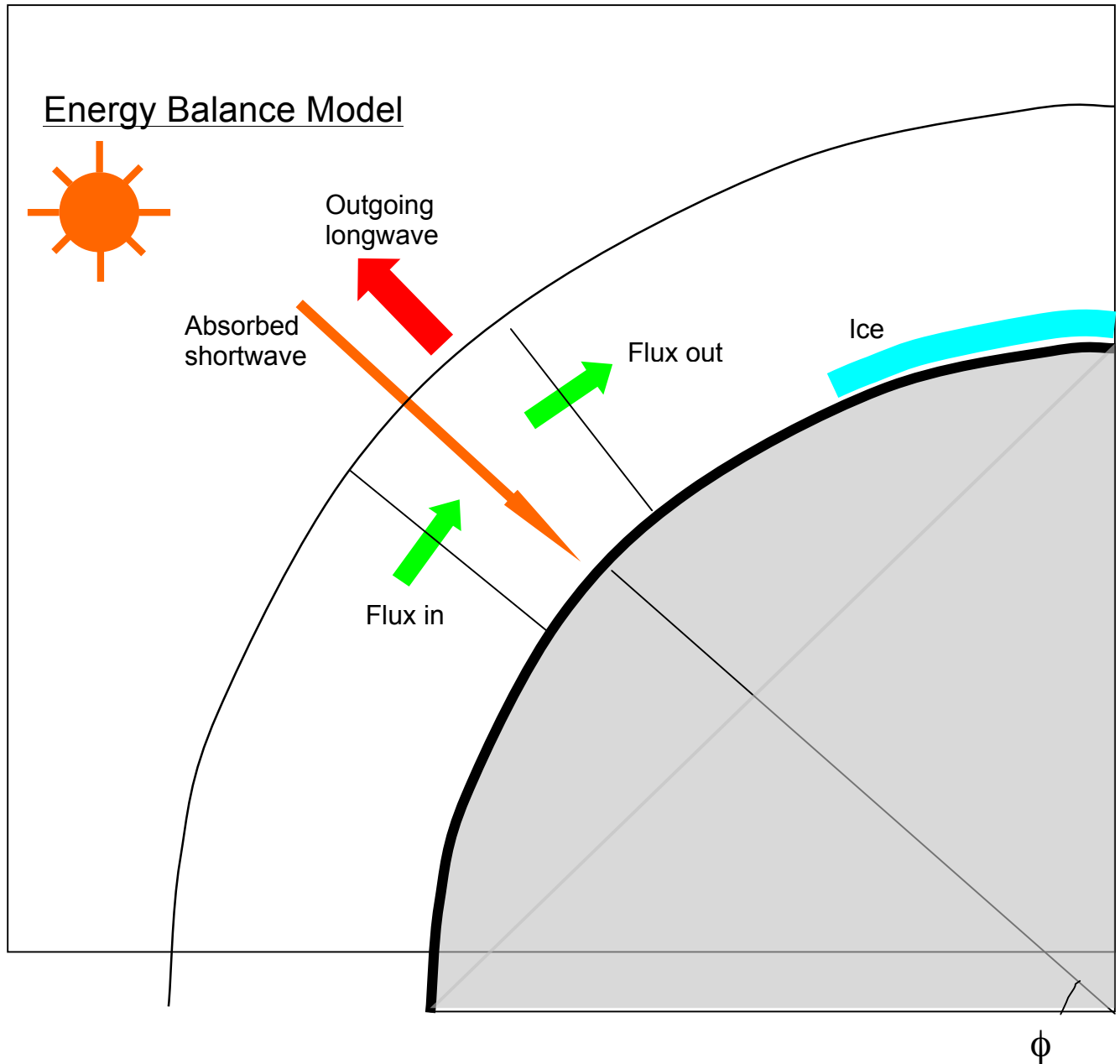


Lab 4: Energy balance climate model.

Due next Friday

This lab uses a climate model to look at heat transport and feedbacks in the climate system. Feel free to scratch notes in the margins of this write-up, but please submit your write-up on separate paper.



The climate model calculates the annual mean temperature, T , as a function of latitude and accounts for the following process (see above diagram)

1. Absorbed shortwave radiation = $Q/4 (1-\alpha) S(\phi)$

$Q = 1367 \text{ Wm}^{-2}$, the solar constant

$S(\phi)$ is a function of latitude, ϕ , and describes how insolation varies with latitude (more in tropics, less in poles).

Albedo feedback: A key to this model is the presence of an albedo feedback. The energy budget is modified by ice cover, which is itself a function of the climate. Thus the input to the system (the absorbed solar radiation) is a function of the output of the system (the climate state), making it a feedback. This is a *positive feedback* – allowing the albedo to vary amplifies the system response to changes in forcing

This albedo feedback is implemented in the following way:

if $T < -10^\circ\text{C}$, $\alpha = 0.6$ (surface assumed to be ice-covered)

if $T > -10^\circ\text{C}$, $\alpha = 0.3$ (surface assumed to be ice-free)

2. Longwave outgoing radiation = $A + BT$

Instead of using σT^4 we assume outgoing longwave varies linearly with temperature. We can do this because temperature does not vary too much with latitude. Satellite measurements suggest values of $A = 203.3 \text{ Wm}^{-2}$ and $B = 2.09 \text{ Wm}^{-2}\text{C}^{-1}$. Note that if temperature goes up, outgoing longwave radiation goes up.

3. Heat flux in atmosphere/ocean: $F = -k dT/dy$, where $y = R_e\phi$,

Heat flux is assumed to be proportional to the North-South temperature gradient.

Note this looks like Fourier's Law for heat conduction, which we have seen already. Because the temperature gradient varies with latitude, the heat flux varies with latitude also.

What follows is a rough explanation of the climate model. We concentrate on what the terms mean physically and are not going to go into the details of the derivation: it is similar to what we did for the diffusion lab, but is trickier because the spherical geometry of the Earth has to be accounted for.

If the climate is in equilibrium, conservation of energy requires that:

$$\begin{array}{lcl} \text{Energy in} & = & \text{Energy out} \\ \Delta y Q_0 / 4 (1-\alpha) S(\phi) + F_{in} & = & F_{out} + \Delta y (A + BT) \end{array}$$

This can be rewritten as

$$\underbrace{Q_0 / 4(1 - \alpha)S(\phi)}_{\text{Net heat absorbed from the sun}} = \underbrace{(A + BT)}_{\text{Longwave emitted to space}} - \underbrace{D \frac{d^2T}{dy^2}}_{\text{Heat divergence: net heat transported out of the box by atmosphere and ocean.}}$$

The climate in each “box” is therefore a ***three-way balance*** between ***absorbed shortwave, emitted longwave, and convergence/divergence of the poleward heat flux.***

Note that the above is a rough derivation. Strictly one needs to account for the geometry of a sphere. This is done formally in notes, which are posted on the class web site. The equation that the model actually solves is the following:

$$\frac{Q_0}{4}(1 - \alpha)S(\phi) = A + BT + \frac{d}{dx}k(1 - x^2)\frac{dT}{dx}$$

where $x = \sin(\phi)$. But the essential physics is exactly the same. This is an equilibrium diffusion equation.

Instructions to run the energy balance model

Download the climate model files onto a directory that you create in D—Temp\

Start the Matlab application

Type “ebm” in the command window (the one with the double chevron prompt), and hit return.

If things go nuts: Close all figure windows by typing “close all; clear all” in the command line (and hit return). Then type “ebm” (and hit return). This should hopefully unstick things.

Tasks

- **The basic climate of the model**

1. Run the model with the standard parameter set.
 - a) What is the pole-to-equator temperature difference?
 - b) What is the maximum poleward heat flux? Give your answer in Peta-Watts (10^{15} watts)?
 - c) Why does the heat flux go to zero at the equator and at the poles?
 - d) Why does the $\nabla.F$ curve in the third panel have a kink in it at the ice line (i.e., at the latitude where $T = -10^\circ\text{C}$)?

- **Varying Q/Q_0 (Note that you enter the ratio of Q/Q_0 in the GUI window)**

- 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.
2. Assuming that this trend will continue, find the increase in the value of Q (to within 1 Wm^{-2}) required to eliminate ice from the earth. How long would it take before there is no ice left?
 3. Find the decrease in Q (to within 1 Wm^{-2}) required to cause complete glaciation, and hence show that the model would predict a snowball earth prior to about 1.1×10^9 years ago.
 4. While there is evidence of extensive (maybe total) glaciations over a half-billion years ago, these periods appear to have been broken by times that were relatively warm. Speculate what assumptions made in the climate model might not have applied to the earth's climate 10^9 years ago.

- **The effects of feedbacks**

5. The modern ice line is at about 72°N . Push the button "no ice-albedo feedback" on the graphical user interface. This fixes the albedo so that it is no longer a function of the temperature. Show that the model is now much less sensitive to changes in Q . That is, find the values of Q required for complete glaciation/deglaciation as in exercises above. Assume that -10°C still denotes where it is cold enough for ice to form. Remember to unset the alternative albedo parameterization when you are finished.

- **Global Warming**

6. A cheap and cheerful way of introducing CO_2 forcing into the model is to adjust the model parameter A by an amount ΔA , where

$$\Delta A = -k \log_e (\text{CO}_2 / 360)$$

where $k = 3 \text{ Wm}^{-2}$, and CO_2 is the level of carbon dioxide in parts per million by volume (ppmv). Thus, an increase in atmospheric CO_2 causes a

decrease in the longwave emissions to space. During the ice ages, records from ice cores show CO₂ varied between 200 ppmv during a glacial period and 280 ppmv during an interglacial period. A doubling of CO₂ from today's values (~360 ppmv) would take it up to around 720 ppmv. This is expected to happen within the next 70 years. Explore what effects these values would have on the climate.

- a. explain (briefly) why changing the parameter A in this way can emulate the effects of changing carbon dioxide.
- b. explore and describe (briefly) the effects on climate of changing CO₂ between glacial and interglacial values of carbon dioxide.
- c. explore and describe (briefly) the effects of doubling carbon dioxide for our future climate.

USEFUL NUMBERS. $\log_e(720/360) = 0.69$; $\log_e(200/360) = -0.59$;
 $\log_e(280/360) = -0.25$
 (note where the minus signs are!)

- **Varying diffusion/heat transport**

7. Set $D = 0$, and find the pole-to-equator temperature difference, and briefly describe the changes to the climate.
8. Try values of $D = 0.25 \text{ Wm}^{-2} \text{ } ^\circ\text{C}^{-1}$ and $D = 0.65 \text{ Wm}^{-2} \text{ } ^\circ\text{C}^{-1}$. Are the changes to the climate consistent with your expectations? Compare the maximum poleward heat flux in these integrations with that using $D = 0.45 \text{ Wm}^{-2} \text{ } ^\circ\text{C}^{-1}$. Explain why the changes to the heat flux are not simply proportional to the changes in D .
9. 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°C and that Ellesmere has not shifted much from its present location (which is true), find the value of D necessary for the crocodiles to have survived. What is the poleward heat flux required for this? Why does the mean global temperature not change?

- **Boil the oceans**

10. Lastly, what value of Q (in Wm^{-2}) would be necessary to begin to boil the oceans?