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A climate feedback metric from phase plane plots of lagged TOA radiation vs temperature

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Abstract

Phase plane plots of CERES radiative flux vs surface temperature with a time lag of nine months of the radiative flux have been studied. Running 13 months centered averages were used both for the radiative fluxes and the temperature anomalies according to HadCRUT3. Those lagged phase plane plots show distinct straight lines with the slopes equal to 6 W m^{-2} for the total net radiative flux and 3 W m^{-2} for both the SW and the LW net radiative fluxes for the two year period of cooling and warming in connection with the 2008 La Niña. A comparison with the results by Spencer and Braswell (2010) indicates that those slopes likely are metrics of the corresponding climate feedback parameters suggesting a fairly insensitive climate system.

Introduction

According to the concepts of radiative forcing and feedback the net radiative flux at the top of the atmosphere (TOA) is separated into a forcing term and a feedback term.

$$N = F - H \quad (1)$$

Gregory et al. (2004) adopted results from model experiments with Global Circulation Models (GCMs) that the feedback term is proportional to the temperature change:

$$H = \alpha \Delta T \quad (2)$$

This gives the following simple linear model equation for the TOA radiative flux:

$$N = F - \alpha \Delta T \quad (3)$$

They used this simple model to study feedback in GCMs and coupled Atmospheric Ocean GCMs (AOGCMs) in model experiments with 2 x CO_2 och 4 x CO_2. In such experiments the radiatvie forcing in principle is changed instantaneously but in reality in the model experiments it is more complicated because the troposphere and the stratosphere respond rather differently to the change in carbon dioxide mixing ratio. The stratosphere reaches equilibrium much faster than the troposphere. As a consequence the forcing due to changed carbon dioxide mixing ratio is often related to the net radiative flux at the top of the troposphere after equilibration of the stratosphere.

Gregory et al. (2004) plotted the net radiative flux N vs the temperature anomaly ΔT both for the TOA and for the top of the troposphere. The relaxation process in the model experiments resulted in straight lines, the slopes of which correspond to the feedback parameter α , the intercepts on the y-axis give values of the radiative forcing and the intercepts on the x-axis are measures of the climate sensitivity in case of a 2 x CO_2 model experiment.

Such plots were done for total net radiative flux, for long wave (LW) radiative flux and for short wave (SW) radiative flux.

Spencer and Braswell (2010) used the same conceptual framework and model equation of the net radiative flux for evaluating radiative flux observations with satellites. They reasoned that if satellite data of net radiative flux is plotted vs temperature anomaly and the points are connected in time sequence to obtain a phase plane plot, segments of straight lines should appear in periods when the radiative forcing is constant. The slope of such segments would be equal to the feedback parameter α. If segments with the same slope would appear several times in the phase plane plot at difference to more randomly occurring slopes of other line segments this would be a strong indication that this slope corresponds to the feedback parameter value.

Spencer and Braswell used one month averaging and three month averaging for CERES data and for ERBE 216 days averages. They found indications of such segments of straight lines (also called striations) when using phase plane plots of net radiative flux vs middle troposphere temperature anomaly both with ERBE and CERES data. The middle troposphere temperature was selected because it is more correlated to the TOA radiative flux than the surface temperature.

They also found interesting great loops in the phase plane diagrams, with large excursions of the temperature anomaly, especially in connection with the Mount Pinatubo cooling in ERBE data and with the 2008 La Niña cooling and subsequent warming in CERES data.

They further applied their phase plane method to the radiative flux data from AOGCMs where they studied phase planes not only with total net radiative flux but also with LW and SW fluxes. In those cases they used surface temperature anomalies and 11 months low pass filtered averages. They studied periods of 50 years of length.

Indications of striations were found in the LW phase planes of four of the AOGCMs and their slopes coincided with the feedback parameter values determined by Foster and Taylor (2006). However, in the phase plane diagrams for total net radiative flux or SW flux none of the AOGCMs produced significant striations. The result with LW phase planes is a support for the method since the AOGCMs confirm that if many striations appear with a common slope, this slope equals the value of the feedback parameter.

The present study is firmly based on the idea of using phase plane plots according to Spencer and Braswell (2010). The main innovation in this study is the usage of phase plane plots where the radiative flux with a time lag is plotted vs surface temperature.

Results

In the present study data for radiative fluxes and surface temperature from a compilation prepared by Spencer and Braswell (2011, see appendix) was used to plot phase plane diagrams based on 13 months centered running averages both for the radiative fluxes and for the temperature anomalies. Surface temperature anomalies from HadCRUT3 were used. The running averages were calculated from the monthly data prepared by Spencer and Braswell.

Figure 1 show the phase plane plots for net radiative flux, LW flux and SW flux. The three straight lines correspond to climate feedback parameter values of 1.2, 3 and 6 W m^{-2}. Note that the negative value of *N* is plotted in order to adapt to the sign convention used by Spencer and Braswell (2010).

In those three phase plane diagrams there are no obvious line segments with a recurring common slope. However, there is a great loop with large temperature excursions, at first cooling and then warming, covering mid 2007 to mid 2009 in all the diagrams corresponding to the 2008 La Niña. Another interesting temperature excursion is seen in the first months with a temperature increase from September 2000 to July 2001.

The form of those phase plane curves suggest that there are great changes in radiative forcing during the 2008 La Niña assuming that equation (3) is a valid model. For the same temperature anomaly we find vastly different radiative fluxes between the upper and lower branch of the great loop, which is only possible if the radiative forcing in equation (3) has changed.

In the next step phase plane plots with lags in the radiative fluxes were investigated. It appeared that increasing the time lag between radiative fluxes and temperature anomalies contracted the loops connected to the 2008 La Niña. It appeared that the loops almost were transformed to straight lines at a time lag of 9 months. This is shown in figure 2.

Comparing with the straight lines with known slopes in the diagrams we may estimate the slopes of those nearly linear segments of the phase plane plots. For the net radiative flux the slope is closest to 6 W m^{-2}, and both for the LW and SW fluxes the slopes are closest to 3 W m^{-2}.

The large temperature increase from September 2000 to July 2001 also exhibits a slope close to 6 W m^{-2} during the first 9 months in the diagram for net radiative. In the other two diagrams straight line segements and their slopes for this temperature increase are less clear.

Discussion

Two possible explanations have been considered in this work for the transformation of the great loops in figure 1 to nearly straight lines in the phase plane plots with lag in figure 2. Equation (3) may be rewritten:

$$\frac{N}{\Delta T}=\frac{F-\alpha\Delta T}{\Delta T} \quad (4)$$

Large radiative forcing

If $F \gg \alpha\Delta T$ then the ratio according to equation (4) will illustrate the relation between change in radiative forcing and temperature change. If the radiative forcing F would be oscillating with the same period and phase as ΔT we would get a constant ratio and a straight line in the phase plane diagram. The slope of this line would however be completely unrelated to α. However, if the radiative forcing would be a delayed effect of the temperature variations (for example via cloud changes) it is reasonable that it oscillates with the same period as the temperature but with a phase shift.

This is illustrated in figure 3 showing curves calculated with sinusoidal functions for F and ΔT with the same period equal to 48 months. However, there is a phase shift with F delayed 11 months. The amplitude of *F* equals 0.5 W m^{-2}, for ΔT the amplitude equals 0.1 K while $\alpha=1.2$ W m^{-2} K^{-1}.

This produces an elliptic phase plane curve when the net radiative flux *N* is plotted vs ΔT. Note the similarity of this curve with the observed phase plane curves in figure 1. However, when *N* is phase shifted with 9 months *N* and ΔT is nearly in phase and the phase plane curve becomes nearly a straight line. However, the slope of this line is unrelated to the value of $\alpha = 1.2$ W m^{-2} K^{-1}.

Small radiative forcing

In this case we have $F \ll \alpha \Delta T$. We assume that the variation in radiative forcing during the great loop of the La Niña episode is negligible, that the radiative forcing is a constant, and that the change in TOA radiative flux with a lag amounting to t_{phs} as a consequence is proportional to the change in temperature anomaly at time *t*:

$$N(t+t_{phs}) = F - \alpha \Delta T(t) \quad (5)$$

When $N(t+t_{phs})$ is plotted vs $\Delta T(t)$ we will again obtain an elliptic phase plane curve (in case of sinusoidal oscillations) similar to the curves in figure 1 since the radiative flux is oscillating with the same period as the temperature anomaly but with a phase shift. Unlike when equation (3) is adopted the difference in radiative flux between the two branches of the elliptic curve is not an indication of changes in radiative forcing. At once we have compensated for the phase shift in a lagged phase plane plot the radiative flux will follow a straight line as seen in figure 2.

In a figure corresponding to figure 3 for this case, the phase plane plots in diagram A. looks almost the same as in figure 3 for $\alpha = 6$ W m^{-2} K^{-1} but the slope of the nearly linear lagged phase plane plot really corresponds to α. In diagram B. the blue and the red curve will coincide as a consequence of equation (5).

Equation (5) represents a modified model compared to equation (3). However, the climate feedback parameter α in equation (5) may also be related to climate sensitivity in a similar way as α in equation (3). If we consider a change between two steady state conditions after a step change in *F* we would from equation (5) obtain for the climate sensitivity *S*, like in the case without lag:

$$S = \frac{1}{\alpha} = \frac{\Delta(\Delta T)}{\Delta F} \quad .$$

Hence the slopes of the lines in figure 2 give us values of the climate feedback parameters that could be a measure of climate sensitivity.

Impact of changes in external radiative forcing

The temperature excursions that were discussed above occur during a period of time of not more than two years. Although external radiative forcing may well change, mostly due to changing greenhouse gas concentrations, during this time interval the changes are fairly small compared to the total change in radiative flux. The greenhouse gas forcing may change around 0.03 W m^{-2} a^{-1}.

Also in the 2008 La Niña episode discussed at first the temperature and the radiative flux decreased during one year and then both increased during the next year while the external radiative forcing is steadily changing in one direction. This means that when calculating an average slope between the two branches of the La Niña episode the change in the greenhouse gas radiative forcing will cancel.

Comparison of the two explanations

The two cases represent rather different cases with respect to the climate sensitivity. The first explanation is compatible with the range of climate sensitivities found in AOGCMs (Forster and

Taylor, 2006). However, an oscillating radiative forcing with an amplitude of 0.5 W m^{-2} K^{-1} may be difficult to grasp conceptually. It appears more likely that internal variations dominate the La Niña and ENSO.

Indeed the second explanation assumes that the changes are driven by internal variations where the temperature changes are solely driven by the ENSO. However, this explanation depends on how reasonable the postulated lag between the feedback radiative change and the temperature change is. Also, this explanation results in a climate feedback parameter value corresponding to a fairly nonsensitive climate system which is far from found in climate models (Forster and Taylor, 2006).

In the latter case we find a great value of the climate feedback parameter for SW flux far from what is found in climate models (Forster and Taylor, 2006). Considering that cloud processes are rather complicated and strongly connected to changes in water vapor in space and time and precipitation processes (Stephens, 2005) this may not be an unreasonable result.

Also the value of the climate feedback parameter for LW is greater than found by Forster and Taylor (2006). A value around 3 W m^{-2} K^{-1} would mean that the water vapor feedback is small or compensated for by other not well understood processes. However, neither this result may be unreasonable considering the complex interactions described by Stephens (2005).

Comparison with the results by Spencer and Braswell

Spencer and Braswell (2010) found straight line segments with a constant recurring value of the slope, which they called striations, in phase plane plots of CERES data for net total radiative flux vs middle tropospheric temperature anomalies. The recurring value of the slope of those striations also were around 6 W m^{-2} but they were mostly not connected to the 2008 La Niña event.

They noted that the middle tropospheric temperature is more correlated to the TOA radiative flux than the surface temperature. A consequence of this could be that changes in the TOA radiative flux come with less lag compared to changes in the middle troposphere temperature. This could mean that straight line segments appear more easily in phase plane plots based on middle tropospheric temperature than based on surface temperature in a period when the radiative forcing is constant.

Combining the results in this study with the results by Spencer and Braswell (2010) suggests that the recurring value of 6 W m^{-2} is more likely to be seen as the value of a climate feedback parameter rather than a ratio between changes in the radiative forcing and changes in temperature. It does not seem likely that the latter type of ratio would have this recurring property.

This is also supported by the results that Spencer and Braswell obtained from phase plane plots on LW radiative flux vs surface temperatures from four AOGCMs that showed clear striations which seem connected to ENSO like phenomena. Those results are found in figure 10 of Spencer and Braswell (2010). In those plots many of the loops are rather narrow and their recurring slopes appear to agree with the feedback parameter values determined for LW radiative flux by Foster and Taylor (2006).

Note that in the corresponding phase plane plots for SW and total net radiative flux in figure 11 and 12 in Spencer and Braswell (2010) striations are not seen but instead great loops, suggesting that there is much more lag between SW and total radiative flux and surface temperature than in case of LW radiative flux in those AOGCMs.

Conclusions

Phase plane plots of TOA total net radiative flux vs surface temperature anomaly with a lag in the radiative flux of 9 months show straight line segments with a slope of 6 W m^{-2} K^{-1}. This result agrees with the straight line segments (called striations) found by Spencer and Braswell (2010) in phase plane plots of TOA radiative flux vs middle tropospheric temperature anomaly. The present study finds support for the hypothesis that such straight line segments show the feedback response by the climate system due to temperature changes forced by internal variations such as the interactions between the deep ocean and the climate system occurring during a La Niña. If this is so a fairly insensitive climate system is indicated.

Literature cited

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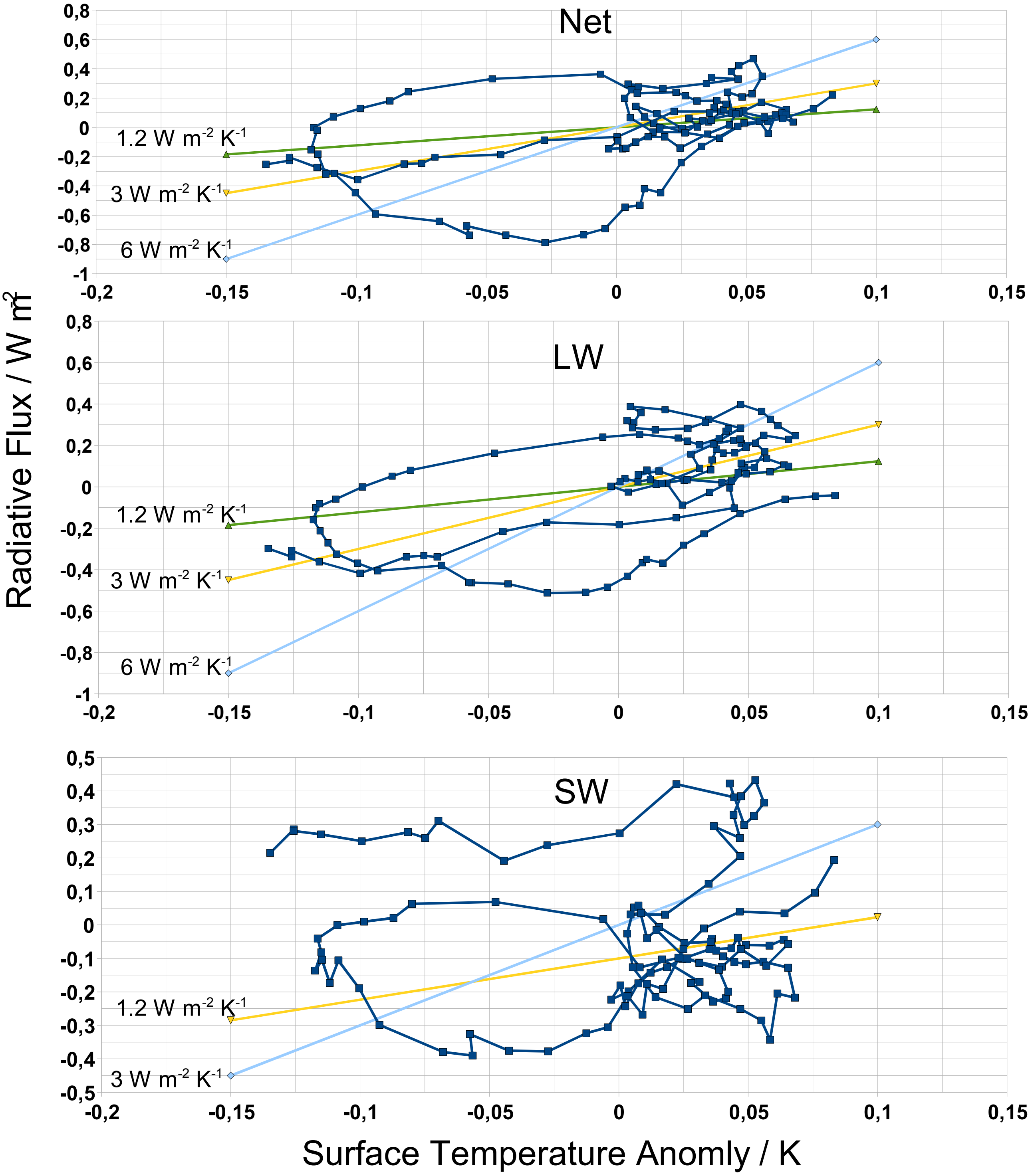

Figure 1. Radiative fluxes from CERES vs surface temperature anomalies from HadCRUT3. The values are centered 13 months averages from Sep 2000 until Dec 2009.

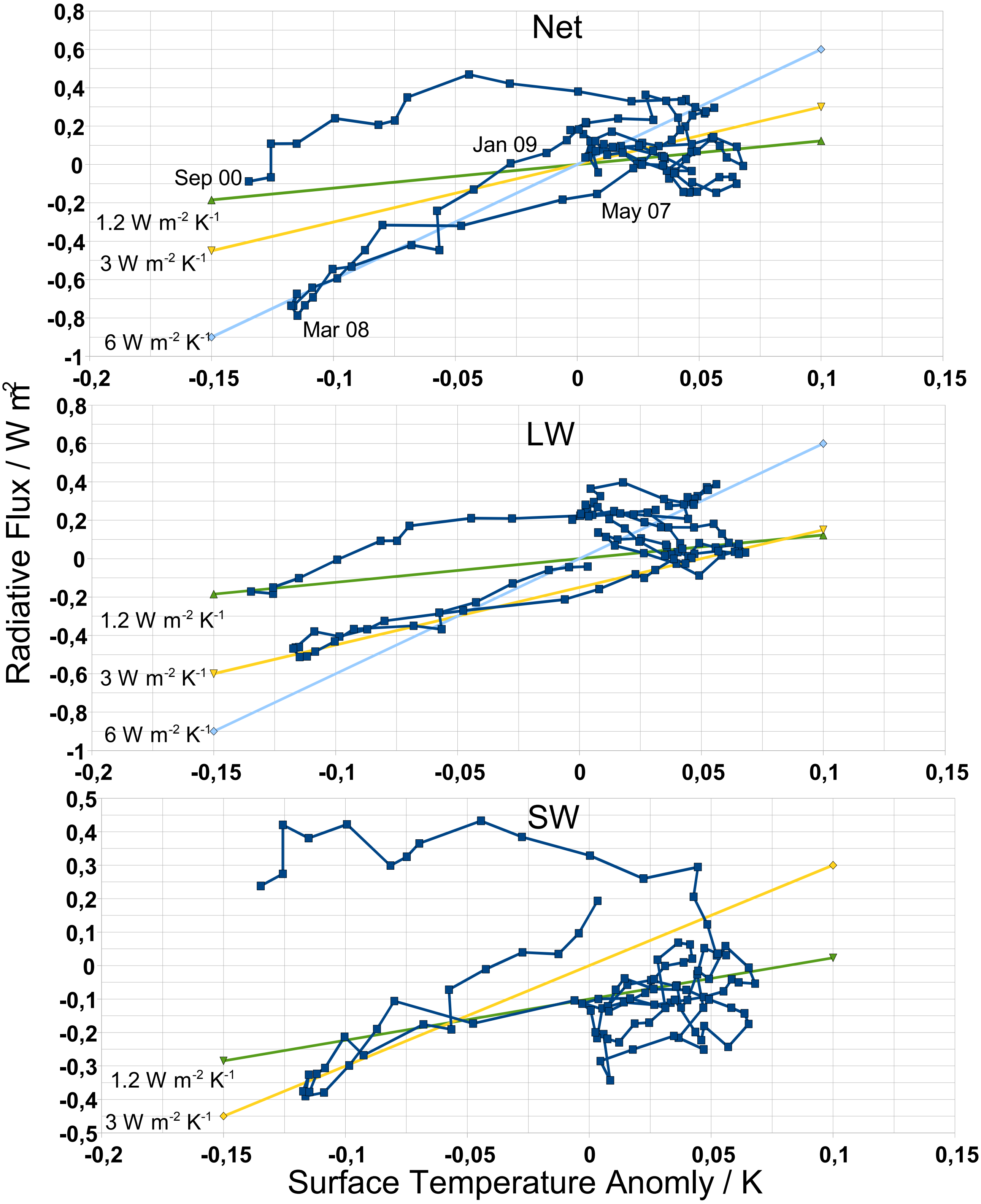

Figure 2. Radiative fluxes from CERES with 9 months lag vs surface temperature anomalies from HadCRUT3. The values are centered 13 months averages from Sep 2000 until Mar 2009 for temperatures and from June 2001 until Dec 2009 for radiative fluxes. Months indicated in the upper diagram refer to temperature values.

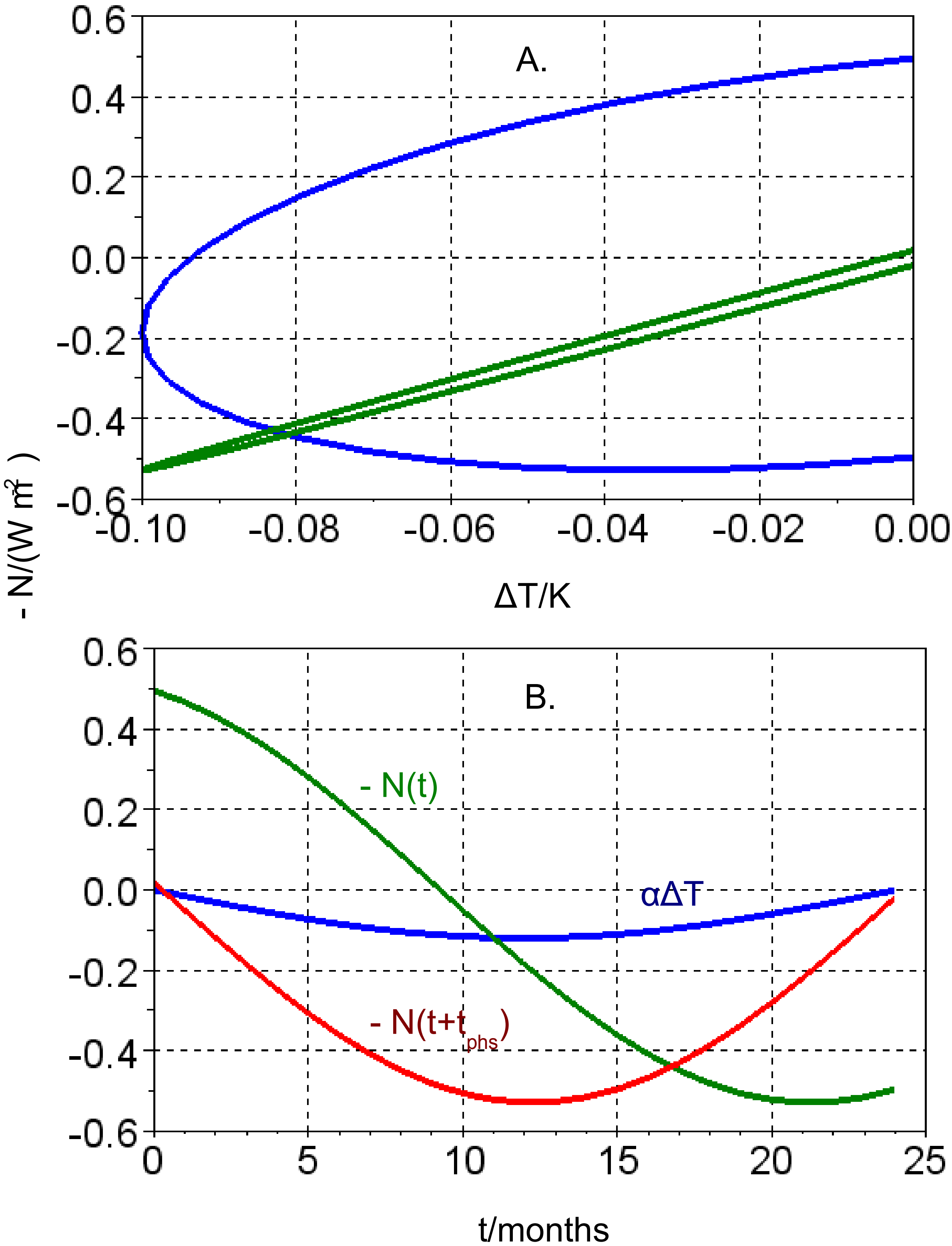

Figure 3. A. Normal (blue) and lagged (green) phase plane plot. Time zero up to the right. B. Net radiative flux (green), feedback radiative flux (blue), net radiative flux after lag compensation (red).

Appendix

Data according to Spencer and Braswell 2011

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