A Procedure for the Automatic Estimation of Mixed Layer Height

R. L. Coulter and D. J. Holdridge
Argonne National Laboratory
Argonne, Illinois

Introduction

The daytime mixed layer results from mechanical and thermal turbulence processes driven by differences in air-surface temperature and moisture. As such, the height of the mixed layer (z_i) is a measure of the effectiveness of energy transfer from the sun to the earth's surface and, in turn, to the lower atmosphere (Stull 1989). Maximum daytime values for z_i in the region of the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) vary from less than 100 m in cloudy, moist, calm, stable conditions to nearly 3 km in clear, dry, unstable conditions. The principal characteristic of the mixed layer is that scalar quantities such as moisture and temperature are mixed throughout. Thus, z_i becomes one of the principal scaling parameters used to describe the structure of the lower planetary boundary layer.

Normally, a stable layer (a potential temperature inversion) at the top of the mixed layer interfaces between processes in the lower atmosphere and in the free atmosphere above. The strength of this inversion limits the rate of growth of z_i with time and the vertical transfer of energy and moisture. When and if z_i reaches the condensation level, clouds can form; hence, cloud base height (particularly for fair weather cumulus clouds) often coincides with z_i later in the day.

Although the concept of the mixed layer height is straight-forward, its measurement can be relatively difficult, or at least awkward. The most reliable method is an analysis of potential temperature and mixing ratio profiles retrieved from balloon ascents. (The potential temperature changes from constant to increasing with height; the mixing ratio changes from constant to decreasing with height.) Often, however, the profiles of temperature and moisture are ambiguous, with multiple inversions or none at all. In addition, these profiles supply only a snapshot of the atmospheric structure that may well be unrepresentative of the average, either in time or space. In some instances, the term "well mixed" should not be applied to the lower atmosphere at all; during and after precipitation, for instance, the changes in surface and lower atmospheric conditions cause large ambiguities. This paper describes an automatic estimation method using radar profiler data and discusses a 1-year climatology of z_i over the SGP CART site.

Automatic Measurement

The 915-MHz radar wind profiler (RWP) can be used to measure z_i. The principal source of scattered signal to the RWP is moisture, which is the primary constituent of fluctuations in the index of refraction in this region of the electromagnetic spectrum. Because the top of the mixed layer is characterized by increased turbulence (due to the strong gradients between moisture and temperature above and below), the signal strength often reaches a relative maximum at or near z_i (Figure 1). A major advantage of

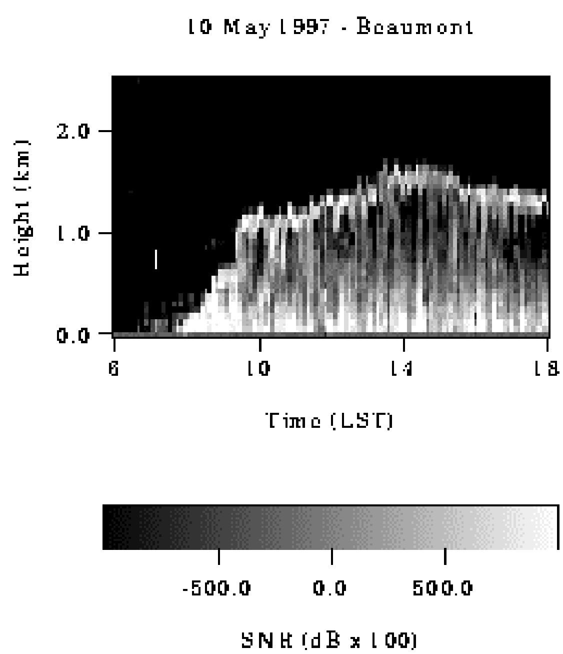

Figure 1. Time-height section of RWP backscatter signal on a clear, well defined day. Increasing signal strength is brighter in tone. The mixed layer is clearly evident.

using RWP data for mixed height measurement is that the data are essentially continuous (see Figure 1), thus avoiding the sampling problems of radiosondes. Another potential advantage, which has been little used, is that the mean subsidence in the atmosphere can sometimes be estimated by measuring the time rate of change of z_i (when it is negative).

We have been investigating the automatic detection of z_i by using RWP data, including signal-to-noise ratio (SNR), wind speed, wind direction, and virtual temperature. The approaches using wind speed and direction rely on the fact that speed and direction should be relatively constant within the mixed layer above the surface layer; the virtual temperature profile should exhibit an increase at the top of the mixed layer (ignoring effects of moisture changes). However, efforts to detect z_i by using wind speed and direction data have been only marginally successful, and the height resolution and height attainment of the temperature profile have often been inadequate for consistent results. Thus, the emphasis has been on the following two approaches using the SNR to estimate z_i.

1. From each hourly profile (although shorter time intervals can be observed by using data for individual spectral moments), determine the relative maxima of SNR values in the profile (after correction for geometric divergence in the signal strength). Use either the first or second local maximum or the overall maximum value, depending on conditions (see below).

2. Maximize the difference between the average SNR below a height (from the first range gate to present range gate) and average SNR above (from the present range gate to the final range gate). The rationale for this approach is that in unambiguous conditions, the signal source (moisture) should be mostly contained within the mixed layer; thus, the difference between average SNR values below and above is maximized near z_i.

In practice, each of these methods has problems. Principal among these is the existence of ground clutter in the lowest few range gates. These strong values can create false maxima in the SNR profile that can be interpreted as indications of z_i. Thus, in general, estimates using the first procedure, ignore relative maxima very near the surface and take the maximum value above the first few range gates. This method of course biases estimates early in the day or on days with small z_i. Clouds present an additional difficulty for both approaches. Fair weather cumulus clouds can provide an intermittent strong signal source that continues above the true z_i. This signal, when averaged over an hour, provides an average representative of nothing.

The following four methods presently being used employ all or part of approaches 1 and 2 above.

1. The height of the second maximum in SNR (or the first if no second exists).

2. The height of the maximum value of SNR.

3. The height at which the difference between average SNR below and average SNR above is at a maximum.

4. The height of the second SNR maximum below that found with method 3, if it exists. If not, use the first SNR maximum below found with method 3. Thus, if there are relative maxima in SNR at range gates 3, 6, 9, and 11, and method 3 produces range gate 13, range gate 9 is chosen.

In practice, methods 2 and 4 give the most consistent results and often agree.

During May 1997, a field experiment with the Cooperative Atmosphere Surface Exchange Study (CASES) program at the Argonne Boundary Layer Experiment (ABLE) facility, which includes the Beaumont intermediate facility of the SGP CART site, measured temperature and moisture profiles with balloons collocated with the Beaumont profiler and two ABLE profilers. Figure 2 illustrates some of the above comments. Results for methods 2 (maximum SNR)

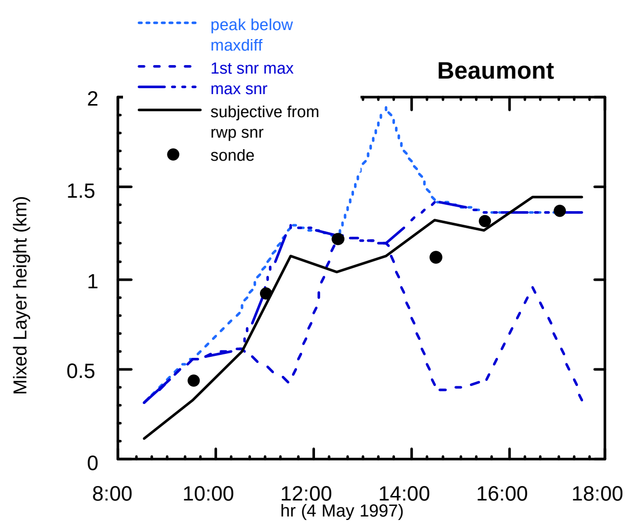

Figure 2. Variation of mixed layer on 4 May 1997 as determined by various methods described in text. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/coulter-98.pdf*.)

and 4 (peak below maximum difference) agree well with one another and with sonde-derived values except at 1330 hr (when there may have been cloud). The first relative maximum in SNR is quite variable and is usually too low because it is influenced by ground clutter. The solid line is a subjective determination from the vertical time section of SNR.

A comparison of methods 2 and 4 with estimates from the sonde temperature profile for 4 days during May 1997 (Figure 3) shows good correlation among the methods. The outliers in the comparison correspond to ground clutter or cloud interference. A one-to-one correspondence is not expected. These results are consistent with the observation that the mixed layer height from radar is usually larger than the height of the temperature inversion (Coulter 1979).

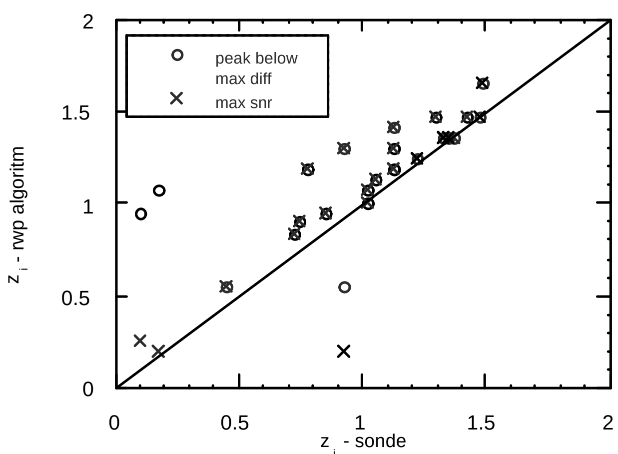

Figure 3. Comparison of methods 2 and 4 with estimates from sonde profiles from May 4, 10, 16, and 20, 1997, at the Beaumont site.

SGP CART Climatology

During the last quarter of 1996, RWPs were installed at the intermediate facilities located at Beaumont, Kansas (BE), Medicine Lodge, Kansas (ML), and Meeker, Oklahoma (MK), locations approximately equidistant from the Central Facility (CF) to the northeast, northwest, and southeast, respectively. Unfortunately, the RWP at Meeker has not been operational for much of the intervening time; however, the remaining two RWPs, plus the CF instrument have been operating for more than a year. The variability of z_i across the site will be representative of the energy fluxes over larger scales than those available directly from the extended facilities.

Daily estimates of mixed layer height in the middle afternoon (1400 hr to 1600 hr) were made from the three operating ARM CART 915-MHz RWPs and from an additional, smaller system operated by ABLE, located approximately 40 km west-northwest of the BE site. Afternoon estimates were chosen because z_i typically changes little at this time of day, and the value is representative of the integrated energy input from the daytime hours. Figure 4 shows the annual variation (by month) of z_i from each of the extended facility sites. The large difference in z_i (almost a factor of three) between winter and summer is well defined at all sites. However, the

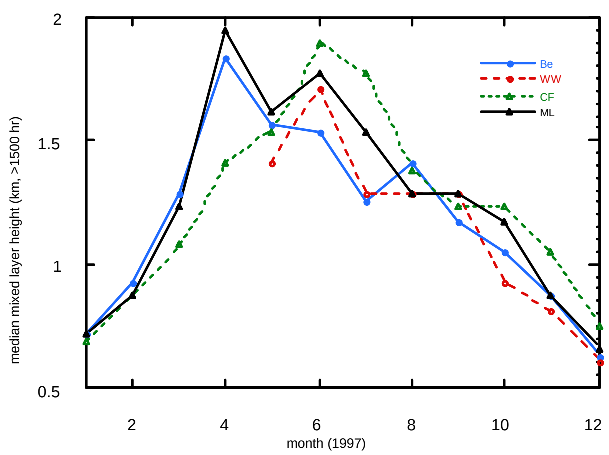

Figure 4. Median of monthly afternoon values of z_i for 1997 for each of the extended facilities plus the Whitewater (WW) site in the ABLE facility. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/coulter-98.pdf*.)

maximum occurs 2 months later at the CF than at the BE or ML sites. (The CF is in a winter-wheat growing area where soil is bare in June after harvest, while the grasslands of the BE and ML sites are still green.) In contrast, the annual variation of heat flux across the site (Figure 5) is not nearly so well defined; the spatial and temporal variability is comparable, but most sites observe a maximum in sensible heat flux during early to middle spring. This is probably due to frequent episodes of cold air advection over rapidly warming land surfaces during spring. The resultant large temperature differences and unstable atmosphere plus reduced vegetation and transpiration during early spring, support this hypothesis. A second peak in October occurs for much the same reason. The maximum in z_i at the BE and ML sites in April follows this pattern; however, there is no evidence of a second maximum in autumn. Several more years of data will be necessary before good statistics can be determined, particularly for the mixed layer heights.

Differences in z_i between sites averaged monthly for 1997 (Figure 6) indicate that ML generally has the largest mixed layers. This is not surprising, because ML is located in the western part of the site, where vegetation is sparse and latent heat is a smaller part of the available energy. Differences between BE and WW are smallest, principally because they are only 40 km in distance. The CF apparently lags the other sites by about 1 month, at least for this data set, for a reason that is not yet apparent. Widespread burning of fields in the BE region during April significantly changes the albedo of the surface near the BE site before new growth appears. This change should lead to an increase in available energy (net radiation) for rapid development of the mixed layer in the ABLE region.

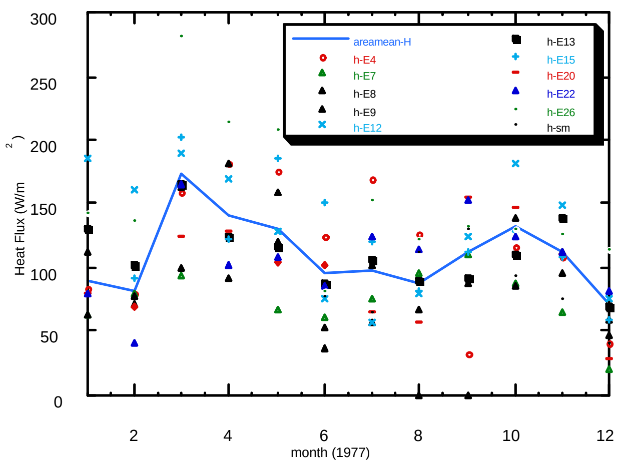

Figure 5. Monthly median heat flux for 1997 for energy balance Bowen ratio systems in the CART site. The SM site is an eddy correlation measurement in the ABLE facility. The solid line is the average of all the sites, which is coincidentally very similar to the values at the CF (E13). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/coulter-98.pdf*.)

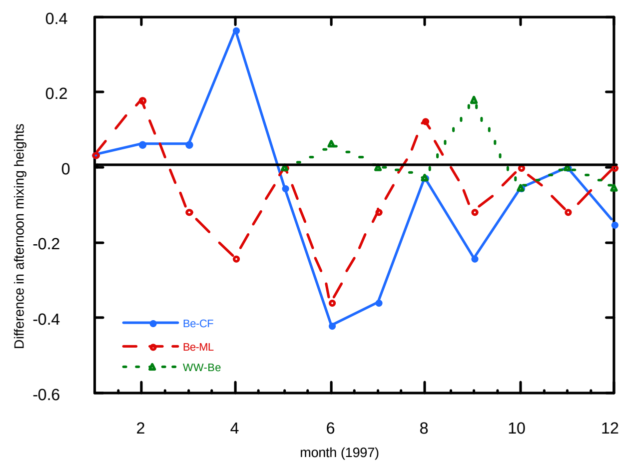

Figure 6. Median monthly differences in z_i between the BE site and the CF, ML, and WW sites. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/coulter-98.pdf*.)

Acknowledgment

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