Climate v. Climate Alarm

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November 19, 2011

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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, theory provides useful constraints and tests when applied to modeling results. This has been notably absent in current work on climate.
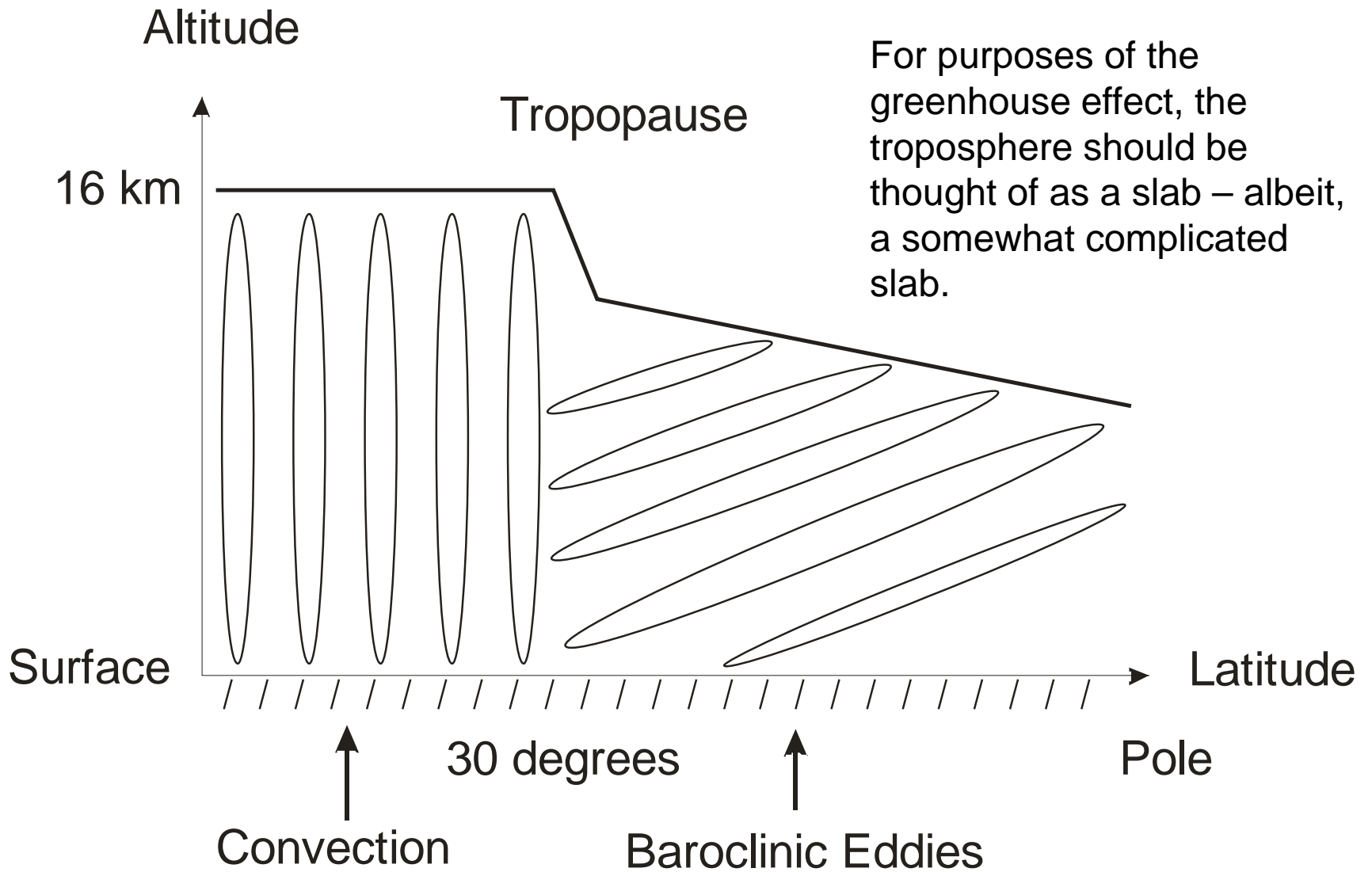
In this talk, I will try to show how the greenhouse effect actually works using relatively simple basic concepts. We will see that the greenhouse effect, itself, presents little cause for alarm from increasing levels of CO_2 since the effect is modest. Concern is associated with the matter of feedbacks that, in models, lead to amplified responses to CO_2. Considerations of basic physics (as opposed to simply intercomparing models) suggests that current models display exaggerated sensitivity. A variety of independent arguments all lead to the same conclusion.

Understanding the greenhouse effect is an important preliminary for dealing with direct measurement of sensitivity.

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' can be 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. Moreover, the moist adiabat in the tropics does not have a uniform lapse rate with altitude (viz the 'hot spot'). 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.

Altitude

Tropopause

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

16 km

Surface

Latitude

30 degrees

Pole

Convection

Baroclinic Eddies

Schematic of the troposphere as a dynamically mixed layer.

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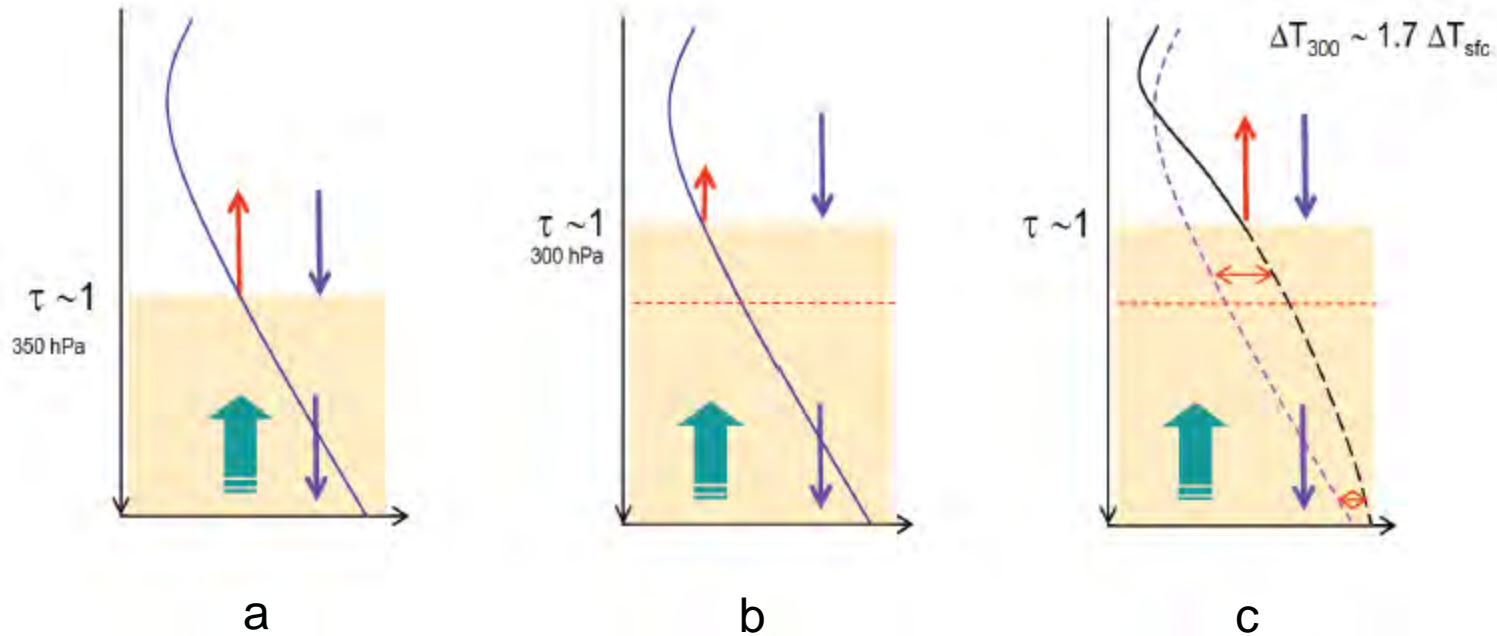
a) Situation with atmosphere in equilibrium with space. b) The situation when added greenhouse gas elevates the characteristic emission level to a cooler level, leaving a radiative imbalance that constitutes the radiative forcing. c) Re-equilibration with moist adiabat.

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

Interesting and important aside.

These points also lead to the approximate 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, latent heat flux (ie evaporation) is dominant. That flux 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.

Altitude

Radiative
Forcing=F
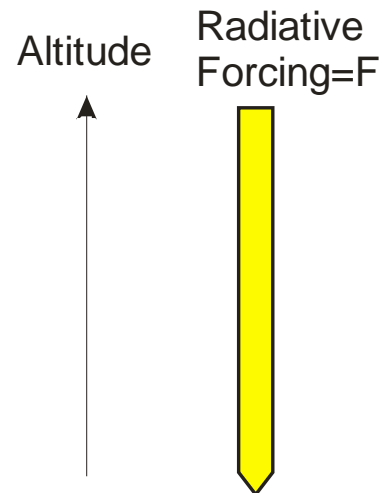
This approximate non-divergence of flux is the rationale for assuming that radiative forcing is acting at the surface in simple energy balance models.
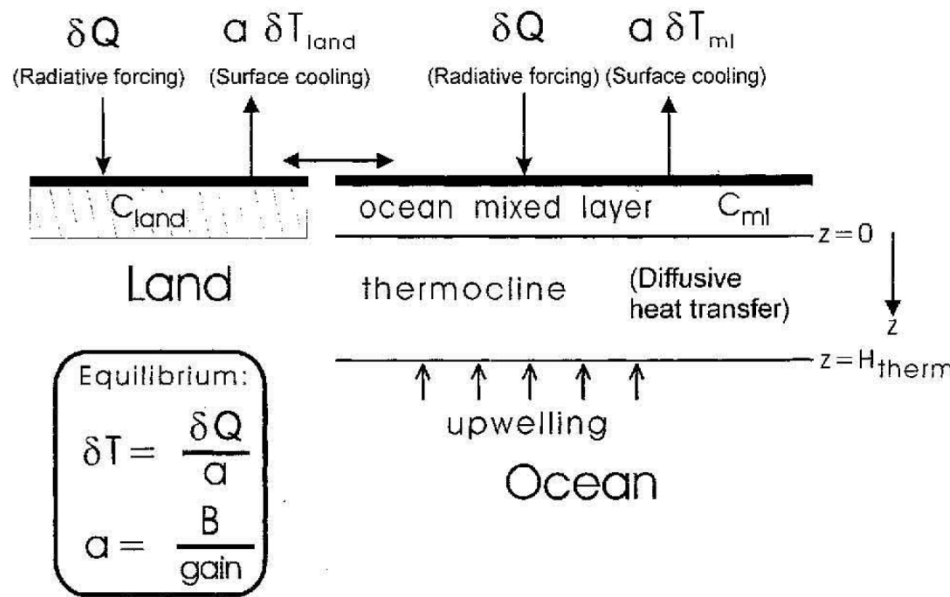
Note that high gain (sensitivity) implies weak thermal coupling between the atmosphere and ocean. Such coupling is obviously important for air-sea interactions.

A variety of important phenomena (El Nino, Pacific Decadal Oscillation, Atlantic Multidecadal oscillation) depend on such interactions, and models do poorly in simulating these phenomena.

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

Energy balance models clearly demonstrate the relation between climate sensitivity and response time. **The crucial point is that climate sensitivity (essentially ΔT/ΔF) translates immediately into the time scale for response of the system, with high sensitivity associated with long response times.**

Lindzen and Giannitsis (1998) looked at the long term response to sequences of volcanic eruptions. (The short term response – one to two years -- to single volcanoes did not distinguish among sensitivities.)
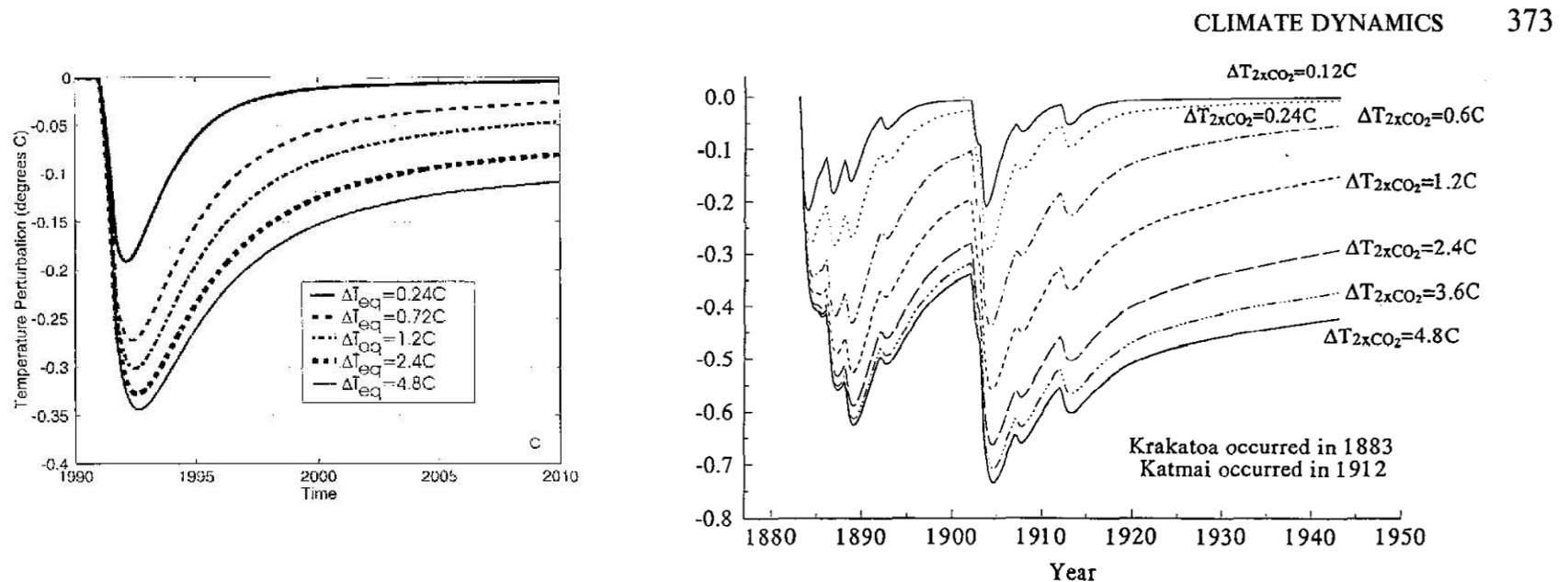
Figure 16 Response to series of volcanoes between Krakatoa in 1883 and Katmai in 1912. (From Lindzen 1993b.)
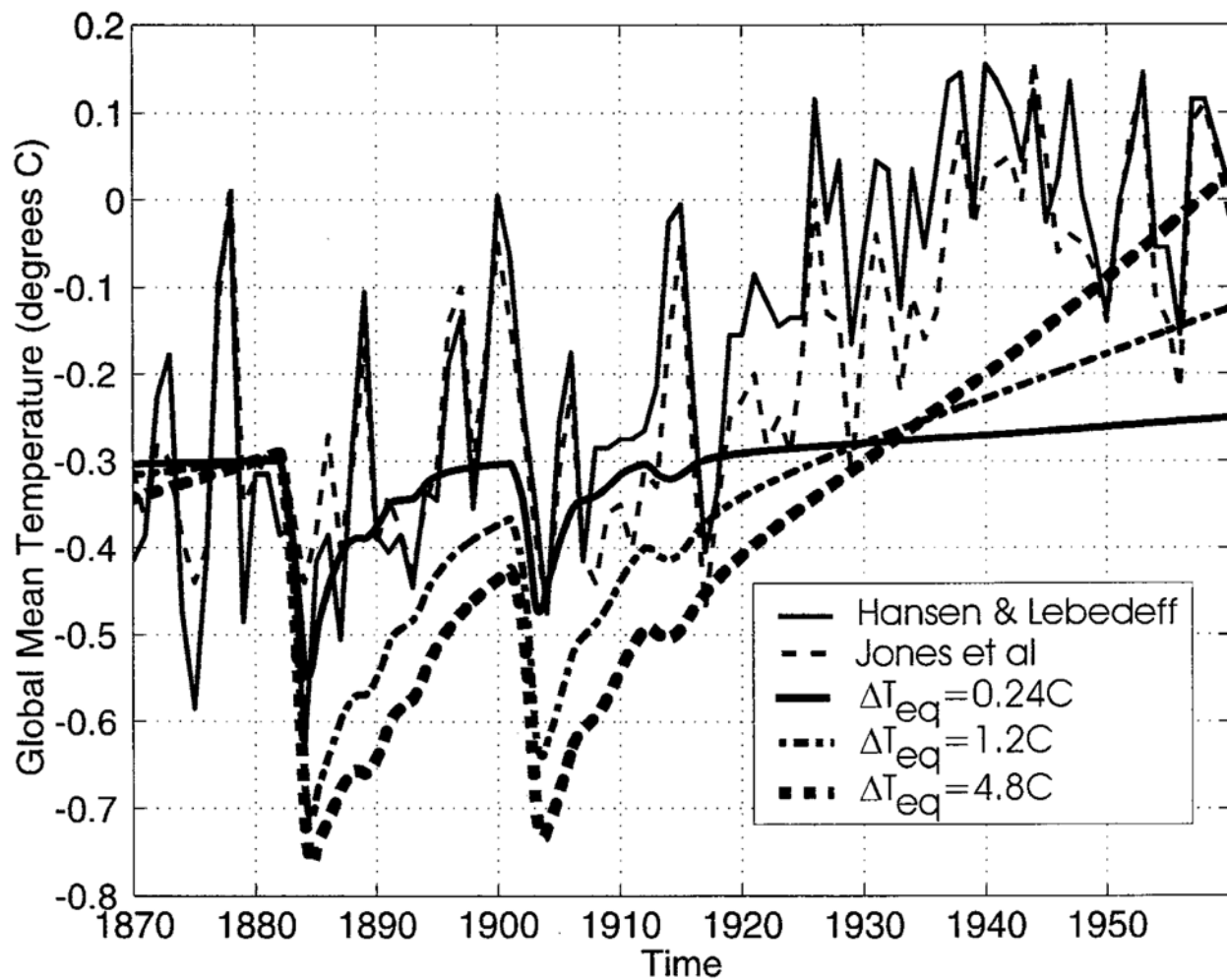
Figure 8. Comparison of observed changes in globally averaged temperature [*Hansen and Lebedeff*, 1988; *Jones et al.*, 1986] and model predictions, using combined CO_2 and volcanic radiative forcing.

Another possible approach to estimating response times emerges from Roe (2009). He shows that power spectrum for Pacific Decadal Oscillation can be simulated by an AR(1) process with a response time of 1.6 +/- 0.8 years. It should be possible to examine the PDO index in models to see if the time series corresponds to a much longer response time. This would be strong evidence that model sensitivity was excessive. Note that current models do not simulate the PDO. We are currently beginning such a study.
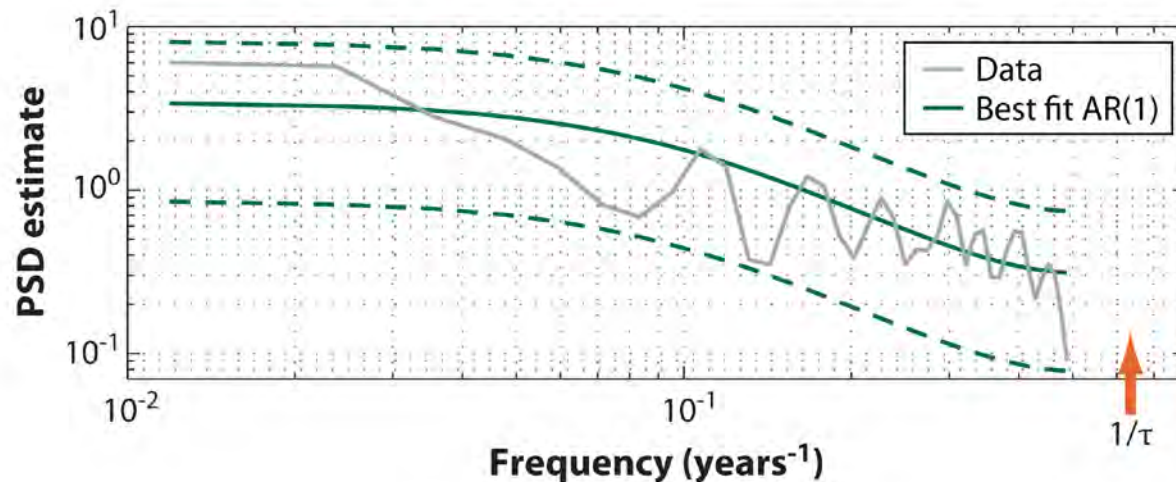

Figure 8

Power spectral estimate of the springtime (March-April-May, or MAM) PDO index (*gray line*) using a periodogram with a 30-year Hanning window; and the theoretical power spectrum of the best-fit red-noise process (*green line*), with a response time of $\tau = 1.6 \pm 0.8$ years. The green dashed lines give the 95% confidence interval for the red-noise process, and the orange arrow shows $1/\tau$. The spectrum illustrates that half of the variance occurs at periods that are at least 2π times longer than the physical response time.

If models display a longer τ, it would confirm that model sensitivity is excessive.

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.

The above implicitly involved two additional concepts.

# *The moist adiabat and the Rossby radius of deformation.*

The moist adiabat refers to the temperature profile of 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. It also is characterized by greater changes in the upper troposphere than at the ground.

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:

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

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.
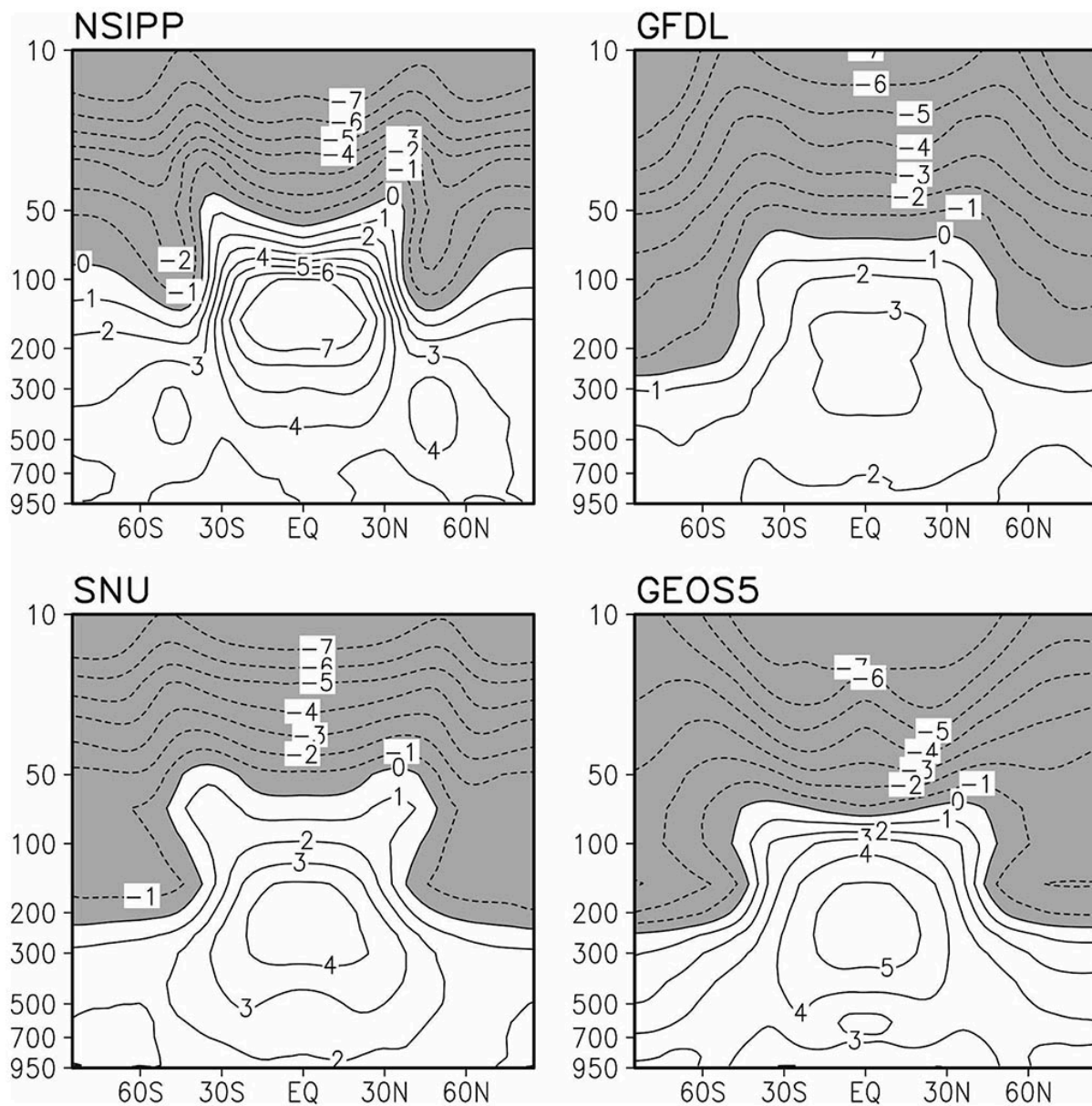
Here we see the meridional distribution of the temperature response to a doubling of CO_2 from four typical models. The response is characterized by the so-called hot spot (ie, the response in the tropical upper troposphere is from 2-3 times larger than the surface response). We know that the models 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.

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

However, the temperature trends obtained from observations fail to show the hot spot.
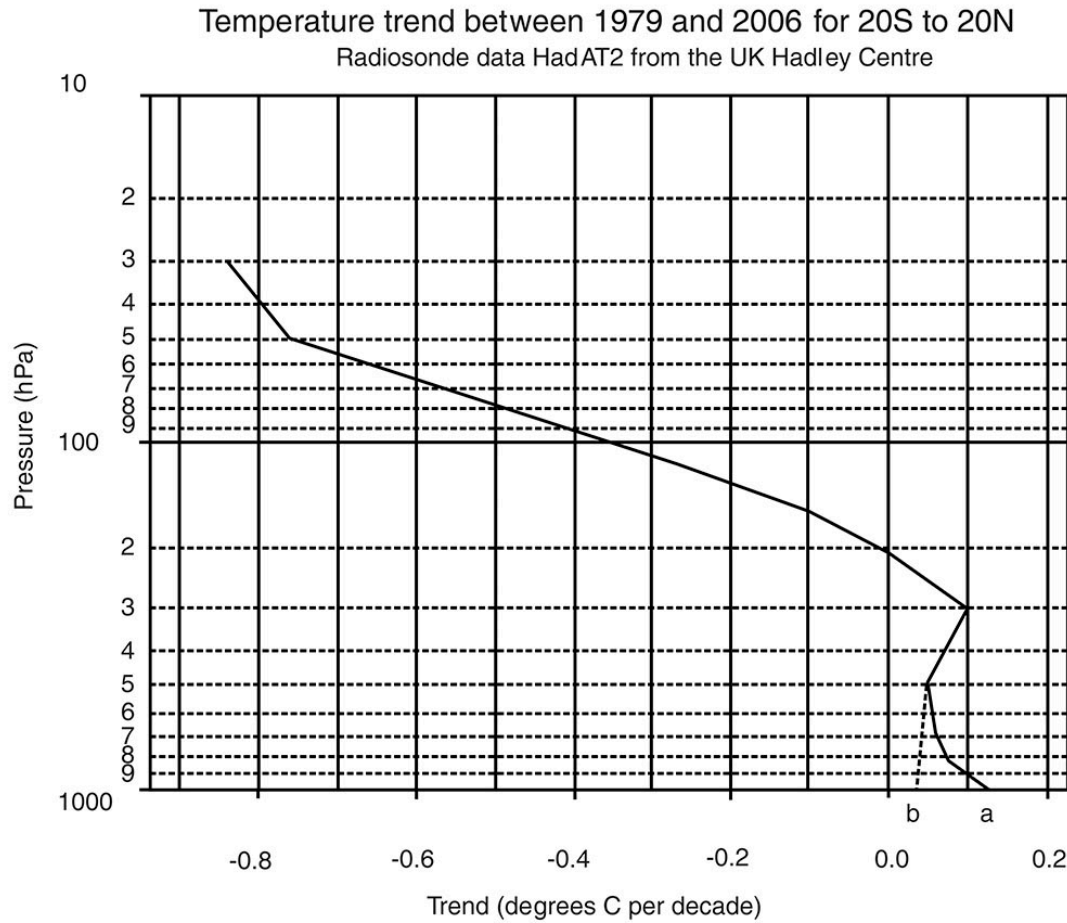
The resolution of the discrepancy demands that either the upper troposphere measurements are wrong, the surface measurements are wrong or both. If it is the surface measurements, then the surface trend must be reduced from 'a' to 'b'.

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 reason involves the **Rossby Radius**.

Temperature trend between 1979 and 2006 for 20S to 20N
Radiosonde data Had AT2 from the UK Hadley Centre

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 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 (accounting for the fact that the whole tropics are characterized by the moist adiabat). However, this smoothing is most effective where turbulent diffusion is too large. 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.

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

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.

Note that although I don't think that one can convincingly determine sensitivity from temperature time series (because we don't know all sources of forcing), the possible reduction of measured surface warming from 1979 until 2006 by 2/3 would be very hard to simulate without reducing model sensitivity.

That said, it is probably helpful to put the temperature changes we are discussing into some sort of perspective.

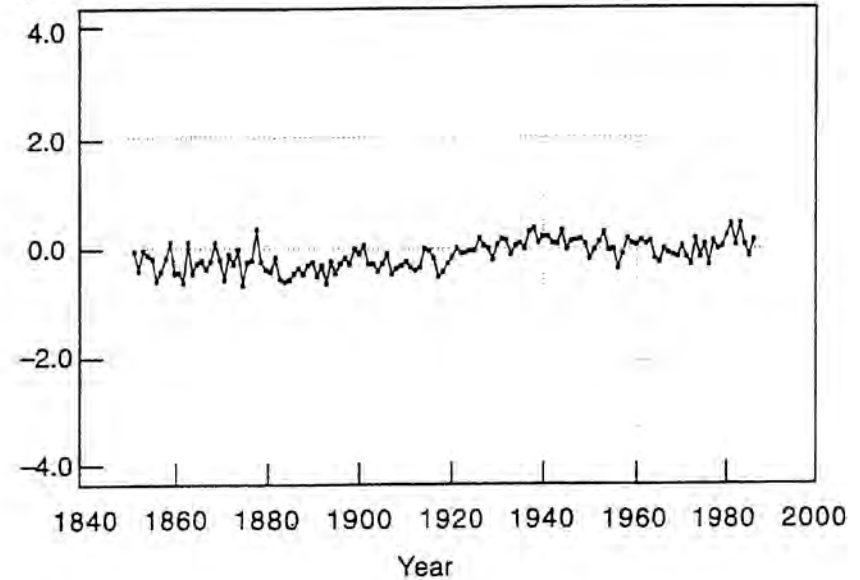**Deviations of Annual MeanTemperature from Long-term Average**
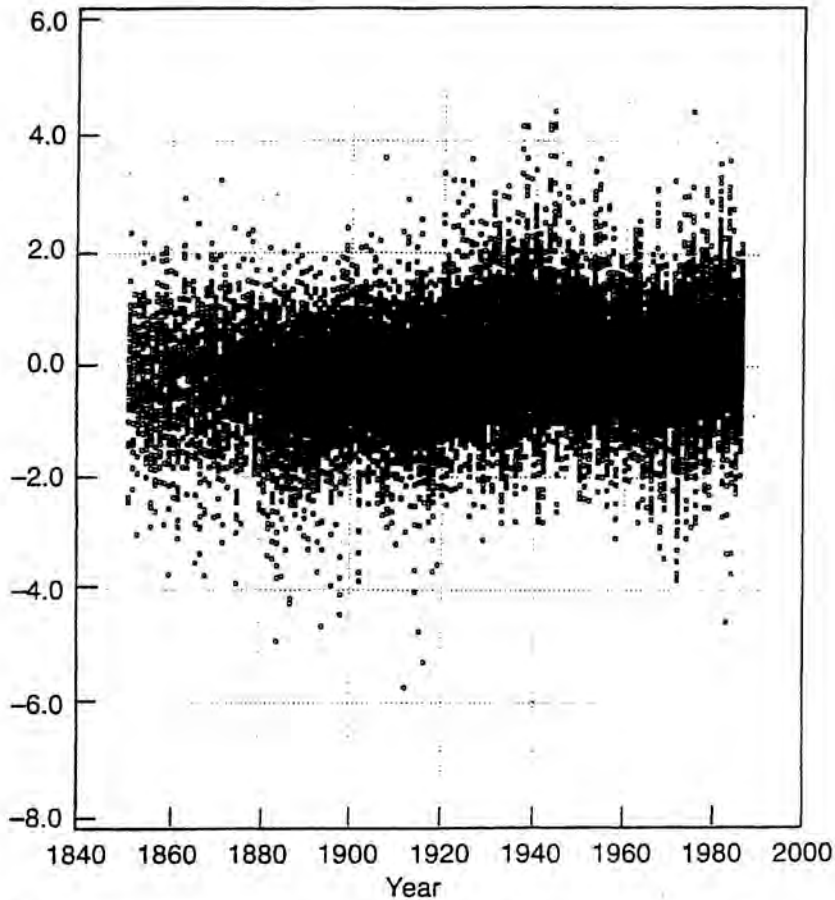
Temperature Anomaly (°C)

1. Data points averaged to obtain time record of global mean temperature. Note points range from less than -2C to more than +2C.

Source: S. L. Grotch, Lawrence Livermore Laboratory, Livermore California

Globally Averaged Deviations from Average Temperature Plotted on a Scale Relevant to the Individual Station Deviations
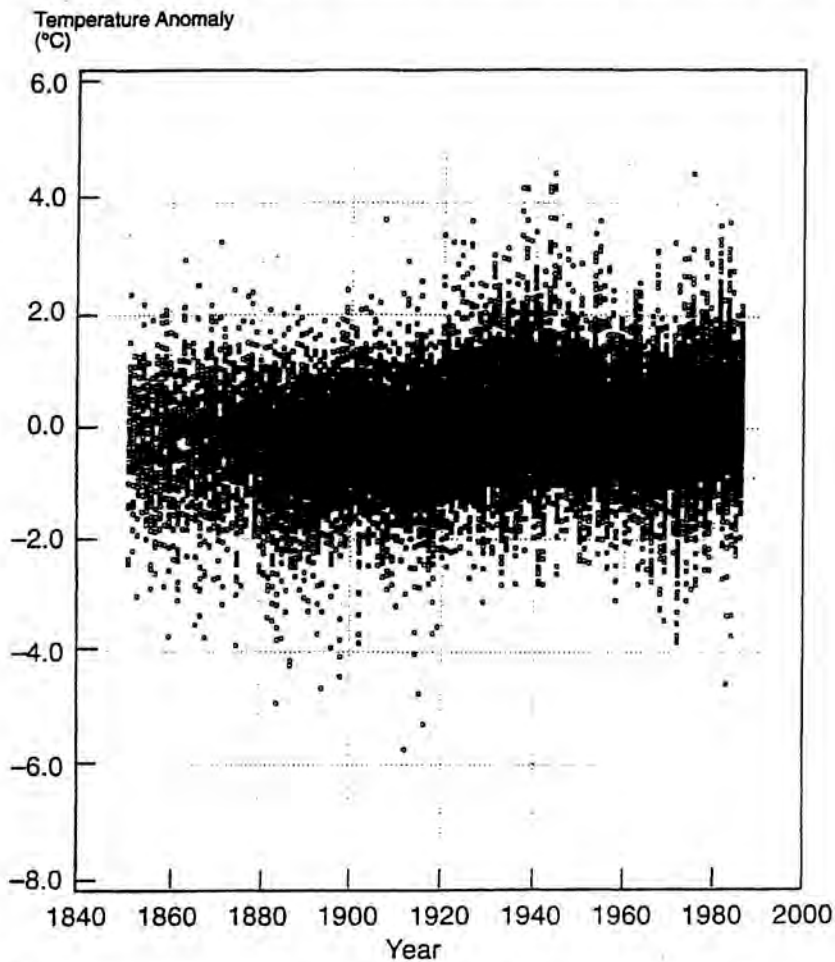
Temperature Anomaly (°C)
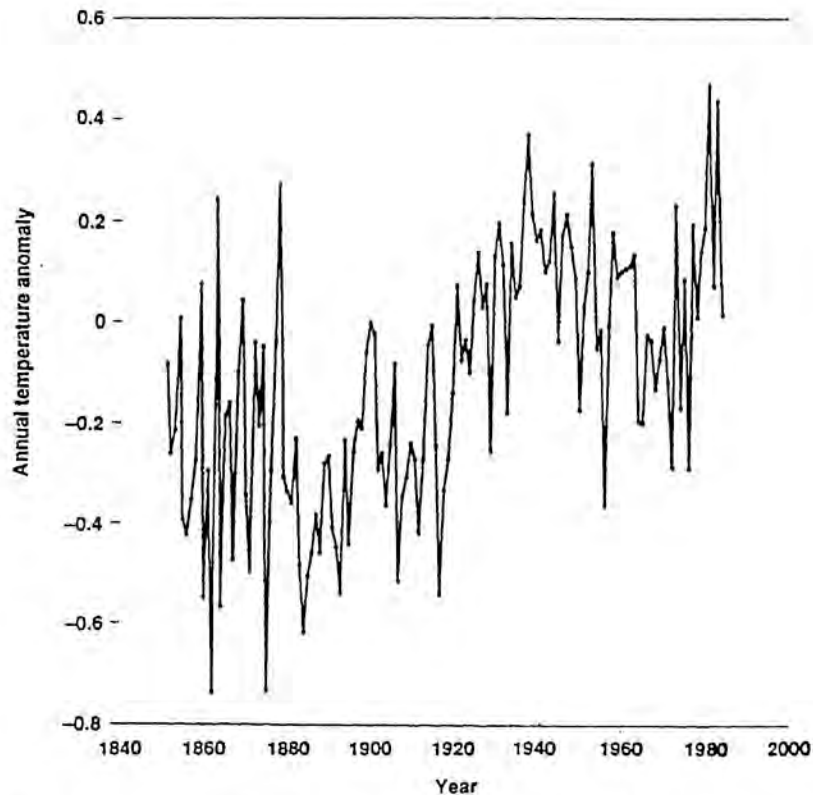
2. Average of points in previous figure.

Notice the vertical scale in the above diagrams. Relative to the variability in the data, the changes in the globally averaged temperature anomaly look negligible.

Deviations of Annual MeanTemperature from Long-term Average

Temperature Anomaly (°C)

1. Data points averaged to obtain time record of global mean temperature. Note points range from less than -2C to more than +2C.

Source: S. L. Grotch, Lawrence Livermore Laboratory, Livermore California

CRU NH Average Annual Anomalies (1851-1984)

Annual temperature anomaly

3. Curve in previous figure stretched to fill graph. Note that range is now from about -0.6C to +0.3C.

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April 30, 2008
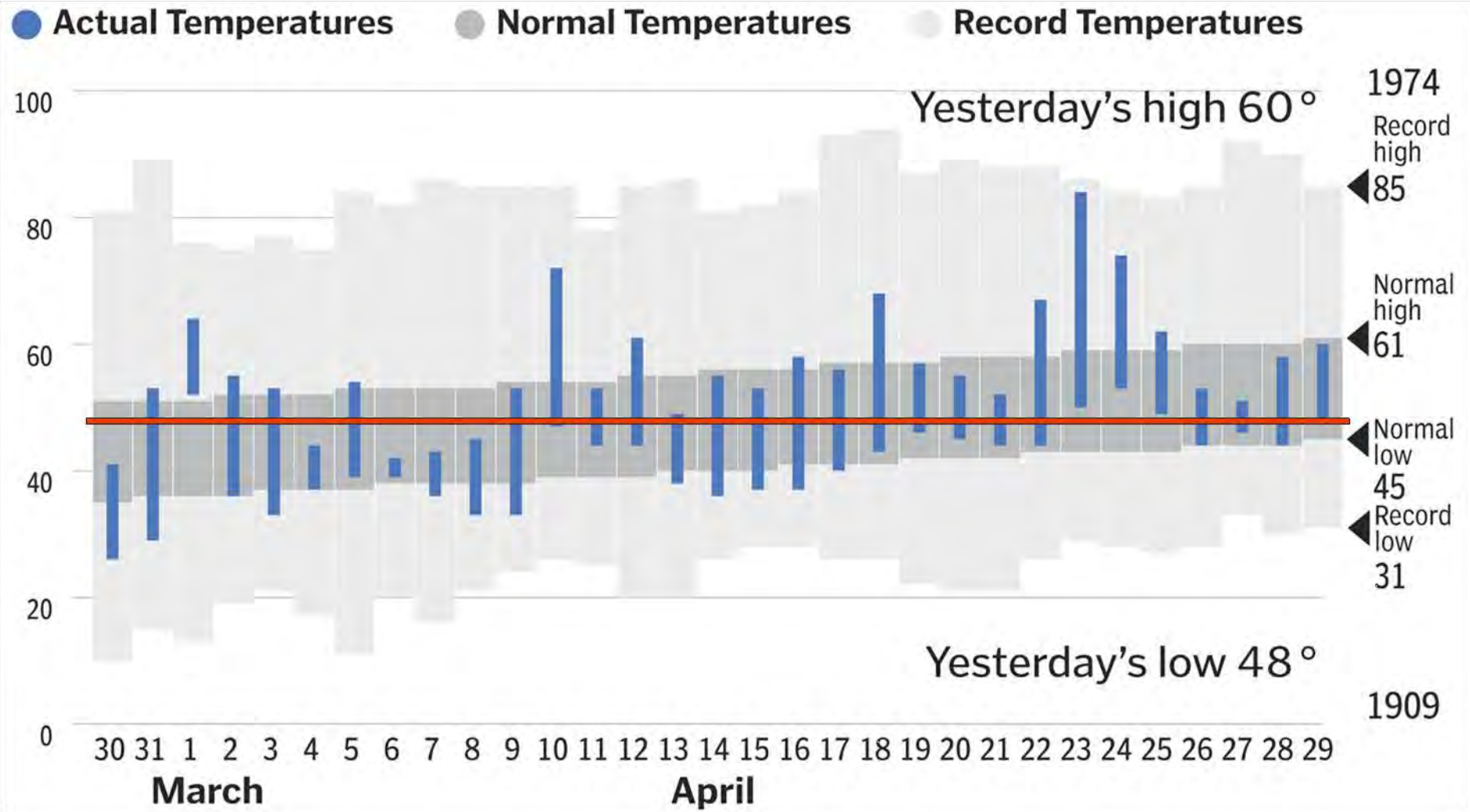
One month's record of high and low temperatures for Boston.

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An obvious approach to measuring feedbacks would be to see how outgoing radiation responds to surface temperature fluctuations, but it has difficulties.

Feedback Schematic

Net incoming solar radiation
Outgoing heat radiation

Added greenhouse gas

Change in radiative substances (water vapor and clouds) resulting from warming

Initially, net incoming solar radiation and outgoing heat radiation are in balance.

Added greenhouse gas initially reduces outgoing radiation, leading to warming until outgoing radiation again balances incoming radiation.

Warming, in turn, causes changes in radiative substances or feedback. In models, this causes further reduction in outgoing radiation, leading to still more warming.

The crucial point about the feedbacks is that they respond to surface temperature fluctuations regardless of the origin of the fluctuations.

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.

Time scales on the order of 1-3 months are, thus, certainly appropriate for sensitivity studies. Longer time scales also involve 'pollution' from seasonal effects, etc. This is the approach taken in Lindzen and Choi (2009, 2011).

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.

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.

Lindzen and Choi, 2011, describes how we deal with these issues. **Here, I will simply describe the signature of the second problem: namely, when one has an unambiguous feedback, a plot of r^2 and/or $\Delta F/\Delta T$ v. Lag has a single maximum at a small lag. If, however, the non-feedback variations are large, then these relations have an S-shape, and the regression at zero lag can be completely misleading.**

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.
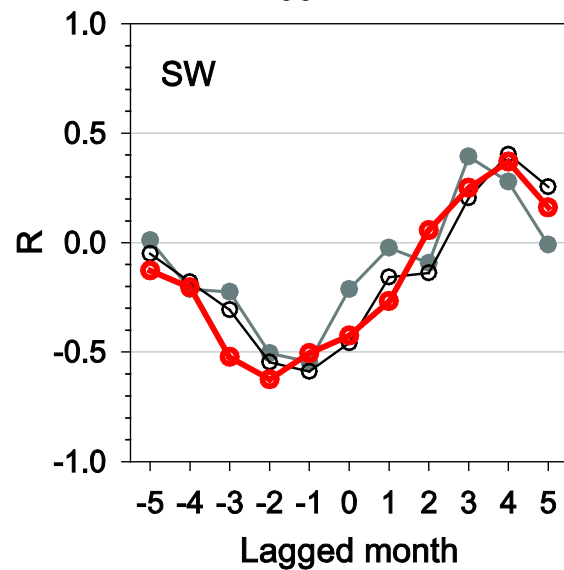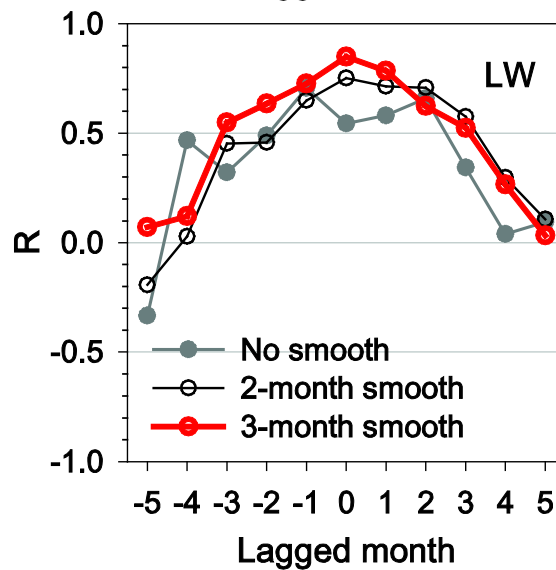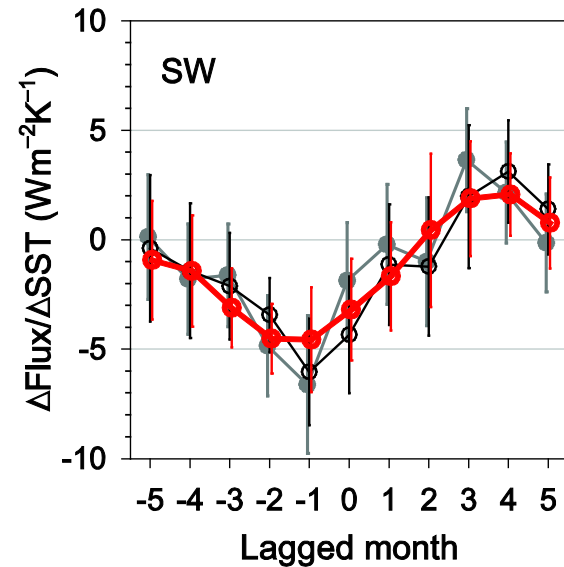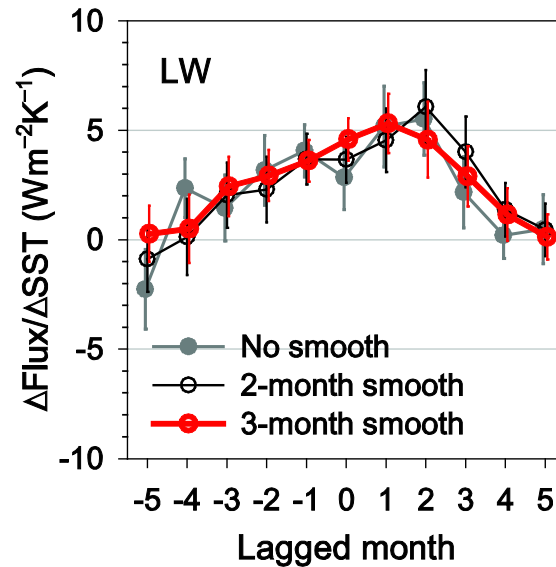
The data used by Dessler (2010) was subjected to our approach in two steps. In A we contrast Dessler's simple regression approach with our use of appropriate segments. We actually get a bigger 'apparent' positive feedback with a much larger r^2. In B, we subject both Dessler's method and ours to lead-lag 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.
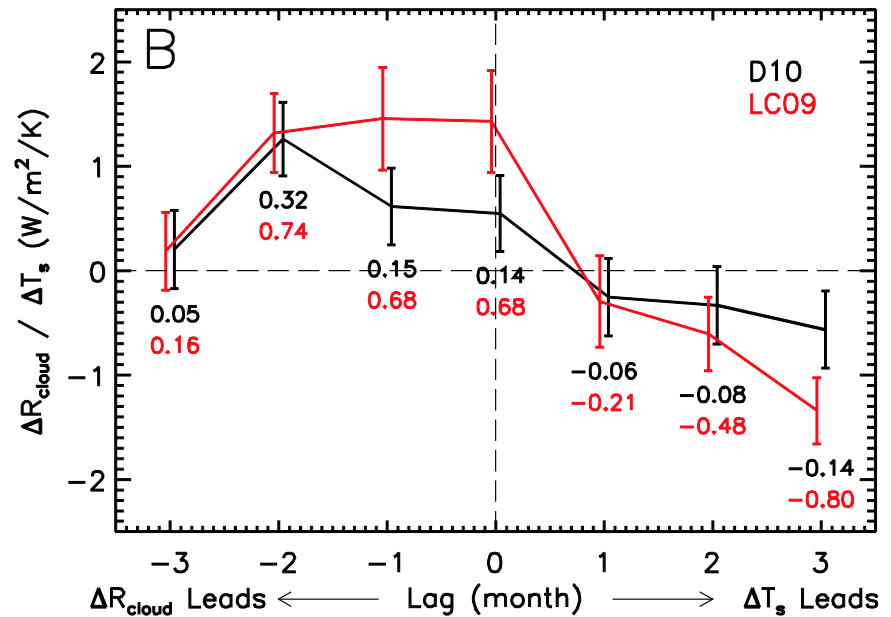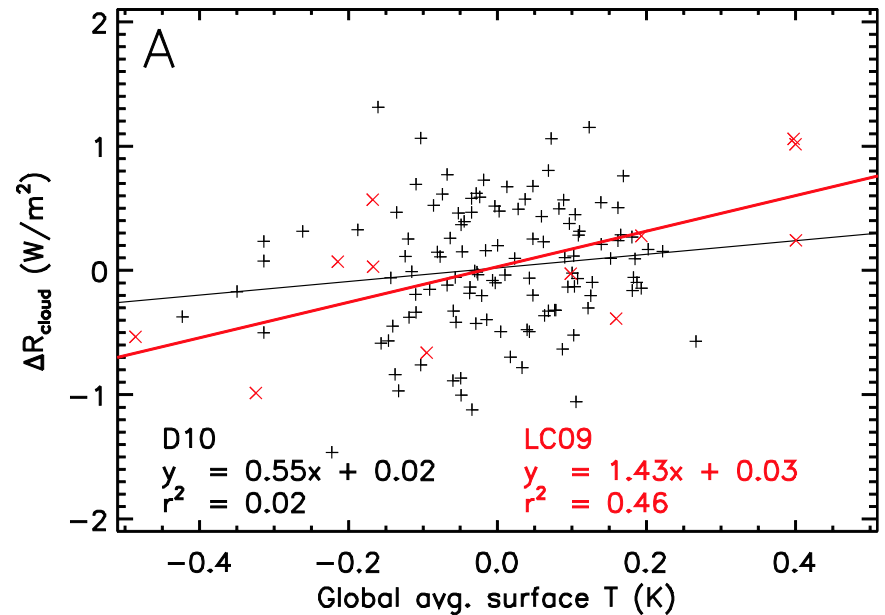
Lindzen and Choi, 2011, show that all IPCC models are consistent with positive (amplifying) feedbacks, but that the observations are not.
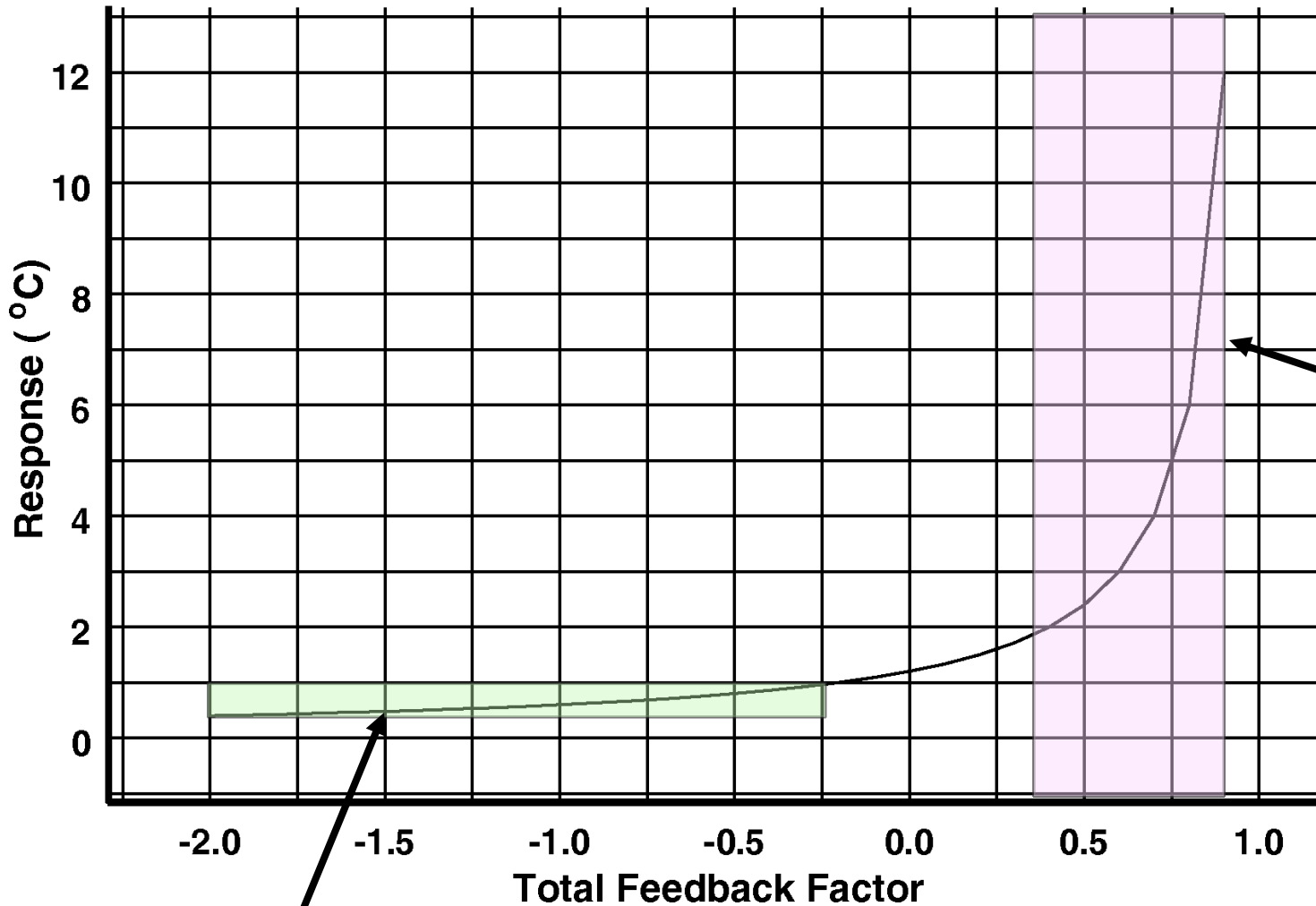
Models

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

Response as a function of Total Feedback Factor
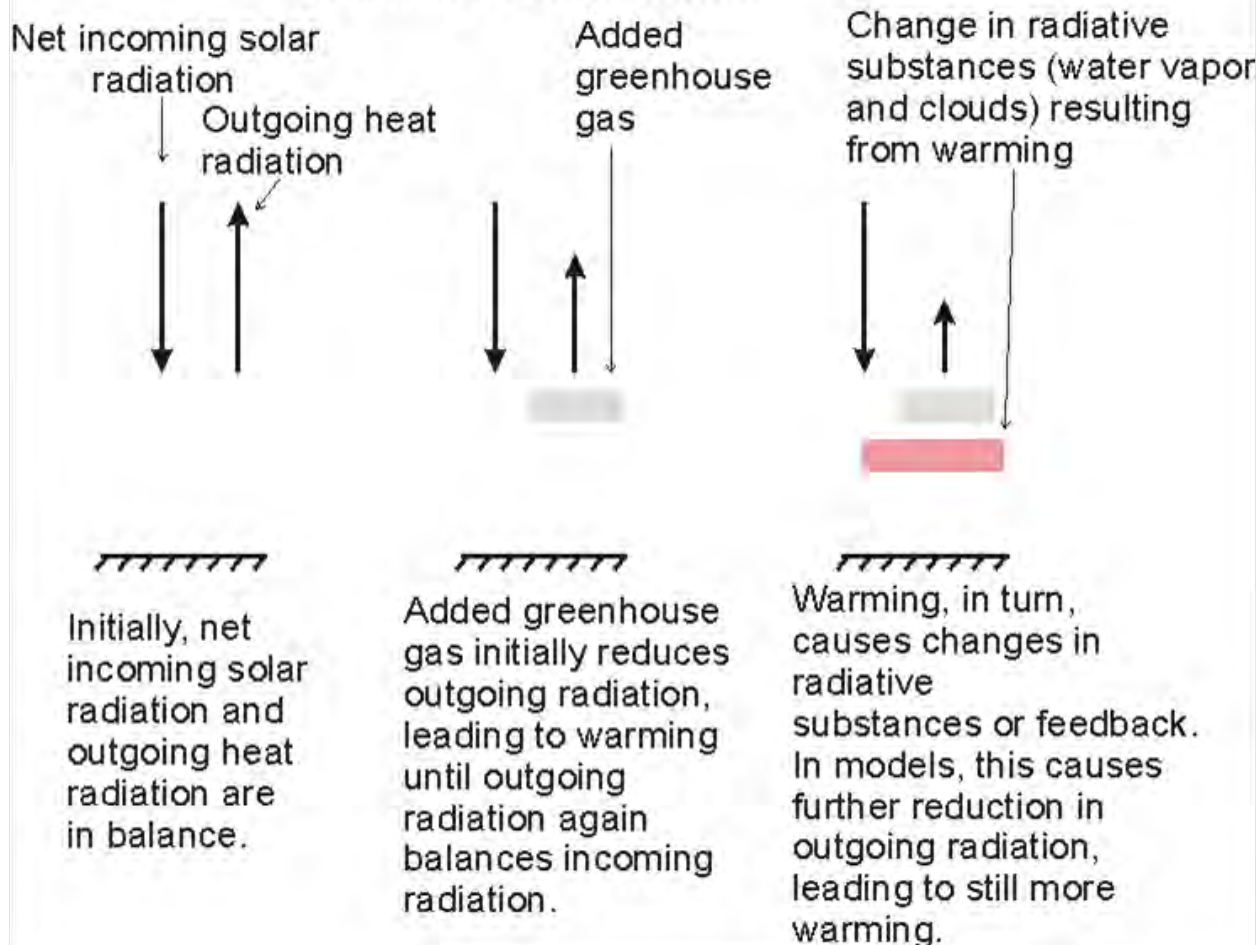

For positive feedbacks, relatively small variations in feedback lead to large changes in response.

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.

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

Recall that the approximate non-divergence of flux allows us to relate the top of the atmosphere fluxes in the figure explaining feedbacks to surface fluxes. It turns out that heat fluxes at the surface are dominated by latent heat fluxes (ie evaporation).

Feedback Schematic

Net incoming solar radiation

Outgoing heat radiation

Added greenhouse gas

Change in radiative substances (water vapor and clouds) resulting from warming

Initially, net incoming solar radiation and outgoing heat radiation are in balance.

Added greenhouse gas initially reduces outgoing radiation, leading to warming until outgoing radiation again balances incoming radiation.

Warming, in turn, causes changes in radiative substances or feedback. In models, this causes further reduction in outgoing radiation, leading to still more warming.

The radiative imbalance in the third panel determines the climate sensitivity and hence the change in temperature once the system re-equilibrates. At the surface, the imbalance will be approximately between the net incoming solar radiation and the evaporation.

For simplicity, let's ignore shortwave feedbacks. Then the net incoming solar flux remains constant. Initially, evaporation balances net incoming solar flux, and after equilibration, evaporation once again must equal the net incoming solar flux, but the temperature will be different. Thus, relative humidity must change so as to prevent evaporation from increasing. This is a surprising result, since the heart of the positive water vapor feedback is the assumed constancy of relative humidity. In point of fact, rh does not have to change much to hold evaporation constant and even in models, rh varies with warming.

At short time scales, the change in evaporation will have to match the climate sensitivity. To be sure, this depends on the absence of short wave feedbacks and on ignoring sensible heat flux – both of which may be serious (and are being looked at in a more serious study). However, as an exercise in numerology, it is interesting to look at some results.

Wentz, F.J. et al (How much more rain will global warming bring. *ScienceExpress*, **31** May 2007) used bulk aerodynamic formulas 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 essentially $\Delta T/\Delta F$.

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.

My last point is that feedback factors are not constant. In point of fact, feedback factors can vary because cloud radiative properties are modified by aerosols and possibly by cosmic rays.
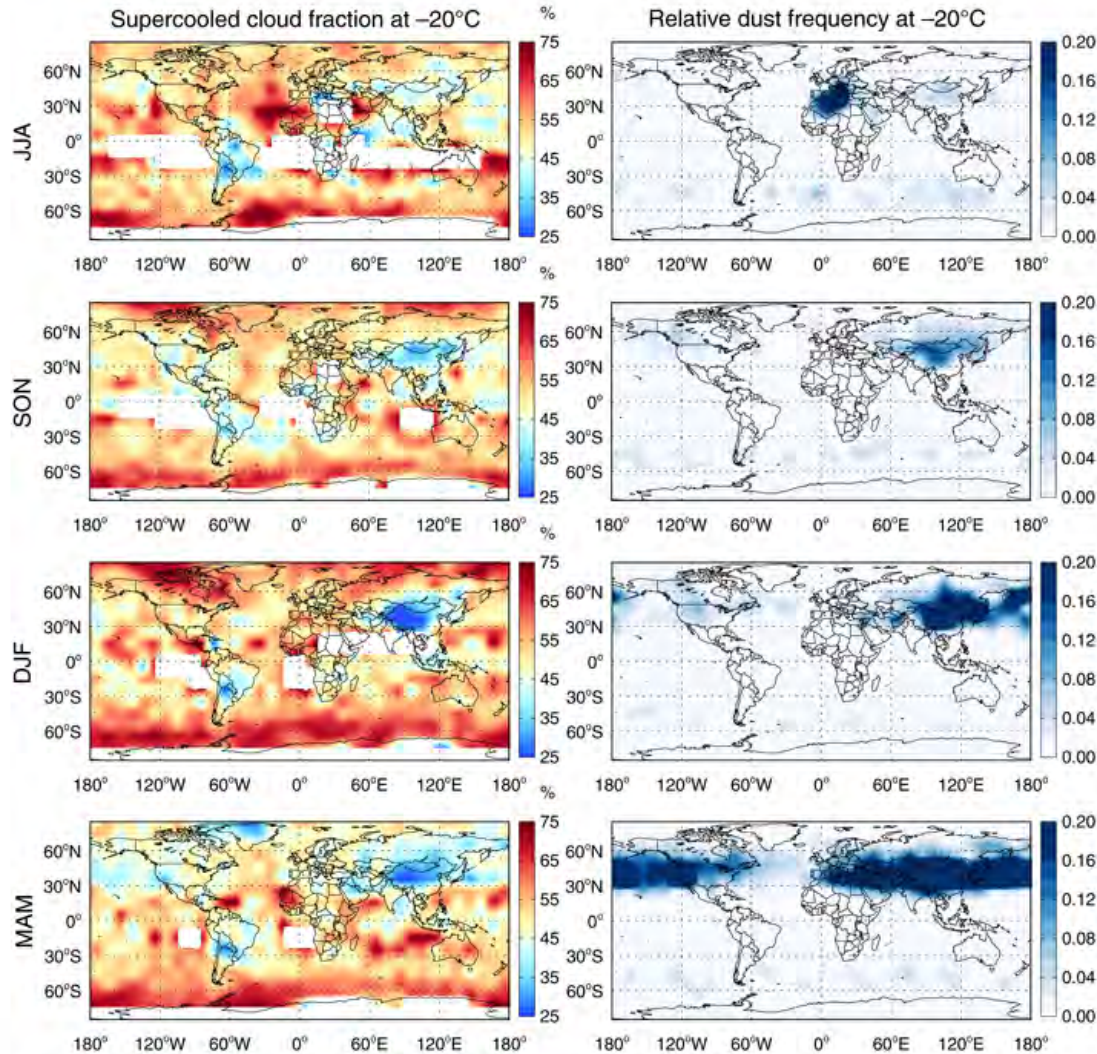

Given this, it seems likely that if the feedback factor is around 0.8, then sometime during the earth's 4.5 billion years, it exceeded one.

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.

Choi et al.

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I would suggest that if the sensitivity were really around 5C for a doubling of CO_2, then we would not be here discussing it.