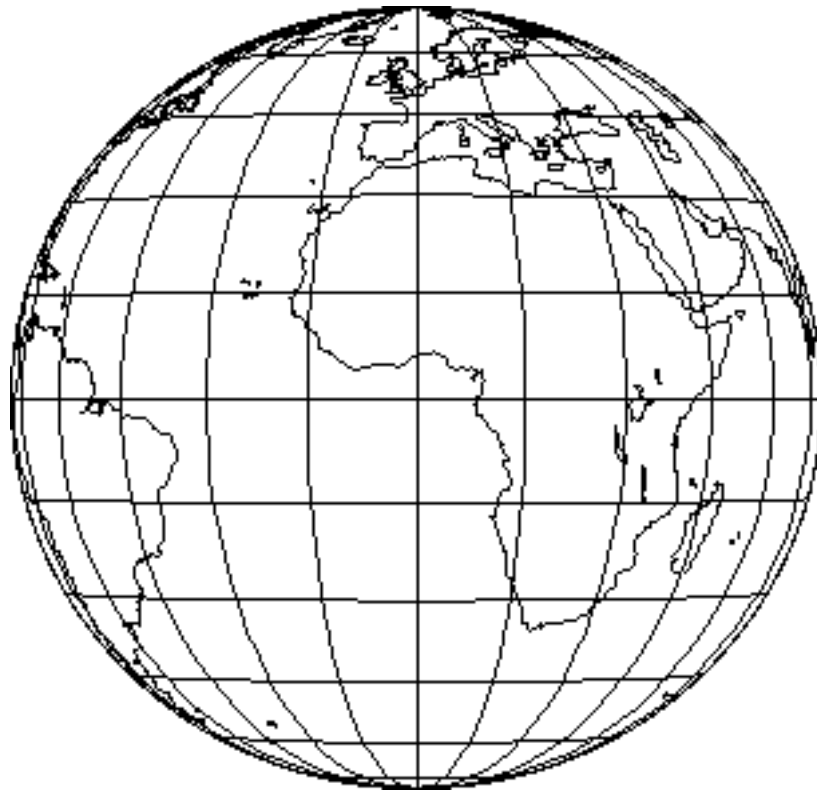


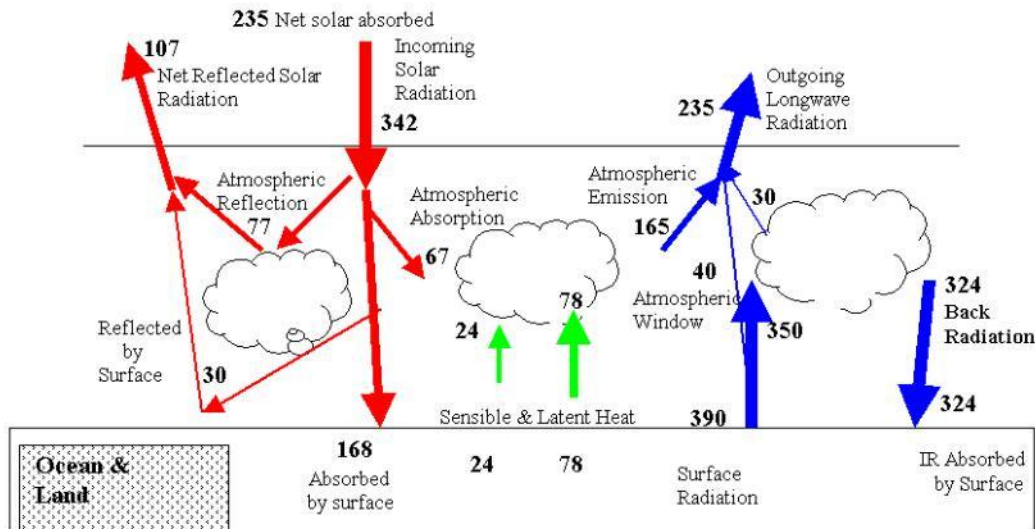
Global Energy Balance Climate Model



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Earth's Annual Energy Balance

After Khiel and Trenberth 1997, Bulletin of the American Meteorological Society.



*all numerical values are W/m²

(note: the value of 342 W/m² given in this figure is the solar constant divided by 4.0 (1368/4.0). This represents the average solar intensity considering day and night and average incident angle of solar radiation)

Our Global Energy Balance Model (GEBM) of the climate system is based on the information contained within this figure. For simplicity the model planet is assumed to be completely covered by water of uniform depth. The rate at which the surface temperature changes depends on the top of atmosphere (TOA) solar intensity, the surface and atmospheric reflectivities, and the atmospheric absorption of solar radiation (these radiative processes are represented by the red arrows in the figure above). The surface temperature change rate also depends on the surface temperature, atmospheric emissivity, atmospheric temperature, and the flux of latent and sensible heat from the surface (blue and green arrows in the figure above). The model assumes that the atmospheric emissivity can change with carbon dioxide concentration, atmospheric water vapor content, and high or low cloud amounts. High and low clouds also alter the atmosphere's reflectivity (albedo). When all feedbacks are turned on, the model assumes that the surface reflectivity and atmospheric water vapor content depend on surface temperature, and that the flux of latent and sensible heat from the surface is driven by the magnitude of the temperature difference between the surface and atmosphere. These assumptions provide ice albedo, water vapor, and latent and sensible heat flux feedbacks.

Getting Started

ebm - Microsoft Internet Explorer - [Working Offline]
 File Edit View Favorites Tools Help

Initial Surface Temperature, T_0 (K)=288.08 ; Final Srf Temp, T_F (K)=288.06 ; Temp Change DT (K)=***
 CO2(ppm)=320.0 CO2 growth rate (% per year)=0.0 Final CO2 (ppm)=***
 H2O**=1.0
 Solar Constant** 1.0 Surface Albedo (0 to 1) 1.0
 Solar Atmos Absorption** 1.0 Solar Atmos Reflectivity from air molecules** 1.0
 Low Cloud Amount** 1.0 High Cloud Amount ** 1.0
 Volcanic eruption strength (0 to 1) 1.0 (not active until checkbox checked)
 Ocean Mixed Layer Depth (m) 100.0 **fraction of base value (1.0 is default)

Ice Albedo Feedback water Vapor feedback surface latent and sensible heat flux feedback
 Volcanic Eruption at year 10 Run1 Run2 Run3 Clear Reset [To Graph & Output Table](#)

You can make several runs with different colors on the same graph for comparison. [To Model Input & control](#)

Global Climate Change

Srf Temp (K)

293

288

283

0 25 t(yrs) 50

Using either the Netscape Navigator or Internet Explorer browser, open the global energy balance model ebm.htm opening the URL

<http://www.atmosedu.com/Geol390/physlets/GEBM/ebm.htm>

The Control panel shown above allows you to control the following inputs of the model planet:

- Initial absolute temperature T_0 (in Kelvin)
- Final absolute temperature T_F (in Kelvin) **This is an output only; not set by the user**
- Temperature change DT (K) ** output only**
- CO2 - Carbon Dioxide concentration in parts per million (ppm)
- CO2 growth rate in percent per year (set to zero for fixed CO2 simulations)
- Final value of CO2 after 50 year simulation (ppm) ** output only**
- H2O- Water Vapor amount (Fraction of model's base value)
- Solar Constant -[Top of atmosphere \(TOA\)](#) solar intensity as a fraction of its present day average (1368 W/m^2).
- Surface Albedo (reflectivity) as a fraction of the model's base value of 0.088.
- Solar Atmospheric Absorption – Fraction of TOA Solar absorbed by atmosphere
- Solar Atmospheric Reflectivity from air molecules (Fraction of model's base value)

- Low Cloud Amount (Fraction of model's base value)
- High Cloud Amount (Fraction of model's base value)
- Volcanic eruption strength (0 to 1) which is not activated until the volcanic eruption box is checked.
- MLD - Mean mixed layer depth of the aqua planet model (meters)

Four check boxes for:

- Ice albedo feedback
- Water vapor feedback
- Latent and sensible heat flux feedback
- Add volcanic eruption at year 10 of the simulation.

The output graph gives a surface air temperature plot for the 50 year simulation. The Run1, Run2, and Run3 buttons all run the model but are represented as different colored lines on the graph. This make it easy to compare two runs with different inputs.

The output table gives **the Intial values** of:

Planetary Albedo (total TOA solar reflected back to space), Infrared radiative flux leaving the top of the atmosphere into space, and the net solar radiative flux absorbed by the planet. When these two fluxes are equal the planet is said to be in radiative equilibrium. Whenever something changes to offset this balance the planet's temperature must change until radiative equilibrium is regained. Numerical values of the surface and atmospheric temperatures are then given for each year of the simulation followed **by the final values** of Albedo and net TOA radiative fluxes.

Assignment #1:

Without changing any input parameters, run the model for a 50 year simulation to make sure that the model is in radiative equilibrium for the initial input values; i.e. the surface temperature does not change and the TOA IR flux into space equals the total solar radiation absorbed by the model planet. Record the control run equilibrium surface temperature for later reference.

$$T_{\text{surf}} = \underline{\hspace{10em}}$$

Experiments will be performed to study how the model's surface temperature responds to changes (perturbations) in other parts of the climate system.

For example, a 10 % increase in surface albedo can be made by changing Surface albedo control value from 1.0 to 1.1, and a 10 % decrease in surface albedo can be made by changing Surface albedo control value from 1.0 to 0.90.

Prediction #1: Will the surface temperature increase or decrease as the surface reflectivity (albedo) increases? (you are not penalized in anyway for incorrect predictions so give it your best shot)

Test your Prediction: Perform the experiments in the table below to test your prediction. Reset Surface albedo back to 1.0 after performing the experiment, [Click Reset makes this easy]. The equilibrium surface temperature change is the Final surface temperature after the 50 year simulation minus the control run equilibrium surface temperature and is given in the output box labeled **DT** in units of Kelvin (or degrees Celsius since a change of 1.0 K = 1.0 degree C).

Parameter	Change from to	Equilibrium surface Temp. Change (DT (K))
Surface Albedo	1.0 to 1.1	
Surface Albedo	1.0 to 0.90	

Does T_{surface} increase or decrease as the surface reflectivity is increased? **increase or decrease**
 Was this in agreement with your prediction? **Yes or No**

Does T_{surface} increase or decrease as the surface reflectivity is decreased?
increase or decrease

When the surface reflectivity is *increased* does the initial TOA IR (*increase, decrease or stay the same*)? [see top of output table for TOA IR](#)

When the surface reflectivity is *increased* does the net solar absorbed (*increase, decrease or stay the same*)? [see top of output table](#)

Question: Which statement below is most accurate (circle the best choice):

- A) As the surface albedo increases less infrared radiation is trapped by the model planet so the surface temperature drops.
- B) As the surface albedo increases more infrared radiation is released by the model planet so the surface temperature drops.
- C) As the surface albedo increases less solar radiation is absorbed by the model planet so the surface temperature drops.
- D) As the surface albedo increases more solar radiation is absorbed by the model planet so the surface temperature drops.

Click [**Reset**] to return base run.

Prediction #2: Will the surface temperature increase or decrease as the amount of solar radiation absorbed by *the atmosphere* increases? (remember you are not penalized for your predictions)

Run the model to Test your Prediction: Perform the experiment shown in the table below to test your prediction.

Parameter	Change from to	DT (K)
Solar atmos Absorp	1.0 to 1.2 (increase)	
Solar atmos Absorp	1.0 to 0.8 (decrease)	

Does the surface temperature increase or decrease as the amount of solar radiation *absorbed by the atmosphere increases*? **increase or decrease**

Was this in agreement with your prediction? **Yes or No**

Write a short paragraph below to explain why the surface temperature responds to changes in atmospheric solar absorptivity as it does.

Question: When the atmosphere absorbs more solar radiation

- a) more solar energy reaches the surface and the surface temperature goes up.
- b) more solar energy reaches the surface and the surface temperature goes down.
- c) less solar energy reaches the surface and the surface temperature goes up.
- d) less solar energy reaches the surface and the surface temperature goes down.

Question: Looking at the response over the 50 year simulation to answer the following question. When the atmosphere absorbs more solar radiation, the surface temperature _____. This results in _____ surface infrared radiation heating the atmosphere and a _____ in atmospheric temperature.

- a) decreases, less, decrease
- b) decreases, more, decrease
- c) decreases, less, increase
- d) increases, less, decrease

[Reset] to base run

Prediction #3: Will the surface temperature increase or decrease as the amount of atmospheric water vapor increases?

Test your Prediction: Perform the experiment below to test your prediction. Does the surface temperature increase or decrease as the amount of atmospheric water vapor increases? **increase or decrease**

Was this in agreement with your prediction? **Yes or No**

Parameter	Change from to	Equilibrium surface Temp. Change (ΔT_{eq})
H2O	1.0 to 1.2	
H2O	1.0 to 0.8	

Question: Which statement below is most accurate (circle the best choice):

- A) As atmospheric water vapor increases, less infrared radiation is trapped by the model planet so the surface temperature decreases.
- B) As atmospheric water vapor increases, more infrared radiation is trapped by the model planet so the surface temperature decreases.
- C) As atmospheric water vapor increases, more infrared radiation is trapped by the model planet so the surface temperature increases.
- D) As atmospheric water vapor increases, less infrared radiation is trapped by the model planet so the surface temperature increases.

** hint: when more infrared radiation is trapped by the atmosphere less (initially) gets out into space.

Assignment #2 Radiative forcing

[Reset] to base run

Prediction #4: Will the surface temperature increase or decrease as the concentration of CO2 increases?

Test your Prediction: Perform the experiment below to test your prediction.
 Does the surface temperature increase or decrease as the concentration of CO₂ increases?
increase or decrease

Was this in agreement with your prediction? **Yes or No**

Parameter	Change from	to	DT (K)
CO ₂	320	to 640	
CO ₂	320	to 160	

Question: Which statement below is most accurate (circle the best choice):

- A) As CO₂ increases, more infrared radiation is trapped by the model planet so the surface temperature decreases.
- B) As CO₂ increases, less infrared radiation is trapped by the model planet so the surface temperature increases
- C) As CO₂ increases, less infrared radiation is trapped by the model planet so the surface temperature decreases.
- D) As CO₂ increases, more infrared radiation is trapped by the model planet so the surface temperature increases.

** hint: when more infrared radiation is trapped by the atmosphere less (initially) gets out into space.

[Reset] to base run

Prediction #5: Will the surface temperature increase or decrease as the top of atmosphere solar intensity (Solar constant) increases?

Test your Prediction: Perform the experiment below to test your prediction.
 Does the surface temperature increase or decrease as the solar constant increases? **increase or decrease**

Was this in agreement with your prediction? **Yes or No**

Parameter	Change from	to	DT (K)
Solar Constant	1.0	to 1.01	
Solar Constant	1.0	to 0.90	

Extra Credit Radiative Forcing(definition)

The change in radiative forcing can be useful for understanding the response of the climate system to changes in solar radiation, greenhouse gases, clouds etc. It is defined to be the increase in net radiation absorbed by the climate system. This can be from an increase in net absorbed incoming solar radiation or an increase in absorbed outgoing longwave radiation.

For example the initial values of **TOA IR** and **Net_Solar absorbed** are 235 W/m². If by changing some parameter(s) **TOA IR drops to 233W/m²** and **Net_Solar absorbed increases to 236 W/m²**, then the net radiative forcing is +3.0 W/m²; +1 W/m² for increase in the net solar absorbed and +2 W/m² for decrease in radiation leaving the climate system, both changes result in warming. The output table can be used to calculate radiative forcing.

$$\text{Radiative forcing (W/m}^2\text{)} = (235 - \text{initial IR}) + (\text{Initial net solar absorbed} - 235)$$

This, of course, is only good for our model with a base radiative of 235 W/m² for IR out and net absorbed solar. Calculate the radiative forcing for each change described below.

Parameter	Change	Radiative Forcing (W/m ²)
CO2	Double from 320 to 640 ppm	+2.2
Solar Constant	Increase from 1.0 to 1.01 (with CO2 back to 320)	+1.3

Select the best answer for each question below.

Question: Something in the climate system changes resulting in less infrared radiation leaving the climate system from the top of the atmosphere out into space. For this case the radiative forcing is _____ and the surface temperature will _____.

- a) positive, decrease
- b) positive, increase**
- c) negative, decrease
- d) negative, increase

Question: Something in the climate system changes resulting in less net solar radiation being absorbed by the climate system. For this case the radiative forcing is _____ and the surface temperature will _____.

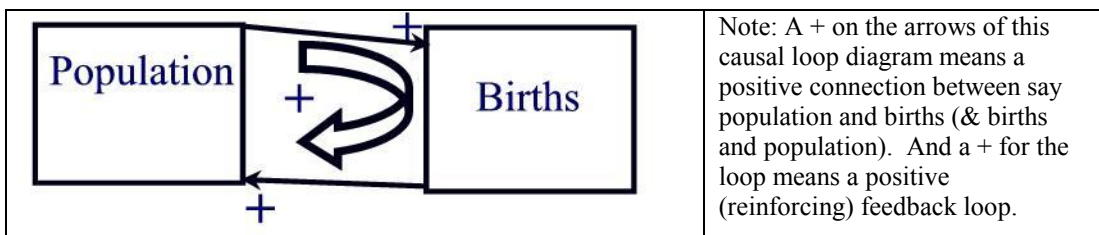
- e) positive, decrease
- f) positive, increase
- g) negative, decrease**
- h) negative, increase

[Reset] to base run.

Assignment #3. Feedback processes in the climate system

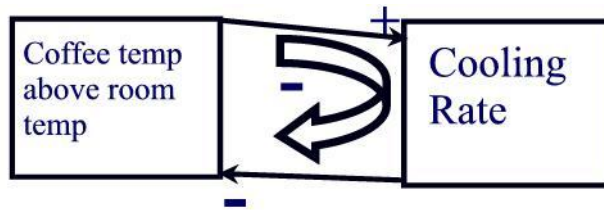
Climate feedbacks can enhance (positive feedback) or buffer (negative feedback) climate change. Positive feedbacks tend to destabilize a system and negative feedbacks stabilize a system about some equilibrium state. Before we get started with using the model to explore climate feedback we'll look at a few examples and gain some familiarity with causal loop diagrams.

A net birth rate (births exceeding deaths) that is directly proportional to the population is a good example of a positive feedback related to population dynamics. That is, if the number of new people added to the earth each year is 1% of the present number, then the population grows exponentially and is considered to be unstable. Of course something gives in any real system and exponential growth can only go on for so long.

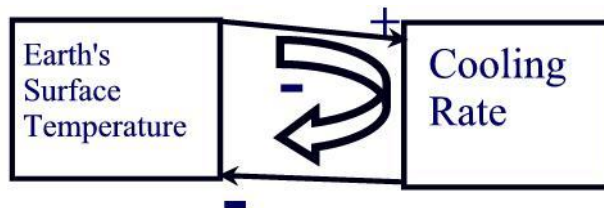


More on casual loop diagrams can be found from the “System Thinker” at <http://www.thesystemsthinker.com/tstcld.html> and <http://www.thesystemsthinker.com/tstgdlines.html>

A simple negative feedback linking temperature to itself is a cup of coffee sitting in a room. The rate at which the coffee cools depends on how hot the coffee is compare to the room. The hotter the coffee, the faster it cools and the closer it is to room temperature, the slower it cools. For the coffee cup the hotter it is the larger the cooling rate (a positive connection) and a large cooling rate results in cooler temperature a negative connection. Multiplying all of the connecting arrow +’s and -’s gives the net effect of the loop. In this case $(+) \times (-) = -$, a negative feedback loop. Think about it. Whether the cup of coffee starts out really hot or really cool it, left alone for long enough it with eventual reach room temperature (a very stable situation).

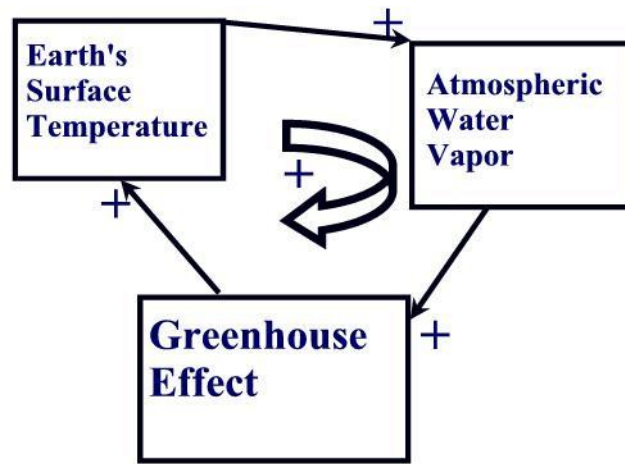


The Earth’s surface acts much like the coffee cup in this regard. As something causes it to get warm (like an increase in absorbed solar energy) it would give off more IR radiation and tend to cool faster. This feedback between surface temperature and cooling rate adds stability to Earths climate system.

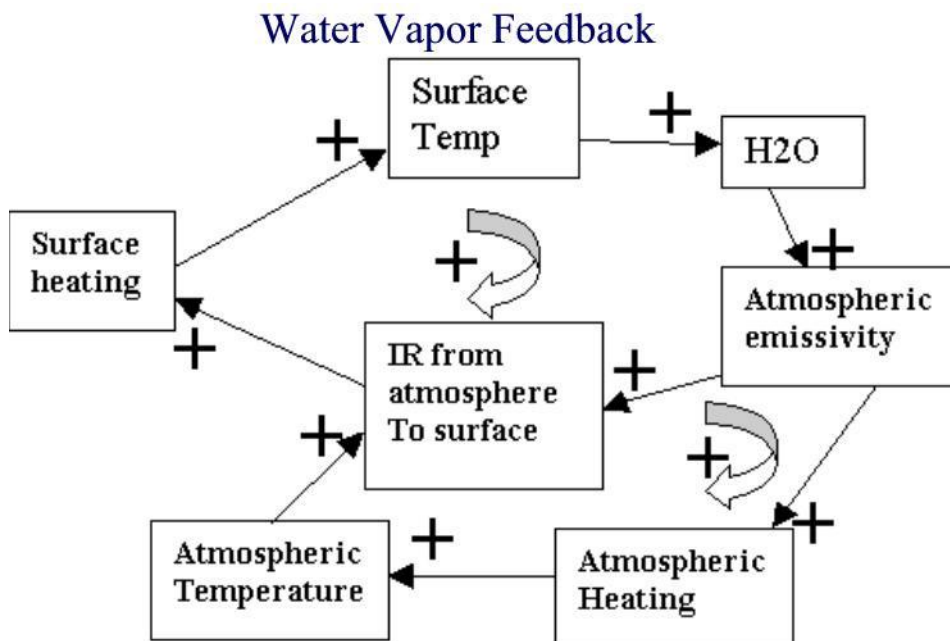


Water Vapor Feedback.

One well studied feedback which can be simulated by our simplified model is the water vapor feedback. The idea for this is that as Earth’s surface warms due to increases in the greenhouse gases or solar radiation, more water vapor evaporates into the atmosphere. Since water vapor is a strong greenhouse gas, this increase in water vapor enhances, or amplifies, the initial changes in surface temperature. The causal loop diagram below outlines the water vapor feedback. Remember, a + on the arrow means a positive connection between say surface temperature and H2O. And a + for the loop means a positive (reinforcing) feedback loop.



The causal loop diagram below outlines the physical processes responsible for the water vapor feedback in a bit more detail. The top loop illustrates that rising temperatures result in increased atmospheric water vapor. This increases the atmospheric emissivity, resulting in a greater downward flux of IR radiation, which enhances the surface heating rate. The bottom loop illustrates that increased atmospheric water vapor, increases the atmospheric absorbtivity, resulting in a greater mean atmospheric temperature and greater downward flux of IR radiation, which also enhances the surface heating rate.



Question: Based on the above reasoning, if the Earth cooled would there be *more or less* water vapor in the atmosphere?

[Reset] to base run

Prediction #6: Would this tend to *enhance or counteract* the cooling compared to the no feedback case?

To turn on a feedback click on the checkbox for water vapor feedback. This turns control from the fixed numerical value an equation that relates, for example, atmospheric water vapor to

surface temperature. For these simulation it is best to start with the base value of water vapor (H2O=1.0).

Test your prediction: run a half CO2 run with and without water vapor feedback.

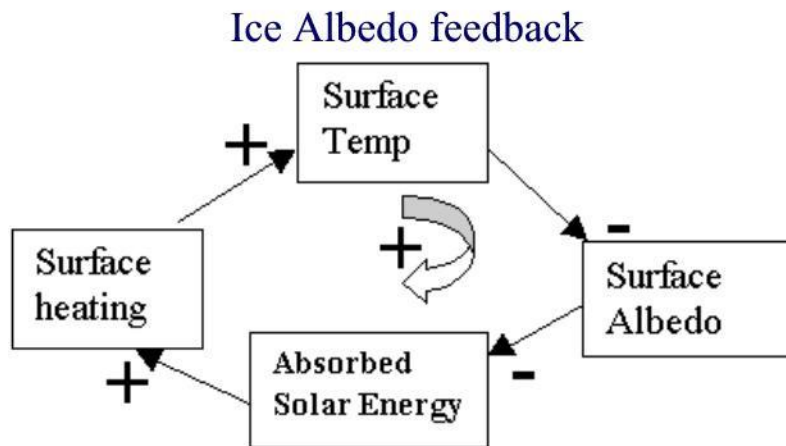
Change CO2 by	Feedback	DT (K)	Amplification
Halve to 160	No feedback		1.0
Halve to 160	H2O (water vapor)		Feedback/(no feedback) =

By how much is **DT** amplified compared to the no feedback case?

Record the difference in the table above. Put a '+' or '-' next to the row in which the feedback was added to indicate whether it is a positive or negative feedback. *(A positive feedback has an amplification greater than 1.0 and a negative feedback has an amplification less than 1.0)*

Ice-Albedo Feedback.

Another possible feedback is the ice albedo feedback. As Earth warms, ice melts, causing Earth's albedo to change. Since ice has a relative high albedo as ice melts Earth's albedo (*increases or decreases*)? The causal loop diagram for the ice-albedo feedback is shown below. Explain why there is a negative causal connection between surface temperature and surface albedo. Write a short paragraph describing this causal loop diagram. (Note: A plus on the end of an arrow connect to parameters indicates that if the first goes up so does the second and if the first goes down so does the second. When tracing a casual loop two minuses make a plus so in the below diagram the total loop is a positive feedback loop (- - + + = +).



Prediction #7: Would you expect the ice albedo feedback to enhance or buffer the temperature change brought about by halving CO2 compared to that with only the water vapor feedback ?

Turn on the ice albedo feedback by checking its checkbox. Now both water vapor and ice albedo feedbacks are on.

Test your prediction.

Change CO2 by	Feedback	DT (K)	Amplification
Halve to 160	None		1.0
Halve to 160	H2O (water vapor)		H2O/none =
Halve to 160	Ice Albedo		(H2O + Ice Alb)/H2O =

*the first two rows are the same as in the last table.

Does the ice albedo feedback to enhance or buffer the temperature change?

By how much is ΔT_{eq} amplified when the ice albedo feedback was added compared to water vapor feedback only case?

Record the ratio in the table above. Put a '+' or '-' next to the row in which the feedback was added to indicate whether it is a positive or negative feedback.

Surface Flux Feedback.

The last feedback we can add assumes that the flux of latent and sensible heat from the surface is directly proportional to the temperature difference between the surface and atmosphere. i.e.

$$\text{Flux} = \text{Constant} * (T_{\text{surf}} - T_{\text{atm}})$$

Prediction: Would you expect the surface flux feedback to be a positive (enhancing) or negative (limiting) feedback?

Turn on the surface flux feedback. Now all three feedbacks are on.

Test your prediction:

Change CO2 by	Feedback	DT (K)	Amplification
Halve to 160	No feedbacks		1.0
Halve to 160	H2O (water vapor)		H2O/none =
Halve to 160	H2O & R:surf (ice - albedo)		(H2O + Ice Alb)/H2O =
Halve to 160	H2O & R:surf & L&SH:flux (Surface flux)		(H2O+IceAlb+LHSH)/(H2O + Ice Alb) =

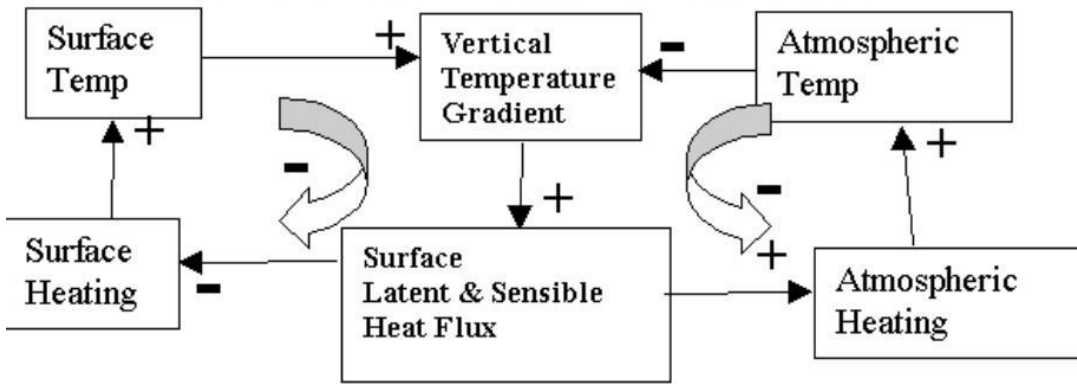
*the first three rows are the same as in the last table.

Is the surface flux feedback a positive or negative feedback?

By how much is ΔT_{eq} altered by the surface flux feedback (put this amplification in the table above)?

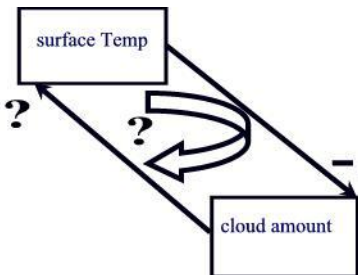
Did this flux increase or decrease after CO2 was halved?

Surface Flux feedback causal loop diagram.



In your own words describe each loop in the above diagram.

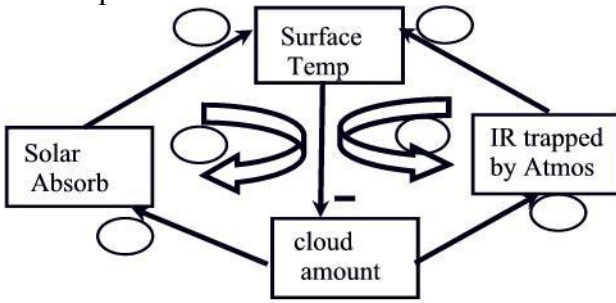
Prediction: If the amount of cloud cover were to decrease as Earth warms, would this constitute a positive or negative feedback? Explain your reasoning with a causal loop diagram. Use your intuition to figure out the causal loop diagram below (this is essentially your prediction). Replace each ? with a + or - to indicate a positive/negative connection or loop.



Test your prediction: If the amount of cloud cover were to decrease as Earth warms, would this constitute a positive or negative feedback? Explain your reasoning with causal loop diagrams. This time use the model to justify your reasoning as to whether increased cloud cover causes surface warming or cooling. You will need two answers(diagrams), one for low cloud and one for high.

<p>Low Cloud feedback. Replace each ? with a + or -to indicate a positive /negative connection or loop for low clouds.</p>	
<p>High Cloud feedback. Replace each ? with a + or -to indicate a positive /negative connection or loop for High clouds.</p>	

As the amount of either high or low clouds increase the amount of solar energy absorbed by the climate system decreases and the amount of IR trapped by the climate system increases. With this in mind add + or - to each oval in the diagram below to indicate positive/negative connections and loops.



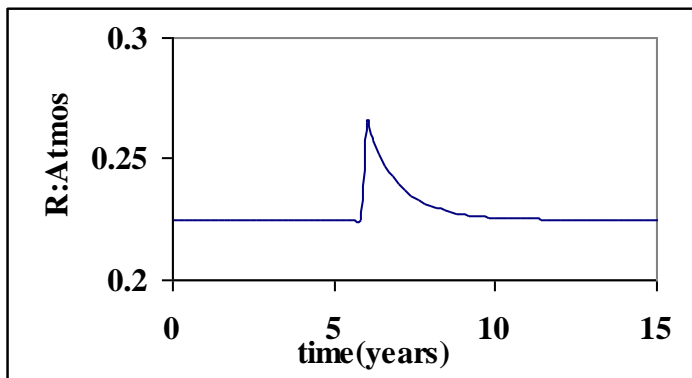
For high clouds the [*left or right*] loop in the diagram above dominates.

For low clouds the [*left or right*] loop dominates.

Click [Reset] to get back to the base climate simulation.

Assignment #4. Volcanoes and response time.

The reflectivity of the atmosphere is altered by volcanic aerosol loading after an eruption. Click the volcano checkbox to simulate a volcanic eruption at 10.0 years into the simulation. The eruption strength can also be altered. The figure below shows an example of how the atmospheric Reflectivity varies over time for a volcanic eruption at 6.0 years. Volcanic induced aerosols stay airborne for 1 to 3 years.



Using CO₂=320 and putting all feedbacks on, run simulations of the volcanic eruption at 10 years. In the table below record the minimum surface temperature reached after the eruption, the maximum temperature drop, and the time in years after the eruption required for the surface temperature to get back to within 0.2 K of its starting value. Use oceanic mixed layer depths (MLD) of 50 meters, 100 m (the default), and 200 m. The MLD can be changed using its input box.

For example, part of the output box for a MLD=30.0 simulation looks like .

```

8 288.07 267.49
9 288.07 267.49
10 288.07 267.49 ***Eruption****
11 282.1 263.98 The minimum surface temperature is 282.1
12 282.99 264.39 (a maximum drop of 288.08-282.1= 5.97 K)
13 284.43 265.24
14 285.63 265.98
15 286.5 266.51
16 287.08 266.87
17 287.45 267.1
18 287.69 267.25
19 287.83 267.34 The time it take to get back to 287.88 K (within 0.2 K of 288.08 K)
20 287.93 267.39 is 19.5-10=9.5 years
21 287.98 267.43
22 288.02 267.45
23 288.04 267.47
24 288.05 267.47
25 288.06 267.48
26 288.07 267.48

```

The output table will be helpful here. You may have to scroll up and down the table to see the numbers that you want to see. When running a simulation make sure that the output table is not in view as it makes the simulation run much more slowly.

MLD (meters)	Min Temp (K)	Max Temp drop (K)	Time to 0.2 K (years)
50			
100			
200			

Does the maximum temperature drop increase or decrease as the assumed oceanic mixed layer depth increases? Explain.

Does the recovery time (time to get back to within 0.2 K of equilibrium value) increase or decrease as the assumed oceanic mixed layer depth increases? Explain.

Which has a larger **thermal inertia**, a 50 meter deep oceanic mixed layer or a 200 m deep oceanic mixed layer. Large thermal inertia corresponds to sluggish temperature response.

Write a short paragraph describing what you liked and disliked about this modeling activity. Include whether you think this assignment helped you better understand some of the concepts discussed in class.