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On the determination of the global cloud feedback from satellite measurements

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Abstract

A detailed analysis is presented in order to determine the sensitivity of the estimated short-term cloud feedback to choices of temperature datasets, sources of top-of-atmosphere (TOA) radiative flux data, and temporal averaging. It is shown that the results of a previous analysis, which suggested a likely positive value for the short-term cloud feedback, depended upon combining radiative fluxes from satellite and re-analysis data when determining the cloud radiative forcing (CRF). These results are contradicted when ΔCRF is derived from NASA's Clouds and Earth's Radiant Energy System (CERES) all-sky and clear-sky measurements over the same period, resulting in a likely negative feedback. The differences between the radiative flux data sources are thus explored, along with the potential problems with each method. Overall, there is little correlation between the changes in the CRF and surface temperatures on these timescales, suggesting that the net effect of clouds varies during this time period quite apart from global temperature changes. Attempts to diagnose long-term cloud feedbacks in this manner are unlikely to be robust.

1 Introduction

The cloud feedback is one of the largest sources of uncertainty when trying to determine the global surface temperature response to a doubling of CO_2, and is the primary discrepancy leading to differing climate sensitivities in the global climate models (Bony et al., 2006; Bender, 2011). While many improvements have been made in the way the cloud radiative forcing can be estimated and constrained (Allan, 2011), the response of this net cooling effect of clouds to temperature changes still remains largely uncertain. Within the context of this paper, we use the typical notion of a cloud feedback, whereby it is considered negative if the amount of radiation escaping to space due to clouds (either by reflecting more solar radiation, or allowing more outgoing longwave radiation through the atmosphere) increases with an increase in temperature, and positive if an

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increase in temperature results in the opposite, thereby exacerbating the warming. All radiative fluxes presented in this paper are thus shown with a positive value indicating a downward flux towards the surface.

2 Data and methods

The CRF is determined by the difference between clear-sky and all-sky radiative fluxes at the top of the atmosphere. A simple examination of the change in CRF with respect to a temperature change ($\frac{dCRF}{dT}$) would at first appear to give an estimate of the cloud feedback. However, there are several other climate components that correlate with temperature (surface albedo, water vapor, and the Planck response), which will cause a change in the measured CRF even when no cloud properties have changed (Soden et al., 2008; Shell et al., 2008). Dessler (2010) sought to remove the influence of these non-cloud components on the real-world estimates of ΔCRF before computing the cloud feedback, noting that there was only a slight difference between the calculated ΔCRF and ΔR_{cloud}, although the issue with such an approach is discussed further in Sect. 2.4. Regardless, it is clear that the method of determining ΔCRF – and in particular, the choice for clear-sky flux – is of primary importance when calculating the cloud feedback in this manner.

2.1 All-sky radiative fluxes

For all-sky TOA fluxes (Fig. 1a), we use CERES Single Scanner Footprint (SSF) 1° global means (version 2.6) (Wielicki et al., 1996). We have chosen the CERES SSF1 degree product for consistency with Dessler (2010), and because it is more stable with respect to anomalies than its Energy Balanced and Filled (EBAF) counterpart. There are two periods over which we perform the analysis: the Terra period (Table 1), stretching from March 2000 to June 2011, during which time we use the measurements from the CERES instrument aboard the Terra satellite; and the Aqua period (Table 2), from

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September 2002 to June 2011, during which we average the CERES products coming from the different Terra and Aqua satellites. For each analysis, we calculate anomalies relative to their respective time intervals. We note that the CERES measurements aboard Aqua actually begin in July 2002, but the relevant data from the Atmospheric Infrared Sounder (AIRS) instrument aboard the same satellite is only available beginning in September of that year.

2.2 Clear-sky radiative fluxes

We use multiple sources of clear-sky radiative fluxes in order to determine the sensitivity to each choice. Figure 1b shows the net clear-sky flux anomaly for CERES (Terra) and ERA-Interim, while Fig. 2 plots the shortwave and longwave components of clear-sky flux anomalies for the different data products below.

2.2.1 CERES clear-sky

Similar to all-sky fluxes, we use CERES clear-sky fluxes from aboard the Terra satellite over the longer period analysis, and then average the data products during the overlapping Terra and Aqua interval. There are, however, several potential issues with using the CERES clear-sky fluxes to determine the CRF that must be considered. For one, there is a known clear-sky bias for OLR in absolute CERES CRF measurements (Sohn and Bennartz, 2008), as the observations made over areas during clear-sky conditions coincide with less water vapor in that area. The difference between all-sky and clear-sky fluxes thus aliases some of the OLR trapping properties of the water vapor in with the LW CRF. We note here that if the bias is significant in affecting the changes in ΔCRF (rather than simply in the absolute calculation), a rise in temperature would likely lead to increasing water vapor that traps more OLR, which will then appear to bias the LW component towards a more positive cloud feedback. Such a bias would be insignificant for the shortwave component.

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Another potential issue with the CERES clear-sky fluxes is the difficulty of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument in detecting thin cirrus clouds. The MODIS instrument aboard the same satellites (Terra and Aqua) is used to determine whether a scene is considered clear or cloudy, and misidentification would lead to biases in the reported CERES observations. We note that although the misidentification is prevalent, with 40 % of tropical scenes considered to be clear-sky containing thin cirrus clouds, the actual radiative effect of these clouds relative to the total CRF in the tropics is small: ~4 % for the SW component (due to their low albedo), and ~10 % for the LW (Lee et al., 2008). The degree to which this would bias the diagnosed feedback in this analysis thus depends on the variability of the thin cirrus cloud types relative to all other clouds types, and the bias for the SW and LW components would be in opposite directions.

The third issue with respect to the CERES clear-sky fluxes is the infrequent sampling of clear-sky scenes over regions that are typically cloudy. The fewer data points over these areas may thus lead to noisier estimates. This is a strong reason for averaging the Terra and Aqua measurements over their overlapping period, as their different orbits, viewing angles, and cloud conditions for a location can serve to reduce some of the noise.

2.2.2 ECMWF ERA-interim clear-sky

Dessler (2010) determined the CRF by subtracting the modeled reanalysis clear-sky fluxes from the CERES measured all-sky fluxes, rather than using the CERES measurements for both the clear-sky and all-sky measurements, specifically to avoid the dry, clear-sky bias discussed above. In particular, the primary source for the clear-sky flux was the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-interim reanalysis (Dee et al., 2011), which we use as a source here as well. However, we note that there are significant issues with this approach. First, although the radiative transfer model may accurately derive OLR clear-sky fluxes from temperature and water vapor profiles, the modeling of these temperature and water vapor components

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themselves is questionable, with spurious water vapor trends noted in current reanalysis (and ERA interim in particular) (John et al, 2009). Similarly, for the shortwave component, there are several problems with the snow analysis that regulates interannual surface albedo changes (Dee et al., 2011), suggesting that the ERA Interim clear-sky fluxes may not properly represent the real-world albedo changes. Finally, as Dessler (2010) notes, the interannual changes in aerosol forcing affecting the all-sky CERES fluxes are not present in the modeled clear-sky fluxes, adding in another discrepancy. Although there is not necessarily a reason to believe these aerosol effects would correlate with surface temperature anomalies, the low correlation between ΔCRF and $\Delta T_{\text{surface}}$ means that a few large discrepancies can have a major impact on the estimate.

We note that the general method of combining two different sources of TOA radiative flux data (measured vs. modeled) can be dangerous in this scenario, as the magnitude of the changes flux is far smaller than the magnitude of the total flux, and any discrepancy between the two sources will be aliased into the ΔCRF. If there exist inaccuracies in either of the two sources, even if unrelated to clear-sky vs. all-sky differences, it will still appear in the combined ΔCRF, whereas if the single CERES dataset contains slightly inaccurate flux values it will not adversely affect the ΔCRF, as long as the bias is not specifically related to those clear-sky vs. all-sky differences.

2.2.3 AIRS modelled clear-sky

We also generate our own estimate for clear-sky LW fluxes, using the AIRX3STM v5 data product from the Atmospheric Infrared Sounder (AIRS) aboard NASA's Aqua satellite (Aumann et al, 2006) for the gridded observations of temperature and water vapor, then combining it with the radiative kernels calculated from the Global Fluid Dynamics Laboratory (GFDL) model (Soden et al., 2008). We use 0.25 W m^{-2} as the estimate for the change in clear-sky forcing for well-mixed greenhouse gases over this Aqua time period. Such an approach is advantageous in that it takes advantage of the accuracy of the GFDL RTM while also using measured temperature and water vapor

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profiles. Furthermore, this kernel approach focuses on the anomalies in the fluxes rather than in absolute estimates. Unfortunately, AIRS temperature and water vapor profiles may also have an absolute bias due to undetected thin cirrus clouds (Sun et al., 2011), and this approach still suffers from the general drawbacks of combining measured and modeled flux sources discussed above.

2.3 Surface temperature

For surface temperatures, anomalies are calculated from GISS (Hansen et al., 2010) and NCDC (Smith et al., 2008) with respect to the two baseline periods (Terra and Aqua) discussed above.

2.4 Removing non-cloud components from ΔCRF

The measured ΔCRF is influenced by other climate components besides clouds, due to the preferential TOA radiative effect these components have in clear-sky versus cloudy scenes. Generally, the positive surface albedo and water vapor feedbacks will bias towards a negative cloud feedback if these effects are not removed, while the Planck response will create a bias in the opposite (positive) direction, although the magnitude of the net bias is unclear. Dessler (2010) attempted to remove these non-cloud components from ΔCRF using the same method that has been used in models (Soden et al., 2008; Shell et al., 2008), combining the radiative kernels with the reanalysis values instead of the model outputs. However, we note that the spurious trends in the reanalysis data discussed previously may introduce an invalid trend in the cloud feedback due simply to these adjustments. Furthermore, since GCMs generally do a poor job of reproducing the vertical distribution of clouds (Zhang et al., 2005), the all-sky kernels calculated from such a model are unlikely to accurately represent the real-world effect of these non-cloud components on the TOA radiation budget. For these reasons we present our regressions of ΔCRF against surface temperature without attempting to make further adjustments (Tables 1 and 2).

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Nonetheless, for an estimate of the effect of these non-cloud components, we make adjustments for temperature and water vapor using the AIRS measured profiles and GFDL kernels during the Aqua period (Fig. 3), noting the limitations mentioned above. Like Dessler (2010), we use 0.16 to represent the degree to which the WMGHG forcing preferentially affects the OLR in clear-sky vs. all-sky. No adjustments for surface albedo impacts have been made due to the lack of reliable data for interannual changes over this period, but we note that this is likely to have a considerably smaller impact than water vapor (Soden et al., 2008; Shell et al., 2008), and since it is a slower feedback should have less of an effect on month-to-month ΔCRF changes.

3 Results

Tables 1 and 2 shows the results of the OLS regressions, with uncertainties presented for the 2.5 % to 97.5 % confidence interval as a result of those regressions (no explicit uncertainty calculations have been made for uncertainty in forcings or measurements). The r^2 values for these regressions using monthly anomalies and CERES-only derived ΔCRF during the Terra period are 5.3 % and 3.6 % for GISS and NCDC respectively, compared to the 0.2 % and 0.1 % values using the same temperature sets with CERES-ECMWF. It is during this time period that the larger discrepancy between the two estimates exists, with the CERES-only estimate suggesting a modest to large negative cloud feedback (depending on the magnitude of the non-cloud component bias), whereas the CERES-ECMWF estimate implies a modest positive cloud feedback.

During the Aqua period there is better agreement among the ERA-Interim, CERES, and AIRS modelled clear sky estimates, with a slightly negative to neutral cloud feedback implied, although the r^2 values for each of these net regressions is less than 1 %. Adjusting for the Planck, water vapor, and WMGHG contributions to CRF for the CERES-only GISS regression results in an estimate of $-0.48 \pm 0.83\,\mathrm{W\,m^{-2}\,K^{-1}}$, compared to $-0.36 \pm 0.86\,\mathrm{W\,m^{-2}\,K^{-1}}$ for the raw ΔCRF, meaning that the net combination of these components actually leads to a slight positive bias. This runs contrary to the

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long-term effect of these non-cloud components in models, but likely results here from the better month-to-month correlation between the Planck response and $\Delta T_{\text{surface}}$ than between water vapor anomalies and $\Delta T_{\text{surface}}$.

Overall, the results show that estimates using this methodology are extremely sensitive to outliers, the time period for which we run the regressions, and the choice of clear-sky radiation fluxes.

4 Discussion

We suggest that combining the reanalysis TOA radiative flux data with that of the measured CERES values in order to determine the changing cloud radiative forcing can introduce new problems. As previously noted, the CERES-only calculated fluxes over the longest period show a likely negative short-term cloud feedback, although the uncertainty is quite large, and the lack of robustness in this estimate makes it difficult to deem the GCM positive cloud feedbacks inconsistent with observations. Similarly, the uncertainty makes it difficult to rule out the possibility of a large negative cloud feedback.

Due to the low correlations between global surface temperature and ΔCRF, it is clear that the variations in the cloud forcing are resulting from other changes in the climatology, and that clouds are acting as more than simple feedbacks on these timescales. This variation may result from a separate fast response to aerosol forcing (Andrews et al., 2010), from tropical intraseasonal oscillations (Spencer et al., 2007), or from other sources of natural variability. To the degree that this radiative noise from cloud fluctuations influences surface temperatures within a lag time shorter than the decorrelation time of the noise (Spencer and Braswell, 2008), this could lead to a positive bias in the diagnosed cloud feedback. An attempt has been made to show that these fluctuations in the cloud forcing are insignificant relative to the variability in ocean heat exchange between layers, noting that the standard deviation of ocean heat flux from ARGO measurements down to the 700 m layer would correspond to a monthly forcing of 13 W m^{-2}

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and a ratio of $\sigma(\Delta F_{ocean})/\sigma(\Delta R_{cloud}) \approx 20$ (Dessler, 2011). However, estimating the heat flux of a more realistic 100 m mixed layer from ocean temperature anomalies (Levitus et al., 2009) results in a standard deviation of 2.1 Wm^{-2} for 3-month averages. A lower value for mixed-layer heat capacity on these times scales is more in line with recent regressions, which have found that the relatively small variations associated with the solar cycle (~0.25 Wm^{-2}) can be detected in global surface temperatures, with an instantaneous response of ~0.4 K/(Wm^{-2}) after only a month lag (Foster and Rahmstorf, 2011). If a similar efficacy were to exist for radiative noise due to cloud variations, this noise could significantly contaminate the cloud feedback estimate. The extent of this contamination thus depends on the amount non-feedback radiative variability, as well as the decorrelation time of the radiative noise produced.

Finally, Dessler (2010) notes that there is no correlation between the short and long term cloud feedbacks among models, so that the long-term feedback may be significantly higher or lower than that diagnosed from interannual variations. This fact, combined with the sensitivity of the estimated short-term feedback to methodological choices, suggests that diagnosing a climate-scale cloud feedback in this manner will require a substantially longer time period.

Supplementary material related to this article is available online at: http://www.earth-syst-dynam-discuss.net/3/73/2012/esdd-3-73-2012-supplement.zip.

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Table 1. The results of OLS regressions of ΔCRF against $\Delta T_{surface}$, with 95 % confidence interval over the March 2000 to June 2011 Terra period. All estimates are in $Wm^{-2} K^{-1}$.

ΔR_{clear}	$T_{surface}$	Monthly anomalies			3-month anomalies		
		Total	Shortwave	Longwave	Total	Shortwave	Longwave
CERES	GISS	−1.06 ± 0.77	−0.72 ± 0.79	−0.34 ± 0.43	−1.35 ± 1.17	−0.95 ± 1.17	−0.40 ± 0.65
ECMWF	GISS	0.18 ± 0.8	0.14 ± 0.84	0.05 ± 0.42	0.01 ± 1.25	−0.07 ± 1.24	0.08 ± 0.60
CERES	NCDC	−1.06 ± 0.93	−0.8 ± 0.95	−0.26 ± 0.52	−1.34 ± 1.49	−0.99 ± 1.46	−0.35 ± 0.81
ECMWF	NCDC	0.18 ± 0.96	0.22 ± 1.01	−0.04 ± 0.5	0.06 ± 1.55	−0.02 ± 1.54	0.08 ± 0.74
Dessler (2010)*	ERA-Interim	0.25 ± 0.77 (0.54 ± 0.74)	(0.12 ± 0.78)	(0.43 ± 0.45)	N/A	N/A	N/A

* ΔCRF was calculated using ECMWF-CERES over the March 2000 through February 2010 period. Values in parentheses are the reported results that include adjustments made to ΔCRF for the removal of non-cloud influences.

Table 2. The results of OLS regressions of ΔCRF against $\Delta T_{surface}$, with 95 % confidence interval over the September 2002 to June 2011 Aqua period. All estimates are in $Wm^{-2} K^{-1}$.

ΔR_{clear}	$T_{surface}$	Monthly anomalies			3-month anomalies		
		Total	Shortwave	Longwave	Total	Shortwave	Longwave
CERES	GISS	−0.36 ± 0.86	−0.42 ± 0.83	0.06 ± 0.49	−0.38 ± 1.47	−0.46 ± 1.28	0.08 ± 0.73
ECMWF	GISS	−0.22 ± 0.94	−0.57 ± 0.97	0.34 ± 0.48	−0.30 ± 1.52	−0.88 ± 1.44	0.59 ± 0.72
AIRS	GISS	N/A	N/A	0.11 ± 0.44	N/A	N/A	0.24 ± 0.67
CERES	NCDC	−0.07 ± 1.04	−0.4 ± 1.01	0.33 ± 0.59	0.15 ± 1.84	−0.22 ± 1.61	0.37 ± 0.89
ECMWF	NCDC	−0.17 ± 1.14	−0.44 ± 1.19	0.27 ± 0.59	−0.15 ± 1.89	−0.7 ± 1.81	0.55 ± 0.91
AIRS	NCDC	N/A	N/A	0.19 ± 0.53	N/A	N/A	0.37 ± 0.83

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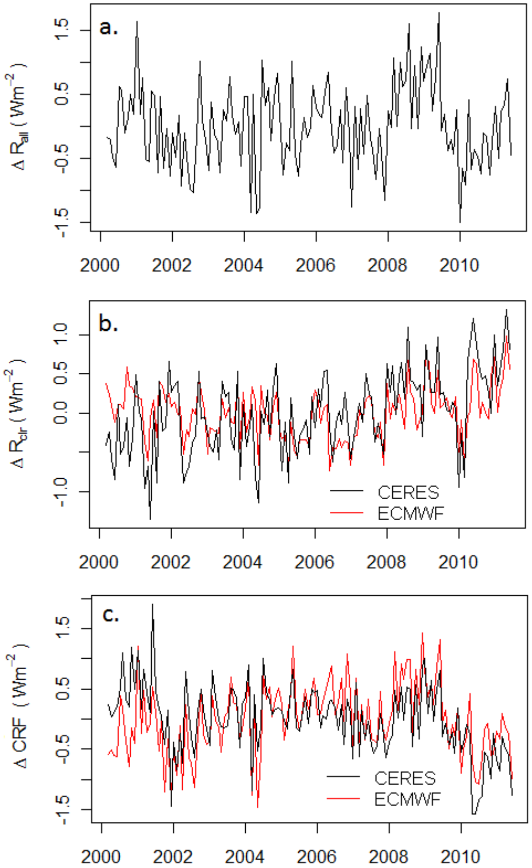

Fig. 1. (a) Global average monthly anomalies for all-sky TOA radiative flux from CERES measurements aboard the Terra satellite. **(b)** Global average monthly anomalies for clear-sky TOA radiative fluxes from CERES and ECMWF ERA-Interim. **(c)** The global average monthly CRF anomalies from CERES-only measurements and ECMWF-CERES measurements.

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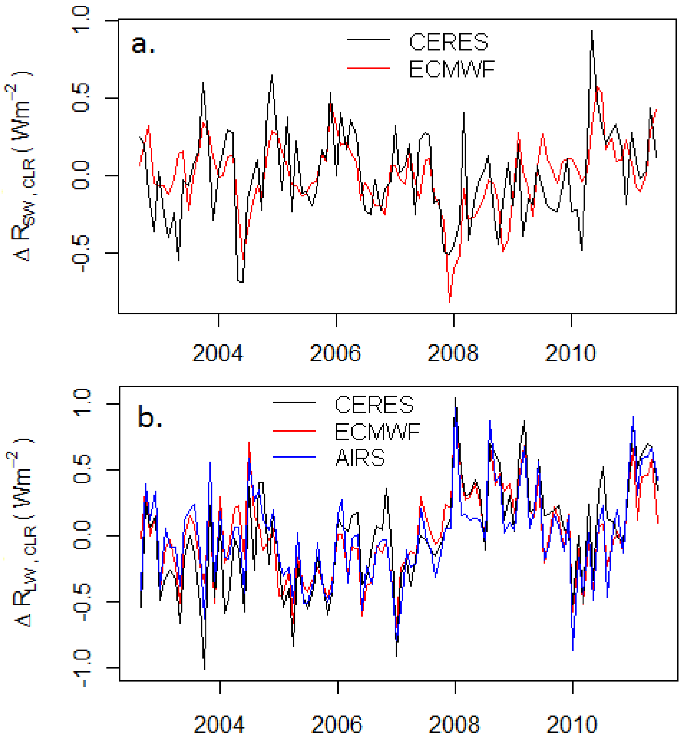

Fig. 2. **(a)** Global monthly anomalies for shortwave, clear-sky TOA radiative flux from CERES and ECMWF ERA-Interim. **(b)** Global monthly anomalies for longwave, clear-sky TOA radiative fluxes from CERES, ECMWF ERA-Interim, and the AIRS and GFDL kernel combination.

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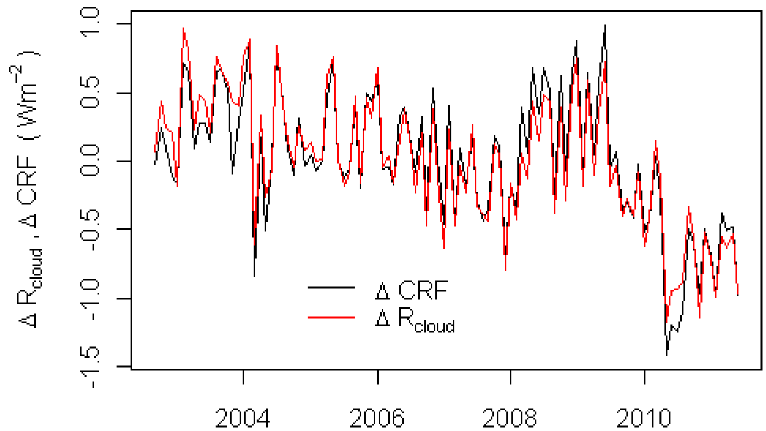

Fig. 3. Global monthly anomalies for the cloud radiative forcing from CERES with adjustements for water vapor, temperature, and WMGHG contributions (ΔR_{cloud}) and without these adjustments (ΔCRF).

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