Seasonal Energy Balance Climate Model

This handout accompanies the second lab class. The seasonal energy balance model is that adpated from that originally used by North and Coakley (1979). It solves two coupled one-dimensional energy balance equations:

$$C_L \frac{dT_L}{dt} = QS(x,t)(1-\alpha_L) - (A+BT_L) + \frac{d}{dx} D(1-x^2)\frac{dT_L}{dx} - \frac{\nu}{f_L(x)}(T_L - T_W)$$

and

$$C_W \frac{dT_W}{dt} = QS(x,t)(1-\alpha_W) - (A+BT_W) + \frac{d}{dx} D(1-x^2)\frac{dT_W}{dx} - \frac{\nu}{f_W(x)}(T_W - T_L)$$

The subscripts L and W refer to land and water respectively. The model represents a fraction of land at each latitude ($f_L(x)$), with the remainder being ocean (i.e. $f_W = 1 - f_L$). ν is the coupling coefficient and changes how strongly the land and ocean temperatures are tied together.

The standard set of parameters and functions for the model are the following:

$$Q = 338.5 \text{ Wm}^{-2}$$

$$A = 203.0 \text{ Wm}^{-2}$$

$$B = 2.09 \text{ Wm}^{-2\circ}\text{C}^{-1}$$

$$D = 0.44 \text{ Wm}^{-2\circ}\text{C}^{-1}$$

$$C_L = 0.45 \text{ Wm}^{-2\circ}\text{C}^{-1} yr$$

$$C_W = 9.8 \text{ Wm}^{-2\circ}\text{C}^{-1} yr$$

$$\nu = 3.0 \text{ Wm}^{-2\circ}\text{C}^{-1}$$

Note that $C_{L,W}/B$ gives the adjustment time scale for land/ocean in $yrs/^\circ$C. In this model the albedo has been parameterized a little differently from the previous model, in order to account for the differing albedos over land and ocean:

$$\alpha_L = \begin{cases} 0.363 + 0.08(3x.^2 - 1)/2; & \text{snow free: } T > -2°\text{C} \\ 0.6; & \text{snow covered: } T \leq -2°\text{C}. \end{cases}$$

$$\alpha_W = \begin{cases} 0.263 + 0.08(3x.^2 - 1)/2; & \text{ice free: } T > -2°\text{C} \\ 0.6; & \text{ice covered: } T \leq -2°\text{C}. \end{cases}$$

We have also included the orbital parameters as quantities you can vary. The values for the present day are:

Eccentricity, e, $= 0.01672$
Obliquity, $\epsilon = 23.44^o$
Perihelion, $\omega = 102.07^o$

The eccentricity is the square root of one minus the square of the ratio of the major and minor axes. The obliquity is the tilt of the rotational axis relative to the orbital plane. The perihelion sets the phase of the seasons relative to the perihelion (or point of closest approach to the sun).

You should play around with all of these parameters to get a feel for what they do.

Sea ice model

This sea ice model is a basic slab model with no leads, to match the simplicity of the EBM. We ignore the salinity of the sea ice in this model and assume all parameters are those of freshwater ice.

The net flux into the top ice surface is

$$F_{\text{net}} = QS(x,t)(1-\alpha_W) - (A + BT_W) + \frac{d}{dx}D(1-x^2)\frac{dT_W}{dx} - \frac{\nu}{f_W(x)}(T_W - T_L)$$

The first step is to see if

$$F_{\text{net}}(T_W) + k\frac{-2 - T_W}{h} = 0$$

yields a physical value for T_w (i.e., $T_W \leq -2°$C). If not, we solve for F_{net} subject to the constraint: $T_W = -2°$C. Regardless of T_w, we compute the ablation/accretion from

$$F_{\text{net}} - F_w = L_f \frac{dh}{dt}$$

where the density is absorbed into L_f. The ocean-ice flux F_w is crudely parameterized here so that it is 4 W m^{-2} if the ice area is only one gridbox wide and it decreases linearly to 0 as the ice covers the globe. A separate value is computed for each hemisphere. The heat that is supplied to the ice via F_w is subsequently taken away from the ice-free ocean grid cells in an energy conserving manner. This is a rather ad hoc attempt to approximate heat transport in the ocean that affects sea ice from below.

Finally we must make a special calculation anytime the ocean temperature drops below -2°C, where we grow just enough ice to bring the temperature back to -2.

GPHYS/ATMS 514 Lab #2, write up due 8 Feb.

The first four exercises are to help you get used to the seasonal climate model, and only require relatively short answers. For the last question we hope you spend more time exploring the model's behavior, and we ask you to produce a short report (maybe 3 written pages) on what you have found.

Exercise 1

The seasonal cycle

For this case, start with the default parameters. Run the model and note the seasonal cycle in the climate. Find the time lag between the time of maximum insolation and the time of maximum temperature over land and also over ocean.

Describe the variation of the response as a function of latitude. Explain this latitudinal variation, noting all the factors that influence it.

How does the model do in reproducing the modern observed climate? Note where the model does well and where it does badly. We have not tried to tune the model all that carefully, so have a go at finding a better set of parameters. There are always trade-offs to be made. Improving one field may often lead to worsening another, which just reflects that we are dealing with a crude model of the climate rather than a direct representation of it (GCMs are often no better).

Next, try systematically varying the heat capacities over land and over ocean (C_L and C_W), and also the coupling coefficient, ν. Explore how the amplitude and time lag of the climate response changes. Describe what you find and explain physically why what you see happens.

Exercise 2

The sea ice model

Explore the behavior of the climate when the sea-ice model is included. In particular, note and explain differences in the polar regions. Explain how and the land temperatures and summer ocean temperatures are affected. Make sure that the model climate has fully equilibrated, altering the integration length if necessary.

Exercise 3

$2 \times CO_2$

Following the last lab exercise, a rough and ready way of introducing CO_2 forcing into the model is to adjust the model parameter A by ΔA, where

$$\Delta A = -k \ln \frac{\mathrm{CO_2}}{360}$$

with $k = 3$ Wm^{-2} and CO_2 is the concentration of CO_2 in ppmv. Thus, an increase in atmospheric CO_2 causes a decrease in the longwave emissions to space.

For a doubling of CO_2, calculate the difference in the climate sensitivity parameter, λ, using the definition from class:

$$\lambda = \frac{\Delta \overline{T}}{\Delta < G >}$$

where $\Delta \overline{T}$ is the difference of global mean temperature between two simulations, and $\Delta < G >$ is the change in radiative forcing. Does having a seasonal cycle affect λ? (For this, you will have to go back and run the annual mean model from the previous lab class, by typing "ebm".)

How does the inclusion of the sea-ice model, or the absence altogether of an albedo feedback affect the sensitivity parameter? Explain why. (Turning off the albedo feedback is a multi-step process with the season model. FIRST run exactly the case from which you want to hold the albedo fixed. SECOND press the "save annual cycle" button. FINALLY press the "no albedo feedback" button and rerun. The model will read in the annual cycle that you saved and use its albedo.)

Exercise 4

Climate stability

The annual mean model required that Q/Q_0 be lowered to below 0.9 to plunge the earth into a snowball climate. Find the change in the climate stability in the seasonal model both with and without the sea-ice model included. Turn off the "Simulate Hadley Cell" button to make the heat flux calculation consistent with the annual mean model. Try to explain the differences that you find, and perhaps design some experiments to confirm any theories that you have.

Exercise 5

Snowball Earth

For this exercise, we are asking you to explore aspects of the climate relating to the snowball earth. We have some guidelines of things that you should consider, but use your own initiative to play around with the model, and design experiments to test your ideas. We would like a fairly detailed write up of what you have found, and if it helps, you can include plots of any results.

Geological data suggests that several episodes may have occurred where the earth was completely glaciated between 500 and 750 million years ago. First the sun was fainter; use a rate of increase of 7% per billion years (not 10 % as in the previous assignment), and the levels of atmospheric CO_2 are not well known. Here are a couple of other points:

The land configuration is known to have been very different from that of today, and we have given you two very different configurations for the continents over that time. One applies for the Ordovician period (450 million years ago), and one for the Pre-Cambrian period (530 million years ago). You should explore and explain what difference the land configuration makes to the climate stability.

The appropriate orbital configuration (and hence the seasonal variation of insolation) for that time is also not known (plus it was also varying in time). Calculations of the earth's orbit are reliable back to maybe only five million years or so ago. However, we can begin by assuming that the parameters that described the orbit then are bounded by their limits for the current configuration:

Eccentricity, the ellipticity of the orbit, varies between values of 0.0 and

0.05. (This number is the square root of one minus the ratio of the major and minor axes of the orbit.)

Obliquity, the tilt of the rotational axis relative to the orbital plane, varies between 22°and 24.5°.

Longitude of the Perihelion, the phase of the seasons relative to the perihelion (or point of closest approach), varies cyclically over the range 0°to 360°.

Any combination of the above parameters is fair game for a snowball earth. You should also try some outlandish values to see what happens to the climate. Note the differences in the insolation and how the climate responds. With respect to the snowball earth, are some combinations of orbital parameters more favorable than others?

Find some different sets of model parameters that lead to a snowball earth. Fully describe the snowball climate, noting changes to the seasonal cycle at all latitudes over land and over ice. How long does it take for the earth to freeze over? Does the time depend on how unstable the climate is?