10.4 Estimating convective mixing heights during Joint URBAN (2003)

Matthew Simpson[1], Sethu Raman[1], Julie K. Lundquist[2], and Martin Leach[2]
[1]Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University, Raleigh, NC 27695-8208, USA
[2]Lawrence Livermore National Laboratory, Livermore, CA 94551

1. INTRODUCTION

Joint URBAN (2003) was a field experiment conducted in Oklahoma City, Oklahoma from 28 June to 31 July. Primary goals of Joint URBAN (2003) include measuring meteorological data at several scales of motion and collecting tracer data that resolves dispersion processes within an urban environment. Data collected during Joint URBAN (2003) will be used to validate and improve existing dispersion models. A more detailed description of the Joint URBAN is provided by Allwine et al. (2003).

Numerous data platforms were used to collect meteorological data during Joint URBAN (2003). Radiosondes were released from two locations within Oklahoma City. One radiosonde site was located upwind of Oklahoma City relative to the dominant wind direction and the other site was located downwind of the city to study the effect of the urban area on the stability of the lower atmosphere. There were 23 surface meteorological stations and 6 stations measuring the surface energy budget located throughout Oklahoma City. Three wind-profiling radars were used to measure wind fields in the lower atmosphere. Profilers were deployed so that the influence of the urban region on wind patterns and atmospheric stability could be studied.

Height of the convective boundary layer (CBL) can be derived from the signal to noise ratio (SNR) measured by profilers using a theory presented by White et al. (1991). Small-scale buoyancy fluctuations within the entrainment zone, located just above the mixed layer, cause a peak in the refractive index structure parameter C_n^2. Otterson (1969) showed that C_n^2 is directly proportional to SNR estimated from wind-profiling radars. A maximum value of C_n^2 or the SNR occurs within the entrainment zone located above the CBL and denotes the height of the boundary layer (Fairall 1991). One method presented by Angevine et al. (1994) for deriving the CBL height from SNR profiles involves finding the median SNR profile from the five-profiler beams and then correlating the peak SNR value to the height of the CBL.

Direct measurements of the boundary layer height using aircraft, lidar, and soundings are expensive and usually have low temporal resolution. Numerous models have been developed to estimate the boundary layer height using only routine meteorological observations. One such boundary layer growth model is AERMET, which is the meteorological preprocessor for the AERMOD dispersion model. AERMET is a two-dimensional diagnostic model that uses the time varying surface heat flux to calculate the evolution of the convective boundary layer height. A thorough evaluation of the AERMOD model has been done, primarily focusing on air quality in a flat rural environment (US EPA 1998). Validation of AERMET performance in an urban area has been less rigorous, mainly due to the lack of information on diurnal variation of mixing height observations.

2. METHODOLOGY

AERMET is a simple diagnostic model that incorporates routine surface observations and upper air soundings to estimate the growth of the boundary layer. Surface observations of the 2 m dry bulb temperature, 10 m wind speed and direction, total cloud cover, and station pressure are required by AERMET. The lapse rate above the morning boundary layer is also needed by the AERMET model to account for the effects of entrainment with the free atmosphere. User defined surface characteristics are needed for the AERMET estimations. A roughness length of 0.1 m and a surface albedo of 0.15 were used for the AERMET calculations.

The first step in estimating growth of the convective boundary layer is calculating net radiation. A thermal radiation balance by Holtslag and van Ulden (1983) estimates net radiation. Total incoming solar radiation is corrected for cloud cover. A simple energy balance given by Oke (1978) is used to estimate the surface sensible heat flux. Here, H is the surface sensible heat flux, R_n is the net radiation, and B_o is the Bowen Ratio. A user defined Bowen ratio value of 2.0 was used as suggested by the AERMET manual for urban area land use.

$$H = \frac{0.9R_n}{\left(1+1/B_0\right)} \qquad (1)$$

Once the sensible heat flux has been estimated, growth of the convective boundary layer can be estimated by AERMET using a simple energy balance model. This model was originally proposed by Carson (1973) and was later modified by Weil and Brower (1983) and is given by

$$z_{ic}\theta\{z_{ic}\} - \int_0^{z_{ic}} \theta\{z\}dz = \left(1+2A\right)\int_0^t \frac{H\{t'\}}{\rho Cp}dt' \qquad (2)$$

where z_{ic} is the height of the convective boundary layer, θ is the potential temperature, A is a constant, and H is the surface sensible heat flux as a function of time beginning at sunrise.

Convective mixing heights were estimated for Oklahoma City, OK from 1 July to 31 July 2003 using the AERMET model. Surface meteorological observations used for the AERMET estimations were from the Oklahoma City Will Rogers International Airport. Will Rogers airport is located within the urban area of Oklahoma City. The lapse rate above the morning boundary layer was derived by AERMET from Norman, OK 12:00 UTC upper air soundings. Norman, OK is located approximately 40 km to the south of the center of Oklahoma City. AERMET is often applied in situations in which information on the lapse rate is derived from soundings over 100 km away from the site of interest, and so the use of the Norman sounding is consistent with typical AERMET applications.

Observed mixing heights over Oklahoma City were derived from signal to noise ratio (SNR) profiles measured by two profilers using the Angevine et al. method. The profilers had 5 beams and measured 30 - minute averages of wind speed and direction and SNRs. Median SNR values of the 5 beams were plotted at each height to create a single SNR profile. Height of the convective boundary layer was then defined as the height of the maximum value in the median SNR profile. Resolution of the profiler was 56 m, resulting in an error of ± 28 m for all profiler derived mixing heights used in this study.

To illustrate the SNR method of deriving mixing height, a median SNR profile with values shown in decibels (dB) measured on 18 July 2003 at 12:00 LST is shown in Figure 1. SNR values are missing up to a height of 400 m because of the influence of ground clutter on the backscattered signal. The SNR values within the mixed layer have a small range with values around 1 to -4 db up to a height of 1800. Around 1700 m above ground level, the SNR values begin to increase indicating the location of the entrainment zone. A maximum SNR value of 6 dB within the entrainment zone is observed at a height of 2007 m. Therefore, an approximate mixed layer height of 2007 m with an error of ± 28 m is derived using the SNR method. This value agrees reasonably well with a mixed layer height of 1960 m derived from a potential temperature sounding. Above 2100 m, the SNR values decrease quickly to around –15 dB, indicating the presence of the free atmosphere.

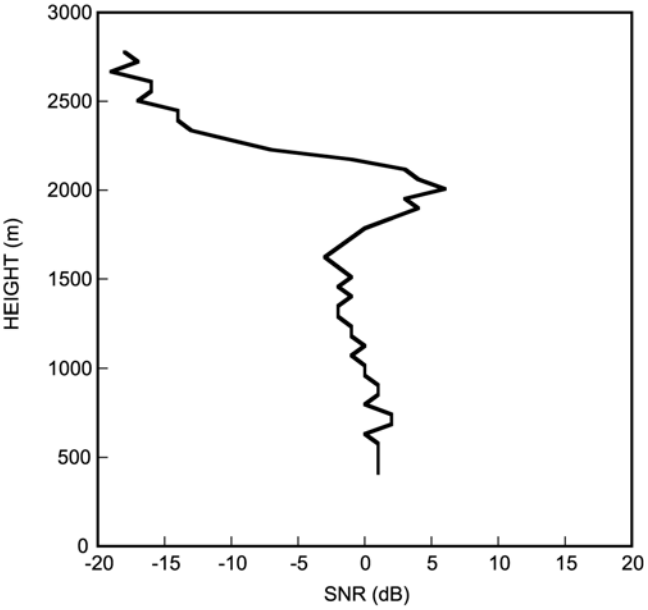

Figure 1. A signal to noise ratio profile (dB) measured by the ANL profiler valid 18 July 2003 at 12:00 LT. Mixed layer height derived from the SNR is 2050 m.

3. RESULTS

A comparison of mixing heights derived from the ANL profiler located near downtown Oklahoma City and AERMET estimated mixing heights from 1 July to 23 July 2003 at 12:00 LST is shown in Figure 2. Mixing heights derived from atmospheric soundings taken within the urban area of Oklahoma City at 12:00 LST are also shown in Figure 2 as additional data to validate the AERMET model. The mixed layer height in the atmospheric soundings is defined as the height of the greatest temperature gradient in the entrainment zone. The comparison does not include the last part of July due to the absence of atmospheric sounding data. Observed mixing heights range from 700 to 2200 m with large day-to-day variation. Mixing heights estimated by AERMET show a similar range as the observed mixing heights with values between 900 and 2300 m. The AERMET estimated mixing heights correspond well with the observed daily mixing height values. Average daily difference between observed and estimated mixing heights is ± 245 m with the majority of the error occurring on a few specific days. The maximum daily difference between an observed mixing height and the AERMET estimated mixing height is 874 m. AERMET was also able to resolve the large daily differences in the observed mixing heights due to changing synoptic conditions.

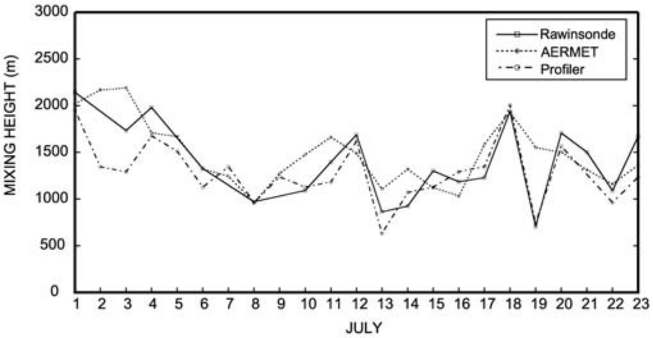

FIGURE 2. Comparison of AERMET estimated mixing heights and observed mixing heights derived from signal to noise ratio data measured by the ANL profiler and ARL potential temperature soundings at 12:00 LT during July of 2003.

Observed mixing heights can be derived every 30 minutes from the profiler data. This high temporal resolution data creates an opportunity to observe the growth of the boundary layer and validate AERMET's performance. Convective mixing heights derived from two profilers and mixing heights estimated using AERMET for 8 July 2003 are shown in Figure 3a. Observed mixing heights are shown every 30 minutes while the AERMET mixing height is shown every hour.

At 9:00 LT, the observed and estimated mixing heights are around 500m. Observed and estimated mixing heights have grown to around 1400 m by 17:00 LT. The maximum estimated mixing height is 1438 m while the highest observed mixing height is 1402 m for both profilers. Observed mixing heights begin decreasing around 18:30 LT while AERMET continues to predict a small amount of growth of the mixed layer until 19:00 LT. Convective boundary layer growth was restricted on this day due to large-scale cloud cover. Overall, AERMET estimated mixing heights corresponded well with the observed mixing heights on this day despite the influence of the cloud cover.

Less cloud cover on 9 July 2003 resulted in higher mixing heights as shown in Figure 3b. Observed and estimated mixing heights are all around 500 m at 9:00 LT. By 16:00 LT the observed mixing heights were between 2000 and 2100 m. The estimated mixing height for 16:00 LT is 2000 m. Due to the development of low clouds, the height of the mixed layer could not be derived from the profilers after 16:30 LT. The estimated mixing heights are shown to increase slightly after 16:30 LT and reach a peak of 2250 m.

Convective boundary layer heights of over 3000 m are not uncommon in Oklahoma City during summer months. High boundary layer episodes typically occur when the air is dry and there is little cloud cover. A comparison of profiler derived boundary layer heights and AERMET estimated mixing heights on 26 July 2003 is shown in Figure 4. Since the profiler data only goes to a height of 2775 m, the convective mixing height derived from Norman, OK sounding at 18:00 LT is included to give a general idea of the height of the late afternoon mixing height for Oklahoma City. The observed and estimated boundary layer heights at 09:00 LT are both around 500 m. Mixing heights grow quickly and by 13:00 LT the observed mixing height is around 2650 m while the estimated mixing height is around 2250 m. After 13:00 LT, the estimated mixing height is seen to grow slowly and reaches a maximum of 3002 m at 18:00 LT. The observed mixing height at 18:00 LT derived form the Norman sounding is around 3300 m, which is in good agreement with the estimated mixing height. AERMET was able to estimate the quick growth of the CBL and the magnitude of the late afternoon mixing height.

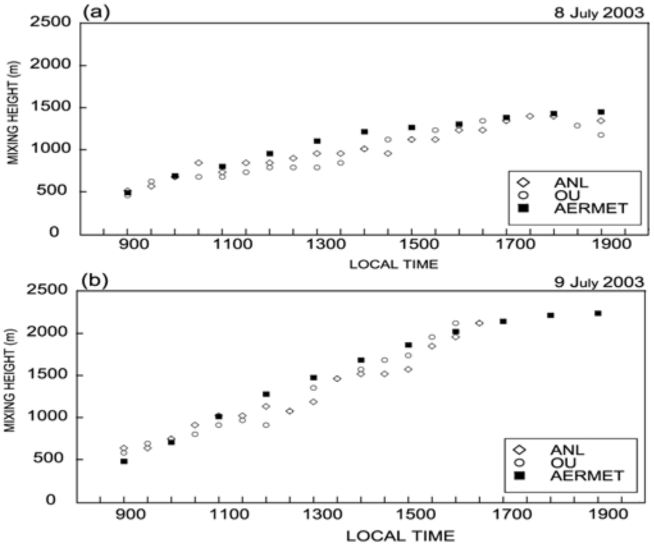

Figure 3. (a) Comparison of AERMET estimated mixing heights and observed mixing heights derived from data collected by the ANL and OU profilers on 8 July 2003. **(b)** Same as (a) but on 9 July 2003.

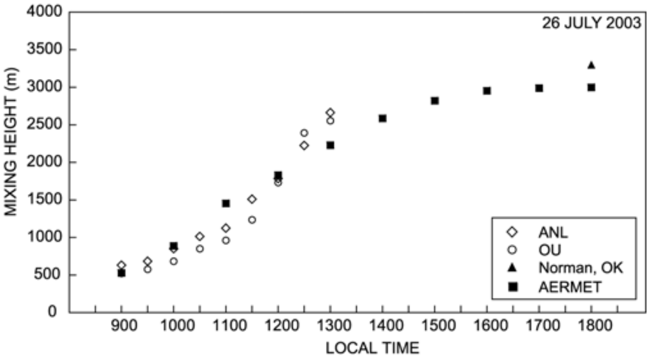

Figure 4. Comparison of AERMET estimated mixing heights and observed mixing heights derived from data collected by ANL and OU profilers and Norman, OK soundings on 26 July 2003 during highly convective conditions.

4. CONCLUSIONS

Correlating the peak signal-to-noise ratio value to the height of the mixed layer is a simple and effective method of validating a boundary layer growth model. Analysis of signal-to-noise ratio profiles shows that the peak value corresponds well to the height of the mixed layer derived from atmospheric soundings. Mixed layer heights can be derived from signal to noise profiles at a temporal resolution capable of showing the growth of the convective boundary layer and can be used to validate boundary layer models.

Large daily variations in the height of the mixed layer in Oklahoma City are caused by different synoptic conditions. Comparison of observed and estimated mixing heights show that AERMET is able to estimate the daily variations in mixing heights caused by changes in surface temperature, total cloud cover, and the lapse rate above the morning boundary layer. AERMET is a simple model using only routine meteorological observations but is able to reasonably estimate mixing heights over a wide range of atmospheric conditions.

Highly convective conditions during the summer result in mixed layer heights of over 3000 m in Oklahoma City. The large amount of boundary layer growth during the late morning to early afternoon hours observed during convective conditions is estimated well by AERMET. Model estimations of the height of the late afternoon mixed layer also correspond well with observations.

Acknowledgements. This work was supported by the State Climate Office of North Carolina. The LLNL portion of this work was performed under the auspices ofthe U.S. Department of Energy by the University of California, Lawrence LivermoreNational Laboratory under contract No. W-7405-Eng-48.

5. REFERENCES

Allwine, K.J., M. J. Leach, L. W. Stockham, J. S. Shinn, R. P. Hosker, J. F. Bowers, and J. C. Pace: Overview of Joint URBAN 2003—An Atmospheric Dispersion Study in Oklahoma City. Preprints, Eighth Symposium on Integrated Observing and Assimilation Systems in the Atmosphere, Seattle, WA, Amer. Meteor. Soc., J7.1.

Angevine, W., A. White, and S. Avery, 1994: Boundary-layer depth and entrainment zone characterization with a boundary-layer profiler. *Boundary Layer Meteorology*, 68, 375-385.

Carson, D.J., 1973: The development of a dry inversion-capped convectively unstable boundary layer. *Quart.J.Roy.Meteor.Soc*., 99, 450-467.

Fairall, C.W., 1991: The humidity /temperature sensitivity of clear-air radars for the cloud free convective boundary layer, *J. Appl. Meteorol*., 8, 1064-1074.

Holtslag, A.A.M. and A.P. van Ulden, 1983: A simple scheme for daytime estimates for the surface fluxes from routine weather data. *J.Climate Appl.Meteor*., 22, 517-529.

Oke, T.R., 1978: Boundary Layer Climates. John Wiley and Sons, New York.

Otterson, H., 1969: Atmospheric structure and radar backscattering in clear air, *Radio Sci*., 4, 1179-1193.

U.S. Environmental Protection Agency (1998b). Draft: Model evaluation results for AERMOD. Environmental Protection Agency.

Weil, J.C. and R.P. Brower, 1983: Estimating convective boundary layer parameters for diffusion applications. PPSP-MD48, Maryland Power Plant Siting Program, Maryland Department of Natural Resources, Baltimore, MD 45pp.

White, A., C. Fairall, and D. Thompson, 1991: Radar observations of humidity variability in and above the marine boundary layer, *J. Atmos. Ocean. Technol*., 8, 639-658.