COMPUTER METHODS AND MODELING IN GEOLOGY
DAISYWORLD

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.

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.

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?

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.

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.

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?

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?

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

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.

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.

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

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, $q=0.2*(SL/\sigma)$.

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?

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?

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

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?

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?

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?

16) What happens if you reduce the albedo contrast?

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.

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?

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.

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