Surface Roughness and Internal Boundary Layer Near a Coastline

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ABSTRACT

Wind profile observations obtained at two sites near the upper Texas coast during onshore winds in June 1968 are used to determine local roughness parameters. Values of 3–4 cm are obtained at a 32 m tower site 90 m inland and 0.8–1.5 cm at 4.8 km inland; both are in close agreement with results of others for similar terrain. The portion of the wind profile obtained at heights between 6.7 and 27 m near the beach is extrapolated downward to obtain a roughness between 0.0001 and 0.0003 cm for the Gulf of Mexico.

An internal boundary layer was detected from the data obtained 90 m inland. The mean height was observed to be 6.7 m—a value associated with a mean slope of about 1:13 for an internal boundary originating at the upwind shoreline roughness discontinuity. Daytime values for the internal boundary height are somewhat higher than the mean, averaging 7.2 m, while the nighttime mean is 5.9 m. The data also suggest a wind speed dependence on the height of the internal boundary layer.

1. Introduction

Changes in the mean wind within the surface boundary layer associated with a change in surface roughness were studied in conjunction with sea breeze investigations of The University of Texas at Austin. The main study was near High Island, on the upper Texas coast midway between Galveston and Sabine Pass. In this region, the coastline is straight and unbroken, making an approximate angle of 23.5° with the latitude circle. The terrain consists of a short region of sand and pebble at the water’s edge, becoming a flat and quite homogeneous coastal marshland of sand and clay with an overgrowth of marsh and salt grasses (Arbignast et al., 1967). The grass density varies and grass heights range from 10–45 cm. The summertime Bermuda high pressure system predominated during the study period, producing periods of steady onshore flow nearly perpendicular to the coast, broken intermittently with superimposed sea and land breeze cycles.

To obtain a vertical cross section of the atmosphere, two telescoping 32 m towers were instrumented at various levels with wind and temperature sensing equipment. One tower was located 90 m onshore and the second, inland about 4.8 km from the beach. The two towers were on a line nearly normal to the coast (see Fig. 1). Using data obtained from these towers, the influence of an abrupt change in surface roughness from water to land was determined and the development of a new internal boundary layer downwind from this change was detected. Vertical profiles of horizontal velocity at the two sites were used to obtain values for the roughness parameter over the land and sea surfaces. For a more detailed analysis of the modification in boundary layer wind structure at this coastal site see Echols (1970).

2. Instrumentation and data reduction

The data analyzed were obtained entirely from the June 1968 sea breeze expedition to the upper Texas coast. The instrumented tower nearest the beach will be called the beach tower and the inland tower will be referred to as the canal tower, since it was located some 150 m shoreward from the Intercoastal Canal. Wind sets were mounted at 1, 2, 3, 4.5, 6.7, 11.6 and 27 m on the beach tower and at 1, 3, 6.7, 11.6 and 27 m on the canal tower (Fig. 2). The heights at which the wind sets were mounted is accurate to within ±1 cm at the 1 m level, increasing to ±10 cm for the 27 m level. The wind sets were attached to booms which extended 1.6 m south-southwest of the tower, thereby minimizing tower interference.

The wind sets used were the Gill microvane and the three-cup anemometer (R. M. Young Company, Traverse City, Mich.). Matching and calibration of the wind sets were done in the laboratory prior to the expedition. The recovery rate and threshold velocity for the instruments demand exclusion of data when wind speeds were low or fluctuated about the threshold value. For this reason only velocity profiles having all wind speeds > 1 m sec⁻¹ will be considered. The anemometer voltage output is linear and directly proportional to wind speed. The wind set output signals
were commutated at a rate of one per second and input directly to a Precision Instrument 6100 magnetic tape recorder at each site to produce a continuous analog signal. Recording of input signals and reference pulses required a total of 16 sec per sounding. Thus, for example, a 12-min average would contain 45 values for both wind speed and direction at each level.

To convert the commuted wind data to a form compatible with The University of Texas at Austin CDC 6000 computer, the analog tape was played back in the laboratory with the output fed into an analog-to-digital converter. This converted signal was recorded on an incremental tape recorder in external binary coded decimal (BCD) format and used as input to a computer program to reduce the data.

Individual 12-min mean wind profiles were initially examined in the time sequence in which they were recorded. Irregular rising and falling of the wind occasionally resulted in considerable spread in mean wind speed values at a given level when averaged profiles were plotted consecutively for a 1–2 hr period. To obtain profiles which would be more representative of a longer term steady wind, the 12-min mean profiles were separated into groups according to wind speed limits placed on the second anemometer level. This level was chosen arbitrarily and was above the earth-air interface by 2 m at the beach and 3 m at the canal. The limits on the second level wind speed were 1.0–1.5, 1.5–2.0, . . . , 4.5–5.0 m sec⁻¹. New mean profiles were then computed from the grouped 12-min profiles. Calculated means containing less than five 12-min profiles were generally not considered. Thus, the new means would represent at least a 1-hr mean of wind speeds within a restricted velocity band. All data points considered in the average were plotted, but only the profile associated with the arithmetic mean for each level was drawn. Straight lines were used to connect these means and, in most cases, these straight line segments described a single straight line (on a semilogarithmic plot). There were two cases when this did

not occur. One case was when large variations from adiabatic stratification occurred. The other was due to the discontinuity associated with the internal boundary layer at the beach tower.

Dry and wet bulb soundings were also made at each tower. The measured accuracy of the thermistors used was ±0.1°C. This instrument package made a continuous sounding by being lifted and lowered with a motorized pulley system. Sixteen minutes were required for a complete ascent and descent (~8 min each way). The sounding extended from 1.3–26.5 m. Thermistor outputs were amplified and recorded on Easterline-Angus strip chart recorders.

3. General features of the wind data

For onshore flow the instruments were placed on the beach tower so that measurements would be obtained both within the developing internal boundary layer as well as above it in air still essentially in equilibrium with the upwind water surface. As the air travels inland, it begins to approach a flow equilibrium with the
land surface in the lower levels and the internal boundary layer continues to grow. The canal tower, some 4.8 km inland, should give measurements of this new near-equilibrium flow (Taylor, 1970).

Wind and temperature data were available for analysis from portions of four days beginning 14 June and ending 17 June 1968. Data on 14 June were recorded only at the beach tower. During this period moderate onshore flow occurred with very little cloudiness to inhibit radiational heating during the day or cooling in the evening. During the day on 16 June, winds were not as strong as on the 14th and there was some increase in cloudiness. An early morning land breeze and rain showers disturbed the flow until mid-afternoon. After 2100 CDT on 16 June the effects of an approaching line of thunderstorms were noticed and all data after that period were affected by rain showers and thunderstorms in the area. Data were not analyzed for these periods of extremely non-steady flow, nor when the wind deviated from onshore flow. Unfortunately, the 27 m level anemometer output at the canal had not been connected and no wind speed were available for that level until the last 65 min of the analysis period.

4. Determination of roughness parameters

Sutton (1953) gives a summary of roughness lengths determined experimentally for various natural surfaces. Values include 0.001 cm for smooth surfaces (mud flats, ice), 2.3 cm for thick grass (up to 10 cm high), and 5 cm for thin grass (up to 50 cm high). The grass at the beach and canal sites would be intermediate between the thick 10-cm grass and the thin 50-cm grass described by Sutton. We might then expect the roughness values as determined from the mean profiles to lie within a 2.3–5 cm range.

Daytime profiles under nearly adiabatic conditions at the beach give $Z_0$ values very near 3 cm on 14 June and range between 3 and 4 cm for 16 June. The values were determined using only the lower four to five wind measuring levels. Nighttime values (midnight to 0400 CDT on 16 June) give $Z_0$ values near 5 cm. Slight concave curvature (indicative of stability) is present in the nighttime profiles. Because this slight curvature is not adequately described below 1 m, extrapolation of available nighttime data to the height of zero mean wind speed tends to overestimate $Z_0$. Values for the gradient Richardson number obtained at the beach for daytime measurements show, at most, only weak gradients and therefore no major deviation from adiabatic stratification. Nighttime values show stronger, though still relatively weak, stable gradients near the ground. The roughness values as determined from the daytime wind profiles at the beach site are thus thought to be more valid.

The top three levels at the beach were used to determine a roughness value representative of the adiabatic flow over the Gulf of Mexico before encountering the land. Since the wind profile over water after a long fetch is expected to be logarithmic, this region of the profile above the new boundary layer will be assumed to represent the upper portion of that overwater profile. The values of $Z_0$ obtained from the upper levels of the beach tower ranged from 0.0001–0.0003 cm. This range was noticed for both day and night profiles with no wind speed magnitude preference for either. These values are only slightly smaller than those obtained by Hsu (1971). The relatively small $Z_0$ values suggest that the sea was acting as an aerodynamically smooth surface. Wind speeds at the 27 m level range from 2.5–6.5 m sec$^{-1}$ in the profiles used for our $Z_0$ determination, indicating a rather constant roughness value even with moderate variations in wind speed. These results are at variance with those of Ruggles (1970). It is entirely possible, however, that much of the discrepancy can be attributed to the smoothing effects of oil and other pollutants in the water as described by Barger et al. (1970). The purity of the Gulf of Mexico in our study area is substantially disturbed by local shipping (Port Arthur and Houston) as well as offshore oil drilling operations.

The terrain between the shore and canal tower some 4.8 km inland is flat and rather homogeneously covered with grass. There is a gentle rise of about one meter in the surface above mean sea level as compared to the beach site. The grasses in the vicinity of the canal site are a little shorter than near the beach site with a few open areas of bare sand and small shallow water-filled depressions shoreward from the site. Air flowing from the beach during the day would be affected to a greater depth by heating as mechanically and thermally driven turbulent exchange grows to a greater height. Because of radiational cooling over land the wind structure inland at night would tend to be much more stable than at the beach.

Daytime profiles at the canal site are nearly logarithmic, but have slight convex curvature indicative of the thermal instability expected at this inland station. Roughness parameter values ranged from 0.8–1.5 cm, which, as expected, are slightly lower than the 3–4 cm found at the beach. Although these values were determined under other than strictly adiabatic conditions, it was felt that the lowest levels of the profile would give a good estimation of the canal site roughness parameter.

The nighttime wind profiles at the canal show pronounced stable curvature. Using the lower two anemometer levels, the measured value of $Z_0$ ranges from 1.5–3 cm. It is noticed that the measured nighttime roughness values are higher than daytime, as previously found at the beach site. This overestimate of $Z_0$ is assumed to be due to an incomplete description of the curvature of the profile below the 1 m level. Gradient Richardson numbers calculated for the canal site
indicate that only slightly superadiabatic curvature is expected in the daytime wind profiles, while the nighttime values predict curvature characteristic of stable thermal stratification. The daytime roughness parameter determinations will be assumed as the most representative.

5. Height of the internal boundary layer

Examination of the beach site wind profiles shows a "kink" in the profile at approximately the 6.7 m level which is associated with an internal boundary layer originating at the coastline and deepening as the air moves inland. The following technique will be used to uniquely define the height of the internal boundary layer. We will assume a logarithmic wind profile above the internal boundary. The wind profile which was measured below the internal boundary will be extrapolated upward until it intersects with the logarithmic profile. The point of intersection of the two profiles is assumed to be the height of the internal boundary layer. Wind profiles obtained at the beach tower are shown in Fig. 3. Because of the wind speed grouping as described in Section 2, it is generally impossible to assign a representative mean time to any of the profiles. However, daytime profiles were obtained between 1500 and 2000 CDT on 14 June and between 1600 and 2000 CDT on 16 June. Maximum daytime speeds generally occurred near 1800 on both days. Nighttime data were obtained on 16 June between midnight and 0400. Maximum nighttime wind speeds occurred near midnight and decreased until 0400. A detailed presentation of the wind variations is available in Echols (1970).

Elliott (1958) states that the thickness of the internal boundary layer downstream from a change in surface roughness grows at a rate of approximately 1:10 compared to downstream distance, though at very short distances downwind the slope would be larger. More recent theories generally predict a slower growth rate; for example, Panofsky and Townsend (1964) predict a value of about 1:20. It should be noted that all theories predict that the canal tower would be totally within the internal boundary layer having an origin near the shoreline. For the beach tower, strict application of Elliott's theory would give a height of about 16 m for the top of the internal boundary layer for winds blowing directly onshore. Slopes of 1:10 and 1:20 would correspond to heights of 9 m and 4.5 m, respectively, on the beach tower. The observed height near 6.7 m for our data falls within this latter range. It is possible, however, that the upwind topography (Fig. 2) has some effect on the observed height.

Boundary layer theory supported by laboratory experiments (Schlichting, 1955) shows that the depth of an internal boundary layer should decrease with increasing wind speed. Our daytime wind profiles as shown in Fig. 3 suggest this expected general downward trend in the internal boundary layer height.

The nighttime profiles show internal boundary layer heights which are lower than the daytime values but which increase in height with increasing wind speed. This could be attributed to a tendency toward laminar flow under the more stable nighttime conditions. Boundary layer thickness under laminar flow conditions is less than when the flow is turbulent (Schlichting, 1955). In this case, increasing wind speed would tend to destroy the laminar character of the boundary layer by causing increased mechanical turbulence. The result would be the observed increase in internal boundary layer height with increasing wind speed.

As expected from the above argument and as predicted by Elliott (1958), in the mean, the height of the internal boundary is lower at night than during the day.

6. Summary and conclusions

Wind speed measurements from two 32 m towers allowed determination of the aerodynamic roughness of the land surface near the beach and at the inland site. The profiles yielded values of 3–4 cm for the roughness at the beach site and 0.8–1.5 cm at the inland canal site. These values agree well with estimates by other authors for similar terrain.

Analysis of the wind profiles revealed a "kink" near the 6.7 m level at the beach site. This kink was most
evident in profiles for the higher wind speeds. The assumption was made that the newly forming internal boundary layer was below this level, while above the profile was representative of the undisturbed flow over water. Under this assumption an aerodynamic roughness value was determined for the Gulf surface by extending this profile downward to the Z-axis intercept. Values of roughness over the water for both day and night ranged between 0.0001 and 0.0003 cm. These values indicate that the Gulf surface is aerodynamically smooth for wind speeds <7 m sec\(^{-1}\) (referenced to the 10 m level).

Wind profiles measured 90 m onshore and downwind from the coastline indicate a mean depth of the internal boundary layer of approximately 6.7 m, with somewhat higher values on the average during the daytime (7.2 m) and lower values at night (5.9 m). Although the data are rather limited, the height of the internal boundary layer during the daytime appears to be higher for light winds, decreasing slightly as the wind speed increases. This variation is in substantial agreement with classical boundary layer theory. At night, however, the height of the internal boundary layer appears to increase with increasing wind speed. It is hypothesized that this variation can be attributed to a tendency toward laminar flow conditions at night. Increased wind speed would increase mechanically induced turbulence thus destroying the laminar character of the boundary layer and increasing its height.

REFERENCES


