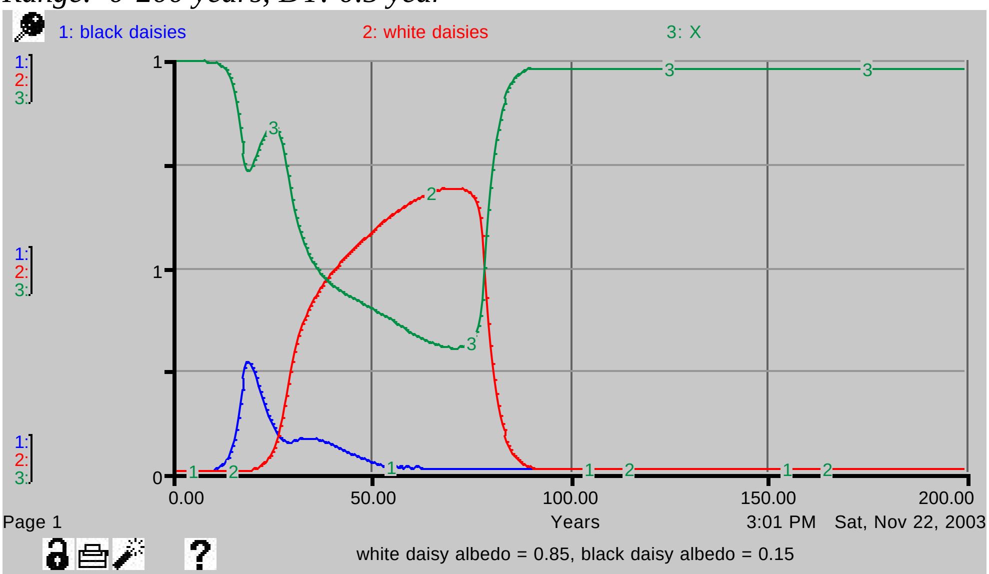


Changing the luminosity to a 5% increase each year results in a decrease in the population sizes of both black and white daisies, as well as a large decrease in the amount of time that the daisies may survive on the planet before it gets too hot. Because *their populations are small and they are short-lived on the planet, the daisies have very little effect on the average planetary temperature over time.*

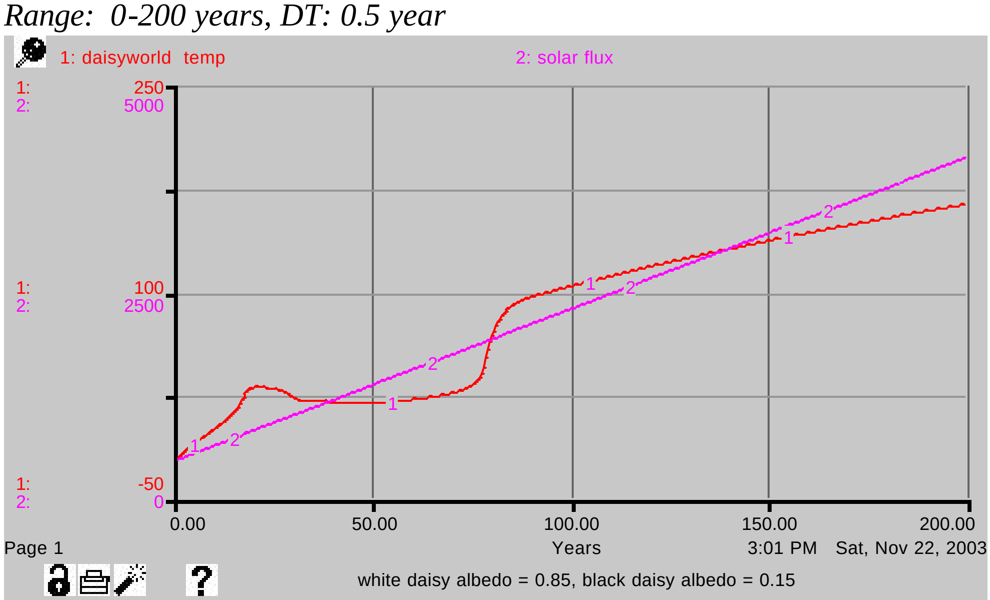
15) Set your luminosity increase back to 2% a year and re-run the model to make sure that everything is as it was. Now we'll fiddle with the albedo a bit. What happens to the population curves and the planetary temperature if you enhance the albedo contrast between the white and black daisies?

In the first experiment, we change the white daisy albedo from 0.75 to 0.85 and the black daisy albedo from 0.25 to 0.15.

Range: 0-200 years, DT: 0.5 year



Range: 0-200 years, DT: 0.5 year



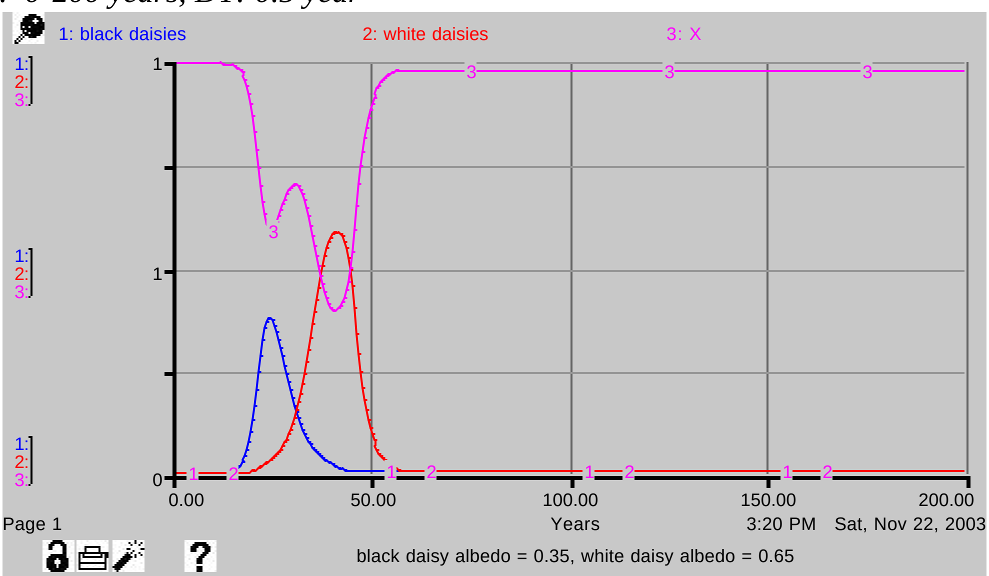
Increasing the albedo contrast results in a shift towards earlier production of black daisies than in the previous 2% per year luminosity increase experiment (compare to results in problem 13). However, the amount of the black population decreases relative to the previous experiment, as does its duration on the planet. The planetary temperature graph shows that the temperature of the planet initially increases faster due to the decreased albedo of the black daisies. They absorb more radiation, and thus warm the planet more quickly than in the previous scenario. Because they warm the planet so quickly, however, the black daisies quickly die out.

The higher albedo of the white daisies allows them to exist on the planet for a much longer time than in the previous experiment (problem 13), though their peak population number is about the same as before.

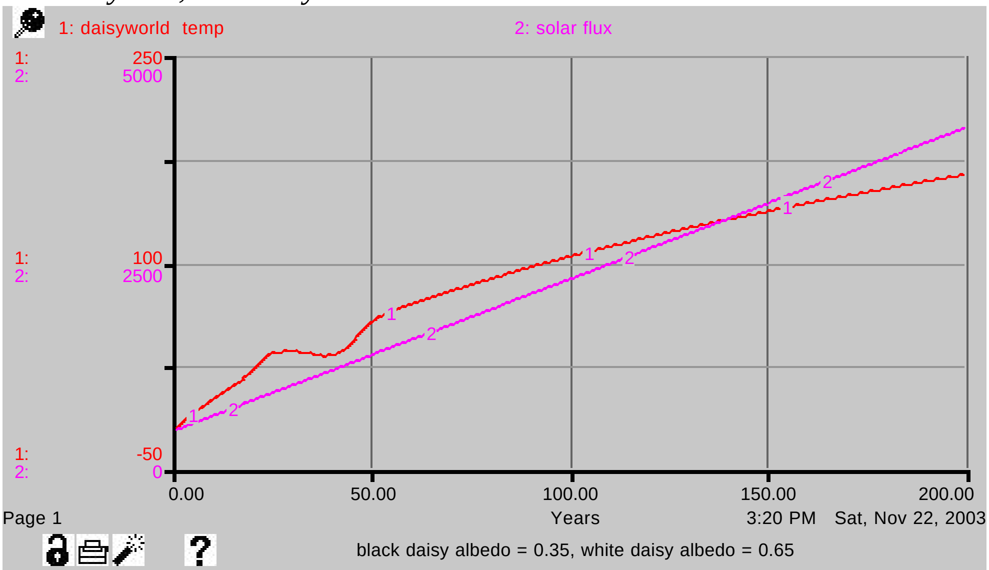
16) What happens if you reduce the albedo contrast?

In this experiment, we change the black daisy albedo from 0.25 to 0.35 and the white daisy albedo from 0.75 to 0.65.

Range: 0-200 years, DT: 0.5 year



Range: 0-200 years, DT: 0.5 year

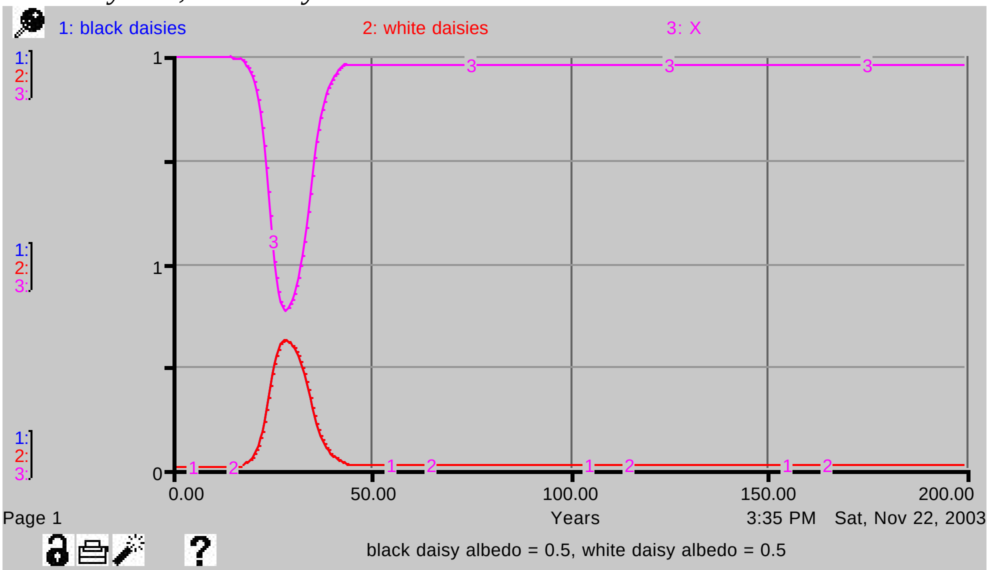


Decreasing the albedo contrast causes the two populations to react to the increased luminosity with greater similarity. The population time spans of the two classes of daisies are closer in length, as are the population amounts, compared to the scenario in problem 13. Because they have closer albedos, the length of time that the two populations can flourish under increasing temperatures is more similar than in problem 13.

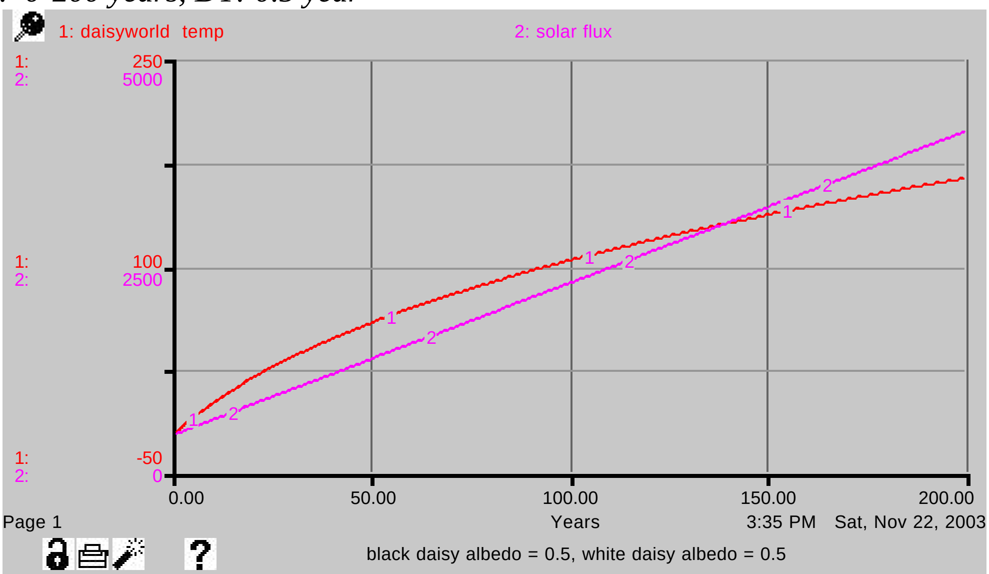
17) If you make the albedo of white and black daisies equivalent to the bare ground albedo, what do you predict will happen? Were your predictions correct? **Describe and explain** what you see in your graphs.

An accurate prediction is that the population curves for both the white and black daisies will be identical, due to their identical albedos.

Range: 0-200 years, DT: 0.5 year



Range: 0-200 years, DT: 0.5 year

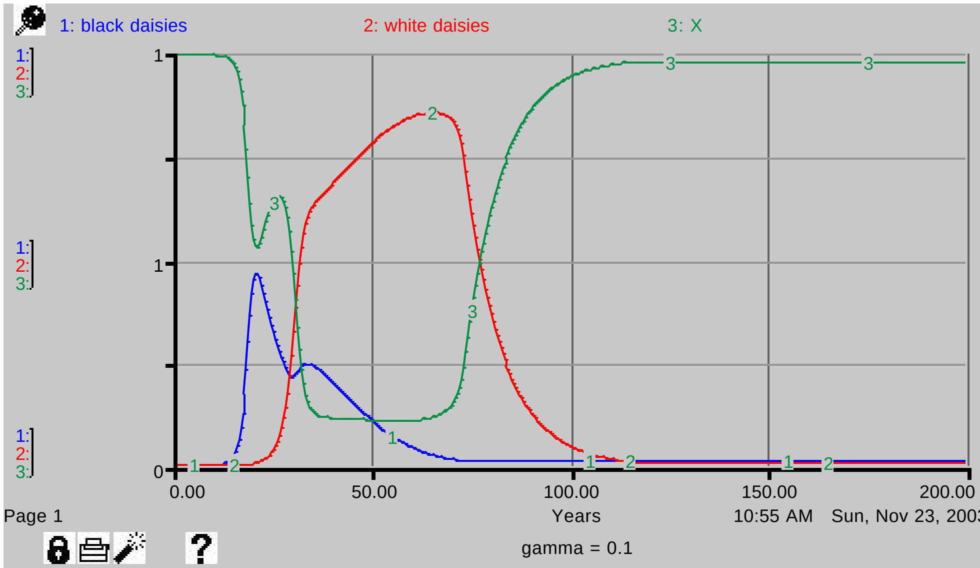


The upper graph shows that, indeed, the population curves are identical for identical albedos. This happens because both of the daisy populations absorb and reflect light at equal amounts, allowing both to flourish at the same time and rate. In the lower graph, it is clear that there is no impact of the daisies on the temperature of the planet over time.

18) Set your albedo conditions back to the way they were originally. Rerun your model to make sure you've reset the conditions. Now experiment with death rates. What impact does changing the death rates of the black and white daisies have on the system?

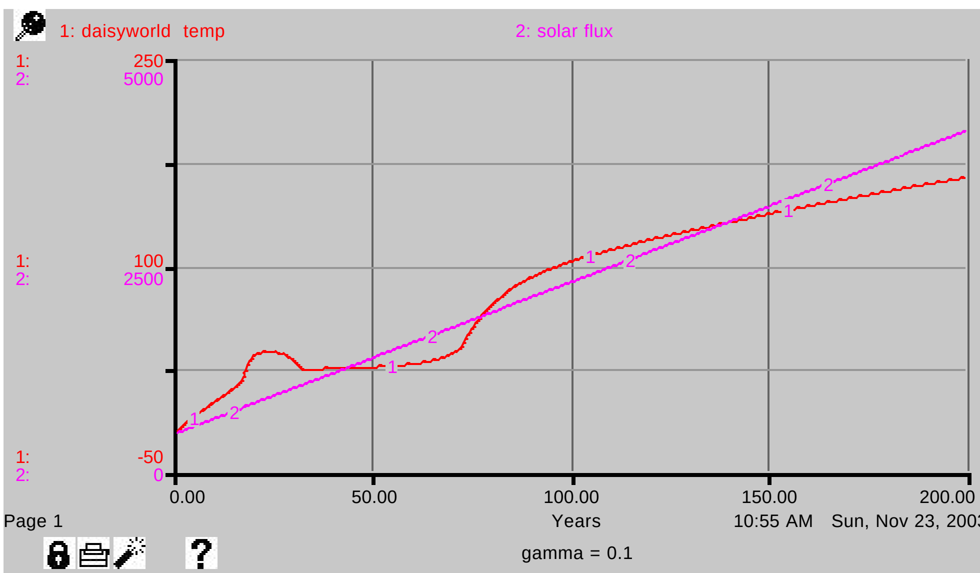
Decrease of death rates from 0.3 to 0.1:

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year



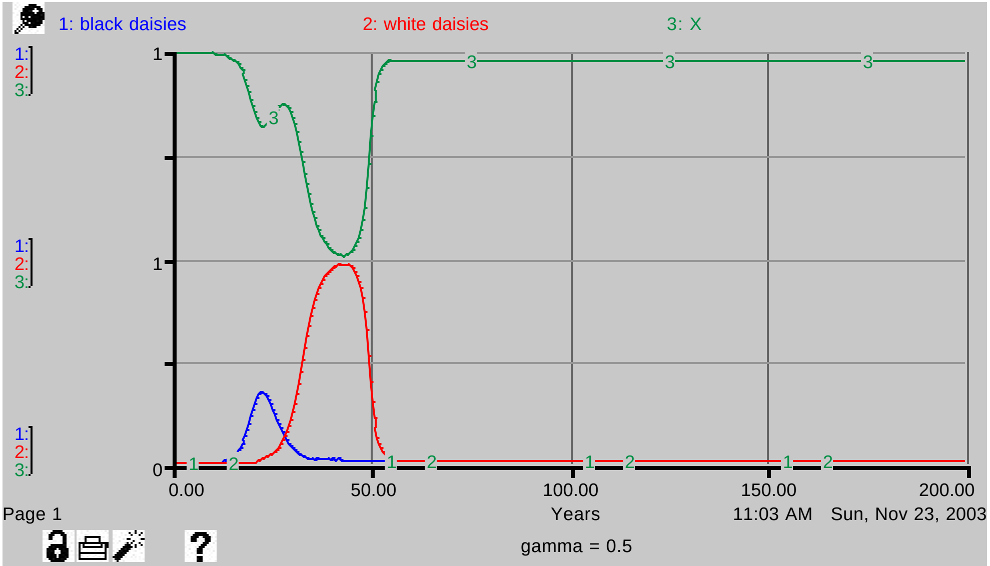
Decreasing the death rates from 0.3 to 0.1 results in a longer lifespan for both black and white daisies on Daisyworld compared to the initial case in problem 13. In addition, both populations are able to grow to larger total numbers before declining. The longer lifespan for the daisy populations ensures that the planetary temperature is regulated for a longer time (see graph below).

Range: 0-200 years, DT: 0.5 year



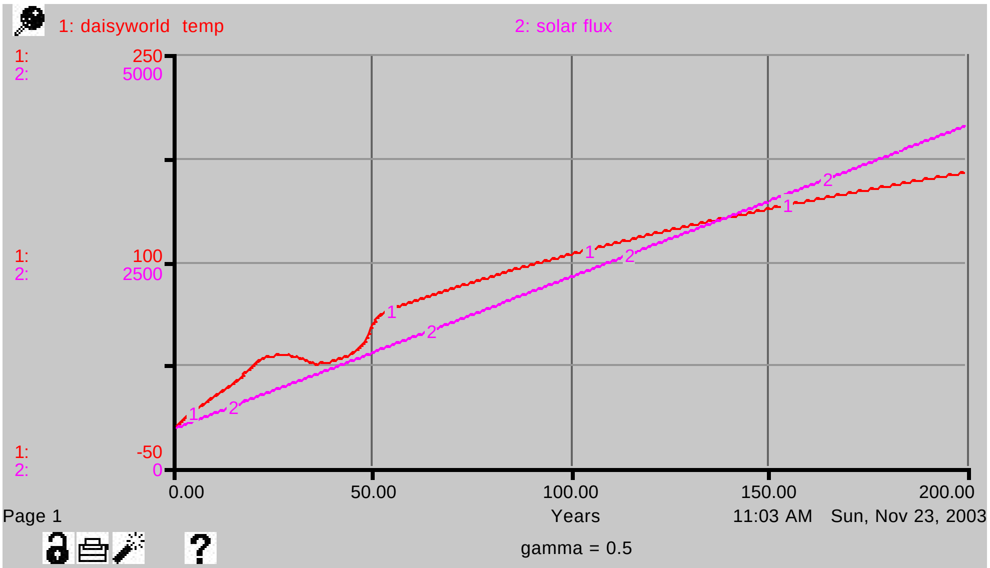
Increase of death rates from 0.3 to 0.5:

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year



Changing the death rates results in a decrease in the amplitude and duration of existence of the daisy populations. As a result, daisies modulate the planetary temperature for a shorter length of time than in the initial case in problem 13:

Range: 0-200 years, DT: 0.5 year

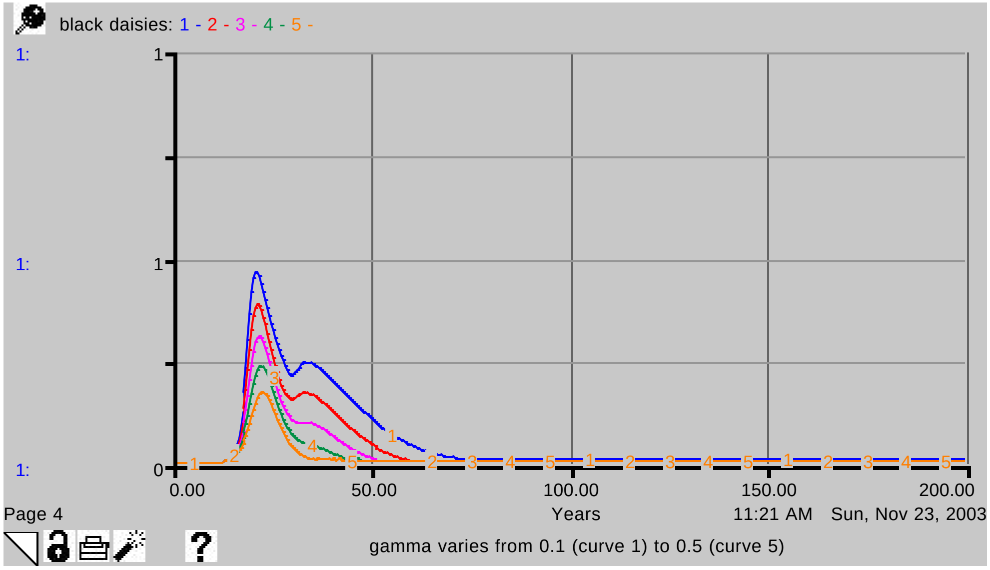


STELLA can be set up to do sensitivity experiments on individual variables. To conduct such experiments, go to the Run menu, select Sensi Specs, and then select the variable *you would like to experiment on. Once selected, highlight the variable and then fill in the box for the number of runs you would like to conduct. Up to 1000 runs are possible. After hitting the return key, the "variation type" part of the dialog box becomes accessible.*

The plots below were created using an "incremental" variation type with gamma ranging from 0.1 to 0.5 over 5 iterations. Before closing out of the Sensi specs dialog box, go to Define: Graph to select the variable you would like to graph during the sensitivity analysis run.

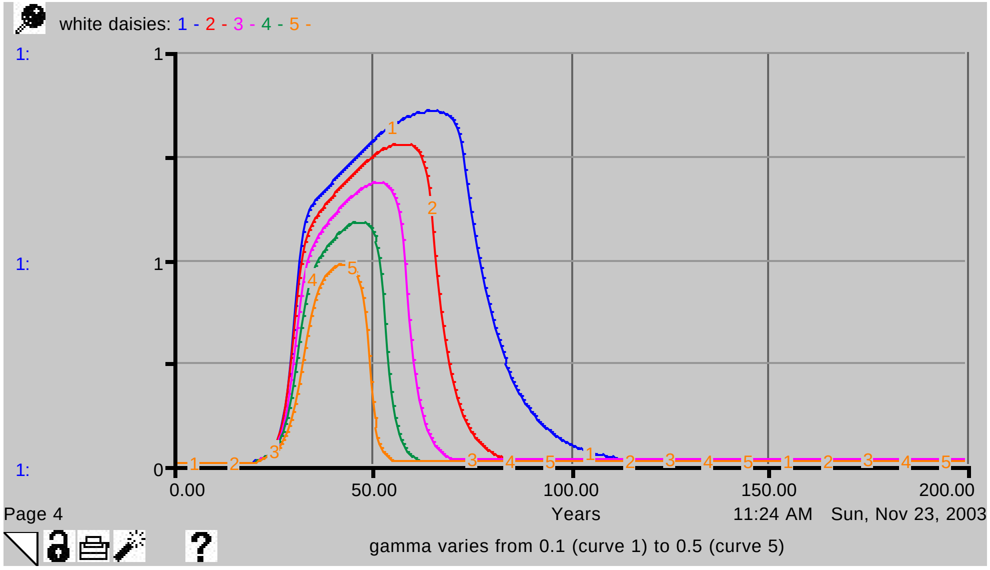
The graph below shows the impact of changes in gamma on the population of black daisies over time. Curve 1 represents the lowest death rate (0.1), and death rates increase incrementally to 0.5 (curve 5).

DT: 0.5 year



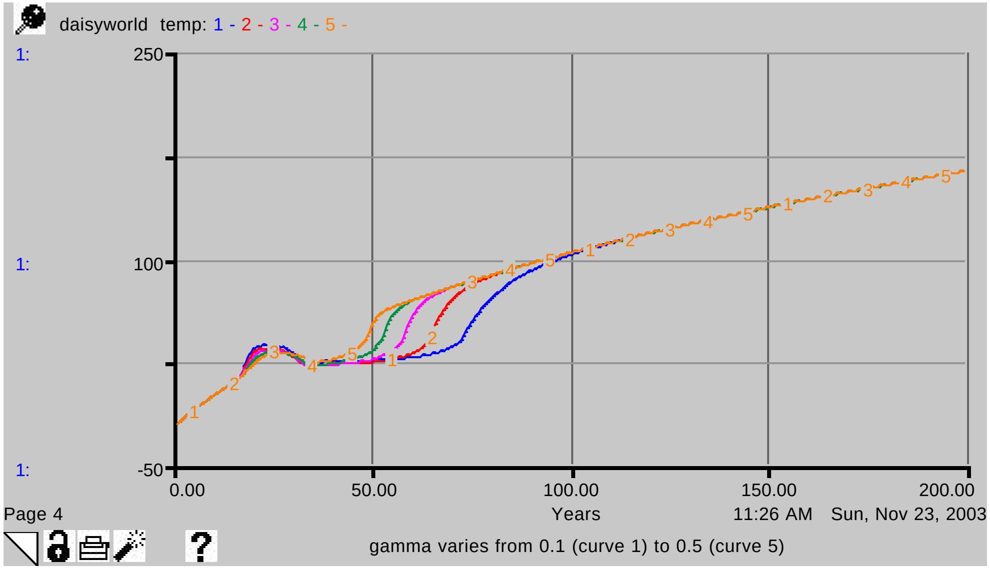
The graph below shows the impact of the same sensitivity analysis on the population of white daisies. Again, curve 1 is the lowest death rate (0.1) and curve 5 the highest (0.5):

DT: 0.5 year



The results of the sensitivity analyses on gamma on planetary temperature are as follows:

DT: 0.5 year

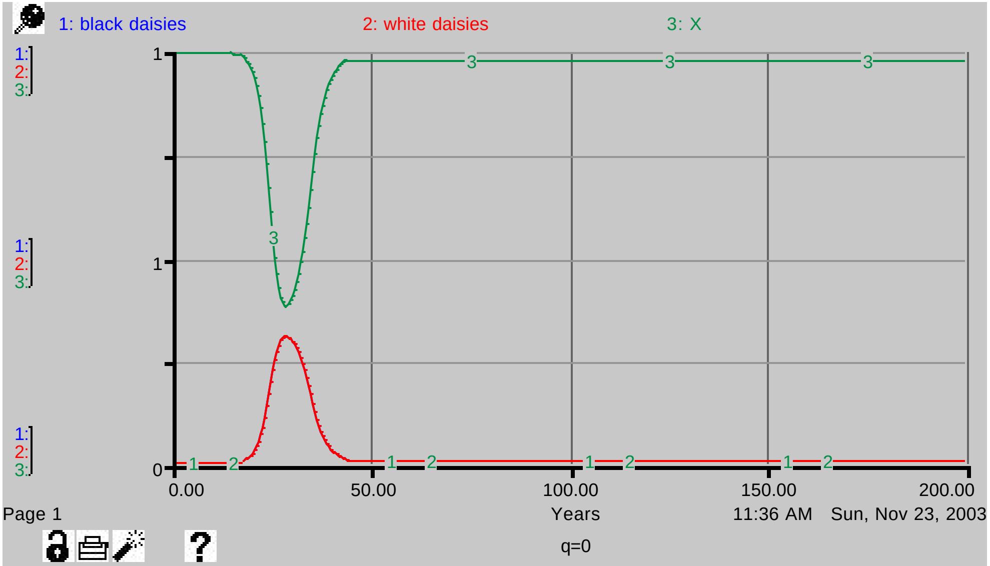


Changing the death rates results in an increase or decrease in the amount of time that the Daisyworld temperature curve is affected by the daisy populations.

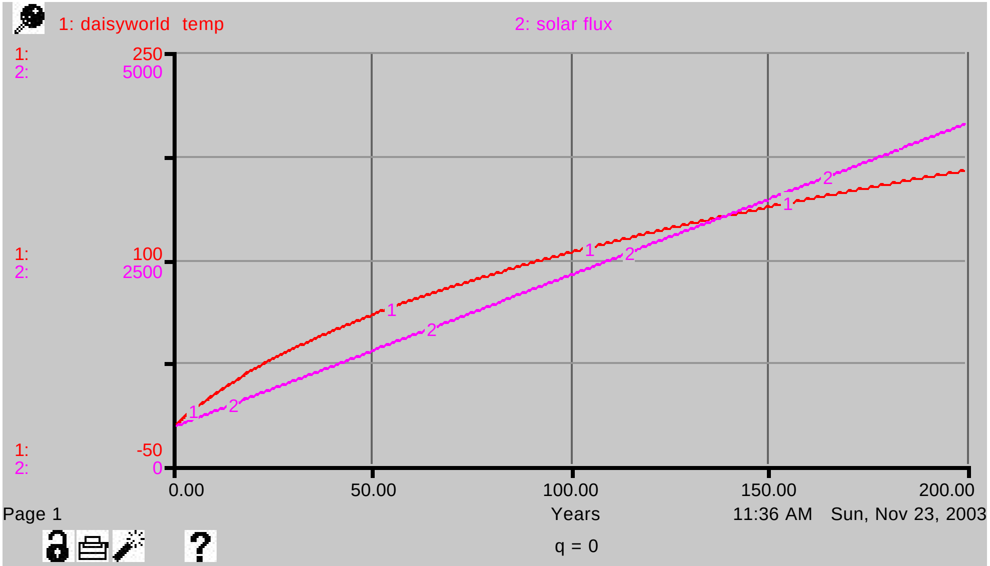
19) Set the death rates back to their original values of 0.3. Now run an experiment in which you set q = 0. Explain what this means physically and then **describe and explain** the system behavior you observe.

Q is a positive constant that expresses the degree to which absorbed solar energy is redistributed to the three types of surfaces on the planet. A q value equal to zero corresponds to perfect conduction according to Watson and Lovelock. Therefore, though the three surfaces (black daisies, white daisies, and bare ground) are absorbing different amounts of energy, that energy is immediately redistributed to create a uniform value for the whole planet. Given the uniformity in surface energy content, the local temperatures of the three surfaces are all equal to the mean planetary temperature. The result is analogous to the uniform albedo case:

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year



This graph was created by running the model with the following Run SPECS:
Range:1-200, DT: 0.5

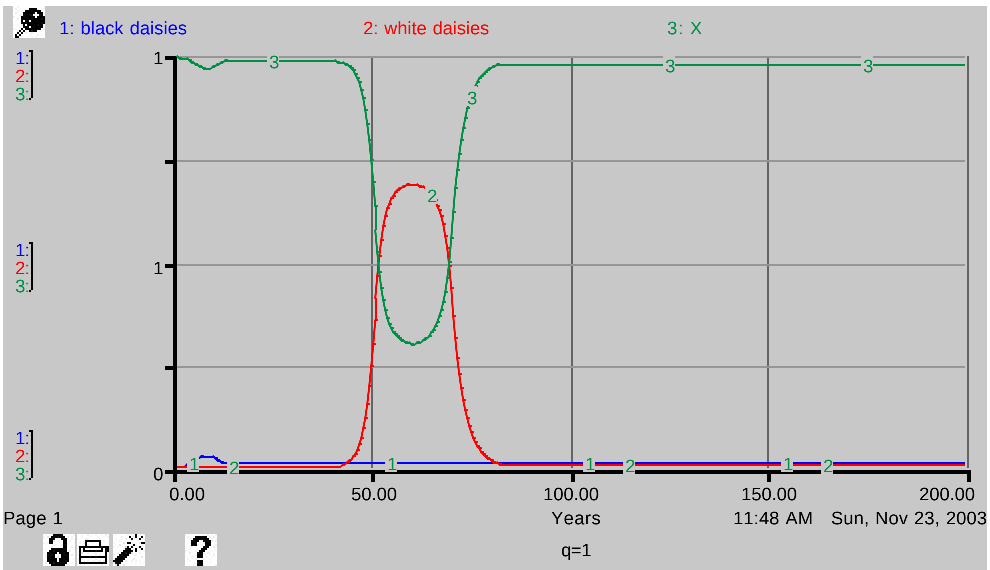


Since differences in energy absorption related to albedo are immediately obliterated by perfect conduction, white and black daisy populations reach the same temperature, and therefore grow at identical rates and times.

20) Run one more experiment in which you set q = 1* SL / σ. Explain what this means physically and then **describe and explain** the system behavior you observe.

When q is equal to 1, there is no redistribution of energy amongst the different parts of the planet. Excess energy absorbed by the low albedo black daisies does not flow to other parts of the planet, but instead remains localized in the black daisy area. A q value of 1 thus represents perfect "insulation" between different areas.

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year



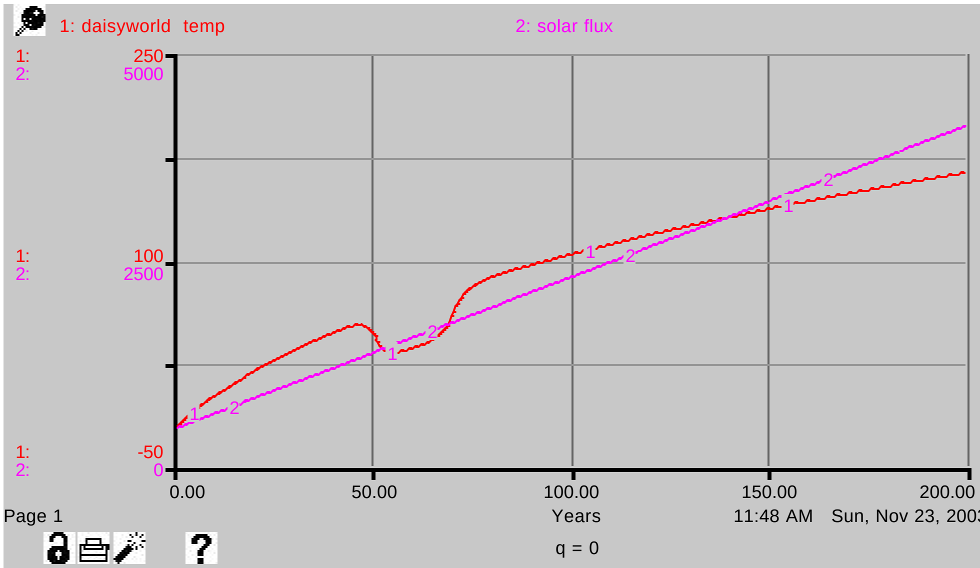
A q value of 1 has a dramatic impact on the population of black daisies. Since these plants are unable to conduct any of the heat they absorb away from themselves, local temperatures very rapidly become too warm to allow any further growth of the black daisies.

On the other hand, because the areas populated by white daisies are not receiving any energy by conduction from the areas populated by black daisies, they are not able to start growing until much later (relative to the initial case in problem 13). They must wait until the solar flux has reached a sufficiently high level to warm them above 5 degrees C.

The time in years between the populations of the black and white daisies is greater than in the initial case (problem 13) because the energy received by the black daises does not contribute to the warming of the entire planet; instead it heats the black population and *then is radiated back out to space. Then, much later when the planet has warmed up sufficiently by itself, the white population can grow.*

The impact of the change to perfect insulation on the temperature of the planet is seen below:

This graph was created by running the model with the following Run SPECS:
Range: 0-200 years, DT: 0.5 year



Compared to the initial case in problem 13, one can see that the modulating effect of the daisies on the temperature of the planet begins much later since the white daisies don't begin to grow until much later.