The Thermostat Hypothesis: A Case Study of a Climate Hypothesis[1]

Ramanathan and Collins(1991) published a paper in Nature in which they put forward the idea that the high albedos attained by deep convective clouds in the tropics placed an upper bound on the SST that could be achieved on Earth. They used radiation budget measurements of radiation budget quantities and cloud forcing from the Earth Radiation Budget Experiment (ERBE, Barkstrom, et al., 1986, Harrison, et al. 1990). As a strating point they formulated the energy balance at the top-of-the-atmosphere(TOA) in terms of the cloud radiative forcings estimated from ERBE. Let's introduce the following symbolism:

$G = E - F$	The total greenhouseeffect
$E = \sigma T_s^4$	The blackbody emission from the surface
F	The OLR for average conditions
F_c	The OLR for clear-sky conditions
$G_a = E - F_c$	The atmospheric or clear-sky greenhouse effect
$C_l = G - G_a = F - F_c$	The longwave cloud radiative forcing at TOA
C_s	The shortwave cloud radiative forcing at TOA
S_c	The shortwave absorbed for clear sky conditions
A	The albedo
S	The TOA insolation, or available solar irradiance
$S(1-A) = S_c + C_s$	The absorbed solar radiation, written two ways
$H = S(1-A) - F$	The net radiative heat input at TOA

OK, if you have all of this, then you can rewrite the net radiation at TOA as:

$$H = S_c + C_s - \sigma T_s^4 + G_a + C_l \tag{1}$$

The way you read this equation is that you put in the clear sky solar heating, S_c, but this is modified by the cloud shortwave forcing, C_s, which is negative, then you would lose the surface blackbody emission, σT_s^4, but you get back the clear-sky greenhouse effect, G_a, and the cloud greenhouse effect, C_l, which are both positive in the tropics. R&C'91 evaluate the sensitivity of these terms to SST, by using differences associated with the 1987 el Niño or spatial gradients across the Pacific Ocean. You get about the same result, either way. Then you can evaluate the contributions to the response of the net radiation at the top of the atmosphere to the SST.

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[1] Since about the mid-80's or so, climate change has become a topic in which the public and politicians are interested. It has received a significant amount of publicity and public funding. Increasingly, scientists have been tempted to try to put more flash into their work and publish in Science and Nature, the tabloid journals of science, in order to enhance their own careers or to generate interest in their discipline. For some reason, papers in Science and Nature are associated with more respect than papers in refereed scientific journals. At the same time, and somewhat perversely, Science and Nature like to publish 'exciting' science, even if it may not be correct. So if you have a controversial but exciting piece of work, your chances of getting it published in one of the science rags is greater than a standard refereed journal, and the reward is greater too. So if you want to be a successful scientist today, or you want your lab or field to be well-funded, get a publicist.

$$\frac{dH}{dT_s} = \frac{dS_c}{dT_s} + \frac{dC_s}{dT_s} - 4\sigma T_s^3 + \frac{dG_a}{dT_s} + \frac{dC_l}{dT_s} \tag{2}$$

What they found is that the clear-sky greenhouse increases at about the same rate that the surface emission increases, so the longwave emission is insensitive to the surface temperature. At the warmest temperatures the total greenhouse effect increases dramatically, because of high water vapor and high clouds, and longwave emission actually decreases with increasing temperature. If you think locally, this suggests a runaway greenhouse. What counterbalances this is a sharp increase in the magnitude of the cloud shortwave forcing as you go to the warmest temperatures. Specifically, as was known since at least Hartmann and Short(1980), there is a near cancellation between the shortwave and longwave effects of tropical convective cloud populations, both terms get big together.

So far, so good, but R&C'91 go on to make some rather bold extrapolations of this information. They assume that the shortwave cloud forcing will be felt at the surface, and that the longwave cloud forcing will be exported by atmospheric dynamics. Then the shortwave cloud forcing becomes an enormous negative feedback on surface temperature, assuming that the sensitivity calculated empirically in (2) can be applied in a climate change context. This is because they estimate: $\frac{dC_s}{dT_s} \approx -25 Wm^{-2}K^{-1}$, which is huge compared to the blackbody feedback: $-\frac{d\sigma T_s^4}{dT_s} \approx -6.1 Wm^{-2}K^{-1}$. So assuming some arbitrary forcing to the climate system, they calculated that the surface temperature would not change much. By some finagling they derive the following equations:

$$SST_{\max} = T_o + \left(S_c + G_o - \sigma T_o^4\right)/\beta \tag{3}$$

where

$$\beta = 4\sigma T_s^3 - \frac{dG_a}{dT_s} - f\frac{dC_l}{dT_s} - \frac{dC_s}{dT_s} \tag{4}$$

Here f is a parameter that measures how much of the greenhouse effect of the clouds is not exported by atmospheric dynamics and is not felt at the surface. They assign a value to f between 0.0 and 0.2. T_o is a reference temperature which they take without explanation to be 300K. $G_a = G_o + \frac{dG_a}{dT_s}$, and G_o = 165 Wm^{-2} is the value of G_a assumed at T_o = 300K. With these assumptions they get $303 < SST_{\max} < 305K$. If this seems like a strange line of argument to you, you are not alone. What is magic about 300K? Why do we assume that the SST is determined by the local TOA fluxes projected into a local surface energy balance? Let's quote from R&C'91. "The feedback between convection, greenhouse effect, and planetary brightness limits the temperatures in the warmest regions of the Earth to less than 305K. What is the implication of this negative feedback if its validity extends to a perturbed atmosphere? It would take more tha an order-of-magnitude increase in atmospheric CO_2 to increase the maximum SST by a few degrees, in spite of a significant warming outside the equatorial regions." Wow!

Needless to say, many people jumped up to object to this silly extrapolation. It makes many assumptions that are easily rejected. 1) It assumes that the spatial gradients of SST and radiation across the Pacific are a good measure of how global climate will respond. We know that a large-scale convergence of moist energy is necessary to sustain the precipitation rate in the warm regions of the tropics. The rain rate is typically twice the precipitation rate. The albedo of convective cloud in the tropics is more sensitive to large-scale convergence than to SST, proven both by observational studies (Hartmann and Michelsen, 1993) and cloud modeling studies (Lau, et al. 1994). 2) Another way of saying this is that the convection and SST are not determined locally, but are part of a system involving the whole tropics and probably the whole globe. (Wallace, 1992; Fu et al., 1992).

Since convergence and upward motion are required to produce high convective cloud albedos, then by conservation of mass, a subsidence region is required in association with strong deep convection to close the mass budget. Hartmann and Michelsen(1993) showed that the positive cloud albedo anomalies over convective regions in the 1987 ENSO event are compensated almost exactly by albedo decreases elsewhere within the tropics. In a heuristic model Hartmann and Michelsen(1993) showed that if you decrease the SST gradients in the tropics, you can warm the mean climate of the tropics, because you reduce the ventilation of the boundary layer by large scale circulations. By this mechanism, cooling over the warmest water caused by cloud albedo actually warms the climate. This mechanism does not include the effects on stratus clouds, however, and these affects could go the other direction, since stratus clouds also like vigorous large-scale circulations to generate the ocean upwelling and atmospheric subsidence that stratus clouds like.

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