Climate v. Climate Alarm

Richard S. Lindzen
Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

American Chemical Society
August 28, 2011

A pdf of these slides is available on request to
rlindzen@mit.edu

The public perception of the climate problem is somewhat schizophrenic. On the one hand, the problem is perceived to be so complex that it cannot be approached without massive computer programs. On the other hand, the physics is claimed to be so basic that the dire conclusions commonly presented are considered to be self-evident.

Consistent with this situation, climate has become a field where there is a distinct separation of theory and modeling. Commonly, in fluid mechanics, theory provides useful constraints and tests when applied to modeling results. This has been notably absent in current work on climate.

In this talk, I will try to show how the greenhouse effect actually works using relatively simple basic concepts. We will see that the greenhouse effect, itself, presents little cause for alarm from increasing levels of CO_2 since the effect is modest. Concern is associated with the matter of feedbacks that, in models, lead to amplified responses to CO_2. Considerations of basic physics (as opposed to simply intercomparing models) suggests that current concerns are likely to be exaggerated. A variety of independent arguments all lead to the same conclusion.

Our discussion of the greenhouse effect draws on three concepts.

The greenhouse effect for the atmosphere

The moist adiabatic lapse rate

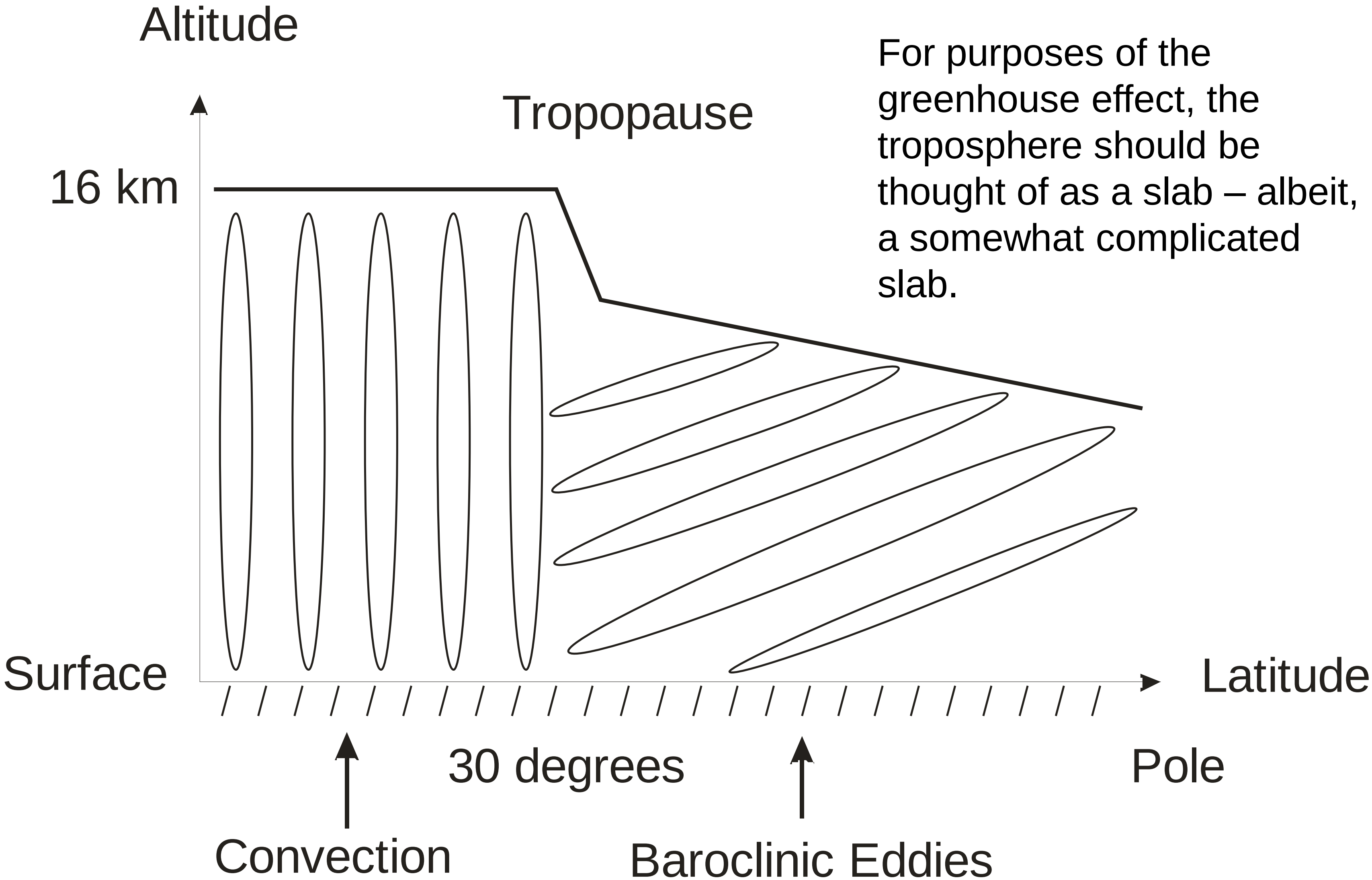
The Rossby radius

A consideration of these 3 concepts will lead to a variety of insights and even conclusions.

Real nature of greenhouse effect

All attempts to estimate how the climate responds to increasing CO_2 depend on how the climate greenhouse actually works. Despite the concerns with the greenhouse effect that have dominated environmental thinking for almost a quarter of a century, the understanding of the effect is far from widespread. Part of the reason is that the popular depiction of the effect as resulting from an infrared 'blanket' is seriously misleading, and, as a result, much of the opposition that focuses purely on the radiation is similarly incorrect. The following description is, itself, somewhat oversimplified; however, it is probably adequate for understanding the underlying physics.

First, one must recognize that the troposphere, the layer of the atmosphere in contact with the surface, is a ***dynamically mixed layer***. For a gaseous atmosphere, mixing requires that the resulting atmosphere is characterized by temperature decreasing with altitude. The rate of decrease is approximately 6.5K/km which is sometimes taken as an approximation to the moist adiabatic lapse rate, but the real situation is more complicated. To be sure, in the tropics, the mixing is effected by moist convection, but outside the tropics, the mixing is accomplished mostly by baroclinic eddies (essentially the large scale storm systems). Moreover, the moist adiabat in the tropics does not have a uniform lapse rate with altitude. For our immediate purposes, the important facts are that the lapse rate is positive (not zero or negative), and relatively uniform over most of the globe.

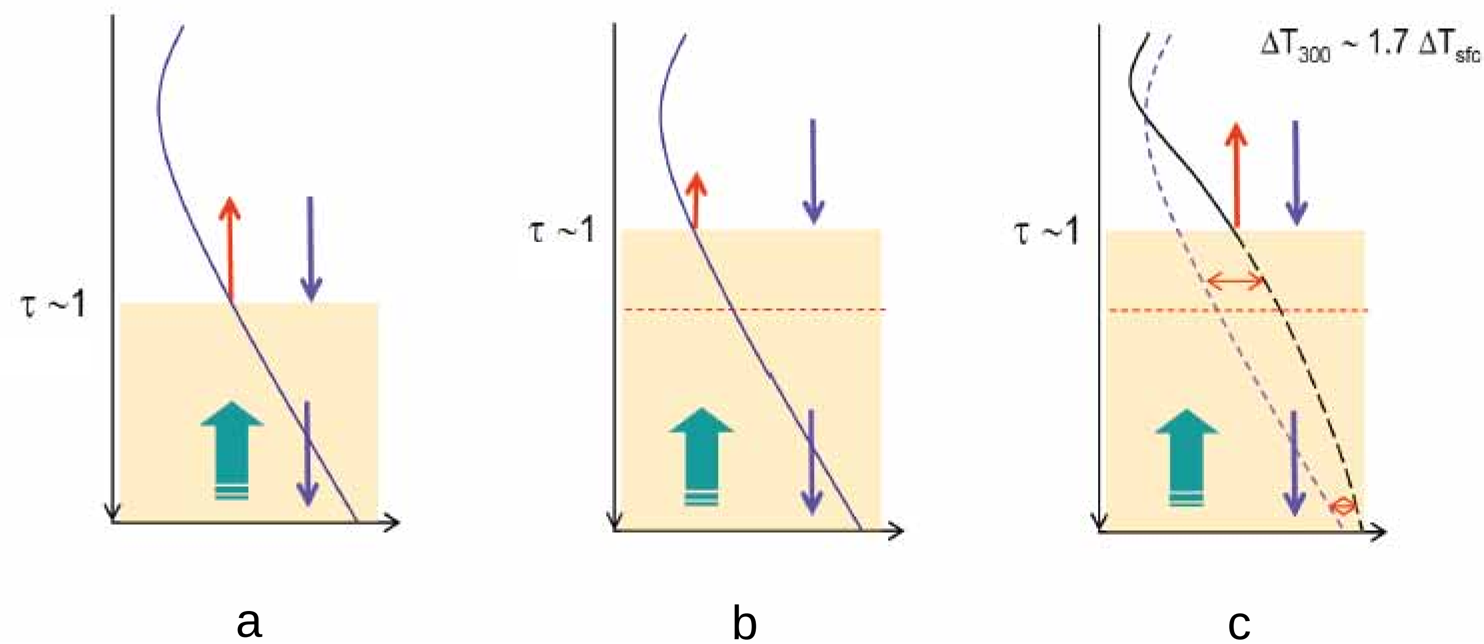


For purposes of the greenhouse effect, the troposphere should be thought of as a slab – albeit, a somewhat complicated slab.

Schematic of the troposphere as a dynamically mixed layer. Convection mixes vertically, while baroclinic eddies mix along isentropic surfaces.

Second, one must recognize that gases within the atmosphere that have significant absorption and emission in the infrared (ie greenhouse gases) radiate to space with a flux characteristic of the temperature of the atmosphere at about one optical depth (measured from space downward). To be sure, this level varies with wavelength, but the average emission level is about 5-6 km above the surface and well within the troposphere.

Third, adding greenhouse gases to the atmosphere must elevate the average emission level, and because of the first point, the new emission level is colder than the original emission level. This reduces the outgoing infrared radiative flux, which no longer balances the net incoming solar radiation. Thus, the troposphere, which is a dynamically mixed layer, must warm as a whole (including the surface) while preserving its lapse rate.

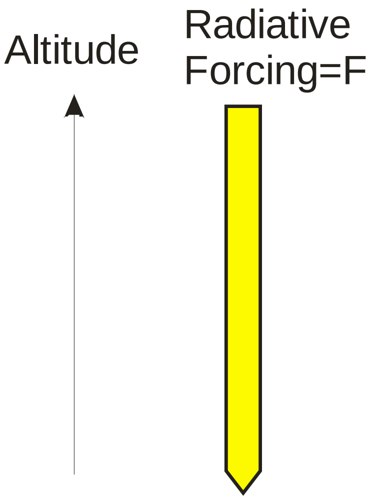


a) Situation with atmosphere in equilibrium with space. b) The situation when added greenhouse gas elevates the characteristic emission level to a cooler level, leaving a radiative imbalance that constitutes the radiative forcing. c) Re-equilibration with moist adiabat.

Note that this mechanism leads to the simple result that doubling CO_2 gives rise to warming of about 1C. This would not lead to significant concern. Larger warming calls for positive feedbacks.

Interesting and important aside.

These points also lead to the almost non-divergence of the total flux with altitude. In order for the dynamically mixed troposphere to warm as a whole, flux imbalance at the top of the atmosphere must approximately equal flux imbalance at the surface. The total flux consists in radiative flux, sensible heat flux, and latent heat flux. At the top of the atmosphere, the flux is exclusively radiative, while at the surface, the flux is primarily in the form of latent heat flux (ie evaporation). That evaporation at the surface must approximately follow radiative imbalance imposed at the top of the atmosphere may, at first, seem counter-intuitive. However, as noted in Lindzen, Hou and Farrell (1981), this is achieved by internal changes in the jump in relative humidity and temperature across the near surface turbulent boundary layer.



The approximate non-divergence of flux is the rationale for assuming that radiative forcing is acting at the surface in simple energy balance models that are commonly used by the IPCC for scenario generation.

$$C_{\mathrm{land}} \frac{\partial \Delta T_{\mathrm{land}}(t)}{\partial t} - \frac{\nu}{A_{\mathrm{land}}}\left(\Delta T_{ml}(t) - \Delta T_{\mathrm{land}}(t)\right) + \frac{B}{\mathrm{gain}} \Delta T_{\mathrm{land}}(t) = \Delta Q(t) \quad (1)$$

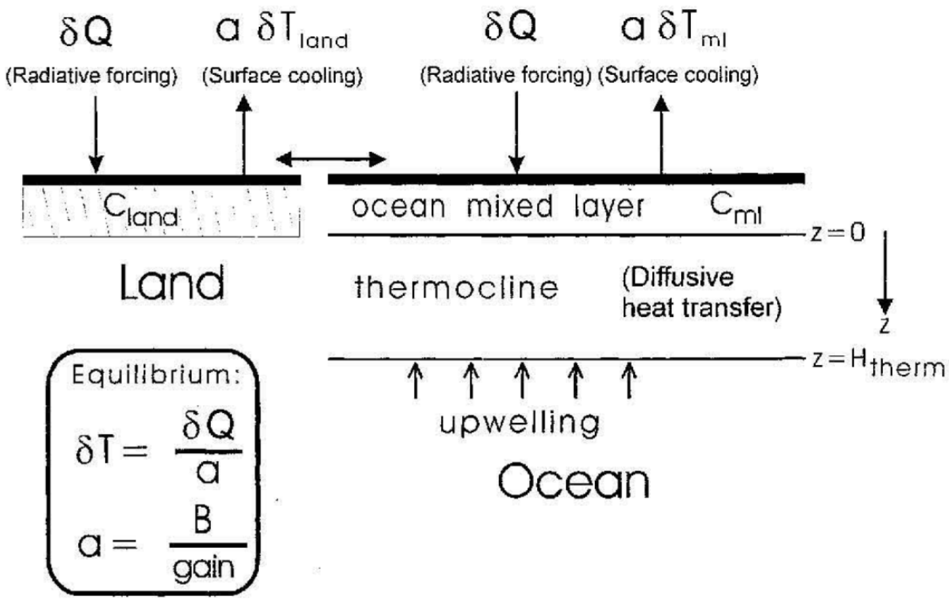


Figure 1. Geometry of simple box model for the climate system response to radiative perturbations.

Note that high gain (sensitivity) implies weak thermal coupling between the atmosphere and ocean. Such coupling is obviously important for air-sea interactions.

IMPORTANT QUESTION:

Would reducing sensitivity (even artificially) improve simulations of ENSO, PDO, etc., and eliminate problems of drift?

An important point that emerges from the preceding discussion is that climate sensitivity is simply the ratio of temperature change to driving flux; ie $\Delta T/\Delta F$. Moreover, as we have just noted, this flux takes the form, primarily, of latent heat flux (ie evaporation) at the surface.

For the last few years, I have attempted to use observations of outgoing radiation from space to measure radiative forcing and climate sensitivity. From the above, we see that an alternative to observing outgoing radiation from space is to measure evaporation from the surface. This has, in fact, been done (though without the current motivation). Wentz, F.J. et al (How much more rain will global warming bring. ScienceExpress, 31 May 2007) used the above and space based observations to measure how evaporation changed with temperature and compared their results with GCM results.

In GCMs, E (evaporation) increased from 1-3% for each degree increase in temperature. Observationally, E increased 5.7%. Now a 1% change in E corresponds to about 0.8 watts m^{-2}. Climate sensitivity is, as I have noted, $\Delta T/\Delta F$.

More specifically,

EC=ΔEvaporation/ΔT (in units of percent change per degree)
CF=Radiative Forcing due to doubling of CO_2=3.6 Watts m^{-2}
FL=Heat Flux associated with EC=0.8 Watts m^{-2} x EC
Climate sensitivity=CF/FL

Source	EC (Percentage change in E per degree)	Climate Sensitivity (Degrees C)
Model Range	1-3	1.5-4.5
Observed	5.7	0.8

We may reasonably consider the observed sensitivity to be an overestimate since Wentz et al explicitly rejected observations that were ‘too’ far from models. The results are, however, very similar to those based on measurements of outgoing radiation.

Note, that if dynamical mixing were to have led to an isothermal atmosphere, then there would be no warming due to added greenhouse gases. In the counterfactual case that mixing were to lead to increasing temperature with altitude, then added greenhouse gases would actually cool the atmosphere. In brief, greenhouse warming depends crucially on the existence and properties of dynamic mixing within the troposphere, and not simply on the radiative picture.

The structure imposed by the dynamics determines how the warming at the characteristic emission level is manifested at the ground.

Let us now continue with the remaining two concepts.

The moist adiabat and the Rossby radius of deformation.

The moist adiabat refers to the temperature profile of a neutrally buoyant saturated parcel of air as it rises in the atmosphere. It is smaller than the dry adiabat because the condensation of water contributes to the buoyancy, and characterizes the whole tropics.

moist-adiabatic lapse rate—(Or saturation-adiabatic lapse rate.) The rate of decrease of temperature with height along a moist adiabat. It is given approximately by Γ_m in the following:

$$\Gamma_m = g \frac{1 + \frac{L_v r_v}{RT}}{c_{pd} + \frac{L_v^2 r_v \epsilon}{RT^2}},$$

where g is gravitational acceleration, c_{pd} is the specific heat at constant pressure of dry air, r_v is the mixing ratio of water vapor, L_v is the latent heat of vaporization, R is the gas constant for dry air, ε is the ratio of the gas constants for dry air and water vapor, and T is temperature. This expression is an approximation to both the reversible moist adiabatic lapse rate and the pseudoadiabatic lapse rate, with more accurate expressions given under those definitions. When most of the condensed water is frozen, this may be replaced by a similar expression but with L_v replaced by the latent heat of sublimation.

Existing models all seem to properly display the moist adiabatic profile in the tropics.

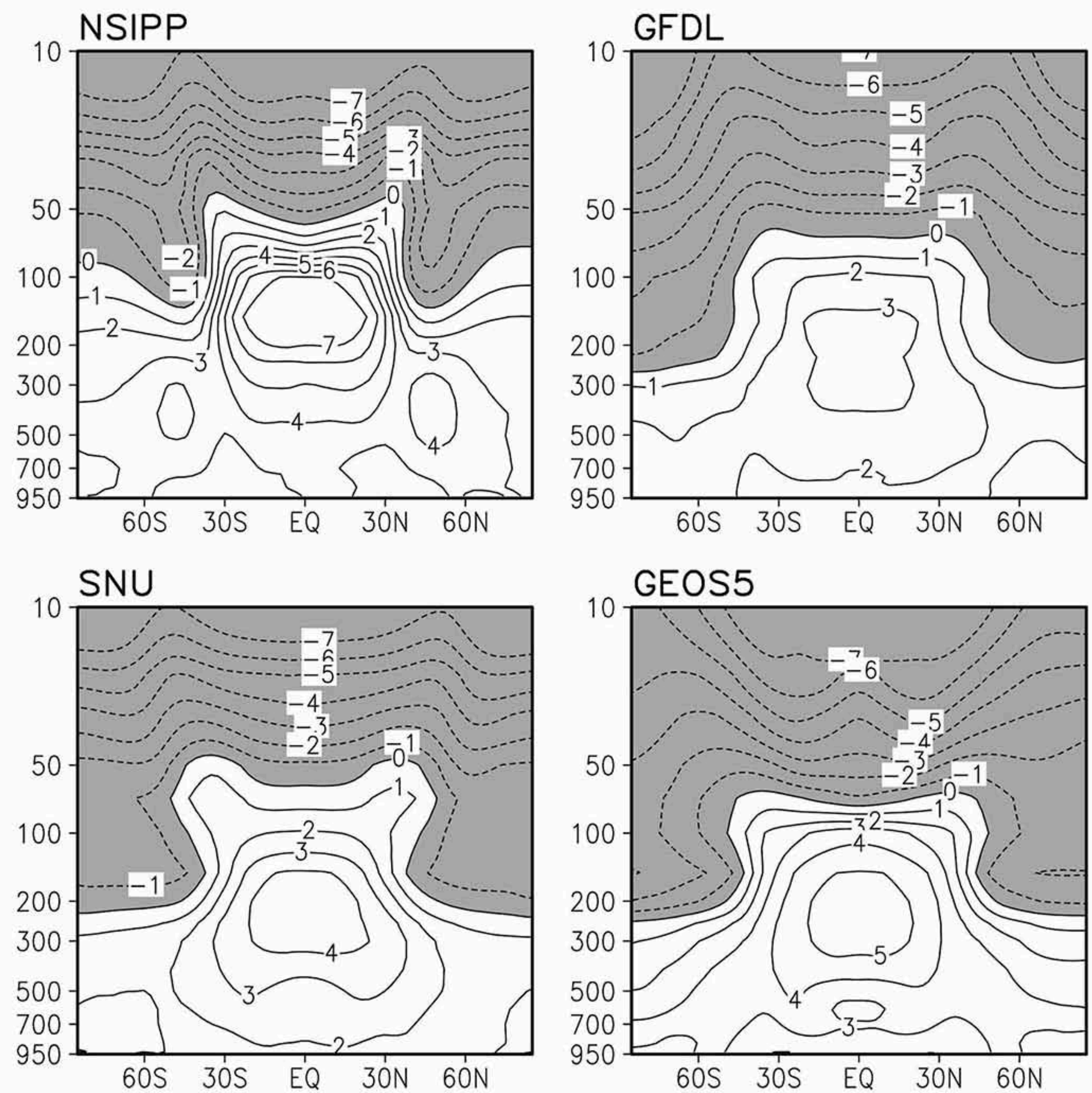


FIG. 14. Zonal-mean distributions of temperature change ($2 \times CO_2$ − Control). Units are kelvin.

Here we see the meridional distribution of the temperature response to a doubling of CO_2 from four typical models. The response is characterized by the so-called hot spot (ie, the response in the tropical upper troposphere is from 2-3 times larger than the surface response). We know that the models are correct in this respect since the hot spot is simply a consequence of the fact that tropical temperatures approximately follow what is known as the moist adiabat. This is simply a consequence of the dominant role of moist convection in the tropics.

Curiously, polar amplification at the surface is not very striking in the models.

However, the temperature trends obtained from observations fail to show the hot spot.

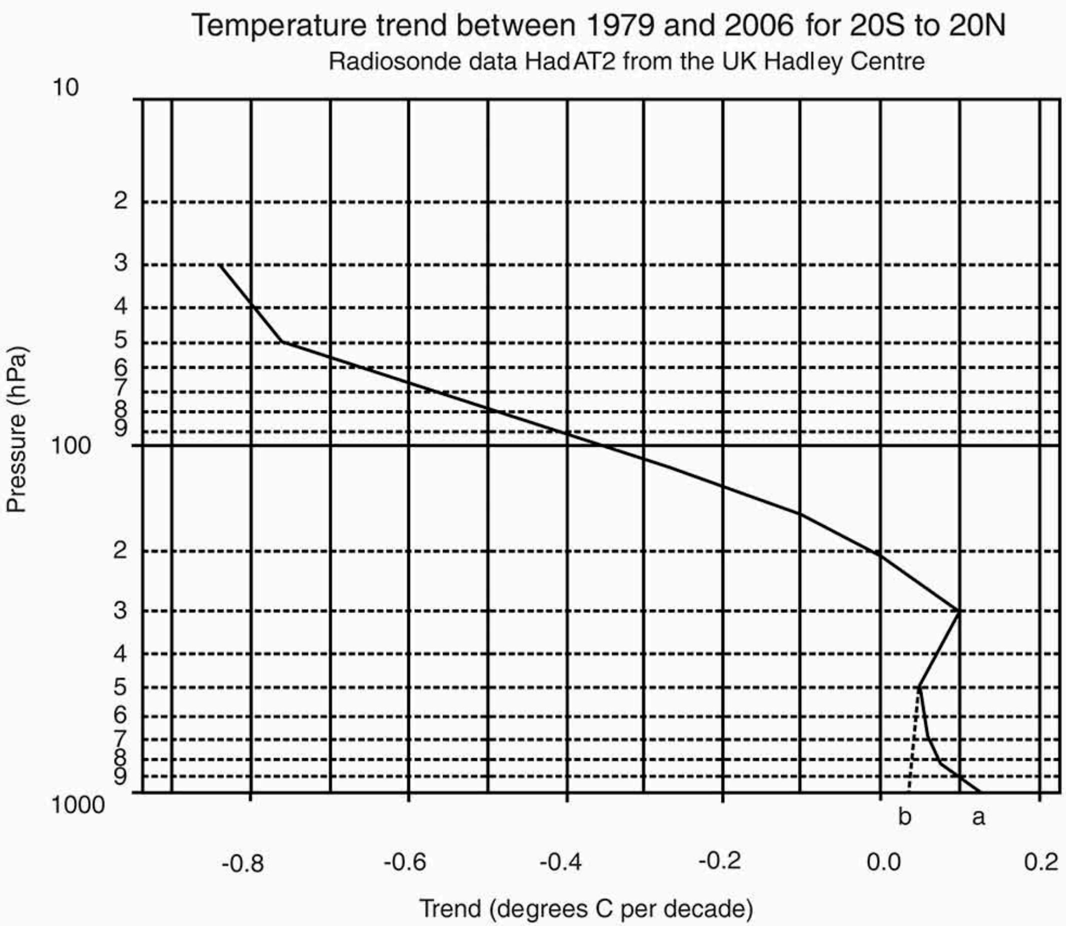


Figure 5: Temperature trend as a function of pressure level for period 1979–2006 in the tropics (20S-20N) based on balloon data analyzed by the Hadley Centre.

The resolution of the discrepancy demands that either the upper troposphere measurements are wrong, the surface measurements are wrong or both. If it is the surface measurements, then the surface trend must be reduced from 'a' to 'b'.

Given how small the trends are, and how large the uncertainties in the analysis, such errors are hardly out of the question. In fact there are excellent reasons to suppose that the error resides in the surface measurements.

The question arises as to why the tropics as a whole are characterized by the moist adiabat. The answer is the ***Rossby Radius***.

The Rossby Radius is the distance over which variables like temperature are smoothed out by the dynamics. This distance is inversely proportional to the Coriolis Parameter (twice the vertical component of the earth's rotation), and this parameter approaches zero as one approaches the tropics so that temperature is smoothed over thousands of kilometers.

$$\lambda_R = \frac{N_{BV} Z_T}{f_c},$$

However, this smoothing is only effective where turbulent diffusion is small. Below about 2 km, we have the turbulent trade wind boundary layer, where such smoothing is much less effective so that there is appreciable local variability of temperature. In practice, this means that for the sparsely sampled tropics, sampling problems above 2 km are much less important than at the surface. Thus, errors are more likely at the surface.

An important philosophical point to this little exercise is that neither ambiguous data nor numerical model outputs should automatically be assumed to be right or wrong. Both should be judged by basic, relatively fundamental theory – where such theory is available.

In the present case, if the surface data is, in fact, incorrect, then the surface warming of the period since 1979 has been greatly exaggerated.

Taking Greenhouse Warming Seriously 943

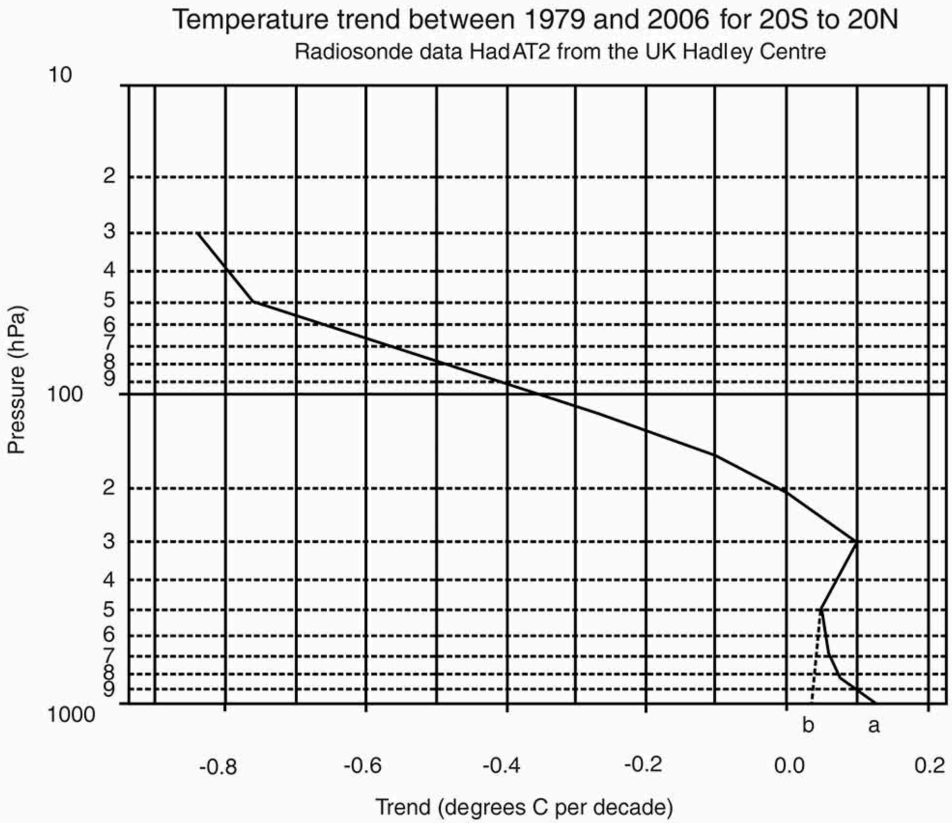


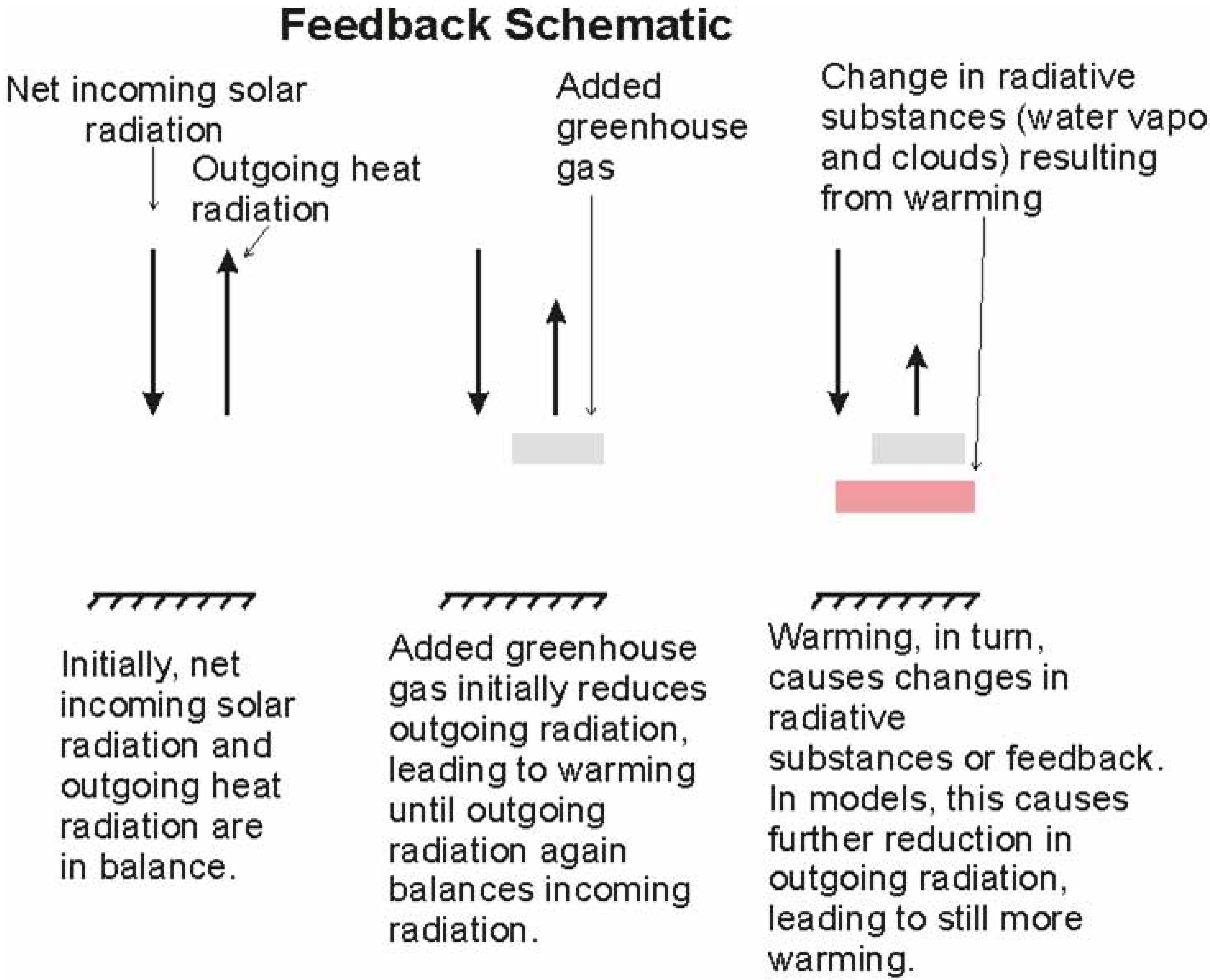
Figure 5: Temperature trend as a function of pressure level for period 1979–2006 in the tropics (20S-20N) based on balloon data analyzed by the Hadley Centre. ‘a’ shows the observed trend at the surface. ‘b’ shows that part of the surface trend that can be attributed to greenhouse warming.

It turns out that current models actually predict larger trends than ‘a’. Modelers then invoke ‘aerosols’ to cancel the excess warming. This, however, is simply an arbitrary adjustment since each model must assume a different value for the cancellation. If ‘b’ is the correct trend, then it is almost impossible for ‘aerosols’ to provide the needed cancellation.

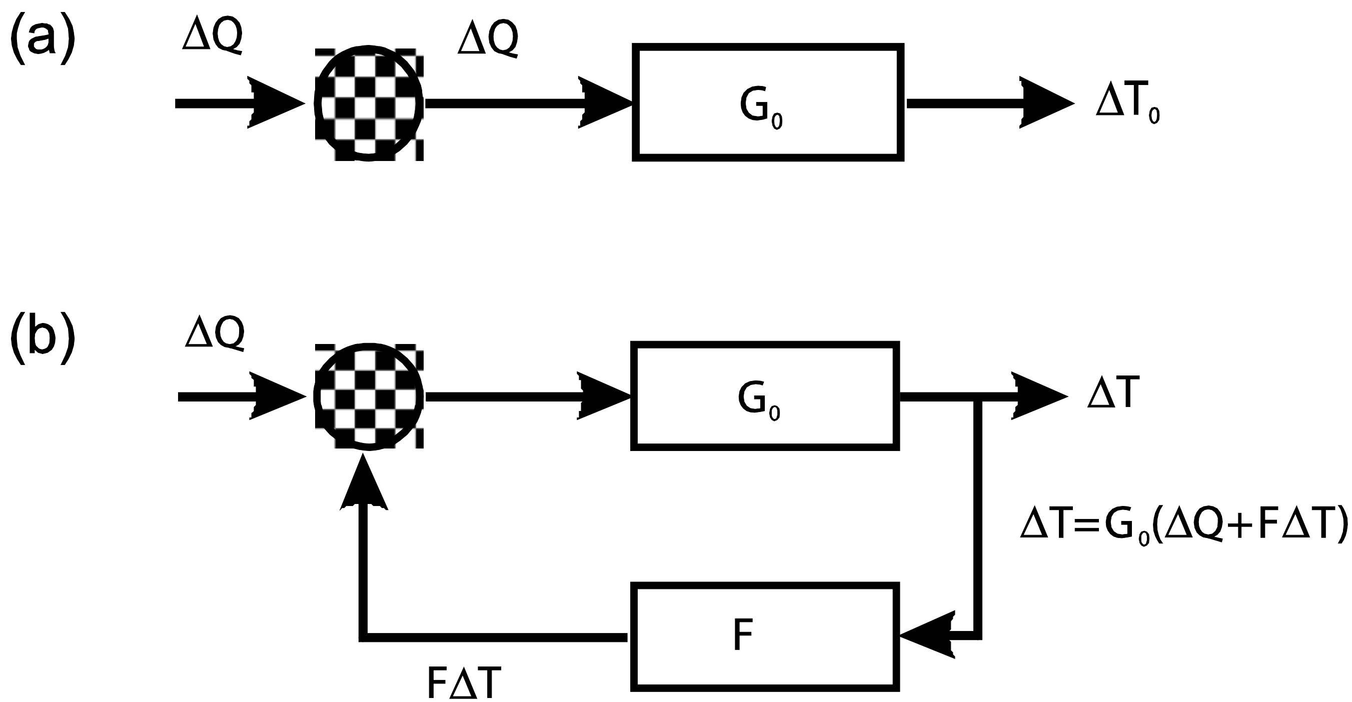
As we have seen, the simple existence of the greenhouse effect is neither new nor a cause for alarm. The critical issue is one of feedbacks. This is not a technical detail; it is central, and there is ample reason (as we have already seen) to think that current models are substantially exaggerating the feedbacks.

That said, climate change is not merely a matter of global mean temperature anomaly. Most climate change involves changes in the equator to pole temperature difference. This is rarely discussed in the popular literature, and is more than can be even cursorily discussed here.

Time also does not permit an adequate discussion of attempts to measure feedbacks from satellite measurements of outgoing radiation, but the general approach is worth explaining.



In all cases, the decrease in outgoing radiation is due to the elevation of the characteristic emission level.



$$\Delta T_0 = G_0 \Delta Q \qquad \Delta T = G_0(\Delta Q + F\Delta T) \qquad \Delta T = \frac{\Delta T_0}{1 - f}$$

$$f = F\,G_0$$

One is able to use satellite data from ERBE and CERES (that measures net outgoing radiation in both the visible and infrared portions of the spectrum) to test the preceding situation, and to quantitatively evaluate climate feedback factors. As we have already noted, these are related to climate sensitivity by the following equation:

$$\Delta T = \frac{\Delta T_0}{1 - f},$$

ΔT_0 is the zero feedback response to a doubling of CO_2. It is about 1C.

The basis of the approach is to see if the satellite measured outgoing radiation associated with short term fluctuations in Sea Surface Temperature (SST) is larger or smaller than what one gets for zero feedback. Remember that a positive feedback will lead to less outgoing radiation, while a negative feedback will lead to more.

It turns out that the model intercomparison program has the models used by the IPCC, forced by actual SST, calculate outgoing radiation. So one can use the same approach with models, while being sure that the models are subject to the same surface temperature fluctuations that applied to the observations.

In principle, this should be a straightforward task. However, in practice, it is rather difficult. The first two difficulties involve basic physical considerations.

First, not all time scales are appropriate for such studies. Greenhouse warming continues until equilibrium is reestablished. At equilibrium, there is no longer any radiative imbalance. If one considers time intervals that are long compared to equilibration times, then one will observe changes in temperature without changes in radiative forcing. The inclusion of such long time scales thus biases results inappropriately toward high sensitivity. Equilibration times depend on climate sensitivity. For sensitivity on the order of 0.5C for a doubling of CO_2, it is on the order of years, and for higher sensitivities it is on the order of decades. In order to avoid biasing sensitivity estimates, one should restrict oneself to time intervals less than a year.

There is also the need to consider time intervals long enough for the relevant feedback processes to operate. For water vapor and cloud feedbacks, these time scales are typically on the order of days. For practical time resolution, this is generally not a problem.

Lindzen and Choi (2009, 2011) dealt with this by focusing on short episodes of warming and cooling over periods on the order of 1-3 months. Longer time scales also involve ‘pollution’ from seasonal effects, etc.

The **second** problem is more difficult. Outgoing radiation varies (especially in the visible) for reasons other than changing surface temperature (volcanoes, non-feedback cloud fluctuations). Such changes are not responses to surface temperature fluctuations but they do cause surface temperature fluctuations. Dealing with this problem requires considering lagged regressions. Positive lags are associated with feedbacks, while negative lags are associated with non-feedback changes in radiation.

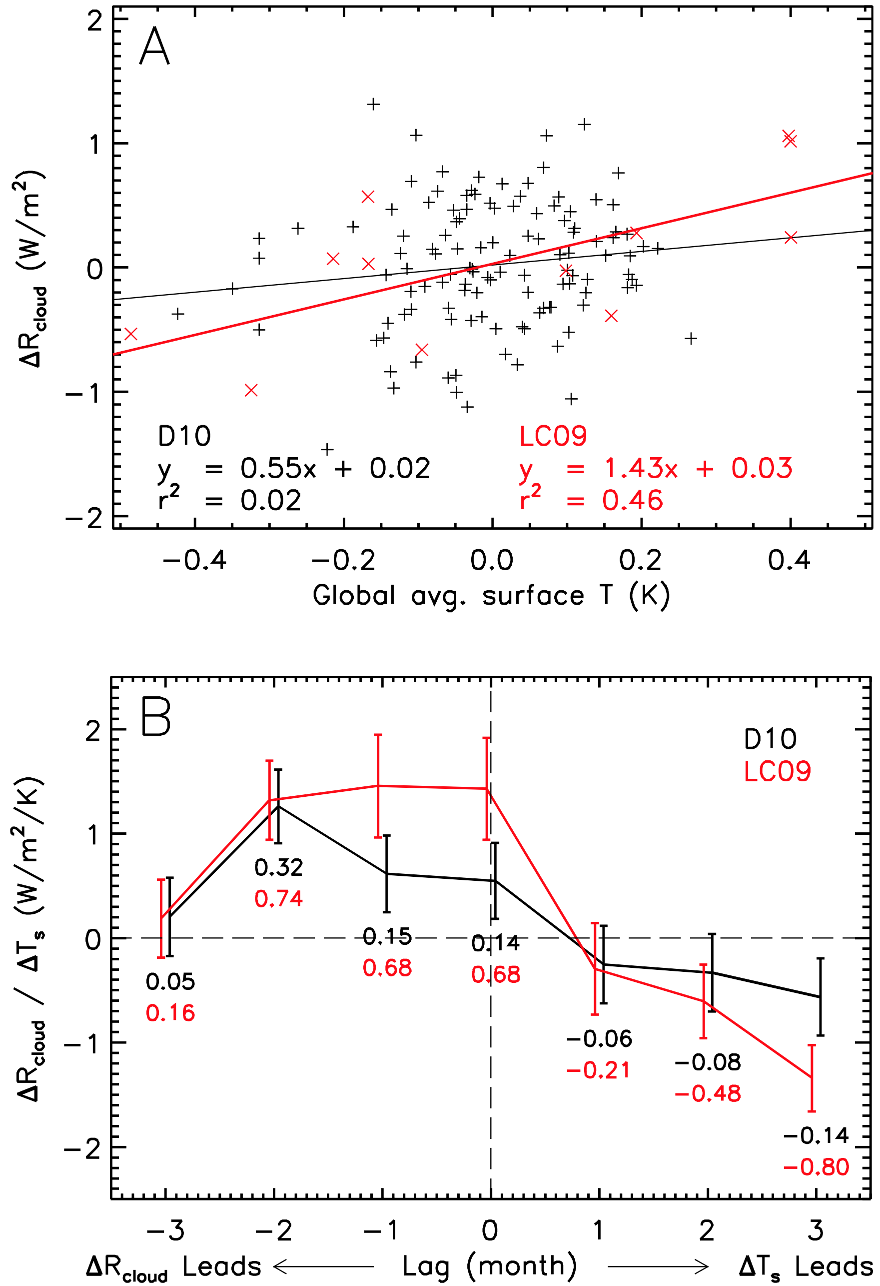
Apart from basic physical issues, there are other practical problems such as the presence of significant gaps in the outgoing radiation data. Also, the radiation data involves two satellite systems (ERBE and CERES) with different properties.

Several approaches have been taken to analyzing the data. In most studies (Trenberth, et al, 2010, Dessler, 2010, Gregory and Foster, 2006, Murphy, 2010), one doesn't even bother to isolate time segments. One simply regresses anomalies, ΔF, on anomalies in surface temperature. Such approaches completely ignore the first and second problems, and lead, as we will see, to incorrect results.

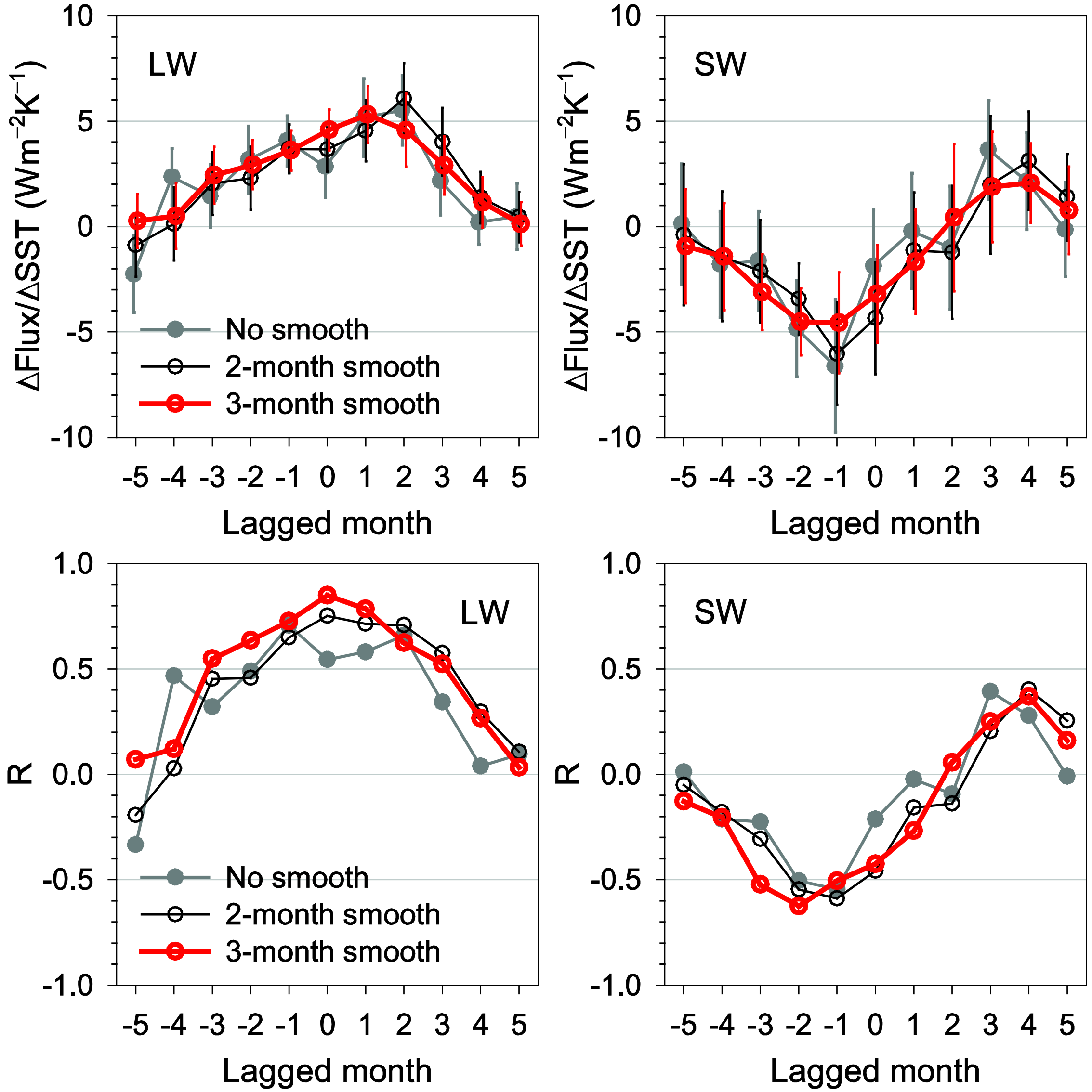
In the following slides, I look at the implications of the two approaches to the problem of assessing feedbacks directly from satellite observations of outgoing radiation.

The data used by Dessler (2010) was subjected to our approach in two steps. In A we contrast Dessler's simple regression approach with our use of appropriate segments. We actually get a bigger 'apparent' positive feedback with a much larger r^2. In B, we subject both Dessler's method and ours to lead-lag analysis. Both now show negative feedback, though, again, our use of segments leads to much higher values of r.

In general, the values of r for Dessler's analysis are extremely low.



Here are our results based primarily on SST and tropical radiation. In evaluating feedbacks, we require that radiative imbalances in the tropics be shared with the globe. Interestingly, the results are similar to what are obtained with data for the whole earth.



All the models are characterized by positive feedback factors (associated with amplifying the effect of changes in CO_2), while the satellite data implies that the feedback should be negative. Similar results are being obtained by Roy Spencer. The results are pretty much what one gets from the evaporation data discussed earlier.

Models

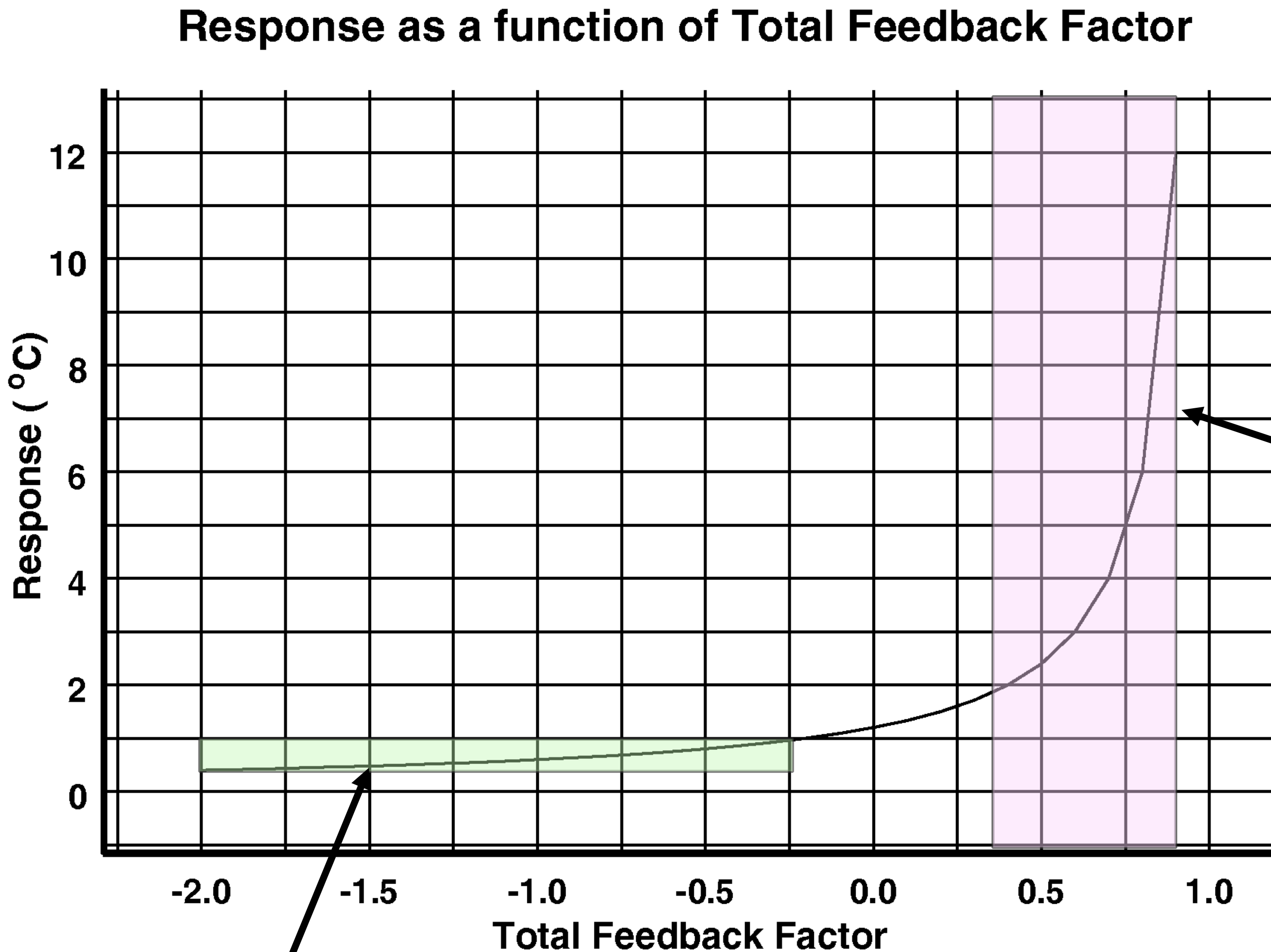
Models	IPCC AR4	Estimate in this study			
	Sensitivity	Sensitivity	Confidence interval of sensitivity		
			90%	95%	99%
CCSM3	2.7	8.1	1.6 – Infinity	1.4 – Infinity	1.1 – Infinity
ECHAM5/MPI-OM	3.4	1.7	0.9 – 8.0	0.9 – 28.2	0.8 – Infinity
FGOALS-g1.0	2.3	7.9	2.2 – Infinity	2.0 – Infinity	1.6 – Infinity
GFDL-CM2.1	3.4	2.2	1.1 – 351.4	1.0 – Infinity	0.8 – Infinity
GISS-ER	2.7	2.5	1.5 – 8.7	1.4 – 16.4	1.2 – Infinity
INM-CM3.0	2.1	2.7	1.3 – Infinity	1.2 – Infinity	1.0 – Infinity
IPSL-CM4	4.4	10.4	2.1 – Infinity	1.8 – Infinity	1.4 – Infinity
MRI-CGCM2.3.2	3.2	Infinity	2.5 – Infinity	2.0 – Infinity	1.4 – Infinity
MIROC3.2(hires)	4.3	2.2	1.3 – 6.4	1.2 – 10.0	1.1 – Infinity
MIROC3.2(medres)	4	2.4	1.3 – 14.7	1.2 – Infinity	1.0 – Infinity
UKMO-HadGEM1	4.4	1.7	1.0 – 8.8	0.9 – 38.9	0.8 – Infinity

Observations

Sensitivity, mean	0.7
Sensitivity, 90%	0.6–1.0
Sensitivity, 95%	0.5–1.1
Sensitivity, 99%	0.5–1.3

$$\Delta T = \frac{\Delta T_0}{1 - f},$$

The implications of values of ‘f’ near +1 are substantial.



For positive feedbacks, relatively small variations in feedback lead to large changes in response.

It is the positive feedbacks in the models that leads to the uncertainty, and, as we will see, to the potential for instability.

For negative feedbacks, large variations in the feedback lead to only small changes in response.

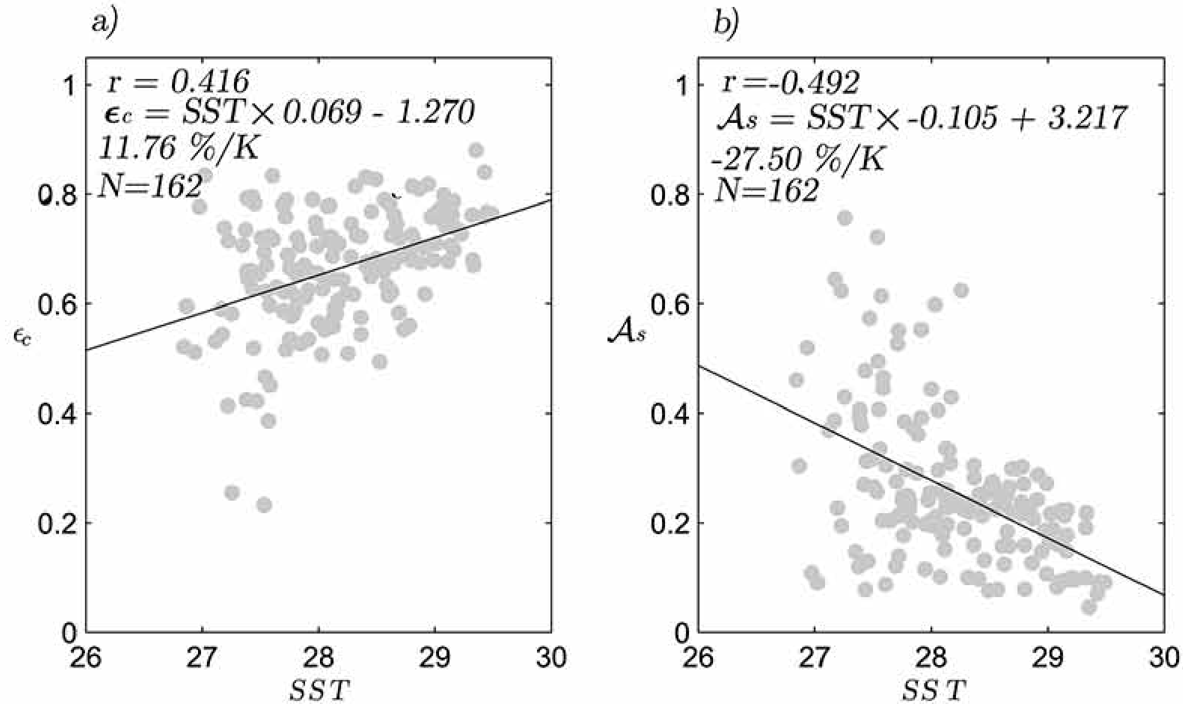


Figure 1. Linear regression between (a) convective fraction ϵ_c and (b) stratiform area per unit precipitation $\mathcal{A}_s$ with respect to the average sea surface temperature (SST) of a region of $10^\circ \times 10^\circ$ around Kwajalein. The period of integration is $\tau = 8$ days. The units of $\mathcal{A}_s$ are KR/[mm h^{-1}], where *KR* is the area covered by the Kwajalein radar.

From Rondanelli and Lindzen, J. Geophys. Res., 2008, but also confirmed independently by Kovari and Delgenio, and Horvath and Soden.

In order to relate this to feedbacks, one needs the optical properties of detrained cirrus.

“However, normalization by the strength of convection has shown that anvil area per unit cumulus area, that is, cirrus detrainment efficiency, actually decreases as SST increases. Finally, both the mean UTH and its detrainment rate have generally increased with SST.

It is noted that a qualitatively similar sea surface temperature dependence of cirrus anvil detrainment efficiency has been observed by Lindzen et al. (2001). They have found that, when large areas of the tropics are considered, there is a strong inverse relation between normalized anvil cloud fraction and the underlying mean SST, and they interpreted the result as reduced cirrus outflow caused by an increase in deep convective precipitation efficiency over warmer oceans. Combining this area effect with a particular set of assumptions on the mean radiative properties of high-level clouds, Lindzen et al. (2001) then proposed a strong negative “iris” feedback that may operate to minimize global warming due to a doubling of CO2. However, all aspects of the iris mechanism have been questioned in the literature. For example, Lin et al. (2002) have found significantly larger cloud albedos and longwave fluxes in state-of-the-art satellite measurements than those assumed by Lindzen et al. (2001), resulting in a weak positive feedback instead of a strong negative feedback. Furthermore, Hartmann and Michelsen (2002) have pointed out that the observed relationship between cloud-weighted SST and normalized anvil fraction results from changes in cloud amount over colder SSTs, which is far removed from tropical deep convection whose anvil clouds Lindzen et al.(2001) have hypothesized are modulated by small SST variations.”

Horvath and Soden, *J. Clim*., 2008

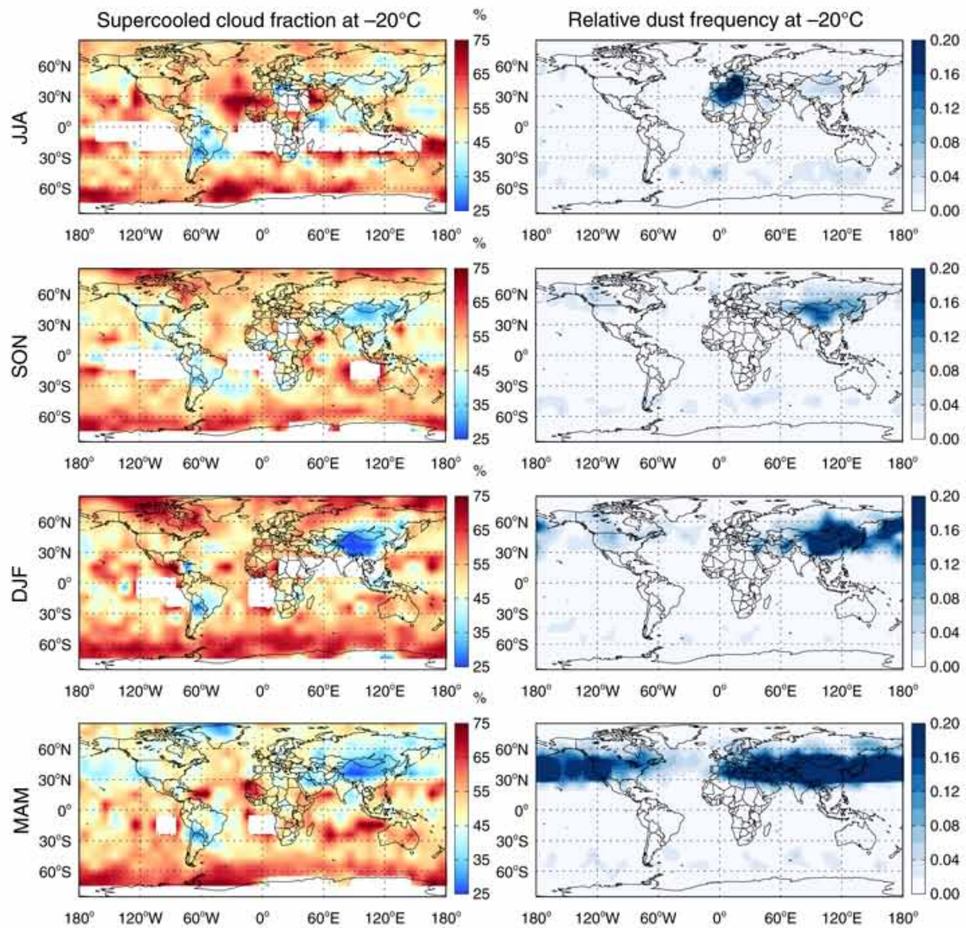


Fig. 2. Seasonal variation in SCF and relative dust frequency (to the highest dust frequency), both at the −20 °C isotherm. Pattern correlation coefficients between SCF and dust frequency for the Northern Hemisphere are negative for all seasons: −0.1, −0.5, −0.5, and −0.6 for JJA, September-October-November (SON), December-January-February (DJF), and MAM, respectively.

11212 | www.pnas.org/cgi/doi/10.1073/pnas.1006241107 Choi et al.

These results suggest that the optical properties of clouds depends on aerosols, and that, therefore, feedback factors could be variable, and, if they were close to +1, they might occasionally exceed +1 leading to instability.

I hope that what has been shown demonstrates that increasing CO_2 and greenhouse warming are not at all indicative of alarm, and that there is ample evidence that the system is not particularly sensitive. Moreover, the high sensitivity of some current models would render the stability of the earth over 4.5 billion years dubious. Engineers have long recognized this and generally avoid feedback factors greater than about 0.1.

In any event, thanks for your attention.

rlindzen@mit.edu