ED41A-01

Internet Lectures on Geophysical Modeling

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Abstract

Advances in modeling software and presentation software now provide the instructor with the means to communicate over the Internet to a global student audience. Modeling in the broadest sense has always been a touchstone tool in geophysics ranging from a drawing of stratigraphy to a numerical climate model. At the undergraduate level even simple models provide insight in the behavior of geophysical systems. By coupling illustrated lectures with hands-on computer models that can be downloaded as a package from the Internet, the instructor can broadly support classroom instruction.

The software, (isee Player) for viewing and manipulating working STELLA models is a free download from isee systems http://www.iseesystems.com. Both Keynote (Macintosh) and PowerPoint (Windows) support adding an audio track to slides, so the instructor can discuss the content and interpretation of slide information. When the lecture on a geophysical process is coupled with a working model the student then gets a hands-on opportunity to explore the responses of the geophysical system as modeled. Examples of STELLA models and coupled lecture and model are available at http://www.ruf.rice.edu/~few.

This presentation was prepared on a **Macintosh (OS X 10.4.9)** using **Keynote (v 3.0.2)**. Audio content was created using **GarageBand (v 3.0.4)** and was attached to the **Keynote** slides. To produce the poster the material was moved from **Keynote** to **Pages (v 2.0.2)**.

Keynote can export its content into **QuickTime** and **PowerPoint** preserving the audio content and into **PDF, HTML** and three other formats without the audio.

This presentation is downloadable from **http://www.ruf.rice.edu/~few** in **Keynote, PowerPoint** and **PDF** formats.

Although somewhat similar to a podcast, this format allows full screen graphics, and it enables the user to move forward or backward fully controlling the individual slides with their attached audio.

The Early Faint Sun Paradox

I selected the "early faint Sun paradox" as this presentation example because it is particularly instructive for undergraduate students.

Concepts that they will learn in this exercise are: energy balance modeling, the blackbody radiation law, planetary effective temperatures, positive feedback, greenhouse warming, and the Gaia hypothesis among others.

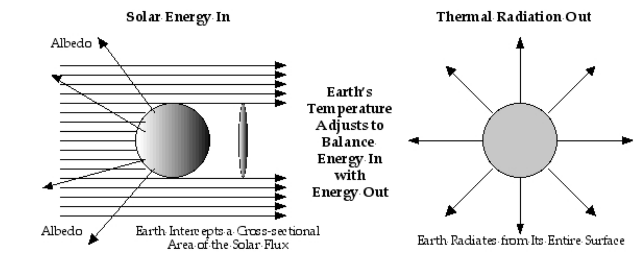
The Early Faint Sun Paradox

The early faint Sun paradox as originally posed is: the Sun 4 billion years ago produced only 70% of it's present power output, the Earth receiving 30% less power would be a frozen planet, and once covered with ice the albedo would be so large that the Earth would remain frozen even when the Sun increased it's output.

The scientific community now considers the paradox solved; although, we still see occasional scientific discussions of the details. We have recently seen a new, but related problem, the "snowball" Earth emerge.

The general problem of how to defrost an ice-covered Earth is interesting and instructive. It provides a good learning experience for undergraduates in the behavior of climate systems with positive feedbacks. By adding computer modeling to the exercise the students get hands-on experience and are encouraged to investigate the model behavior under a variety of parameters and assumptions.

We start with the basic conceptual model of the Sun-Earth interaction.



Power In $= S(1-A)E_C$

$S =$ Solar constant $= 1368\ \mathrm{Wm^{-2}}$

$A =$ albedo $= 0.30$

$E_C =$ Earth's cross-sectional area $= 1.275\times10^{14}\ \mathrm{m^2}$

Power Out $= E_S\sigma T_{EE}^4$

$E_S =$ Earth's surface area $= 5.10\times10^{14}\ \mathrm{m^2}$

$\sigma =$ Stefan-Boltzmann constant $= 5.67\times10^{-8}\ \mathrm{Wm^{-2}}K^{-4}$

$T_{EE} =$ Earth's effective temperature

When the Earth is in radiation balance with the incoming Solar radiation,
Power Out = Power In

$$E_S\sigma T_{EE}^4 = S(1-A)E_C$$

$$E_S/E_C = 4$$

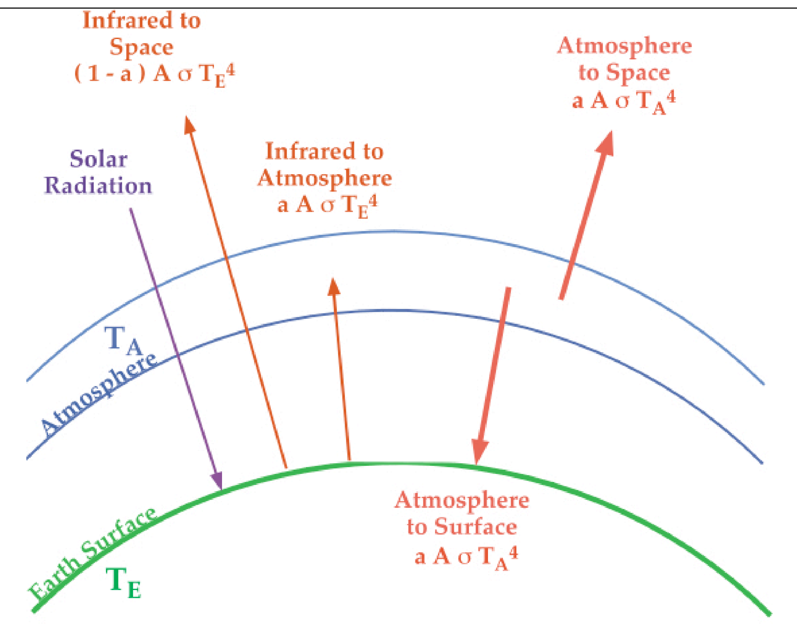
$$T_{EE} = \sqrt[4]{\frac{S(1-A)}{4\sigma}}$$

Using current values for S and A we find that
TEE = 255ºK = -18ºC.

This seems much too cold to us on the surface, but of the Earth's outgoing infrared radiation only ~7% comes from the surface with ~93% coming from the atmosphere, mostly from the cloud tops, which can be cold. The mean surface temperature, TS , is 15ºC; the difference, TS - TEE , is 33ºC. The current greenhouse warming of the Earth is this 33ºC.

This simple algebraic solution for the radiation balance is instructive; however, to understand greenhouse contribution to energy balance we need to include an atmosphere.

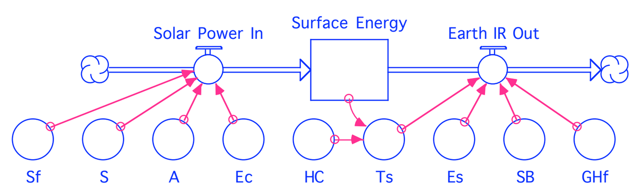
On the following slide we present the conceptual model for greenhouse warming.



When we include an atmosphere in our model for the Earth, we see that the surface is now receiving radiation from the atmosphere in addition to the sun, thus further warming the surface. The atmospheric radiation comes from the greenhouse gasses and the clouds.

To study the "Early Faint Sun Paradox" we need to create a dynamic model because the solar constant, S, and the albedo, A, are variables. S(t) will be a function of time, and A(T_S) will be a function of the surface temperature. The albedo will depend in part on the amount of highly reflective ice on the surface. This is a positive feedback process: the colder the surface the greater is the surface ice, which reflects more sunlight; this increases the albedo and further cools the surface.

We are using STELLA from isee Systems to construct and run the dynamic models. In STELLA the outline of the dynamic model in a system diagram format is shown below. Solar power in the visible wavelengths interact with the Earth system; the part that is not reflected (albedo) is absorbed and stored as surface energy. As the surface energy increases the temperature of the surface increases and radiates energy back to space in infrared wavelengths. This continues until the system reaches equilibrium. The definitions for the elements seen below are given on the following slide.



The solar constant, S, and the Stefan-Boltzmann constant, SB, have units with seconds; the Watt, W, is a Joule/s. When working on longer time scales, a second is much to small, so we will convert these to years. An average year has 365.25 days (including leap years); this yields 31,557,600 s/yr. Also the Earth responds fairly rapidly to changes in the solar output, so it is unnecessary to run the model for 5 billion years; we will compress the time scale to one hundred years.

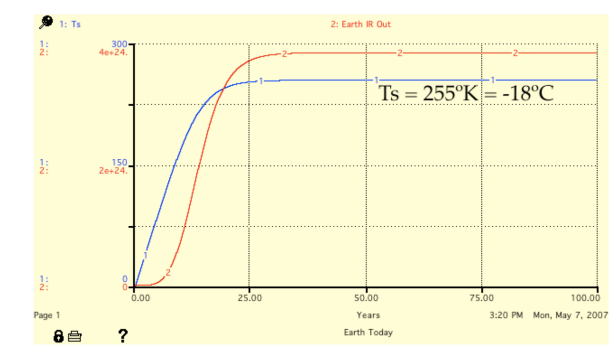
$$\mathrm{S} = 1368\ \mathrm{Wm^{-2}} = 4.3171\mathrm{x}10^{10}\ \mathrm{Jyr^{-1}m^{-2}}$$
$$\mathrm{SB} = 5.67\mathrm{x}10^{-8}\ \mathrm{Wm^{-2}K^{-4}} = 1.789\ \mathrm{Jyr^{-1}m^{-2}K^{-4}}$$

Other Information Required

The "surface" is Earth totally covered with 100 m of water or ice.
HC_w, the surface heat constant for water = 100 m*E_S*1000 kg m^{-3} *4218 J K^{-1}kg^{-1} = 2.151x10^{23} JK^{-1}.
HC_i, the surface heat constant for ice = 100 m * E_S* 1000 kg m^{-3} 2106 J K^{-1}kg^{-1} = 1.074x10^{23} J K^{-1}.
T_S, the surface temperature is to be determined by the model = Surface Energy/HC.
Sf is the parameter (0 to 1) used to change the solar output.
GHf is the parameter (0 to 1) used to simulate the greenhouse effect.

The Earth's Effective Temperature Today.

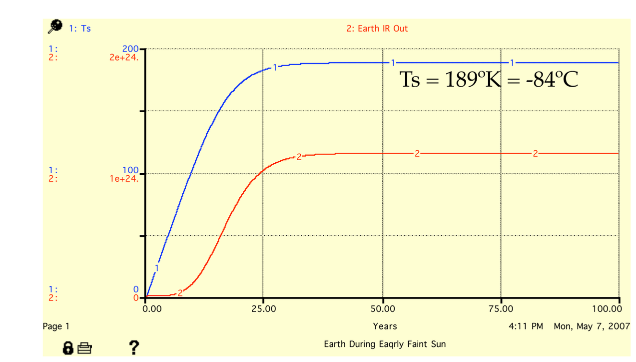
This first model run will use values for the current conditions:
Sf =1, GHf=1, HC=HC_w,



The initial surface energy was set to zero; thus the surface temperature is also zero. In this model run we see that it requires approximately 35 years for the sun to warm 100 m of water to its equilibrium temperature of 255ºK. This was the same temperature that we found earlier using the algebraic equations.

The Earth's Effective Temperature Early Faint Sun Conditions.

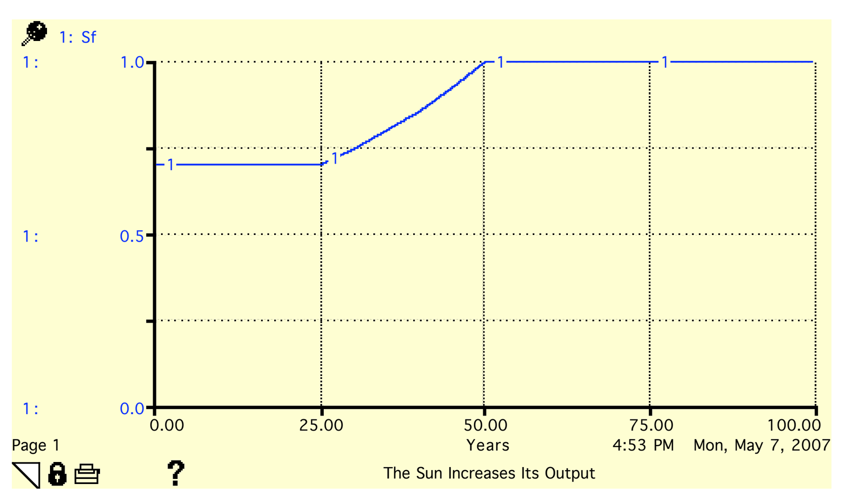
This second model run will use values for the early faint Sun:
Sf =0.7, GHf=1, HC=HC_i, A=0.7
An ice-covered planet will have a high albedo; Venus, which is white due to clouds has an albedo of 0.7.



At -84ºC the Earth is definitely completely frozen. It takes the Sun approximately 40 years to warm the ice to its equilibrium temperature.

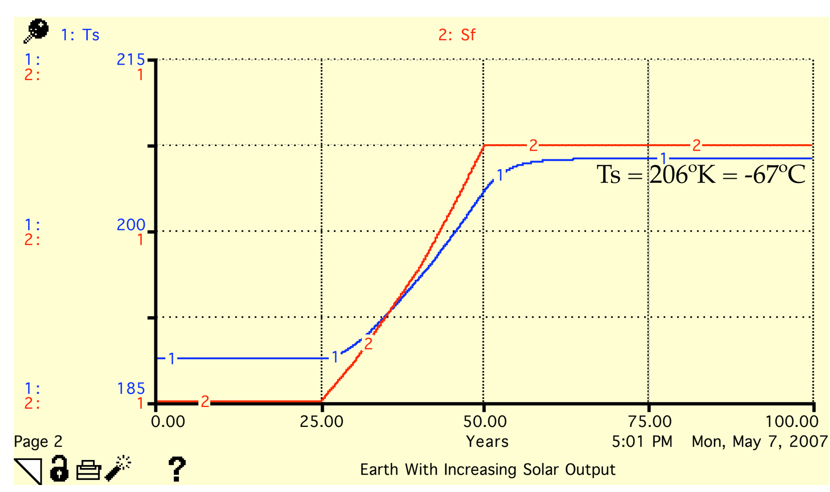
The Sun Increases Its Output.

In this third model we start Sf at 0.7 then after 25 years (~1 billion years real time) we ramp up the Sun's output to Sf = 1 over another 25 years then hold it constant. The value of Sf is shown in the graph below. The other change is to use the equilibrium value for the surface energy from the previous model as the initial value in this model to eliminate the ocean warming time.



The Sun Increases Its Output.

In this third model we increase the Sun's output leaving the other parameters of model unchanged except for the initial value of the surface energy.

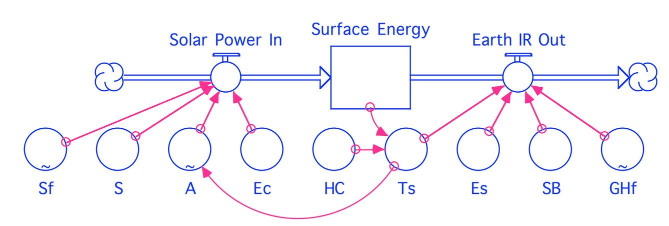


The 206ºK = -67ºC is an improvement over the 189ºK of the previous model, but it is not enough to defrost the Earth; hence, the early faint Sun paradox.

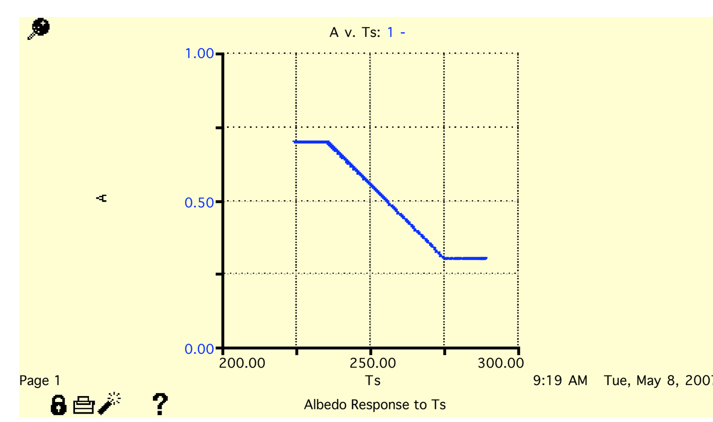
Resolving the Early Faint Sun Paradox

The early atmosphere of Earth was not like today's atmosphere; only in the last ~20% of the Earth's history have we had a significant component of oxygen in our atmosphere. Earth's early atmosphere was probably much like what we now see in Venus's atmosphere - mostly CO_2, a strong greenhouse gas.

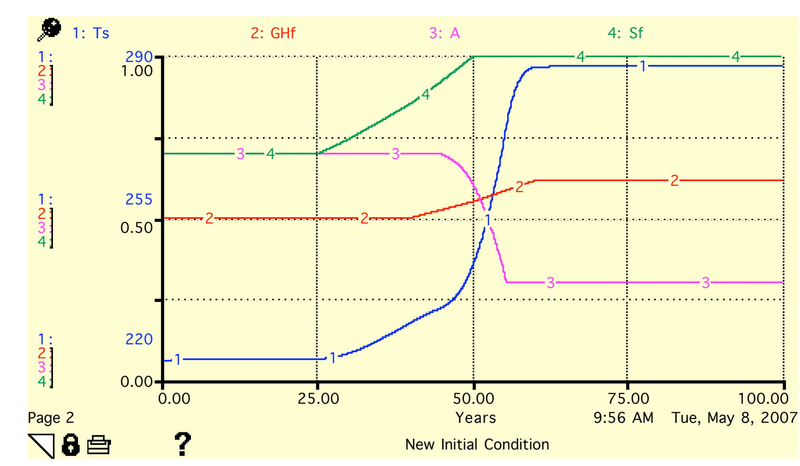
We need to make three changes in our model:
1. Add a greenhouse effect, GHf. We do this by decreasing GHf, which "traps" a fraction of the outgoing radiation.
2. Modify the albedo to allow for melting of the ice. (Note the addition of the red arrow connecting Ts to A.)
3. Adjust the initial condition of surface energy to be consistent with the addition of the GHf. We do this by running the model for 25 years to get the surface energy under the new conditions = 2.406x10^{25}.



The graph below shows the albedo, A, as a function of the surface temperature, Ts. The albedo remains at a constant 0.7 for temperatures below those shown and 0.3 for higher temperatures than those shown. The geologic record indicates the the surface temperature range between glacial and interglacial is ~10ºC; we see below that for the extreme conditions considered in this case we have the transition occurring over ~40ºC.



The Frozen Earth Defrosts



The magenta line, 3, is the albedo; near the 50-year mark it makes a rapid transition from ice covered (A=0.7) to ice free (A=0.3). Even though the strength of the greenhouse effect, GHf (orange 2), decreases (GHf increases from 0.5 to 0.615) the Earth's surface temperature, Ts, increases to 288ºK, which is the mean surface temperature for the Earth today.

The Early Faint Sun Paradox Is Resolved

The early Earth had an atmosphere with strong greenhouse warming, and this prevented the Earth from freezing over.

In the previous slide the parameters were adjusted to produce the transition when the Sun increased its output, and to reproduce the present surface temperature. With additional adjustments of the greenhouse factor and the associated initial conditions the transition can be moved to earlier times.