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A FUZZY LOGIC METHOD FOR ESTIMATING THE CONVECTIVE BOUNDARY LAYER MIXING DEPTH

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1. INTRODUCTION

The depth of the convective boundary layer is of first-order importance for air quality monitoring and prediction and can also be important in initializing and evaluating numerical weather prediction models. Previous studies (White 1993; Angevine et al. 1994) have had success in determining the convective boundary layer mixing depth using wind profiling radars. The procedure is based on the fact that in the convective boundary layer, the refractive index structure parameter, C_n^2, has a local maximum at the inversion due to small-scale buoyancy fluctuations associated with the entrainment process. C_n^2, in turn, is directly proportional to the range-corrected signal-to-noise-Ratio (SNR) of the backscatted signals recorded by wind profiling radars, thus allowing for continuous monitoring of the boundary layer depth. To estimate mixing layer depth, Angevine et al. (1994) simply selected the height of the maximum value in the hourly averaged, range-corrected SNR profile as the height of the boundary layer mixing depth.

Although this simple method is of considerable help in determining the boundary layer depth, it can fail for several reasons. First, errors in the estimation of the SNR due to ground clutter, radio-frequency interference, or atmospheric point targets such as birds will produce erroneous mixing layer depths. Second, the algorithm can fail if an elevated layer of high refractivity present due to the residual inversion from the previous day's boundary layer. Third, the algorithm can lead to significant errors in estimating the mixing depth during periods when the entrainment process is weak or when the entrainment zone is large, resulting in a deep layer with nearly uniform SNR.

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For these reasons we have developed a new boundary layer depth algorithm for use with wind profiling radars. This new algorithm differs in that it 1) incorporates information on the vertical profile of the variance of vertical velocity, and 2) uses "fuzzy logic" in both the determination of the SNR and in the final selection of the boundary layer height. Fuzzy logic, as implemented here, is simply the use of a set of smoothly varying functions, operating on multiple variables, that are combined with a set of rules to determine the quality of a given measurement (Klir and Yuan 1997).

2. COMPARISON OF METHODS

Figure 1 compares the original mixed-layer depth estimation method of Angevine et al. (1994) with the new method that is based on fuzzy logic. The first boxes of the two procedures indicate the methods used for the detection and differentiation of clutter and atmospheric spectral peaks. In the original method an attempt was made to remove ground clutter, using the method of Riddle and Angevine (1991), but not radio frequency interference (RFI) or point target clutter. In this method we start with the assumption that for each profiler site a fixed height can be found that is low enough that atmospheric peaks will always be present, but high enough that ground clutter will not be present. Using the vertical continuity of the atmospheric signal together with the symmetry of a ground clutter signal at about zero velocity, this method tries to distinguish between the two types of signal. It can fail when the original assumptions are not met, or when the clutter and atmospheric signals are so close that the noise floor is not reached between them. After attempting to separate ground clutter from the atmospheric signal, the atmospheric peak detection is then accomplished using the standard method of Strauch et al. (1984).

In contrast, the first step of the new method uses fuzzy logic to determine that part of the radar's measured Doppler spectrum that is associated with the true atmospheric signal. A similar method for recognizing clear air echoes in a Doppler spectrum has been developed by studying the characteristics of different kinds of clutter in real situations (Cornman et al. 1998). In our procedure, at each range gate several quantities are computed for each spectral point; these help to distinguish clutter from the atmospheric signal. At the end of the identification process the fuzzy logic procedure gives a "score" to each spectral point, characterizing the extent to which this signal can be interpreted to be atmospheric rather than generated by clutter. A threshold is then applied to each of these scores. The threshold is used to identify which part of the spectra will be included in the radar moments estimation and which part will be ignored as a clutter-generated signal.

The second box of the two procedures represents the calculation of the radar moments. The zeroth moment of the radar spectrum, also known as the SNR, is the ratio of the area under the signal peak to the noise power; the first moment is the distance of the peak from zero frequency, and represents the Doppler shift associated with the wind velocity; the second moment is the width of the atmospheric spectral peak, and is related to the variance of the radial velocity. In both methods, the moments estimation is accomplished using the standard procedure of Strauch et al. (1984).

In the third part of both procedures, hourly mixing depth values are determined from the vertical beam of the wind profiling radar. In the original method the mixing depth is taken as the height of the maximum in range-corrected SNR. In the new method, a further algorithm based on the fuzzy logic is applied. For each hourly profile of SNR, we calculate a new set of scores that takes into account statistics from the profile of SNR, as well as the variance of the vertical velocity, measured by the wind profiler's vertical antenna. The maximum score in each hourly profile then identifies the top of the boundary layer.

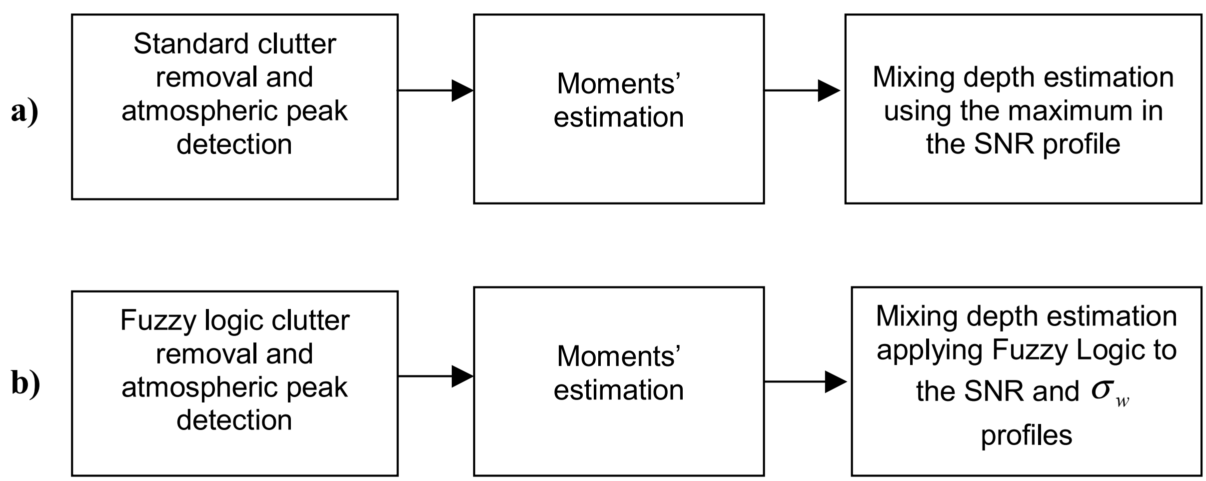

Figure 1. A schematic representation of **a)** the original procedure of Angevine et al. (1994), shown in the top panel, and **b)** the new procedure using fuzzy logic, shown in the bottom panel.

3. DATA ANALYSIS AND RESULTS

The analysis has been performed using data collected by a 915-MHz wind profiler sited at the Wharton Power Plant near Houston, Texas (latitude: 29.95 N, longitude: 94.54 W, altitude: 35 m). Because Houston is near the coast of the Gulf of Mexico, it routinely experiences sea breezes, and has relatively weak temperature gradients at the capping inversion. At the wind profler site, 36 rawinsonde profiles were taken over 17 days between 21 August and 9 September 2000. The rawinsonde data and the RASS profiles provided verification for the mixing depths computed using the two mixing depth identification methods.

RASS data were collected during two 5 min periods at the start and middle of each hour. These two profiles were averaged and the mixing depth was determined from this average profile. The radar's virtual temperature (T_v) profiles, determined by RASS, and its SNR profiles, have a range resolution of 60 m, starting from a height of 120 m AGL. In a convective boundary layer we expect to have a near-constant value for the virtual potential temperature in the mixing layer, and a sharp increase within the boundary layer's capping inversion. For this reason we convert T_v to virtual potential temperature, θ_v, and determine the first point in the θ_v profile at which the value of the gradient of θ_v as a function of height is larger than 0.5 °C/Δr, where Δr is the range resolution ofthe RASS (60 m).

RASS signals from 915 MHz wind profilers generally do not reach the same heights as do the SNR measurements because of acoustic attenuation, and because of degradation of the signal by atmospheric turbulence and winds. For the days analyzed here the RASS temperature profiles typically reach 800 m, while the SNR and wind profiles typically reach 3000 m.

The results obtained for the Wharton site are summarized in two scatter plots (Figs. 2 and 3). The comparison between the mixing depths obtained from the RASS/rawinsonde profiles versus those obtained from the standard SNR and mixing depth algorithms is shown in Fig. 2, while the comparison with the two fuzzy logic algorithms is shown in Fig. 3.

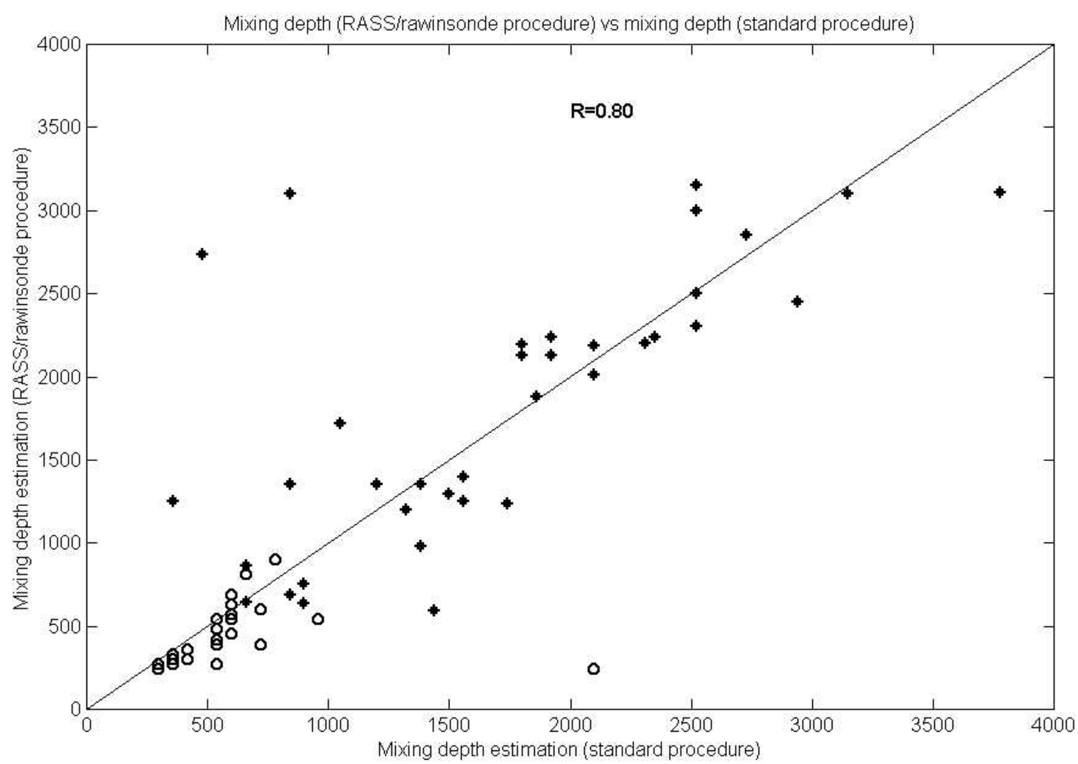

Figure 2. Scatter plot of mixing depths from RASS (stars) and rawinsonde measurements (circles) vs. mixing depths from the standard algorithms for the Wharton site.

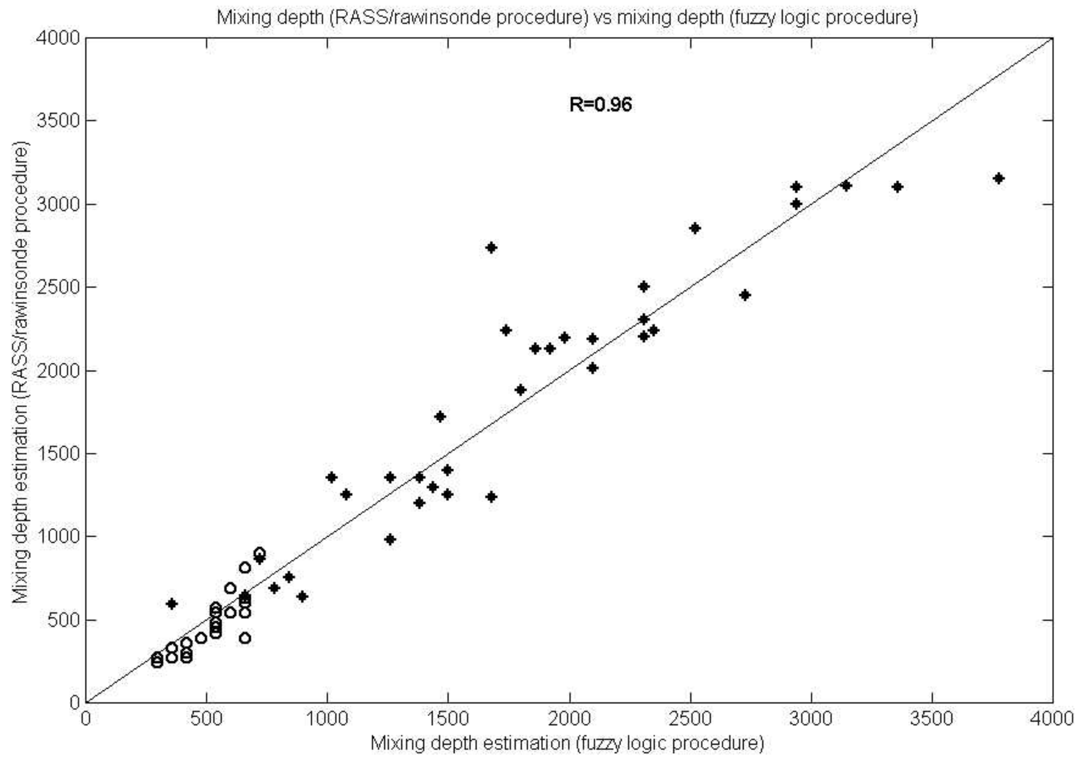

Figure 3. Scatter plot of mixing depths from RASS (stars) and rawinsonde measurements (circles) vs. mixing depths from the fuzzy logic algorithms for the Wharton site.

At this site the mixing depth reached extremely high values, up to almost 4000 m. For this reason we have used wind profier data collected at both high resolution/low maximum heightt (Δr = 60 m, first height = 120 m, max height = 2220 m) and at low resolution/high maximum height (Δr = 210 m, max height = 4200 m). The low-resolution data were used only for periods when the high-resolution data were unable to reach the top of the boundary layer. The results obtained by the combination of the two fuzzy logic methods are significantly better (Table 1).

Table 1. Correlation coefficient for the mixing depth comparison data shown in Fig. 2 and Fig. 3.

Method	Correlation coefficient, r
RASS/Rawinsonde versus standard algorithm	0.80
RAA/Rawinsonde versus fuzzy logic algorithm	0.96

4. SUMMARY AND CONCLUSIONS

A new method for determining convective atmospheric boundary layer mixing depth by wind profiling radars has been developed that is based on the application of fuzzy logic techniques. This technique first applies a fuzzy logic algorithm to the radar spectra to reduce the influence of clutter from a variety of sources, including ground clutter, radio frequency interference, and point targets. A second fuzzy logic algorithm then uses the clutter-suppressed radar SNR measurements to determine the depth of the mixing layer. This second algorithm incorporates values of the peak, gradient, and curvature of hourly median SNR profiles, as well as the profiles of hourly variances of SNR and vertical velocity.

The new fuzzy-logic-based method was applied to a 915-MHz wind profiler dataset, and the results were compared with independent measurements of mixing depth obtained from RASS and rawinsonde temperature profiles. The new method is found to provide substantially more accurate mixing depth estimates compared to previous methods.

5. ACKNOWLEDGEMENTS

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