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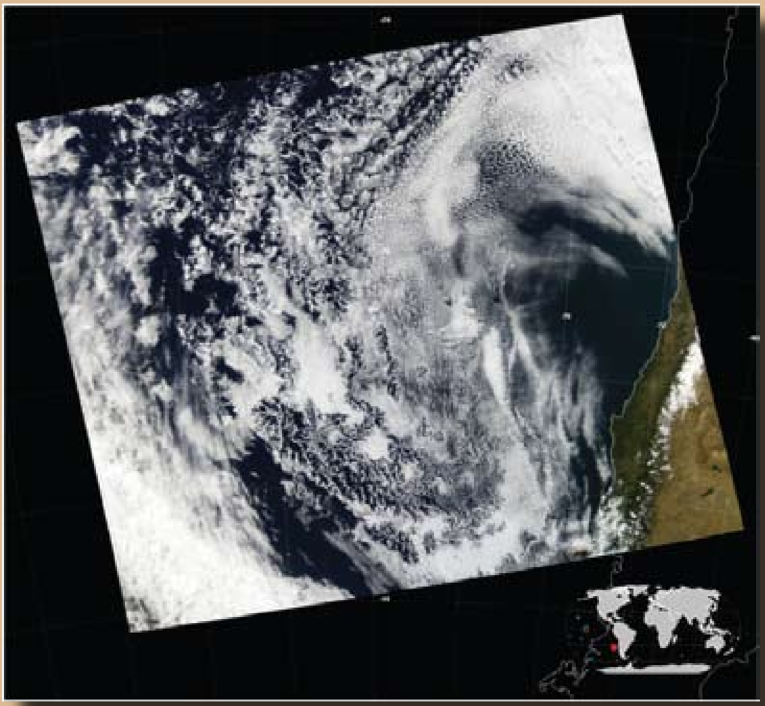
Is There a Missing Low Cloud Feedback in Current Climate Models?

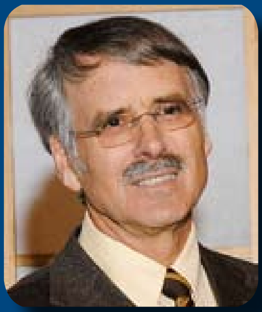
An analysis **by Prof. Graeme Stephens in the article on page 5** suggests that solar radiation reflected by low clouds is significantly enhanced in models compared to real cloud observations. This finding has major implications for the cloud-climate feedback problem in models.



A MODIS false color image of low clouds that formed as part of a larger weather system just west of Chile on 3 June 2007. The properties of the low clouds inferred from MODIS were matched to CloudSat and CALIPSO observations, and other sensor data from the A-Train to provide new insights on the properties of these clouds.

GEWEX Welcomes New Chair and Vice-Chair of the Scientific Steering Group

(See Page 3)



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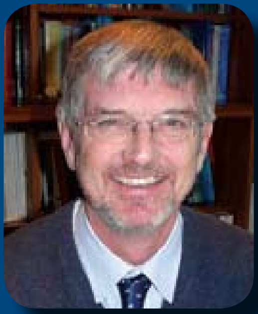

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Is There a Missing Low Cloud Feedback in Current Climate Models?

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Radiative feedbacks involving low level clouds are a primary cause of uncertainty in global climate model projections. The feedback in models is not only uncertain in magnitude, but even its sign varies across climate models (e.g., Bony and Dufresne, 2005). These low cloud feedbacks have been hypothesized in terms of the effects of two primary cloud variables—low cloud amount and cloud optical depth. The basis of these feedbacks relies on the connection between these variables and the solar radiation leaving the planet exemplified in the following simple expressions (Stephens, 2005).

$$\begin{aligned} F_{obs} &= (1 - A_c)F_{clr} + A_cF_{cldy} \\ CRE &= -(F_{obs} - F_{clr}) = -A_c(F_{cld} - F_{clr}) \end{aligned} \qquad (1)$$

where F_{obs} is the observed top-of-atmosphere reflected flux, F_{clr} is the clear sky flux, F_{cld} is the cloudy sky flux and A_c is the cloud amount. *CRE* , the cloud radiative effect is also referred to as cloud radiative forcing. This quantity is a measure of the effect of clouds on the reflected solar flux relative to the clear-sky flux. Estimates of the magnitude and sign of the *CRE* from observations was a focus of much research in the 1970s (e.g., see Stephens et al., 1981) but it was not until the launch of the Earth Radiation Budget Experiment (ERBE) in 1984 that we were able to deduce the global value and distribution of *CRE* (Harrison et al., 1990). The global-mean value of the net (longwave plus shortwave) *CRE* is negative and approximately –20 Wm^{-2} (Harrison et al., 1990) implying a cooling effect of clouds on climate. Closer analysis reveals this is dominated by low clouds (e.g., Hartman et al., 1992, and others). One of the more important activities of the GEWEX Radiation Panel is the flux assessment effort that seeks to provide the most authoritative estimates on *CRE* and other components of the global and regional radiative balance.

> ***One of the remarkable findings of the study was that approximately 40 percent of all low clouds observed contain detectable amounts of either rain or drizzle and this in turn affects the radiative properties of clouds.***

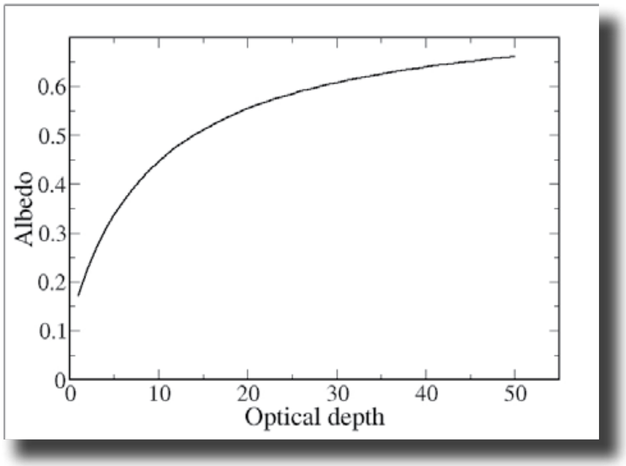
Cloud feedback is often measured in terms of the sensitivity of *CRE* to changing surface temperature that we write as

$$\frac{\Delta CRE}{\Delta T_s} = -\frac{\Delta A_c}{\Delta T_s}F_{cld} - A_c\frac{\Delta F_{cld}}{\Delta T_s} \qquad (2)$$

and note it is comprised of two terms. One governed by cloud amount changes such that a decrease in cloud is a positive feedback. The second is governed by the cloud optical depth through its controlling influence on cloud albedo α which in turn determines the cloudy sky flux ($F_{cld} = \alpha F_0$; F_0 is the top of the atmosphere incident solar radiation). Thus an increase in optical depth with an increase in temperature results in an increase in cloud albedo, suggesting a negative feedback. The meaning of the operator is left vague at this point although it is meant to represent a difference of the given variable between one climate state and another.

Low cloud amount is controlled by a number of different pathways that often oppose one another. The result is a feedback that can be complicated with no obvious sign. This is one of the reasons quantifying cloud feedback has been so elusive and is one of the motivating forces behind the GEWEX Cloud System Study (GCSS) activity. Two examples illustrate this complexity. It is well established that the profiles of lower tropospheric temperature, expressed for example by the Estimate Inversion Strength (EIS, Wood and Bretherton, 2006), correlate strongly with low cloud amount. In a warmed climate state, the EIS appears to increase over the subtropical stratiform cloud regions, suggesting cloud amount increases there. This increase further implies a negative cloud amount feedback associated with the warming sea surface temperatures. However, other processes that superimpose on this feedback can oppose these changes, altering the sign of the feedback. For example, changes in the larger scale circulation that result in weakening of the subsidence, which is also predicted in climate warming simulations, may well shift clouds from a stratiform regime to a more convective cloud regime with reduced cloud amount, suggesting a positive feedback.

The second source of feedback is the optical depth feedback associated with the effects of a surface warming on cloud albedo. Paltridge (1980) first introduced the idea of a cloud optical depth feedback. He proposed that a feedback might exist given the association between optical depth and liquid water path introduced earlier by Stephens (1978) and given the expectation that a relation between cloud liquid water path (LWP) and temperature exists (e.g., Betts and Harshvardham, 1987). The early notions of this feedback were simple enough—that warmer clouds are wetter clouds as defined by larger LWPs and thus warmer clouds have larger optical depths. Estimates of the strength of this particular negative feedback based in idealistic climate model simulations suggested this negative feedback might be substantial, capable in reducing the projected global warming of carbon dioxide by a factor of two (Sommerville and Remer, 1984). Attempts to determine if this feedback really operates in the real climate system have been inconclusive (Stephens, 2005). One of the relevant aspects of this feedback is exemplified in the figure on the next page which shows a simple model-based relation between cloud optical depth and cloud albedo. This relation



Calculated relationship between cloud albedo and optical depth based on a simple radiation model where vertically incident sunlight is assumed.

has a simple linear growth regime at low optical depths below about 10 and asymptotes to a limit at high optical depths (the semi infinite limit, Stephens and Tsay, 1990). As a result of this well-known behavior, the sensitivity of cloud albedo to optical depth ($\partial\alpha/\partial\tau$) at $\tau \sim 8$ is about 4-fold greater than is the sensitivity at $\tau \sim 20$–30. These differences are relevant to the discussion below.

Given the complexities described, it is tempting to look to observations alone to diagnose the magnitude and sign of cloud feedbacks [e.g., Clement et al. (2009); Lindzen and Choi, 2009; among many other examples]. However, these studies are subject to greater uncertainty, requiring essential assumptions that have to do with the cause and effect. Quantitative feedback analysis typically requires one to be more precise about what the difference in quantities in (2) represent, and specifically that

$$\frac{\Delta A_c}{\Delta T_s} \equiv \frac{\partial A_c}{\partial T_s} \qquad (3)$$

This equality implies that we have to interpret the given observed changes in cloud amount as due solely to the observed surface temperature change, thereby assigning a cause to an effect. Clearly we cannot assert causality without major assumption that is often either not justified or not testable with the observations alone.

One approach to studying feedback is to use observations of present climate and its variability to test the key (physical) mechanisms represented in models. In a recent paper (Stephens et al., 2010) collected low cloud data obtained from A-Train sensors including Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar, CloudSat radar, Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) instrument data. The observations were cast in terms of information about the occurrence of precipitation in low clouds, the cloud LWP, the cloud particle size (effective radius, r_e) and the cloud optical depth. These data were used to evaluate how well models represent low cloud radiative properties, including optical depth.

Table 1 summarizes the oceanic mean values of the low cloud properties observed. **One of the remarkable findings of the study was that approximately 40 percent of all low clouds observed contain detectable amounts of either rain or drizzle and this in turn affects the radiative properties of clouds.** The observations are grouped into four categories—all low clouds (all), clouds containing neither drizzle nor rain (cloud-only), clouds containing drizzle but no rain (drizzle), and clouds that contain rain (rain). The difference between the "all" category and "cloud-only" category thus provides some indication of the effect of drizzle and rain on the global-mean statistics of low cloud properties. The mean LWP of all low clouds is approximately 50 percent higher than the respective cloud only values. The mean effective radius (r_e) of all clouds is also about 15 percent larger than the respective cloud-only values and drizzling and raining clouds are observed to be deeper than non-raining clouds by up to a kilometer in the mean, which is one of the main factors that governs the larger LWPs of these clouds. Although the r_e of drizzling and raining clouds is almost 50 percent larger than the particle sizes of the cloud-only category (21 and 24 µm compared to 14 µm), these larger particle sizes do not offset the effects of the increased water path on optical depth (e.g., Stephens et al., 2008) such that the oceanic-mean optical depth of drizzling or raining low clouds is increased by approximately 25 percent over the cloud-only values. This suggests the presence of drizzle and rain has significant effects on the mean LWP, mean particle sizes and optical depths of all low clouds and therefore this presence exerts a significant influence on the radiative properties of the oceanic low clouds. This effect is rarely included in models.

A comparison of these observed properties to equivalent low clouds properties taken from a weather forecast and climate model is given in Table 2. A number of remarkable differences

Table 1. Seasonal averages of global oceanic-mean properties of low clouds derived from A-Train observations for the period of 2006–2007.

JJA	LWP (gm^{-2})	Optical Depth	r_e (µm)	Cloud Top Height (km)
All	116.0	9.5	15.9	1.44
Cloud-only	78.0	7.5	14.2	1.26
Drizzle	255.1	17.0	21.9	2.02
Rain	303.6	18.9	24.0	2.28
DJF				
All	110.4	9.0	15.0	1.54
Cloud-only	71.2	6.7	13.6	1.35
Drizzle	288.9	19.1	21.4	2.35
Rain	327.3	20.7	22.8	2.54

Table 2. Monthly comparison between observed and cloud properties from two models.

JJA	LWP (gm^{-2})	Optical Depth	r_e (µm)
Observed			
All	116.4	9.5	15.9
Cloud only	78.0	7.5	14.2
ECMWF			
All	224.0	30.0	9.0
Cloud only	161.0	22.0	9.0
CAM3.6			
Cloud only	194.0	20.0	14.0

appear in this simple comparison. The LWPs of the two global general circulation models are significantly higher than the observed values and the differences are significantly greater than any error that can be assumed for the observations. The non-raining cloud LWP of the GCMs, a quantity typically used in radiation schemes to define cloud optical properties, even exceeds the observed values of clouds that include effects of rain and drizzle. A second major model bias evident from this comparison is the difference between the observed and model assumed effective radius values, with model values being much smaller than observed and not reflective of the presence of drizzle or rain.

The net consequence of these biases is that the optical depth of low clouds in GCMs is more than a factor of two greater than observed, resulting in albedos of clouds that are too high. This model low-cloud albedo bias is not a new finding and is not a feature of just these two models. The study of Allan et al. (2007), for example, also noted how the reflection by low-level clouds in the unified model of the UK Meteorological Office is significantly larger than matched satellite observations of albedo, suggesting that this bias also exists in that model. The mean LWP of model clouds that contributed to this in the most recent Intergovernmental Panel on Climate Change assessment is close to 200 g/m^2, which is also nearly a factor of two larger than observed.

The implication of this optical depth bias that owes its source to biases in both the LWP and particle sizes is that the solar radiation reflected by low clouds is significantly enhanced in models compared to real clouds. This reflected sunlight bias has significant implications for the cloud-climate feedback problem. The consequence is that this bias artificially suppresses the low cloud optical depth feedback in models by almost a factor of four and thus its potential role as a negative feedback. This bias explains why the optical depth feedback is practically negligible in most global models (e.g., Colman et al., 2003) and why it has received scant attention in low cloud feedback discussion. These results are also relevant to the model biases in absorbed solar radiation discussed recently by Trenberth and Fasullo (2010) and as explored in more detail in Stephens et al. (2010).

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