NOTES AND CORRESPONDENCE

Some Observations of Vertical Velocity Skewness in the Convective Planetary Boundary Layer

MARGARET A. LEMONE

National Center for Atmospheric Research,[1] *Boulder, Colorado 80307*

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ABSTRACT

Previously published profiles of vertical velocity (w) skewness observed in the convective atmospheric boundary layer show deficits in the upper part of the layer, relative to large eddy simulations designed to apply to highly convective cloudless planetary boundary layers. Thus, we examine w-skewness profiles from data collected in other experiments. We find that skewness profiles in the three highly convective cases with the fewest and smallest clouds agree better with the large eddy simulation results than other profiles presented here and previously; however the deficit at the top of the boundary layer—though smaller—remains.

We hypothesize that the remaining deficit for these three cases results from the presence of ~10-km wavelength quasi two-dimensional sinusoidal structures, which have near-zero skewness. The small domain and periodic boundary conditions of a large eddy simulation may not allow such structures to develop fully. Removal of the effects of these structures by counting only flight legs nearly parallel to their axes, for two of the cases, improves agreement between the simulation and observations. We speculate that these structures result from gravity waves interacting with the boundary layer.

1. Introduction

This note is stimulated by its companion paper, "Vertical-Velocity Skewness in the buoyancy-driven boundary layer," by Moeng and Rotunno (1989). In their paper, Moeng and Rotunno note that, while large eddy simulations (LES) manage to replicate the vertical velocity skewness, $\overline{w^3}/(\overline{w^2})^{3/2}$ in the lower part of the boundary layer, the agreement between LES and observations in the upper boundary layer is poor. After running several sets of direct simulations, they conclude that the discrepancy does not result from model deficiencies. Instead, they second Mason's (1989) hypothesis that the observed skewnesses at the top of the mixed layer are lower than the simulated ones due to the presence of "larger scale features and inhomogeneities in nature." If these features contribute to $\overline{w^2}$ but have small or zero $\overline{w_f^3}$, where the subscript f refers to feature scale, and if these features are not produced in the LES, their presence in nature would reduce the observed skewness to below that predicted by the LES. This note is an endorsement of that hypothesis.

We present in this note several observed profiles of vertical velocity skewness, and then focus on the three that best agree with the model results. Like the data in the Moeng–Rotunno paper, all show fairly good agreement with the simulation in the lower boundary layer, but only three show good agreement in the upper part of the layer. The better agreement of these three profiles with LES data appears to result at least partially from the closeness of the simulated conditions to those under which the observations were taken.

The skewness deficit in the upper part of the boundary layer is reduced further if we remove the apparent effects of the mesoscale features present. These features are evident on all three of these days. On two of the three days, they are well-defined, sinusoidal (near-zero skewness) and nearly two-dimensional. Fortuitously, the structures are also aligned nearly parallel and perpendicular to the flight legs, enabling partial removal of the structures' effects by including only data from flight legs nearly parallel to the structure axis. We speculate that these structures, shown by LeMone and Meitin (1984) to be common in the GATE boundary layer, result from the interaction of tropospheric gravity waves with the boundary layer, as discussed by Clark et al. (1986).

2. The data

The data presented here are from the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment, GATE (Nicholls and LeMone 1980), which was conducted over the tropical east Atlantic in 1974, and from an experiment conducted over the

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Corresponding author address: Dr. Margaret A. LeMone, NCAR, MMM, P.O. Box 3000, Boulder, Colorado 80307-3000.

ocean to the north of Puerto Rico in 1972 (Pennell and LeMone 1974). In both cases, the data are collected using gust-probe aircraft. In GATE, two aircraft flew coordinated L-shaped patterns with ~35-km legs parallel and perpendicular to the mean boundary-layer wind. These straight-and-level legs were flown at several levels, from 30 m above the surface to above the inversion. The presence of two aircraft enabled repeating the legs at each level from two to eight times. One aircraft flew a similar pattern in the Puerto Rico experiment when the cumulus clouds disrupted the roll-vortex circulations that were common in that strong-wind regime. However, when clouds were small and the rolls were evident, the legs were flown mainly crosswind, or across the roll axes. The nominal leg length for Puerto Rico was 21 km.

For comparison, the observed skewnesses cited by Moeng and Rotunno come from two rather different sources. Those from AMTEX (the Airmass Transformation Experiment, Lenschow et al. 1980) were collected over the North China Sea in L-shaped patterns similar to those of GATE, but with individual legs nominally 7–10 min (42–60 km) in length. These legs were separated into 204.8-s (~21-km) segments for processing. The Minnesota data were collected from instruments mounted on a balloon tether (Kaimal et al. 1976).

The skewnesses presented here are calculated for each straight-and-level flight leg, after linear detrending, i.e.

$$sk_w = \frac{\frac{1}{N}\sum_{i=1}^{N} w_i'^3}{\left(\frac{1}{N}\sum_{i=1}^{N} w_i'^2\right)^{3/2}}$$

where N is the number of points in the flight leg, and the primes are deviations from the linear trend. Only the data for 330 m and below on 31 August are high-pass filtered, in order to remove some data problems.

The characteristics of the boundary layer for the eight cases shown here are compared to the typical conditions

TABLE 1. Characteristics of GATE, AMTEX, Minnesota and Puerto Rico Boundary Layers.

Year	Date	z_i (m)	u_* $(\overline{uw}^2 + \overline{vw}^2)^{1/4}$ [a] (m s^{-1})	Q_{0v} $\overline{wT_v}_0$ [a] (K m s^{-1})	$\overline{T_v}$ (K)	$-L$ $\left(\frac{u_*^3 \overline{T_v}}{kgQ_{0v}}\right)$ [b] (m)	$-z_i/L$	Clouds/Weather
AMTEX (Lenschow et al. 1980)								
1975	15–26 Feb	680–1400	0.30–0.58	.05–.24	280–283	19–67	13–63	Scattered-broken Sc, some drizzle
MINNESOTA (Kaimal et al. 1976)								
1973	10–19 Sept	1020–2300	0.18–0.45	.10–.22	300	6–42	91–370	1200–1800 LST, Cu likely
PUERTO RICO [LeMone and Pennell (1976) and tabulated data]								
1972	14 Dec	600	0.40	0.020[c]	301	250	2.4	Widely-scattered "forced" Cu (Stull 1985)
	15 Dec E	610	0.45	0.020	301	350	1.7	Scattered "forced" Cu
	15 Dec W	590	0.40	0.020[c]	301	250	2.4	Scattered-broken active Cu
GATE [Nicholls and LeMone (1976) and tabulated data]								
1974	6 Aug–*Oceanographer*[d]	450	0.17	0.01	302	37	12	Cu, widely scattered showers
	6 Aug–*Meteor*[c]	500	0.18	0.008	302	58	9	Cu
	31 Aug	450	0.13	0.009	301	18	25	Cu, scattered showers
	7 Sept	450	0.25	0.016	302	76	6	Cu, some TCu, showers
	10 Sept	550	<.10	0.012	302	<10	>55	Scattered Cu, few active
	15 Sept	550	0.14	0.008	302	26	21	Scattered Cu, few active

[a] u, v, and w are components of the fluctuating (departure from linear trend) wind vector, T_v is the fluctuation virtual temperature, the subscript zero denotes fluxes extrapolated to the surface; overbar indicates linear average.
[b] Obukhov length, with g = acceleration of gravity. Von Karman constant $k = 0.4$.
[c] No measurement available; used 15 Dec E value.
[d] GATE ships around which patterns were flown.

in the Minnesota and AMTEX datasets in the table, based primarily on descriptions in the literature (cited in the table). The inversion height z_i in the GATE, Minnesota, and Puerto Rico cases corresponds to the top of the mixed layer in the absence of clouds, or roughly to cloud base when cumulus clouds are present. In contrast, z_i in AMTEX is close to the top of the stratocumulus. These slightly different definitions of z_i are justified on the basis of the large intermittency of cumuliform clouds and the close match of stratus and cumulus-topped boundary-layer characteristics when normalized this way.

The Minnesota, AMTEX and GATE boundary layers are mostly highly convective, with large values of $-z_i/L$, while the Puerto Rico cases are near-neutral. Cumuliform clouds were present during the GATE and Puerto Rico observations, with an occasional isolated shower at least in some GATE cases. From climatology, we expect cumulus over Minnesota as well. Scattered to broken stratocumulus clouds with patches of light drizzle (Lenshow, personal communication, 1989) formed the top of the AMTEX boundary layer.

3. Results

Figure 1, from Moeng and Rotunno (1990) shows the w-skewness profiles for the AMTEX and Minnesota data, superimposed on the skewness based on Moeng and Wyngaard's (1988) large-eddy simulation of a highly convective boundary layer with no clouds. While the agreement is fairly good in the lower levels, there is a significant difference between the observed and modeled skewness at higher levels. Inadequate model resolution prevents good agreement at $z/z_i < 0.1$ (Moeng and Rotunno (1990).

Figure 2 represents the w-skewness profiles for eight cases from GATE and Puerto Rico. The number next to each point is the total number of legs n at that level; the horizontal lines give the standard deviation σ_{n-1}. Three of the GATE cases—6 August, 10 September, and 15 September—have w skewnesses which follow the Moeng–Wyngaard curve in Fig. 1 fairly well—even close to the top of the mixed layer. All of the cases are convective (larger $-z_i/L$), with small clouds. On 6 August, showers were present. However, these showers were small and widely scattered. Furthermore, flight legs obviously affected by showers are excluded from the dataset. Thus we believe that these days are a good match to the highly convective cloudless conditions represented by the Moeng–Wyngaard (1988) numerical simulation whose profile appears in Fig. 1 of Moeng and Rotunno (1990) and Fig. 1 of this note.

One of the GATE days, 31 August, has high skewnesses near z_i, but there is large scatter. Although the table and figures show this day to have about as many showers as the 6th, there are almost certainly more. First, the data on 6 August were collected in two locations, separated by 170 km. Only one of these had

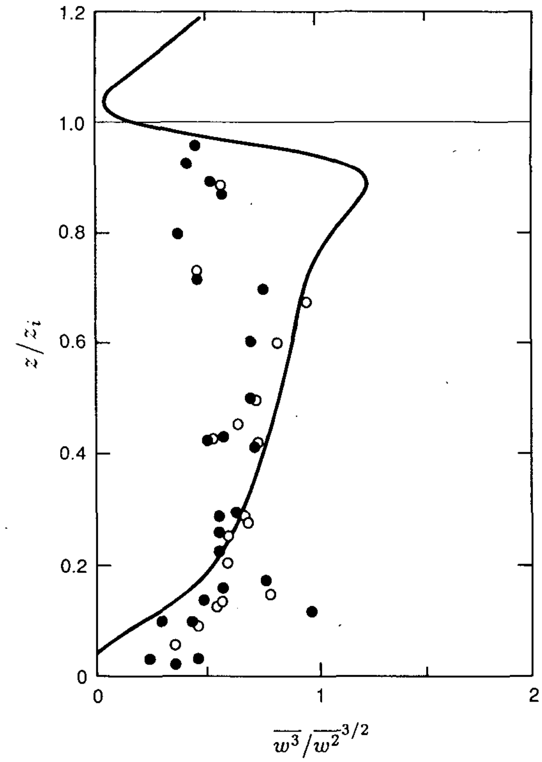

FIG. 1. Vertical distribution of the vertical-velocity skewness in the convective boundary layer. Solid curve is from large eddy simulation of clear-air boundary layer by Moeng and Wyngaard (1988), solid circles are Minnesota data (Wyngaard 1988), and open circles are AMTEX data (Lenschow et al. 1980). Figure courtesy of Moeng and Rotunno (1990).

widely scattered showers. Second, if we compare the time series of 31 August to those for the showery location on 6 August, those for the 31st show more evidence of precipitating convection. Some of these legs on the 31st might have been counted in the statistics. Finally, the thermal stratification on 31 August was slightly stable ($\Delta\theta_v$ between the surface and z_i is ~0.5 K), more like that of 7 September ($\Delta\theta_v$ ~0.5 K) than 6 August ($\Delta\theta_v$ ~0.2 K in the area with showers, zero in the area without).[2]

In contrast, the other four cases behave more like the observed data in Fig. 1, with lower skewnesses near z_i. Compared to the four cases discussed above, these four have weather conditions less like those the Moeng–Wyngaard (1988) simulation is designed to replicate: The GATE 7 September case is rainier and less convective (smaller values of $-z_i/L$), and the Puerto Rico cases are near neutral.

We combine the vertical velocity skewness profiles for the three days best matching the model conditions in Fig. 3. For comparison the Moeng–Wyngaard curve

[2] $\Delta\theta_v$ on other GATE and Puerto Rico days ~ 0.

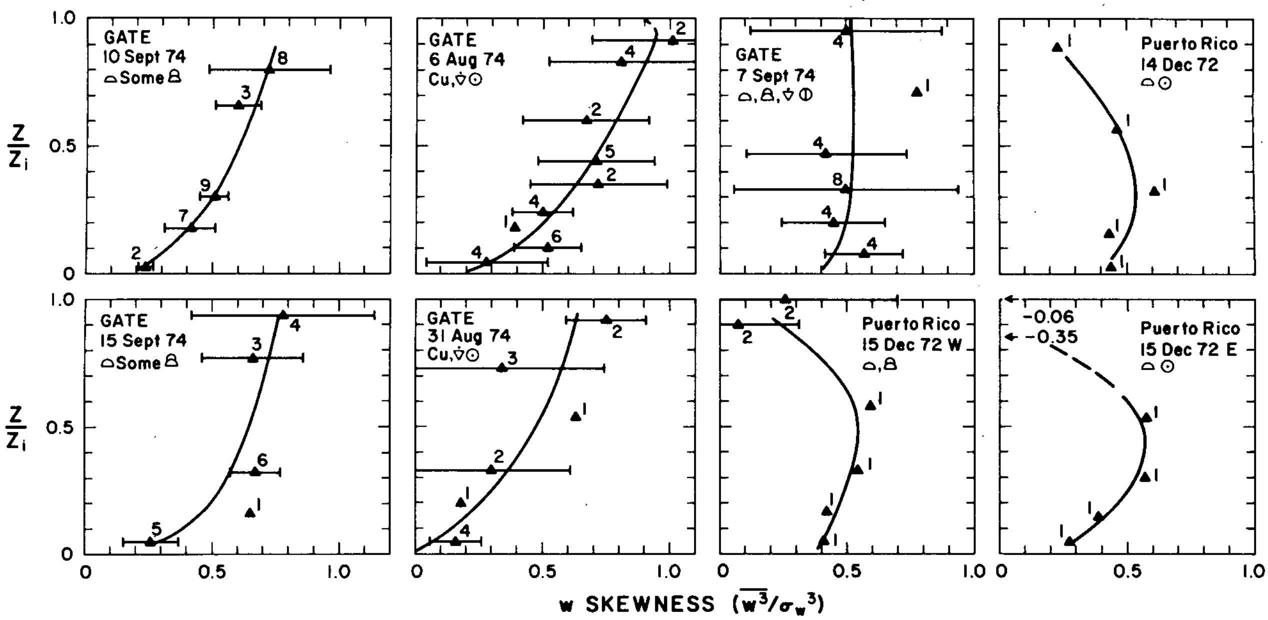

FIG. 2. Vertical distribution of the vertical-velocity skewness for eight examples of fair-weather convective boundary layer from GATE and Puerto Rico. Horizontal lines indicate standard deviations (σ_{n-1}, where n is the number of legs); the number to the right of each point is the number of legs (nominal length 35 km for GATE, 21 km for Puerto Rico); ⌓ = cumulus, Ȣ = towering cu or active cu, ⊙ = widely scattered, ⌽ = scattered, $\dot{\nabla}$ = shower.

is superimposed. Although there is better agreement between model and observations in the upper boundary layer, the observed values are still lower than the model values. There is also a discrepancy for $z/z_i < 0.1$, the result of inadequate resolution in the model (Moeng and Rotunno 1990).

4. Discussion

Although Moeng and Rotunno have increased our insight into skewness in the somewhat idealized, highly convective, clear-air boundary layer, the presence of clouds, precipitation, larger scale or sinusoidal features, stronger winds and slight differences in thermal stratification, can influence the w-skewness in ways not yet completely understood. Below, we focus on sinusoidal structures and show how these might lower the skewness of the three GATE profiles of Fig. 3, and present evidence that they might result from the interaction of tropospheric gravity waves with the boundary layer as hypothesized by Clark et al. (1986).

Mason (1989) hypothesizes that skewness in the boundary layer can be lowered below that replicated in simulations by the presence of mesoscale features. This is certainly true if (a) these features are sinusoidal, and hence contribute to total vertical-velocity variance but have near-zero skewness; and (b) if these features cannot be replicated by the simulation in question. The simulation producing the Moeng–Wyngaard curve in Fig. 1 was over a 5-km × 5-km domain, with periodic horizontal boundary conditions. The thermal boundary layer occupied the lower 1-km of a 2-km vertical domain, which was topped by a rigid lid. The 5-km domain implies that no structure with a longer wavelength can be replicated; the periodic boundary conditions will distort any structures near the boundaries.

According to LeMone and Meitin (1984), such structures are common in the GATE fair weather boundary layer. Figure 4 shows an example on 10 September 1974, one of the days in the Fig. 3 composite, and one of the days documented in LeMone and Meitin. Note the roughly 10-km wavelength and the NW–

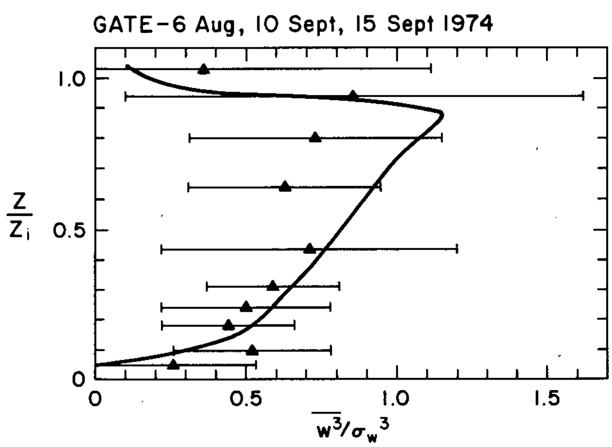

FIG. 3. Vertical distribution of the vertical-velocity skewness averaged from the 6 August, 10 September, and 15 September cases. The heavy solid line is the simulated skewness from Fig. 1. Horizontal lines give the 90% confidence limit, based on the Student's t-test.

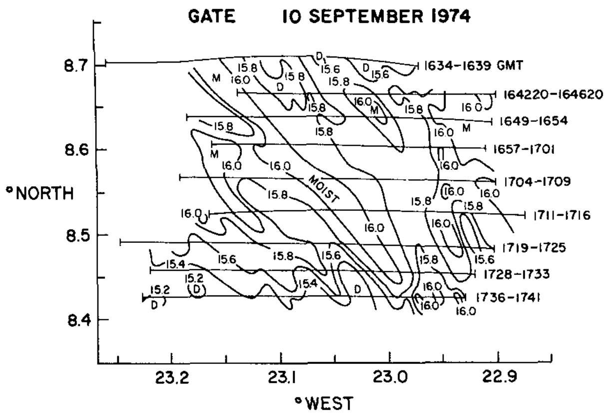

FIG. 4. Plan view of the specific humidity (g kg^{-1}) at 150 m, on 10 September 1974, based on data collected after the L-pattern profile flights were completed; 1° longitude ~ 1° latitude ≈ 11 km.

SE orientation. Ten-second block averages were used in preparing the map. The leg positions have not been corrected for advection. Correcting the aircraft positions for advection by the subcloud-layer wind rotates the pattern so that its axes are aligned NNW–SSE, as it appears in LeMone and Meitin's Fig. 4. If one corrects the aircraft positions for advection by the wind just above the subcloud layer, the axes retain their NW–SE orientation.

Most of the aircraft legs flown on this day were fortuitously aligned either nearly along or normal to the axes of these structures. This suggests that the skewness will be a function of aircraft heading, being lower for the legs flown across the pattern. Thus counting the legs flown parallel to the structure axis should minimize the contribution of the structures to the average w skewness and lead to larger average values.

Consider the following argument. Assume the structures are exactly sinusoidal with amplitude unity, that the cross-structure legs cross $2\pi(n + f_1)$ cycles, and that the along-structure legs cross $2\pi(m + f_2)$ cycles, where m and n are integers, $n > m$, and $0 \leq f_1, f_2 \leq 1$. We find that the skewness of the structures sensed by the cross-structure legs is:

$$sk = \frac{\frac{1}{3}\cos^3(2\pi f_1) - \cos(2\pi f_1) + \frac{2}{3}}{[\pi(n + f_1) - \frac{1}{4}\sin(4\pi f_1)]^{3/2}}.$$

That is, the larger the number of wavelengths traversed, the smaller the skewness. We note that the numerator divided by $2\pi(n + f_1)$ is the average cube of the vertical velocity, which decreases to zero (although not monotonically) with the number of cycles crossed. The denominator raised to the two-third (⅔) power and then divided by $2\pi(n + f_1)$ is the average vertical velocity variance, which approaches 0.5 as the number of cycles traversed becomes large.

For simplicity, we select $f_1 = f_2 = ½$, for which skewness should be largest, to compare the skewness along the two headings, obtaining for the legs flown nearly normal to the structures:

$$sk_\perp = \frac{\frac{4}{3}}{\left[\pi\left(n + \frac{1}{2}\right)\right]^{3/2}},$$

so that the ratio of skewness for the legs nearly perpendicular to the structures to those nearly parallel is:

$$\frac{sk_\perp}{sk_\parallel} = \left(\frac{m + \frac{1}{2}}{n + \frac{1}{2}}\right)^{3/2}.$$

That is, the skewness of the "perpendicular" legs should be smaller. The relative size of the along- and cross-pattern skewness, plotted for 10 September in Fig. 5a, is in agreement with expectations.

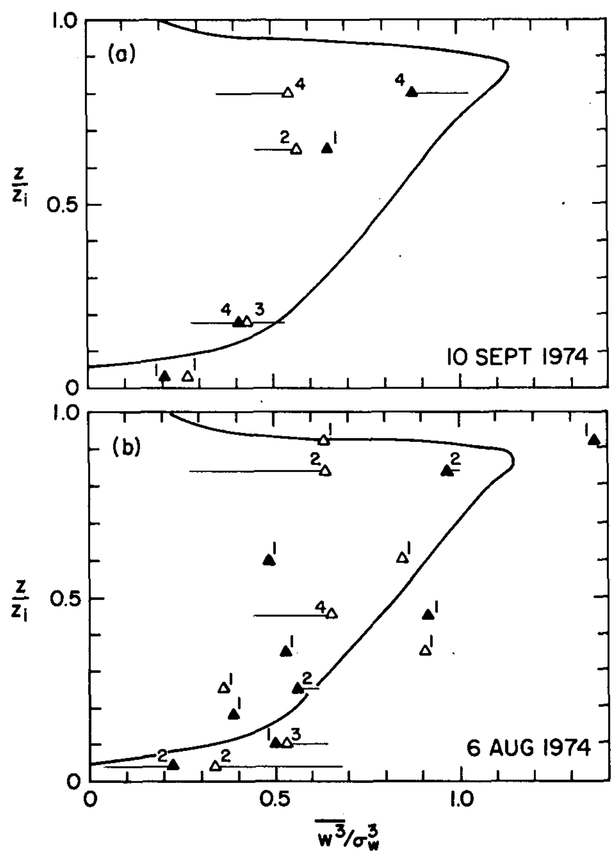

FIG. 5. Apparent effects of the presence of mesoscale two-dimensional structure on the w-skewness profile, isolated by stratifying data according to whether flight legs are flown more parallel (solid symbols) or perpendicular (outlined symbols) to the structure axes, for (a) 10 September, whose mesoscale structure appears in Fig. 4, and (b) 6 August. Horizontal lines are standard deviations (σ_{n-1}) where n is the number of flight legs. Only the outer error bars are drawn to avoid overlap.

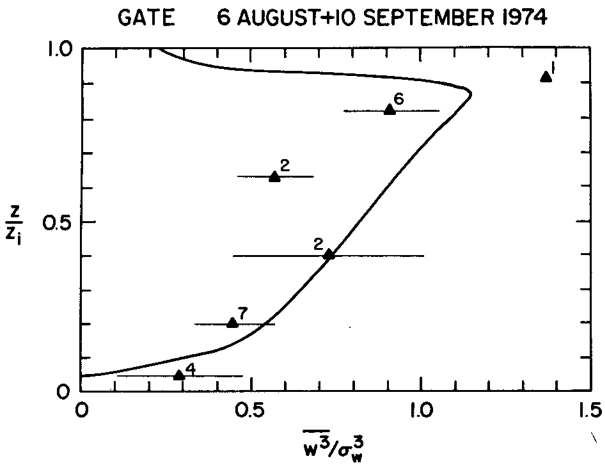

FIG. 6. The combined w-skewness profile for 6 August and 10 September. The effect of mesoscale structures is lessened by counting only flight legs nearly parallel to their axes. The Moeng–Wyngaard LES w-skewness profile is superimposed for comparison. Horizontal lines are standard deviations (σ_{n-1}).

Examination of the time series for the other two days included in Fig. 3 reveals fluctuations on both days on scales greater than 10 km, suggesting the presence of mesoscale features. On 6 August, the structures are well defined at both locations. They have a wavelength of 10–15 km and appear to be oriented roughly east–west, roughly along and normal to the flight tracks. This allows us to separate out the legs with the skewnesses less affected by the structures, as we did for 10 September. The results of this separation appear in Fig. 5b. Note as before that the skewnesses at the two high levels are higher for the legs flown more along the structure axis, with scatter below. Unfortunately, the lack of structure definition prevented a similar exercise for 15 September.

Figure 6 compares the combined along-structure skewness profiles for 6 August and 10 September to the Moeng–Wyngaard curve of Fig. 1. Note the improved agreement at higher levels relative to Fig. 3. The worse agreement at $0.63z_i$ is undoubtedly related to the small sample (only two legs). Indeed, the 10% confidence limits for all the points are so large that standard deviations are used instead. It is fortunate that the sample is relatively good (7 legs) at 0.8–$1.0z_i$, the levels upon which we are focusing. Presumably complete removal of the effect of these structures and a greater sample would improve agreement further.

We speculate that these structures are related to tropospheric gravity waves, as characterized by Clark et al. (1986).[3] This hypothesis is supported by the fact that Balaji (personal communication, 1988) was able to reproduce the quasi-two-dimensional structure on another one of the days described in LeMone and Meitin with Clark's model. Furthermore, the orientation of the 10 September structures is roughly normal to the shear across the inversion (See e.g., Nicholls et al. 1982); and, to within the certainty of our knowledge of the structure orientation, (within 30° of north), the same is true of 6 August. This is consistent with the behavior discussed in Clark et al. (1986). That the structures do not affect the skewness at lower levels can be related to two factors. First, as one approaches the surface, turbulence statistics are increasingly dominated by smaller scales, while the vertical velocity oscillations associated with the larger scale structures become relatively smaller as a simple consequence of continuity, horizontal scale, and the zero vertical velocity at the surface. Second, if these structures are damped gravity waves, they should become more damped nearer the surface. This effect should be secondary for the long waves considered here. This can be seen from the wave equation for a two-dimensional stably stratified fluid (e.g., Gossard and Hooke 1975):

$$w_{zz} + \left(\frac{N^2k^2}{(\omega - Uk)^2} + \frac{kU_{zz}}{\omega - Uk} - k^2\right)w = 0$$

where N is the Brunt–Väisälä frequency, ω is angular frequency, k is the wavenumber and the subscript z indicates differentiation with respect to height. For the GATE environment, $U_{zz} \sim 0$. As the thermal stratification approaches neutral (N approaches zero), the equation becomes

$$w_{zz} - k^2w = 0,$$

which implies smaller damping for larger wavelength (smaller k). This also explains why the humidity field in Fig. 4 remains so well defined at 150 m.

5. Conclusions

Vertical velocity skewness profiles from eight fair weather marine boundary layer cases sampled in GATE and to the north of Puerto Rico are compared to the profile from a large eddy simulation of a cloudless convective boundary layer by Moeng and Rotunno (1990). The three profiles sampled under conditions most similar to those in the simulation have the skewness profiles which are most similar to the Moeng–Wyngaard results. A deficit in skewness in the upper boundary layer remains, but it is smaller than for the other cases presented here and smaller than in the observed profiles from AMTEX and the Minnesota experiment, which were presented in Moeng and Rotunno (1990).

As predicted by Mason (1989) and Moeng and Rotunno (1990), the remaining skewness deficit on these three days may result from the presence of mesoscale (≳10-km) quasi-two-dimensional structures that have near-zero skewness. In fact, we can reduce the deficit by counting only flight legs thought to be flown nearly along their axes. These structures, thought by LeMone

[3] It is recognized that more than one gravity-wave mode could be present; we speak here of the dominant one.

and Meitin (1984) to be common in the GATE fair-weather boundary layer, may be related to gravity waves interacting with the boundary layer as described by Clark et al. (1986).

It is possible that similar sinusidal structures lowered the skewness in some of the other cases, including those from AMTEX and the Minnesota experiment. This needs further investigation.

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