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A Study of the Internal Boundary Layer due to a Roughness Change in Neutral Conditions Observed During the LINEX Field Campaigns

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With 5 Figures

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Summary

As an aspect of the LINEX field studies (1996–1997; Lindenberg near Beeskow, Germany), the characteristics of the internal boundary layer (IBL) that is associated with a step change of the surface roughnesses in neutral constant stress layers was investigated and is reported in this paper. Both smooth to rough (in 1996) and rough to smooth (in 1997) types of flow, have been studied based upon the profiles of mean wind and temperature realised from a 10-m mast and eddy correlation measurements taken at two levels (2 m and 5 m). Depending upon wind direction, the fetch at the site varied between 140 m and 315 m within the wind sector (200° to 340°) used for the field investigations. The height of the IBL, δ, had been determined from the intersect of the logarithmic wind-profiles below (<2 m) and above (>6) the interface. Values of δ obtained at the experimental site compared fairly well to the existing theoretical/empirical fetch-height relationships of the form: $\delta = a \cdot x^b$, where a, b, are empirical constants. The ratio for the friction velocities below and above the IBL as measured directly by the eddy correlation techniques showed that for fetches less than 250 m there was an increase (decrease) of about 20% of the momentum flux arising from the smooth to rough (rough to smooth) transitions. Influences of distant obstructions (e.g., bushes, pockets of trees) on the surface flow were markedly important on the examined wind profiles and such can be indicative as multiple IBLs.

1. Introduction

In the summers of 1996 and 1997, the Meteorological Observatory of the German Weather Service in Lindenberg conducted intensive field investigations for the surface energy exchanges and boundary layer processes at a measurement field ‘Gemeinsames Meßfeld’ near Falkenberg (52° 10′ 02″ N, 14° 07′ 24″ E, 73 m a. s. l.), designated as LINEX-96/2 (Foken et al., 1997a) and LINEX-97/1 (Foken, 1998), respectively. The field studies were implemented to acquire quality micrometeorological data within the overall project: Lindenberg Inhomogeneous Terrain-Fluxes between Atmosphere and Surface: a Long-term Study (LITFASS; see Müller et al., 1995; Foken et al., 1997b). The LINEX data sets will be used to validate a three-dimensional, non-hydrostatic LITFASS Local Model (LLM) and soil-vegetation-atmosphere transfer (SVAT) models over different land surfaces.

Considering the complex terrain of the Lindenberg area (comprising of forests, small lakes, meadows, farmlands, etc.), it is apparent that significant advection problems could be posed towards eddy correlation measurements at the experimental site. It is of note that internal boundary layers (IBL) are the important meteorological consequences of air movements across changes in the land surface conditions. Hence from the LINEX field studies, we have used profiles of the mean wind speed and temperature and eddy correlation measurements in the near surface layer to investigate the characteristics of IBLs that occurred by air flow across a change in the surface roughness in neutral conditions.

The set research objectives for conducting the present study were the following. The first was to determine from the mean wind speed profiles (and eddy correlation measurements) whether indeed there were any IBLs at the measurement site and to estimate the corresponding heights. A second objective was to validate well-known empirical fetch-height relationships of the IBL (see Walmsley, 1989; Foken, 1990; Raabe, 1991) using the LINEX data. A broader aspect of this study was to determine appropriate measurement/placement heights for eddy correlation devices (e.g., sonic anemometers, Lyman-alpha hygrometers, etc.) in non-uniform terrain so as to measure fluxes that are not influenced by the overlying IBL (that is, in equilibrium with the surface). Finally, the ratio of friction velocity, u_*, below and above the IBL, as determined by direct eddy correlation measurements and from a theoretical relationship were compared.

2. The Internal Boundary Layer

Internal boundary layers generally do develop as a result of the response of atmospheric flow to a discontinuity in surface conditions, be it a step change in roughness (mechanical), temperature or humidity (thermal). Theoretical and experimental studies of IBLs due to a change in the surface roughness in neutral conditions have received far more attention than any other (see Elliot, 1958; Bradley, 1968; Shir, 1972; Logan and Fichtl, 1975; Schwiesow and Lawrence, 1982; Sempreviva et al., 1990). The attractiveness in studying the neutral IBL is because it is easily amenable to analysis (Shir, 1972; Garratt, 1990). However, comparative studies for the non-neutral cases suggest that relationships similar to those for the neutral IBL are applicable but subject to slightly varying values of the empirical coefficients (Cannemeijer and Vugts, 1982). The IBL that is formed by a step change of the surface roughness in neutral conditions is investigated is in the present paper.

Within the IBL are significant changes in both the wind profile and the surface stresses from upstream conditions (Garratt, 1990). The height of IBL as defined by Rao et al. (1974) is taken as the level at which the velocity, $u = 0.99u_\infty$, where u_∞ is the free stream velocity. Similarly, it has been defined to be the level at which the stress is within one per cent the value of the upstream flow. However, it should be noted that IBL height estimated using the velocity criterion is shallower than what is obtained using the stress criterion. This is because the wind velocity adjusts itself more slowly to the new roughness than the stress (Garratt, 1992). Shir (1972) has estimated the stress-determined IBL height to be roughly twice that determined from the velocity profiles.

Radikevitch (1971) and Rao et al. (1974) separately have shown that the IBL can be partitioned into an inner equilibrium layer (IEL), which is close to the surface downstream of the change in roughness, and above it, a transition or blending region as shown in Fig. 1. It is assumed that within the IEL, the profile conditions are fully governed by the local boundary conditions downstream from the leading edge, and the wind profile within the layer is logarithmic. The IEL is

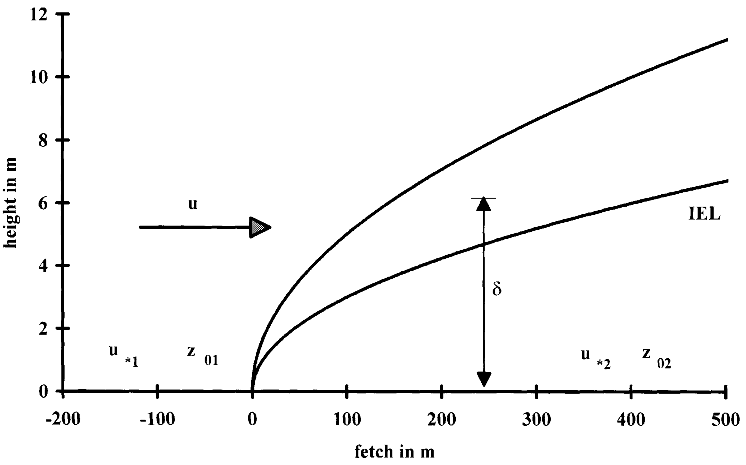

Fig. 1. Schematic representation of the IBL

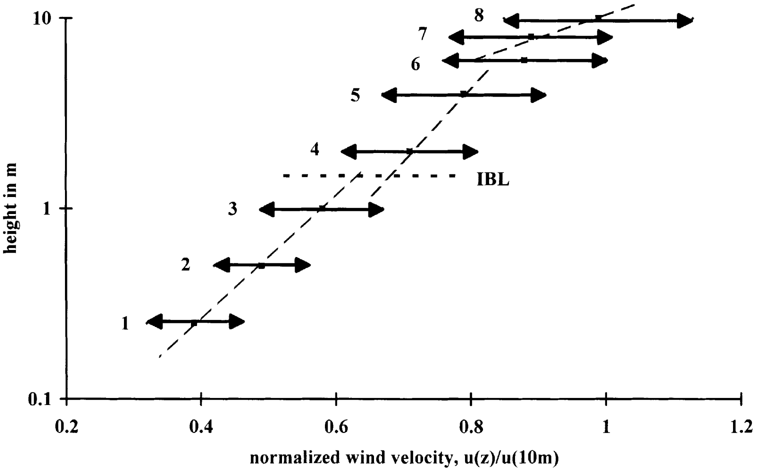

Fig. 2. Mean wind profile for the sector 250°–260° during LINEX-96/2. For interpretation of positions 7 and 8 see section 4.3

of a special importance in micrometeorology since flux measurements can correctly be made within this sub-layer without the influence of overlying IBL. Above the sub-layer there is gradual transition to the original logarithmic wind profile of the upwind conditions above. For a smooth to rough transition, the IBL height, δ, can be identified as the surface which separates the region of decelerated flow below from the region of accelerated flow above. The converse holds true in rough to smooth flows.

To a first approximation, the height of the IBL away from the step change is given by the following empirical relationship (Elliot, 1958; Raabe, 1991)

$$\delta = a \cdot x^b \tag{1}$$

where x is the downwind distance (or fetch), and a, b are empirical constants. For fetch distances ranging between 0.01 and 20 km, Raabe (1986) had obtained values for a and b (which is taken as a fixed exponent) to be 0.30±0.05 m and 0.5 respectively. Over much shorter distances (fetches from about 0.01 m to 160 m), Walmsey (1989) has adopted the values: $a = 0.75$ m and $b = 0.8$, based on validated experimental data.

From a two-level eddy correlation measurements of the momentum flux, the value of the ratio of friction velocity, u_*, can indicate whether or not an IBL exists. Radikevitch (1971) and Logan and Fichtl (1975) have shown that the magnitude of this ratio is dependent both on the relative roughness of the two surfaces and the height of the IBL. This dependence is given by the relationship:

$$\frac{u_{*_2}}{u_{*_1}} = 1 - \frac{\ln(z_{01}/z_{02})}{\ln(\delta/z_{01})}, \tag{2}$$

where z_{01} and z_{02} denote the upwind and downwind surface roughness, and, u_{*1} and u_{*2} are the friction velocities above and below the IBL respectively.

From the mean wind speed profiles, the height of the IBL can be estimated by a variety of methods. Foken (1990) contains a literature review of the popularly used techniques together with their major disadvantages. A practical method which is often used determines δ to be the level at which a discontinuity (kink) appears in the log-linear plot of height (z) against the horizontal wind speed (Bradley, 1968; Garratt, 1990). A similar technique that is used is based on the plot of the wind speed against $z^{1/2}$. In a different procedure which described by Foken (1990), obtains δ as intersect of the wind profiles derived at the lowest levels ($z \ll \delta$) and uppermost levels ($z \gg \delta$). This method is well tested (Foken, 1990) and is adapted in the present study for the LINEX data. This method is illustrated by Fig. 2, which shows the mean profile of about 100 the single measurements and the standard deviation for each level. The measuring levels 1, 2 and 3 were related to the new surface while the levels 4 and 5 were indicative of the upwind conditions from the measurement field. Connecting the 10 min. mean wind speed values at the respective heights with straight lines, the position of IBL is then observed as a kink in the profile. Due to accelerations of the wind field over the smooth surface, there are sometimes missing exact positions where the lines from both portions of the profile crossed over (see Foken, 1990). This analysis was done for each profile (not from Fig. 2) and the mean height of IBL was determined from the individual traces. For an interpretation of the measurements at levels 7 and 8, see section 4.3. It should be remarked here that there is some considerable subjectivity in the use of this method since the wind profile alone is insufficient to obtain a precise determination. To examine the results, friction velocities for the different layers of the wind profile were calculated and compared with direct flux measurements if these data were available (only at 2 m and 5 m) for the investigated layers.

3. Experimental Design

The experimental area designated for the LINEX field studies was located very near Falkenberg, which is a small township village located about 5 km south of the Lindenberg Meteorological Observatory. The topography of the whole area is fairly flat but weakly slopes westwards. In Fig. 3 is shown a sketch of the L-shaped field (measurement area, about 9 hectares) including markers identifying the positions used for the field instrumentation. A narrow unpaved road at the northern limits of the measurement site links it to a main road. The experimental area has been primarily selected to conduct the investigations of land surface energy exchanges and boundary layer processes on a long term basis.

To investigate the structure of IBLs at the site, an assortment of micrometeorological instrumentation for mean and eddy correlation measurements were deployed. These included cup anemometers and pyschrometers (platinum resistance, 100Ω) placed at several levels on a slim 10-m mast (having a triangular frame of 0.3 m) to obtain the profiles of horizontal wind speed and temperature. The booms used for the anemometers were 1.5 m long, and oriented to the south-west direction, and the boom length for the psychrometers was 0.5 m. Two eddy correlation devices (Kaijo-Denki sonic anemometers) were balanced on top of thin pipe stands (80 mm diameter) of heights 2.0 and 5.0 m which were installed about 30 m north-west from the 10-m mast. The masts were positioned mid-way along the eastern edge of the field (see Fig. 3) so that fetches for westerly winds were between 140 m and 315 m. If the land bordering to the west is of the same cover as on the measurement area, then this fetch will increase dramatically to between 0.5 and 1 km.

The list of the instrumentation used is given in Table 1. More details about the additional meteorological measurements including the synoptic conditions is found in Foken et al. (1997a) and Foken (1998). The change of some of the devices (cup anemometers and psychrometers) to the commercial types in 1997 of nearly the same characteristics is because a more

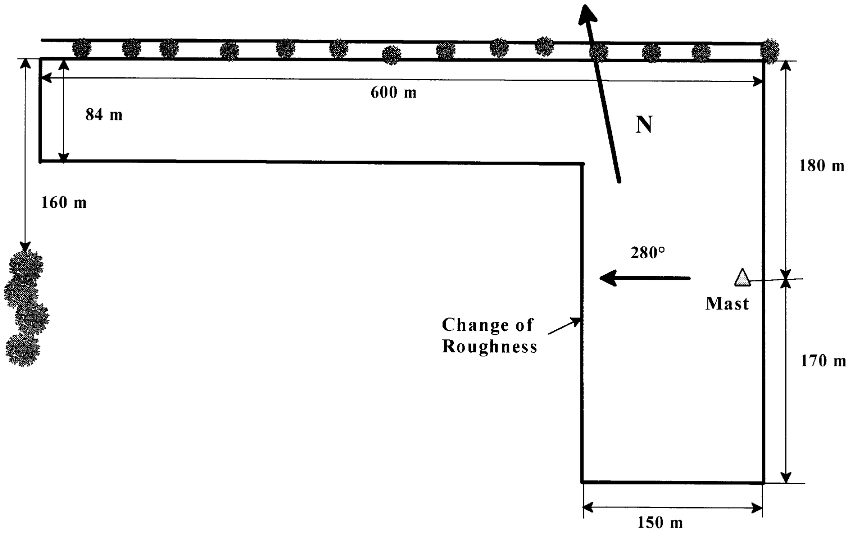

Fig. 3. Schematic diagram of the LINEX measurement area, near Falkenberg

Table 1. *Instrumentation used During Both Experiments*

Height	LINEX-96/2	LINEX-97/1
$0.25^{*)}$, $0.5^{*)}$, $1.0^{*)}$, $2.0^{*)}$, 3.0, 4.0, 6.0, 8.0, 10.0	anemometer by Brömme et al. (1991)	Climatronics anemometer model F 460
$0.25^{*)}$ (in 1996), $0.5^{*)}1.0^{*)}$, $2.0^{*)}$, 4.0 (1997), 10.0	psychrometer by Baum et al. (1994)	‘Frankenberger’ psychrometer
12.0	potentiometer type wind vane	potentiometer type wind vane
2.0, 5.0	Kaijo-Denki DAT 310/A Hanafusa et al. (1982)	Kaijo-Denki DAT 310/A Hanafusa et al. (1982)

$^{*)}$ height above zero-plane displacement

Table 2. *Types of the Underlying Surface and Canopy Heights during the SOPs of Both Experiments*

Surface	LINEX-96/2	LINEX-97/1
Measurement area	grass $z = 0.5$–0.7 m $z_0 = 0.032 \pm 0.009$ m	grass $z = 0.2$–0.4 m $z_0 = 0.014 \pm 0.004$ m
Upwind site	bare soil $z = 0.0$ m $z_0 = 0.008 \pm 0.006$ m	tall wheat (*Tritikale*) $z = 0.9$–1.1 m $z_0 = 0.053 \pm 0.043$ m

permanent tower later installed at the side instead of the mobile research type used in 1996. The field data were collected by two separate systems: slow and fast, for the profile (mean) and turbulence measurements respectively. The profile measurements were sampled at a rate of 1 Hz and then later stored as 10-minute averages. The sonic measurements (for turbulence parameters) were sampled and stored with 20 Hz. Orientation of the two sonics into the mean wind direction were controlled automatically by rotors attached to the base of masts. The turbulent fluxes were averaged over a period of 30 minutes. From selected neutral wind profiles ($-0.0625 < z/L < 0.125$; where L is the Obukhov length), roughness lengths for both surfaces (upwind and downwind of the change of roughness) have been determined. The results are presented in Table 2 both for the LINEX-96/2 and LINEX-97/1 data.

3.1 LINEX-96/2 Campaign

The measurement phase for LINEX-96/2 field study took place between 30th May and 24th June, 1996, of which the period: 10th to 24th June was designated as a special observation period, SOP (see Foken et al., 1997a). During the SOP both the profile and flux measurements were operated together. The grass height by May 30th was about 15 cm and this grew to about 62 cm by 24th of June, the end of the SOP. Within the measurement area the grass height was generally not uniform and hence, such a surface was regarded as inhomogeneous, or type A, according to classification given by De Bruin et al. (1991). The westward flank to the measurement field was of bare soil, and for the westerly flow, it was indicative of a step change in surface roughness of the type from smooth to rough.

For the SOP period of LINEX-96/2, Fig. 4a shows the joint-frequency distribution for the layer averaged wind speeds in the following classes: 0–2 ms^{-1}, 2–4 ms^{-1}, and $>4\,\mathrm{ms}^{-1}$. Westerly winds (sectors: South-West-North) at the site represented a cumulative frequency of about 90% and altogether, 1851 mean wind profiles (as 10-minute averages) were realized for the same period.

3.2 LINEX-97/1 Campaign

The follow-up field study, designated as LINEX-97/1, was conducted between 2nd and 26th June, 1997 at the same site and using essentially the same measurements configurations as were for

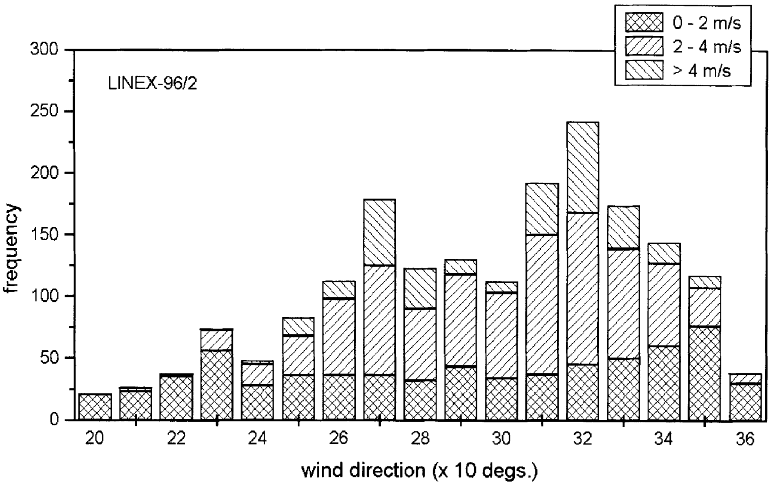

Fig. 4a. The joint-frequency distribution of layer averaged winds at the measurement site during SOP of LINEX-96/2

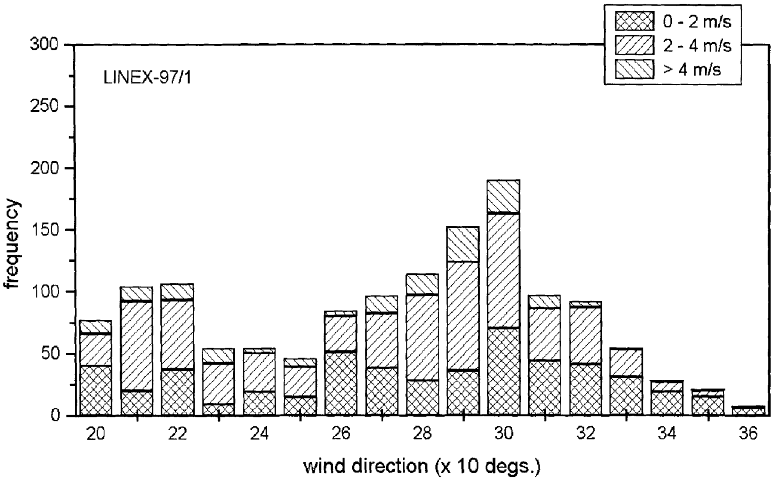

Fig. 4b. Same as Fig. 4a, but for SOP of LINEX-97/1

the preceding LINEX-96/2 campaign. Between 9th and 23rd June, 1997, when both the mean and flux measurements complexes were conducted simultaneously, the period was chosen as the SOP. Within the measurement area was short-grass (about 10 cm high, which grew during the experiment to about 40 cm) surrounded by tall wheat (*Tritikale*, of height 60 cm, and grew to about 110 cm). Hence for westerly winds at the measurement site, the flows represented a rough to smooth transitions across the step.

In Fig. 4b the joint-frequency distribution is shown the joint-frequency distribution for the layer averaged wind speeds (in the same classes as those given in the Fig. 4a) during the SOP of LINEX-97/1. In this period, about 65% of the winds came from the westerly directions which represented a total of 1376 profiles (10-minute averages) realized for the present investigation.

4. Results

Comparing both LINEX-96/2 and LINEX-97/1 data sets (see Fig. 4a and 4b), it can be noticed that the surface winds were frequently westerly, although more occurring and intense in 1996. Also noticeable is that northwesterly winds were almost in 1997. The weaker surface flow in the month of June 1997 is attributed to the lower pressure gradients recorded unlike frequently occurring cyclonic conditions as observed during the same period in June 1996. The implication of this is that the number of the neutral wind profiles realized for 1997 was considerably fewer than for 1996.

4.1 Smooth to Rough Transitions (LINEX-96/2 Data)

The wind profiles from this phase of the field studies were investigated for IBL. The profiles examined included only those in which the surface layer exhibited neutral/near-neutral conditions ($-0.0625 < z/L < 0.125$) and high surface wind speeds ($u_{2m} > 1\,\mathrm{m\,s^{-1}}$). Whether or not an IBL is present in any particular case, visual inspections were first made of the logarithmic wind profiles to detect for discontinuities (kinks) in them. Subsequently, the IBL height, δ, was determined from the intersect of the logarithmic wind-profiles from below (<2 m) and above (>6 m) the interface. Shown in Fig. 5a is the IBL height estimated for the various fetches (taken here as wind directions) along the periphery of the measurement area and their respective standard deviations, σ_δ. Also shown are the theoretical/empirical fits to the data obtained from Eq. (1). If the lowest limit of estimated IBL height (that is, $\delta_1 = \delta - \sigma_\delta$), is assumed to be the height of the IEL, then Eq. (1) together with values of the coefficients a and b given by Raabe (1986) give a good approximation to the data. Values of these empirical coefficients are given in Table 3. Also in the table are values for the coefficient a when the value of the fixed exponent b is taken as 4/5, as had earlier been used by several authors (see Raabe, 1991).

The height to the fetch ratio (δ/x) for the cases of smooth to rough ($z_{02}/z_{01} = 4$) transitions obtained at our site was approximately 1:35.

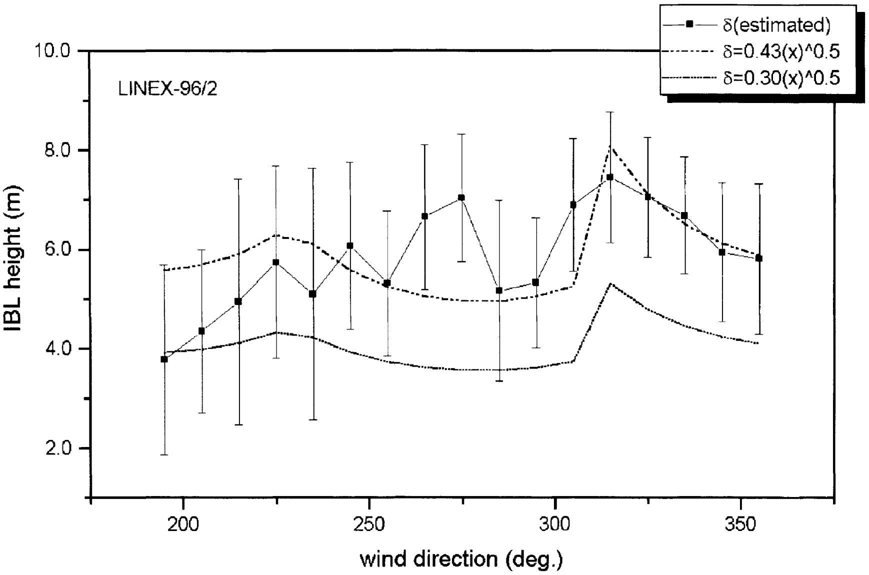

Fig. 5a. Estimated IBL height as a function of wind direction during SOP of LINEX-96/2 including coefficients according Eq. (1)

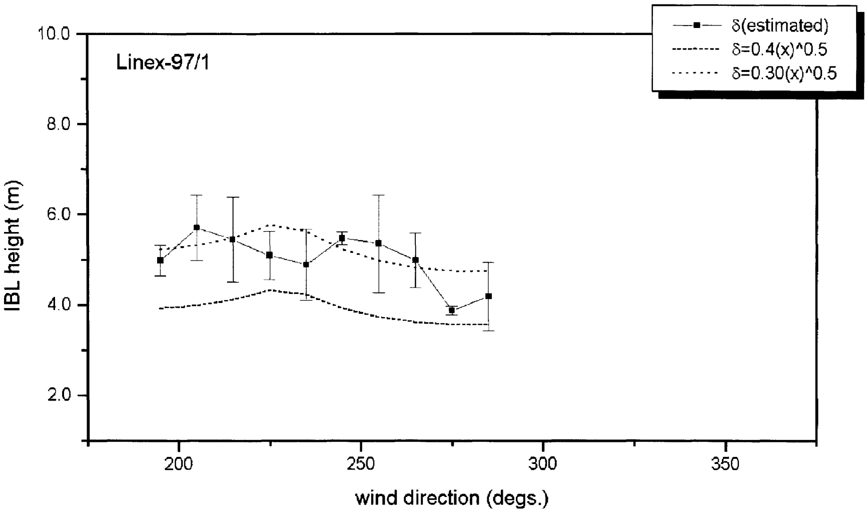

Fig. 5b. Same as Fig. 5a, but for SOP of LINEX-97/1

This ratio is in good agreement with other published data (see Bradley, 1968). Physically based formulations for the IBL depth suggest that this ratio ranges between 1/10 at the IBL top and 1/200 at the top of the IEL (Garratt, 1990).

Additional indication for existence of internal boundary layers was obtained from the ratio of the friction velocity at two heights. In this study, one sonic anemometer was placed very near the surface (within the IEL), while the other was placed at a higher position (5 m), which may be within or above the transition layer. Results obtained show that for fetches less than 250 m, there was a significant increase of about 13% for friction velocity at the 5 m level (200°–300° sector). Using Eq. (2) with the values for the roughness lengths (in Table 2) estimated from profiles in neutral conditions and the corresponding values for heights of IBL, the ratio obtained for the friction velocities is higher than the flux measurements (see Table 4a).

Table 3. *Approximation of the Height of the IEL and the IBL According to Eq. (1)*

IEL/IBL	fixed exponent b	a[m]	reference
IEL	1/2	0.3	Raabe (1991)
	1/2	0.31	LINEX-96/2
	1/2	0.32	LINEX-97/1
	4/5	0.06	LINEX-96/2
	4/5	0.07	LINEX-97/1
IBL	1/2	0.43	LINEX-96/2
	1/2	0.40	LINEX-97/1
	4/5	0.09	LINEX-96/2
	4/5	0.09	LINEX-97/1

4.2 Rough to Smooth Transitions (LINEX-97/1 Data)

Similar estimations of IBL heights were made for the various downwind distances (from the western flank) by using the LINEX-97/1 data.

Table 4a. *Ratio of the Friction Velocity Below and Above the IBL According to Eq. (2) with the LINEX-96/2 Data (smooth to rough: $z_{02}/z_{01} = 4.0$)*

Wind sector	Height of IBL (Fig. 4a)	N	u (2 m) m/s	u_{*2}/u_{*1} eddy corr.	u_{*2}/u_{*1} Eq. (2) Profile	u_{*2}/u_{*1} Eq. (2) Eq. (1)
200–220°	4.6±2.1	63	1.10	1.20(r = 0.90)	1.22	1.21
220–240°	5.4±1.1	121	1.62	1.36(r = 0.74)	1.21	1.21
240–260°	5.7±1.6	195	2.42	1.09(r = 0.96)	1.20	1.21
260–280°	6.8±1.4	302	2.92	1.09(r = 0.97)	1.21	1.22
280–300°	5.2±1.6	242	2.25	1.09(r = 0.98)	1.21	1.22
300–320°	7.2±1.3	434	2.93	1.09(r = 0.93)	1.20	1.20
320–340°	6.9±1.4	318	2.44	1.01(r = 0.97)	1.21	1.21

Table 4b. *Ratio of the Friction Velocity Below and Above the IBL According to Eq. (2) with the LINEX-97/1 Data (rough to smooth: $z_{02}/z_{01} = 0.26$)*

Wind sector	Height of IBL (Fig. 4b)	N	u (2m)	u_{*2}/u_{*1} eddy corr.	u_{*2}/u_{*1} Eq. 2 Profile	u_{*2}/u_{*1} Eq. 2 Eq. 1
200–220°	5.6±0.8	58	2.25	0.80(r = 0.96)	0.71	0.71
220–240°	5.0±0.7	18	2.11	0.84(r = 0.98)	0.71	0.72
240–260°	5.4±0.6	31	1.67	0.78(r = 0.97)	0.71	0.71
260–280°	5.2±0.8	41	1.68	0.77(r = 0.98)	0.71	0.71
280–300°	4.0±0.4	15	2.85	0.76(r = 0.96)	0.69	0.70

The IBL height shown in Fig. 5b is estimated for the various fetches, along the periphery of the measurement area. However, due to insufficient number of profiles for the winds from the northerly sectors (280–300°), no reliable estimates for the IBL heights could be obtained for these sectors. The coefficients of the empirical fetch-height relationship in Eq. (1) for the rough to smooth transitions were also determined for the present data. The values of these coefficients are also listed in the Table 3.

The ratio of the friction velocity below and above the IBL as determined both by direct flux measurements and from Eq. (2) for the various wind directions (fetches) at the site is presented in Table 4b. Values of the ratio obtained suggested that for fetches less than 300 m, there was a reduction of nearly 20% in friction velocity at about 5 m.

4.3 Similarities/Differences between the 'Smooth to Rough' and 'Rough to Smooth' Types of IBLs

The height of IBLs formed due to step changes of the surface roughness in neutral conditions is fairly well predicted by the empirical relationship in Eq. (1) for both 'smooth to rough' and 'rough to smooth' transitions (small scale flows, $x < 300$ m). Values of the coefficients in Table 3 did not suggest any remarkable differences between the two types of flows for the horizontal scale considered. Although a slightly slower growth is reported elsewhere for the cases of rough to smooth transitions (see Garratt, 1990).

For the winds between 200° and 260°, well developed IBLs were found for both flow transitions. In the sectors from 260° to 300°, the IBLs were prominent for the rough to smooth profiles only, but the layer was non-existent for the smooth to rough profiles. This may be due to the cluster of bushes (about 500 m away) which dominate the 'smooth' upwind roughness in those directions. The estimated heights of the IBL gave the values which range between 6 and 8 m instead of about 4 m predicted according to Eq. (1). The discrepancy is brought about by appearance of a threefold (multiple) internal boundary layers in the wind profiles (Fig. 2). In this case, the IEL was determined by the grass (rough, positions 1–3), while the middle layer is due to the bare soil (smooth, position 4 and 5), and the upper layer is indicative of the cluster of bushes (rough, position 7 and 8), which dominated the upwind roughness further away from the step.

In the 1996 data, a similar long range effect is also noticeable in the wind sector 300–360° (Fig. 5a). The high values obtained for the IBL (about 7 m) was due to a long fetch (which was rough) and a 'smooth influenced' layer above it. Comparison of the data with the terrain conditions showed that a line of small trees and crops of bushes at the northern boundary of the measurement area created a 'barrier effect' and consequently, reduction of the wind speed, which was indicated as a 'smooth profile'. Perturbations of the wind flow as it moves over the bare soil ('smooth') in the corner of the L-shaped field was not noticeable.

An explanation for the discrepancy between values of u_* in Table 4a and 4b estimated by the two methods may be because of the different footprints for both the wind speed and the friction velocity, which is smaller for u_* according to Schmid (1997). The wind velocity adjusts more slowly to a roughness change than stresses do (Garratt, 1990). Furthermore, the flux measurements made at 5 m may or not be within the transition layer. In the present study, in both cases the heights of the IBLs estimated were found to be independent of the wind speed.

5. Conclusions

Internal boundary layers have an important influence on the wind, temperature and humidity profiles as well as on the surface fluxes (friction velocity, sensible and latent heat fluxes) even for small differences in the change of the roughness. It has been well demonstrated in this study that to measure the surface fluxes, the expression: $\delta = 0.3x^{0.5}$ can safely be used to determine the height of IEL which is free of the influences of overlying IBLs both for the 'smooth to rough' and 'rough to smooth' flow transitions. The mean height of the transition layer can be determined using as value for the empirical coefficient, $a \sim 0.4$ m. This result is in a good agreement with the literature values suggested by Raabe (1991). Approximations with value of the fixed exponent $b = 4/5$ used in Eq. (1), is also valid (see Table 3).

In the present study, there was no significant influence of direction of transition (smooth to rough or rough to smooth) found.

In the cases where it was established that the IBL existed, differences in values of friction velocity inside the IEL and at about 5 m height were found to be about 20%. For the IEL with estimated heights than the upper turbulence measuring position, the value of the ratio of friction velocity approached unitary (see for example, sectors 300°–340° in LINEX-96/2 data). Differences in the obtained values of this ratio between eddy-correlation and profile measurements was due primarily to the different footprints for fluxes and mean parameters (see Schmid, 1997). As has been shown in this paper, Eq. (2) gives a good prospect to estimate the value of this ratio as a function of the roughness parameter and height of the IBL. However, this equation can still be used to determine values of the friction velocity on either side for an IBL as has been verified in the present paper.

Internal boundary layers are a meteorological phenomenon, which can be detected in profile measurements as well as in eddy correlation measurements. The height of this layer should be well determined before any micrometeorological measurements is conducted since the wrong placement of instruments which may or not be inside of the IEL can severely impair the quality of turbulence data.

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References

Baum, W., Foken, Th., Lattauschke, J., Rettig, W., Mattern, W., 1994: Entwicklung, Bau und Test eines Vertikalpsychrometers. *DWD, Forschung und Entwicklung, Arbeitsergebnisse,* **12**, 18 pp.*)

Bradley, E. F., 1968: A micrometeorological study of velocity profiles and surface drag in the region modified by a change in surface roughness. *Quart. J. Roy. Meteor. Soc.,* **94**, 361–379.

Brömme, G., Woitzik, B., Jörn, M., Schindler, V., 1991: Feinanemometer für mikrometeorologische Anwendungen. *Abh. Meteorol. Dienstes,* **146**, 23–26.

Cannemeijer, F., Vugts, H. F., 1982: Wind speed and temperature profiles at a coastal zone. *Proceedings of the First International Conference on Meteorology and Air-Sea Interaction of the Coastal Zone.* May 10–14, 1982, The Hague, Netherlands, 25–27.

DeBruin, H. A. R., Bink, N. J., Kroon, L. J. M., 1991: Fluxes in the surface layer under advective conditions. In: Schmugge, T. J., André, J. C. (eds.) *Workshop on Land Surface Evaporation, Measurement and Parametrization.* Heidelberg, New York: Springer, pp. 157–169.

Elliot, W. P., 1958. The growth of the atmospheric internal boundary layer. *Trans. Am. Geophys. Union,* **39**, 1048–1054.

Foken, Th., 1990: Turbulenter Energieaustausch zwischen Atmosphäre und Unterlage, Methoden, meßtechnische Realisierung, sowie ihre Grenzen und Anwendungsmöglichkeiten. *Ber. Dt. Wetterdienstes,* **180**, 287.

Foken, Th. (ed.), 1998: Ergebnisse des LINEX-97/1 Experimentes. *DWD, Forschung und Entwicklung, Arbeitsergebnisse,* Nr. 53, 38 pp.*)

Foken, Th., Jegede, O. O., Weisensee, U., Richter, S. H., Handorf, D., Görsdorf, U., Vogel, G., Schubert, U., Kirtzel, H.-J., Thiermann, V., 1997a: Results of the LINEX-96/2 experiment. *DWD, Forschung und Entwicklung, Arbeitsergebnisse,* Nr. 48, 75 pp.*)

Foken, Th., Neisser, J., Richter, S. H., Rosenow, W., Weisensee, U., Heise, E., Müller, E., Herzog, H.-J., 1997b: The 'LITFASS' project of the German Weather Service, *Proceedings of the 12th Symposium on Boundary Layers and Turbulence, Vancouver, Canada, July 28–Aug. 1, Am. Meteorol. Soc.,* 567–568.

Garratt, J. R., 1990: The international boundary layer – a review, *Bound.-Layer Meteor.,* **50**, 171–203.

Garratt, J. R., 1992: *The Atmospheric Boundary Layer.* Cambridge: Cambridge Univ. Press, 316 pp.

Hanafusa, T., Fujitani, T., Kobori, Y., Mitsuta, Y., 1982: A new type sonic anemometerthermometer for field operations. *Papers in Meteorol. & Geophys.,* **33**, 1–19.

Logan, Jr., E., Fichtl, G., 1995: Rough-to-smooth transition of an equilibrium neutral stress layer. *Bound.-Layer Meteor.,* **8**, 525–528.

Müller, E., Foken, Th., Heise, E., Majewski, D., 1995: LITFASS – a nucleus for a BALTEX field experiment. *DWD, Forschung und Entwicklung, Arbeitsergebnisse,* **33**, 17 pp., App.*)

Raabe, A., 1986: Zur Höhe der internen Grenzschicht bei ablandigem Wind über See. *Z. Meteorol.,* **36**, 308–311.

Raabe, A., 1991: Die Höhe der internen Grenzschicht. *Z. Meteorol.,* **41**, 251–261.

Radikevitch, V. M., 1971: Transformacija dinamičeskich characteristik vozdušnogo potoka pod vlijaniem izmerenija šerochovatosi podstilajuščej poverchnosti. *Izv. AN SSSR, Fiz. atm. i okeana.,* **7**, 1241–1250.

Rao, K. S., Wyngaard, J. C., Coté, O. R., 1974: The structure of a two-dimensional internal boundary layer over a sudden change of surface roughness. *J. Atmos. Sci.,* **31**, 738–746.

Schmid, H. P., 1997: Experimental design for flux measurements: Matching scales of observations and fluxes. *Agric. Forest Meteor.,* **87**, 179–200.

Schwiesow, R. L., Lawrence, R. S., 1982: Effects of a change of terrain height and roughness on a wind profile. *Bound.-Layer Meteor.,* **22**, 109–122.

Sempreviva, A. M., Larsen, S. E., Mortensen, N. G., Troen, I., 1990: Response of neutral boundary layers to change of roughness. *Bound.-Layer Meteor.,* **50**, 205–225

Shir, C. C., 1972: A numerical computation of air flow over a sudden change of surface roughness. *J. Atmos. Sci.,* **29**. 304–310.

Walmsley, J. L., 1989: Internal bounary-layer height formulae – a comparison with atmospheric data. *Bound.-Layer Meteor.,* **47**, 251–262.

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