HW 4, ATMS/ESS 559 OCEAN 558, due 6 May 2008

In this exercise you will use the single-column, thermodynamic sea ice model from Bitz and Lipscomb (1999) coded in MATLAB. Sea ice is modeled as a motionless single slab, with no open water fraction. The ice temperature is resolved in 10 layers, and brine pockets are parameterized explicitly with a temperature and salinity dependent heat capacity and conductivity, following Maykut and Untersteiner (1971). Unlike MU71, this model takes into account the internal melt in brine pockets when computing the ice growth or melt rate, and thus it was termed an "Energy Conserving Sea-Ice Model" by BL99. The atmospheric model forcing is from the standard case in MU71, which is based on the work of Fletcher (1965). The turbulent heat fluxes are prescribed and hence are not parameterized as a function of surface temperature. The surface albedo is 0.63 for bare ice, 0.75 for wet snow, and 0.80 for dry snow.

The model is composed of 10 MATLAB scripts and one data file. You will need access to a computer with MATLAB. The model may be downloaded as a tarfile from http://www.atmos.washington.edu/∼bitz/column.tar (untar by typing *tar xvf column.tar*), or as individual files from http://www.atmos.washington.edu/∼bitz/column/.

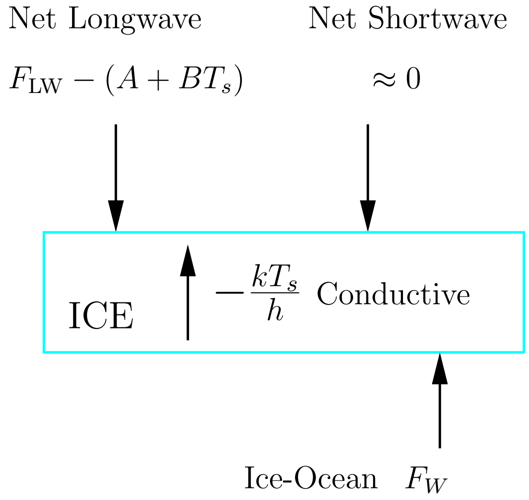
You don't need the startup script from the first assignment. Use a fast computer: Olympus is fine or try Ed's computer named snowman.atmos.washington.edu . To familiarize yourself with the model, run it once with the default parameters and forcings by typing *column;* in the MATLAB command window. When it is finished, type *help column* in the same window to learn how to vary the model options. Note that including a semicolon supresses the model from filling up the screen with numbers, preventing you from seeing the summary output. Get in the habit of including the semicolon, and better yet type *[hi, hs, Ts]=column;* so you will have variables for ice thickness, snow depth and surface temperature in your MATLAB workspace after running the model. From there you can compute statics on these variables as you like.

Part 1 Investigate the model sensitivity to varying the downward longwave radiative flux F_{LW}. Perturb the downward longwave flux (i.e., F'_{LW}) year through the function call list (e.g., type *column(-2)*) and make a table of the corresponding annual mean thickness $\bar{h}$ and mean February-March surface temperature T_{FM} in the final year of the run (the model displays these statistics in the command window). If necessary, increase the number of run years so the model reaches an approximate equilibrium by the time it finishes. Vary F_{LW} between +/-10 W m^{-2} in increments of about 2 W m^{-2}, but do not reduce F_{LW} so much that the snow does not melt in summer. Plot T_{FM} as a function of $\bar{h}$ and discuss the results. Plus

1) Why does the time to reach equilibrium vary? And why is the plot of $T_{\mathrm{FM}}(\bar{h})$ nonlinear? (The answers are similar and not obvious. Look carefully at a plot of the h timeseries. Which season accomplishes most of the adjustment?)

2) Using a hierarchy of models can be useful for understanding model results. Even the column themodynamic model coded in MATLAB is quite complex. Relate your results to an analytical "toy" model (Thorndike, 1992), which ignores surface turbulent heat fluxes and sea ice heat capacity. It also assumes winter is totally dark and summer is uniformly lit with no transition seasons in between:

Winter Energy Balance



The flux balance at the top surface is

$$F_{\mathrm{LW}} - (A + BT_s) = \frac{kT_s}{h},$$

where surface outgoing longwave $\epsilon\sigma T_s^4$ is approximated as $A + BT_s$, turbulent heat fluxes are neglected, and the temperature profile in the ice is assumed to be linear. Letting $W = F_{\mathrm{LW}} - A$:

$$W - BT_s = \frac{kT_s}{h},$$

Solve this equation for $h(T_s)$.

Your expression for $h(T_s)$ can be considered an average for ice thickness yearround as a function of the late winter surface temperature, $\bar{h}(T_{\mathrm{FM}})$. Plot the function on the curve you created with output from the MATLAB model. Use the following parameters: $W = -160$ W m^{-2}, $B = 4.6$ W m^{-2} (deg C)$^{-1}$, and $k = 2$ W m^{-1} (degC)$^{-1}$, to give you h in meters (not centimeters as in the MATLAB model).

Annual Energy Balance

The same picture applies in summer, except the net shortwave is not zero and the surface temperature is assumed to be zero Celsius. When the ice reaches an equilibrium thickness, the annual heat input into the ice must be zero. In the spirit of Thorndike (1992), let

$$\tau_{\mathrm{W}}(W - BT_s) + \tau_{\mathrm{S}}S + (\tau_{\mathrm{W}} + \tau_{\mathrm{S}})F_w = 0$$

where T_s is from the winter season, S is the net downward radiative flux in summer, $\tau_{\mathrm{W,S}}$ is the length of the winter or summer (and no other seasons exist). After substituting from the winter energy balance, we arrive at

$$\tau_{\mathrm{W}}(kT_s/h) + \tau_{\mathrm{S}}S + (\tau_{\mathrm{W}} + \tau_{\mathrm{S}})F_W = 0,$$

Solve for $T_s(h) \approx T_{\mathrm{FM}}(\bar{h})$ and plot it on your figure. Use $S = 22$ W m^{-2}, $F_W = 2$ W m^{-2} and for simplicity $\tau_{\mathrm{W}} = \tau_{\mathrm{S}}$. The intersection of the two analytical expression from the toy model gives an approximate solution to the Thorndike toy model.

Part 2 A climate modeler faced with biases in their model will often tune the surface albedo. This question invites you to explore some of the consequences. Find two different combinations for F_{LW} and surface albedo α that give roughly the same T_{FM}, $\bar{h}$ state. Vary α (0.05 is sufficient) by editing the script "calc_albedo.m" and vary F_{LW} from the function call list. Be sure to apply the same perturbations year round.

Now perturb the downward longwave further by $\delta F_{\mathrm{LW}} = 2$ W m^{-2} for each F_{LW}, α pair and find the thickness sensitivity $\delta h/\delta F_{\mathrm{LW}}$. Do they differ substantially? Why or why not?

Compute $\delta h/\delta F_{\mathrm{LW}}$ for your MATLAB runs from part 1 and note that it varies considerably. Why?

Part 3 How do F_{LW} perturbations isolated to the winter or summer season affect the ice thickness? Design your own experiments to investigate this question. Type *help column* in the matlab command window to find a quick way to perturb F_{LW} in winter or summer only. The time of year when downward longwave has the most spread among models is winter, because climate models have large spread in their simulation of wintertime cloud fraction.

Part 4 Briefly discuss the extent to which these exercise are applicable to global climate modeling.

MATLAB plotting hints.

Given a table of data:

x	y
2	4
4	16
6	36
8	64

MATLAB commands to plot the data are

```
x = [2 4 6 8];
y = [4 16 36 64];
plot(x,y,'o');
```

To add a line for the function $y = x^2$ type

```
x = 0:1:10; % creates an array
hold; plot(x,x.*x,'r-'); hold
xlabel('x'); ylabel('y');
```

The dot before the star is needed when multiplying array elements. Type *help plot* to see more options. Note that you can also plot(sqrt(x),x,'r-').

See the MATLAB "file" pulldown menu to open a new window with an editor to create new files. You can place all commands in a file, save it with the name myfile.m, and then type *myfile* in the MATLAB command window to run it.