Evaluating the accuracy of parameterizations for effective cloud fractions for small cumulus clouds in the longwave using ARM data

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INTRODUCTION

Modeling the three-dimensional effects of broken cloud fields is beyond the scope of most climate models. Assuming an effective cloud fraction reduces the three-dimensional cloud field to an average of plane parallel solutions — a much easier problem.

For broken cloud conditions, the longwave flux (F) can be written as the weighted average of clear and overcast fluxes:

\[ F = (1 - N_e)F_{\text{clear}} + N_e F_{\text{overcast}} \]  

(1)

\( F_{\text{clear}} \) is the clear sky flux; the flux that would occur if the broken cloud field was removed. \( F_{\text{overcast}} \) is the flux that would occur if the broken cloud field became completely overcast. \( N_e \) is the fractional sky coverage of flat black plates.

Previous works (Ellingson, 1982; Killen and Ellingson 1994; Ellingson and Han 1999) gave \( N_e \) as a function of absolute cloud amount (N) and cloud aspect ratio (\( \beta \)):

\[ N_e = N_e(N, \beta) \]  

(2)

The purpose of this work is to test the \( N_e \) parameterizations by using measured values of \( N_e \), N and \( \beta \).

INSTRUMENTS AND MEASUREMENTS

This work is based on measurements made at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) central facility from April through June 1997. Five instruments of the ARM SGP central facility have principal roles in this study. The millimeter wave cloud radar (MMCR) is used to measure N and \( \beta \). The microwave radiometer (MWR) is used to determine when water clouds are overhead; water clouds are present when the liquid water in the atmospheric column becomes significant. The atmospheric emitted radiance interferometer (AERI) measures the downwelling radiance at the surface from 520-1250cm\(^{-1}\) with high resolution. Pyrgeometers measure the longwave (0-3000cm\(^{-1}\)) downward flux at the surface. The MMCR, MWR, and AERI look directly upward with a small field of view; the pyrgeometers have a full hemispheric view.

Re-arranging (1) to solve for \( N_e \) yields:

\[ N_e = \frac{F - F_{\text{clear}}}{F_{\text{overcast}} - F_{\text{clear}}} \]  

(3)
F can be measured directly by the pyrgeometers. $F_{\text{clear}}$ and $F_{\text{overcast}}$ are computed using the AERI spectral data and cloud base data from the BLC or MMCR. In this way, $N_c$ can be derived from measurements.

**COMPUTING $F_{\text{clear}}$ AND $F_{\text{overcast}}$**

In order to compute $F_{\text{clear}}$ and $F_{\text{overcast}}$ during a particular 24-hour period, occurrences of clear or overcast skies must be identified. The AERI is used for this purpose. The AERI radiance standard deviation in the 985-990 cm$^{-1}$ interval is a good indicator for clear or overcast skies; low standard deviations indicate either clear or overcast skies. High standard deviations indicate broken cloud fields. Overcast skies have high radiances and low standard deviations; clear skies have low radiances and low standard deviations.

The clear and overcast AERI radiances are used to compute limiting values of clear and overcast radiances throughout the day. Computing the limiting values requires information on the changing conditions both at the surface and in the atmosphere. The AERI can provide this information because of its high spectral resolution.

The longwave downwelling radiance at the surface can be broken up into two spectral regimes, window and non-window. Within the 833-1250 cm$^{-1}$ window the atmosphere is relatively transparent. The downwelling surface is due primarily to water vapor and clouds (when they are present). Outside the window, the atmosphere is nearly opaque; the surface temperature determines the surface radiance. Breaking up the AERI radiance into window and non-window components separates the effects of changes in the vertical profile and changes in the surface temperature.

The opaque or surface component ($I_{\text{opaque}}$) of the AERI flux is

$$I_{\text{opaque}} = \int_{520}^{833} I(v) \, dv + \int_{833}^{1250} I(v) \, dv$$

Since the radiance in the opaque region is basically the Planck function at the surface temperature, this can be re-written as

$$I_{\text{opaque}} = \int_{520}^{833} B(T_{\text{surf}}, v) \, dv + \int_{833}^{1250} B(T_{\text{surf}}, v) \, dv$$

Finally,

$$I_{\text{opaque}} = B_{\text{opaque}}$$

Part of the AERI data stream is the surface temperature. Given $T_{\text{surf}}$, $B_{\text{opaque}}$ can be readily computed.

The window or vertical component ($I_{\text{window}}$) of the AERI flux is

$$I_{\text{window}} = \int_{833}^{1250} I(v) \, dv$$

For known clear or overcast radiances, $I_{\text{window}}$ can be found by subtracting $B_{\text{opaque}}$.

$$I_{\text{window}}^\text{overcast} = I_{\text{AERI}}^\text{observed} - B_{\text{opaque}}(T_{\text{surf}})$$
I_{\text{clear window}} = I_{\text{clear AERI observed}} - B_{\text{opaque} (T_{\text{surf}})} \quad (6b)

Assuming that the water vapor and/or cloud vertical profile does not change dramatically, \( I_{\text{window}} \) is constant. This allows us to compute clear and overcast AERI radiances (recall that the AERI data includes \( T_{\text{surf}} \) at each time step).

\[ I_{\text{AERI (estimated)}}^{\text{overcast}} = I_{\text{window}}^{\text{overcast}} + B_{\text{opaque} (T_{\text{surf}})} \quad (7a) \]

\[ I_{\text{AERI (estimated)}}^{\text{clear}} = I_{\text{window}}^{\text{clear}} + B_{\text{opaque} (T_{\text{surf}})} \quad (7b) \]

Using 7a to go from one overcast radiance to another, limiting values of overcast AERI radiance can be computed throughout the day. Likewise, 7b can be used to compute values of clear AERI radiance. This requires an iteration process that will progressively identify all the overcast and clear radiances.

The accuracy of these computed clear and overcast radiances depends on the constancy of \( I_{\text{window}} \) in the intervals between observed clear and overcast radiance.

Once the clear and overcast AERI radiances (\( I_{\text{AERI}} \)) are computed, they are multiplied by a conversion factor (L) to yield AERI fluxes (\( F_{\text{AERI}} \)).

\[ F_{\text{AERI}} = LI_{\text{AERI}} \quad (8a) \]

For clear skies \( L=3.45 \); for cloudy skies \( L \) ranges linearly from \( \pi \) at the surface to 3.25 at 6km.

The lower limit of the AERI range is 520 cm\(^{-1}\) so the integrated Planck function must be added:

\[ F_{\text{uncorrected}} = F_{\text{AERI}} + \pi \int_{0 \text{cm}^{-1}}^{520 \text{cm}^{-1}} B(T_{\text{surf}}, \nu) d\nu \quad (8b) \]

Lastly, to correct for AERI-pyrgeometer biases, a correction factor is necessary.

\[ F = F_{\text{uncorrected}} + \delta F_{\text{offset}} \quad (8c) \]

\( \delta F_{\text{offset}} \) is found by averaging the difference between \( F_{\text{uncorrected}} \) and the pyrgeometer flux for known clear and overcast.

Figure 1a is a plot of the pyrgeometer measured instantaneous flux and the clear, overcast, and instantaneous fluxes computed from the AERI measurements on May 22, 1997. The absolute and percentage differences in the instantaneous fluxes are shown in 1b. The fluxes are very close for clear and overcast conditions. Even under broken clouds, the fluxes are within 8%. This indicates that the derived \( N_c \) will be fairly accurate.
**DETERMINING N AND $\beta$**

$N$ and $\beta$ were found using the methods described in Han and Ellingson (1999). Briefly, the ratio of the time the MMCR detected a cloud to the total measurement time is related to $N$. Assuming the clouds are advecting over the MMCR at the wind speed, the cloud diameter can be found. Combined with the cloud thickness measured by the MMCR, the aspect ratio $\beta$ is found.

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**Fig. 2a** AERI derived clear ($F_{clr}$) and overcast ($F_{ovr}$) fluxes (blue, small dashes), pyrgeometer flux ($F_{pyr}$ - red), and the instantaneous AERI flux ($F_{AERI}$ - black) on May 22, 1997.

**Fig. 1b** Absolute difference ($\delta F$), black, and percent difference ($\%F$), red, between the measured pyrgeometer flux and the instantaneous AERI flux on May 22, 1997. Values for $\delta F$ are on the left $y$-axis; values for $\%F$ on the right $y$-axis.
Most parameterizations for $N_c$ assume that water clouds are black. This assumption can lead to large errors in $N_c$ when the measured values of $N$ are incorrect. The well-documented atmospheric plankton or bug problem can lead to an overestimation of $N$. Another potential problem is anomalous thin cumulus clouds composed of large water droplets that have a large radar cross section but little effect in the longwave.

In order to screen out the bugs and anomalous thin cumulus clouds, the MWR was used to determine if a significant amount of liquid water was present. The screening procedure was based on the standard deviation of liquid water in a half-hour interval centered on the time in question. Figure 2a shows the liquid water amount and its standard deviation measured by the MWR on June 13, 1997. Figure 2b shows old values of $N$ (derived without MWR screening) and the new values (with MWR cloud screening). Note that the reduction in $N$ is quite significant.

![Figure 2a. MWR measured column liquid water (blue dots) and the standard deviation of the measurement for a half-hour interval (red dots) on June 13, 1997.](image)
COMPARING $N_e$

Figures 3a and 3b shows $N_e$ curves of the randomly overlapping cylinder parameterization in Ellingson, 1982 and the data points corresponding to the AERI retrieved $N_e$ and the old (without MWR screening) and new (with MWR screening) $N$, on June 13, 1997 and June 29, 1997. The upper and lower dashed curves represent the highest and lowest cloud aspect ratios for that day, upper and lower limits for the parameterization.

Fig 3a. Upper and lower limit $N_e$ curves for $\beta_{\text{max}}$ and $\beta_{\text{min}}$ and $(N, N_e)$ data points derived from measurements taken on June 13, 1997. The blue points are for the new values of $N$, red for the old

Figure 2b. New and old MMCR measurements of $N$ vs. time on June 13, 1997 blue dots for the new values, red dots for the old values. The AERI retrieved $N_e$ is the solid black line.
To place each data point on those graphs, two values are needed, Ne and N. Since the AERI fluxes are comparable favorably with the pyrgeometer fluxes, the Ne values should be reasonable. Assuming that to be true, old N values are too large in both cases. The red points do not approach the bounding curves of the Ne parameterization. The new (blue) N, Ne points are consistently to the left of the old points. In both Figures 3a and 3b, the new values of N have a larger spread, ranging from 0 to 0.6 in 3a and from 0 to 0.75 in 3b. The old values of N range from 0.35 to 0.9 and from 0.3 to 0.9 respectively.

The cloud screening is partially successful in Figure 3a; four of the new points are within the bounding curves. Five of the new N values are too small, zero or approaching zero; this is somewhat reasonable since the derived value of Ne is less than 0.2. Approximately ten of the new N's remain too large, ranging from 0.2 to 0.6. The screening is not as successful in 3b. While several of the new points are close to the bounding curves, the most are not close. A large number of the new N are zero; this is less acceptable than in 3a because the derived values of Ne are much larger. Most of the derived Ne are larger than 0.2. This indicates that the screening algorithm is filtering out significant clouds as well as unimportant ones. As in 3a, a number of the new N’s are too large. These preliminary results indicate that the MWR screening can be helpful, but more work needs to be done on the algorithm.

There is another possible reason for the difference between the measured Ne and N besides bugs and anomalous thin cumulus. In Han and Ellingson (1999) it is assumed that the clouds advect over the instruments without significant changes in the time/length scale considered. Changes due to cloud generation or dissipation were averaged out. From the output of the video time lapse camera (VTLC) there are several days in 1999 where there is considerable amounts of local cloud generation and dissipation over periods as long as three hours. This is bound to increase the uncertainty in N. If the generation/dissipation is random over the space and time considered, the effect would be to increase
the noise in \(N\). However, if the generation/dissipation is ordered over the space and time considered, the effect would be to skew the measurement of \(N\). Further investigation with wide field of view instruments such as the VTLC, whole sky imager (WSI), and total sky imager (TSI) will help resolve this question.

**SUMMARY AND CONCLUSIONS**

A method for deriving the effective cloud fraction, \(N_e\), from ARM measurements was presented. The fluxes computed from the AERI seemed to be in good agreement with the fluxes measured by the pyrgeometers. It was inferred that the \(N_e\) were reasonable since they are based on the AERI fluxes. The column liquid water measured by the MWR was used to screen out bugs and anomalous thin cumulus clouds that have large radar cross sections but no effect in the longwave.

While the MWR cloud screening was partially successful, the algorithm needs more work. Another possible problem is the generation/dissipation of clouds over the instrument suite. In order to isolate separate these problems data from the Tropical Western Pacific will be useful because cumulus clouds are plentiful and there are no bugs. Re-examining the cloud data with input from wide field of view instruments such as the VTLC, WSI, and TSI will be helpful in determining the stability of the cloud fields.

**ACKNOWLEDGMENTS**

This paper was sponsored in part by the U.S. Department of Energy’s Atmospheric Radiation Measurements (ARM) program under grant DEFG0294ER61746.

**REFERENCES**

