Simple Biospheric Feedback Model: 'Daisyworld'

MSc course: Land-Climate Interactions
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1 Introduction

The so-called 'daisyworld' model (*Watson and Lovelock* [1983]) is a nice example illustrating the potential role of the biosphere in controlling local and global climate. It was used by Watson and Lovelock to examplify how the biosphere could foster 'homeostasis' (or equilibrium) within the Earth's climate. The background for this model was the Gaia hypothesis formulated by Lovelock in the 1960's, suggesting that the Earth was behaving similarly to a single organism and that the biosphere had a self-regulatory effect on the Earth's environment (creating ideal conditions for its survival). While the Gaia hypothesis has been and still is the subject of strong debate, the daisyworld model is a good tool to comprehend some of the mechanisms by which feedback loops can control the climate system.

2 Daisyworld model

Daisyworld is populated by two types of daisies, one darker and the other lighter than the bare ground. As with life on Earth, the daisies do not grow at extreme temperatures and have optimum growth at moderate temperatures. The darker, 'black' daisies absorb more radiation than the lighter, 'white' daisies (lower albedo). If the black daisy population grows and spreads over a larger area, an increased amount of solar energy will be absorbed, which will ultimately raise the temperature of the planet. Conversely, an increase in the white daisy population will result in more radiation being reflected away, lowering the planet's temperature. The question to be answered is:
Under what conditions, if any, will the daisy population and temperature reach equilibrium?

3 Model assumptions

The model makes a number of fundamental assumptions about the functioning of the system, namely:

1. The rate of population change for both species of daisy depends on the death rate and the potential birth rate for that species, and the amount of fertile land available for growth;
2. The birth rate for both species of daisy depends on the local temperature;
3. The local temperature depends on the difference between the global and local albedo, and on the global temperature;
4. The global temperature depends on the luminosity of the sun and the planetary albedo;
5. The planetary albedo is the sum of the local albedo components (i.e., the albedo of the black and white daisies and of the bare ground);
6. The amount of fertile land available for further growth of the black and white daisies depends on the total amount of fertile land (fixed) and the current coverage the two species of daisy.

4 Mathematical formulation

The Daisyworld model can be represented in mathematical terms by means of the following formulae (note the small differences to the formulae presented in *Watson and Lovelock* [1983]):
1. The amount of fertile land available for daisy growth is given by:

$$x = (P - (a_b + a_w)) \tag{1}$$

where x is the amount of available land, P is the proportion of land available for growth (default $P = 1.0$), a_b is the area of black daisies ($a_b = 0.2$ initially), and a_w is the area of white daisies ($a_w = 0.2$ initially).

2. The total (overall) albedo for the planet (albedo is the amount of radiation out divided by the amount of radiation in) is given by:

$$A = x(A_g) + a_b(A_b) + a_w(A_w) \tag{2}$$

where A is the albedo of the planet, A_g albedo of bare ground (default $A_g = 0.5$), A_b albedo of black daisies (default $A_b = 0.25$, and A_w albedo of white daisies (default $A_w = 0.75$).

3. The globally-averaged temperature of the planet is given by:

$$T_e = (\frac{SL(1-A)}{s})^{0.25} - 273 \tag{3}$$

T_e is the globally-averaged temperature, S is a solar constant (energy from the sun; default $S = 1000$) L is the solar luminosity (proportion of present day value; 0.5 initially, but increasing in steps of 0.002), and s is the Stefan Boltzmann constant ($5.67 * 10^-8$).

4. The local temperatures for populations of black and white daisies are:

$$T_b = (q(A - A_b) + T_e) \tag{4}$$

$$T_w = (q(A - A_w) + T_e) \tag{5}$$

where T_b is the local temperature of black daisies, T_w is the local temperature of white daisies, and q is a constant used to calculate local temperature as a function of albedo (default $q = 20$).

5. The growth rate of the populations of black and white daisies is given by:

$$B_b = (1 - (0.003265(22.5 - T_b)^2)) \tag{6}$$

$$B_w = (1 - (0.003265(22.5 - T_w)^2)) \tag{7}$$

where B_b is the growth rate for black daisies, B_w is the growth rate for white daisies and $1, 0.003265$ and 22.5 are all constants so that growth occurs between 5° and 40° and peaks at 22° .

6. The change in area of black and white daisies over time is given by:

$$\frac{da_b}{dt} = (a_b(xB_b - y)) \tag{8}$$

$$\frac{da_w}{dt} = (a_w(xB_w - y)) \tag{9}$$

where da_b is the change in area of black daisies1, da_w is the change in area of white daisies, y is the death rate (default $y = 0.2$), and t is time.

7. The new area of black and white daisies is given by:

$$a_b = (\frac{da_b}{dt} + a_b) \tag{10}$$

$$a_w = (\frac{da_w}{dt} + a_w) \tag{11}$$

where a_b is the new area of black daisies, and a_w is the new area of white daisies.

5 Exercice

We can now use the matlab program daisy.m to find some steady states of Daisyworld. What is of interest is the effect of the daisy feedback on the range of parameter values for which non-zero steady states exist. If we fix all other Daisyworld parameters, we find that non-zero steady states will exist for a range of solar luminosities which we characterize by the parameter L. Recall, that L is the multiple of the solar constant S that Daisyworld receives. In the paper *Watson and Lovelock* [1983] you can see the steady state solutions which should be reproduced.

A)

1. Implement equations 4 and 5 in the program daisy.m (otherwise it does not work!).
2. First consider the case where the albedo of the daisies and the ground are set to the same value. This means the daisy population has no effect on the planetary temperature, i.e. there is no feedback. How does the temperature dependency on the radiation forcing look like?
3. Now consider a population of black daisies only. How is the temperature impacted by the presence of the black daisies?
4. How about the case of a population of white daisies only? What happens if the solar luminosity is lowered as opposed to being raised incrementally?
5. Consider a population of both black and white daisies: What is the impact of having both types of daisies?
6. How does the result depend on the ground albedo? What happens if both daisies are darker, respectively lighter than the ground?
7. Test various limits of the model: e.g. What happens if the daisies do not have the same optimal temperature? Therefore, slight modifications of the code are necessary.
8. Have a look at more sophisticated versions of daisyworld: 3D, more than 2 different daisies etc.
   http://www.gingerbooth.com/courseware/pages/demos.html

B) Try to answer the following questions which are the main 'take home messages' of the exercise:

1. Describe the main feedback processe(s) in Daisyworld
2. What other processes should be implemented to make the model more realistic?
3. For instance, how would the daisy distribution look like on a sphere (i.e. with differential heating with latitude)?
4. Also, what are other physical/biospheric processes leading to significant feedbacks at the local and global scale?
5. Do you see other types of feedbacks leading to a stabilization of the Earth's local or global climate (or homeostasis)?
6. Could you see at least some parallels with the functioning of living organisms in these regulatory mechanisms (i.e. with regard to the stabilization of the body temperature in mammals)?
7. Are there feedbacks mechanisms which tend to contradict the Gaia hypothesis?

6 Matlab tips

1. Download daisy.m from lecture homepage:
   https://www.iac.ethz.ch/education/master/land-climate_interactions

2. Start matlab by opening /Programme/mathematics/matlab

3. Run the model by typing daisy

7 Acknowledgements

Material from the following web pages was used for this exercise:
www.cima.fcen.uba.ar/ mnunez/modelos/lab5.pdf
http://serc.carleton.edu/resources/14130.html