PCC 587 Project 1: Write-up due October 22, 2009

Energy Balance Climate Model

This handout describes the first project, and hopefully explains enough to make it work for everyone! If you have questions you think are of general interest, post them on the class message board. If you are having more specific problems, write directly to Dargan.

We'll be working with a simple one-dimensional climate model that calculates temperature as a function of latitude. The model uses the one-dimensional steady state energy balance equation, and assumes that the energy transport by the atmosphere and ocean acts diffusively (energy flux proportional to temperature gradient):

$$QS(x)(1-\alpha(T)) = A + BT - \frac{d}{dx}D(1-x^2)\frac{dT}{dx}$$

Throughout, x is defined as the sine of latitude, which is a convenient variable for energy balance calculations on the surface of a sphere (it succinctly takes into account the fact that latitude circles become smaller near the pole. sin(lat) is the fractional area equatorward of that latitude). The model plots the output fields as a function of degrees latitude.

In the above equation, solar radiation (and the effect of albedo to reflect away solar radiation) is on the left-hand side of the equation, and outgoing longwave radiation (parameterized as a linear function of temperature) and diffusive energy transport are on the right-hand side. The standard set of parameters and functions for the model are the following:

$Q = 338.5\ W/m^2$ (global average shortwave radiation at the top of the atmosphere)
$A = 203.3\ W/m^2$ (outgoing longwave radiation at 0 Celsius)
$B = 2.09\ W/m^2/°C$ (increase in outgoing longwave radiation per degree temperature increase)
$D = 0.44\ W/m^2/°C$ (diffusivity)
$S(x) = 1 - 0.482\left(\frac{3x^2-1}{2}\right)$ (latitudinal form of solar radiation. The part in parentheses is the 2nd Legendre polynomial, a polynomial that integrates to zero over the sphere)
$\alpha = 0.3$ if $T \geq -10°C$ (ice free)
$\alpha = 0.6$ if $T < -10°C$ (ice covered) (if temperatures get sufficiently below freezing, we assume ice coverage and increase the albedo)

You will be asked to vary these default parameter values in the project exercises.

We encourage you to work together with your group on the project assignments, but to turn in individual responses to the questions. We also encourage thoughtful, thorough and succinct answers in your writeups (several sentences or a short paragraph should be adequate for discussing each question).

Logistics

Where and how to get onto computers

If you have access to Matlab and just need the EBM code, you can download it from the course web's Projects page.

The computer lab is in the Atmospheric Science Geophysics (ATG) Building on the 6th floor (room 623). A class account has been set up with the username *pcc587*. To log in, you will need this username as well as the account password, which will be revealed in class. Open a terminal window by clicking the terminal icon on the top left of the screen. (You can also use *ssh* to connect to the account remotely: *ssh –Y pcc587@ olympus.atmos.washington.edu* should work)

To set yourself up to run the energy balance model, follow these simple steps:

1. Make yourself a directory off the account's home directory.

   mkdir yourdirectoryname

   To check that you have successfully completed this task, type the list command (that first letter is an L):

   ls

   You should see a listing of everything in the home directory, including your newly created directory.
2. Now copy the necessary files into your directory:

   cp matlab_files/ yourdirectoryname/*
3. Enter your directory:

   cd yourdirectoryname/
4. Start Matlab:

   matlab -nojvm
5. At the Matlab prompt, launch the graphical user interface (GUI) for the energy balance model:

   ebm

   This will bring up the GUI for the EBM. The assigment can be done without touching the model code at all.

Using the GUI

1. The model parameters are given in separate boxes in the GUI. You may need to resize this window to see all the available options. The values may be changed by editing the numbers in the respective boxes. Q/Q_0 is the ratio of the solar constant to the current one (i.e. $Q_0 = 338.5$ W/m^2).
2. The model is run by clicking on the *Run EBM* box. This causes the model

to be integrated to equilibrium for the chosen set of parameters. When complete, Matlab will bring up a separate figure window showing three plots: a) temperature, b) poleward heat flux in petawatts (10^{15} *W*), and c) the three terms in the energy balance equation (shortwave, longwave, and heat flux convergence). You can move the graph legends around by clicking and dragging, and you can resize the figure window itself. Each time you run the EBM, a new figure window will be produced. You can drag them around your screen in order to compare the results of different simulations.

3. At any time you can revert to the standard parameter set by clicking on the *Use Defaults* button.
4. Use the zoom in button on the plot windows to read the exact values of fluxes, temperatures, etc. Double click the plot with the zoom tool to snap the plot back to its original axes.
5. Graphs can be printed out on the lab printers in Atmospheric Sciences by clicking on the tiny thing that resembles a printer in the figure window.
6. The GUI can get mixed up sometimes. If it does behave strangely ever, the best course of action may be to close all the graphics windows (type *close all* in the matlab window), wipe out everything (*clear all*), and start again (*ebm*).
7. If the model integration does not converge (reach equilibrium), matlab will produce a warning message and tell you how far out of equilibrium the worst grid point is. This can especially occur if you try too large values for diffusivity (the numerical routine can't handle this). Just try different parameter values if this happens.

Exercise 0

Describe (briefly) the terms and variables in the equation above. What is the physical interpretation of each?

Exercise 1: Varying D

1. Run the model with the standard parameter set. Note the maximum poleward heat flux, the mean global temperature (T), and the pole-to-equator temperature difference (ΔT_{p-e}). Compare with values for the current climate on the slides shown in class. (*matlab hint*: you can use the magnifying glass tool in the plots to zoom in to particular parts of the plot to get exact values. Double-click on the plot with this tool to get back to the original axes.)

2. What happens when there is no meridional heat transport (D = 0)? Estimate T and ΔT_{p-e} , and briefly describe the changes to the climate.

3. Try values of D = 0.22 $W\,m^{-2}\,^{\circ}C^{-1}$ and D = 0.88 $W\,m^{-2}\,^{\circ}C^{-1}$. Are the changes to the climate consistent with your expectations? For example, note changes to T

and ΔT_{p-e} . Compare the maximum poleward heat flux in these integrations with that using D = 0.44 $W\,m^{-2}\,{}^{\circ}C^{-1}$. Explain why the changes to the heat flux are not simply proportional to the changes in D.

4. Use the model to estimate how the model will behave in the limit of an infinite D value. (Note: The model will not behave if you make D too big: a value of 8 should suffice.) Speculate on what would happen to the pole-to-equator temperature difference in the limit of an infinite D value. What is the maximum heat flux at a D value of 10? Do you think this value would increase significantly in the limit of an infinite D value? (Hint: note where the ice edge is in this run, and look at the shape of the outgoing long wave radiation curve as a function of latitude)
Extra Credit: Verify the upper limit of the meridional heat flux analytically using a spatially invariant albedo of .3 (or describe how you would calculate this value).

5. Fossilized remains of crocodiles dating back to the Eocene (53-37 million years ago) have been found on Ellesmere Island (latitude is now 80N). Assuming crocodiles can survive when the mean annual temperature is 10 $^{\circ}C$ and that Ellesmere has not shifted much from its present location (which is true), find the rough value of D necessary for the crocodiles to have survived. What is the poleward heat flux required for this? Make a wild guess about what might change D in this way (Don't worry— no one else knows either).

Exercise 2: Varying Q

The sun's luminosity is not constant in time. It has been gradually increasing. Models of solar evolution suggest that the sun's intensity (i.e. Q) has increased by roughly 10% over the last 10^9 years. Assume that this trend is linear and will continue. Start with the standard initial temperature profile for each part of this exercise.

1. Find the increase in the value of Q (to within 1 $W\,m^{-2}$) required to eliminate ice from the earth (assume ice exists when the temperature is below -10 $^{\circ}C$). How long would it take before there is no ice left (assume nothing else changes)?

2. Find the decrease in Q (to within 1 $W\,m^{-2}$) required to cause complete glaciation, and hence show that the model would predict a snowball earth prior to about 1.0×10^9 years ago. Describe the changes in climate state between snowball climates and climates just warm enough to break out of the snowball.

Exercise 3: No albedo feedback

This exercise is designed to illustrate the different climate sensitivities with and without albedo feedback. Use the standard parameter set for this exercise, except for the albedo parameterization.

1. The modern ice line is at about 72° N (or x = 0.95). Click on the no ice-albedo feedback button on the graphical user interface to fix the ice line at this value (i.e., when "no albedo feedback" is selected, poleward of 72 always has an albedo of 0.6, and equatorward of this always has an albedo of 0.3, regardless of the temperatures). Fixing the albedo in this way turns off the feedback between the temperature and the albedo. Show that the model is now much less sensitive to changes in Q. To do this, find the values of Q required for complete glaciation/deglaciation as in exercise 3, assuming that –10° C is still the temperature at which ice forms.
2. Is the global mean temperature sensitive to the value of D? Answer this for the "no albedo feedback" case as well as the default case with ice-albedo feedback. Why?

Exercise 4: Sensitivity to initial conditions

The above exercises have all started off with warm initial conditions for the model. However the model has multiple equilibrium solutions for some range of Q. To show this, begin with the default model. Map out the variations in the ice-line as Q varies over the range 290 $W\,m^{-2}$ to 420 $W\,m^{-2}$. Now instead start off with a cold initial temperature profile by clicking on the cold start button. Map out the ice line variations over the same range. This will show the hysteresis loop in the climate system and is a measure of how difficult it is to get out of a completely glaciated state.

This exercise illustrates the faint young sun paradox. Because the sun is known to have been weaker in the past, the earth should have had cold "initial conditions" then. Yet snowball earth conditions are thought to have been rare and discontinuous.

Optional Exercises (for extra credit)

These are some other ideas to explore with the simple EBM. Try one (or more) of them if you'd like to earn some extra credit. A detailed investigation is not required, but we hope that you have some fun just playing around with the model. If any other ideas occur to you, feel free to explore those instead and write those up for extra credit too.

Varying A and B

1. Alternative sets of longwave parameters have sometimes been used. For example try implementing values of A = 211.2 $W\,m^{-2}$ and B = 1.55 $W\,m^{-2}\,{}^{\circ}C^{-1}$ in the model (holding everything else at the standard values). Describe briefly how the resulting climate is different from that using the standard parameters.
2. For this choice of A and B, and using D = 0.52 $W\,m^{-2}\,{}^{\circ}C^{-1}$ (in order to get back a climate more closely resembling the modern one), find the decrease in Q (to

within 1 $W\,m^{-2}$) required for complete glaciation. Explain why a smaller decrease in Q is now required to produce a snowball earth. (You may want to think about this in terms of the climate sensitivity as well.)

CO_2 increases

A crude way of introducing CO_2 forcing into to the model is to adjust the model parameter A by ΔA, where

$\Delta A = -k \ln (CO_2/380)$ 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, so the temperatures have to rise to achieve balance. During the ice ages, records from ice cores show CO_2 varied between 200 ppmv and 280 ppmv. A doubling (or tripling) of CO_2 from preindustrial values would take carbon dioxide levels up to around 560 (or 840) ppmv, respectively. Explore what effects these values would have on the climate of this model.

Spatial variations in D

The Hadley Cell is an up-down/north-south tropospheric circulation in the atmosphere which operates in the tropics (from the equator to about 30° N/S). Very basically, it takes the intensely heated air at the surface near the equator, lifts it and spreads it poleward at the tropopause. Once the air aloft reaches about 30° , it sinks back toward the surface. After it reaches the surface, the air returns toward the equator, completing the circuit. The Hadley Cell helps to tranpsort heat from the tropics to the polar regions.

Lindzen and Farrell (J. Atmos. Sci., 1977) suggested that since the Hadley Cell was more effective at redistributing heat than extratropical weather systems, D should vary with latitude (i.e. D = D(x)). They suggested using a larger value of D within the tropics. This can be crudely represented by increasing D by a factor of 10 (equatorwards of about 30° , say). An implementation that will achieve this is the following:

$D = 0.45[1 + 9 \exp(-(x/ \sin 30^\circ)^6)]$

Don't panic – all you have to do is push the simulate Hadley Cell button. Describe the resulting climate. Examine and try to explain the effect on the decrease in Q required for complete glaciation.