

## Cloud variations and the Earth's energy budget

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[1] The question of whether clouds are the cause of surface temperature changes, rather than acting as a feedback in response to those temperature changes, is explored using data obtained between 2000 and 2010. An energy budget calculation shows that the radiative impact of clouds accounts for little of the observed climate variations. It is also shown that observations of the lagged response of top-of-atmosphere (TOA) energy fluxes to surface temperature variations are not evidence that clouds are causing climate change. **Citation:** Dessler, A. E. (2011), Cloud variations and the Earth's energy budget, *Geophys. Res. Lett.*, 38, L19701, doi:10.1029/2011GL049236.

### 1. Introduction

[2] The usual way to think about clouds in the climate system is that they are a feedback — as the climate warms, clouds change in response and either amplify (positive cloud feedback) or ameliorate (negative cloud feedback) the initial change [e.g., *Stephens*, 2005]. In recent papers, *Lindzen and Choi* [2011, hereinafter LC11] and *Spencer and Braswell* [2011, hereinafter SB11] have argued that clouds are **not** an important source of radiative forcing for the climate — meaning that clouds are also an initiator of climate change. If this claim is correct, then significant revisions to climate science may be required.

### 2. Energy Budget Calculation

[3] Equation 8 of LC11 and equation 1 of SB11 both write the Earth's energy budget as:

$$C \frac{dT_s}{dt} = \Delta R_{\text{cloud}} + \Delta F_{\text{ocean}} - \lambda \Delta T_s \quad (1)$$

$C$  is the heat capacity of the ocean's mixed layer,  $\Delta T_s$  is the surface temperature, and  $\Delta F_{\text{ocean}}$  is the heating of the climate system by the ocean. The term  $-\lambda \Delta T_s$  represents the enhanced emission of energy to space as the planet warms.  $\lambda$  is the climate sensitivity and it contains the Planck response as well as the climate feedbacks.  $\Delta R_{\text{cloud}}$  is the change in TOA flux due to clouds (including both solar and infrared contributions). Note that  $\Delta R_{\text{cloud}}$  is not a feedback in this formulation — it is a forcing and is independent of surface temperature (the cloud feedback is in the  $-\lambda \Delta T_s$  term). All quantities are global monthly average anomalies (anomalies are calculated by subtracting the mean annual cycle.). Other terms, such as the change in radiative forcing by greenhouse gases, are small over the period examined, so they are ignored.

[4] The formulation of equation (1) is potentially problematic because the climate system is defined to include the

ocean, yet one of the heating terms is flow of energy to/from the ocean ( $\Delta F_{\text{ocean}}$ ). This leads to the contradictory situation where heating of their climate system by the ocean ( $\Delta F_{\text{ocean}} > 0$ ) causes an increase of energy in the ocean ( $C(dT_s/dt) > 0$ ), apparently violating energy conservation. While it may be possible to define the terms so that equation (1) conserves energy, LC11 and SB11 do not provide enough information to show that they have actually done so. However, to comprehensively evaluate the arguments of LC11 and SB11, I simply note this potential problem and assume in the rest of the paper that equation (1) is correct.

[5] In their analyses, LC11 and SB11 test equation (1) by creating synthetic data for  $\Delta F_{\text{ocean}}$  and  $\Delta R_{\text{cloud}}$ , and this requires an assumption about the relative magnitudes of these terms. LC11 choose the ratios of the standard deviations of the time series  $\sigma(\Delta F_{\text{ocean}})/\sigma(\Delta R_{\text{cloud}}) \approx 2$  while SB11 choose, for their most realistic case,  $\sigma(\Delta F_{\text{ocean}})/\sigma(\Delta R_{\text{cloud}}) \approx 0.5$  (the time series are anomalies, so their means are zero by definition; thus, the standard deviation is a measure of the magnitude of the terms).

[6] However, it is possible to use data to estimate the magnitude of  $\sigma(\Delta F_{\text{ocean}})/\sigma(\Delta R_{\text{cloud}})$ . I will focus on the period from March 2000 to February 2010, during which good data exist and the primary climate variations were caused by El Niño–Southern Oscillation (ENSO). This is the same period evaluated by SB11, and LC11's analysis also included this period.

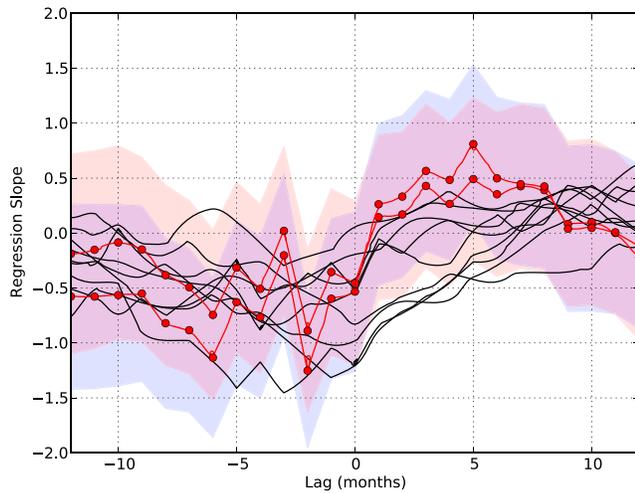
[7] To evaluate the magnitude of the first term,  $C(dT_s/dt)$ , I assume a heat capacity  $C$  of 168 W-month/m<sup>2</sup>/K, the same value used by LC11 (as discussed below, SB11's heat capacity is too small). The time derivative is estimated by subtracting each month's global average ocean surface temperature from the previous month's value. Temperatures used in this calculation come from NASA's Modern Era Retrospective-analysis for Research and Application (MERRA) [*Rienecker et al.*, 2011]. The standard deviation of the monthly anomaly time series,  $\sigma(C(dT_s/dt))$ , is 9 W/m<sup>2</sup>.

[8] This can be confirmed by looking at the Argo ocean heat content data covering the top 750 m of the ocean over the period 2003–2008. Using data reported by *Douglass and Knox* [2009], the month-to-month change in monthly interannual heat content anomalies can be calculated ( $\sigma = 1.2 \times 10^{22}$  J/month). Assuming the ocean covers 70% of the planet, this corresponds to 13 W/m<sup>2</sup>, in agreement with the previous estimate.

[9] In the work by *Dessler* [2010, hereinafter D10], the change in TOA flux due to clouds each month over this period was computed (LC11 calculated similar values). If all of this energy is assumed to be a climate forcing — i.e., unrelated to surface temperature changes — then I can use these values for  $\Delta R_{\text{cloud}}$ . This yields  $\sigma(\Delta R_{\text{cloud}}) = 0.5$  W/m<sup>2</sup>. Calculations for potential water vapor forcing are of a similar magnitude.

[10] To calculate  $\lambda \Delta T_s$ , I assume that  $\lambda$  is between 1 and 6 W/m<sup>2</sup>/K. Global and monthly averaged  $\Delta T_s$  are from the MERRA reanalysis. I calculate that  $\sigma(\lambda \Delta T_s) < 0.4$  W/m<sup>2</sup>.

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**Figure 1.** The slope of the regression ( $\text{W/m}^2/\text{K}$ ) of the change in TOA flux due to clouds  $\Delta R_{\text{cloud}}$  vs. surface temperature  $\Delta T_s$ , as a function of the lag between the time series in months. Negative values of lag indicate that  $\Delta R_{\text{cloud}}$  leads  $\Delta T_s$ . The red lines are based on the observations of D10, using CERES flux data [Wielicki et al., 1996] and either ERA-Interim [Dee et al., 2011] or MERRA reanalyses [Rienecker et al., 2011]. The red and blue shading indicates the  $2\sigma$  uncertainty of the lines (purple shading is where the red and blue shading overlaps). The thin black lines are AMIP climate model runs.

[11]  $\Delta F_{\text{ocean}}$  can be calculated as a residual using equation (1) and the terms calculated above. The result is that  $\Delta F_{\text{ocean}} \approx C(dT_s/dt)$ , and that  $\sigma(\Delta F_{\text{ocean}}) \approx \sigma(C(dT_s/dt))$ . Despite potential problems in equation (1), the conclusion here is robust: the radiative effects of clouds can explain only a few percent of the surface temperature changes. This is consistent with previous work showing that heating of the surface and atmosphere during ENSO comes from ocean heat transport [e.g., Trenberth et al., 2002, 2010] and it means that clouds were not causing significant climate change over this period.

[12] A related point made by both LC11 and SB11 is that regressions of TOA flux or its components vs.  $\Delta T_s$  will not yield an accurate estimate of the climate sensitivity  $\lambda$  or the cloud feedback. This conclusion, however, relies on their particular values for  $\sigma(\Delta F_{\text{ocean}})$  and  $\sigma(\Delta R_{\text{cloud}})$ . Using a more realistic value of  $\sigma(\Delta F_{\text{ocean}})/\sigma(\Delta R_{\text{cloud}}) = 20$  in their model, regression of TOA flux vs.  $\Delta T_s$  yields a slope that is within 0.4% of  $\lambda$ , a result confirmed by Spencer and Braswell [2008, Figure 2b]. This also applies to the individual components of the TOA flux, meaning that regression of  $\Delta R_{\text{cloud}}$  vs.  $\Delta T_s$  yields an accurate estimate of the magnitude of the cloud feedback, thereby confirming the results of D10.

[13] As a side note, SB11 estimated their heat capacity by regressing  $\Delta R_{\text{cloud}}$  vs.  $dT_s/dt$  and assuming that  $C$  is the slope. This is only correct, however, if  $\Delta F_{\text{ocean}} = 0$ . For the realistic case where  $\sigma(\Delta F_{\text{ocean}}) \gg \sigma(\Delta R_{\text{cloud}})$ , the slope is much less than  $C$ , which explains why SB11's heat capacity is too small.

### 3. Comparison With Models: LC11

[14] LC11 base their conclusion that clouds are a forcing rather a feedback on a plot like the one in Figure 1 (see

Figure 9 of LC11). The figure shows the slope of the correlation between  $\Delta R_{\text{cloud}}$  and  $\Delta T_s$  as a function of lag for the observations by D10.

[15] The observations show that larger negative slopes exist when the cloud time series leads the surface temperature, with mostly positive slopes when the temperatures leads the cloud time series. Based on this correlation, LC11 conclude that clouds must be initiating the climate variations.

[16] I've also plotted the results from nine models from the Atmospheric Model Intercomparison Project (AMIP) (CNRM CM3, INMCM 3.0, IPSL CM4, MIROC 3.2 MEDRES, MIROC 3.2 HIRES, MPI ECHAM 5, MRI CGCM 2.3.2a, NCAR CCSM, UKMO HADGEM1). While some disagreements between the observations and models exist, the models clearly simulate the key aspect of the data identified by LC11: larger negative slopes when  $\Delta R_{\text{cloud}}$  leads  $\Delta T_s$ .

[17] This is an important result because the sea surface temperatures (SST) are specified in AMIP models. This means the interaction in these models is one-way: clouds respond to SST changes, but SST does not respond to cloud changes. The plot shows that realistic  $\Delta R_{\text{cloud}}$  variations are generated in these models by specifying  $\Delta T_s$  variations. This suggests that the observed lead-lag relation is a result of variations in atmospheric circulation driven by  $\Delta T_s$  variations and is not evidence that clouds are initiating climate variations. This conclusion also agrees with the energy budget presented earlier that concluded that clouds are not trapping enough energy to explain the  $\Delta T_s$  variations.

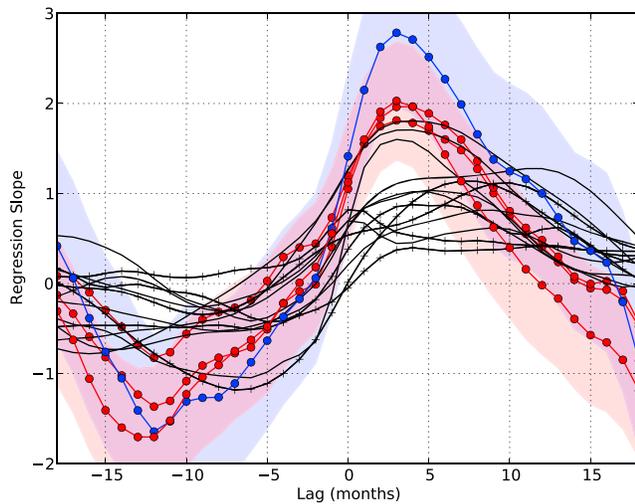
[18] Calculations using fully coupled models yield similar lead-lag relations as the AMIP models. This means that closing the loop to allow clouds to affect SST does not change these conclusions.

### 4. Comparison With Models: SB11

[19] SB11's analysis is built on a plot like LC11's, but using TOA net flux instead of  $\Delta R_{\text{cloud}}$ . Figure 2 shows my reconstruction of SB11's Figure 3. Each line shows, for a single data set, the slope of the relation between TOA net flux and  $\Delta T_s$  as a function of lag between them. The colored lines are observations: the blue line shows the data used by SB11 (CERES fluxes and HadCRUT3 temperature [Brohan et al., 2006]); the red lines use the same flux data, but different surface temperature data sets (MERRA, ERA-Interim, GISTEMP [Hansen et al., 2010]). The shaded regions show the  $2\sigma$  uncertainties of the observations using GISTEMP and HadCRUT3. As done by SB11, all data have been 1-2-1 filtered.

[20] The black lines are from pre-industrial control runs of 13 fully coupled climate models (CCCMA CGCM 3.1, CNRM CM3, GFDL CM 2.0, GFDL CM 2.1, GISS ER, FGOALS 1.0G, INMCM 3.0, IPSL CM4, MIROC 3.2 HIRES, MIROC 3.2 MEDRES, MPI ECHAM5, MRI CGCM 2.3.2A, NCAR CCSM 3.0) from the CMIP3 database [Meehl et al., 2007] (SB11 used de-trended 20th century runs; differences with my calculations appear minor). The models with the crosses '+' are 5 of the 6 models analyzed by SB11.

[21] There are three notable points to be made. First, SB11 analyzed 14 models, but they plotted only six models and the particular observational data set that provided maximum support for their hypothesis. Plotting all of the models and all of the data provide a much different conclusion. Second,



**Figure 2.** Slope of the relation between TOA net flux and  $\Delta T_s$ , in  $W/m^2/K$  as a function of lag between the data sets (negative lags mean that the flux time series leads  $\Delta T_s$ ). The colored lines are from observations (covering 3/2000–2/2010 using the same TOA flux data, but different time series for  $\Delta T_s$ ); the shading represents the  $2\sigma$  uncertainty of two of the data sets. The black lines are from 13 fully coupled pre-industrial control runs; lines with the crosses ‘+’ are models used by SB11. Following SB11, all data are 1-2-1 filtered. See the text for more details about the plot.

some of the models (not plotted by SB11) agree with the observations, which means that the observations are not fundamentally inconsistent with mainstream climate models containing positive net feedbacks. Third, the models that do a good job simulating the observations (GFDL CM 2.1, MPI ECHAM5, and MRI CGCM 2.3.2A) are among those that have been identified as realistically reproducing ENSO [Lin, 2007]. And since most of the climate variations over this period were due to ENSO, this suggests that the ability to reproduce ENSO is what’s being tested here, not anything directly related to equilibrium climate sensitivity.

## 5. ENSO Coupling in the Model

[22] This leads us to another fundamental problem in their analysis of equation (1): LC11 and SB11 model  $\Delta F_{\text{ocean}}$  as random time series, but this is incorrect.  $\Delta F_{\text{ocean}}$  is actually a function of  $\Delta T_s$ , with the coupling occurring via the ENSO dynamics:  $\Delta T_s$  controls the atmospheric circulation, which drives ocean circulation, which determines  $\Delta F_{\text{ocean}}$ , which controls  $\Delta T_s$ .

[23] Putting everything together, the evolution of  $\Delta T_s$  during ENSO is due primarily to heat transport by the ocean. As the AMIP models show, these changes in  $\Delta T_s$  also change clouds, but the impact of these cloud changes on  $\Delta T_s$  is small. Thus, the lead-lag relation between TOA flux and  $\Delta T_s$  tells us nothing about the physics driving  $\Delta T_s$ .

## 6. Conclusions

[24] These calculations show that clouds did not cause significant climate change over the last decade (over the

decades or centuries relevant for long-term climate change, clouds acting as a feedback can indeed cause significant warming). Rather, the evolution of the surface and atmosphere during ENSO variations are dominated by oceanic heat transport. This means in turn that regressions of TOA fluxes vs.  $\Delta T_s$  can be used to accurately estimate climate sensitivity or the magnitude of climate feedbacks. In addition, observations presented by LC11 and SB11 are not in fundamental disagreement with mainstream climate models, nor do they provide evidence that clouds are causing climate change. Suggestions that significant revisions to mainstream climate science are required are therefore not supported.

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