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CLOUD DETECTION USING RADAR WIND PROFILER OUTPUT

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1. INTRODUCTION

The Department of Energy's Atmospheric Radiation Program (ARM) has as a major goal the improvement of the treatment of clouds in climate models (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003). To this end state of the art cloud sensing capabilities, including a Millimeter Cloud Radar (MMCR) have been installed at each of the ARM measurement sites; they are placed at a single, central location. Results from the MMCR along with ancillary data (e.g. ceilometers) are used in an algorithm named "Active Remote Sensing of Cloud Layers" (ARSCL), which has been shown to provide accurate, high resolutions profiles of cloud location in the column. (Moran et al., 1998; Clothiaux et al., 1998,1999) Knowledge of the cloud structure over a wider area, particularly at the Boundary Facilities (BF's), which are of the order of 100km from the central facility, would enable more rigorous testing of parameterizations used in climate models.

A potential source of additional data is the National Oceanic and Atmospheric Administration (NOAA) 404 MHz (74 cm wavelength) radar wind profilers (RWP), which are located close to the ARM Boundary Facilities (Ralph et al. 1995). In a winter case study Orr and Martner (1996) compared RWP reflectivity with that of a MMCR and showed that the RWP had some skill in detecting clouds. Data from the RWP's is provided by NOAA and are archived by the ARM program. The RWP utilizes the Doppler shift of signals reflected from fluctuations in the refractive index of the atmosphere to determine mean radial velocities along three beam axis (vertical, tilted to the North or East) which are converted to a three dimensional wind vector. The RWP operates in two modes: the low mode samples from 0.5 to 9.25 km above the ground with a resolution of 320 m, the high mode samples from 7.6 km to 16.25 with a 900 m resolution.

The RWP based cloud detection algorithm presented here postulates that clouds are characterized by anomalously large refractive gradients, largely because clouds tend to be significantly more turbulent than clear sky; thus increasing the reflectivity and spectral width signals relative to clear sky observations. At the BF's one also has ceilometer and GOES data available to augment the RWP.

2. ALGORITHM METHODOLOGY

The "input" reflectivity and spectral width, *R(z,t)* and *S(z,t)*, are the six-minute data available from the ARM archive, averaged over the radar beams. Normalized reflectivity and spectral width variables are derived from the input data are used in order to reduce the altitude and diurnal effects:

$$R_n(z,t) = \frac{R(z,t)-\mu_R(z,t)}{\sigma_R(z,t)} \qquad (1)$$

The subscript ***n*** indicates that the variable has been normalized and ***S_n(z,t)*** is defined using the same form as (1).

The altitude, (***z***), and time of day, (***t***), dependent offset variable, ***μ(z,t)***, can be either the average of the signal over a multi-day period; or an average over those time periods for which GOES satellite indicates zero (or minimum) cloud cover. The latter is used in the analysis presented below; it produced better skill level than the straight average. The scaling denominator, ***σ(z,t)***, is the standard deviation of the signal over a muliti-day period. The averaging time period must be long enough to develop robust statistics, but short enough so that the average conditions can be considered representative of any non-cloud conditions during the time period. A calendar month was used here; although sensitivity to the averaging period was found to be low. The normalized values from the low and high mode are merged by a simple interpolation scheme to form one reflectivity and spectral width profile for each time step. In addition to reducing diurnal and altitude effects and minimizing mismatches between the two altitude modes this normalization removes calibration errors. As Orr and Martner (1995) point out RWP need not be calibrated for its primary mission.

The basis of the algorithm is the assumption that a linear combination of the two normalized radar wind profiler variables will be greater than a given threshold when cloud is present, i.e.:

$$\textbf{\textit{IF}}\ \beta R_n(z,t) + (1-\beta)S_n(z,t) > \alpha\ \ \textbf{\textit{THEN}}\ c(z,t) = 1 \qquad (2)$$

where c(z,t) is the binary cloud mask, *β* is between zero and one. The threshold value *α*, because of the variable normalization, is of the order unity. The optimization of

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the *α* and *ß* parameters is performed by comparing results with the ARSCL derived binary cloud mask, as discussed in the next section.

RWP cloud predictions can be constrained by other data available collected at the ARM boundary facilities and available in the ARM data archive. Ceilometer data can be used to limit cloud base the RWP data,

$$\textbf{\textit{IF}}\ z < z_{CB}(t)\ \textbf{\textit{THEN}}\ c(z,t)=0 \qquad (3)$$

where z_{CB} is the cloud base reported by the ceilometer. Note this is used only to override equation 2.

GOES data can be used in two ways. Firstly if GOES-8 data indicates zero cloud fraction, it is assumed that no cloud exists for that time period no matter what other indications there are:

$$\textbf{\textit{IF}}\ F(t) = 0\ \textbf{\textit{THEN}}\ c(z,t)=0 \qquad (4)$$

where F is the total cloud fraction reported by GOES-8.

Secondly the GOES reported cloud top can be used to limit the RWP cloud top estimate. GOES-8 cloud height is estimated from IR cloud top temperatures and reduced data are available for the ARM SGP region in the ARM archive. The use of GOES-8 cloud height information to augment the cloud presence criteria can be expressed as:

$$\textbf{\textit{IF}}\ z > z_{CH}(t)\ \textbf{\textit{THEN}}\ c(z,t)=0 \qquad (5)$$

where z_{CH} is the GOES-8 determined cloud height.

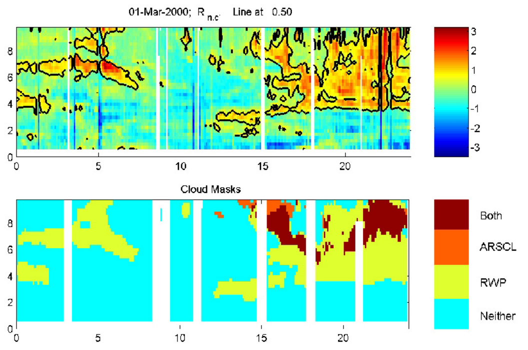

Figure 1 Optimized results for 1 March 2000 using the RWP criteria (equation 2) only. Top: Normalized RWP reflectivity contours as a function of time of day (UTC) and altitude (km); bottom: cloud mask contours.

3. OPTIMIZATION

Comparison with 6 minute averaged ARSCL data is used to find optimized values of α and β on a day by day basis; and to determine the utility of the ceilometer and GOES auxiliary data. The quantitative measure of skill used to optimize and evaluate RWP algorithms is the "Receiver Operating Characteristic" (ROC); a tool appropriate for assessing the performance of a procedure that has a binary output (Thurner, 1998; Swets, 1988). The ROC skill score ,ϵ, is the fraction of altitude-time points correctly identified as cloud minus the fraction of clear air points erroneously identified as cloud. Random procedures would yield a score of zero; perfect procedures, unity.

Figure 1 shows the results obtained using only the normalized RWP moments (equation 2) for 1 March 2000. The maximum skill was obtained for *α*=0.5 and *β* =1 (i. e. the reflectivity alone gives the best results). The upper frame is a time - altitude plot of the normalized reflectivity with the value 0.5 emphasized. The region where $R_{n,c}(z,t)$ exceeds 0.5 identifies where the algorithm predicts clouds. The lower frame shows where the RWP and ARSCL predict clouds (dark brown), where each predicts clouds (red or green) and where both predict clear air (blue). It can be seen that smoothing has removed some isolated points - either clear or cloud. These distributions yield a skill score of ϵ=0.53. The RWP predicts middle level clouds (4 km to 6 km) the entire time period and high clouds (6 to 10 km) after 1500 UTC. ARSCL shows high clouds only from 1400 UTC with a gap from 1830 to 2000 UTC.

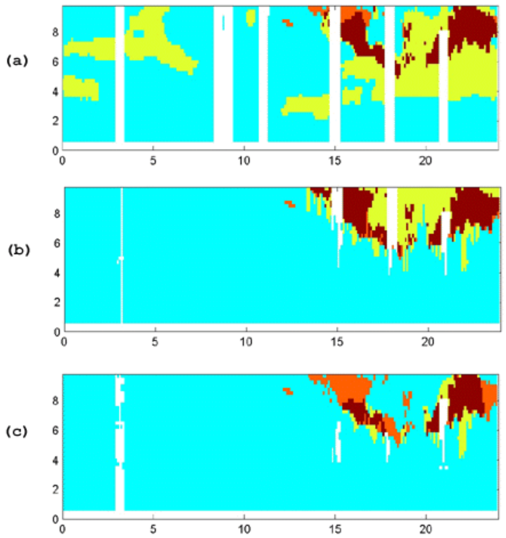

Figure 2 RWP cloud masks as a function of hour (UTC) and altitude (km) compared with ARSCL for 01 Mar 2000 using three sets of options: (a) RWP only (equation 2), (b) RWP (equation 2), GOES clouds fraction (equation 4), and ceilometer data (equation 3), (c) same as (b) plus GOES determined cloud height (equation 5). Color coding is the same as for Figure 1b. The skill scores for the three masks are 0.53, 0.84 and 0.44.

TABLE 1. Mean (μ) and standard deviation(σ) of skill scores for various versions of the of algorithm. Southern Great Plains data for the year 2000.

Data used:				Skill Score	
RWP (Eq. 2)	Ceilometer . cloud base. (Eq. 3)	GOES Cloud Fraction (Eq. 4)	Goes Cloud Top (Eq. 5)	μ	σ
Optimized				0.49	0.21
Optimized		X	X	0.44	0.23
Optimized	X			0.50	0.23
Optimized	X	X		0.51	0.23
Optimized	X	X	X	0.38	0.23
Not used.	X	X	X	0.39	0.23
Fixed α, β	X	X	X	0.34	0.21
Fixed α, β	X	X		0.41	0.23
Fixed β	X	X		0.49	0.23

The effect of using the additional criteria (equations 3, 4, and 5) is shown in figure 2.

It can be seen that inclusion of the GOES fraction criteria (equation 4) removes large "False" cloud area from 0000 UTC to 0800 UTC. There is a significant removal of "False" cloud areas below cloud resulting from the ceilometer criteria (equation 3) that can be seen in frame (b). Frame (c) shows that the utilization of GOES derived cloud top removes some "True" cloud areas. This decreases the skill value. ("True" and "False" are as defined by ARSCL.) Behavior of this type, while not universal, is common.

4. EVALUATION

A full year (2000) of RWP and ARSCL data from ARM Southern Great Plains site were used to test the RWP algorithm and the use of auxiliary data; the results are shown in Table1. The first four columns describe the algorithm options exercised. The last two columns give the average and standard deviation of the ROC skill scores.

The first column indicates some variations on the use of the RWP; the first 5 rows indicates that the ROC score was maximized by varying the α and β variables in equation 2 (this is the standard technique). The best results are mean skill scores of about 0.5 with a standard deviation of about 0.2. This is obtained just so long as we optimize on α and β and do not use the GOES derived cloud top.

The sixth row indicates that the RWP was ignored and ceilometer and GOES defined cloud top alone were used to estimate the boundaries of a single cloud layer; this produced relatively low skill scores.

Rows five and six gives the result of arbitrarily fixing α and β; the skill scores are low, particularly if GOES cloud top is used. In general it was found that the results were more sensitive to α than to β. This is emphasized in the final row which indicates that if one searches for an optimum α and fixes β arbitrarily the mean skill score approached 0.5, very close, indeed, to the highest mean attained.

5. CONCLUSIONS

Using the RWP, along with ancillary data, to locate cloud layers gives results that are significantly better than chance but clearly less than perfect. To a large extent the decision as to whether or not the results are satisfactory depends upon the application. For example the method would likely be unsatisfactory for a quantitative evaluation of advective tendencies. The method might well be useful if applied at the ARM Boundary Facilities to give an estimate of the representativeness of a central facility measured cloud field to the rest of the site.

The reason that the use of GOES cloud top data did not improve the skill of the cloud estimate is probably because of the spatial scale mismatch between the radar data and the half degree by half degree averaged GOES data that is in the ARM archive. However comparisons of either ARM archive data or 4 km by 4 km resolution GOES cloud top data with ARSCL showed appreciable scatter; and experiments using the 4 km data did not improve the skill scores. Additional constraints on the GOES data from a more careful, case by case, analysis may be required to permit greater confidence in the cloud top estimates (Heck 2002).

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