ATOC 7500: The Art of Climate and Environmental Modeling
Week 2 Lab Assignment
Greenhouse model with water vapor feedback

Construct a climate model that can be used to estimate the climate sensitivity" (defined as the surface temperature change for doubled CO_2 relative to the preindustrial concentration of CO_2 = 280 ppmv). The model will need to include both an atmosphere (for greenhouse trapping), and a surface (to calculate the surface temperature).

With the energy budget of Kiehl and Trenberth (1996) in mind, the surface energy balance at the surface ocean (upper 70m) may be written:

$$C_{ocn}\frac{dT_s}{dt} = S_{down} + L_{down} - L_{up} - H \quad (1)$$

where S_{down} is the downwelling solar radiation, L_{down} is downwelling longwave radiation from the atmosphere, L_{up} is longwave radiation emitted by the surface, and H is the exchange of sensible and latent heat from the ocean to the atmosphere. C_{ocn} is the heat capacity of the ocean. A simple energy budget of a one layer atmosphere may be written:

$$C_{atm}\frac{dT}{dt} = f(1-\alpha)\frac{S}{4} - 2\varepsilon_{atm}\sigma T^4 + \varepsilon_{atm}L_{up} + H \quad (2)$$

The first term on the right is the heating due to the absorption of solar radiation (largely by ozone and clouds), with the remaining shortwave radiation passing to the surface. The second term is the thermal emission both upward to space, as well as "back radiation" downward to the surface. The atmosphere also gains heat through absorption of upwelling longwave radiation, and heating by sensible and latent energy exchange. A simple method for estimating H is to write a linear exchange: $H = \kappa(T_s - T)$, where κ is an exchange coefficient and has units s^{-1}.

The strength of atmospheric absorption of longwave radiation, *i.e.*, the greenhouse effect, is included via the atmospheric emissivity that depends on both the dry composition of the atmosphere, the amount of water vapor and the amount of CO_2. As such we may write:

$$\varepsilon_{atm} = \varepsilon_{dry} + \varepsilon_w + \varepsilon_c.$$

While the emissivity of the dry atmosphere is almost constant, we introduce a *parameterization* of emissivity due to CO_2 as:

$$\varepsilon_c = \varepsilon_c^* + a\ln\left(\frac{CO_2}{CO_2^*}\right) \quad (3)$$

Changes in emissivity are considered relative to some reference CO_2 concentration. Similarly, and justified by the Clausius-Clapeyron relationship, we may write the emissivity associated with water vapor as proportional to the surface temperature

$$\varepsilon_w = \varepsilon_w^* + b\left(T_s - T^*\right) \quad (4)$$

Notice that while (4) follow from a first order (linear) Taylor expansion since we suspect changes in the water vapor will be small. In contrast (3) is nonlinear because we are making large changes in CO_2.

To close this system, we must choose values for the all free parameters. Some are well known from observations, others can be derived, and the remained must be guessed or otherwise inferred. A starting place for the emissivity could be the following:

ε_{atm} ~ 0.7-0.8
ε_{dry} = 0.12
ε_c^* = 0.054
ε_w^* = 0.64
CO_2^* = 280 ppmv
T^* = 282 K
a = 0.0235
b = 0.0101 K^{-1}

Tips/suggestions for implementation

- Start with the one parameter EBM from last week, and change the time stepping to be a centered difference “leapfrog” scheme
- Modify the code to compute the radiative equilibrium of the two reservoirs (ocean and atmosphere) at the same time.
- Modify the solar flux (partition absorption between atmosphere and ocean), and add extra longwave radiation terms, and the sensible and latent heat flux.
- Add equation for changes in emissivity due to CO_2.
- Add equation for changes in emissivity due to water vapor.
- *Optionally*, add a second “box” to represent the polar regions and add a horizontal energy flux.

Question for discussion and experiments:

1) How can we validate the model?
2) On what criterion due you choose the drag coefficient κ?
3) What fraction of the temperature change is due to the water vapor feedback?
4) Is the climate sensitivity the same for different epochs? (Today CO2=365 ppmv, preindustrial = 280 ppmv, Last Glacial Maximum CO2 = 200 ppmv)
5) Is the water vapor feedback as important for all epochs?
6) Is the water vapor feedback linear?
7) Are you confident in your findings? Why?
8) How does the model change if there is also an albedo feedback? (Is the water vapor feedback more or less important for “snowball Earth”?)
9) Consider adding a second box so that there is both a “tropics” and a “polar region”, with some meridional energy transport. How does this change the climate sensitivity? Which aspects are most crucial?