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Effects of cloud overlap on radiative feedbacks

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Abstract The column radiative model (CRM) of the National Center for Atmospheric Research Community Climate Model has been used to test feedbacks associated with changes in monthly mean cloudiness for atmospheres with two different prescriptions of how clouds overlap in the vertical. The first specification is the default CRM random overlap assumption. The second, called the nonrandom case, uses an estimate of the observed overlap based upon an analysis of satellite- and surface-based observations. The results are presented primarily in terms of the changes in top-of-the-atmosphere net cloud radiative forcing resulting from a 25% increase in total cloud water and separate 16.5% increases in low, middle and high cloud layer amounts and differences that occurred during the 1987 El Niño/Southern Oscillation (ENSO) event. Overall, the random model is about 20% more sensitive to 16.5% increases in low clouds than the nonrandom model, but the nonrandom model is about twice as sensitive to increases in middle cloud. Differences in sensitivity for changes in high cloud amount and total cloud water are relatively small. In the areas near the large sea surface temperature anomalies the 1987 ENSO related departures in the nonrandom model are 0.5–2 Wm$^{-2}$ greater than for the random model. Thus, this analysis strongly suggests that accurate specification of overlap in climate models is critical to the calculation of the appropriate radiative feedbacks and sensitivities of models to external forcing such as increased carbon dioxide or sulfate aerosols.

1 Introduction

Clouds are a major contributor to our uncertainty concerning the nature of climate and climate change. An important tool to aid in the understanding of cloud/ climate interactions is the evaluation of cloud radiative forcing derived from the Earth Radiation Budget Experiment (ERBE; Ramanathan et al. 1989) satellite systems. Although there is a good general understanding of mean cloud radiative forcing, there has been much less progress in discerning how these fluxes might vary during a climatic change. Sinha and Shine (1995; hereafter SS95) investigated this problem using a hybrid approach in which a sophisticated radiative transfer model was driven by the International Satellite Cloud Climatology (ISCCP; Rossow and Garder 1993) C2 estimates of cloud amount and optical depth. Using this model SS95 made an assessment of how specified variations in cloud alter the radiation fluxes at the top of the atmosphere.

More recently, Weare (1997a) used multiple regression analysis to relate interannual variations in the Earth Radiation Budget Satellite (ERBS; Harrison et al. 1990) cloud radiative forcing to changes in monthly mean ISCCP total cloud water and layer cloud amounts and European Centre for Medium-range Weather Forecasting (ECMWF) analyses of temperature and humidity. Regression equations were developed for 10° latitudinal strips both separately for land and ocean and for the combination. The estimated changes of cloud forcing due to 16.5% increases in low, middle and high cloud amounts and 25% increases in cloud water agree with modeled estimates made by SS95 with respect to the signs of the responses and the order of the significance of the dependent variables for net cloud radiative forcing.

One important parameter necessary for radiative transfer model calculations such as those of SS95, which is not available from the ISCCP observations, is the vertical overlap of the cloud layers. For instance, the low cloud fraction determined by a satellite radiometer will not be equivalent to the amount in the lowest layer of a model, nor to the simple sum of the amount over a range of layers. In general the observed low cloud fraction may only be compared to model cloud amounts after the latter have been summed over the appropriate layers of...
the atmosphere and account has been made for the possible obscuration of lower layers by higher ones. This is usually done in terms of an overlap assumption (Tian and Curry 1989). The two extreme assumptions are “no overlap,” in which no cloud is assumed to be above or below another cloud, and “full overlap,” in which clouds are assumed to be stacked vertically to the maximum extent possible. The most common overlap assumptions are “random overlap” in which clouds at various levels are assumed to be randomly distributed in the horizontal, and “mixed” in which convective clouds are assumed to be maximally and all other clouds randomly overlapped. However, any combination of overlap between the no and full overlap extremes is possible.

Here cloud monthly mean radiative forcing calculations using the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) Column Radiation Model (CRM; Kiehl et al. 1994) will be analyzed in a manner similar to SS95. Emphasis will be given to the differences between results using two models: one which assumes randomly overlapping clouds, and one which specifies the overlapping of clouds based upon an analysis of satellite and surface based observations. It will be shown that important differences exist in the sensitivity of top-of-the-atmosphere net cloud radiative forcing (netCRF) to changes in cloud properties for these two models.

2 Observed \( a_{overlap} \)

In order to specify the observed cloud overlap in the CRM a simple overlap parameter will be utilized. This overlap parameter \( a_{overlap} \) is defined in the expression

\[
1 - Total = a_{overlap} \prod_{i=1}^{3} (1 - f_i) 
\]

where the \( f_i \)’s are the cloud amounts in low, middle and high layers, and \( Total \) is the total cloud amount as observed from either a satellite or a surface observer. Written in this way Eq. 1 is a simple modification of the random overlap assumption such that clouds are relatively densely stacked in the vertical more if \( a_{overlap} \) is greater than one, and relatively spread out horizontally if \( a_{overlap} \) is less than one.

Estimates of \( a_{overlap} \) are derived from the analysis of Weare (1999), which combined monthly mean ISCCP C2 satellite and Hahn et al. (1996) surface observation for the years 1984 through 1988. This analysis method uses the observations from both the surface and the top-of-the-atmosphere to estimate the probabilities of all possible cloud configurations in a three-layer atmosphere. A knowledge of these probabilities allows one to separately evaluate the cloud amounts in each layer \( f_i \) and the total cloud cover. Since the spatial coverage of this analysis requires surface observations estimates of \( a_{overlap} \) are not available for some land points in the interiors of continents. Also many ocean points south of 20°N, which have less than five surface observations per month, have quite noisy estimates of \( a_{overlap} \).

Figure 1 illustrates the annual mean of the estimates of \( a_{overlap} \). Overall \( a_{overlap} \) is greater than one nearly everywhere indicating that clouds tend to be more vertically stacked than assumed in the random overlap assumption (Weare 1999). The largest values are in the convective regions of the tropics and the storm tracks of the North Atlantic and Pacific Oceans. This is consistent with the fact that these regions often have cumulus or deep frontal clouds. The smallest values of \( a_{overlap} \) are in the surface data-poor regions south of 20°S and over the relatively cloud free zones of the continental subtropics. For these latter regions values of \( a_{overlap} \) around one suggests that clouds are approximately randomly overlapping. This is consistent with the monthly mean cloudiness being represented by clouds at different levels during different days of a month. Other low values of \( a_{overlap} \) exist in the eastern Southern Pacific and the Arabian Sea. These regions are dominated by stratus cloud with sporadic higher or convective clouds. Thus, although the \( a_{overlap} \) field is rather noisy, its spatial pattern of variation shown in Fig. 1 agrees with general knowledge of cloud overlap, especially north of 20°S.

3 Model-NCAR CCM3 CRM

The CRM has been configured to directly use the 17 levels of the National Center for Environmental Prediction (NCEP; Kalnay et al. 1995) reanalysis data. Layer cloud fractions and water contents are provided from ISCCP level cloud amounts and optical depths by the method suggested by Bergman and Hendon (1998). The three ISCCP cloud height categories are used such that the cloud amounts are put in the layers corresponding to the ISCCP C2 cloud top pressures. The CRM assumes a simplified version of randomly overlapping clouds in both solar and infrared wavelengths (Briegleb 1992).

Unfortunately, the random overlap assumption is tightly and deeply written into the CCM3 CRM computer code, especially for longwave radiation. Most other radiative transfer codes in climate models also have algorithms which are closely tied to a single theoretical overlap assumption (e.g., Räisänen 1998). Since the purpose of this work is to provide an initial estimate as to whether different overlap assumptions lead to different feedbacks, it was decided to modify the cloud inputs to the CRM to approximate the influence of nonrandom overlap, rather than completely rewrite the CRM. In this case nonrandomly overlapping cloud calculations were achieved for the three ISCCP cloud layers \( j \) by transforming the true layer cloud amounts \( f_i \) into “randomized” values \( f'_i \) in a way such that the total cloud amount and cloud fraction weighted optical depths are conserved. For instance total cloud cover \( T \) is given by

\[
T = 1 - a_{overlap} \prod_{i=1}^{3} (1 - f_i) = 1 - \prod_{i=1}^{3} (1 - f'_i)
\]

Similarly, to conserve the total cloud-fraction weighted optical depth,

\[
\tau_{total} = \sum_{i=1}^{3} F_i \tau_i = \sum_{i=1}^{3} F'_i \tau'_i
\]