Climate sensitivity and feedbacks

Consider a climatic variable (e.g. the global mean surface temperature T_s). Its sensitivity to a forcing F can be written as,

$$\lambda = \frac{dT_s}{dF} = \frac{\partial T_s}{\partial F} + \sum_i \frac{\partial T_s}{\partial y_i}\frac{dy_i}{dF} \tag{1.1}$$

Common forcing considered is radiative, from changes in solar luminosity, CO2 increase, or albedo change. The variables y_i may be, e.g. water vapor. They respond to Ts and further affect Ts. These are called feedbacks in the system. The sensitivity without feedbacks is the partial derivative: $\lambda_0 = \frac{\partial T_s}{\partial F}$. If we use the Stefan-Boltzmann law, this gives us a sensitivity of 0.26K per W/m^2. Doubling CO2, from radiative transfer calculations, perturbs the radiation budget by 4W/m2, and would result in a 1C increase in global mean surface temperature without other feedbacks. We can rewrite Eq. (1.1) as

$$\frac{dT_s}{dF} = \frac{\partial T_s}{\partial F} + \frac{dT_s}{dF}\sum_i f_i \tag{1.2}$$

where

$$f_i = \frac{\partial T_s}{\partial y_i}\frac{dy_i}{dT_s}$$

are the feedback factors.

The feedback factors are additive and we can define f=sum(f_i) and solve Eq.(1.2) so that

$$\frac{dT_s}{dF} = \frac{\partial T_s}{\partial F}\frac{1}{1-f}$$

So the climate sensitivity is amplified by the gain factor g=1/(1-f). When f≥1, the system is unstable.

The above discussion is only applicable to perturbations sufficiently small for the system to be regarded as linear. Also Ts (or whichever variable you choose) is a function of time. Given the finite (sometimes long) adjustment time of the climate system, the sensitivity is different for Ts at different times, and therefore should be represented as a sensitivity function that depends on time. Often, people use one number for climate sensitivity. That only makes sense when one specify the time for this response. In general, people are referring to the equilibrium response, (i.e. time goes to infinity), which may or may not be the relevant sensitivity. It is also important to remember the global mean surface temperature may not be the most relevant variable even though it's one that is often used. In general, keep in mind this feedback framework is useful but may often be too simplistic.

Water vapor feedback:

As temperature increases, the amount of water vapor in saturated air increases by ~7%/K. Models tend to consistently predict a constant relative humidity. To what extent this is true in nature is still debatable, although some confirmation can be seen from the constancy in relative humidity over a seasonal cycle. Assuming this is more or less true, this implies an increase in the amount of water vapor in the atmosphere, which is the principal greenhouse gas and will raise the surface temperature even further. One can quantify this with radiative-convective equilibrium calculations or GCM simulations. With water vapor feedback included, the climate sensitivity is doubled to ~0.5K/(Wm^{-2}). Due to the nonlinearity of the Clausius-Clapeyron equation, the strength of the water vapor feedback increases with temperature. When there is a lot of water vapor in the atmosphere, the longwave cooling may become independent of the surface temperature. This could lead to runaway greenhouse effect, where the whole ocean evaporates, eventually leading to lose of water to space. This is believed to have happened on Venus.

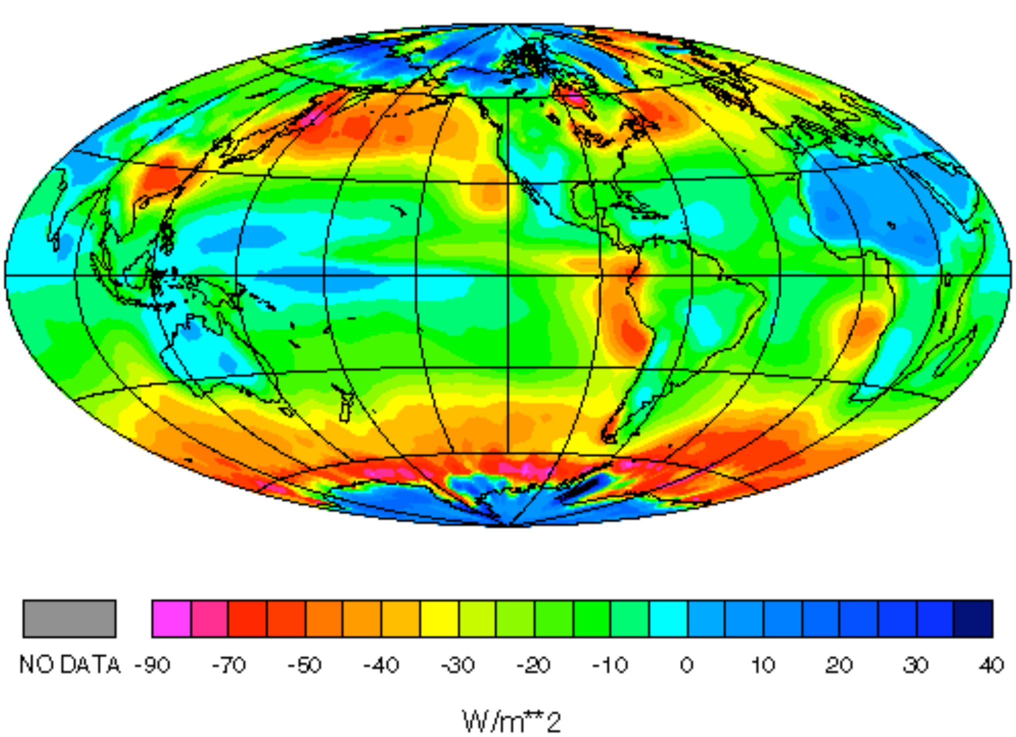
Lapse-rate feedback:

If convection maintains temperature close to a moist adiabat, this implies temperature change in the upper troposphere will be greater than that near the surface. This will allow more cooling in the upper troposphere, a negative feedback. On the other hand, if the relative humidity remains constant, this implies more water vapor in the upper troposphere, which is a positive feedback. They two cancel to some extent. This cancellation however depends on the constant relative humidity assumption.

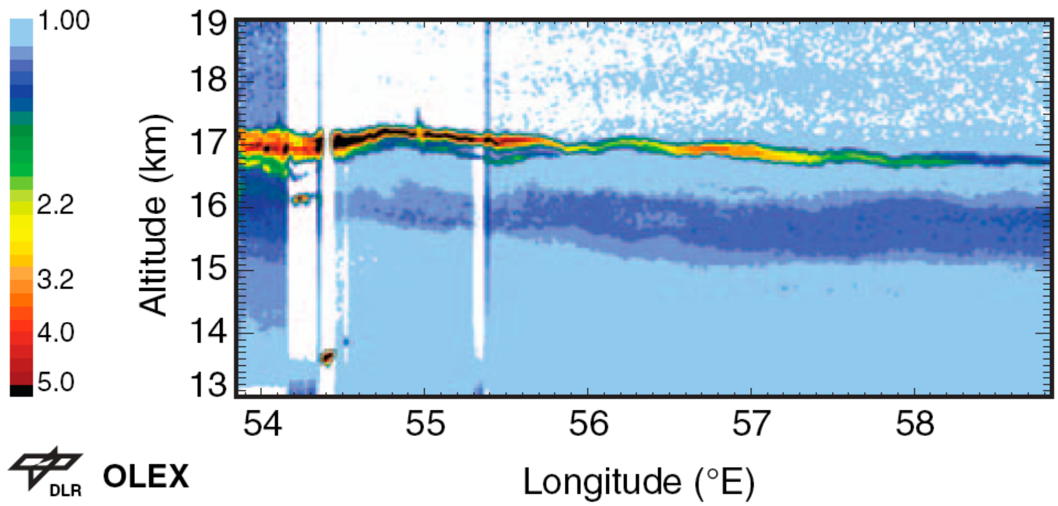
Cloud feedback

We know that clouds have important effects on the radiation budget. If they change, they could provide significant feedbacks.

Annual ERBE Net Radiative Cloud Forcing



One example is the stratus/stratocumulus, which has a strong negative radiative forcing. If its extent increases in a warming scenario, it will provide a negative feedback. Since these clouds are found over cold waters, one may be tempted to say that they will decrease in a warming world, thus a positive feedback. It's not quite so simple though. These clouds depend more on the potential difference between the surface and the boundary layer top. If the ocean surface temperature increases uniformly, the boundary layer top temperature will increase more because of the Clausius-Clapeyron relation. This would imply increased stratus/stratocumulus amount, and thus a negative feedback. The sign of the feedback from these clouds remains uncertain. Another example is the subvisible cirrus, which has a net warming effect. The recent NASA instrument CALIPSO makes global measurements of such clouds.



(Tropical thermostat: Some time ago, there was this hypothesis that since we now observe deep convection when SST is above ~27C. As the globe warms, we should see more deep convection and more anvil clouds and that would cool the ocean surface. Does this make sense? There are also other tropical thermostat ideas.)

Snow/ice albedo feedback

Snow and ice, being brighter and forming at cold temperatures, contribute a positive feedback. We played with it in our first homework. In reality, it's more complicated to quantify. The presence of clouds, e.g., may reduce the albedo contrast between regions covered by snow/ice and those that are not. Surface hydrology may also come into play. If the ground thaws earlier in the spring, the ground may get dried up by summer so that its surface temperature may increase more. Sea ice is also a good insulator that reduces the surface fluxes from the ocean. Continental ice sheets modify orography and can change the atmospheric circulation, which could influence remote regions and also feedback onto themselves.

Dynamical feedbacks

If one makes the meridional temperature gradient stronger, one expects the atmosphere to become more baroclinically unstable so that eddy heat flux will increase to reduce the meridional temperature gradient, a negative feedback. One may use some scaling arguments to derive how the eddy heat flux may scale with the meridional temperature gradient. Note however, this only applies to the free troposphere. The boundary layer may become decoupled from the free troposphere in polar regions so the equator to pole surface temperature gradient can change more strongly. And there is paleo evidence that it does.

Longwave and evaporation feedback

Near the temperature of 300K, as the surface warms, radiative transfer calculation shows that the net longwave cooling at the surface decreases by about $3Wm^{-2}K^{-1}$. This is a positive feedback. However, this is countered by a negative feedback from surface evaporations; higher SST will give greater surface evaporation, roughly by $7Wm^{-2}K^{-1}$ around 300K, if we assume the surface relative humidity, surface winds, and the drag coefficient remain unchanged. The combined effect of the two would be to make the SST more stable. Given the many assumptions that go into this, this is hardly a complete theory, which remains to be developed.

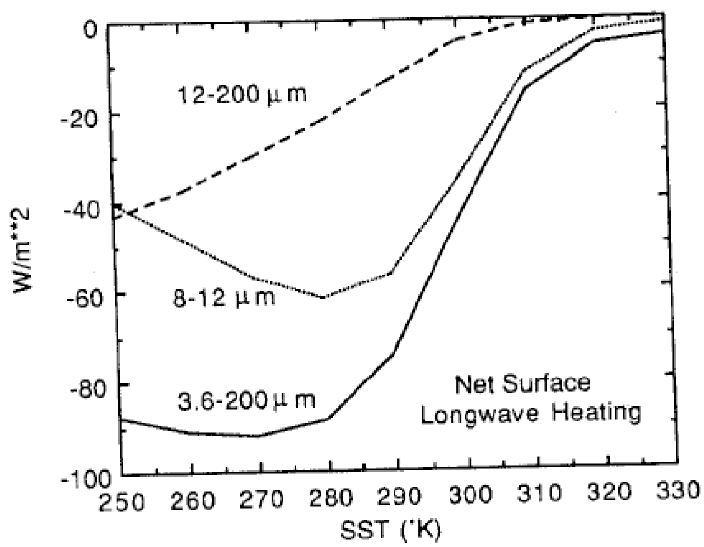


Fig. 9.8 Net longwave energy flux at the surface as a function of surface temperature, calculated using a fixed lapse rate and relative humidity distribution. Curves are shown for the total terrestrial flux and the flux within the wavelength intervals indicated. [From Hartmann and Michelsen (1993). Reprinted with permission from the American Meteorological Society.]

Climate models:

Climate models are often useful tools to put together the relevant processes. However, climate modeling is difficult. One is faced with a system of enormous complexity. A key thing to remember is that all models are wrong but some are useful.

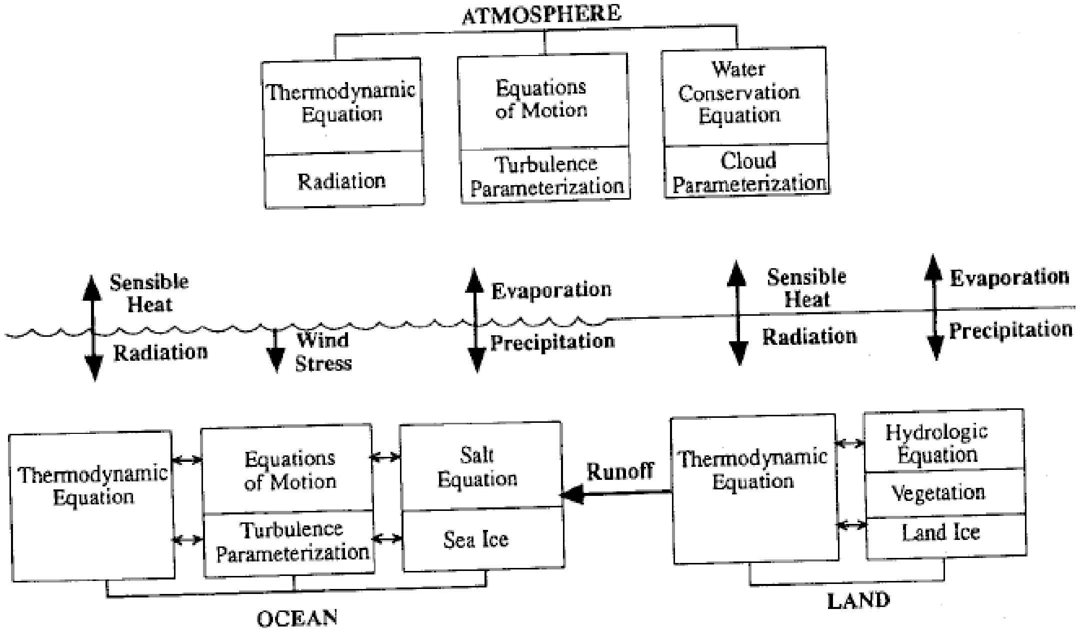


Fig. 10.1 Schematic diagram showing the components of a global climate model.

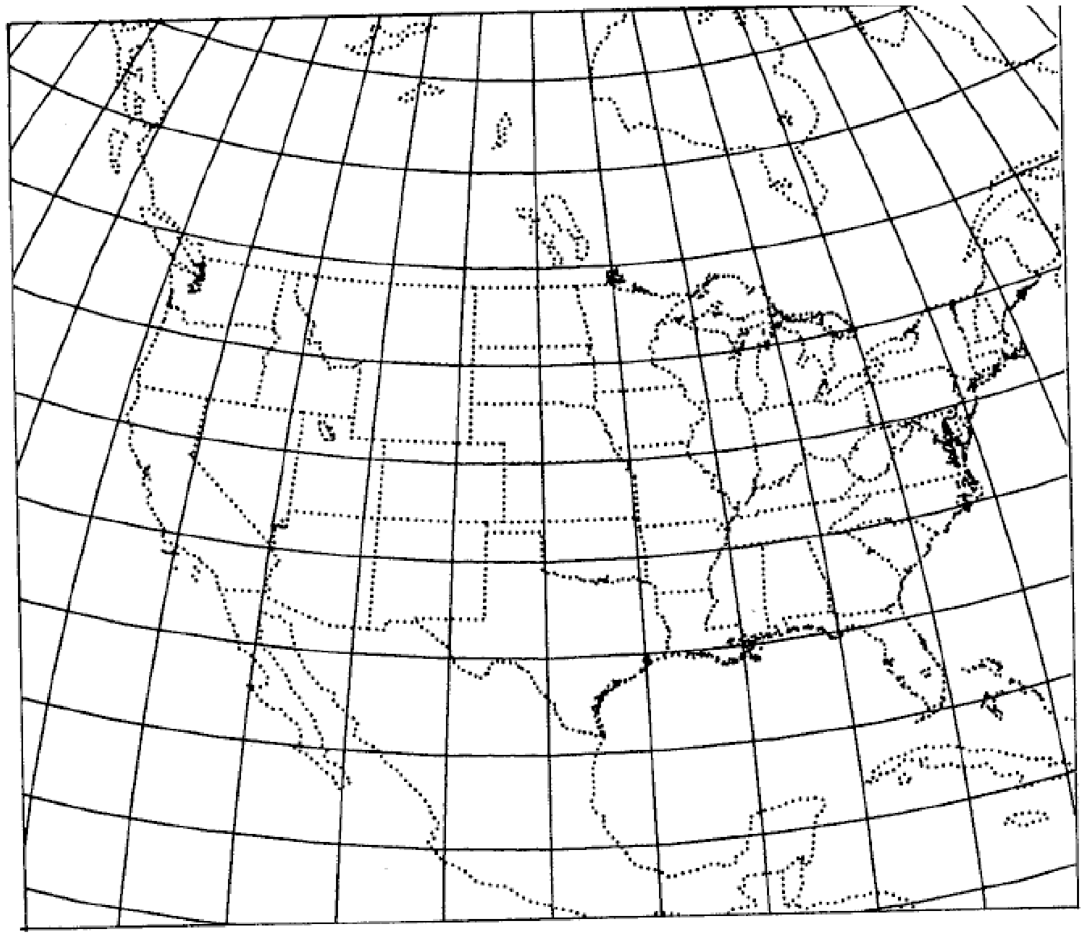


Fig. 10.2 Illustration of 5-degree latitude–longitude resolution typical of some current climate models intended for long-term integrations. Orthographic projection over North America.

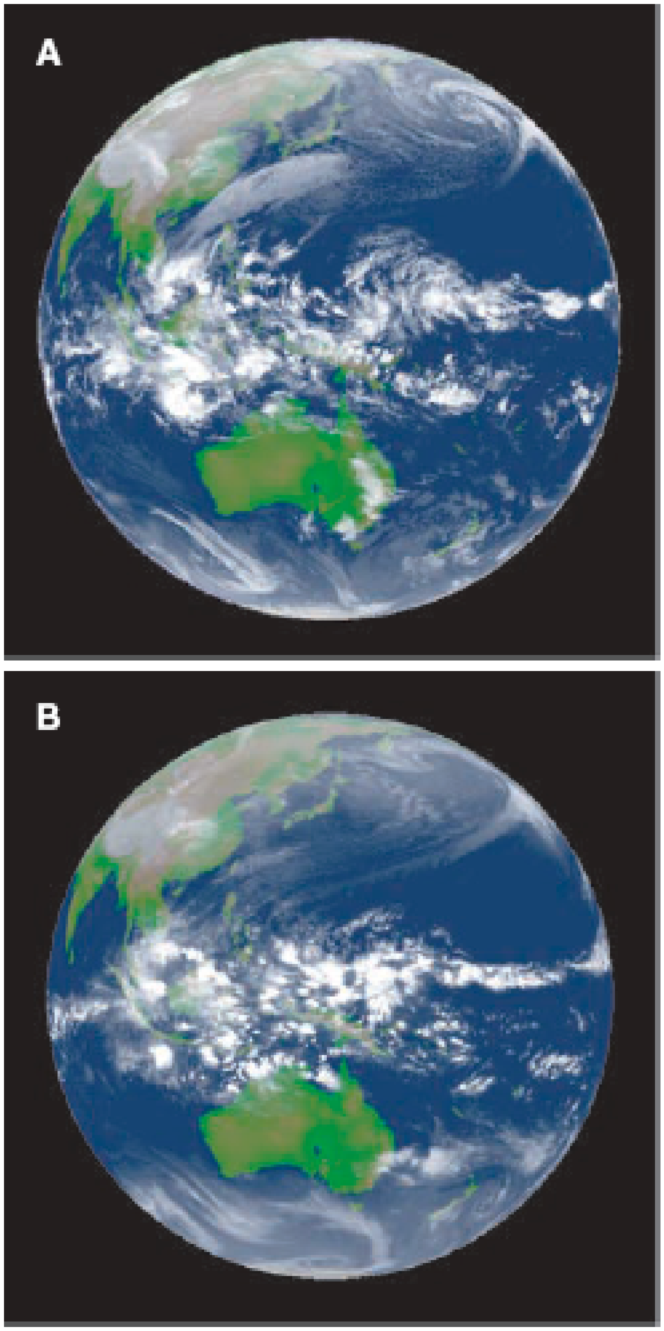


Fig. 1. (**A**) Infrared image from the Multi-Functional Transport Satellite (MTSAT-1R) at 00:30 UTC on 31 December 2006 and (**B**) outgoing long-wave radiation from the 3.5-km run averaged from 00:00 UTC to 01:30 UTC on 31 December 2006.