Relationship between the Longwave Cloud Radiative Forcing at the Surface and the Top of the Atmosphere

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(Manuscript received 2 April 1990, in final form 20 June 1990)

ABSTRACT

Attempts to map the global longwave surface radiation budget from space have been thwarted by the presence of clouds. Unlike the shortwave, there is no physical relationship between the outgoing longwave and the surface longwave under cloudy skies. Therefore, there is no correlation between spatial and temporal averages of the outgoing longwave radiation and net longwave radiation at the surface. However, in regions where a particular cloud regime exists preferentially, a relationship between the mean longwave cloud radiative forcing (CRF) at the top of the atmosphere and at the surface can be shown to exist. Results from a general circulation model suggest that this relationship for monthly means is coherent over fairly large geographical areas. For example, in tropical convective areas, the longwave CRF at the top is very large, but at the surface it is quite small because of the high opacity of the lowest layers of the atmosphere. On the other hand, in areas of stratus over cool ocean surfaces, the longwave CRF at the top is very small but at the surface, it is quite substantial.

To the extent that the cloudiness simulated in the model mimics the real atmosphere, it may be possible to estimate the monthly mean longwave CRF at the surface from the Earth Radiation Budget Experiment cloud forcing at the top. The net longwave radiation at the surface can then be mapped if monthly means of the clear-sky fluxes are obtained by some independent technique.

1. Introduction

Currently, there is a need in the atmospheric and oceanographic communities for reliable estimates of the components of the surface radiation budget (WCP–92 1984). This is particularly crucial in the study of the coupled atmosphere–ocean system in the tropics (NAS 1983). Since there are very few surface stations measuring the radiation budget routinely and reliably, it has been realized that space-based observations are the only means to obtain global coverage. Several investigators have had considerable success in obtaining the solar flux components at the surface using radiances measured at the top of the atmosphere by operational satellites (e.g., Gautier et al. 1980; Raschke and Preuss 1979; Tarpley 1979; Pinker and Ewing 1985; Justus et al. 1986). This success can be explained on theoretical grounds. The atmosphere is a conservatively scattering medium over a major portion of the solar spectrum, and the total atmospheric absorption in the presence of clouds is not very different from the clear-sky value (Ramanathan 1986). This is because clouds absorb at roughly the same near infrared wavelengths as water vapor, and this absorption is therefore at the expense of vapor absorption below the cloud deck.

In the case of longwave radiation, it is not at all evident that the surface radiation budget components can be obtained from top of the atmosphere (TOA) radiance measurements. Even for clear-sky conditions, it may be shown that the bulk of the downward longwave radiation emanates from the lowest hundreds of meters of the atmosphere (Schmetz et al. 1986; Gupta 1989). Fairly accurate estimates of the near surface air temperature and humidity, and the sea-surface or ground temperature are prerequisites for the computation of the longwave fluxes at the surface. This problem is further compounded by the presence of clouds. The downward emission from the cloud base is a major component of the downward longwave flux unless the cloud base is very high and the boundary layer is very moist. Since there is as yet no proven technique for locating cloud bases from space, investigators have been forced to rely on other means to estimate the downward emission.

There is now considerable literature available on estimates of the surface longwave fluxes, both regionally and globally. All of them rely on estimates of near surface conditions or the vertical profile of temperature

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and humidity to compute clear sky fluxes using bulk formulae or a radiative transfer model and modifications for observed or climatological cloudiness. Fung et al. (1984) reviewed several bulk formulae used for this purpose and compared them with a radiative transfer model. They concluded that uncertainties in the longwave fluxes due to lack of knowledge about cloud properties is larger than that due to expected uncertainties in temperature or humidity. Frouin et al. (1988) compared several methods arranged in order of decreasing sophistication to compute the downward longwave surface fluxes for comparison with observation taken during the Mixed Layer Dynamics Experiment (MILDEX). A technique that can be used only during daytime involving an estimate of the liquid water column amount in the cloud had the best correlation with observed fluxes. A relationship between cloud properties in the solar and cloud thickness was also used by Schmetz et al. (1986). Chou (1985) used cloud thicknesses based on London's (1957) climatology whereas Darnell et al. (1986) and Gupta (1988) used a fixed cloud thickness of 50 mb.

Apart from the problem of locating the cloud base, there is also the question of the fractional coverage of clouds that should be used in weighting the clear and cloudy sky contributions. Recently, Wu and Cheng (1989) have used HIRS2/MSU sounding data to extract all the relevant cloud parameters needed for their algorithm to compute the downward longwave flux globally for January and July 1979. There is no satisfactory verification for any of these methods.

In this paper we present a theoretical framework that avoids the explicit computation of cloud fraction and the location of cloud base. Our hope is that global maps of the monthly mean net longwave flux at the surface may eventually be obtained in this manner.

2. Surface radiation budget

In general, the surface radiation budget has four components: the upward and downward directed longwave radiation, the incoming solar radiation at the surface, and the reflected solar radiation. The latter two components are, of course, present only during daylight hours. For some applications it is sufficient to know the net radiation, which is the algebraic sum of the upward and downward components.

The net solar radiation at the surface is the surface absorption and varies from 0 to 1200 W m^{-2}, while the net longwave at the surface is a radiative loss by the surface that can range from -200 W m^{-2} for a warm desert surface under clear-sky conditions to near zero in the presence of low thick clouds. The theory underlying techniques for estimating these quantities from space based observation systems is the relationship between the upwelling radiation at the top of the atmosphere and the components of radiation at the surface.

The theoretical basis for such a relationship in the case of solar radiation has been discussed by several authors, e.g., Gautier et al. (1980). All techniques for inferring the solar radiation at the surface rely on essentially the same principle. The chief uncertainty is in assigning absorption by water vapor in the clear atmosphere and by clouds and vapor for the cloudy case. As pointed out by Ramanathan (1986), compensating effects result in this absorption being fairly insensitive to location and in fact, cloudiness conditions. Modeling studies quoted by Ramanathan (1986) and Weare (1989) confirm that there should be a strong correlation, at least for monthly means, between the net solar radiation at the top of the atmosphere, which is the absorption by the surface and atmosphere, and the net at the surface which is simply the surface absorption. However, the same modeling studies show that there is no correlation whatsoever between the net longwave radiation at the top of the atmosphere and the net longwave at the surface.

Although Weare (1989) confirmed Pinker et al.'s (1985) finding that there is a strong correlation between the net total radiation at the top of the atmosphere and that at the surface, this is explained by the fact that the variation in the net total radiation at the surface is dominated by solar radiation.

An illustrative way to show the correlation or lack thereof is with a scatter diagram of the radiation field at the top of the atmosphere plotted against the surface quantity. This can be done for contemporaneous measurements made at a surface site and satellite measurements of the same general area. This is, in fact, the usual manner in which regression equations for the surface radiative fluxes are calibrated. The regressions could also be for temporal means, or if several surface sites are available, an area average may be considered. Model simulations of the radiation fields can also be shown on a scatter plot.

Following Ramanathan (1986), we show in Figs. 1a,b, the monthly mean net longwave radiation at the top and the surface as simulated by the UCLA/CSU General Circulation Model (GCM). Details of the radiation and cloud parameterization in the model and simulated fields of cloudiness and radiative fluxes may be found in Harshvardhan et al. (1989). A brief description of the GCM may be found in the Appendix of Randall et al. (1989). Each point represents the mean for one grid point of the model for January and July, respectively. The horizontal resolution of the model is 4° in latitude by 5° in longitude. It is evident that the longwave radiation at the top is uncorrelated with that at the surface, and Ramanathan (1986) has shown that this holds true even if selected regions are considered in isolation. Although total fluxes are not correlated, the hope that window radiances provide information on near-surface conditions has led to the development of hybrid techniques in which satellite measurements are used to reconstruct the temperature

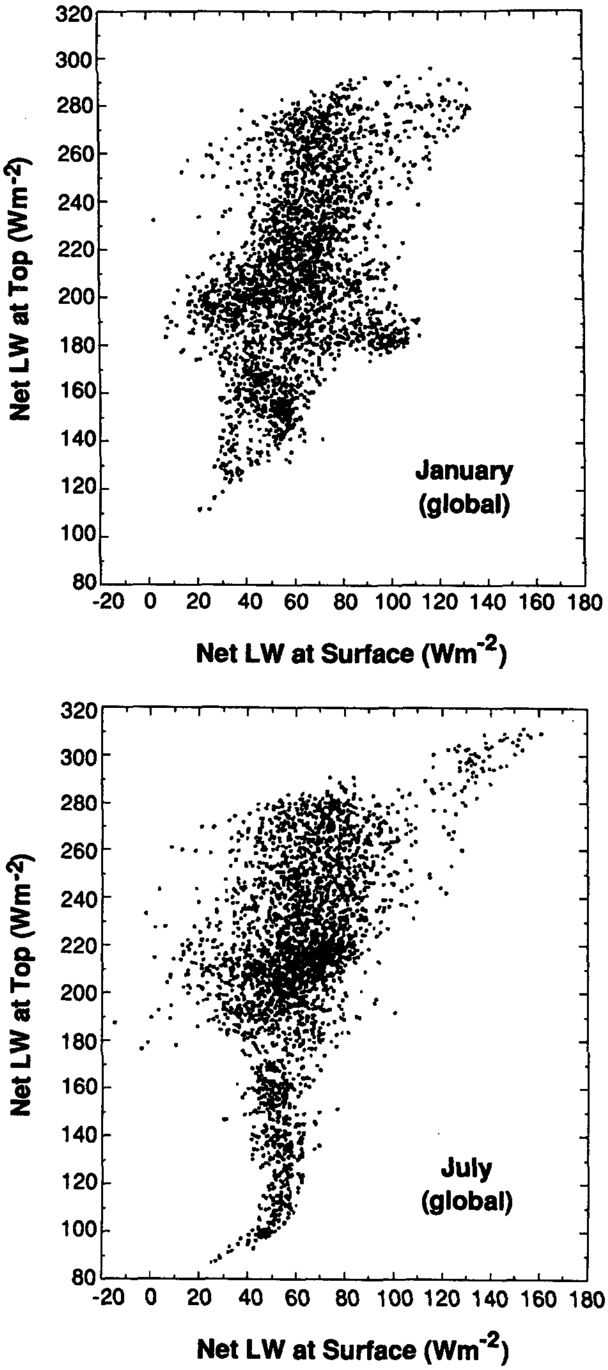

FIG. 1. Scatter plots of the monthly mean net longwave radiation at the top of the atmosphere vs the net longwave radiation at the surface for (a) January, and (b) July. Results are from a simulation of the UCLA/CSU GCM and each data point on the plot represents a 4° Latitude × 5° Longitude grid point.

and humidity profile and a radiative transfer code is used to compute the downward longwave flux (e.g., Frouin et al. 1988; Gupta 1989; Wu and Cheng 1989). As stated earlier, all techniques suffer from uncertainties or even total lack of knowledge concerning cloud cover and cloud base location.

3. Cloud Radiative Forcing

The role of clouds in modifying the radiation field can be studied through the analysis of the cloud radiative forcing (CRF). Although originally introduced in connection with the exiting shortwave and longwave fluxes at the top of the atmosphere (Charlock and Ramanathan 1985; Ramanathan 1987), the cloud radiative forcing at the surface maybe defined as

$$\text{surface CRF} = \text{surface flux} - \text{clear-sky surface flux}. \quad (1)$$

In the above, the flux at the surface may be shortwave, longwave, or total, and could refer to the downward or net flux at the surface. The clear sky flux in a model may be obtained in one of two ways. The radiation fluxes may be computed at every grid point for the diagnosed cloud cover and also for zero cloud cover at the same time. The clear sky values may then be subtracted from the actual values to yield the CRF. This has been called "Method II" by Cess and Potter (1987) and is the method used in this study. An alternate approach is to sample the clear-sky fluxes only when clouds do not occur and build up a clear-sky climatology for a particular grid point over an integrating time interval, such as a month. This is "Method I" and is used in the Earth Radiation Budget Experiment (ERBE; Ramanathan 1987) and is, of course, the only option in any measurement program.

The importance of cloud radiative forcing at the surface may be illustrated by examining the energy budget at the atmosphere–ocean interface and implications regarding the required meridional energy transport in the ocean for global balance over the annual cycle. Esbensen and Kushnir (1981) have computed the individual components of the heat budget over the oceans using standard bulk formulae (Sellers 1965; Budyko 1974). Over a complete annual cycle, assuming that there is no heat storage in the oceans, an implied poleward energy transport across latitude belts maybe computed based on the excess or deficit of energy at each latitude. The results of Esbensen and Kushnir are shown in Fig. 2 by the solid line labeled EK. An independent estimate of the meridional oceanic transport has been made by Carissimo et al. (1985) who have updated the earlier work of Oort and Vonder Haar (1976). This is shown by the solid line in Fig. 2 labeled COV. They computed the poleward transport of energy by the oceans and atmosphere using measurements of net radiation at the top of the atmosphere. The procedure for estimating the atmospheric component is described in Oort and Peixoto (1983). The oceanic transport is then obtained as a residual.

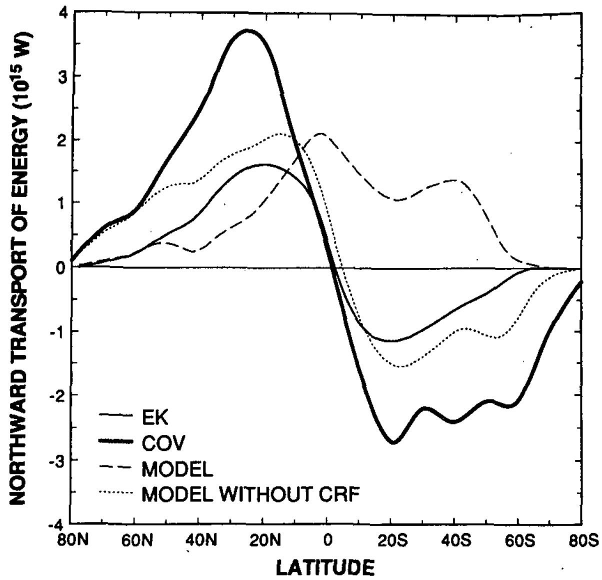

FIG. 2. Estimates of the annual meridional energy transport in the oceans. Solid line is from Carissimo et al. (COV) and Esbensen and Kushnir (EK). Dashed line is from an atmospheric general circulation model. Dotted line is from the same model but without cloud radiative forcing (CRF). Northward transport is positive.

Figure 2 also shows by dashed lines the implied meridional transport in the oceans from a five-year annual cycle run of an atmospheric general circulation model with prescribed seasonally varying sea surface temperatures. The procedure used to obtain the transport is the same as for the EK curve, except that the simulated components of the energy budget have been used. Although the magnitude of the transport in the Northern Hemisphere is within the range of the other estimates, it is the implied transport in the Southern Hemisphere that is truly striking. Over the annual cycle, the net oceanic transport is northward at all latitudes! The situation is improved markedly by the removal of the radiative contribution of clouds, as shown by the dotted line. An examination of the radiation budget in the Southern Hemisphere midlatitudes indicates that there is a gross underestimation of cloud cover in that region. Since the sea surface temperature is prescribed in the model, these errors are of no consequence as far as the atmospheric simulation is concerned. However, errors such as this could prove to be disastrous in a coupled interactive atmosphere–ocean climate model.

Figure 3 is a scatter plot of the monthly mean shortwave CRF at the top of the atmosphere versus the shortwave CRF at the surface as simulated by the UCLA/CSU GCM. Each point represents the monthly mean (July in this case) value for each grid point. The CRF has been computed using Method II, in that clear-sky values were calculated and stored for every computation of the radiative fluxes. A linear correlation is evident and simply indicates that a loss of solar insolation at the surface due to cloud cover appears as an increase in the solar radiation reflected to space. The net shortwave at the top and surface vary in lock step with changing cloud cover. It is this feature that is primarily responsible for the success of surface shortwave insolation techniques based on satellite measurements of reflected radiances.

It is instructive to investigate the simulated relationships between the longwave CRF at the top and surface, to see if any correlations are predicted by the model. The shortwave correlations could have been anticipated by inspection of Fig. 10 in Harshvardhan et al. (1989) in which the zonal means of the cloud radiative forcing from the same model are displayed. The zonal mean shortwave cloud radiative forcing at the top of the atmosphere is virtually identical to the forcing at the surface with the atmospheric component alone being essentially zero. As explained in section 1 this is because the cloud layer absorbs solar radiation at the expense of water-vapor absorption below the cloud deck and the vertically integrated column absorption is therefore virtually unchanged in the presence of clouds (although the heating profile is certainly quite different).

Figure 4 shows a scatter plot of the monthly means of the longwave CRF at the top of the atmosphere versus the surface CRF for every grid point in the GCM. Note the radically different distribution from Fig. 1, which is a plot of the net longwave radiation. Although the scatter is incoherent as the shortwave CRF shown in Fig. 3, there are unmistakable correlations among groups of points. It appears, in fact, that certain clusters of points are linearly organized, albeit with different slopes. These groups of points represent grid points at which, for the month considered, a preferred type of

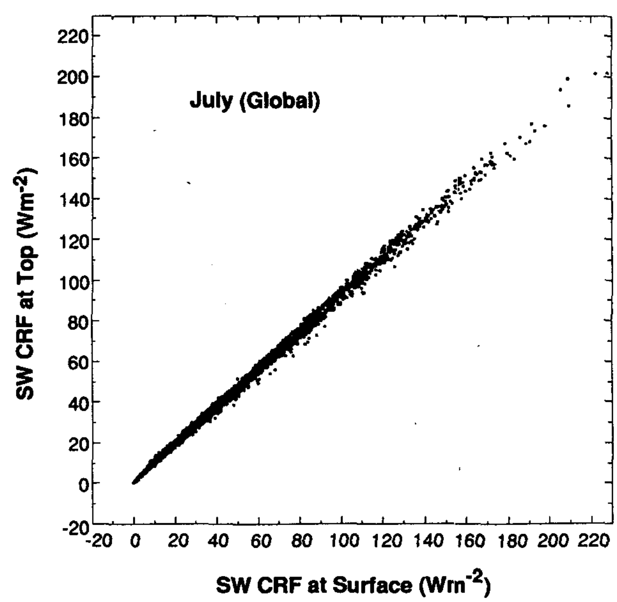

FIG. 3. Scatter plot of the July mean shortwave cloud radiative forcing (SWCRF) at the top of the atmosphere vs the SWCRF at the surface as simulated by the UCLA/CSU GCM for all grid points.

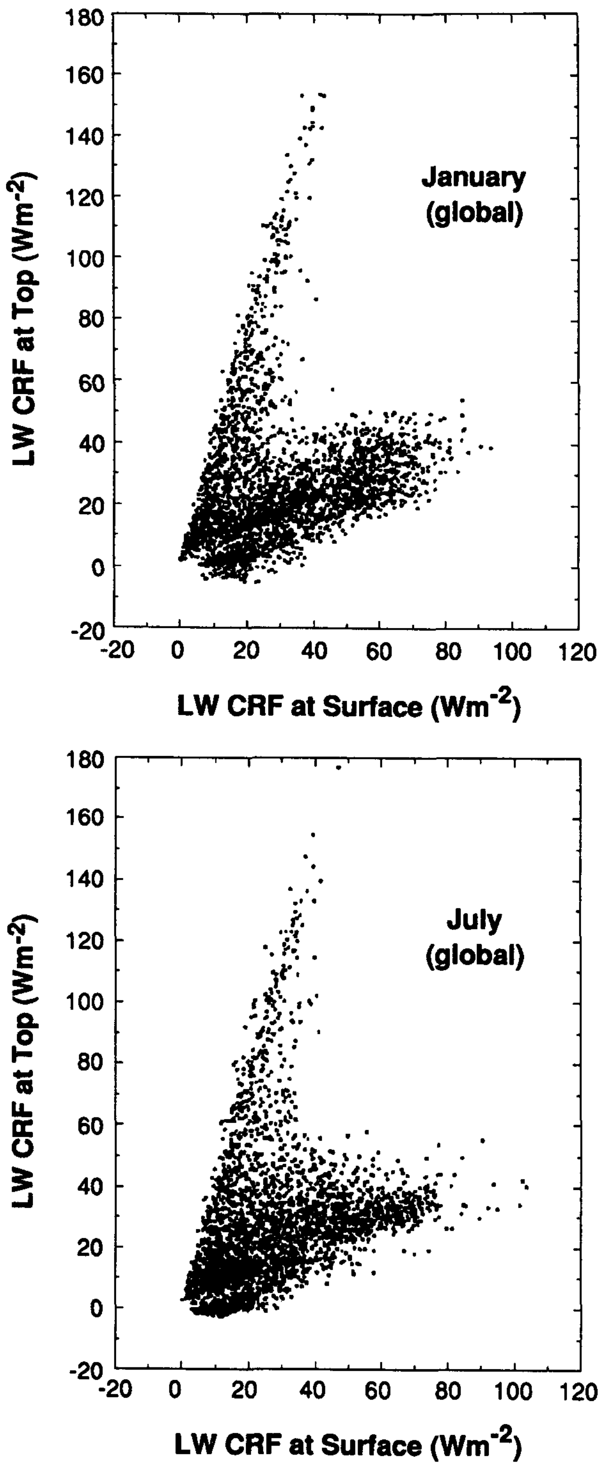

FIG. 4. As in Fig. 3 but for the longwave cloud radiative forcing (LWCRF) for (a) January and (b) July.

cloud cover exists such as low or convective. This becomes clear when subsets of the global grid are considered where one would expect this sort of preference to hold.

Figure 5a shows the scatter plot for two zonal strips in the tropics in July. The points are all the GCM grids, centered at 10° and 14°N (144 in all). Figure 5b is the same plot for two bands centered at 58° and 62°S. The former includes areas of high convective clouds whereas the latter is a region of low stratus. The longwave CRF at the top of the atmosphere in the tropics can be very large since the cold cloud tops diminish the outgoing longwave radiation considerably. However, at the surface, in the tropics, clouds have a minimal effect on longwave radiation because the lowest layers of the atmosphere have a very high water-vapor content, essentially saturating most of the longwave

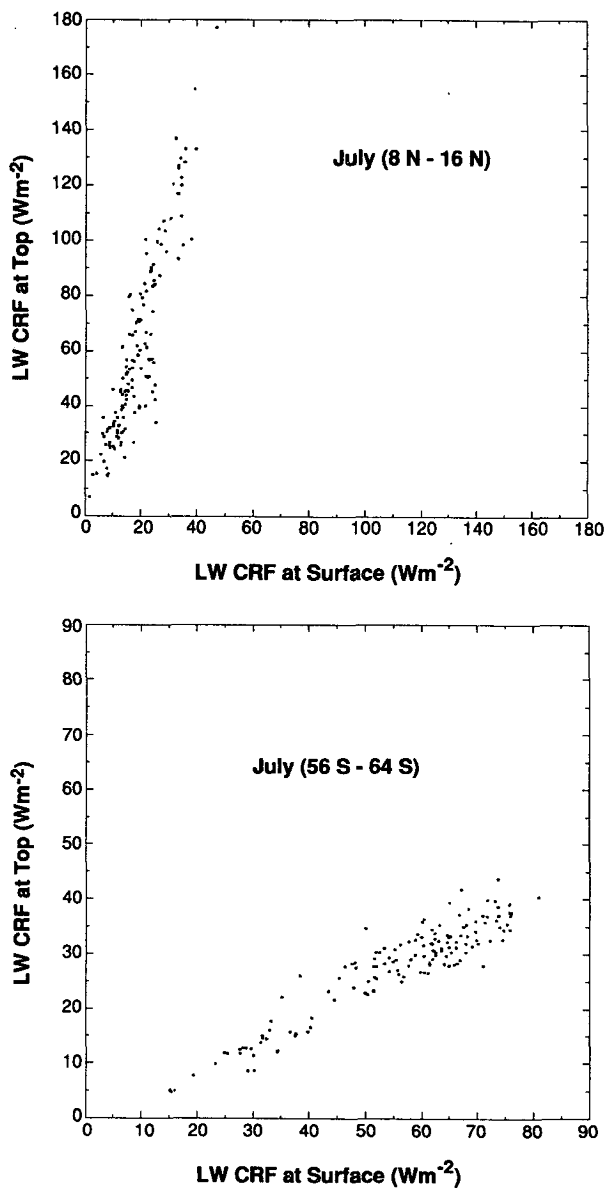

FIG. 5. As in Fig. 4 for July but only for grid points in zonal belts centered at (a) 10° and 14°N and (b) 58° and 62°S.

spectrum for downwelling radiation. The presence of an emitting cloud base does not result in much enhanced downward longwave radiation. Moreover, in the model, low-level convective clouds are ignored in that the cloud fraction is set to zero, so the cloud base is quite high unless stratiform clouds occur simultaneously. The situation at high latitudes in drier conditions is just the opposite. Stratus clouds do not modify the outgoing longwave radiation much, but radically alter the downward longwave flux towards the surface. Figure 5b also indicates that middle and high clouds occurred infrequently, if at all, during this time period at the grid points considered.

The points in both Fig. 5a,b are not clustered at the upper right-hand corner of the distribution, but are spread out fairly even along the line of correlation. The position of a point is an indication of the monthly mean cloud cover for the grid point in question. From Eq. (1) we note that the first term on the rhs includes the cloud cover implicitly, such that if there is zero cloud cover at a grid point, the CRF at both the top of the atmosphere and surface will be zero.

The character of the correlations shown in Fig. 4a,b can be best appreciated by considering the simulated longwave CRF at the top of the atmosphere and surface for standard atmospheric profiles in which clouds are inserted at different levels in isolation. We have chosen to show standard profiles from McClatchey et al. (1972) and cloud layers corresponding to the 9-layer UCLA/CSU GCM. Optical properties of the clouds are as in the GCM (Harshvardhan et al. 1989); essentially, the longwave emittance is a function of temperature and cloud thickness, but, for all practical purposes, this dependence exists only for temperatures well below freezing. For water clouds and ice clouds that form as convective anvils, the emittance is unity.

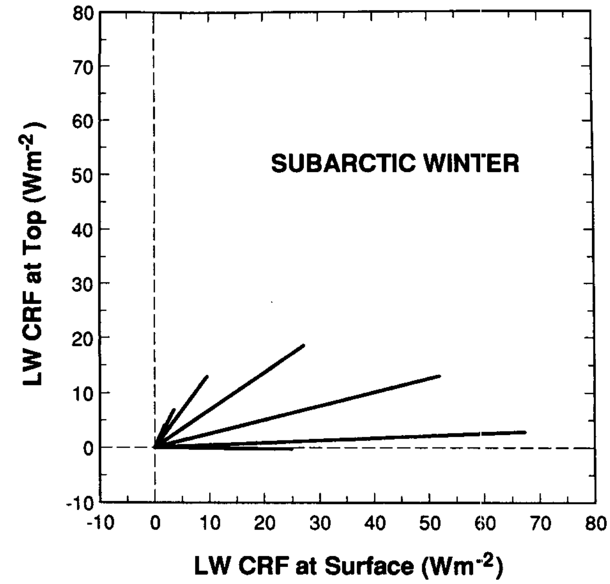

FIG. 7. As in Fig. 6 but for a subarctic winter atmospheric profile.

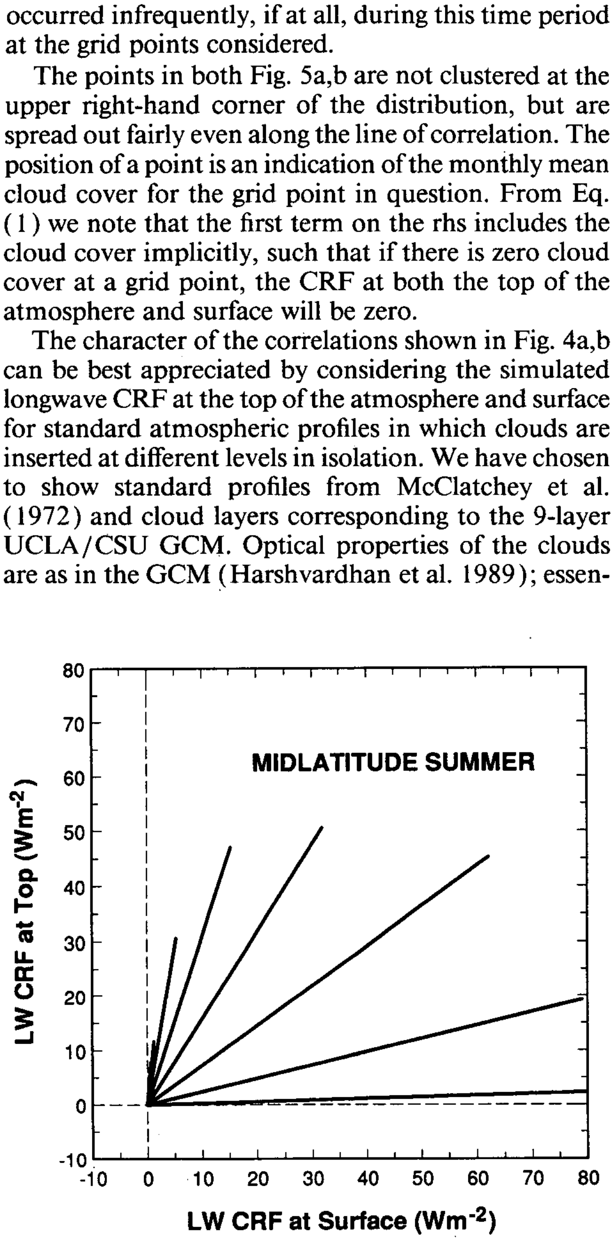

FIG. 6. The locus of points representing the variation of LWCRF at the top of the atmosphere vs the LWCRF at the surface when cloud cover varies from 0% to 100% in each layer of a model in isolation. A midlatitude summer atmospheric profile is used and the cloud properties and layer positions are as in the UCLA/CSU GCM.

Figure 6 is a plot of the longwave CRF at the top of the atmosphere versus the surface CRF. It shows the locus of all points representing cloud cover in one layer of the model for a midlatitude summer atmospheric profile. There are eight different lines, one for each layer in which clouds are permitted to occur in the GCM. The origin represents the case of no cloud cover while the terminus of each line represents 100% cloud cover. The line with the lowest values of longwave CRF at the top and highest values of longwave CRF at the surface corresponds to a cloud in the lowest layer of the model. Clouds in higher layers proceed in a counterclockwise sense up to the topmost cloud layer in the model.

The CRF of a cloud in the highest layer, with a top at 100 mb, is barely perceptible because the emittance is close to zero and even complete cloud cover hardly affects the outgoing longwave radiation. It should be stressed that points on a scatter plot would follow these lines only if cloud existence occurred in that particular layer alone, not if clouds existed simultaneously in more than one layer.

Figure 7 is similar to Fig. 6, but for a subarctic winter atmospheric profile. Figure 8 is for the particular case of tropical convective anvils, which in the model extend from about 400 mb to the top of the detrainment layer in the convective parameterization (Randall et al. 1989). These anvils then have the same base level, but have varying tops up to 100 mb. Low-level convective

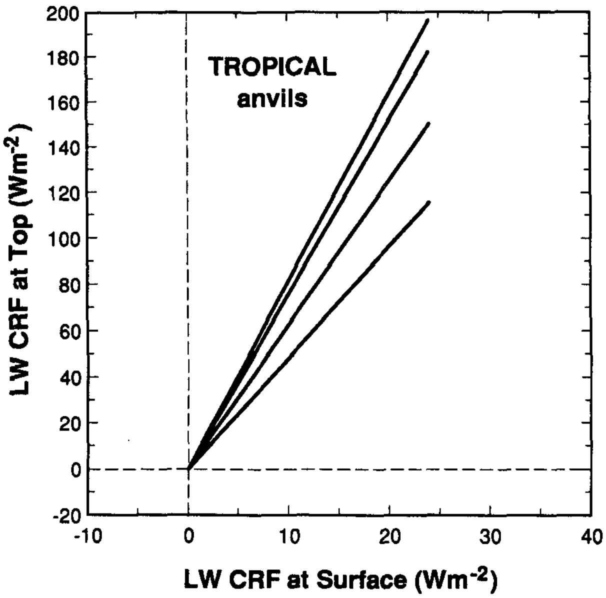

FIG. 8. As in Fig. 6 but for convective anvils and a tropical atmospheric profile.

clouds are completely ignored, at present, in the radiation computations.

The simulations shown in Figs. 6–8 explain the nature of the scatter plots shown in Figs. 4, 5. The model tends to generate a preferred type of cloud at a particular grid point during a particular season. Although simultaneous occurrence of multilayer clouds is simulated, there are several regions in which a particular cloud type predominates. For example, Fig. 5a clearly shows the effects of tropical anvils. Some grid points along these zonal bands exhibit a slightly different cloud pattern, but there is a large area of coherence. The same is true of Fig. 5b, which is dominated by low-level clouds, and may be compared with the lowest line in Fig. 6.

Regions with a preferred type of cloudiness were identified by Hartmann and Short (1980) using the day-to-day variability of the outgoing longwave radiation and shortwave albedo. They found that the characteristic slope of the line of regression of changes in outgoing longwave radiation and shortwave albedo was a very sensitive indicator of low cloud regimes.

We have shown that the characteristic slope of the line of regression of the longwave CRF at the top of the atmosphere and the surface CRF also identifies cloud regimes. Following Hartmann and Short (1980) maps of the ratio of the longwave CRF at the top of the atmosphere to the longwave CRF at the surface for January and July are shown in Figs. 9a,b, respectively. The map was produced from the data in the scatter plots shown in Figs. 4a,b. Regions for which this ratio is small can be identified with areas of predominantly low-level clouds or clouds in high latitudes in the winter. Large values of the ratio indicate convective anvils. The maps in Figs. 9a,b are thus an indication of the regional cloud climatology of the model. This identification can perhaps be utilized to estimate the monthly mean net longwave radiation at the surface.

4. Conclusions

All methods for extracting the surface longwave radiation suffer from uncertainties regarding cloud cover and cloud base temperature. The analysis presented in this study suggests a technique that may be able to avoid this problem. The longwave cloud radiative forcing (LWCRF) at the top of the atmosphere is currently being compiled by the Earth Radiation Budget Experiment (ERBE). The mean downward longwave radiation can be computed for clear sky conditions if a mean profile of temperature and water-vapor mixing ratio is available. The upward longwave radiation at the surface may be computed from a retrieved ground temperature. The LWCRF at the top contains information on the mean cloud cover and cloud type for the time period considered. If monthly means are used, the LWCRF at the surface may be obtained from a global map of the LWCRF at the top if maps of the ratio, such as shown in Fig. 9, were available. This would not require explicit knowledge of the mean cloud fraction. Of course, acceptance of the results of a general circulation model is not a viable option. To some extent the standard deviation of daily mean values of the ratio of cloud forcing from the model could be used to judge the appropriateness of this technique for a particular grid point. This will involve reliance on the model that is probably not warranted at this stage. Some information can also be obtained, however, from the results of recent or planned field experiments.

Certain elements required for this procedure to be tested are already in place. The data products released by the International Satellite Cloud Climatology Project (ISCCP, Schiffer and Rossow 1983) can be directly used in this scheme. ISCCP provides a daily profile of temperature and precipitable water as well as surface temperature at a $2.5° \times 2.5°$ horizontal resolution that may be used to generate clear sky downward longwave fluxes and upward fluxes, at least over the oceans where the once-a-day sampling is acceptable. As part of ISCCP, there have been field experiments to study cirrus and marine stratus cloud regions (Starr 1987; Albrecht et al. 1988). At least for these cases, an estimate of the mean LWCRF at the surface for an integrating time period comparable to ERBE can be obtained. On a global scale, of course, model simulations are the only choice.

Since current needs for surface radiation budget estimates are being determined primarily for application in the tropical oceans (WCP–92 1984), a start could perhaps be made to generate monthly mean surface longwave radiation maps for the tropical Pacific using

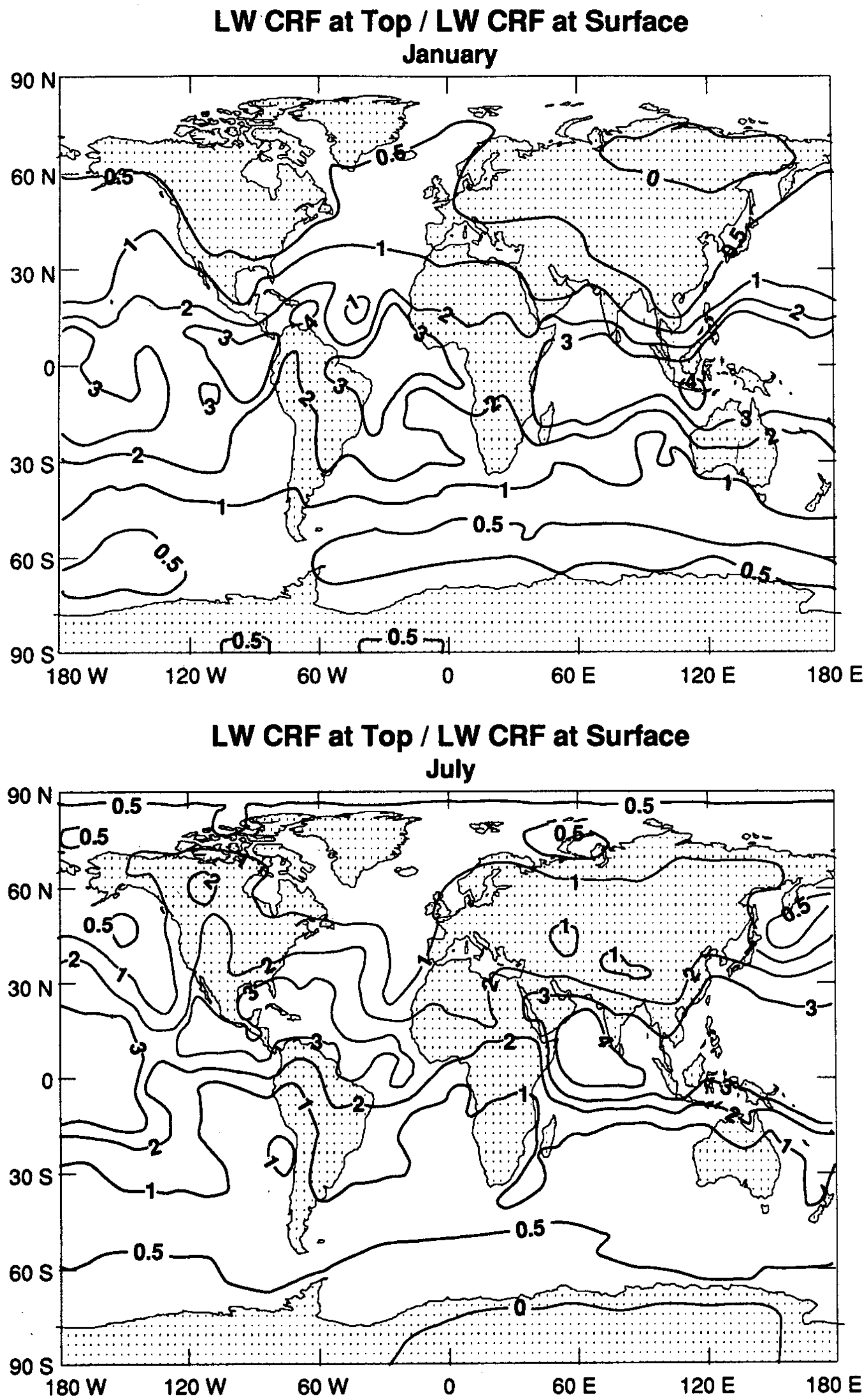

FIG. 9. Global maps of the ratio of the LWCRF at the top and at the surface for (a) January, and (b) July constructed from a simulation of the UCLA/CSU GCM. The ratio was obtained from points plotted in Fig. 4.

the procedure outlined in this study. The method should have a greater chance of success in that region based on the correlation shown in Fig. 5a. A test could be made as soon as ERBE and ISCCP data are available for the same time period.

To summarize, although it appears at first glance that longwave fluxes measured at the top of the atmosphere provide very little information on surface fluxes, it is possible to extract information from an analysis of the mean cloud radiative forcing that can be used to generate regional, if not global, maps of the net surface longwave radiation. We have not attempted to estimate quantitatively, the accuracy of the final product, but have merely suggested a methodology that utilizes cloud and radiation datasets that are currently being compiled under the auspices of ISCCP and ERBE.

Acknowledgments. This study was made possible by the support of the National Aeronautics and Space Administration through grants NAG5-1125 to Purdue University and NAG5-1058 to Colorado State University. Computing resources were provided by the Numerical Aerodynamic Simulation Facility at NASA/Ames. Mr. Hui Zhi of Purdue University provided programming assistance. Useful discussions with Wayne Darnell and Shashi Gupta of NASA/Langley are gratefully acknowledged.

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