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Relationships between tropical sea surface temperature and top-of-atmosphere radiation

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[1] To assess climate sensitivity from Earth radiation observations of limited duration and observed sea surface temperatures (SSTs) requires a closed and therefore global domain, equilibrium between the fields, and robust methods of dealing with noise. Noise arises from natural variability in the atmosphere and observational noise in precessing satellite observations. This paper explores the meaning of results that use only the tropical region. We compute correlations and regressions between tropical SSTs and top-of-atmosphere (TOA) longwave, shortwave and net radiation using a variety of methods to test robustness of results. The main changes in SSTs throughout the tropics are associated with El Niño Southern Oscillation (ENSO) events in which the dominant changes in energy into an atmospheric column come from ocean heat exchange through evaporation, latent heat release in precipitation, and redistribution of that heat through atmospheric winds. These changes can be an order of magnitude larger than the net TOA radiation changes, and their effects are teleconnected globally, and especially into the subtropics. Atmospheric model results are explored and found to be consistent with observations. From 1985 to 1999 the largest perturbation in TOA radiative fluxes was from the eruption of Mount Pinatubo and clearly models which do not include that forcing will not simulate the effects. Consequently, regressions of radiation with SSTs in the tropics may have nothing to say about climate sensitivity.
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1. Introduction

[2] It is enticing to think that perhaps critical feedbacks and climate sensitivity can be estimated from direct observations of surface temperatures and top-of-atmosphere (TOA) radiation [*Gregory et al.*, 2004; *Forster and Gregory*, 2006]. Particular challenges are how to handle the large radiative perturbations from the Mount Pinatubo volcanic eruption in 1991, and possible spurious changes over time. Whether or not the results provide meaningful insight depends critically on assumptions, methods and the time scales, and some recently published work reports results that are flawed in this regard.

[3] A linearized version of the Earth's global energy balance is

$$R_T = F - \lambda\Delta T + \varepsilon \quad (1)$$

where R_T is the net energy radiation at the TOA into the Earth, F is the net forcing, $\lambda\Delta T$ is the change in net radiation due to a temperature change ΔT, and ε is the noise and internal variability [*Forster and Gregory*, 2006; *Murphy et al.*, 2009]. λ is called the feedback parameter, and in equilibrium, when $R_T = 0$, $\Delta T = F/\lambda$. For doubled carbon dioxide levels, where $F = 3.7$ W m^{-2}, $\Delta T = F/\lambda$ represents the climate sensitivity. For an Earth without climate feedbacks other than the Planck response, λ is expected to have a value of roughly 3.3 W m^{-2} K^{-1}; hence values of λ less than (greater than) this value correspond to a climate with a globally positive (negative) feedback [*Forster and Gregory*, 2006].

[4] Several recent attempts have been made to estimate λ using values of F and ΔT with linear regression. *Forster and Gregory* [2006] used near-global Earth Radiation Budget Experiment (ERBE) data from 1985 to 1996 and applied various averaging methods on seasonal and interannual time scales to find a value of about 2.3 ± 1.4 W m^{-2} K^{-1}. *Murphy et al.* [2009] also used ERBE as well as Clouds and the Earth's Radiant Energy System (CERES) data to make related regression estimates although they carefully note that their results may not relate to climate sensitivity. Following many ways of processing the data, they adopt a value of $\lambda = 1.25 \pm 0.5$ W m^{-2} K^{-1} as an estimate of the response of net radiation to temperature variations. They also estimate regressions with the outgoing longwave radiation (OLR) of 2.8 ± 0.4 W m^{-2} K^{-1} and reflected shortwave radiation (RSW) of -1.9 ± 0.7 W m^{-2} K^{-1} for interannual perturbations from ERBE.

[5] Here we adopt the convention that the TOA net radiation downward R_T = ASR − OLR, where ASR is the absorbed solar radiation and is the solar irradiance minus RSW. To the extent that the TOA solar irradiance is a function of season and latitude, anomalies in ASR are simply opposite to those in RSW, although changes in irradiance such as with the 11 year solar cycle would alter this.

[6] Another recent attempt to estimate sensitivity and λ [*Lindzen and Choi*, 2009, hereafter LC09] notes that there are many pitfalls to be avoided in assessing climate feedbacks in models using observations of radiation at TOA. While they adopt a procedure to avoid one of these pitfalls, they fail to recognize and account for several others, they do not account for external forcings, and their use of a limited tropical domain is especially problematic. Moreover their results do not stand up to independent testing. Accordingly, one focus of this article is to carry out a more robust analysis of the tropical domain results and its implications, if any, for

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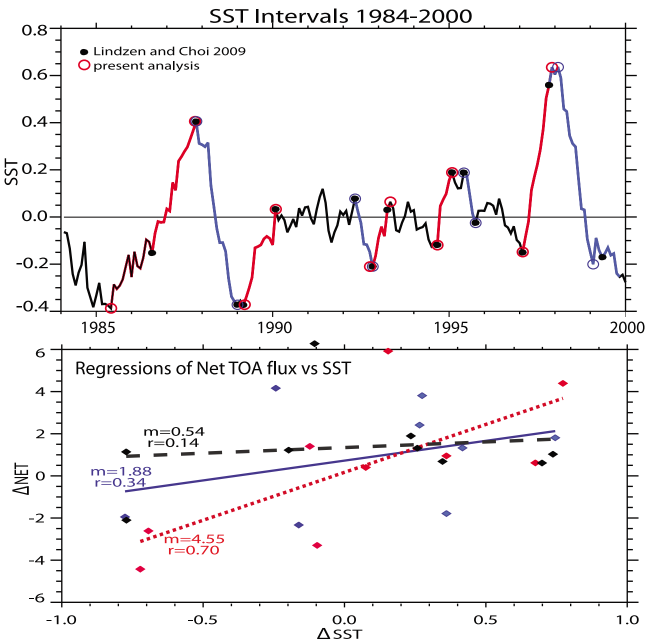

Figure 1. (top) Warming (red) and cooling (blue) intervals of HADISST tropical SST (20°N–20°S) used by LC09 (solid circles) and an alternative selection proposed here derived from an objective approach (open circles). (bottom) Linearly regressed slope (m) and associated correlation (r) of the relationship between SST and net TOA flux from ERBS using approaches that shift the endpoints of intervals by 1 month or less from LC09's result (dotted red).

climate sensitivity. We also resolve why there was an apparent discrepancy between model and observed results.

2. Tropical Sea Surface Temperature Relationships

[7] Available data for TOA radiation come from the ERBE mission and CERES. ERBE consists of two broadband instrument records (the narrow field of view scanner and the wide field of view non-scanner) from three satellites (NOAA-9, NOAA-10 and ERBS). The multi-satellite ERBE scanner dataset provided near-global values, while ERBS nonscanner, which was on a precessing satellite with period of 72 days, provided data coverage to about ±60° latitude. For the ERBS nonscanner, used by LC09, a full diurnal sampling of all regions in the tropics is realized over a 36-day period using both descending and ascending orbits. ERBE scanner data are only available from 1985 until 1989 but ERBS nonscanner data continued until 1999. The ERBS nonscanner data have undergone several revisions to correct data problems [*Trenberth*, 2002; *Wielicki et al.*, 2002; *Wong et al.*, 2006; *Trenberth et al.*, 2007]. While the stability of the ERBS nonscanner total channel (LW+SW) blackbody sensor was monitored directly using solar irradiance and deep space, and the latest data (Edition3_Rev1) compared well with other long term records [*Wong et al.*, 2006], the low frequency changes remain somewhat uncertain. This is one issue in trying to determine λ from observations.

[8] CERES is the follow-on mission to ERBE with an improved instrument and algorithms to reduce data uncertainty by a factor of 2 to 3 over ERBE [*Wielicki et al.*, 1996]. As it is an advanced radiation dataset, the CERES data that begin in 2000 have some differences with ERBE data [*Fasullo and Trenberth*, 2008] that also need to be recognized.

[9] To summarize LC09's approach, variability in the TOA energy budget was assessed as it relates to variability in tropical (20°N to 20°S) SSTs from 1985 to late 1999 for both nature and 11 atmospheric climate models run with specified SSTs. Fluxes from the ERBS sensor were used, excepting for gaps in 1993, 1998, and 1999. Major intervals of warming and cooling in SST were identified to quantify the change in TOA fluxes across these intervals. Owing in part to the precession of the ERBS satellite, there is considerable noise in monthly means used by LC09, although they apply a 7-month smoother to RSW to reduce this. LC09 avoid the uncertainties in trends problem by choosing short-term segments "that are long compared to the time scales associated with the feedback processes, but short compared to the response time over which the system equilibrates." The segments range from about 4 to 18 months and mainly reflect ENSO fluctuations. A serious omission of LC09's is that they did not consider the forcing F in equation (1) in their regressions, and this is an especially grievous error when the period following the large perturbation associated with the Mount Pinatubo eruption in April 1991 is considered.

[10] In attempting to reproduce LC09's results (Figure 1, top) we found extreme sensitivities to their method. Note that the "Net" radiation by LC09 is outwards and thus has the opposite sign to R_T. As the dates used by LC09 are not provided, they were estimated from their Figure 1. Sensitivity to the method was examined by allowing for a displacement of the endpoints of their warming and cooling intervals by a month or less (Figure 1). *Lindzen and Choi*'s [2009, Figure 2] result is equivalent to the m = 4.55 W m^{-2} K^{-1} slope in Figure 1 (bottom), and the higher correlation is because the noise (not the signal) is being explained. It is evident that the uncertainty is very large. As the filter employed by LC09 is not given, we used a 7-month running mean although a Gaussian and other filters were tried, and results are not a strong function of the filter used.

[11] Moreover, their selection of dates for the intervals (LC09's Figure 1, and Figure 1 (top) here) is frequently not justifiable. This is evident if an objective method of identifying the intervals is employed, for example, to identify local minima and maxima exceeding 0.1°C in low-pass filtered data (see Figure 1 (top)). For example, for the warming event in 1997/98, the warming declared by LC09 ceases in mid-1997 rather than at the obvious SST peak in Jan 1998. Also, the warming during the 1986/87 ENSO is assumed to begin in mid-1986 when it can alternatively be proposed that warming began in 1985. Warming is declared by LC09 to end in early 1993, well prior to the peak in SST in the middle of the year.

[12] Hence we find that LC09's results are neither robust nor meaningful, as small sensible changes in the dates bounding their warming and cooling intervals entirely change the conclusions. To perform a more robust analysis, experimentation has revealed that simple correlation analysis between anomalies is preferable. Sensitivity of results to possible problems has been tested using regression analysis, see Table 1, for cases as follows: 1) All 137 36-day anomalies from 1985 to 1999, based on 1985–1989 climatology, excluding missing ERBS data. 2) Same as (1) but limited to the 9 LC09 36-day

Table 1. Results for Regressions for ERBE Nonscanner Data in Cases 1 to 4 Using LC09 and Other Periods as Described in the Text[a]

	Case 1 137 All	Case 2 83 LC09	Case 3 72 no Pinatubo	Case 4 112 no Pinatubo	LC09
OLR	3.0 ± 0.5	3.3 ± 0.5	3.1 ± 0.5	2.7 ± 0.4	3.5 ± 0.5
RSW	−2.6 ± 1.0	−2.7 ± 0.8	−2.3 ± 0.6	−1.1 ± 0.5	1.0 ± 1.7
R_T	−0.4 ± 0.8	−0.7 ± 0.7	−0.8 ± 0.7	−1.6 ± 0.5	−4.5 ± 1.6

[a]LC09's results are also given. Values given are the slope ±1-sigma uncertainty in Wm^{-2} K^{-1}.

periods; total points: 83. 3) Same as (2) but also excluding the Mt. Pinatubo period (1991–1993), total points: 72. 4) All 36-day anomalies excluding missing ERBS data and the Mt. Pinatubo period, but with anomalies for 1985 to 1990 and 1994 to 1999 calculated relative to 1985–1989 and 1994–1997 means, respectively, to remove the low frequency ERBS changes, total points: 112. We also performed tests with the forcing term accounted for (discussed in section 3).

[13] The differences between cases 2 and 3 (Table 1) highlight the effects of Pinatubo, which did not change the results very much. The results are very robust across the first three cases. However, case 4 suggests some sensitivity to the base ERBS levels before and after 1991 to 1993. In Table 1 the OLR regression values are positive, while the RSW results mostly produce negative slopes, unlike LC09, so there is a lot of cancellation, as expected [*Kiehl*, 1994], and the R_T regressions are quite a lot smaller than those from LC09. In all cases, the R_T regression is less than the global Planck function response, in contrast to LC09, suggesting an overall positive feedback.

[14] To explore the effects of changing tropical SST on radiative fluxes outside of the tropics, we have performed correlation and regression analyses of the tropical mean (20°N–20°S) SSTs with global OLR, ASR and R_T for scanner ERBE data (February 1985 to April 1989) and for CERES from March 2000 to November 2005 (Figure 2). Separate analyses for each period give similar results which have therefore been combined but with anomalies computed separately for each period to remove any biases of ERBE relative to CERES. This also removes low frequency variability or trends. For a total of 119 months if independent, the 5% significance level is 0.18.

[15] The tropical SST time series lags Niño 3.4 SSTs by a few months, is correlated 0.71 at zero lag [*Trenberth et al.*, 2002b] and exhibits about 22% of its amplitude (the standard deviations of tropical SST is 0.21°C and for the Niño 3.4 region 0.95°C). *Trenberth et al.*'s [2002b] correlations between global mean temperature and Niño3.4 SST for 1950 to 1998 were 0.53 with global temperatures lagging by 3 months. It is apparent that ENSO is the dominant influence on the variability. Indeed the patterns of change in OLR and ASR (Figure 2) correspond mostly to well known shifts in the InterTropical Convergence Zone (ITCZ) and South Pacific Convergence Zone with magnitudes exceeding 50 W m^{-2} K^{-1}, but the strong cancellation in R_T leaves few areas exceeding 10 W m^{-2} K^{-1}. Note however, that as the

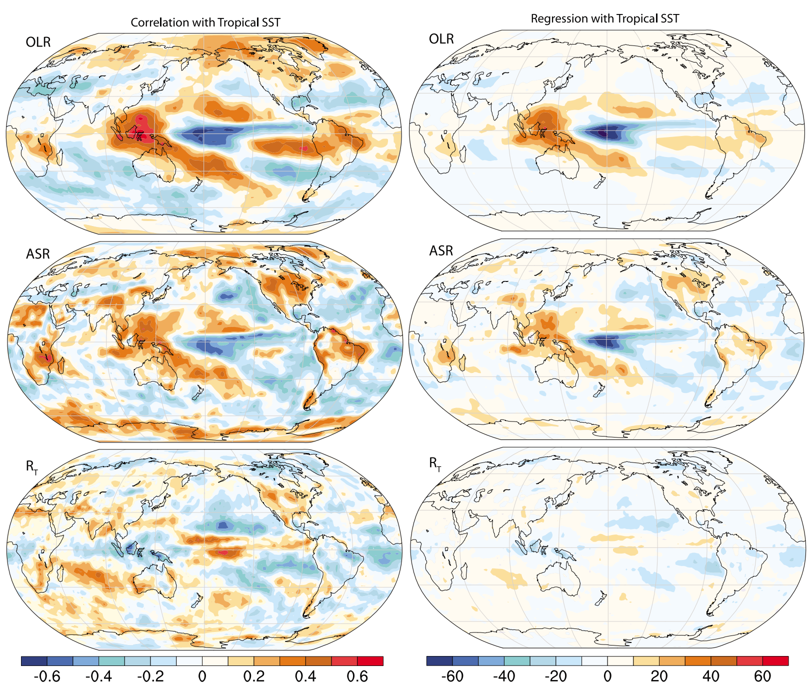

Figure 2. (left) Correlation and (right) regression in W m^{-2} K^{-1} for OLR, ASR and R_T with tropical SST anomalies 20°N and 20°S for ERBE February 1985 to April 1989 and CERES March 2000 to November 2005; the anomalies in each interval are relative to that mean thereby removing any biases between ERBE and CERES.

Table 2. Results for Regressions Using Different Methods for AMIP Models[a]

	LC09	LC09 Method and Dates	LC09 Method, Revised Dates	Monthly Anomaly Correlation
OLR	1.0	1.5 ± 0.9	1.9 ± 1.0	1.9 ± 0.9
RSW	−3.5	−2.9 ± 1.3	−1.6 ± 0.9	−1.2 ± 0.9
R_T	2.5 ± 1.8	1.4 ± 0.6	−0.3 ± 0.7	−0.7 ± 0.7

[a]Column cases are 1) from LC09 with OLR and RSW values read from graphs; 2) using LC09's methods and dates; 3) LC09 with more sensible dates; 4) using correlation-of-monthly-anomalies. Values given are the slope ± 1-sigma uncertainty in W m^{-2} K^{-1}.

maximum perturbation in tropical SSTs is 0.6°C (Figure 1) in 1997/98 the values realized in nature in W m^{-2} are smaller than in Figure 2.

[16] The maps highlight strong connections extending to ±45° latitude in both hemispheres in the Pacific so that confining the domain to ±20° fails to account for key dynamical and radiative feedbacks. The global mean regression coefficients with tropical SSTs in W m^{-2} K^{-1} are: 0.075 for OLR, 0.024 for ASR (or opposite sign for RSW), and −0.040 for R_T, with only the OLR value statistically significant (at 1%). These results, however, are not applicable to the determination of climate sensitivity; *Forster and Gregory*'s [2006] results using global surface temperatures are more pertinent to real responses for assessing feedback.

3. Assumptions on Forcings and Closure

[17] The forcings that should also be considered in determining λ in (1) during this period include the small but steady increase in greenhouse gases, the 11-year solar cycle which has an amplitude of order 0.1%, the Pinatubo volcanic aerosols, and tropospheric aerosols. We tested the results in Table 1 to account for the forcing data [from *Murphy et al.*, 2009] and for case 4, where the Pinatubo period was already excluded, the differences are less than 0.1 in the regression values. Comparison of Table 1 results with *Murphy et al.*'s [2009] for the global or near global domain shows that while the sign of the values are the same, the magnitudes differ somewhat. *Forster and Gregory* [2006] found that tropospheric aerosols did not affect results.

[18] The dominant interannual variations in TOA radiative fluxes in the tropics occur with ENSO, which involves a buildup of heat during La Niña and a discharge of heat during El Niño [*Trenberth et al.*, 2002a, 2002b]. The SST anomalies during ENSO events are sustained by ocean heat transports that allow the events to persist for a year or so. In the tropical Pacific during large El Niño events the anomalous divergence of the atmospheric energy transports exceeds 50 W m^{-2} over broad regions for several months [*Trenberth et al.*, 2002a], and this energy does not come from net radiation (Figure 2). The main surface flux is evaporative cooling of the ocean and the added atmospheric moisture fuels convection, and promotes release of latent heat in precipitation, that drives atmospheric teleconnections globally. The global nature of ENSO is thus known to include a substantial dispersion of energy beyond the tropics, and clouds and convection fail to achieve a local equilibrium with the surface. LC09 however, limit their domain to the tropics only. The assumption of a negligible role played by ocean and atmospheric transports and thus a closed system in the tropical energy budget on monthly to interannual timescales is invalid, and this affects the interpretation of the results.

[19] Even within ENSO events, intraseasonal variability (such as the Madden-Julian Oscillation) dominates the monthly records and creates considerable unforced noise in monthly means [*Lin et al.*, 2006] so that cloud variability cannot be interpreted as a deterministic response to SST on these short timescales.

4. AMIP Model Results

[20] The use of models driven by observed SST to diagnose radiative feedbacks is questionable because feedbacks on the SSTs are not included. LC09 find that a set of 11 climate models forced with observed SSTs and run from 1979 to around 2000, the so-called AMIP (Atmospheric Model Intercomparison Project) runs, have opposite behavior to the ERBE results over the same 1985–1999 time period. Using the approach summarized in section 2, they find that the tropical mean model response to surface temperature changes is approximately as given in the first column of Table 2 (see LC09, Figure 3). These surprising results are in stark contrast to the observed behavior from Table 1.

[21] We attempt to reproduce LC09's results using three different methods and 9 models available to us (excluding miroc3_2_hires and mri_cgcm2): first, using the same basic method as LC09, then repeated with more sensible dates for the period end points, and finally with monthly surface temperature and the corresponding flux anomalies; see Table 2. When revised dates are used, the RSW regression decreases in magnitude and the net radiation regression reverses sign to become the same as for observations (Table 1). Our AMIP model results (Table 2) from both valid methods are consistent with the ERBE observations for OLR, RSW, and R_T to within error bars. Those of LC09 are not. The large mean slope for LC09 is removed if more appropriate dates for starting and ending of segments are used (and in particular moving the boundary for rising to falling SSTs to Jan 1998).

[22] The eruption of Mt. Pinatubo in June 1991 is clearly evident in the ERBS nonscanner record and the TOA RSW flux response exceeds 5 W m^{-2} and is the largest perturbation in TOA radiation. Hence a fundamental shortcoming of LC09's is the failure to recognize that 9 of the 11 models used for comparisons during the ERBS nonscanner period did not include Pinatubo aerosol forcing. There is also no accounting of other aerosols, either anthropogenic or natural, in the AMIP runs. Hence there is no forcing F (equation (1)) in most AMIP runs. However, for the monthly anomaly correlation technique we examined the 2 AMIP models that included Pinatubo forcings vs the 7 that did not and results were unchanged.

5. Concluding Remarks

[23] It is not controversial to state that climate models are deficient in terms of tropical variability in the atmosphere on many timescales [*Lin et al.*, 2006; *Lin*, 2007] and a more realistic simulation of ENSO events in coupled simulations remains a high priority for model developers. During El Niño, the warming of the tropical eastern Pacific and associated changes in the Walker circulation, atmospheric stability, and winds lead to decreases in stratocumulus clouds, increased solar radiation at the surface, and an enhanced warming so

that even models without ocean dynamics are capable of emulating some ENSO-like variability [*Kitoh et al.*, 1999]. Positive cloud feedbacks in observations have been shown to occur in association with ENSO and these variations are generally not well depicted in models [*Kang et al.*, 2002; *Clement et al.*, 2009], but challenges also exist for diagnosing these interactions in observations, as it is difficult to identify cause and effect in the context of multiple interactive variations. *Murphy et al.* [2009] address changes in the energy budget with surface temperatures for a much larger domain and present a much more complete analysis and discussion of issues, and show that recent observed variability indeed supports a positive shortwave cloud feedback. However, the feedbacks from processes other than the Planck function response are clearly positive in both observations and models, in contrast to LC09's conclusions.

[24] As shown here, the approach taken by LC09 is flawed, and its results are seriously in error. LC09's choice of dates has distorted their results and underscores the defective nature of their analysis. Incidentally, LC09 incorrectly computed the climate sensitivity by not allowing for the Planck function in their feedback parameter. For their slope of -4.5 W m^{-2} K^{-1} and using the correct equations (section 1), LC09 should obtain a feedback parameter and climate sensitivity of -0.125 and 0.82 K, respectively, rather than their values of -1.1 and 0.5 K. In contrast, the case 4 (Table 1) results yield a positive feedback parameter of 0.6 and a climate sensitivity of 2.3 K. Moreover LC09 failed to account for the forcings in estimating sensitivity.

[25] However, it is not appropriate to use only tropical SSTs and TOA radiation for feedback analysis as the transports into the extratropics are substantial. Any feedback analysis must also recognize changes in ocean heat storage and atmospheric energy transport into and out of the tropics which are especially large during ENSO events. While the tropics are important in climate sensitivity, values of the latter based on only tropical results are misleading.

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