Internal Radiative Forcing And The Illusion Of A Sensitive Climate System“

by

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SPPI Reprint Series

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1. Background

Many of us, especially those who were trained as meteorologists, have long questioned the climate research community's reliance on computerized climate models for global warming projections. In contrast to our perception that the real climate system is constantly readjusting to internal fluctuations in ways that stabilize the system, climate models built upon measured climate behavior invariably suggest a climate system that is quite sensitive - sometimes catastrophically sensitive — to perturbations such as those from anthropogenic greenhouse gas emissions. Unfortunately, it has been difficult to articulate our 'hand-waving' concerns in ways that the modelers would appreciate, i.e., through equations.

After years of pondering this issue, and after working on our two latest papers on feedbacks (Spencer et al., 2007; Spencer and Braswell, 2008, hereafter SB08), I believe that I can now explain the main reason for this dichotomy. Taking the example of clouds in the climate system, the issue can be introduced in the form of a question:

To what extent are climatic variations in clouds caused by temperature change (feedback), versus temperature change being the result of cloud variations?

I will demonstrate that the answer to this seemingly innocuous question has a huge impact on whether we view the climate system as either sensitive or insensitive. And since models, by necessity, are constructed based upon the observed behavior of the climate system, their behavior also depends on our interpretation of *what is causing what* in the climate system.

While my claim that causation is important might seem rather obvious to some, it has not been an overriding concern to many researchers whose publications suggest that one needs only to measure the co-variability between different variables - not the direction of causation between the variables - in order to diagnose feedbacks. For instance, Kiehl and Ramanathan (2006) have offered this definition of cloud feedback:

"The change in a cloud process associated with a fluctuation of the climate state represents a cloud-climate feedback."

While this definition accommodates the fact that causality can — and does — flow in both directions when clouds interact with other processes in the climate system, it unintentionally obscures an important process which can corrupt feedback estimates if not accounted for.

Here I will show with a simple climate model that those who have been diagnosing feedbacks in the climate system have, either knowingly or unknowingly, been assuming causation in only one direction, and that faulty assumption has biased their interpretation of climate sensitivity. That this source of bias is independent of time scale will be demonstrated with two examples: 1) daily noise in cloud cover, and 2) multi-decadal cloud cover changes assumed to be associated with low frequency modes of climate variability such as the Pacific Decadal Oscillation and El Nino/La Nina.

Finally, we will see that by taking the direction of causation into account, some previously published results which have remained puzzling now take on new meaning.

2. The 800-Pound Gorilla We've Missed: Internal Radiative Forcing

Researchers who diagnose feedbacks from observational data tend to view observed fluctuations in the climate system in the context of temperature changes causing other things to change, which can then feed back upon temperature. Yet we know that, at least in the case of clouds, there are a wide variety of non-feedback processes that can affect cloud formation and dissipation, thus impacting the planetary albedo and Earth's radiative budget. The complexity of the processes which affect clouds was one of the central messages in Stephens' (2005) extensive and critical review of cloud feedback.

Non-feedback radiative changes internal to the climate system would most easily be envisioned when the general circulation of the atmosphere undergoes fluctuations. Horizontal temperature gradients, inversion location and strength, wind shear, and even land cover changes are potential sources of top-of-atmosphere (TOA) variations in the Earth's radiative energy budget which do not have to be caused by a change in surface temperature *per se*.

For instance, it has been shown that daily noise in cloud cover can cause temperature variability that "looks like" positive cloud feedback (SB08). But it turns out that this was just one example of a more general problem, a problem which amounts to the omission of a heating term in the heat budget equation. And since "external radiative forcing" has come to mean radiative changes external to the normal operation of the climate system, it makes sense to call the neglected term "internal radiative forcing", for which I tentatively propose the following definition:

Internal radiative forcing refers to any change in the top-of-atmosphere radiative budget resulting from an internally generated fluctuation in the ocean-atmosphere system that is not the direct result of feedback on temperature.

That the work of the IPCC has been biased against the existence of internal sources of radiative forcing is clear from reading the IPCC reports. For instance, even though "radiative forcing" is defined early in the Technical Summary of the Report of Working Group I in such a way that would include both internal and external sources, the report's subsequent 100 references to radiative forcing are only in the context of *external* sources. These typically include anthropogenic greenhouse gas and aerosol emissions, volcanic eruptions, and variations in solar flux.

We will see that the neglect of internal sources of radiative forcing represents more than just a source of error. It impacts our perception of natural climate variability and what the climate system is telling us about climate sensitivity.

3. A Simple Climate Model

We start with a simple time-dependent model of temperature anomalies (T) around an equilibrium state,

$$\mathrm{Cp}\ \mathrm{d}T/\mathrm{d}t = f + S - \lambda T + I \qquad (1)$$

where Cp is the heat capacity of the system; f is any "external" radiative forcing leading to a TOA radiative imbalance such as anthropogenic greenhouse gas emissions, volcanic aerosols, or solar variations; S represents non-radiative sources of heating (*e.g.*, variations in upwelling from the deep ocean); and λ is the total feedback parameter. This feedback parameter represents the sum of all (assumed linear) radiative feedbacks on temperature, including the Planck response component of thermally emitted longwave (LW) variability (about 3.3 W m^{-2} K^{-1}, Forster and Taylor, 2006, hereafter FT06).

Any temperature deviations away from equilibrium resulting from the heating terms on the RHS of (1) will then lead to radiative feedback on temperature through the λT term, such as through reflected solar shortwave (SW) or thermally emitted longwave (LW) cloud feedbacks. By convention, a negative component of the feedback parameter represents positive feedback, while a positive component of the feedback parameter represents negative feedback. If the total feedback parameter λ is negative, the system is inherently unstable. These, then, are the customary terms which are included when discussing global mean climate variability.

But what is typically ignored is any source of internally-generated radiative forcing within the climate system, represented by I in Eq. 1. We will see that its relationship to temperature is fundamentally different from that of the feedback term.

4. Daily Stochastic Cloud Variations

A finite difference version of the model represented by (1) was run at daily time resolution with the following parameters: $f = 0$; a system heat capacity equivalent to a 50 m deep 'swamp' ocean; and a total feedback parameter $\lambda = 3.5$ W m^{-2} K^{-1} representing a slight negative feedback component (0.2 W m^{-2} K^{-1}), assumed to represent SW cloud feedback, combined with LW Planck response to temperature (3.3 W m^{-2} K^{-1}).

The model was forced with daily random fluctuations in non-radiative changes in surface temperature S and internally-generated radiative changes I of sufficient magnitudes to cause the model variability to match the satellite-observed monthly standard deviations of tropical (20^{o}N to 20^{o}S) oceanic reflected SW variability retrieved from the CERES (Clouds and the Earth's Radiant Energy System, Wielicki *et al.,* 1996) instrument flying on NASA's Terra satellite, and sea surface temperatures measured by the Tropical Rain

Measuring Mission (TRMM) Microwave Imager (TMI, Kummerow *et al.*, 1998). The resulting modeled temperature time series in Fig. 1a shows substantial low frequency variability, driven entirely by the daily noise in heating. A change in the noise generator seed leads to different model realizations.

If we then plot monthly averages of *T* versus the total radiative variability for the realization shown in Fig. 1a, we get a linear regression estimate of the feedback parameter λ' = 2.94 W m^{-2} K^{-1} (Fig. 1b). Note that it departs substantially from the specified value of λ = 3.5 W m^{-2} K^{-1}, thus producing a positive feedback bias of -0.56 W m^{-2} K^{-1}.

In Monte Carlo simulations using the model represented by Eq. 1 and daily random noise in heating, SB08 found positive feedback errors generally in the range -0.3 to -0.8 W m^{-2} K^{-1}. The magnitude of the positive bias in diagnosed feedbacks depends upon the relative strengths of internal radiative forcing (*I*) versus internal non-radiative forcing of the surface (*S*). If there is *only* internal radiative forcing, then any feedback diagnosis will, in general, be strongly biased toward positive feedback. If, on the other hand, the non-radiative forcing is the only source of temperature variability, then there is a perfect correlation, and there is no error in the diagnosed feedback (not shown). The strength of the correlation as a possible indicator of a biased feedback parameter will be addressed later.

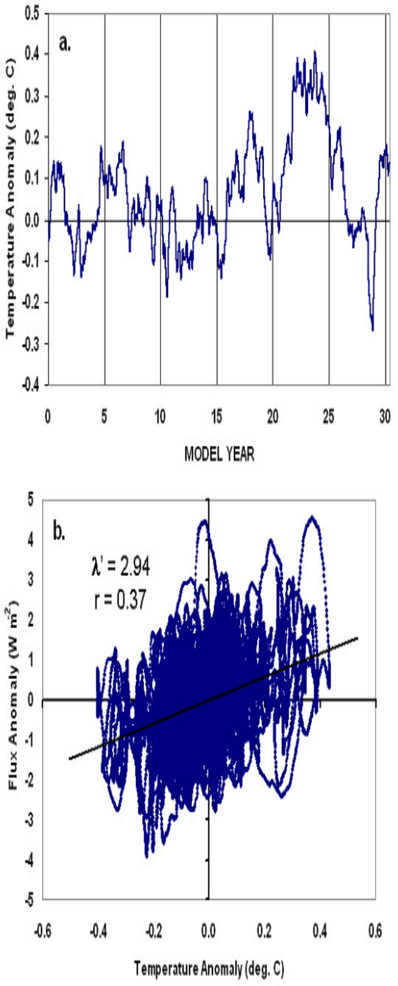

Fig. 1 *a) Thirty years of modeled daily temperature variations of a 50 m deep swamp ocean being driven by daily random fluctuations in heat input; b) plot of 80 years of model output monthly average temperature versus total reflected SW (random forcing plus specified feedback). The diagnosed feedback parameter λ' (line slope) does not change substantially with averaging times up to yearly.*

5. Low-Frequency Variability from ENSO and the PDO

While the previous section addressed high-frequency noise in cloud cover as a source of bias in our diagnosis of feedbacks, the fundamental issue of internal radiative forcing is independent of time scale. For example, it is reasonable to hypothesize that internal modes of climate variability have associated changes in albedo which are not the result of feedback on surface temperature. But while persistent radiative imbalances on the order of 1 W m^{-2} are sufficient to cause substantial temperature changes on multi-decadal time scales, our satellite measurements of clouds and radiative fluxes are neither long enough, nor accurate enough, to measure such changes.

This is not, however, a sufficient reason to assume they do not exist.

For instance, the major features of global mean temperature variations since 1900 (Fig. 2a) have usually been explained as a combination of anthropogenic greenhouse gas and aerosol emissions, possibly combined with a small amount of increased solar forcing (IPCC, 2007). While this is indeed one possible explanation, it is also possible that some part of the temperature change represents internal variability in the climate system in the form of radiative forcing which is not the result of feedback. After all, it is well known that ENSO has warm and cool phases which occur irregularly every few years, and that the warm phase (El Nino) has been more frequent during the warming experienced since the 1970's (see Fig. 2b). Similarly, the lower-frequency Pacific Decadal Oscillation (PDO, Mantua *et al.*, 1997) was more often in its positive phase during the period of global mean warmth around 1940, as well as during the warming since the 1970s (Fig. 2c).

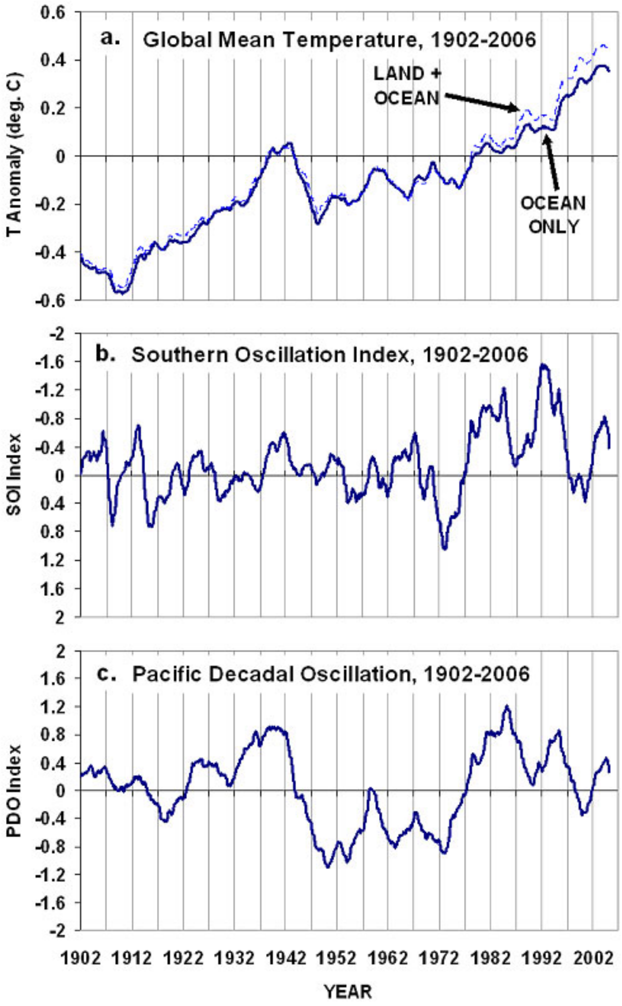

Fig. 2. *Monthly running 5-year means of: a) global mean surface temperature from the HadCRUT3 dataset; b) the Southern Oscillation Index (note the scale is inverted), and c) the Pacific Decadal Oscillation Index. The data included in the 5-year averaging are from January, 1900 through February, 2008.*

It is not unreasonable to hypothesize that the small changes in atmospheric and oceanic circulation associated with these modes of climate variability have caused corresponding non-feedback changes in clouds, which then impact the radiative budget of the Earth.

It is critical to understand that, even though neither of the climate indices in Fig. 2 'looks like' the corresponding temperature time series, we do not expect them to if they are associated with internal radiative forcing (*I* in Eq. 1). This is because *I* is not proportional to temperature, but to the change in temperature with time.

We will hypothesize that the PDO and ENSO indices have associated with them some amount of internal radiative forcing due to cloud changes. Again using the basic form of Eq. 1, we now assume that the only heating term is a linear function of the SOI and PDO indices,

$$\mathrm{Cp}\ dT/dt = \alpha\,(\beta_{PDO}PDO + \beta_{SOI}SOI\,) - \lambda T \qquad (2)$$

where $$\beta_{PDO} + \beta_{SOI} = 1. \qquad (3)$$

In this case, the heating term is a weighted average of the monthly PDO index value (*PDO*), and the negative of the monthly SOI index value (*SOI*); the two β coefficients provide the weights; and α is an empirical scaling factor in W m^{-2}. The total feedback parameter (l) again represents a combination of the infrared Planck response to temperature (3.3 W m^{-2} K^{-1}) plus all other radiative feedbacks such as clouds, water vapor, lapse rate, *etc*.

Physically, Eqs. 2 and 3 simply say that the time rate of change of the system temperature around its equilibrium state is assumed to result from a net heating term made up of a linear combination the SOI and PDO climate indices, modified by feedbacks on that temperature. Since the model is sensitive to noise in the SOI and PDO indices, here we will use monthly running 5-year means of those indices, rather than their raw monthly values.

If we run a finite difference version of the model represented by Eqs. 2 and 3 at monthly time resolution and modify the adjustable parameters of the model (Cp, which is proportional to the ocean depth; the scaling factor α; the heating term weights β_{PDO} & β_{SOI}; and the feedback parameter λ) we quickly find that a high correlation (0.94) is achieved between the model temperature and observed global temperatures for a model mixed layer depth of 1,000 m, and when the SOI term is weighted somewhat more heavily than the PDO term ($\beta_{PDO} = 0.37$, $\beta_{SOI} = 0.63$). The correlation and temperature trend of the model output were found to not be very sensitive to positive or negative feedback parameters within 1 W m^{-2} K^{-1} of the nominal Planck response value of $\lambda = 3.3$ W m^{-2} K^{-1}.

This specific combination of the adjustable parameters produces the model temperature time series seen in Fig. 3b, where Fig. 3a shows the weighted combination of *PDO* and *SOI*, scaled by $\alpha = 2.7$ W m^{-2}, that forms the total heating term which forces the model. The model was initialized with a heating value -0.53 W m^{-2} so that the modeled and observed average temperature anomalies were equal for the first 50 years of record (approximately 1900 to 1950). Adjustment of this initial value causes only a temperature offset of the model curve, not its shape.

It can be seen from Fig. 3 that this simple model captures a large portion of the major features of temperature change since 1900: warming until about 1940, slight cooling up to the 1970s, and then resumed warming since the 1970s. The model warming trend (+0.50 deg. C/century) is 70% of the observed warming trend (+0.69 deg. C/century).

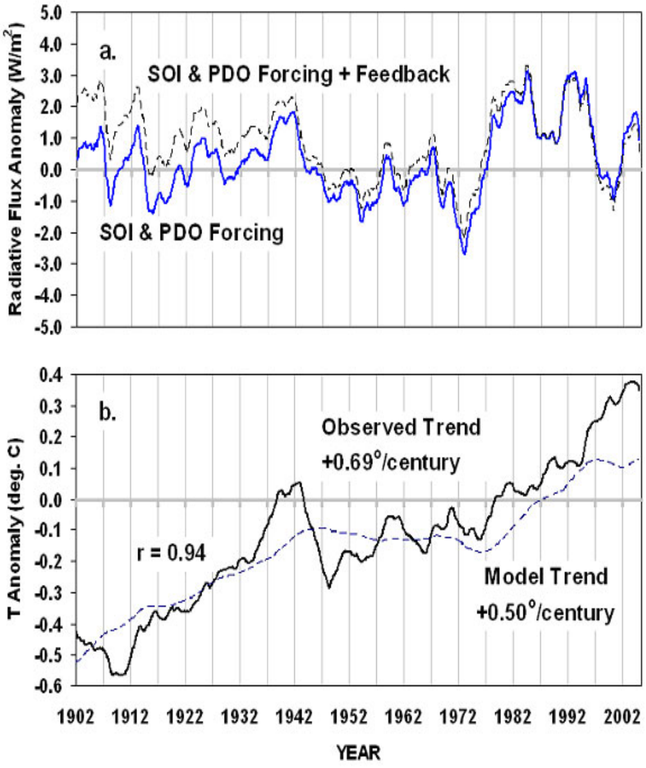

Fig. 3. *a) Assumed internal radiative forcing proportional to a linear combination of the Pacific Decadal Oscillation index and that Southern Oscillation Index, used to force a simple model of temperature variability for a uniformly mixed ocean of adjustable depth; and b) the observed (HadSST2), and model output, sea surface temperatures for a combination of model adjustable parameters that yielded a high correlation between the model output and observations. See text for additional details.*

One could presumably use other climate indices to force the model with, or more complex interactions between the indices. For instance, Tsonis *et al.* (2007) addressed the nonlinear interaction of four different internal modes of climate variability in a statistical framework for explaining climate variability since 1900. But there are only a few degrees of freedom contained in the low frequency temperature variability since 1900, and the intent here is only to demonstrate that a simple physical model, driven by two well known modes of internal climate variability, can explain most of the major features of global mean temperature changes since 1900 *without resorting to anthropogenic greenhouse gas and aerosol forcing.*

While it might be argued that the mechanism proposed here is speculative, it is also speculative to assume that the radiative flows of energy in and out of the Earth system are stable to much less than 1% of their mean (of about 235 W m^{-2}) on multi-decadal time scales in the presence of known modes of internally generated climate variability. The forcing used here (Fig. 3a) has a standard deviation of only 1.2 W m^{-2}, which is 0.5% of the average radiative energy flows in and out of the Earth's climate system.

If we then plot the temperature variations in Fig. 3b against the assumed internally-generated radiative forcing from Fig. 3a (plus the radiative feedback using $\lambda = 3.3$ W m^{-2} K^{-1}), we obtain a diagnosed feedback parameter of 1.3 W m^{-2} K^{-1} with a correlation of 0.19 (not shown). This diagnosis of the feedback parameter thus has a large positive feedback bias of 2 W m^{-2} K^{-1} when compared to the specified feedback of 3.3 W m^{-2} K^{-1}.

It should be noted that this large positive bias in the diagnosed feedback is due to the assumption that all of the forcing was radiative, that is, the forcing was assumed to be entirely contained in the I term in Eq. 1, with no contribution from the S term. Alternatively, we could have assumed that the heating in Fig. 3a was entirely due to the non-radiative heating term, S, in Eq. 1. In this case, the model output temperature variability would have been regressed against the only source of radiative variability - the feedback term λT - and then the diagnosed feedback parameter, l', would have equaled the specified one ($\lambda = 3.3$ W m^{-2} K^{-1}). But in the former case, the corresponding correlation was very low ($r = 0.19$), while in the latter case a perfect correlation ($r = 1.0$, not shown) was the result.

So once again, as was the case for the model forced with daily noise in heating, we see that the issue of causation is critical when we examine cloud variability and make assumptions regarding the existence of feedback in the system. It is helpful to remember that feedback must have some source of temperature variability on which to operate, and for internally generated variability, that source can either be radiative (the I term), or non-radiative (the S term). If it is entirely from the non-radiative (S) term, there will be no error in the diagnosed feedback. But to the extent that some of the temperature variability is internally-generated non-feedback radiative forcing (I), the diagnosis of a feedback parameter from the data will be biased in the positive direction.

And again, a major difference between these two cases as expressed in model output is a low correlation when only internal radiative forcing is involved, and a high correlation when only non-radiative sources of heating are involved.

6. Cause or Effect?

While atmospheric scientists are usually reluctant to attribute causation when discussing the complex interactions involved in atmospheric circulation systems, we can be sure that cause and effect do indeed exist, for scientific study would be impossible without them. As we have seen from the examples above, it makes a great deal of difference when we observe climate variability whether we think clouds drive temperature, or temperature drives clouds, or some combination of both. If we mistakenly assume that all radiative fluctuations resulting from processes internal to the climate system are only the result of feedback on surface temperature (temperature causing cloud changes rather than non-feedback sources of cloud change causing temperature change), then our estimates of feedback will be biased in the direction of positive feedback and the climate system will appear more sensitive than it really is.

The reason that the bias in diagnosed feedback is only in the direction of positive feedback is because, as an energetic necessity, a specific change in clouds can cause a change in temperature in only one direction. Phrased somewhat differently, if cloud variations cause a temperature change, the diagnosed feedback parameter (ratio of the cloud-induced radiative forcing to its temperature response) can have only one sign; true feedback, in contrast, can be of either sign.

This is one reason why internal radiative forcing needs to be considered as a heating term separate from feedback. Otherwise, we can be faced with the perplexing situation where a feedback appears to change in its magnitude (or even sign) over time, when what is really happening is that the amount of internal radiative forcing mixed in with the feedback is varying.

Unfortunately, it seems unlikely that we will be able to separate cause and effect *per se* from observational data, so we will likely have to estimate feedbacks from statistics of the co-variability between temperature and radiation changes. For instance, Aires and Rossow (2003) provided a methodology for computing such sensitivity relationships. But it is not obvious which set of these statistical metrics of climate variability, if any, are a unique signature of the underlying forcings and feedbacks. For instance, the SB08 model results based upon assumed daily random cloud variations in the context of the model represented by Eq. 1 suggested that the temperature and radiative flux co-variability was not uniquely related to a specific feedback. They instead found that the same satellite measures of monthly variability in T and SW fluxes could be reproduced with feedbacks ranging from strongly positive to strongly negative.

It is clear that the cloud feedback problem, as a general issue, is far from solved. But by recognizing the existence of internal radiative forcing as one component of the climate variability that has been mistakenly assumed to be a part of feedback, it is believed that progress can be made in that direction. And, in the process, we find that some unexplained results from previous investigations take on new meaning.

7. A Fresh Look at Some Previous Climate Diagnostics

The problem discussed here is of fundamental importance to our interpretation of observed climate variability. Forster and Gregory (2006, hereafter FG06) showed that all IPCC models produced total radiative (LW+SW) feedbacks more positive than current best estimates from satellite observations. Rather than questioning the realism of the model feedbacks, the authors instead attributed this discrepancy to errors in the observational estimates of feedback.

But this discrepancy between models and observations might alternatively be evidence that the models have cloud parameterizations which are based upon observed cloud behavior for which causality in only one direction was assumed, in which case they would be biased toward positive feedback. Causation is implicit in climate models due to the specific sequence of coded instructions.

Again, to the extent that non-feedback sources of cloud variability cause temperature change, the misinterpretation of cloud-temperature relationships as only feedback will result in a bias in the direction of positive feedback. Cloud parameterizations based upon such misinterpretations could then produce model behavior with unrealistically high sensitivity.

Another curious feature of the observational results shown by FG06 is the low correlation (average of the absolute values, 0.37) between temperature changes and SW fluctuations for the diagnosed feedback parameters. While one might attribute this to just noise in the observational data, there is an alternative explanation. If only linear feedback is operating upon non-radiative sources of temperature variation (S), and there are no sources internal radiative forcing (I), then the diagnosed feedback parameter has no error, and the corresponding correlation is always 1.0. But once a source of internal radiative forcing is included, one gets much lower correlations, an example of which is seen in Fig. 1b (where the correlation is, coincidently, also 0.37). Thus, the existence of low correlations in FG06 could, by itself, be evidence for internal radiative forcing in the SW fluxes.

A related curiosity of the diagnosed SW feedback parameters in FG06 is the wide range of correlations: from -0.51 to +0.57. As previously addressed, the magnitude of internal radiative forcing mixed in with the feedback signal can determine the magnitude, and even the sign, of the diagnosed feedbacks. This makes it appear as though different feedbacks are operating at different times, while instead it could be evidence for different amounts of internal radiative forcing versus non-radiative forcing of surface temperature.

Finally, the existence of internal radiative forcing also implies more *total radiative variability* in the climate system. In this context, it is interesting that Wielicki *et al.* (2002) noted that satellite observations revealed tropical variations in SW and LW radiative fluxes which were considerably larger than those exhibited by climate models. This large variability might be further evidence of non-feedback radiative 'noise', either high frequency or low frequency, generated within the climate system which is underrepresented in the models.

8. Summary and Discussion

It is more than a little ironic that the direction of causation involved in manmade global warming (a radiative change causing a temperature change) has been abandoned, and even reversed, when researchers observe natural climate variability - for they claim to see only temperature change causing a radiative change (feedback). Here, both observational and theoretical evidences have been presented for the view that non-feedback sources of internally-forced non-feedback variations in the radiation budget of the climate system have not been sufficiently accounted for in either 1) the diagnosis of feedbacks in observational data, or 2) in the assigning of causation for observed climate change. The issue has a large impact on our perception of climate sensitivity, and could be important for the formulation of cloud parameterizations in climate models.

The fundamental issue can be framed as a question of cause and effect, for instance: To what extent are climatic variations in clouds caused by temperature change (feedback), versus temperature change being the result of cloud variations? If variability in cloudiness on any time scale is caused by some internal process other than feedback, the resulting relationship between temperature and radiative fluxes will 'look like' positive feedback — possibly even obscuring the signature of true negative cloud feedback.

Note that this issue is not restricted to only cloud feedback. Water vapor feedback is another example. We know that higher temperatures are, on average, associated with higher water vapor contents in the atmosphere. This is commonly pointed to as evidence of positive water vapor feedback. But what we neglect is the possibility of causation in the other direction. For instance, changes in precipitation efficiency (say due to a change in wind shear) can cause water vapor contents to change, which then can cause temperature change (e.g., Renno et al., 1994). If this happens, it will always look like positive water vapor feedback, even if no feedback is involved.

Simple models presented here which are driven with two types of assumed internal radiative forcing have also shed light on some features of observed climate variability which have not been adequately explained before. These include: the large magnitude of satellite-observed radiative variability on interannual time scales compared to climate models; the low and highly variable correlations between global, time-averaged temperature and radiative fluxes; the tendency for model-produced feedbacks to be more positive than those observed in the climate system; and even the potential role of internally generated radiative forcing as a partial explanation for the major low frequency features of the global mean temperature record since 1900.

On this last issue, low frequency, internal radiative forcing amounting to little more than 1 W m^{-2}, assumed to be proportional to a weighted average of the Southern Oscillation and Pacific Decadal Oscillation indices since 1900, produces ocean temperature behavior similar to that observed: warming from 1900 to 1940, then slight cooling through the 1970s, then resumed warming up to the present, as well as 70% of the observed centennial temperature trend. While the proposed mechanism is admittedly speculative, it is also speculative to alternatively assume that low frequency changes in the general circulation associated with ENSO and the PDO do not cause non-feedback TOA radiative budget changes on the order 1 W m^{-2} - an amount that is less than 1% of the mean radiant energy flows of 235 W m^{-2} in and out of the Earth's climate system.

Based upon the evidence, it seems likely that the neglect of sources of internal radiative forcing has resulted in diagnosed feedbacks which give the illusion of a climate system that is more sensitive than it really is. This has then led to the development of climate models which produce too much global warming in response to the external radiative forcing caused by anthropogenic greenhouse gas emissions.

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Source: http://climatesci.org/2008/04/22/internal-radiative-forcing-and-the-illusion-of-a-sensitive-climate-system-by-roy-spencer/

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