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On the observational determination of climate sensitivity and its implications

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It is usually claimed that the heart of the global warming issue is so-called greenhouse warming. This simply refers to the fact that the earth balances the heat received from the sun (mostly in the visible spectrum) by radiating in the infrared portion of the spectrum back to space. Gases that are relatively transparent to visible light but strongly absorbent in the infrared (greenhouse gases) will interfere with the cooling of the planet, thus forcing it to become warmer in order to emit sufficient infrared radiation to balance the net incoming sunlight. By the net incoming sunlight, we mean that portion of the sun's radiation that is not reflected back to space by clouds and the earth's surface. The issue then focuses on a particular greenhouse gas, carbon dioxide. Although carbon dioxide is a relatively minor greenhouse gas, it has increased significantly since the beginning of the industrial age from about 280 ppmv to about 390 ppmv, and it is widely accepted that this increase is primarily due to man's emissions. However, it is also widely accepted that the warming from a doubling of carbon dioxide would only be about 1°C (based on simple Planck black body calculations; it is also the case that a doubling of any concentration in ppmv produces the same warming because of the logarithmic dependence of carbon dioxide's absorption on the amount of carbon dioxide).

This amount of warming is not considered catastrophic, and, more importantly, this is much less than current climate models suggest the warming from a doubling of carbon dioxide will be. The usual claim from the models is that a doubling of carbon dioxide will lead to warming of from 1.5°C to 5°C and even more. What then is really fundamental to alarming predictions? It is the 'feedback' within models from the much more important greenhouse substances, water vapor and clouds. Within all current climate models, water vapor increases with increasing temperature so as to further inhibit infrared cooling. Clouds also change so that their net effect resulting from both their infrared absorptivity and their visible reflectivity is to further reduce the net cooling of the earth. These feedbacks are still acknowledged to be highly uncertain, but the fact that these feedbacks are strongly positive in most models is considered to be a significant indication that the result has to be basically correct. Methodologically, this is a most peculiar approach to such an important issue. In normal science, one would seek an observational test of the issue. As it turns out, it is relatively easy to test the issue with existing data from satellites and there has recently been a paper (Lindzen and Choi, 2009) that has done this.

A little bit of simple theory shows how one can go about doing this. In the absence of feedbacks, the behavior of the climate system can be described by the following illustration.

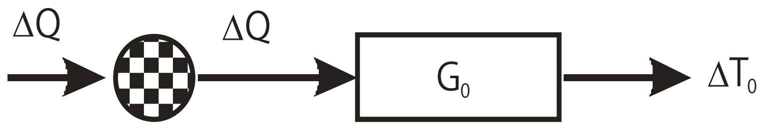

Fig. 1. A schematic for the behavior of the climate system in the absence of feedbacks.

ΔQ is the radiative forcing, G_0 is the zero-feedback response function of the climate system, and ΔT_0 is the response of the climate system in the absence of feedbacks. The checkered circle is a node. Fig. 1 symbolizes the temperature increment, ΔT_0, that a forcing increment, ΔQ, would produce with no feedback,

$$\Delta T_0 = G_0 \Delta Q \qquad (1)$$

It is generally accepted (Hartmann, 1994) that without feedback, doubling of carbon dioxide will cause a forcing of $\Delta Q \approx 3.7\ \mathrm{Wm}^{-2}$ (due to the black body response), and will increase the temperature by $\Delta T_0 \approx 1^o\mathrm{C}$. We therefore take the zero-feedback response function of (1) to be $G_0 = (1/3.7)\ ^o\mathrm{C\ W^{-1}m^2}$ for the earth as a whole.

With feedback, Fig. 1 is modified to

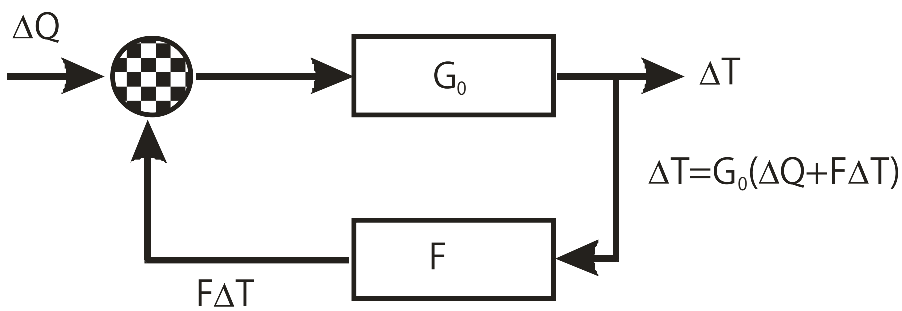

Fig. 2. A schematic for the behavior of the climate system in the presence of feedbacks.

The response is now

$$\Delta T = G_0(\Delta Q + F\Delta T) \qquad (2)$$

Here F is a feedback function that represents all changes in the climate system (for example, changes in cloud cover or humidity) that act to increase or decrease feedback-free effects. Thus, F should not include the response to ΔT that is already incorporated into G_0. However, it turns out that one can use zero for the tropics with little error. This will be explained in more detail in the additional comments that are at the end of this paper.

Solving (2) for the temperature increment ΔT we find

$$\Delta T = \frac{\Delta T_0}{1-f}. \qquad (3)$$

The dimensionless feedback fraction is $f = F\,G_0$.

From Figure 2, the relation of the change in flux, Δ Flux, to the change in temperature is given by

$$\Delta\ \text{Flux} = -\frac{f}{G_0}\Delta T. \tag{4}$$

The quantity on the left side of the equation is the amount by which feedbacks supplement the zero-feedback response to ΔQ. For the tropics, this corresponds to the observed flux changes. At this point, it is crucial to recognize that our equations, thus far, are predicated on the assumption that the ΔT to which the feedbacks are responding is that produced by ΔQ. Physically, however, any fluctuation in ΔT should elicit the same flux regardless of the origin of ΔT. The corresponding Δ Flux will be this flux minus the zero-feedback contribution from ΔT. When looking at the observations, we emphasize this by rewriting (4) as

$$\Delta\ \text{Flux} = -\frac{f}{G_0}\Delta \text{SST} \tag{5}$$

Here we can identify Δ Flux as the change in the outgoing longwave and shortwave radiation flux measured by satellites associated with the measured ΔSST, the change of the sea-surface temperature. If we plot Δ Flux versus ΔSST, we expect to find a straight line with a slope of $-f/G_0$. Since we know the value of G_0, the experimentally determined slope allows us to evaluate the magnitude and sign of the feedback factor f. Note that the natural forcing, ΔSST, that can be observed, is different from the equilibrium response temperature ΔT in Eq. (3). The latter cannot be observed since, for the short intervals considered, the system cannot be in equilibrium, and over the much longer periods needed for equilibration of the whole climate system, Δ Flux at the top of the atmosphere is restored to zero. Indeed, as explained in Lindzen and Choi (2009), it is, in fact, essential, that the time intervals considered, be short compared to the time it takes for the system to equilibrate, while long compared to the time scale on which the feedback processes operate. The latter is on the order of a day, while the former depends on the climate sensitivity, and ranges from years for sensitivities of 0.5°C for a doubling of CO_2 to many decades for higher sensitivities (Lindzen and Giannitsis, 1998).

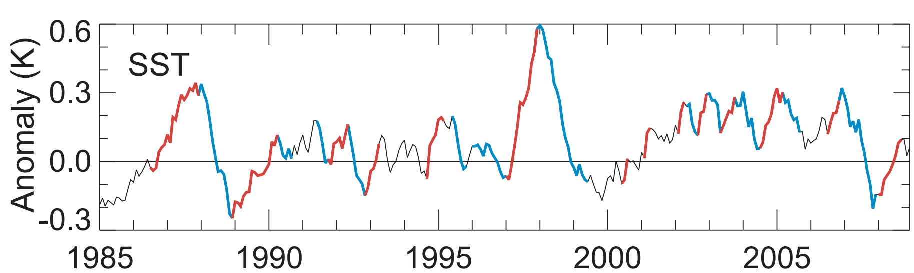

Fig. 3. Tropical mean (20°S to 20°N latitude) monthly sea surface temperature anomalies; the anomalies are referenced to the monthly means for the period of 1985 through 1989. Red and blue colors indicate the major temperature fluctuations exceeding 0.1°C.

Now, it turns out that sea surface temperature is measured (Kanamitsu et al., 2002), and is always fluctuating as we see from Fig. 3. In addition, the net outgoing radiative flux from the earth has been monitored since 1985 by the ERBE satellite, and since 2000 by the CERES instrument aboard the Terra satellite (Wielicki et al., 1998). The results for both long wave (infrared) radiation and short wave (visible) radiation are shown in Fig. 4. The sum is the net flux.

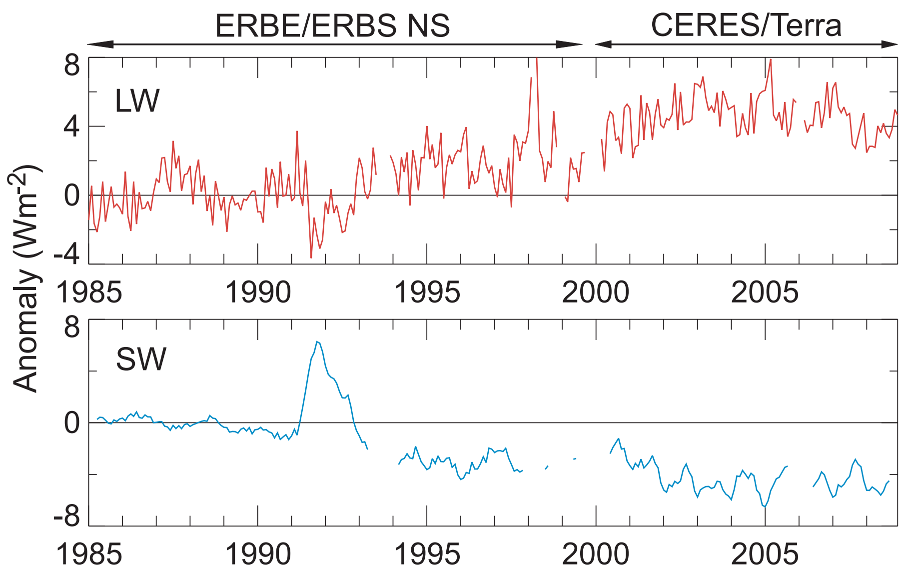

Fig. 4. The same as Fig. 3 but for outgoing longwave (red) and reflected shortwave (blue) radiation from ERBE and CERES satellite instruments.

Finally, the AMIP (atmospheric model intercomparison projects) program that is responsible for intercomparing models used by the IPCC (the Intergovernmental Panel on Climate Change), has obtained the calculated changes in both short and long wave radiation from models forced by the observed sea surface temperatures shown in Fig. 3. These results are shown in Figs. 5 and 6 where the observed results are also plotted for comparison. We can already see that there are significant differences.

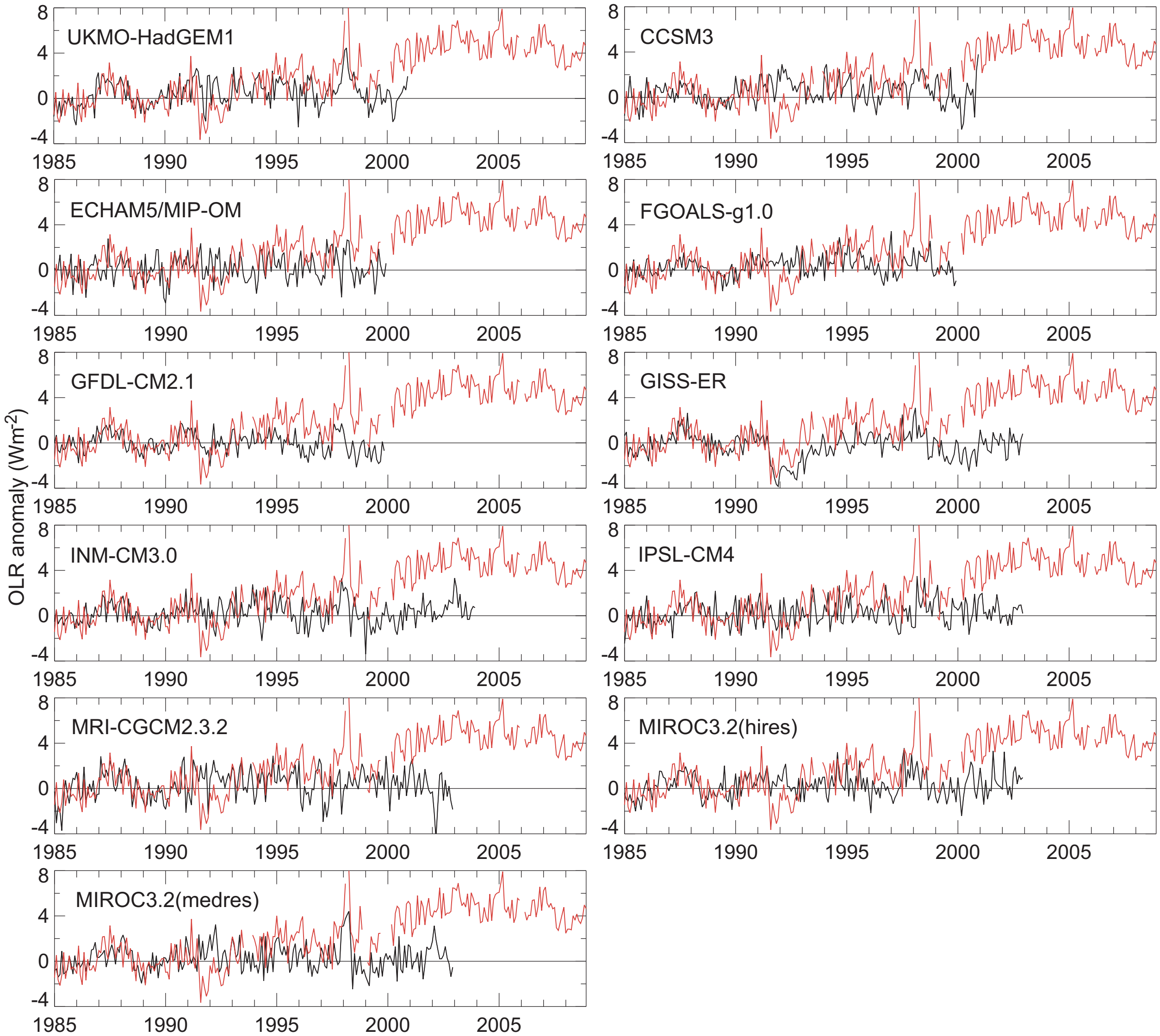

Fig. 5. Comparison of outgoing longwave radiations from AMIP models (black) and the observations (red).

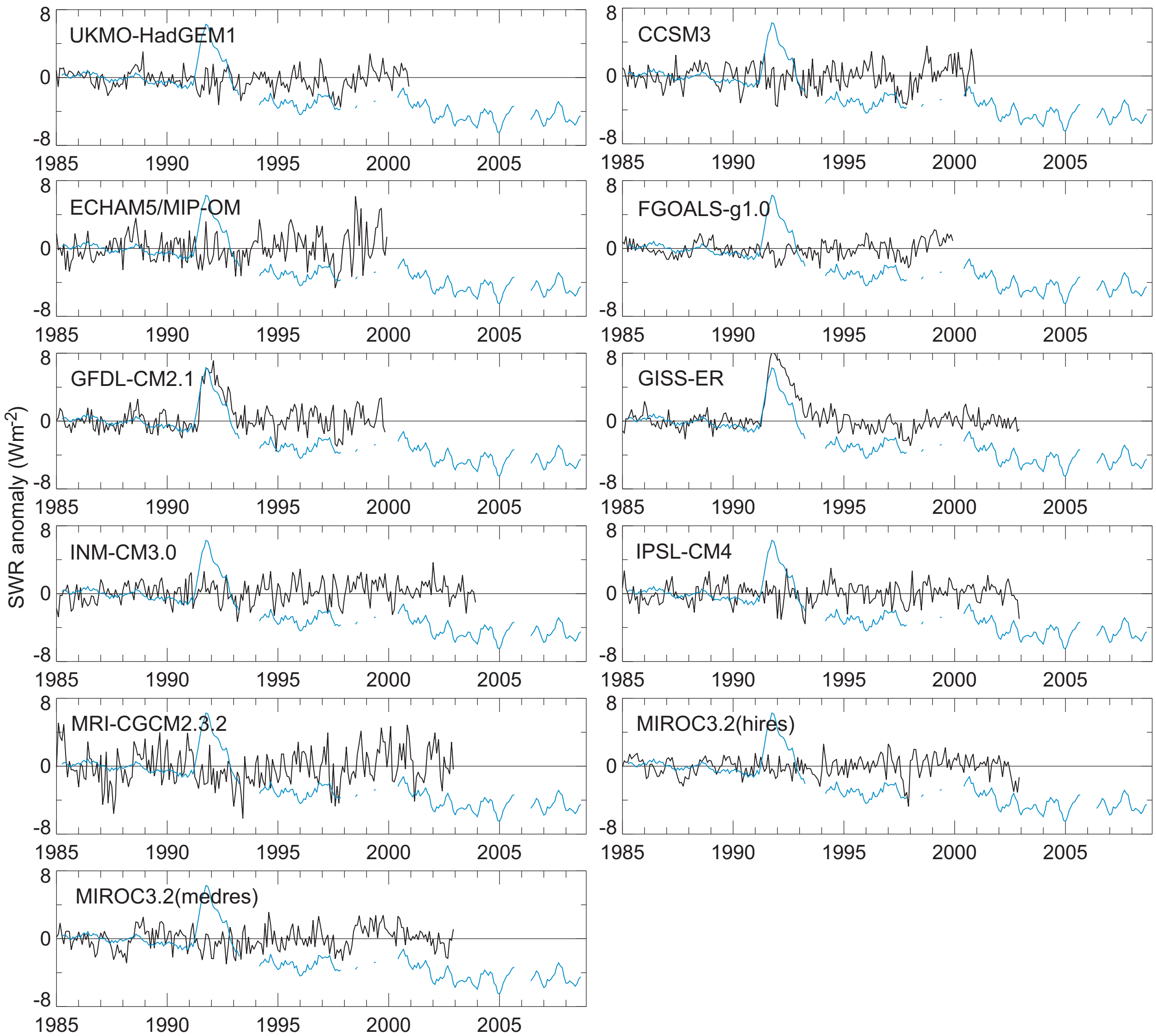

Fig. 6. Comparison of reflected shortwave radiations from AMIP models (black) and the observations (blue).

With all the above readily available, it is now possible to directly test the ability of models to adequately simulate the sensitivity of climate. The procedure is simply to identify intervals of change for ΔSST in Fig. 3 (for reasons we will discuss at the end, it is advisable to restrict oneself to changes greater than 0.1°C), and for each such interval, to find the change in flux. The change in flux is simply $-F\Delta$SST and the slope is $-F$. The results for the IPCC models are shown in Fig. 7. Not surprisingly, each model displays a negative slope consistent with the dominance of positive feedbacks in these models. This usefully confirms our methodology. In Fig. 8, we show the results for the observations. The result is quite fascinating. The slope is positive and greater in magnitude than the slopes in Fig. 7. That is, nature differs from all models and displays a strong negative feedback. Note that N for the data differs from the N's for the models because model output was not available for all time intervals.

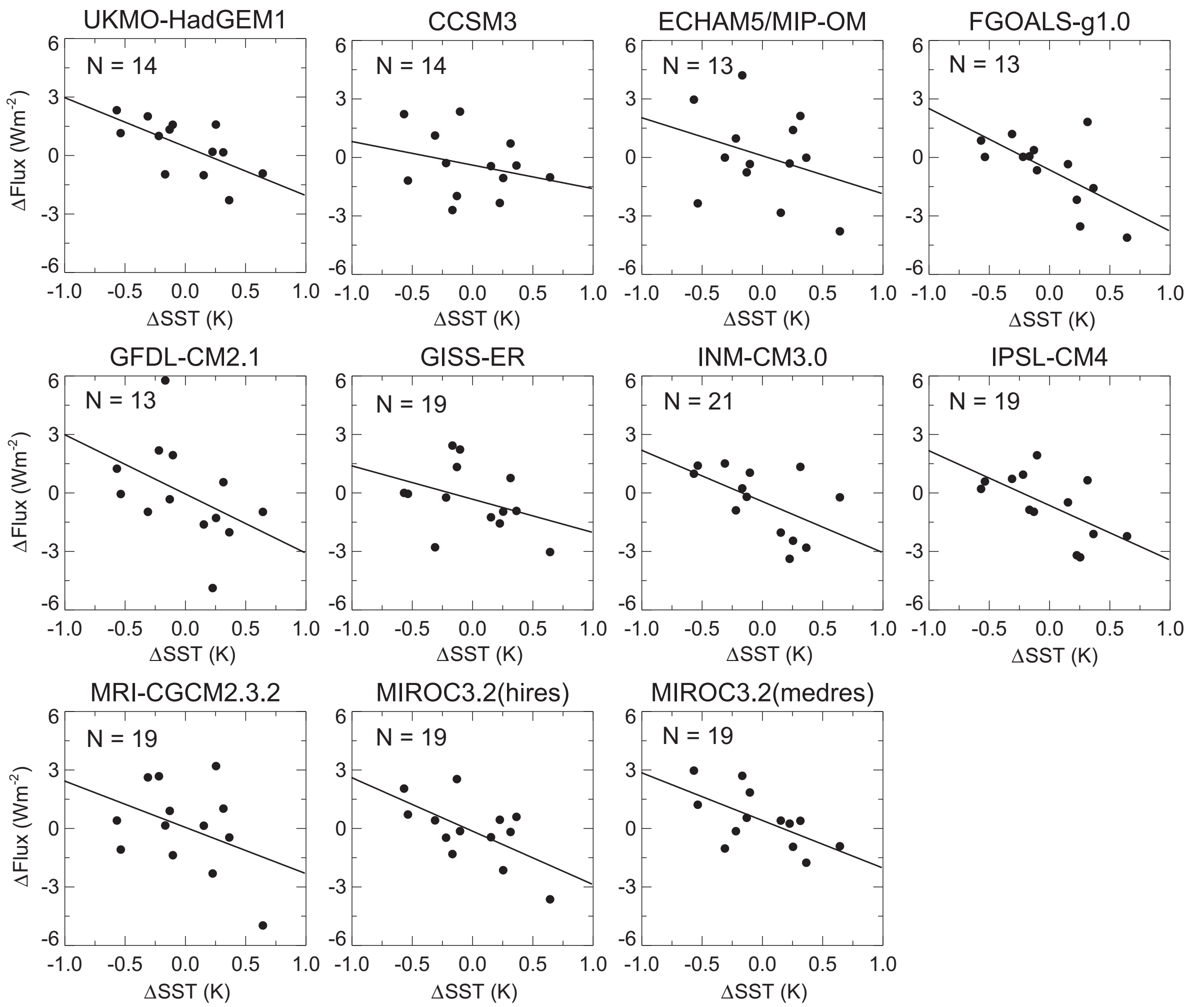

Fig. 7. Scatterplots of net ΔFlux against ΔSST for 11 AMIP models.

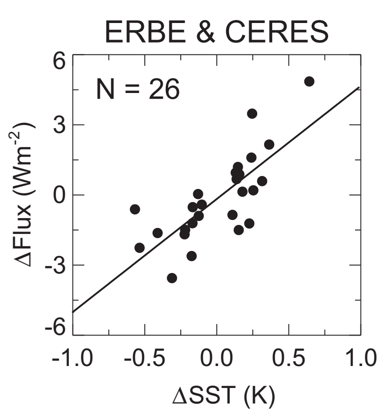

Fig. 8. The same as Fig. 7 but for the ERBE and CERES observations.

The implications of this for climate sensitivity (i.e., the warming from a doubling of carbon dioxide) are readily obtained from Eq. (3), and are plotted in Fig. 9. We note that for *f* greater than about 0.5 (as is the case for all models), uncertainties in flux make it impossible to distinguish sensitivities in the range of about 1.5°C to infinity. As noted by Roe and Baker (2007), this is probably why the range of model generated climate sensitivity has not diminished since the 1979 Charney report. To be sure, the upper bound is rarely reported as being infinite. However, this is almost certainly due to the fact that the sensitivity determines the degree of coupling between the ocean surface and the atmosphere, and that, therefore, the response time of the system goes to infinity as the sensitivity goes to infinity (Lindzen and Giannitsis, 1998). By a sensitivity of 5°C the response time is on the order of centuries, and the computer runs made to estimate sensitivity rarely are sufficiently long to determine larger sensitivities. From Fig. 9, we see that no such problem pertains to nature, where *f* appears to be approximately –1. To be sure, the data used is from the tropics. If there is no feedback from the extratropics, then the tropical flux would have to be shared over the globe, and *f* would be cut in half. This would still leave the sensitivity small.

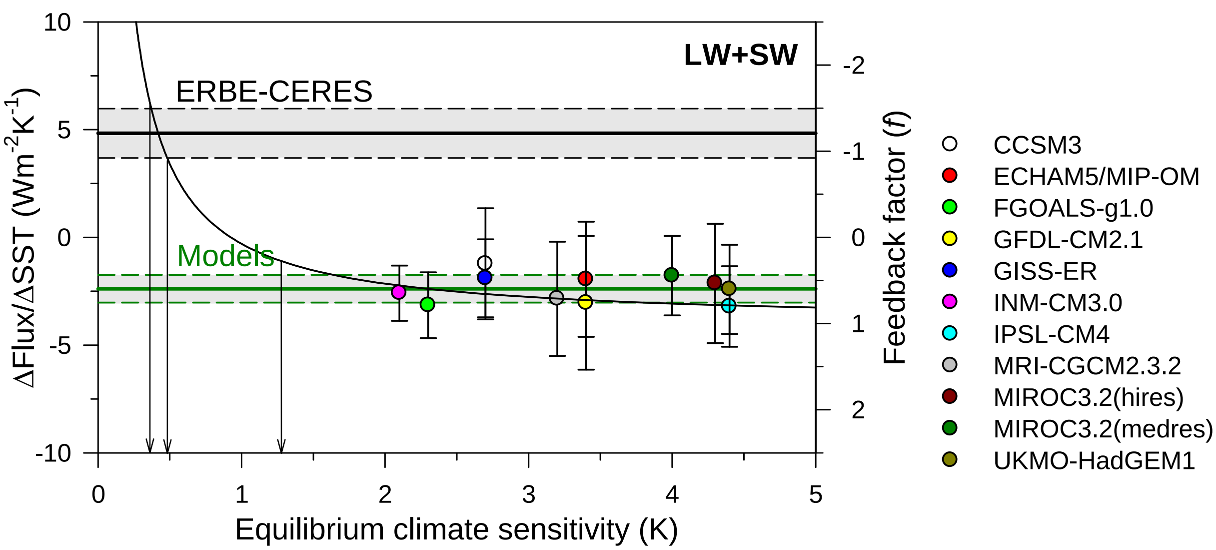

Fig. 9. Net ΔFlux/ΔSST and *f* with respect to the equilibrium climate sensitivity to a doubling of carbon dioxide. Gray bands indicate uncertainty (±1σ standard error). Note that for negative feedback the uncertainty in *f* does not produce much change in sensitivity. However, for positive feedbacks this is not the case.

Since our analysis of the data only demands relative instrumental stability over short periods, it is difficult to see what data problems might change our results significantly. The addition of CERES data to the ERBE data used by Lindzen and Choi (2009) certainly does little to change their results (It is also true for the case that CERES data is only used.). The inescapable conclusion is that all current models greatly exaggerate climate sensitivity, and that current concerns are largely baseless. It also suggests, incidentally, that in current coupled atmosphere-ocean models, that the atmosphere and ocean are too weakly coupled since coupling is inversely proportional to sensitivity (Lindzen and Giannitsis, 1998). It has been noted by Newman et al. (2009) that coupling is crucial to the simulation of phenomena like El Nino. Thus, corrections of the sensitivity of current climate models might well improve the behavior of coupled models. It should also be noted that there have been independent tests that also suggest sensitivities less than predicted by current models though these tests were not as direct as the present test (Lindzen and Giannitsis, 1998, based on response time to sequences of volcanic eruptions; Lindzen, 2007, and Douglass et al., 2007, both based on the vertical structure of observed versus modeled temperature increase; and Schwartz, 2007, 2008, based on ocean heating). Most claims of greater sensitivity are based on the models that we have just shown are highly misleading on this matter. There have been attempts to infer sensitivity from paleoclimate data (Hansen, 1993), but these are not really tests since the forcing is essentially unknown and may be adjusted to produce any sensitivity one wishes. Thus, the overwhelming evidence is that climate sensitivity is low. It is important to note that climate sensitivity is essentially a single number. Economists who treat climate sensitivity as a probability distribution function (Weitzman, 2009, Stern, 2008, Sokolov et al., 2009) are mistakenly confusing model uncertainty concerning this particular number with the existence of a real range of possibility.

One final point needs to be made. Low sensitivity of global mean temperature anomaly to global scale forcing does not imply that major climate change cannot occur. The earth has, of course, experienced major cool periods such as those associated with ice ages and warm periods such as the Eocene (Crowley and North, 1991). As noted, however, in Lindzen (1993), these episodes were primarily associated with changes in the equator-to-pole temperature difference and spatially heterogeneous forcing. Changes in global mean temperature were simply the residue of such changes and not the cause. It is worth noting that current climate GCMs have not been very successful in simulating these *changes* in past climate.

Additional Comments

1. The smaller fluctuations in temperature in Fig. 3 may well represent instrumental noise. Therefore, we examined the impact of thresholds for ΔSST on the statistics of the results. Of course, setting too high a threshold reduces the number of samples. Table 1 summarizes the results for intervals for with ΔSST exceeded 0.1 K, 0.2 K, …, for 3, 5, and 7 month time smoothing, for all monthly intervals. The result implies that a threshold of approximately 0.1°C for unfiltered time series is optimal.

Table 1. Regression statistics between net ΔFlux and ΔSST for observations and models. SW is filtered with 7-month smoother in all cases. The smaller number for model results is due to the shorter data period than ERBE-CERES merged data.

Case	ERBE-CERES merged data				Model average			
	N	R	SE	Slope	N	R	SE	Slope
0.1 K, Unfiltered	26	0.76	1.14	4.83	16.64	–0.45	2.20	–2.39
0.2 K, Unfiltered	13	0.80	1.38	4.94	9.09	–0.54	1.73	–2.21
0.3 K, Unfiltered	7	0.86	1.34	4.98	6.00	–0.58	1.49	–2.00
0.4 K, Unfiltered	4	0.96	1.32	5.42	3.00	–0.88	1.54	–2.62
0.1 K, 3 months	6	0.83	1.8	5.60	5.00	–0.64	1.46	–2.14
0.1 K, 5 months	5	0.78	3.95	8.59	4.00	–0.34	2.02	–1.60
0.1 K, 7 months	4	0.93	1.83	9.26	4.00	–0.21	3.37	–1.51
0.2 K, 3 months	5	0.90	1.84	6.30	4.00	–0.61	1.33	–1.99
0.2 K, 5 months	3	0.95	6.89	11.4	3.00	–0.49	1.82	–2.73
Monthly interval	244	0.01	36.03	0.25	202.82	–0.06	13.96	–1.71
0.05 K, Monthly	80	–0.06	2.3	–1.14	61.36	–0.12	2.62	–2.32
0.1 K, Monthly	8	0.15	3.96	1.68	6.64	–0.34	5.25	–4.82

*N: data number, R: Correlation coefficient, SE: Standard error of the slope

2. While the present analysis is a direct test of feedback factors, it does not provide much insight into detailed mechanism. Nevertheless, separating the contributions to f from long wave and short wave contributions provides some interesting insights. The results are shown in the table below. It should be noted the consideration of the zero-feedback Planck response 4 W m^{-2} K^{-1} by Lindzen and Choi (2009) is not actually necessary for our measurements from the Tropics (see note 3). Accordingly, with respect to separating longwave and shortwave feedbacks, the interpretation by Lindzen and Choi (2009) needs to be corrected. This table shows recalculated feedback factors under the absence of the zero-feedback Planck response. The negative feedback from observations is largely from longwave radiation, while the positive feedback from models is primarily from shortwave radiation.

Table 2. Regression statistics for ΔOLR/ΔSST and ΔSWR/ΔSST, which are used for calculations of f_{LW} and f_{SW}, respectively.

	Longwave					Shortwave				
	N	R	SE	ΔOLR/ ΔSST	f_{LW}	N	R	SE	ΔSWR/ ΔSST	f_{SW}
ERBE-CERES	26	0.74	1.68	5.5	–1.38	26	–0.12	1.61	–0.67	0.17
Model average	16	0.32	2.06	1.48	–0.37	16	–0.58	2.44	–3.87	0.97

CCSM3	14	0.65	1.53	2	−0.50	14	−0.59	2.16	−3.23	0.81
ECHAM5/MIP-OM	13	0.12	2.12	0.43	−0.11	13	−0.29	3.98	−2.38	0.60
FGOALS-g1.0	13	−0.21	2.48	−0.99	0.25	13	−0.58	2.09	−2.16	0.54
GFDL-CM2.1	13	0.24	2.24	0.77	−0.19	13	−0.55	3.36	−3.8	0.95
GISS-ER	19	0.18	1.96	0.83	−0.21	19	−0.38	2.3	−2.73	0.68
INM-CM3.0	21	0.66	1.44	3.42	−0.86	21	−0.86	1.42	−6.01	1.50
IPSL-CM4	19	0.24	1.58	0.99	−0.25	19	−0.68	1.89	−4.2	1.05
MRI-CGCM2.3.2	19	−0.08	1.98	−0.46	0.12	19	−0.48	1.56	−2.38	0.60
MIROC3.2(hires)	19	0.45	2.22	2.35	−0.59	19	−0.57	2.52	−4.5	1.13
MIROC3.2(medres)	19	0.63	1.54	3.14	−0.79	19	−0.63	2.6	−4.93	1.23
UKMO-HadGEM1	14	0.61	3.56	3.84	−0.96	14	−0.79	3	−6.25	1.56

*f_{LW}: longwave feedback, f_{SW}: shortwave feedback

As concerns the infrared, there is, indeed, evidence for a positive water vapor feedback (Soden et al., 2005), but, if this is true, this feedback is presumably cancelled by a negative infrared feedback such as that proposed by Lindzen et al. (2001) in their paper on the iris effect. The absence of a positive long wave feedback in the models is somewhat puzzling, but it is possible that the so-called lapse rate feedback as well as negative longwave cloud feedback serves to cancel the TOA OLR feedback. The table implies that TOA longwave and shortwave contributions are tightly coupled in models (the correlation coefficient between f_{LW} and f_{SW} from models is over −0.9.). This coupling most likely is associated with the primary clouds in models — optically thick high-top clouds (Webb et al., 2006). As Webb et al. (2006) showed, in most climate models, the feedbacks from these clouds are simulated to be negative in longwave and strong positive in shortwave, and dominate the entire cloud feedback (Webb et al., 2006). Therefore, the cloud feedbacks must also serve to contribute to the negative OLR feedback and the positive SWR feedback in the table. New spaceborne data from CALIPSO lidar (CALIOP; Winker et al., 2007) and CloudSat radar (CPR; Im et al., 2005) should provide a breakdown of cloud behavior with altitude which may give some insight into what exactly is contributing to the radiation.

3. . The identification of the zero-feedback contribution from the tropics is not altogether trivial. Calculations by Pierrehumbert (2009) suggest that this might be small. However, it turns out that Pierrehumbert fixed relative humidity which means that there was a feedback in his calculation. Fixing specific humidity leads to a large zero-feedback contribution, but including the fact that raising surface temperature leads to an increase in tropopause height (Lindzen, 1988) reduces this again to a small value. Perhaps the most practical approach is to ask what contribution leads to model results for feedback that are most consistent with model sensitivities. This too leads to contributions sufficiently small to be approximated by zero. Note that this is an example of what we regard as the appropriate use of models: namely, to sort out complex but specific interactions. The details of this matter will be presented in a separate paper.

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