LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-JRNL-224108

A Study of the Variation of Urban Mixed Layer Heights

M. Simpson, S. Raman, J. Lundquist, M. Leach

August 31, 2006

Natural Hazards

A study of the variation of urban mixed layer heights

by

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

May 10, 2006

Matthew D. Simpson
North Carolina State University
Suite 240, Research III Building
1005 Capability Drive, Centennial Campus
Raleigh, NC 27695 - 7236
Tel: 919-515-3056; Fax: 919-515 -1441
Email: matthew.drennan@gmail.com

Abstract—The AERMET model is used to estimate hourly mixing heights during the Joint URBAN (2003) experiment in Oklahoma City, Oklahoma. AERMET is a simple 2-D model that requires only routine meteorological observations and an early morning atmospheric sounding to estimate convective boundary layer growth. Estimated mixing heights are compared with observed mixing heights measured during Joint URBAN 2003. Observed convective boundary layer heights are derived from profiler data using a peak signal to noise ratio method. The method of deriving mixing heights from profiler data is validated using daily atmospheric sounding data. Estimated mixing heights using AERMET show good agreement with observations on days of varying temperature and cloud cover. AERMET was able to estimate the rapid boundary layer growth observed in the late morning and early afternoon hours during highly convective conditions. Convective boundary layer heights of over 3000 m are observed in sounding data during the late afternoon. Estimated convective boundary layer heights of over 3000 m during the late afternoon agreed well with observations from the sounding and profiler data.

Key words. AERMET, convective boundary layer, profiler, Joint URBAN (2003), signal to noise ratio.

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 detailed description of the Joint URBAN is provided by Allwine *et al*. (2004).

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 (Wyngaard, and LeMone, 1980; 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. Additions to the Angevine *et al*. method have been made by Bianco and Wilczak (2002) to increase skill in the method, where profiles of vertical velocity variance and varying functions that determine the quaility of a given measurement are incorporated.

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 (EPA, 1998a), which is the meteorological preprocessor for the AERMOD (Cimorelli *et al*. 1998) 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. Weil and Brower (1983) found good agreement between estimated and observed mixing heights for a rural environment using the time varying heat flux model. A thorough evaluation of the AERMOD model has been done, primarily focusing on air quality in a flat rural environment (EPA 1998b). 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.

Objectives of this paper are to create an observational data set of CBL heights using the Angevine *et al*. method from profiler data measured during Joint URBAN (2003). Observed mixing heights will be compared with convective mixing heights estimated using the AERMET model. Comparisons will be made on a wide range of synoptic conditions covering cloudy days to highly convective periods.

2. Methodology

2.1 AERMET estimation of CBL heights

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 was used for 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 (R_n) as:

$$R_n = \frac{(1 - r(\phi))R + c_1 T^6 - \sigma_{SB} T^4 + c_2 n}{1 + c_3} \tag{1}$$

where R(φ) is the time varying albedo based on solar elevation angle, R is total incoming solar radiation, T is the 2 m dry bulb temperature, σ_{SB} is the Stefan-Boltzman constant, n is cloud cover fraction, and c_1,c_2, and c_3 are empirical constants equal to 5.31 x 10^{-13} W m^{-2} K^{-6}, 60 W m^{-2}, and 0.12 respectively. Total incoming solar radiation (R) is corrected for cloud cover using the estimate from Kastan and Czeplak (1980),

$$R = R_o(1 + b_1 n^{b2}) \tag{2}$$

where n is the fractional opaque cloud cover and R_o is the incoming solar radiation at ground level for clear skies based on solar elevation angle.

A simple energy balance given by Oke (1978) is used to estimate the surface sensible heat flux,

$$H = \frac{0.9R_n}{\left(1+1/B_0\right)}. \tag{3}$$

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.

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

$$z_{ic}\theta\{z_{ic}\} - \int_0^{z_{ic}} \theta\{z\}dz = \left(1+2A\right)\int_0^t \frac{H\{t'\}}{\rho Cp}dt' \tag{4}$$

where z_{ic} is the height of the convective boundary layer, θ is the potential temperature, A is a constant equal to 0.2 given by Deardorff (1980), 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. Location of the Will Rogers airport is shown in Figure 1. The lapse rate above the morning boundary layer was derived by AERMET from Norman, OK 12:00 UTC upper air soundings. Norman, OK is approximately 40 km from the center of Oklahoma City and its location is shown in Figure 1. 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.

2.2 Profiler-derived CBL heights

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. Locations of the Argonne National Laboratory (ANL) and Oklahoma University (OU) profilers are shown in Figure 1. 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.

A potential temperature sounding taken at Oklahoma City on 18 July 2003 at 12:00 LST is shown in Figure 2a. An unstable surface layer extends to a height of about 250 m above ground level. A mixed layer was observed from 250 to 1900 m above ground. Above the mixed layer, a strong inversion associated with an entrainment zone between the mixed layer and the free atmosphere was located in the layer from 1900 to 2100 m above ground. It is within the entrainment zone that the greatest mixing was occurring and the maximum SNR value was expected to occur. A boundary layer height of 1960 m was estimated from the potential temperature profile.

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 2b. 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 increases indicating the location of the entrainment zone. A maximum SNR value of 6 dB within the entrainment zone was measured at a height of 2007 m. Therefore, an approximate mixed layer height of 2007 m with an error of ±28 m was derived using the SNR method. This value agrees reasonably well with a mixed layer height of 1960 m derived from the potential temperature sounding. Above 2100 m, the SNR values decreased quickly to around –15 dB, indicating the presence of the free atmosphere.

3. Discussion of 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 3. Mixing heights derived from atmospheric soundings taken within the urban area of Oklahoma City at 12:00 LST are also shown in Figure 3 as additional data to validate the AERMET model. The mixed layer height in the atmospheric soundings was 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 ranged from 700 to 2200 m with large day-to-day variations. 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. The average of daily mean absolute error between observed and estimated mixing heights was ± 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 was 874 m. AERMET was also able to resolve the large daily differences in the observed mixing heights due to changing synoptic conditions.

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 7 July 2003 are shown in Figure 4a. Observed mixing heights are shown every 30 minutes while the AERMET mixing height is shown every hour. At 9:00 LT, observed and estimated mixing heights were all around 500 m. Steady growth of the CBL was observed to 17:00 LT in the afternoon with observed CBL heights of 1550 to 1750 m. The estimated mixing height at 17:00 LT was 1765 m, which agrees well with observations. Observed mixing decreased slightly after 17:00 LT while estimated mixing heights continued to grow to a maximum of 1815 m at 19:00 LT.

Observed convective mixing heights were lower on 8 July 2003 because of increased cloud cover (Figure 4b). At 9:00 LT, the observed and estimated mixing heights were around 500m. Observed and estimated mixing heights grew to around 1400 m by 17:00 LT. The maximum estimated mixing height was 1438 m while the highest observed mixing height was 1402 m for both profilers. Observed mixing heights began decreasing around 18:30 LT while AERMET continued to predict a small amount of boundary layer growth until 19:00 LT. Overall, AERMET estimated mixing heights corresponded well with the observed mixing heights on this day despite the large amount of cloud cover.

Less cloud cover in the morning of 9 July 2003 resulted in higher mixing heights as shown in Figure 4c. Observed and estimated mixing heights were 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 was 2000m. 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 increased slightly after 16:30 LT and reached 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 5a. 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 were both around 500 m. Mixing heights grew quickly and by 13:00 LT the observed mixing height was around 2650 m while the estimated mixing height is around 2250 m. After 13:00 LT, the estimated mixing height grew slowly and reached a maximum of 3002 m at 18:00 LT. The observed mixing height at 18:00 LT derived form the Norman sounding was around 3300 m, which was 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.

A comparison of estimated mixing heights with profiler derived mixing heights on 27 July 2003 for Oklahoma City is shown in Figure 5b. Again, the observed mixing height at 18:00 LT derived form a Norman, OK sounding is also shown in Figure 5b. Both observed and estimated mixing heights were around 500 m at 09:00 LT. Rapid boundary layer growth was once again observed between 11:00 LT and 13:00 LT with the mixed layer height growing from 1050 m to 2700 m. Estimated mixing heights show a similar quick growth of the CBL between 11:00 LT and 13:00 LT with mixing heights growing from 1240 to 2320 m. Estimated mixing heights reached a maximum value of 2960 m at 18:00 LT, which agrees well with the observed mixing height of 3050 m derived from a Norman, OK sounding.

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 of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. Data used in this study were collected by Jeff Basara and Don Guiliano from Oklahoma University, Rich Coulter, Tim Martin, Mikhail Pekhour, and Erin Hokanson from Argonne National Laboratory, Ron Cionco and Young Yee from the Army Research Laboratory, and Jerry Allwine, Will Shaw, Stephan De Wekker, and Larry Berg from the Pacific Northwest National Lab. UCRL-JRNL-206521.

References

Allwine, K.J., Leach, M. J., Stockham, L. W., Shinn, J. S., Hosker, R. P., Bowers, J. F., and Pace, J. C. , 2004. 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., White, A., and Avery, S., 1994. Boundary-layer depth and entrainment zone characterization with a boundary-layer profiler. *Boundary Layer Meteorology*, 68, 375-385.

Bianco, L., and Wilczak, M., 2002. Convective boundary layer depth: Improved measurement by doppler radar wind profiler using fuzzy logic methods. *Journal of Atmospheric and Oceanic Technology*, 19, 1745-1758.

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

Cimorelli, A. J., Perry, S. G., Venkatram, A., Weil ,J.C., Paine, R. J., Wilson, R. B., Lee, R. F., and Peters, W.D., 1998. AERMOD: Description of Model. EPA-454/R-03-004, September 2004.

Deardorff, J.W., 1980. Progress in Understanding Entrainment at the Top of a Mixed Layer, in Workshop on the Planetary Boundary Layer, J.C. Wyngaard, Ed., American Meteorological Society, Boston, MA.

Environmental Protection Agency, U.S.A., 1998a. Revised draft: User's guide for the AERMOD meteorological preprocessor (AERMET). Environmental Protection Agency, Research Triangle Park, NC.

Environmental Protection Agency, U.S.A., 1998b. Draft: Model evaluation results for AERMOD. Environmental Protection Agency, Research Triangle Park, NC.

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

Kasten, F., and Czeplak, G., 1980. Solar and terrestrial radiation dependent on the amount and type of cloud. *Solar Energy*, 24, 177-189.

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.

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

Wyngaard, J. C. and LeMone, M. A., 1980. Behavior of the refractive index structure parameter in the entraining convective boundary layer, *J. Atmos. Sci*., 37, 1573-1585.

Figure Captions

Figure 1. Location of ANL and OU profilers, Will Rogers Airport, ARL rawinsonde, and Norman, Oklahoma rawinsonde data sites during the Joint URBAN Experiment in Oklahoma City are shown.

Figure 2. (a) Potential temperature (K) profile from Oklahoma City, Oklahoma on 18 July 2003 at 12:00 LT. Height of the mixed layer derived from the profile is around 1960 m. (b) A signal to noise ratio profile (dB) measured by the ANL profiler on 18 July 2003 at 12:00 LT.

Figure 3. Comparison of AERMET estimated mixing heights and observed mixing heights derived from data measured by the ANL profiler and ARL soundings at 12:00 LT during July of 2003.

Figure 4. (a) Comparison of AERMET estimated mixing heights and observed mixing heights derived from data collected by the ANL and OU profilers on 7 July 2003. (b) Same as (a) but on 8 July 2003. (c) Same as (a) but on 9 July 2003.

Figure 5. (a) 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. (b) Same as (a) but on 27 July 2003.

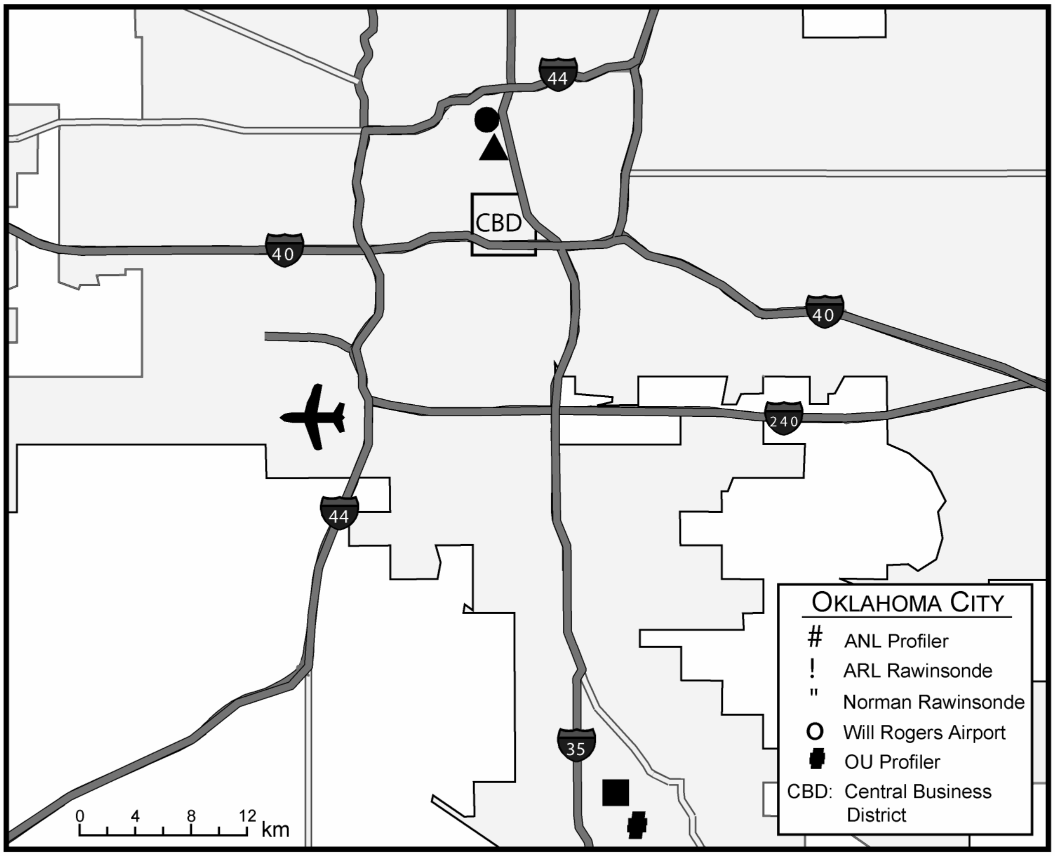

Figure 1. Location of ANL and OU profilers, Will Rogers Airport, ARL rawinsonde, and Norman, Oklahoma rawinsonde data sites during the Joint URBAN (2003) Experiment in Oklahoma City are shown. The central business district is also shown.

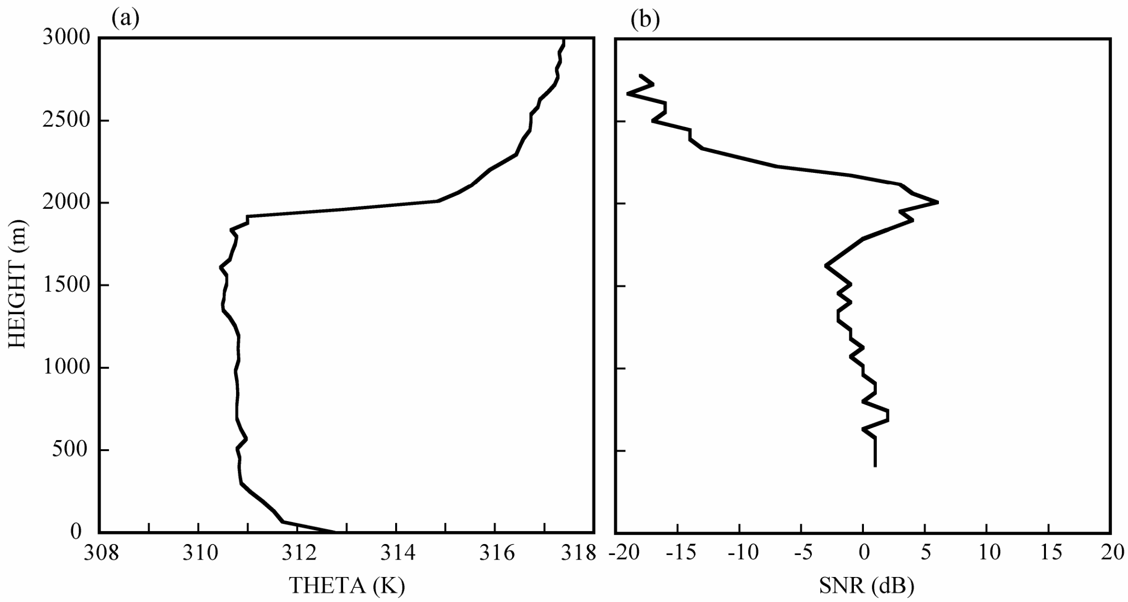

Figure 2. (a) Potential temperature (K) profile from Oklahoma City, Oklahoma on 18 July 2003 at 12:00 LT. Height of the mixed layer derived from the profile was around 1960 m. (b) A signal to noise ratio profile (dB) measured by the ANL profiler on 18 July 2003 at 12:00 LT. Mixed layer height derived from the SNR was around 2050 m.

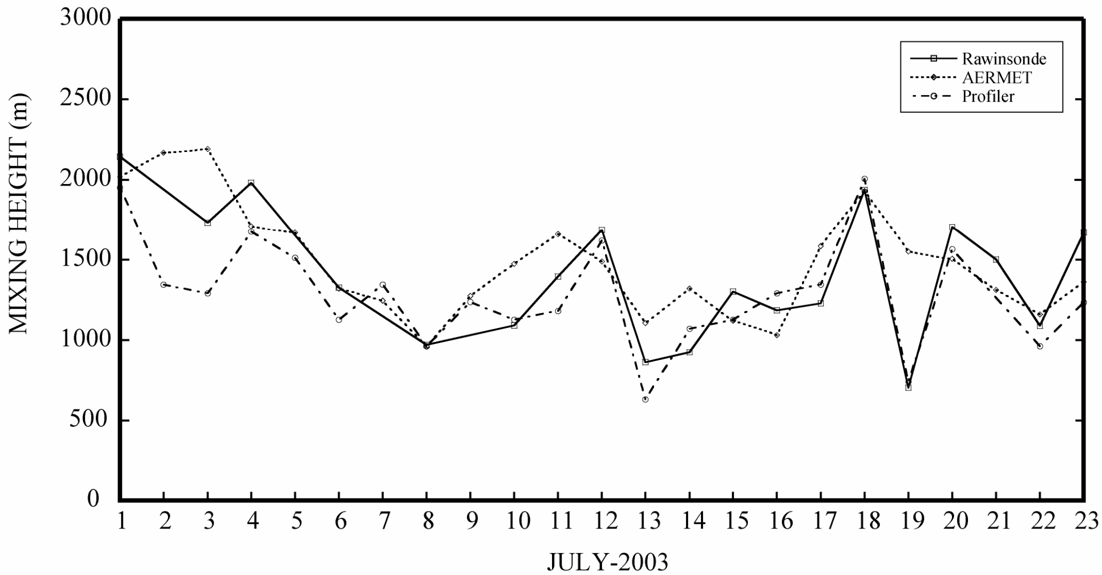

Figure 3. Comparison of AERMET estimated mixing heights and observed mixing heights derived from signal to noise ratio data measured by the ANL profiler. Mixing heights derived from potential temperature soundings at 12:00 LT during July of 2003 are also shown.

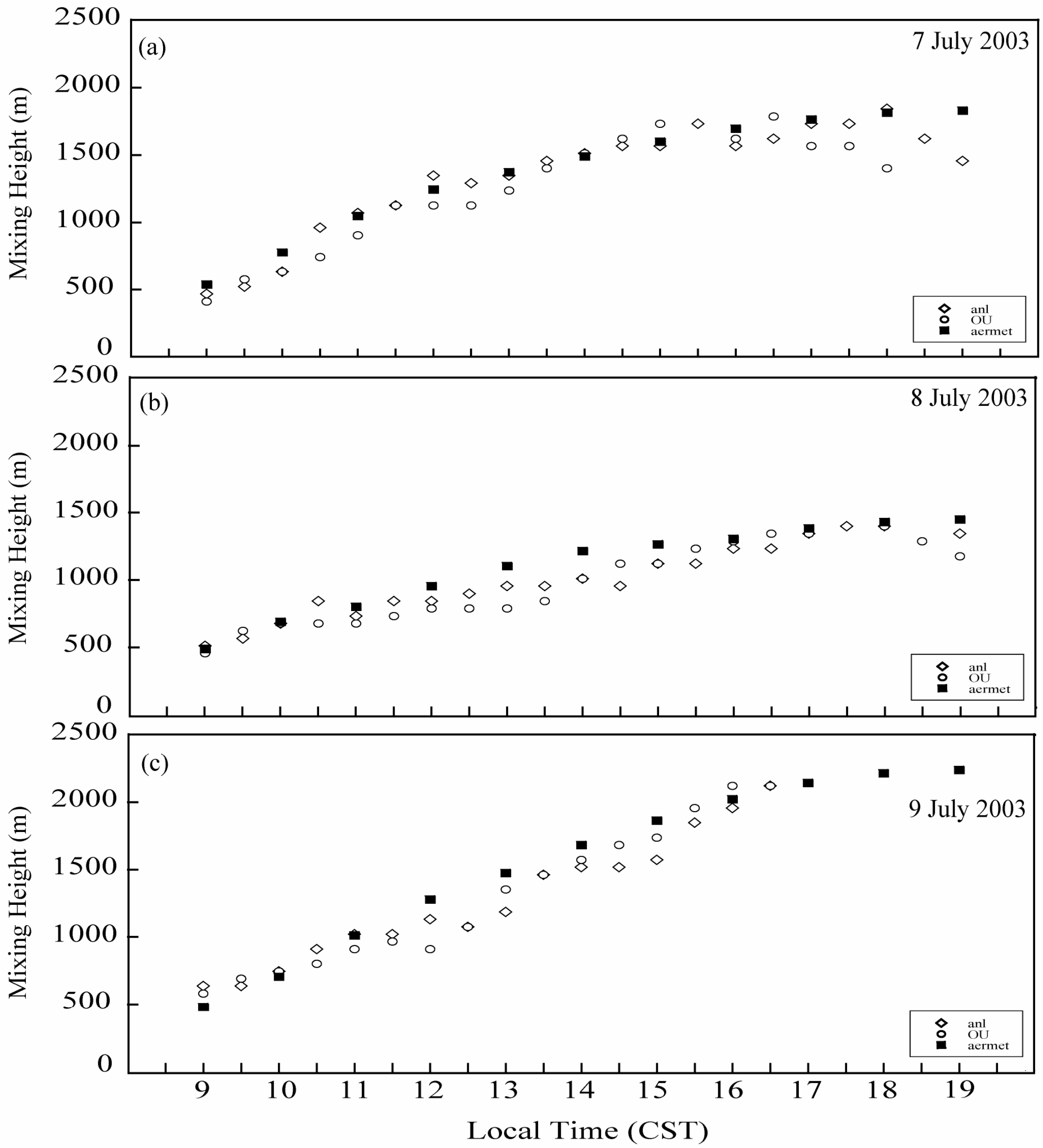

Figure 4. (a) Comparison of AERMET estimated mixing heights and observed mixing heights derived from signal to noise ratio data measured by the ANL and OU profilers on 7 July 2003. (b) Same as (a) but on 8 July 2003. (c) Same as (a) but on 9 July 2003.

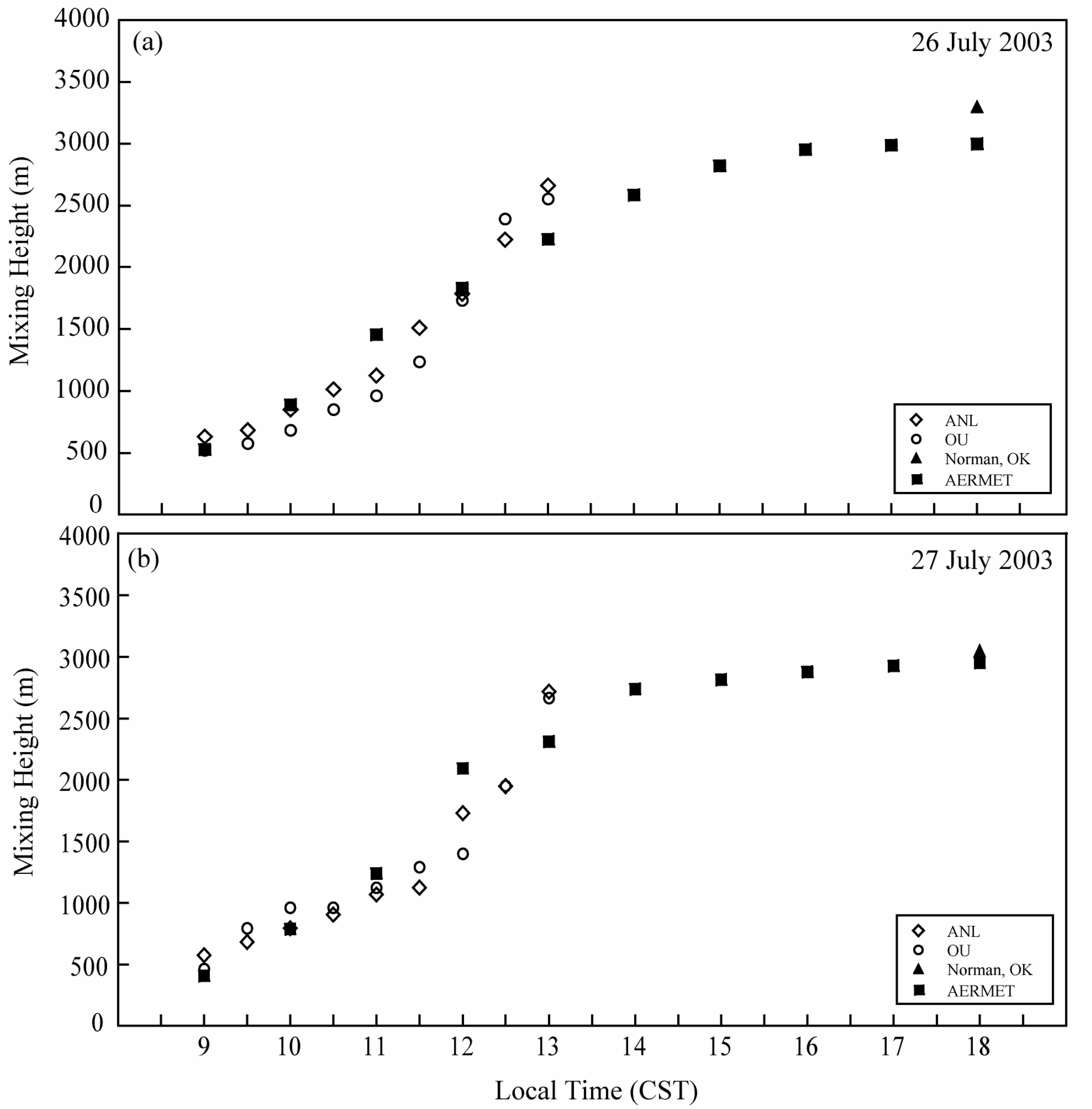

Figure 5.(a) Comparison of AERMET estimated mixing heights and observed mixing heights derived from profiler data collected by ANL and OU profilers and soundings from Norman, OK on 26 July 2003 during highly convective conditions. (b) Same as (a) but on 27 July 2003.