COMPUTER METHODS AND MODELING IN GEOLOGY
MODELING EARTH'S TEMPERATURE

The parts of this exercise for students are in normal text, whereas answers and explanations for faculty are italicized.

In this week's lab we will learn how to create hierarchies of models of increasing complexity to understand some physical process - in this case, the absorption of solar energy by the Earth and its radiation of that energy back to space. Whenever you set out to understand a complex phenomenon, it is best to start with the simplest possible model that explains most of the behavior of that phenomenon and to build upward in complexity gradually. We will see how to do this today by modeling the energy balance at Earth's surface. We will first assume that the Earth is a perfect black body lacking an atmosphere, then move on to incorporate the fact that Earth reflects much of the solar radiation incident upon it, and later incorporate the fact that Earth has an atmosphere. Each time we build on to our model we will evaluate the output and compare it to actual Earth surface conditions to see how well each model refinement captures the reality of the physics of heat absorption, exchange, and emission.

Readings

Few, A.A., 1996, System Behavior and System Modeling, Sausalito, CA: University Science Books, p. 27-37. I don't have students read this because it gives away too much of the model and I want them to think through the steps themselves. A large part of the models constructed here comes from Few's way of thinking about the problem, however, so you should get this reference for yourself.

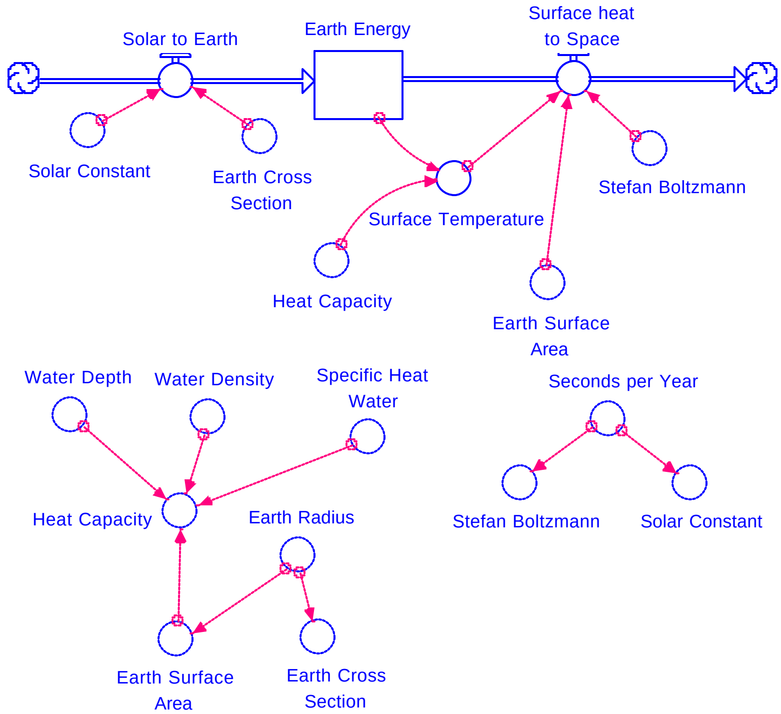
Graedel, T.E., and Crutzen, P.J., 1993, Atmospheric Change: An Earth System Perspective, New York: W.H. Freeman and Company, 446 p.

Harte, J., 1988, Consider a Spherical Cow, Sausalito, CA: University Science Books, p. 69-72, p. 160-167.

Exercises

1) Using the first Harte reading (p. 69-72) create a Stella model of an Earth that behaves like a perfect black body. Use the Stefan-Boltzmann law to determine what Earth's surface temperature would be given the values of the solar constant and the Stefan-Boltzmann constant reported in the reading. Report your results in both Kelvin and Celsius units, and paste a copy of your model into your word file. How do your results compare to Earth's actual average surface temperature?

<u>*Black Body Model*</u>

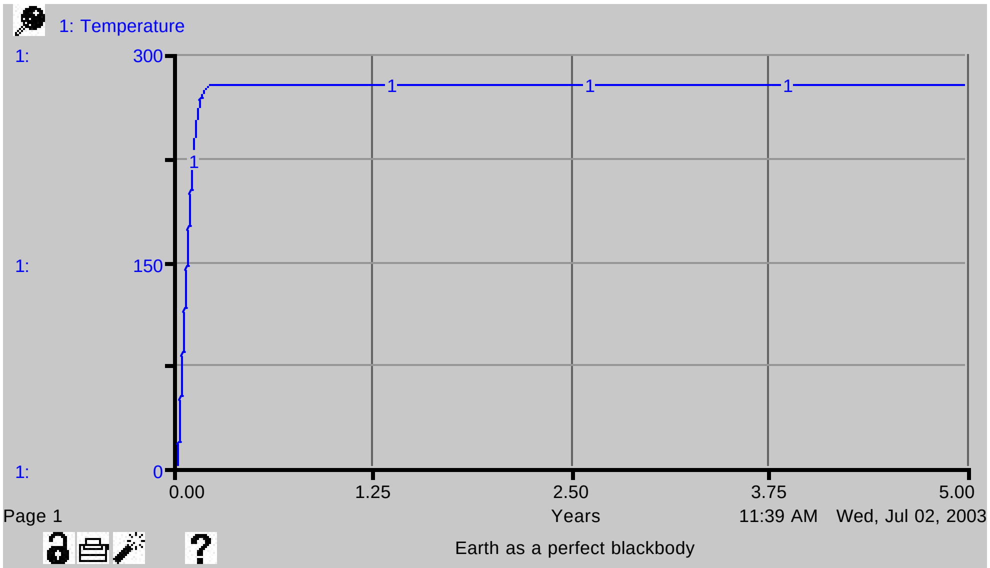


Note: Images of all the models presented in this answer key are available in PDF format in this same folder. Some of the models are so large that pasting them into this document made them unreadable.

<u>*Black Body STELLA Model Code*</u>

*Earth_Energy(t) = Earth_Energy(t - dt) + (Solar_to_Earth - Surface_heat_to_Space) * dt*
INIT Earth_Energy = 0.0
INFLOWS:
*Solar_to_Earth = Solar_Constant*Earth_Cross_Section*
OUTFLOWS:
*Surface_heat_to_Space = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4*
CONVERTERS:
Earth_Cross_Section = PI(Earth_Radius^2)*
Earth_Radius = 6371.0e3
*Earth_Surface_Area = 4*PI*(Earth_Radius^2)*
*Heat_Capacity = Water_Depth*Earth_Surface_Area*Water_Density*Specific_Heat_Water*
Seconds_per_Year = 3.15576e7
*Solar_Constant = 1368.0*Seconds_per_Year*
Specific_Heat_Water = 4218.0

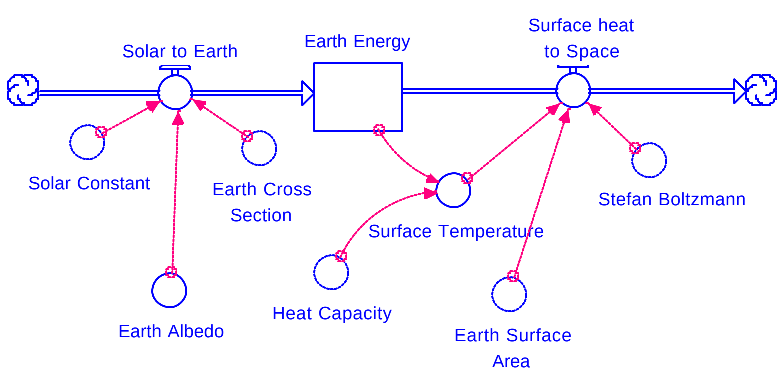
*Stefan_Boltzmann = 5.67e-8*Seconds_per_Year*
Surface_Temperature = Earth_Energy/Heat_Capacity
Water_Density = 1000.0
Water_Depth = 1.0

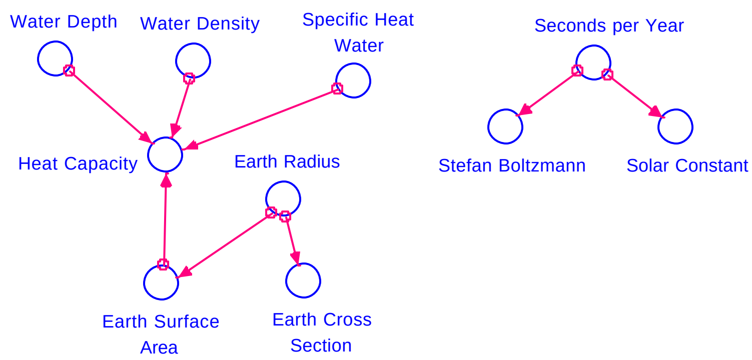


Earth's Temperature = 279 K, 6 ºC. These results are 11 degrees lower than the Earth's actual average surface temperature (290 K).

2) Now add a little more complexity to your model. Incorporate the fact that Earth is not a perfect absorber of solar radiation, but instead reflects a sizable portion of the energy incident upon it. What do you predict will happen to Earth's surface temperature? Was your prediction correct? How does the new surface temperature compare to Earth's actual average surface temperature? Paste a copy of your new model into your word file so I can see how you've modified your model.

<u>Black Body + Albedo Model</u>

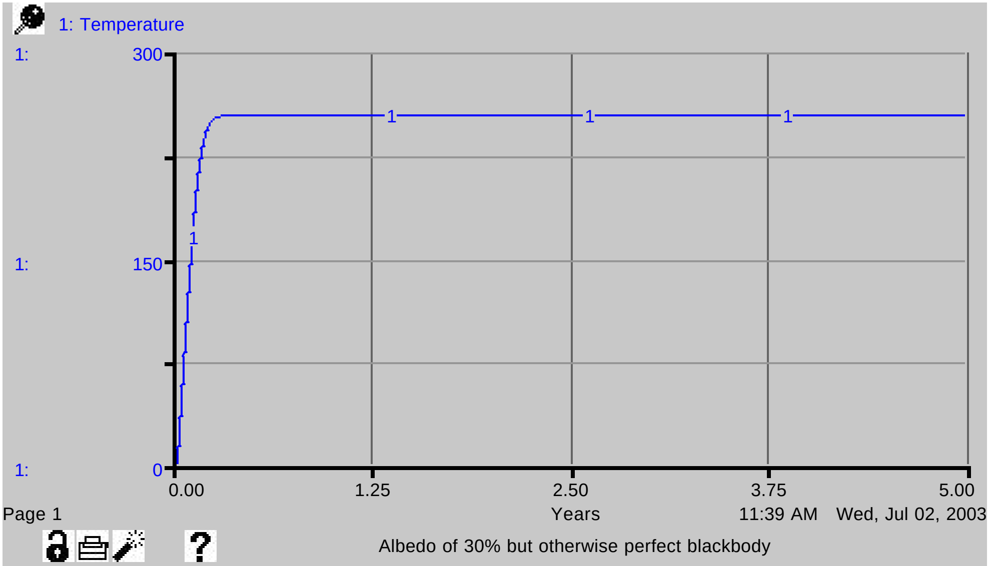




** Above images available in PDF format*

<u>Black Body + Albedo STELLA Model Code</u>

*Earth_Energy(t) = Earth_Energy(t - dt) + (Solar_to_Earth - Surface_heat_to_Space) * dt*
INIT Earth_Energy = 0.0
INFLOWS:
Solar_to_Earth = Solar_Constant(1-Earth_Albedo)*Earth_Cross_Section*
OUTFLOWS:
*Surface_heat_to_Space = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4*
CONVERTERS:
Earth_Albedo = 0.3
Earth_Cross_Section = PI(Earth_Radius^2)*
Earth_Radius = 6371.0e3
*Earth_Surface_Area = 4*PI*(Earth_Radius^2)*
*Heat_Capacity = Water_Depth*Earth_Surface_Area*Water_Density*Specific_Heat_Water*
Seconds_per_Year = 3.15576e7
*Solar_Constant = 1368.0*Seconds_per_Year*
Specific_Heat_Water = 4218.0
*Stefan_Boltzmann = 5.67e-8*Seconds_per_Year*
Surface_Temperature = Earth_Energy/Heat_Capacity
Water_Density = 1000.0
Water_Depth = 1.0

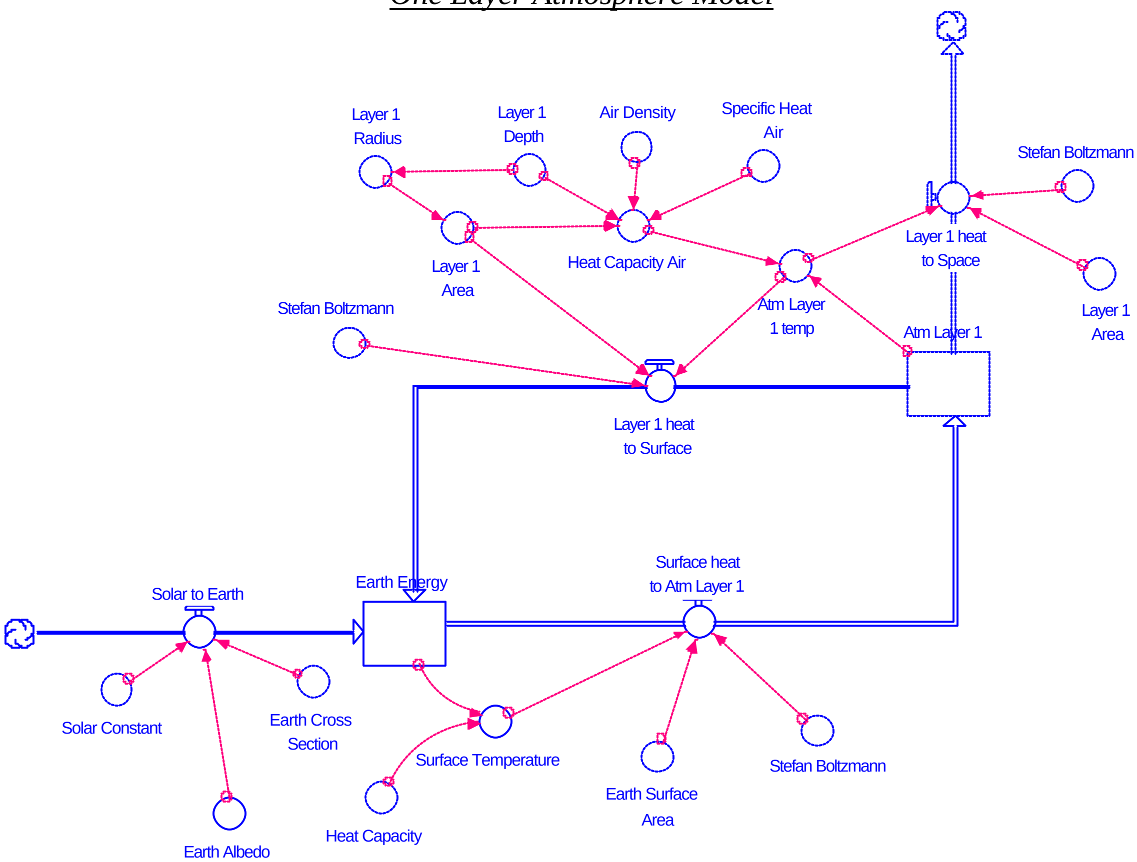


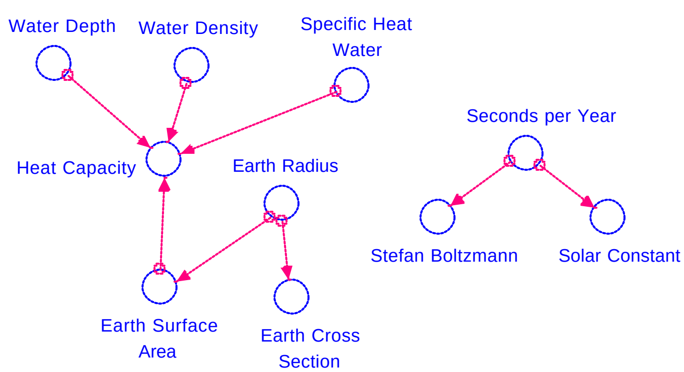
Taking into account the reflection of solar radiation decreases the Earth's surface temperature. This temperature (255 K, -18 ºC) is much lower than the actual average surface temperature of the Earth (290 K, 17 ºC).

3) To this point we have neglected the fact that Earth has an atmosphere. From your Harte and Graedel and Crutzen readings you learned that Earth's atmosphere is transparent to most of the incoming radiation given off by the sun, which is in the visible part of the light spectrum, but that it is largely opaque to the infrared radiation emitted by Earth's surface. The re-radiation of energy absorbed by the atmosphere down to the surface causes Earth's surface to be warmer than it would be in the absence of an atmosphere, and is an important variable we cannot neglect.

Add a one-layer atmosphere (following the methodology outlined in Harte, pg. 160-167, but using only 1 layer rather than n layers) to your model. Assume that all of the radiation given off by Earth's surface is absorbed by the atmosphere, but that none of the incoming solar radiation is absorbed. Determine the resulting temperature of Earth's surface and of the atmosphere. Paste your Stella model into your word document so I can see how you've changed your model.

One Layer Atmosphere Model



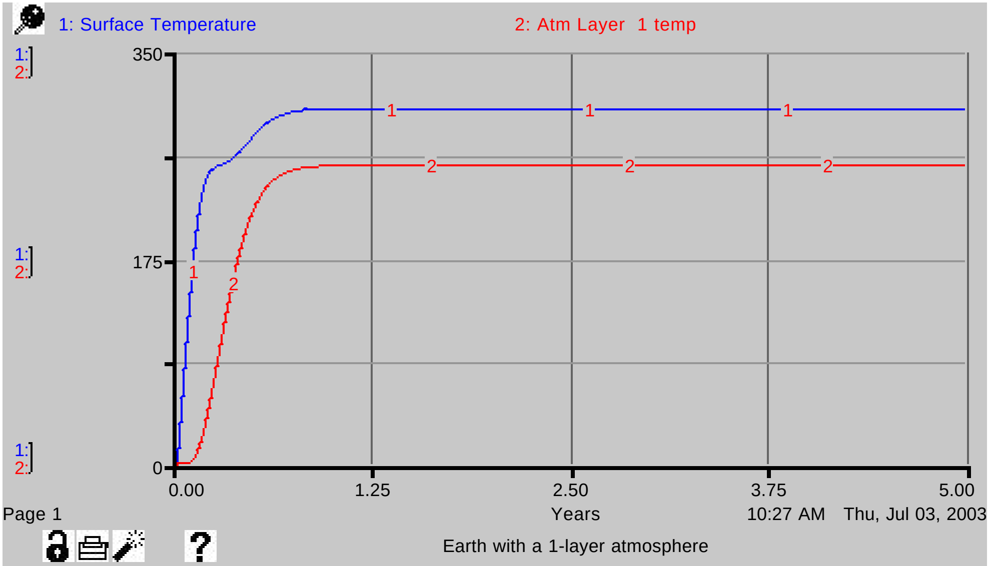


** Above images available in PDF format*

One Layer Atmosphere STELLA Model Code

*Atm_Layer_1(t) = Atm_Layer_1(t - dt) + (Surface_heat_to_Atm_Layer_1 - Layer_1_heat_to_Surface - Layer_1_heat_to_Space) * dt*
INIT Atm_Layer_1 = 0.0
INFLOWS:
*Surface_heat_to_Atm_Layer_1 = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4*
OUTFLOWS:

*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Layer_1_heat_to_Space = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Earth_Energy(t) = Earth_Energy(t - dt) + (Solar_to_Earth + Layer_1_heat_to_Surface - Surface_heat_to_Atm_Layer_1) * dt*
INIT Earth_Energy = 0.0
INFLOWS:
Solar_to_Earth = Solar_Constant(1-Earth_Albedo)*Earth_Cross_Section*
*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
OUTFLOWS:
*Surface_heat_to_Atm_Layer_1 = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4*
CONVERTERS:
Air_Density = 1.3
Atm_Layer__1_temp = Atm_Layer_1/Heat_Capacity_Air
Earth_Albedo = 0.3
Earth_Cross_Section = PI(Earth_Radius^2)*
Earth_Radius = 6371.0e3
*Earth_Surface_Area = 4*PI*(Earth_Radius^2)*
*Heat_Capacity = Water_Depth*Earth_Surface_Area*Water_Density*Specific_Heat_Water*
*Heat_Capacity_Air = Layer_1_Depth*Layer_1_Area*Air_Density*Specific_Heat_Air*
*Layer_1_Area = 4*PI*(Layer_1_Radius^2)*
Layer_1_Depth = 10.0e3
Layer_1_Radius = 6371.0e3+Layer_1_Depth
Seconds_per_Year = 3.15576e7
*Solar_Constant = 1368.0*Seconds_per_Year*
Specific_Heat_Air = 750.0
Specific_Heat_Water = 4218.0
*Stefan_Boltzmann = 5.67e-8*Seconds_per_Year*
Surface_Temperature = Earth_Energy/Heat_Capacity
Water_Density = 1000.0
Water_Depth = 1.0

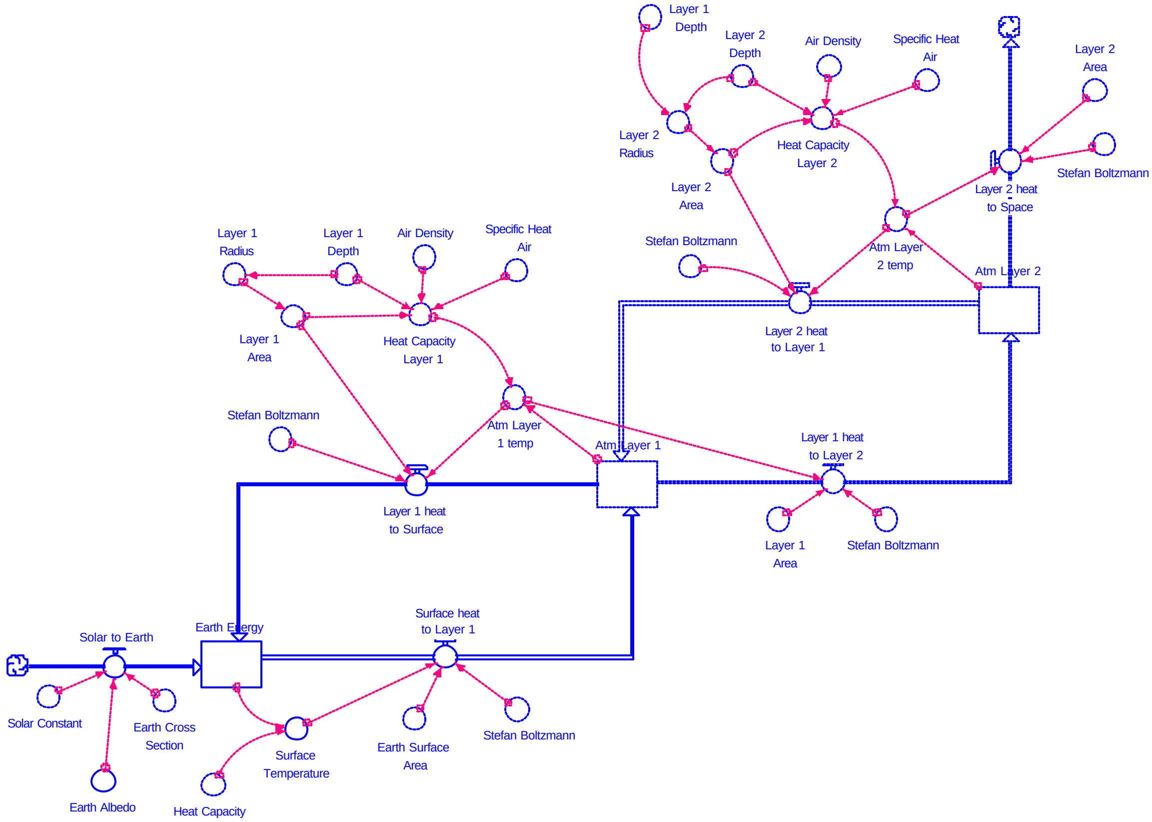


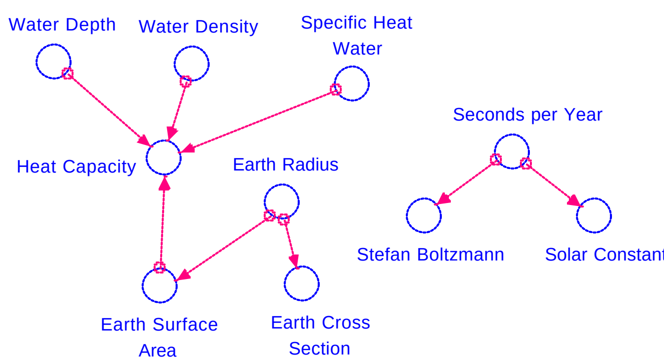
Earth's Surface Temperature = 303 K, 30 ºC.
Layer 1 Temperature = 255 K, -18 ºC.

With the addition of a one-layer atmosphere Earth's surface temperature has risen substantially and is now higher than in real life. Note that the temperature of the atmospheric layer is identical to the temperature of Earth's surface in the absence of an atmosphere (the previous problem). This is because the planet as a whole maintains a radiative equilibrium between energy coming in and energy going out.

4) Now add a second layer to your atmosphere as described in Harte (his n on pg. 163-164 is the number of layers in the atmosphere). How is the surface temperature affected by this change? How does the modeled surface temperature compare to the actual surface temperature of Earth?

Two Layer Atmosphere Model





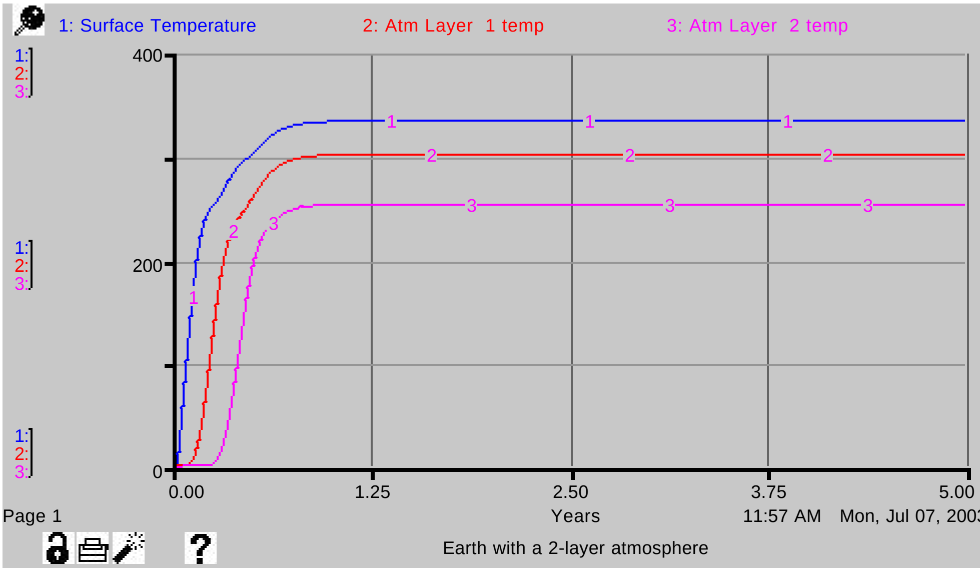
*Above images available in PDF format

Two Layer Atmosphere STELLA Model Code

Atm_Layer_1(t) = Atm_Layer_1(t - dt) + (Surface_heat_to_Layer_1 + Layer_2_heat_to_Layer_1 - Layer_1_heat_to_Surface - Layer_1_heat_to_Layer_2) * dt
INIT Atm_Layer_1 = 0.0
INFLOWS:
Surface_heat_to_Layer_1 = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4
Layer_2_heat_to_Layer_1 = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)

OUTFLOWS:
*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Layer_1_heat_to_Layer_2 = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Atm_Layer_2(t) = Atm_Layer_2(t - dt) + (Layer_1_heat_to_Layer_2 - Layer_2_heat_to_Layer_1 - Layer_2_heat_to_Space) * dt*
INIT Atm_Layer_2 = 0
INFLOWS:
*Layer_1_heat_to_Layer_2 = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
OUTFLOWS:
*Layer_2_heat_to_Layer_1 = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)*
*Layer_2_heat_to_Space = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)*
*Earth_Energy(t) = Earth_Energy(t - dt) + (Solar_to_Earth + Layer_1_heat_to_Surface - Surface_heat_to_Layer_1) * dt*
INIT Earth_Energy = 0.0
INFLOWS:
Solar_to_Earth = Solar_Constant(1-Earth_Albedo)*Earth_Cross_Section*
*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
OUTFLOWS:
*Surface_heat_to_Layer_1 = Earth_Surface_Area*Stefan_Boltzmann*Surface_Temperature^4*
CONVERTERS:
Air_Density = 1.3
Atm_Layer__1_temp = Atm_Layer_1/Heat_Capacity__Layer_1
Atm_Layer__2_temp = Atm_Layer_2/Heat_Capacity_Layer_2
Earth_Albedo = 0.3
Earth_Cross_Section = PI(Earth_Radius^2)*
Earth_Radius = 6371.0e3
*Earth_Surface_Area = 4*PI*(Earth_Radius^2)*
*Heat_Capacity = Water_Depth*Earth_Surface_Area*Water_Density*Specific_Heat_Water*
*Heat_Capacity_Layer_2 = Layer_2_Depth*Layer_2_Area*Air_Density*Specific_Heat_Air*
*Heat_Capacity__Layer_1 = Layer_1_Depth*Layer_1_Area*Air_Density*Specific_Heat_Air*
*Layer_1_Area = 4*PI*(Layer_1_Radius^2)*
Layer_1_Depth = 5.0e3
Layer_1_Radius = 6371.0e3+Layer_1_Depth
*Layer_2_Area = 4*PI*(Layer_2_Radius^2)*
Layer_2_Depth = 5.0e3
Layer_2_Radius = 6371.0e3+Layer_2_Depth+Layer_1_Depth
Seconds_per_Year = 3.15576e7
*Solar_Constant = 1368.0*Seconds_per_Year*
Specific_Heat_Air = 750.0
Specific_Heat_Water = 4218.0
*Stefan_Boltzmann = 5.67e-8*Seconds_per_Year*
Surface_Temperature = Earth_Energy/Heat_Capacity

Water_Density = 1000.0
Water_Depth = 1.0



Earth's Surface Temperature = 335 K, 62 ºC.
Layer 1 Temperature = 303 K, 30 ºC.
Layer 2 Temperature = 255 K, -18 ºC.

The surface temperature rises from the addition of a second atmospheric layer and is now much greater than the actual surface temperature of the Earth (290 K). Note that it is now the temperature of layer 2 that reflects the radiative equilibrium temperature for a blackbody planet with 30% albedo.

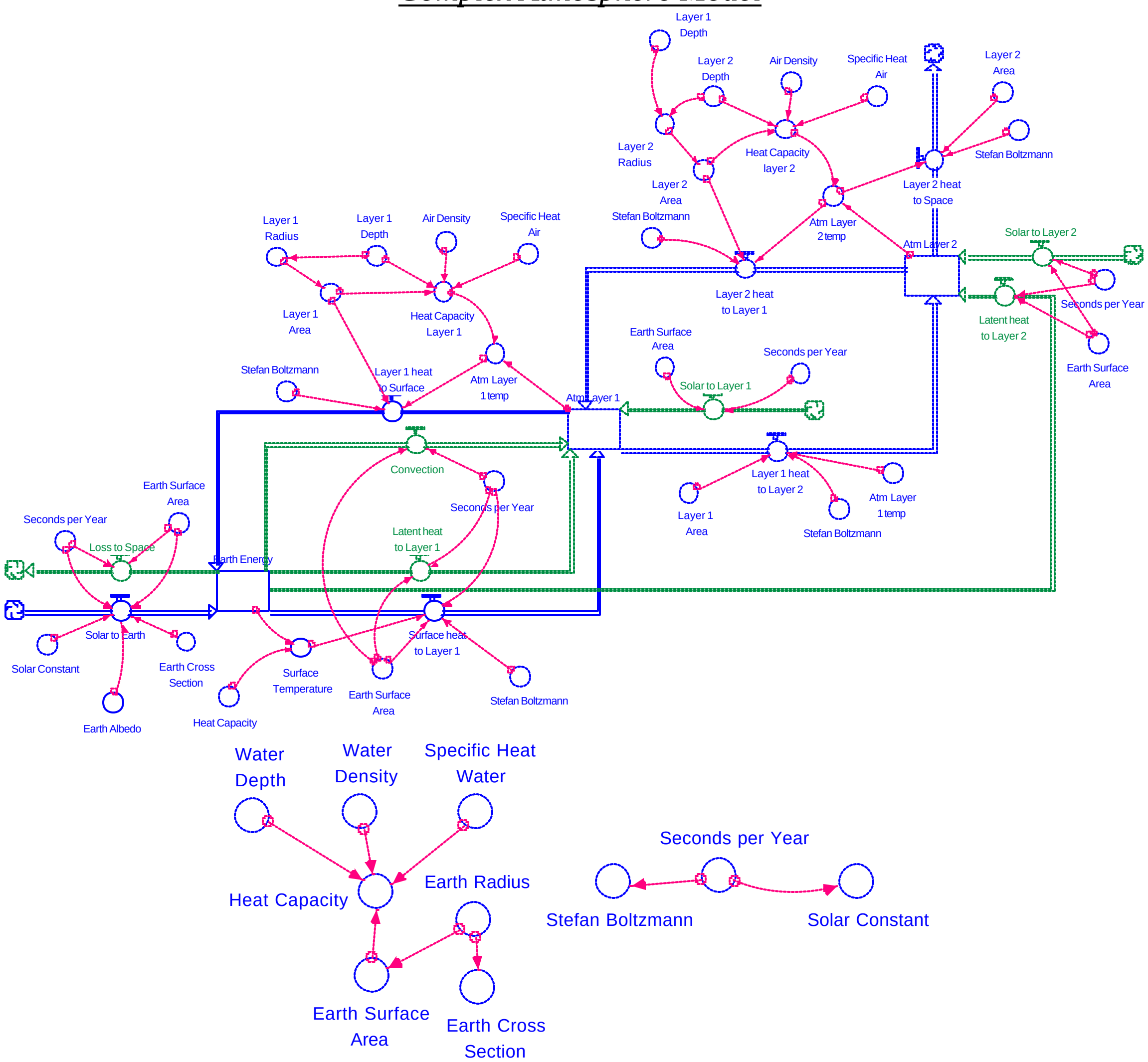
5) You have now created a pretty sophisticated model of the Earth's energy balance. However, the values of temperature you're getting are too hot. What components of the energy balance have we neglected to this point? Hint: the neglected parts are discussed in the second Harte reading.

These values are too hot because of the following neglected points:

- *Some of the incoming solar radiation is absorbed into the atmosphere (by water vapor, CO_2, etc.) and this results in an increase in the atmospheric temperature, as opposed to the surface.*
- *Also, some of the Earth's heat is removed by processes other than radiation; for example, by convection and latent heat transfer.*
- *Finally, some of the infrared radiation that is emitted from the Earth's surface is not absorbed by the atmosphere. It passes right into space due to its wavelength.*

6) Incorporate these remaining elements into your model. Show me your final model and report the temperature of Earth's surface and the 2 atmospheric layers.

Complex Atmosphere Model



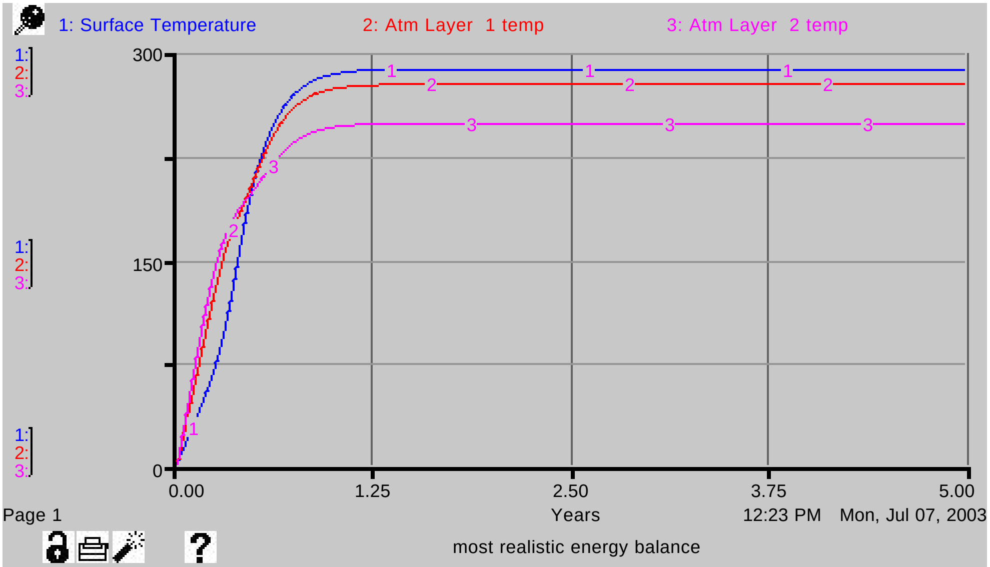
** Above images available in PDF format. The green flows are the new flows and represent the energies we haven't yet taken into account (latent energy, convection, direct absorption of solar energy in the atmosphere, loss of infrared energy from Earth's surface directly to outer space).*

Complex Atmosphere STELLA Model Code

*Atm_Layer_1(t) = Atm_Layer_1(t - dt) + (Surface_heat_to_Layer_1 + Layer_2_heat_to_Layer_1 + Latent_heat_to_Layer_1 + Solar_to_Layer_1 + Convection - Layer_1_heat_to_Surface - Layer_1_heat_to_Layer_2) * dt*
INIT Atm_Layer_1 = 0.0

INFLOWS:
Surface_heat_to_Layer_1 =
*(Earth_Surface_Area*Stefan_Boltzmann*(Surface_Temperature^4))-*
*(20*Seconds_per_Year*Earth_Surface_Area)*
*Layer_2_heat_to_Layer_1 = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)*
*Latent_heat_to_Layer_1 = 40*Seconds_per_Year*Earth_Surface_Area*
*Solar_to_Layer_1 = (0.3*86)*Seconds_per_Year*Earth_Surface_Area*
*Convection = 17*Seconds_per_Year*Earth_Surface_Area*
OUTFLOWS:
*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Layer_1_heat_to_Layer_2 = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
Atm_Layer_2(t) = Atm_Layer_2(t - dt) + (Layer_1_heat_to_Layer_2 +
Latent_heat_to_Layer_2 + Solar_to_Layer_2 - Layer_2_heat_to_Layer_1 -
*Layer_2_heat_to_Space) * dt*
INIT Atm_Layer_2 = 0.0
INFLOWS:
*Layer_1_heat_to_Layer_2 = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
*Latent_heat_to_Layer_2 = 40*Seconds_per_Year*Earth_Surface_Area*
*Solar_to_Layer_2 = (0.7*86)*Seconds_per_Year*Earth_Surface_Area*
OUTFLOWS:
*Layer_2_heat_to_Layer_1 = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)*
*Layer_2_heat_to_Space = Layer_2_Area*Stefan_Boltzmann*(Atm_Layer__2_temp^4)*
Earth_Energy(t) = Earth_Energy(t - dt) + (Solar_to_Earth + Layer_1_heat_to_Surface -
Surface_heat_to_Layer_1 - Loss_to_Space - Latent_heat_to_Layer_1 -
*Latent_heat_to_Layer_2 - Convection) * dt*
INIT Earth_Energy = 0.0
INFLOWS:
Solar_to_Earth = (Solar_Constant(1-Earth_Albedo)*Earth_Cross_Section)-*
*(86*Seconds_per_Year*Earth_Surface_Area)*
*Layer_1_heat_to_Surface = Layer_1_Area*Stefan_Boltzmann*(Atm_Layer__1_temp^4)*
OUTFLOWS:
Surface_heat_to_Layer_1 =
*(Earth_Surface_Area*Stefan_Boltzmann*(Surface_Temperature^4))-*
*(20*Seconds_per_Year*Earth_Surface_Area)*
*Loss_to_Space = 20*Seconds_per_Year*Earth_Surface_Area*
*Latent_heat_to_Layer_1 = 40*Seconds_per_Year*Earth_Surface_Area*
*Latent_heat_to_Layer_2 = 40*Seconds_per_Year*Earth_Surface_Area*
*Convection = 17*Seconds_per_Year*Earth_Surface_Area*
CONVERTERS:
Air_Density = 1.3
Atm_Layer__1_temp = Atm_Layer_1/Heat_Capacity_Layer_1
Atm_Layer__2_temp = Atm_Layer_2/Heat_Capacity_layer_2
Earth_Albedo = 0.3
Earth_Cross_Section = PI(Earth_Radius^2)*
Earth_Radius = 6371.0e3
*Earth_Surface_Area = 4*PI*(Earth_Radius^2)*

*Heat_Capacity = Water_Depth*Earth_Surface_Area*Water_Density*Specific_Heat_Water*
*Heat_Capacity_Layer_1 = Layer_1_Depth*Layer_1_Area*Air_Density*Specific_Heat_Air*
*Heat_Capacity_layer_2 = Layer_2_Depth*Layer_2_Area*Air_Density*Specific_Heat_Air*
*Layer_1_Area = 4*PI*(Layer_1_Radius^2)*
Layer_1_Depth = 5.0e3
Layer_1_Radius = 6371.0e3+Layer_1_Depth
*Layer_2_Area = 4*PI*(Layer_2_Radius^2)*
Layer_2_Depth = 5.0e3
Layer_2_Radius = 6371.0e3+Layer_2_Depth+Layer_1_Depth
Seconds_per_Year = 3.15576e7
*Solar_Constant = 1368.0*Seconds_per_Year*
Specific_Heat_Air = 750.0
Specific_Heat_Water = 4218.0
*Stefan_Boltzmann = 5.67e-8*Seconds_per_Year*
Surface_Temperature = Earth_Energy/Heat_Capacity
Water_Density = 1000.0
Water_Depth = 1.0

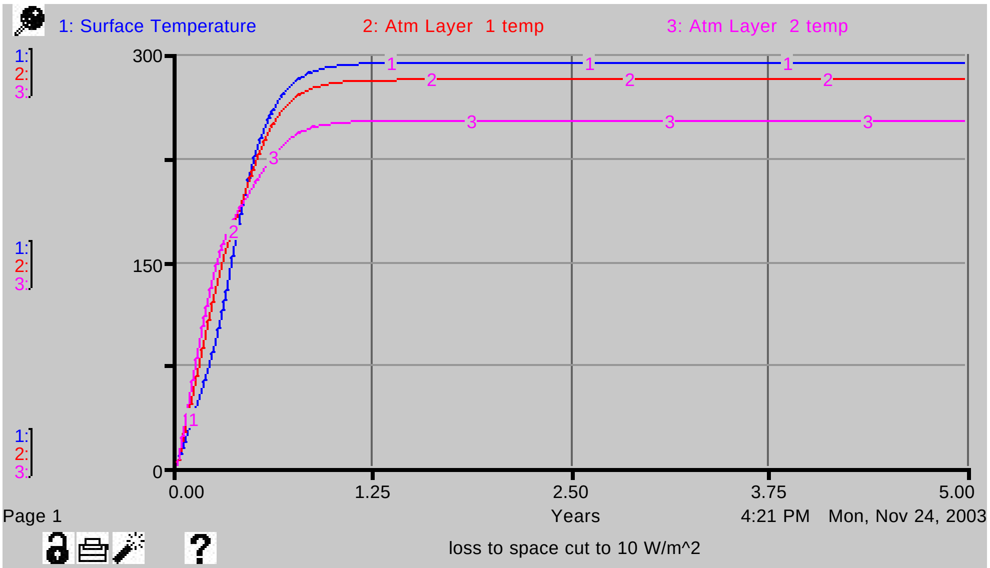


Earth's Surface Temperature = 289 K, 16 ºC.
Layer 1 Temperature = 278 K, 5 ºC.
Layer 2 Temperature = 249 K, -24 ºC.

7) Now that your model is complete, let's run some experiments to see what might happen to Earth's temperature under different climatic scenarios.

a) Global warming scenario. Climatologists believe that increasing the concentration of greenhouse gases that absorb the infrared radiation given off by

Earth will lead to an increase in Earth's surface temperature. Adjust your climate model to decrease the amount of radiation lost from Earth’s surface directly to space by half. What is the impact on both the temperature of the atmosphere and of Earth's surface?



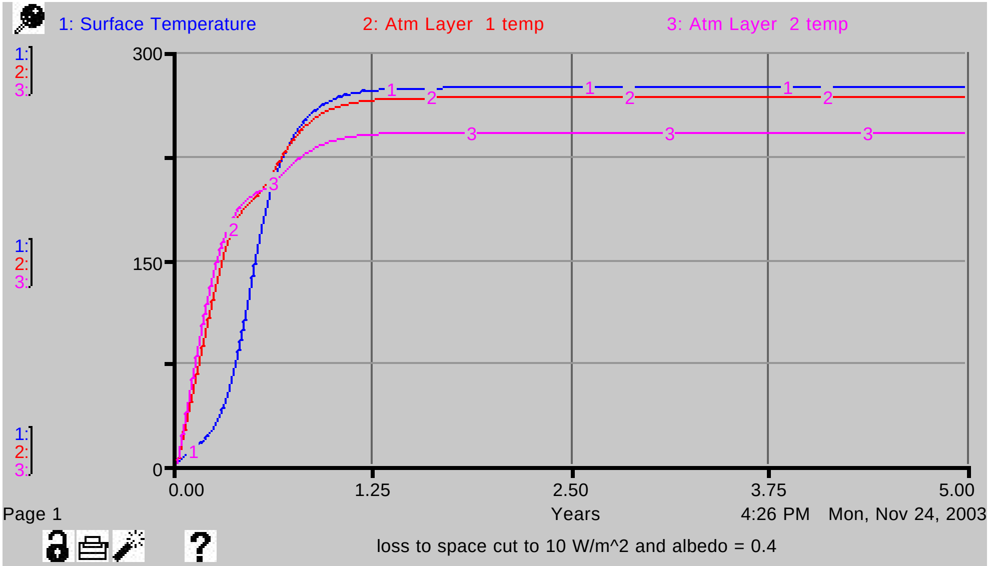
Earth’s Surface Temperature = 294 K, 21 ºC.
Layer 1 Temperature = 282 K, 9 ºC.
Layer 2 Temperature = 252 K, -21 ºC.

A change in the flow “Loss to Space” from 20 to 10 W/m^2 resulted in an increase in the temperature of the surface as well as the layers of the atmosphere. However, the increase in temperature was not the same for all layers; it was greater for the surface and Atmosphere 1 layers and less for Atmosphere 2.

b) One of the possible impacts of global warming is an increase in cloud cover. The warmer temperature of Earth will likely enhance the hydrologic cycle, leading to more water vapor in the atmosphere and a greater abundance of clouds. What impact might this have on Earth temperature? Modify your model to explore this problem, keeping the global warming scenario above intact. Please explain the reasoning behind the changes you make.

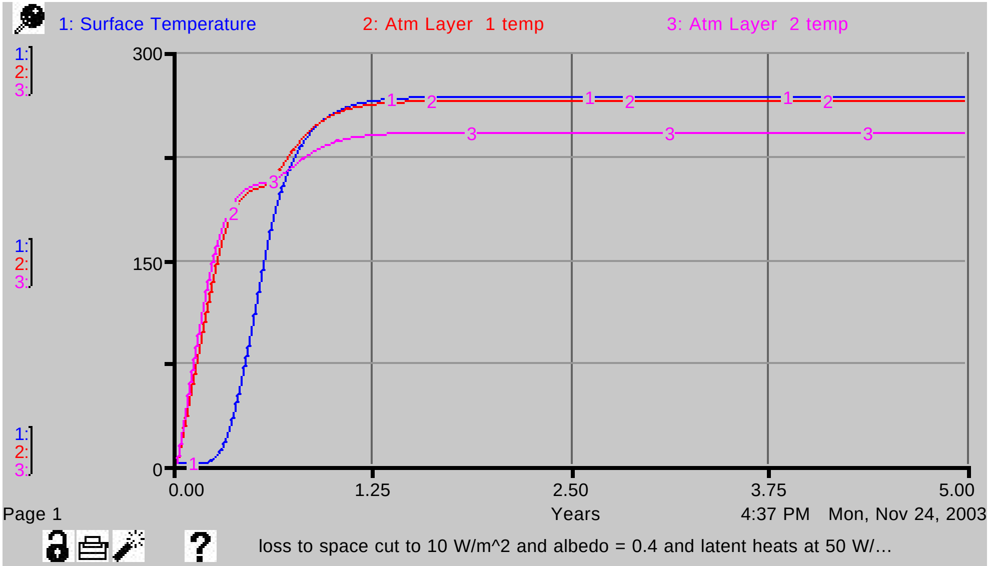
Note: each student will do this in a different way, and there isn't really a right or wrong answer. I'm mostly interested in whether they can explain their reasoning.

An increase in cloud cover will increase the albedo of the earth, resulting in an increase in the reflection of radiation. Because of this change, less radiation will reach the surface and be reradiated towards the atmosphere as infrared radiation. As a result, this will cause a cooling of the surface and of the atmospheric layers. An increase of the albedo to 0.4 results in the following:



Earth's Surface Temperature = 275 K, 2 ºC.
*Layer 1 Temperature = 267 K, -6 º*C.
Layer 2 Temperature = 242 K, -31 ºC.

However, this is not the only change that will occur. An increase in the amount of cloud cover means that there is an increase in the amount of H_2O *in the atmosphere. This will increase the amount of latent heating in the atmospheres. The latent heat values of the model must therefore also be increased. This change will result in a decrease in the temperature of the Earth's surface, while hardly affecting the temperatures of the atmospheric layers. An increase of both latent heat flows to 50 W/m^2 results in the following:*



Earth's Surface Temperature = 268 K, -5 ºC.
Layer 1 Temperature = 265 K, -8 ºC.
Layer 2 Temperature = 242 K, -31 ºC.

Clearly there are other processes that I've neglected here since these changes result in a net cooling when global warming models result in a warming. My point here is not to replicate GCM results with this simple model, but to have students experiment with various flows and explain the resulting behaviors.

c) Finally, explore the potential impact of the sunspot cycle on Earth temperature (set your model conditions back to the pre-global warming scenario). Allow the solar radiation reaching Earth's surface to change by +/- 1%, using a sine wave with period 11 years. First tell me what the equation is for this fluctuating radiation output. Then incorporate it and describe the impact on Earth's surface and atmospheric temperatures.

The equation for Solar_to_Earth oscillation is the following:

Solar_to_Earth = ((Solar_Constant(1-Earth_Albedo)*Earth_Cross_Section)-(86*Seconds_per_Year*Earth_Surface_Area))+0.01*((Solar_Constant*(1-Earth_Albedo)*Earth_Cross_Section)-(86*Seconds_per_Year*Earth_Surface_Area))*SIN(2*PI*(TIME/11))*

Altering the incoming solar flux in this way resulted in a fluctuation of about 1 K in surface temperatures, and about a 1-2 K fluctuation in atmospheric and surface temperatures.