12.340: Global Warming Science
Problem Set #5: Forcings and Feedbacks in Climate
Date assigned: Tuesday, 1 May 2012
Date due: Tuesday, 8 May 2012

Question 1: Aerosols, Climate, and Geoengineering

The amount of aerosol in the atmosphere is normally given by the quantity Aerosol Optical Depth (AOD), denoted τ_{aero}. As discussed in class, this quantity represents the reduction in irradiance of a beam of light as it passes through a column of air containing aerosols, which remove photons from the beam through either direct absorption or scattering. This effect is represented by the Beer's Law equation:

$$I = I_0 e^{-\tau_{aero}}$$

where I is the irradiance at the observer and I_0 is the irradiance at the source.

For current values of atmospheric aerosol concentration and distribution, a reasonable background value for τ_{aero} across the solar spectrum at the surface is 0.005.

a) How much more energy per unit area [W/m^2] would the surface receive if all atmospheric aerosol was removed?

b) Anthropogenic sulfate has increased τ_{aero} by 0.0004. How much is the irradiance at the surface further reduced by anthropogenic aerosols?

c) Compare your answer to the effect of anthropogenic greenhouse gas emissions, which have resulted in an increase in the net energy received at the surface by approximately 2 W/m^2. What AOD would be required to exactly offset this enhanced greenhouse effect?

This scenario—injecting aerosols into the stratosphere to reflect more sunlight to space—is one proposed option for "geoengineering", i.e. purposefully manipulating the climate system in order to counteract the warming due to rising greenhouse gas concentrations.

d) Thought experiment: Let's assume that this approach can indeed perfectly offset the global-mean surface warming due to greenhouse gases. Based solely on the physics of the climate system (i.e. ignoring political/economic considerations), why might this still not "solve" the global warming problem?

e) Reality: In your opinion, do you think this is a reasonable solution? Discuss at least two reasons why this approach would or would not work well.

Question 2: Water Vapor and Climate

Consider a uniform global temperature increase of 1°C everywhere in the atmosphere. Explain your answers to the questions below.

a) The Clausius-Clayperon relation dictates the partial pressure of water vapor for a saturated air parcel at thermodynamic equilibrium with a surface of liquid water (e.g. the ocean). This relation is given by

$$\frac{de^*}{dT} = \frac{L_v e^*}{R_v T^2}$$

Where e^* is the saturation vapor pressure, T is the temperature in Kelvin, L_v is the latent heat of vaporization ($2.5*10^6$ J/kg), and R_v is the water vapor gas constant (461 J/(kg K)). For typical atmospheric conditions, this can be written as

$$e^*(T) = 6.112 \exp\left\{\frac{17.67(T - 273.15)}{T - 29.65}\right\}$$

Use the Clausius-Clapeyron relation to calculate the *percent* change in water vapor content of a saturated parcel of air at a pressure of 1000 hPa for a 1°C warming from an initial temperature of i) 26 °C; ii) 30 °C.

b) The water vapor content of the real, present day atmosphere appears to roughly follow this Clausius-Clapeyron scaling. How would you expect the climate to respond to this increase in water vapor (i.e. beyond the original 1°C warming)?

c) In what ways might the above changes in temperature and water vapor affect cloud formation? What effects might these changes in clouds have on the global climate?

d) Is the increase in water vapor a forcing or feedback? Is the cloud perturbation a forcing or feedback? Explain why.

e) Broadly speaking, climate models predict that relatively dry regions on Earth will get drier and relatively wet regions will get wetter. Based on your answers given above, discuss two potential reasons why this might occur.

Question 3: Milankovitch Cycles and Ice Ages

a) Describe the three Milankovitch cycles.

b) Describe conceptually at which point in the three cycles the ice accumulation feedback in the northern hemisphere dominates.

Though changes in orbital parameters have minimal effects on global mean solar insolation, they have strong effects on its seasonal and latitudinal distribution.

At 60N in Summer, the annual-mean insolation at the top of the atmosphere is $I^* = 385$ W/m^2. The variability due to changes in Earth's precession and obliquity may be represented (with some simplifying assumptions and given an average value for orbital eccentricity) as:

Precession:	$I_P = P_0 \sin(\omega_P t)$	period = 23,000 years	$P_0 = 4$ W/m^2
Obliquity:	$I_T = T_0 \sin(\omega_T t)$	period = 41,000 years	$T_0 = 5$ W/m^2

Recall: for a sine function, the period is $= 2\pi/\omega$.

c) Precession alone
   i. Plot the variability of the solar insolation (I_{solar}) over 500,000 years when only the variation due to precession is included, i.e.

$$I_{solar} = I^* + I_P$$

   ii. Identify the maximum (I_{max}) and minimum (I_{min}) values of this curve.

   iii. Use the 1-layer energy balance model we derived in class to estimate the surface temperatures, T_{max} and T_{min}, associated with I_{max} and I_{min}, respectively, and compare this to the equilibrium temperature, T^*, associated with I^*. For the 1-layer model, use the following parameters: albedo = .3, atmospheric emissivity = .45, surface emissivity = 1 (i.e. blackbody).

   iv. What are the maximum increase and decrease in Summer-mean temperature at 60N due to variation in precession alone?

d) Repeat (c) for the variability due to obliquity alone.

Additionally, changes in the Earth's eccentricity (e) modulate the strength of the effect of orbital precession (I_p). One may represent this simply as

$$I_{Pe} = e * I_P$$

where the effect of changing eccentricity is represented by

$$e = e_0 \sin(\omega_e t) \qquad \text{period} = 100{,}000 \text{ years} \qquad e_0 = 12 \text{ (no units)}$$

e) Repeat (c) for the variability due to all 3 parameters (I_T, I_P, and e). Assume that I_T and I_{Pe} are additive.

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