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ESCUELA DE INGENIERIA CIVIL  
DEPARTAMENTO DE METEOROLOGIA E HIDROLOGIA

MODIFICATION IN SURFACE BOUNDARY LAYER WIND  
STRUCTURE WITH ONSHORE FLOW

Echols

Report No. 23

May 1970

ATMOSPHERIC  
SCIENCE GROUP



The University of Texas  
College of Engineering  
Austin, Texas 78712

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Warren T. Echols

Sponsored by

National Science Foundation  
Grant GA 16167 and Grant GA 367X1

## FOREWORD

The structure of the atmospheric surface layer near a change in the configuration of the lower boundary has received increasing attention recently. This report, which is also Mr. Echols' Master of Science Thesis, examines changes in both the mean structure as well as some aspects of the turbulent structure of air as it moves inland from the Gulf of Mexico.

This research was sponsored by the National Science Foundation through financial support of The University of Texas Sea Breeze Investigation under NSF Grants GA-367X and GA-16167. Field support was provided by the Field Observing Facility of the National Center for Atmospheric Research. The full cooperation of Mr. James B. White of Stowell, Texas, who permitted us use of his ranchland during this study, is gratefully acknowledged.

Norman K. Wagner  
Co-Principal Investigator

#### ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Norman K. Wagner who, as Supervising Professor, gave invaluable guidance during the thesis research and manuscript preparation. The author also wishes to thank Prof. Kenneth H. Jehn for his critical review of the manuscript.

Thanks are also extended to Miss Pam Peterson and Miss Wanda Fowler for typing the manuscript and to Mrs. Jean Gerhke for drafting the figures. The help given by Mr. Tom Phillips in instrument calibration and data reduction is appreciated as are the various ways Mrs. T. O. Womack has assisted the author.

May 1970

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## I. INTRODUCTION

The effects of large adjacent land and water bodies on atmospheric flow patterns have been observed and studied for many years. Differential heating of land and water during the daytime and differential cooling at night is known to be the mechanism for alternately producing sea and land breezes in coastal regions (Schmidt, 1947). The study of these mesoscale systems yields data on the internal and kinetic energy processes of such phenomena while also giving much information concerning the nature of much larger and more complicated weather systems.

One of the notable physical differences between land and sea is the aerodynamic roughness of the surface of each. In many cases the sea surface may be considered aerodynamically "smooth" while the land surface is covered with rocks, grasses, and other obstacles which tend to retard the atmospheric flow near the surface and intensify its turbulent characteristics (Sutton, 1953). With onshore flow this surface roughness difference enhances energy dissipation through increased turbulence. The energy dissipation rate in the surface boundary layer on a global scale is important when considering long-range weather forecasts in that the atmosphere's ability to compensate for this energy loss must be considered.

Air flowing over a surface of uniform roughness for a long period of time can develop an equilibrium or steady state wind profile. Prandtl's "log-law" which relates wind speed to the logarithm of height in the surface layer has been found to satisfactorily describe this equilibrium profile under adiabatic conditions. Near the lower boundary the mean flow is being converted to turbulent flow with production of shear-flow energy. According to Munn (1966) this shear flow production is  $P = \partial(\bar{U} U_*^2)/\partial Z$ , where  $\bar{U}$  is the mean wind and  $U_*$

is the friction velocity. Dimensional arguments concerning the rate of energy dissipation ( $\epsilon$ ) lead to  $\epsilon = U_*^3/Zk$  where  $k$  is von Karman's constant ( $\approx 0.40$ ), and  $Z$  is height. For equilibrium flow  $P$  must equal  $\epsilon$  or

$$U_*^3/kZ = \partial(\bar{U} U_*^2)/\partial Z = U_*^2 \partial\bar{U}/\partial Z$$

and

$$\partial\bar{U}/\partial Z = U_*/kZ.$$

At the height where  $\bar{U} = 0$ , we define  $Z = Z_0$  and integrating yields

$$\bar{U} = \frac{U_*}{k} \ln(Z/Z_0).$$

The parameter  $Z_0$  represents the aerodynamic character of the surface and directly effects the slope of the wind profile above it.

When the aerodynamic roughness below an equilibrium flow changes abruptly, another equilibrium tends to be established after a sufficiently long distance downwind. Very near the leading edge of this abrupt change in roughness, an internal boundary layer begins to develop. For flow from a smooth to rough surface (as from sea to land), mechanical turbulence is increased and this new adjusted layer grows faster than if the new surface were smoother than the original (Blom and Wartena, 1969).

Vertical profiles of horizontal velocity may be used to determine the surface roughness parameter. Under nearly adiabatic conditions the logarithmic wind profile may be assumed. Using the mean wind speeds at each level in the lower layer, the roughness parameter is found to be the height at which the profile intercepts the zero wind speed value. When the profiles used are measured near a change in surface roughness, care must be taken to use only

those values lying within the new internal boundary layer. Measurements at heights above the internal boundary have not been affected by the new surface and would be more closely related to the roughness value of the upwind surface.

The slope of the profiles indicates a characteristic velocity (usually called the friction velocity  $U_*$ ) and for equilibrium flow is related to the shear stress ( $\tau$ ) by  $U_* = (\tau/\rho)^{1/2}$ , where  $\rho$  is the density of air. For logarithmic profiles  $U_*$  and  $\tau$  will be nearly constant through the layer, but their values will change if the flow has not reached equilibrium with the new surface. Munn (1966) states that one criterion for defining the surface boundary layer is that the shear stress vary by no more than 5 percent through its depth.

To study the effects of a change in surface roughness on the surface boundary layer flow, a coastal site having onshore winds perpendicular to the shore would be desirable. Such a site was the one chosen for The University of Texas at Austin Sea Breeze Investigation along the upper Texas coast midway between Galveston and Sabine Pass (see Fig. 1). In this region the coastline is straight and unbroken, making an approximate angle of 23.5 degrees 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 (Arbingast, et al, 1967). The grass density varied and grass heights were from 10 to 45 cm. The summertime Bermuda high pressure system predominated during the study period, producing long 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-meter 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 on a line nearly normal to the

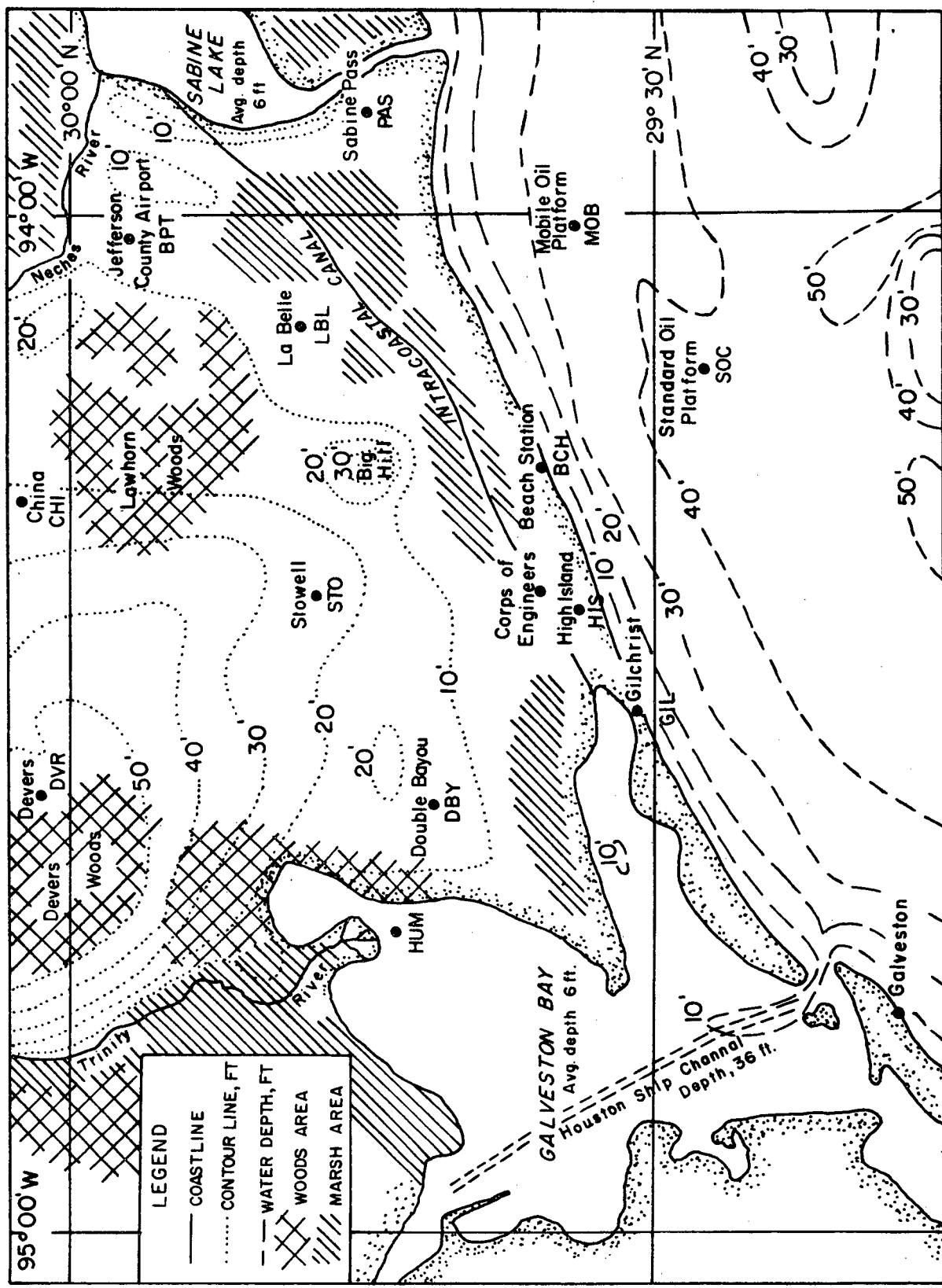


Fig. 1 General features of the study area

coast (see Fig. 2).

The objective of the present analysis is to determine the influence of an abrupt change in surface roughness from water to land on the established surface boundary layer and to detect the development of a new internal boundary layer downwind from this change. Vertical profiles of horizontal velocity at the two sites may be used to obtain values for the roughness parameter over the land and sea surfaces. These values will allow computation of the change in friction velocity in the vertical and horizontal as the flow progresses inland. The kinetic energy loss due to the increased friction over land can be computed between the sites, yielding an estimate of the energy dissipation in the surface boundary layer. The variation of the intensity of turbulence with height and distance inland will give an indication of the turbulent structure in the lower levels of both the established and newly formed surface layer. This analysis was made for both day and night onshore flow.

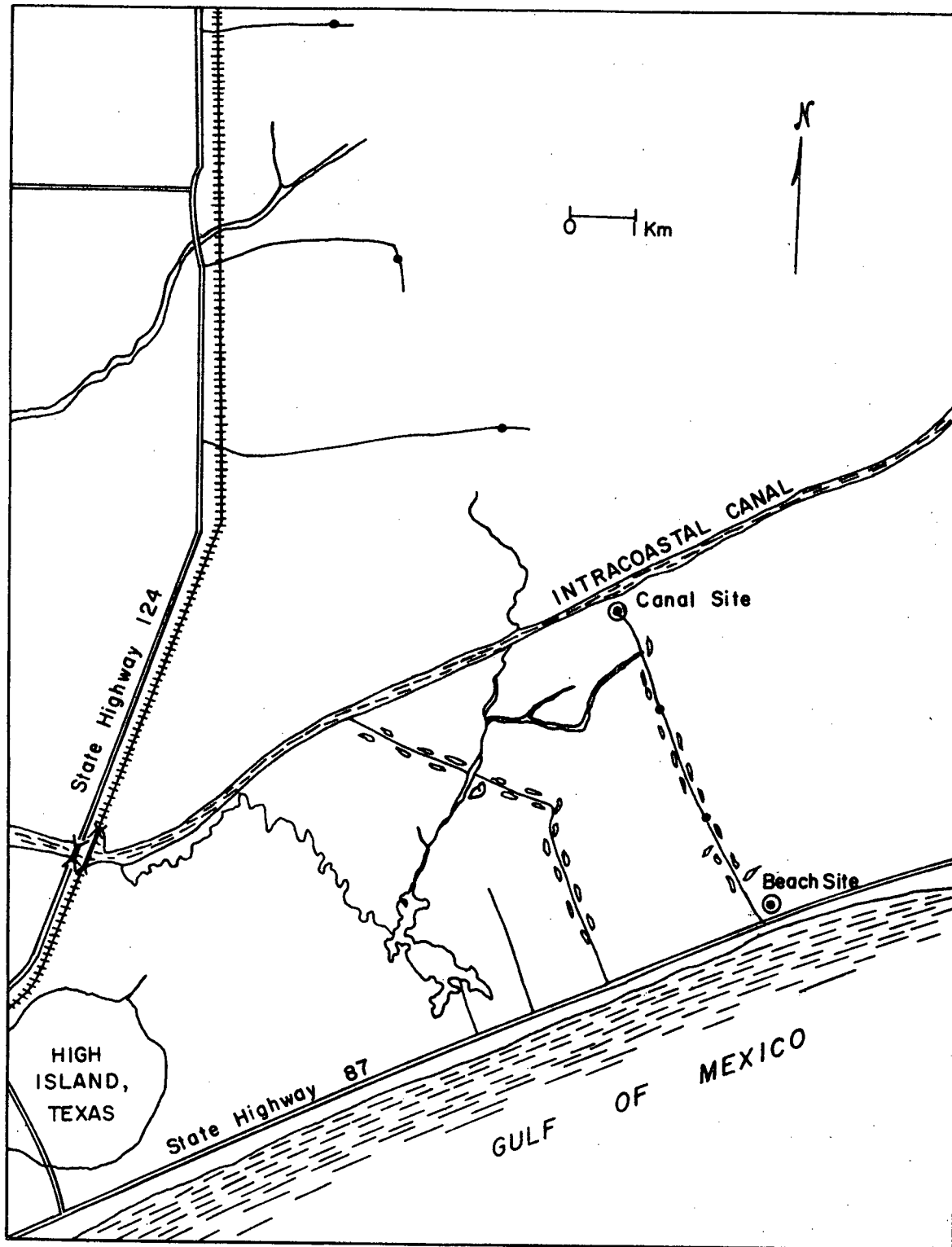


Fig. 2 Location of the instrumented towers

## II. INSTRUMENTATION AND DATA REDUCTION

The data analyzed in this report were obtained entirely from the June 1968 Sea Breeze expedition on the upper Texas coast. The instrumented tower nearest the beach will be called the beach tower and the inland tower will be called the canal tower, since it was located some 150 meters shoreward of the Intracoastal 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 (see Fig. 3). The heights at which the wind sets were mounted must be considered to be accurate only to within  $\pm 2$  cm since the anemometer cups and vane have a finite width. The error would have its greatest effect in the lowest portion of a logarithmic scale. These wind sets were attached to a boom which extended 1.6 meters toward the SSW of the tower, thereby minimizing tower interference. A dead range in wind direction of 18 degrees was characteristic of the vane. This dead range was oriented to coincide with wind directions between 7 and 34 degrees from North, the expected angle of tower interference (tower shadow effect).

The wind sets used in the study were the Gill microvane and three cup anemometer (R. M. Young Company, Ann Arbor, Michigan). Matching and calibration of the wind sets was done in the laboratory just prior to the expedition. The distance constant for the anemometer is 2.8 m for 63 percent recovery. The threshold measurable velocity lies between 0.45 and 0.54 meters per second (m/sec). This recovery rate and threshold velocity will demand exclusion of data when wind speeds were low or fluctuated about this threshold value. For this reason only velocity profiles having wind speeds greater than 1 m/sec will be considered.

The anemometer voltage output is linear and directly proportional to

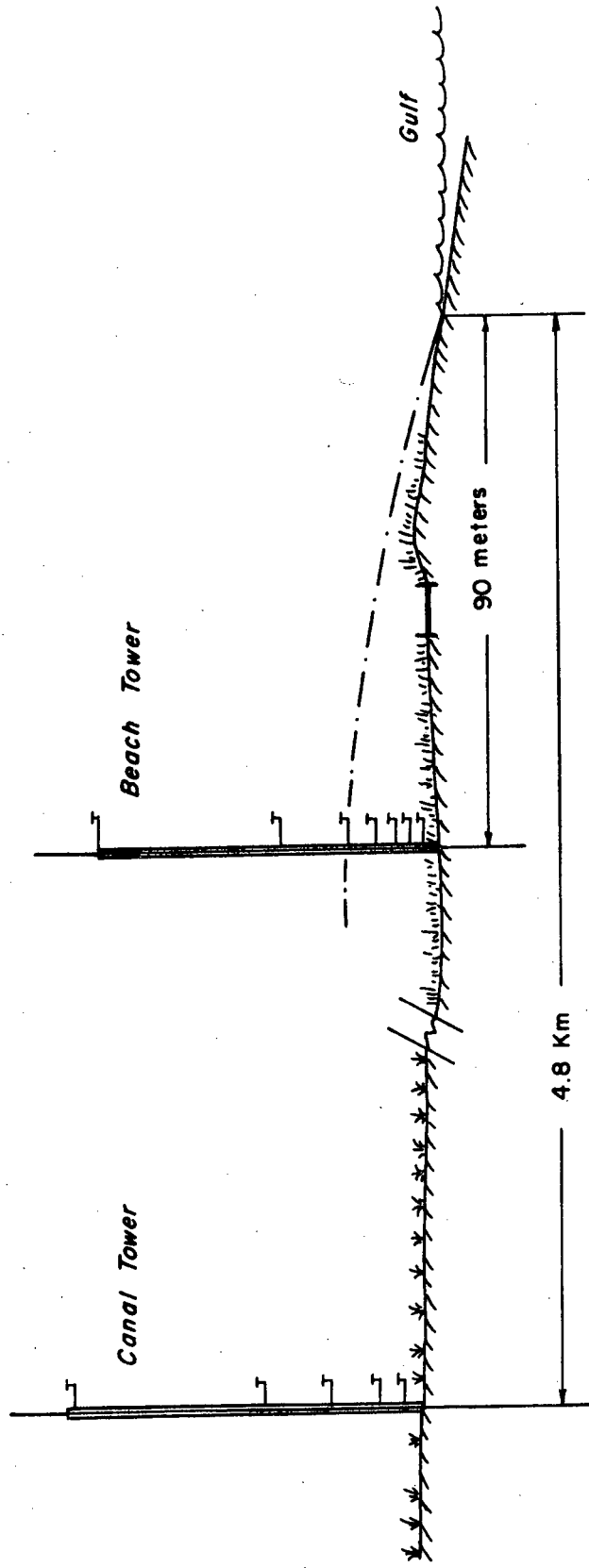


Fig. 3 Cross section of terrain and instrumented tower locations

wind speed. The wind set output signals were input directly to a Precision Instrument 6100 magnetic tape recorder at each site to produce a continuous analog signal. To accommodate the 14 inputs at the beach and 10 inputs at the canal, the signals were commutated at a rate of one per second. Input signals were recorded for one-half second followed by one-half second negative voltage. The commutation began with wind direction, then wind speed at the lowest level, and taking the levels in order up the tower. At the end of each sounding a 1.5 sec reference pulse was recorded, thus requiring a total of 16 sec per sounding. Zeros were read in for the missing levels at the canal, since only 5 levels were instrumented. This commutated signal was fed into one channel of the PI 6100, while another channel was used for a voice recording of tape footage.

To convert the commutated wind data to a form compatible with The University of Texas at Austin CDC 6600 computer, the analog tape was played back on the PI 6100 recorder in the laboratory with the output fed into an analog-to-digital converter. One value was converted from each half second signal after it became electronically stable. This converted signal was recorded on a PI incremental tape recorder while the digitizing was monitored on a dual-trace oscilloscope. The new tape was recorded in external binary coded decimal (BCD) format and was used as input to a computer program run on the CDC 6600.

The PI 6100 recorders had been calibrated so that the output signals from the wind sets ranged from 0.0 to + 1.4 volts (direct current) and the reference signal from + 1.9 to 2.2 volts. However, data values were digitized which fell outside this range. The main reasons for these spurious data are:

1. Noise in the tape recorders.
2. Noise in the commutator.
3. Noise in the A-to-D converter (negative values digitized in place of real data).

The occurrence of this spurious data was infrequent and such data was easily identifiable for the periods analyzed. The computer program which reduced the data was so written that these erroneous values were eliminated.

The arrangement of the data in time, essentially one value at each level every 16 sec, made averaging times of 4, 8, and 12 min most feasible. Averages of wind speed and direction and their standard deviations at each level were made for these three averaging times. Vertical profiles of horizontal velocity, standard deviation of velocity, and standard deviation of wind direction were obtained from the data.

Dry and wet bulb soundings were also made at each tower. Two bead thermistors were mounted in a psychograph housing which was aspirated by a small squirrel cage fan. To obtain a wet bulb reading, one thermistor was covered with a muslin sock which extended into a reservoir of distilled water. The measured accuracy of the thermistors was  $\pm 0.1$  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 decent (about eight minutes each way). The sounding extended from 1.3 to 26.5 m. The thermistor outputs were amplified and recorded on Esterline-Angus strip chart recorders. Side marking pens indicated whether the instrument was in the ascent or decent stage.

### III. DATA ANALYSIS

#### A. General Features of the Available Wind Data

For onshore flow the instruments were placed on the beach tower so that measurements were made both within the developing internal boundary layer as well as above it in the air in equilibrium with a long over-water trajectory. 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 (Wagner, 1966).

Wind and temperature data were available for analysis from portions of four days beginning 14 June and ending 17 June 1968. The data on the 14th were recorded from 1412 CDT to 2208 CDT at the beach tower only. During this period moderate onshore flow occurred with very little cloudiness to inhibit radiational heating during the day or cooling in the evening. Continuous recording of data occurred from 2245 CDT on the 15th to 0730 CDT on the 17th at both sites. A land breeze began after 0500 CDT and isolated rainshowers disturbed the flow until 1430 CDT on the 16th. Data were not analyzed during this period of deviation from onshore flow. Canal data were not usable until just before midnight on the 15th. During the day on the 16th, winds were not as strong as on the 14th and there was some increase in cloudiness. By 2115 CDT on the 16th the effects of an approaching thunderstorm line were noticed and all data after that period were affected by rainshowers and thunderstorms in the area. For this reason, data for the 16th were only analyzed for 1600-2100 CDT at both beach and canal. Unfortunately, the 27 m level anemometer output at the canal had not been connected and no wind speed data were available for that level until the last 65 min of the analysis period.

Analysis of the mean wind direction during the periods to be considered indicates onshore flow perpendicular to the coast to within  $\pm 15$  degrees. For this analysis, parcels of air passing the beach tower would be expected to pass near the canal site some 20 to 30 min later, depending on the wind speed. The variation of wind speed with time for the periods analyzed at each site are given in Figs. 4, 5, 6, 7, and 8.

#### B. Determination of Roughness Parameters

To determine the roughness parameter of the land surface at the beach and canal and an extrapolated value for the profile over water, we will assume the log-law relationship for the wind profile. As stated in Section I, the roughness parameter  $Z_0$  is determined by the intersection of a straight line through the wind speed values on a vertical logarithmic scale with the height scale where the mean wind speed is zero. That is, for  $\bar{U} = \frac{U_*}{k} \ln(Z/Z_0)$ , the slope is  $U_*/k$ , and  $Z_0$  is the Z-axis intercept. For micrometeorological sites where tall vegetation covers the surface, a zero-plane displacement should be considered before analysis for  $Z_0$  values is performed. This was not necessary for the beach and canal sites in this analysis.

Since adiabatic conditions are assumed for the log-law relationship, near adiabatic conditions should exist for  $Z_0$  determination. The air flowing off the sea at the beach site has a short overland trajectory and any heating or cooling would be expected to occur in a shallow layer near the ground. According to Roll (1965) adiabatic thermal stratification occurs quite frequently over the lower layers above the sea, thus the log-law wind profile should be valid for this condition. We would expect the air flowing off the Gulf at the beach site to be in equilibrium after its long over-water fetch. Only the lower layers of the profile at the beach site would be affected by the

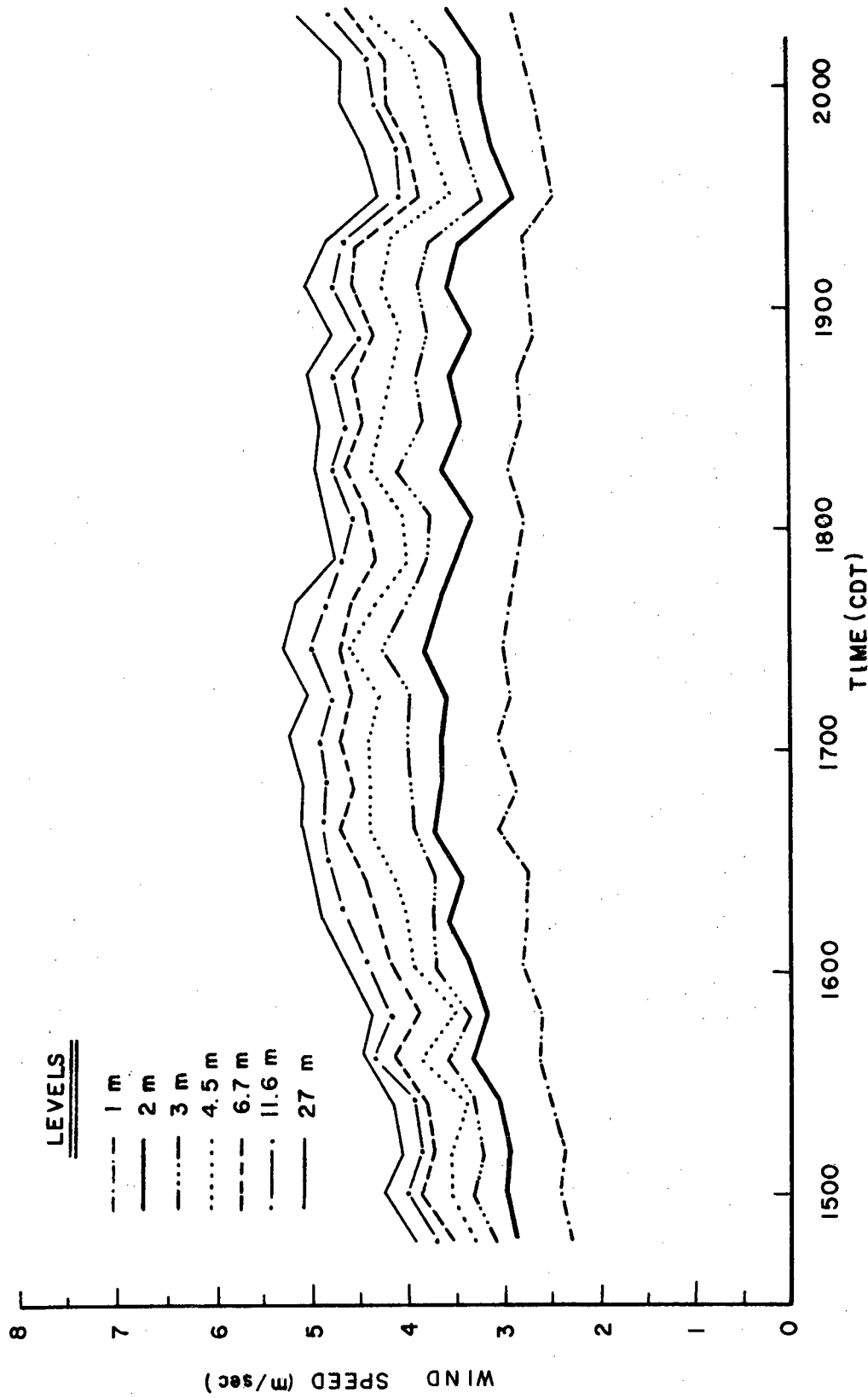


Fig. 4 Wind speed 14 June at beach site (day)

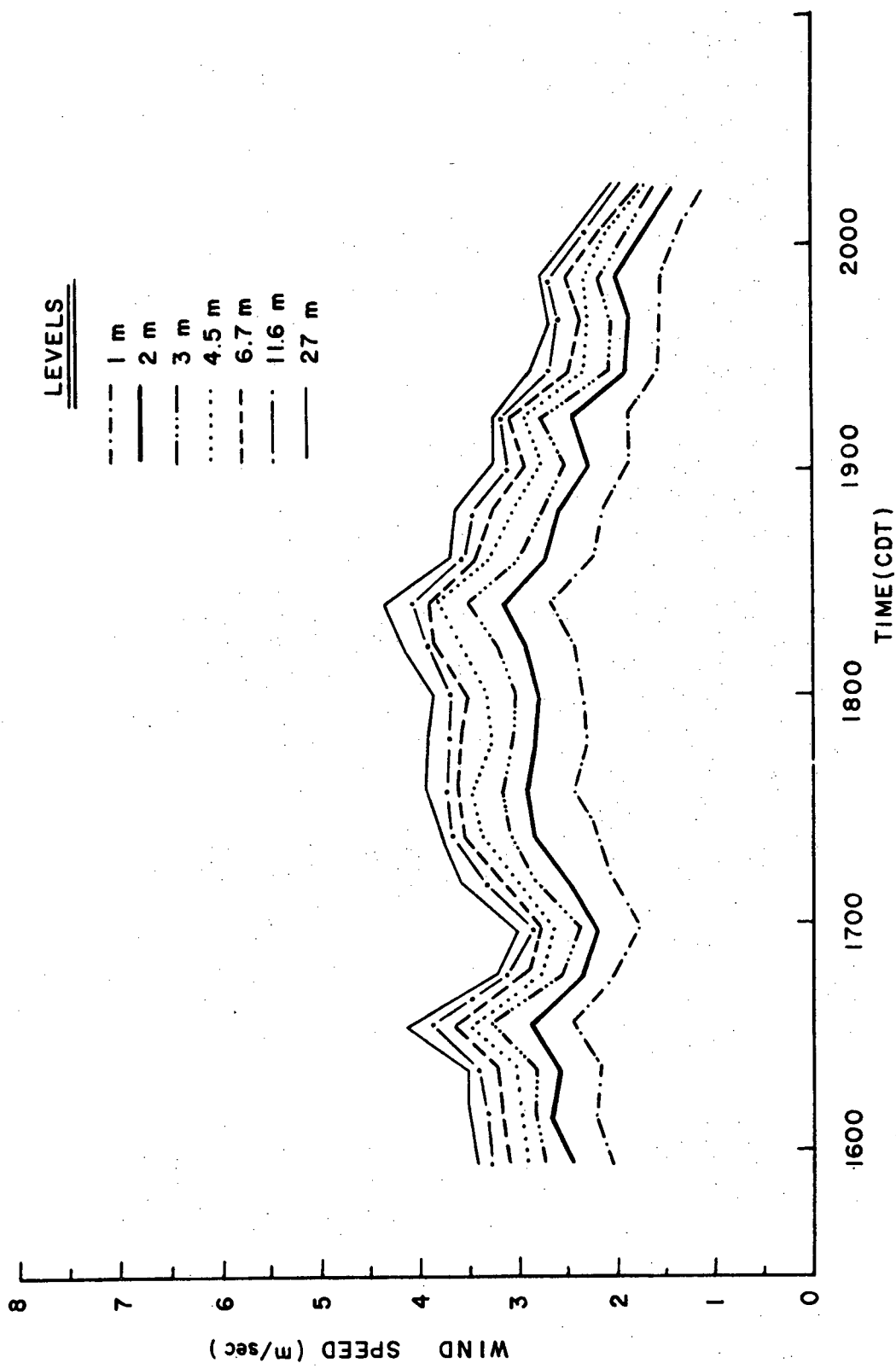


Fig. 5 Wind speed 16 June at beach site (day)

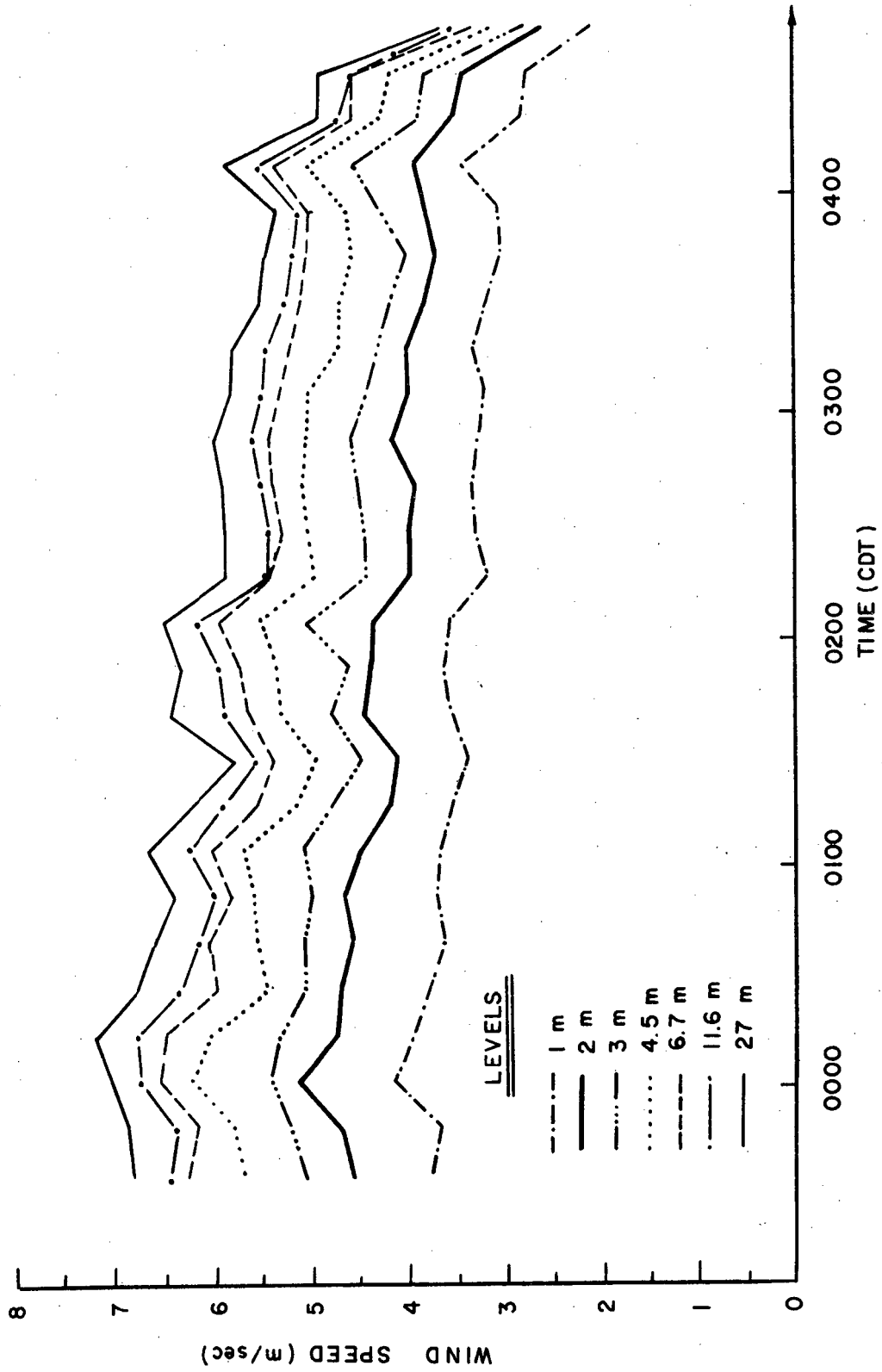


Fig. 6 Wind speed 16 June at beach site (night)

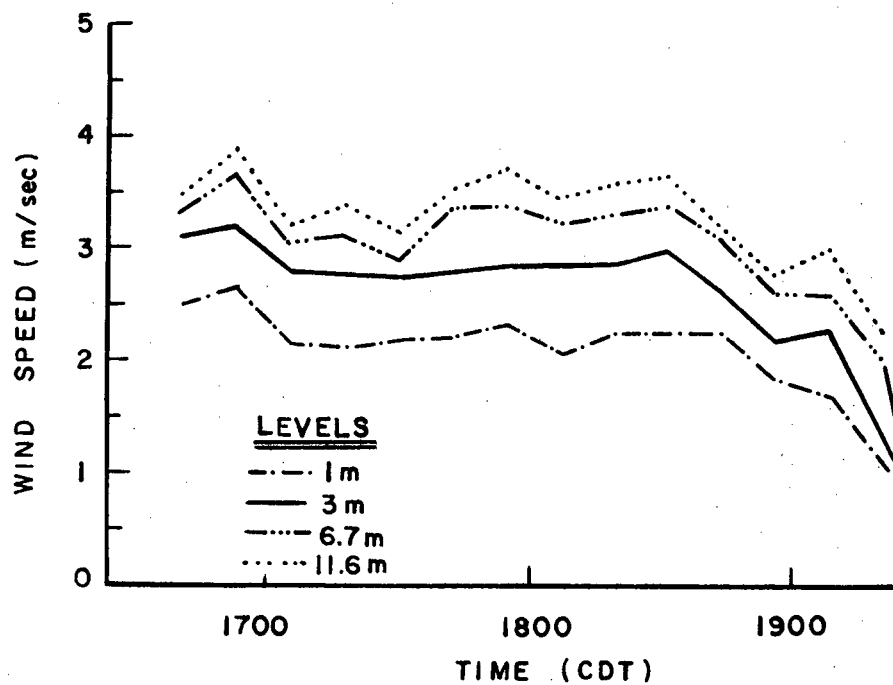


Fig. 7 Wind speed 16 June at canal site (day)

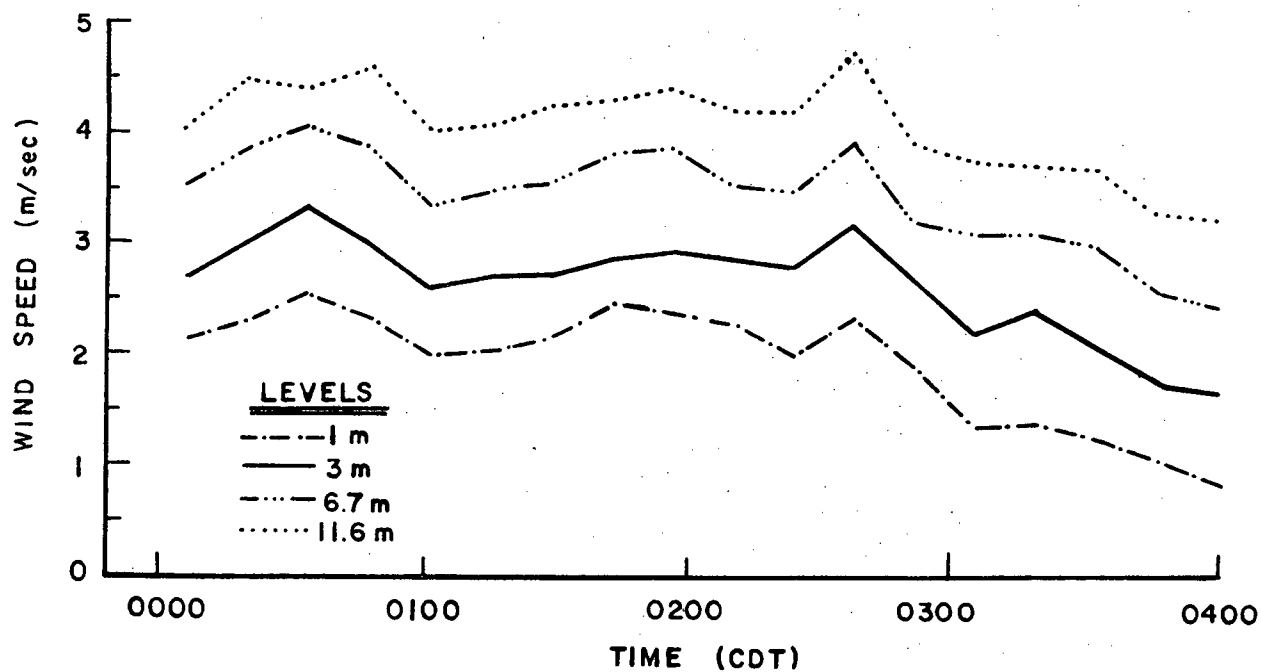


Fig. 8 Wind speed 16 June at canal site (night)

land surface while the upper profile still reflects over-water conditions (Blom and Wartena, 1969). Nickerson (1968) points out that the initial logarithmic profile will undergo a gradual transition of slope to one characteristic of the new value of friction velocity and surface roughness. The changes occur in the lower portion of the profile and are largest just downstream from the change in surface roughness.

To obtain meaningful profiles from the data as recorded on the 14th, 15th, and 16th of June, the 4, 8, and 12 min means were examined in a time sequence as they were recorded. The results indicate two things:

1. The 4 min averages were too short to completely eliminate the effect of non-simultaneous sampling of the wind-set levels, while the 8 min means showed less effect. The 12 min mean was chosen as the best of these three averaging periods.

2. Periodic rising and falling of the wind made considerable spread in wind speed values at a given level when averaged profiles were plotted consecutively for a one to two hour period.

To obtain profiles which would be more representative of a longer term average, the mean profiles for the different averaging times 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. Mean profiles were then computed from the grouped profiles. The limits on the second level wind speeds were 1.0 to 1.5, 1.5 to 2.0, 2.0 to 2.5, ... 4.5 to 5.0 m/sec. Calculated means containing less than five profiles were generally not considered. Then for the 12 min averages, the new means would represent at least a one hour mean of wind speeds within a restricted velocity band. Where there was little data for a particular velocity band some means with less than 5 points were used.

All data points considered in the average were plotted but only the profile representing the arithmetic mean for each level was drawn. Straight lines were used to connect these means and, in most cases the means lay in a straight line (on a semi-logarithmic plot). There were two cases when the means did not lie on a straight line. One case was when large variations from adiabatic stratification occurred. The other was due to a discontinuity associated with the internal boundary layer at the beach. Some of the profiles are shown in Figs. 9 through 13. Of the points considered for each mean, ninety percent lie within the limits shown.

Sutton (1953) gives a summary of roughness lengths determined experimentally for various natural surfaces. Some of his values for  $Z_0$  are 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 as described by Sutton. We might then expect the roughness values as determined from the mean profiles to lie within a 2.3 to 5 cm range. Daytime profiles under nearly adiabatic conditions at the beach give  $Z_0$  values very near 3 cm (14 June) and range between 3 and 4 cm for 16 June. The values were determined using only the lower 4 to 5 levels. Nighttime values (midnight to 0400 CDT on 16 June) give  $Z_0$  values near 5 cm. Slight concave curvature (indicative of stability) was noticed in the nighttime profiles (Fig. 11). This slight curvature may be responsible for the higher values of roughness at night as compared to the daytime values. No data were available below one meter to completely describe the curvature so the available profile would tend to overestimate  $Z_0$  for the nighttime cases.

Deacon (1953) introduced the Richardson number ( $Ri$ ) as the basic parameter in describing the stability criteria for wind profiles. The profiles

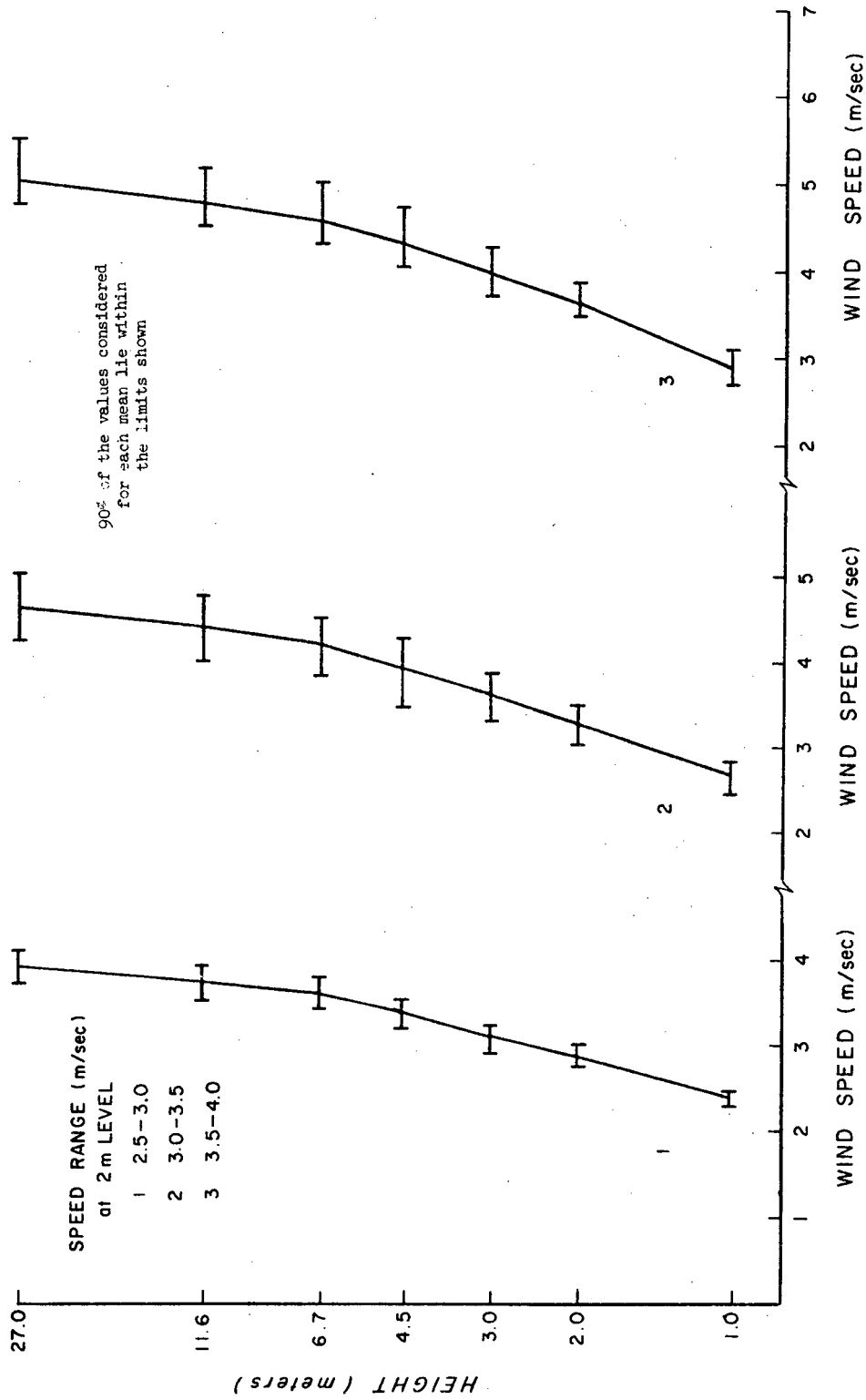


Fig. 9 Vertical profiles of horizontal velocity at beach site 14 June (day)

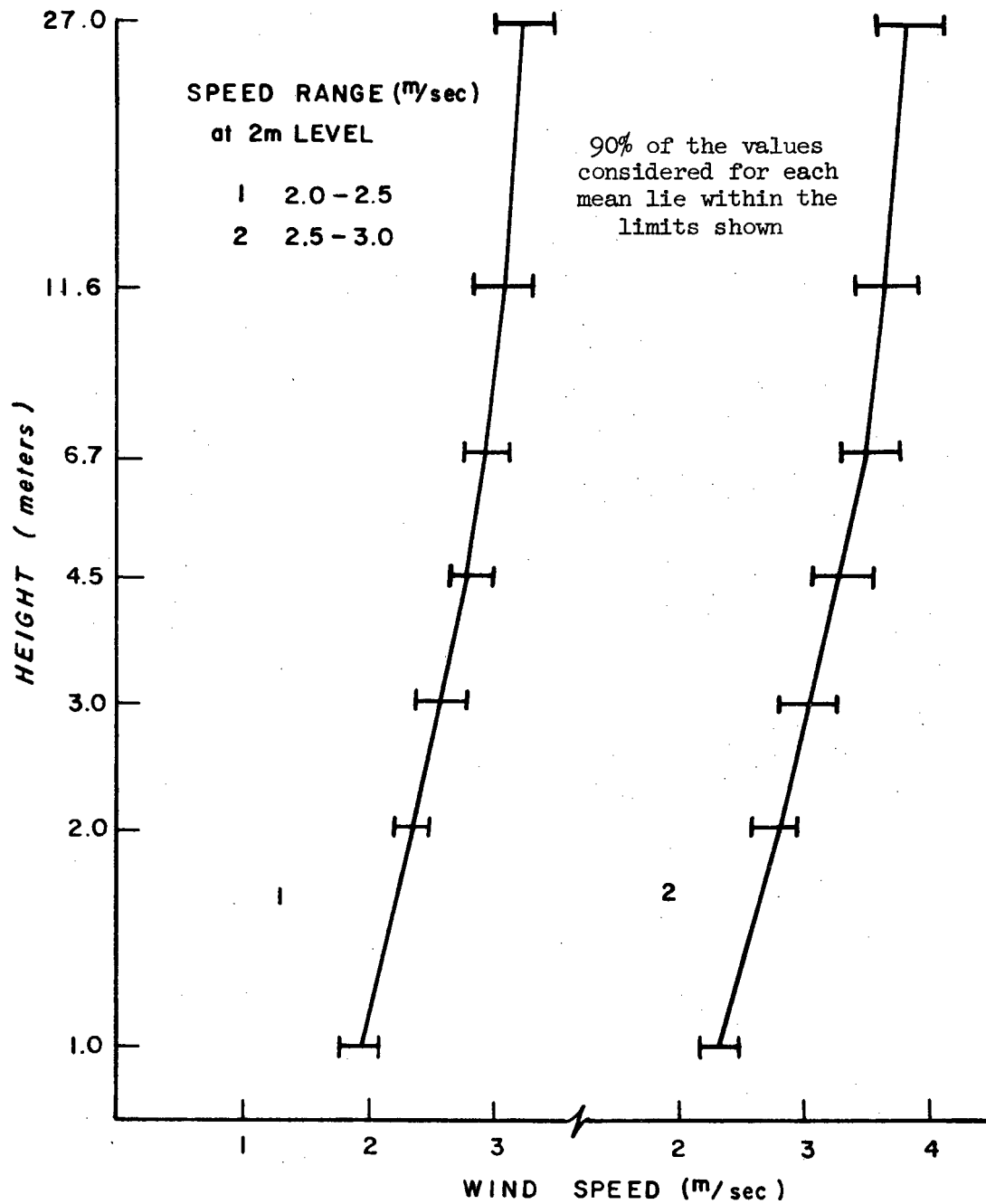


Fig. 10 Vertical profiles of horizontal velocity at beach site 16 June (day)

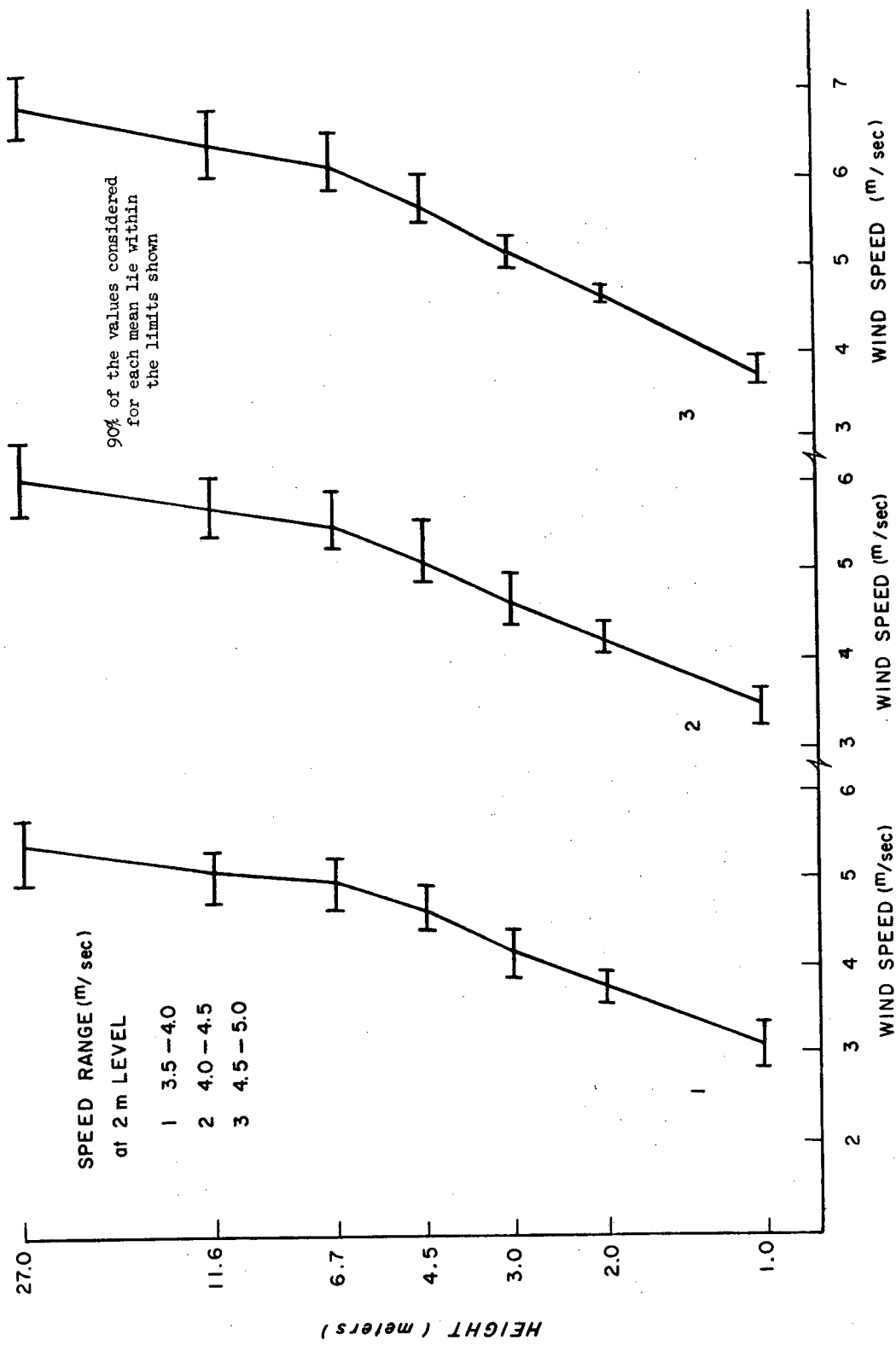


Fig. 11 Vertical profiles of horizontal velocity at beach site 16 June (night)

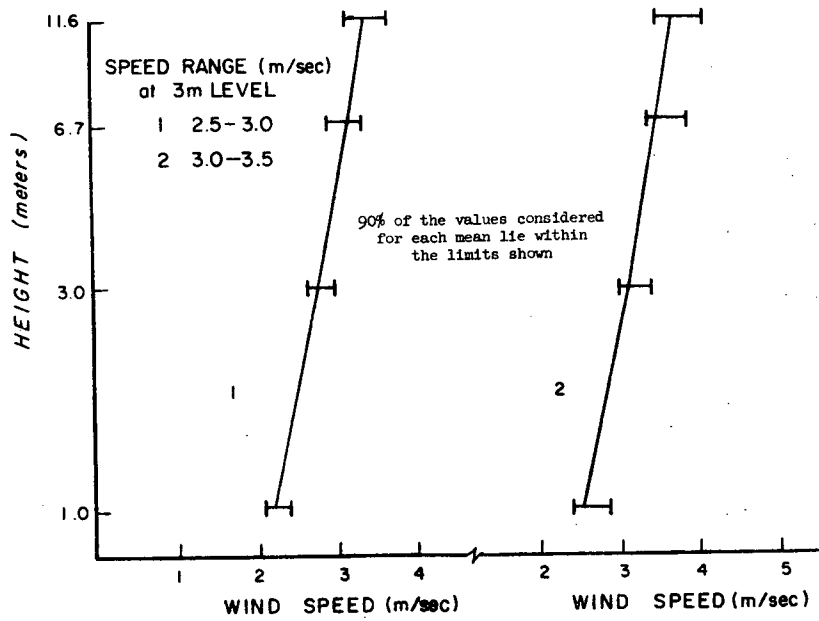


Fig. 12 Vertical profiles of horizontal velocity at canal site 16 June (day)

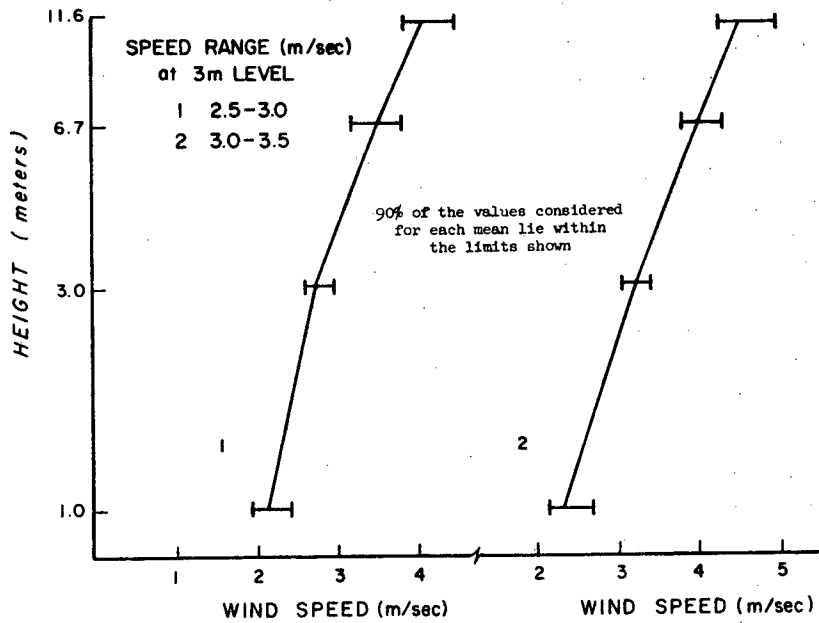


Fig. 13 Vertical profiles of horizontal velocity at canal site 16 June (night)

are classified according to the sign and magnitude of  $Ri$ , where  $Ri < 0$  implies a superadiabatic temperature profile and a convex wind profile,  $Ri = 0$  implies a neutral atmosphere and straight logarithmic wind profile, and  $Ri > 0$  implies an inversion of potential temperature ( $\theta$ ) and a concave wind profile. The gradient form of  $Ri$  may be calculated using

$$Ri = \frac{(g/\bar{\theta}) (\partial\theta/\partial z)}{(\partial\bar{u}/\partial z)^2}$$

where  $g$  is gravitational acceleration and  $\bar{\theta}$  the mean potential temperature through the layer considered. The Richardson number is related to the Deacon number  $\beta$ , where the relation  $\frac{d\bar{u}}{dz} = aZ^{-\beta}$  expresses the wind profiles for various stabilities. The relationship given by Deacon is

$\beta > 1$  for  $Ri < 0$       superadiabatic

$\beta = 1$  for  $Ri = 0$       neutral

$\beta < 1$  for  $Ri > 0$       inversion

where  $\beta$  can be calculated from  $\beta = \frac{\log(U_*/kZ_0) - \log(\partial\bar{u}/\partial z)}{\log(Z/Z_0)}$

The values of  $Ri$  and  $\beta$  found for the lower levels at the beach site are summarized in the table below.

	$Ri$	$\beta$
14 June (day)	-.025	1.02
16 June (day)	-.025	0.99
16 June (night)	-.008	1.03

Sutton and others (Sutton, 1953) have found that the logarithmic profile does not hold in conditions of marked density gradients, thus making the evaluation of  $Z_0$  a function of thermal stratification. The values of  $Ri$  obtained at the beach, however, do not indicate strong gradients and the Deacon numbers reflect a near-logarithmic profile. The values seem to support the validity of the determination of roughness values from the beach site wind profiles.

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 portions of that over water profile. According to Roll, Munk, and others (Roll, 1965) the sea surface can be assumed to be aerodynamically smooth for wind speeds less than 6 to 7 m/sec as measured at a height near 10 m. Above that speed a change of the sea surface from smooth to rough occurs. The wind speeds in the lower levels did not approach or exceed this 6 m/sec limit during the time intervals considered. We would then expect the roughness parameter found from the upper levels at the beach tower to be representative of an aerodynamically smooth surface.

Problems develop when discussing  $Z_0$  values for the sea surface. Since the sea in general is not flat but of swell or wavelike structure with tidal fluctuations, one must consider the displacement of the anemometer levels above the mean sea surface (Wagner, 1958). For most of the observations made in the past, the zero-plane displacement approach has been used and a wide range of values for  $Z_0$  has been obtained. For wind speeds above 7 m/sec Munk found  $Z_0 = 0.6$  cm while Bruch's observations over the Baltic gave  $Z_0 = 0.3$  cm at lower speeds (Sutton, 1953). Roll (1965) reports that values less than 0.1 cm were found by Motzfeld, Portman, Roll and others, while Wagner's results (1958) range

from 0.0005 to 51.0 cm.

Air flowing off the water and over land at the beach site encounters a gentle rise before the land slopes back down to approximately sea level at the base of the beach tower (Fig. 3). For that reason no zero-plane displacement was assumed using the upper level profiles with the base of the tower assumed to be at mean sea level. The values of  $Z_0$  obtained from the upper levels of the beach tower ranged from 0.0001 to 0.0003 cm. This range was noticed for both day and night profiles with no wind speed magnitude preference for either. The relatively low  $Z_0$  values would indicate that the sea was acting as an aerodynamically smooth surface. Wind speeds at the 27 m level ranged from 2.5 to 6.5 m/sec in the profiles used for the  $Z_0$  determination, indicating a rather constant roughness value even with large variations in wind speed.

The terrain between the shore and canal tower some 4.8 km inland is flat and fairly homogeneously covered by grass as described in Section I. 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. Nighttime flow would tend to be stable as compared to the adiabatic structure at the beach because radiational cooling would be occurring at a greater rate over land than over the sea.

Elliott (1958) has presented a theory stating that the internal boundary layer downstream of a change in surface roughness grows at a rate of approximately 1:10 compared to downstream distance. Elliott has also indicated that the depth of this layer is increased slightly for an unstable lapse rate

and decreased slightly for stable conditions as compared to the neutral case. Panofsky and Townsend (1964) predict a somewhat slower growth rate of about 1:20. Both of the theories predict that the canal tower would be totally submerged in the internal boundary layer having an origin near the shoreline.

Vertical profiles of horizontal wind speed at the canal site were obtained only during the onshore flow periods from just before midnight on 15 June to about 2200 CDT on 16 June. Because of a thunderstorm line which passed the canal site at 2135 CDT 16 June the inputs to the tape recorder were disconnected at about 2200 CDT. No data were available after that time. Unfortunately, the 27 m level at the canal was not connected until some 65 min prior to the thunderstorms, giving only a short period of measurement at all instrumented levels. The wind speed at the 1 m level was below 1 m/sec at this time so only the other four levels gave meaningful values. The 65 min data including the top level allowed the discovery of a tape recorder calibration error for the 11.6 m level. Profiles during this period are nearly straight lines except for the 11.6 m level which deviated an average of + 0.23 m/sec from the line. Daytime values at the 11.6 m level were high by this same amount in deviating from the approximately logarithmic profile. Subtracting this observed correction from all data at that level, the resulting profiles were used for roughness parameter determination.

Daytime profiles at the canal site (Fig. 12) are nearly straight lines having only a slight convex curvature indicative of the thermal instability expected at this inland station. Roughness parameter values ranged from 0.8 to 1.5 cm, lower than the 3 to 4 cm found at the beach. These lower values were not unexpected because the grass was shorter and less dense than near the beach site. Although the profiles 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 (Fig. 13) show pronounced stable curvature. Using the lower two anemometer levels the measured value of  $Z_0$  ranges from 1.5 to 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. Richardson and Deacon numbers for the canal site are given below.

	Ri	$\beta$
Canal (day)	-.055	1.0
Canal (night)	+.018	0.93

These values indicate that only slight superadiabatic curvature is expected in the daytime profiles while the nighttime values predict curvature characteristic of stable thermal stratification. The daytime roughness parameter determinations will then be assumed to be the most accurate while nighttime values appear to be too high.

The roughness parameter determinations from the daytime wind profiles at both sites are in good agreement with observations of others with respect to the upstream surface characteristics. The  $Z_0$  values found at both sites for the June 1968 experiment are summarized in Table 1.

Examination of the beach site wind profiles shows a "kink" in the profile at approximately the 6.7 m level. Previously it was assumed that this was the top of the newly developing internal boundary layer and straight lines had simply been used to connect the different levels. This method would not define the height of the internal boundary layer if it were above or below the

Table 1: Roughness length  $Z_0$  (cm) as determined at each tower site.

Site	Day	Night
Beach 14 June	3	No Data
Beach 16 June	3 to 4	5
Canal 16 June	0.8 to 1.5	1.5 to 3
Beach (over water)	0.0001 to 0.0003	

6.7 m level because only a gradual curvature would be observed in the profile at that level. Since the logarithmic profile is assumed both below and above this level, the height of the layer might be better determined by an intersection of the straight lines from each regime. Straight lines would then be used to connect levels adjacent to the 6.7 m level only when it fell very near the profiles passing through the adjacent level. When curvature was observed in the profiles it was considered when drawing for the 6.7 m level. The point of intersection of the two profiles might then be assumed to be the approximate height of the internal boundary layer as shown in Fig. 14.

As previously mentioned, Elliott (1958) gave a value for the slope of the new internal boundary layer of 1:10 for large downwind distances. However, just downwind of the change in surface roughness Elliott's data suggests a larger slope for the internal boundary layer. In our case, his results would give a height of about 16 m for the top of the layer at the beach tower for winds blowing directly onshore. The observation of heights near 6.7 m for our data at the beach falls somewhat below this theoretically predicted value. Elliott also pointed out that the height of the layer increases slightly for daytime (unstable) conditions and decreases slightly for nighttime (stable) conditions. Fig. 14 shows the day and night profiles. The daytime profiles

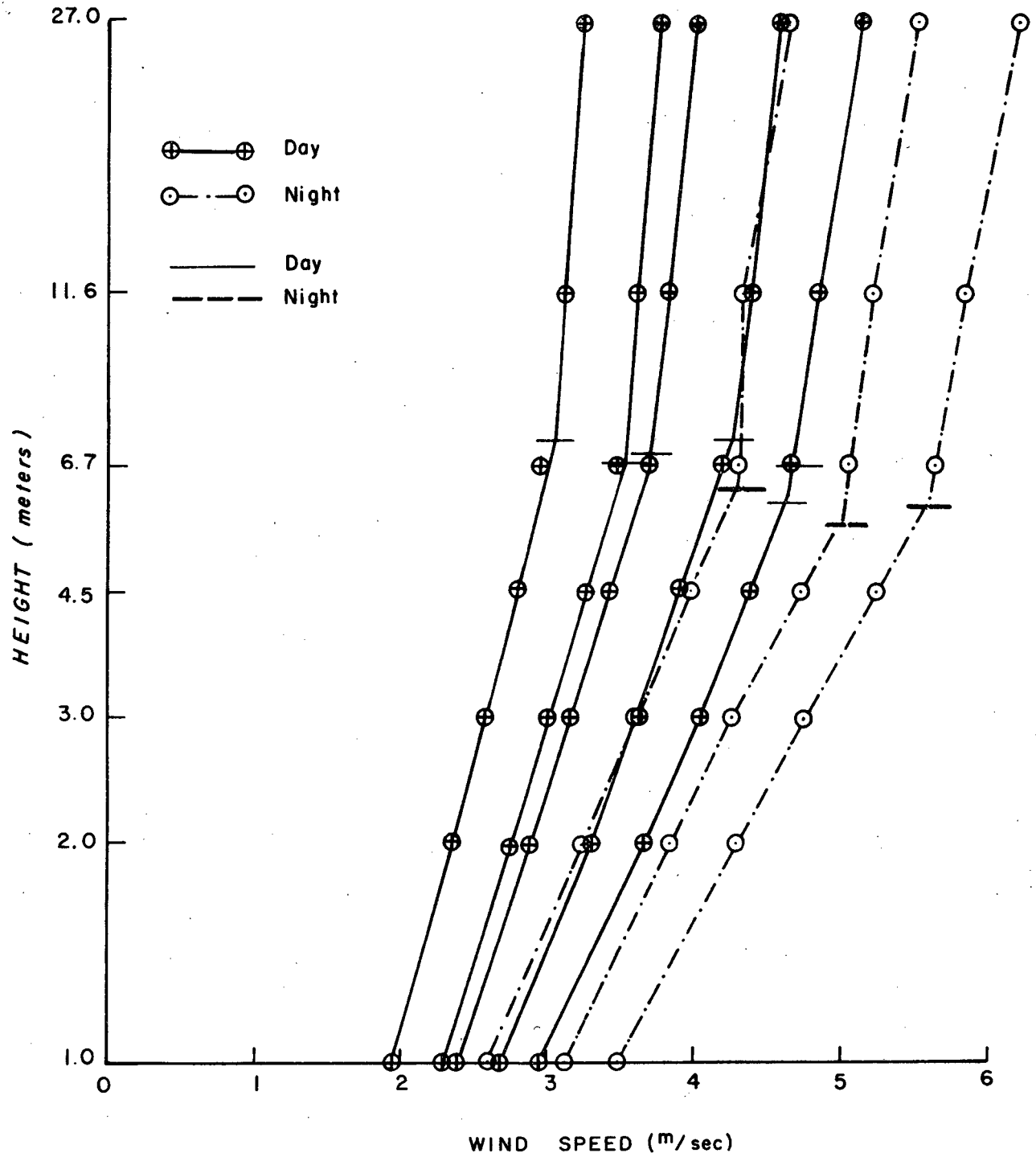


Fig. 14 Estimation of height of internal boundary layer for day and night at the beach site

indicate the height of the top of the layer to be at or slightly greater than 6.7 m except for one occurrence at 6 m for a higher mean wind speed. Nighttime values range from approximately 6.2 to 5.6 m.

### C. Friction Velocity

The friction velocity  $U_*$  is directly proportional to the slope of the logarithmic wind profile with a value nearly constant through an adiabatic layer in equilibrium with the underlying surface (Taylor, 1969). When a change in surface roughness occurs, the lower portion of the profile is altered causing a sharp change in the slope of the profile (Panofsky and Townsend, 1964), which we will interpret as a change in  $U_*$ . For an increase in surface roughness, a sharp increase in  $U_*$  is expected in the newly forming internal boundary layer (Peterson, 1969). With increasing downwind fetch, the layer thickens and approaches an equilibrium value for  $U_*$  which is less than that after the roughness change, but greater than the original equilibrium value (Blom and Wartena, 1969). Wagner (1966) finds that the fetch required to approach 90 percent of the equilibrium value is 5 km or greater. The canal tower is 4.8 km from the shore and it may be profitable to calculate the friction velocity at each site for comparison with the theory.

The profiles most representative of each period were chosen in order to calculate  $U_*$ . Roughness values of 3 cm for the lower levels at the beach, 0.0002 cm for the upper levels at the beach and 1.5 cm for the canal were used. To indicate the decrease in  $U_*$  for levels above the internal boundary layer, values were calculated for the top levels using the roughness value of 3 cm characteristic for the lower profile. The 6.7 m level had friction velocity calculated under both regimes since the top of the boundary layer is suspected to be near that level. Tables 2 through 5 give the friction velocity, roughness

Table 2: Calculated Values of Friction Velocity for the Beach Site 14 June (day).

Z (m)	$\bar{U}$ m/sec	$Z_o = 3.0$ cm	$Z_o = 0.0002$ cm
		$U_*$ cm/sec	$U_*$ cm/sec
1.0	2.67	30.5	
2.0	3.27	31.1	
3.0	3.59	31.2	
4.5	3.89	31.1	
6.7	4.20	31.1	11.2
11.6	4.39	29.1	11.5
27.0	4.62	27.2	11.5

Table 3: Calculated Values of Friction Velocity for the Beach Site 16 June (day).

Z (m)	$\bar{U}$ m/sec	$Z_o = 3.0$ cm	$Z_o = 0.0002$ cm
		$U_*$ cm/sec	$U_*$ cm/sec
1.0	2.29	26.2	
2.0	2.75	26.2	
3.0	2.99	26.0	
4.5	3.27	26.1	
6.7	3.47	25.7	9.2
11.6	3.61	24.2	9.3
27.0	3.79	22.3	9.3

Table 4: Calculated Values of Friction Velocity for the Beach Site 16 June (night)

Z (m)	$\bar{U}$ m/sec	$Z_o = 3.0$ cm	$Z_o = 0.0002$ cm
		$U_*$ cm/sec	$U_*$ cm/sec
1.0	3.10	35.4	
2.0	3.82	36.3	
3.0	4.23	36.8	
4.5	4.72	37.7	
6.7	5.07	37.5	13.5
11.6	5.21	35.0	13.4
27.0	5.54	32.6	13.5

Table 5: Calculated Values of Friction Velocity for the Canal Site 16 June.

Z (m)	(Day) $Z_o = 1.5$ cm		(Night) $Z_o = 1.5$ cm	
	$\bar{U}$ m/sec	$U_*$ cm/sec	$\bar{U}$ m/sec	$U_*$ cm/sec
1.0	2.23	21.1	2.15	20.3
3.0	2.82	21.0	2.76	20.6
6.7	3.22	20.8	3.54	22.9
11.6	3.45	20.6	4.17	24.9

and wind speed used for each level.

The daytime beach profiles show nearly constant  $U_*$  values in the suggested internal boundary layer (Tables 2 and 3) verifying the logarithmic assumption in calculating roughness values. The upper profile using the aerodynamic roughness of 0.0002 cm gives friction velocity values which are significantly lower. The small variability in the vertical for the upper level values supports the logarithmic assumption for over-water profiles. Extending this assumption to conclude that the upper level friction velocity values are representative for the lower levels over the sea, we can see the large predicted increase in  $U_*$  for the increase in surface roughness (Wagner, 1966). These results agree with those of Kutzback (Lettau, 1961) in wind profile modification over the ice on Lake Mendota using inverted bushel baskets as a roughness control. Our nighttime results (Table 4) indicate a slight increase in  $U_*$  from the surface to near 6.7 m with a rapid decrease above. Using the over water roughness parameter, upper level values are again nearly constant, indicating no detectable change in the stability of the marine air. The increase in  $U_*$  in the vertical for the lower levels points out that cooling of the land is significant enough in the 90 m seaward from the tower to increase the stability slightly in the adapted layer at night.

Calculations of friction velocity for the canal during the day (Table 5) indicate a slight decrease in the vertical. This decrease points out the small deviation of the profile from logarithmic toward the unstable superadiabatic regime. Apparently, turbulent mixing has been sufficient to maintain a nearly logarithmic profile. The nighttime values increase rapidly above the 3 m level but are constant below. This increase is characteristic of the stable regime set up by the 4.8 km trajectory of the air over the cooling land. The constancy in the lower levels may indicate that a logarithmic profile does exist

up to that 3 m level. When examining the change in the  $U_*$  with a change in surface roughness, we see the expected sharp increase in values at the beach site lower levels (Tables 2, 3, and 4). Inland there is a gradual approach toward an equilibrium value of  $U_*$  which is smaller than at the beach, but larger than that over water. For the higher wind speeds there is only a small increase in the over-water friction velocity compared to the large increase at the beach lower levels. The largest increase in friction velocity would be expected at or just inland of the change in surface roughness at the shoreline.

D. Kinetic energy calculations for beach and canal sites.

The wind speeds at the different levels for each site may be converted to kinetic energy per unit mass by simply squaring the speed and dividing by two or  $KE = \bar{U}^2/2$ . The kinetic energy is in units of joules/kg. Calculating values for each level one may see the variation in kinetic energy in the vertical with time between the two sites. The availability of the canal data is the limiting factor determining what periods may be analyzed.

A time lag had to be considered when calculating the kinetic energy difference ( $\Delta KE$ ) between the beach and canal since 20 to 30 min was required for a parcel of air to travel this distance. A mean value of kinetic energy was calculated for each level every 30 min. Three values from the 12 min averages nearest that time were used, giving an approximate 36 min mean centered on the hour and half-hour for the daytime data and quarter and three-quarter hour for nighttime data. The availability and arrangement of the data in time dictated this scheme. The mean value for the one-meter level at the beach would then be subtracted from the canal value for 30 min later. This procedure was carried out for the same levels at each site and the kinetic energy difference plotted at the midpoint in time between the two values. Thus, a beach

are much higher than during the day while day and night values at the canal are much the same in the upper levels, but lighter in the lower. Figs. 5 through 8 show the average wind speeds for each site and time of day for the periods analyzed.

Figure 15 shows the kinetic energy difference between the beach and canal as a function of time and level for the daytime and early evening case. Very little difference in kinetic energy is observed at the beginning of the period with the canal kinetic energy slightly larger than that at the beach. Yu's analysis of daytime cases also showed very little difference between the marine and inland stations but the marine kinetic energy value was slightly higher. This minor difference between the two analyses may be attributed to the fact that the mean winds were stronger in Yu's study. Our lighter winds would allow sea breeze type accelerations inland and other perturbations on the flow to be more pronounced thus permitting the possibility of higher kinetic energy inland. As observed by Yu, the small kinetic energy difference indicates that kinetic energy dissipation through turbulence is being compensated for by solar heating with conversion of internal to kinetic energy.

Sunset occurred at approximately 2030 CDT. Prior to that time the reduced solar heating in the late afternoon, causing a reduction in internal energy conversion, appears with a reversal in kinetic energy difference. The overland flow, unable to maintain itself against the frictional loss without internal energy conversion, begins to slow down faster than the beach flow. The onshore flow at the beach is approaching its daily minimum before the late evening resurgence. The maximum daytime and early evening kinetic energy differences are just over 2.3 joules/kg in the upper levels with less than 1 joule/kg difference at the one meter level.

The calculation of  $\Delta KE$  between the sites for the nighttime case

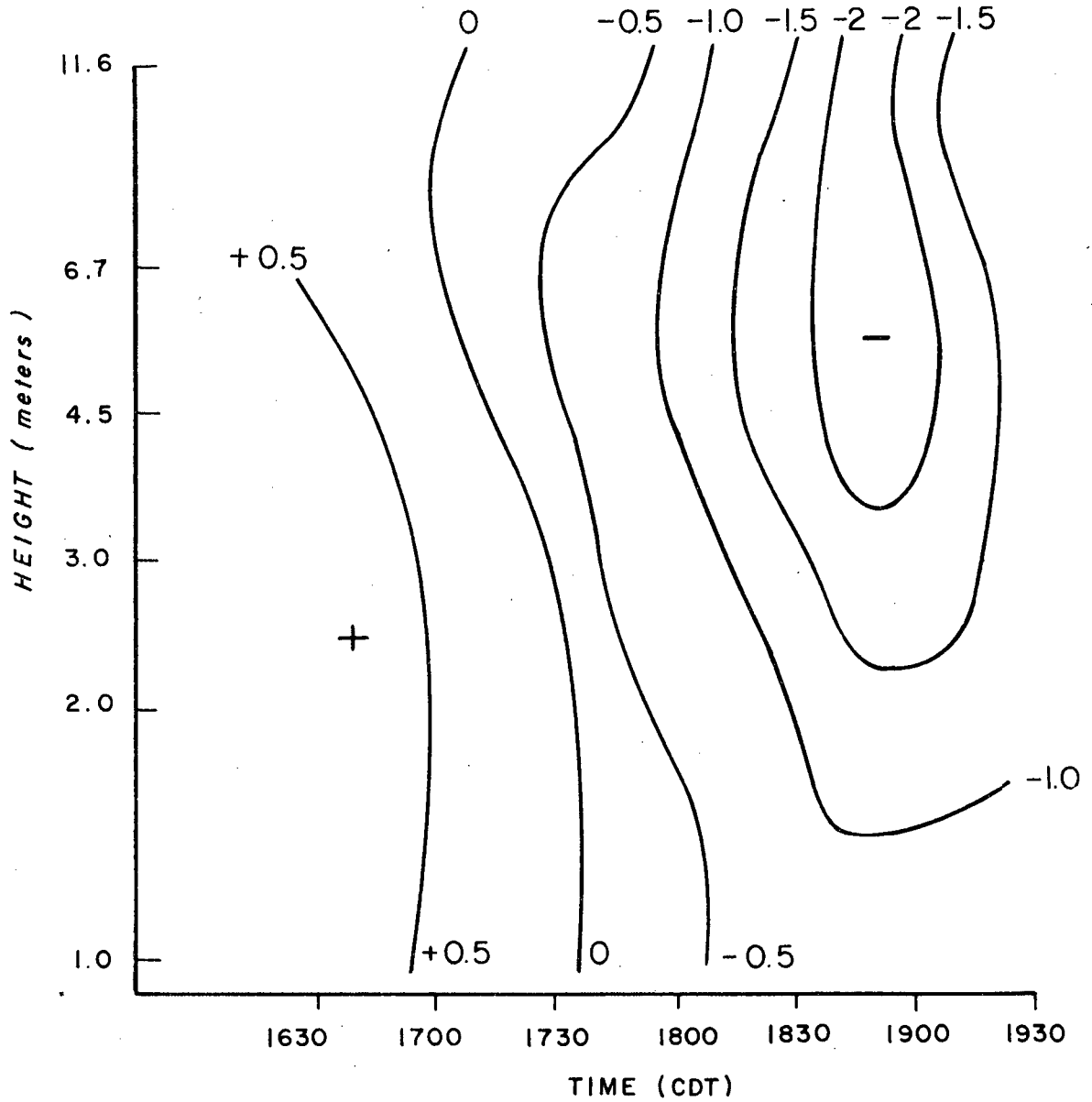


Fig. 15 Vertical distribution of kinetic energy change in joules/kg between the beach site and canal site (day)

(Fig. 16) yields much larger values of kinetic energy loss inland than the afternoon case. Differences at the one meter level range from 3 to nearly 5 joules/kg while upper level values are greater than 12 joules/kg at the beginning of the period coinciding with the midnight maximum at the beach. These results agree well with Yu's findings for nighttime kinetic energy differences at the two meter level. From Yu's graphs of wind speed for the equivalent beach and canal sites, calculated kinetic energy differences range from approximately 11 joules/kg near midnight decreasing to 8 joules/kg near 0400 CDT. Intermediate values at the two-meter level from Fig. 16 give  $\Delta KE$  to be approximately 8 joules/kg near midnight to a minimum of 5 to 6 joules/kg near the end of the period. The smaller values for the tower analysis may be attributed to the fact that Yu's data was taken under stronger onshore flow.

Comparison of the day and nighttime kinetic energy differences point out the large energy loss inland through friction at night and compensation for this loss during the day by conversion of internal to kinetic energy. For a discussion of this energy conversion process in a coastal region see Yu (1970). Comparison of Figs. 15 and 16 also indicates much larger variation in the vertical at night than in the day. This difference implies that the atmosphere is well mixed during the day with sea breeze type accelerations occurring over the heated land. At night no energy source is available to replace the loss of kinetic energy due to friction for the inland station. An apparent maximum of kinetic energy loss at the 6.7 m level is evident from the figures. This maximum occurs in conjunction with the height of the internal boundary layer at the beach. At this height the slope of the beach wind profile changes (as defined by  $U_x$ ) producing the relative maximum. This finding supports the placing of the height of the new internal boundary layer at the beach near the 6.7 m level.

Although no tower data were available between the shore and the beach tower, Yu's analysis points out that significant reduction in wind speed occurs

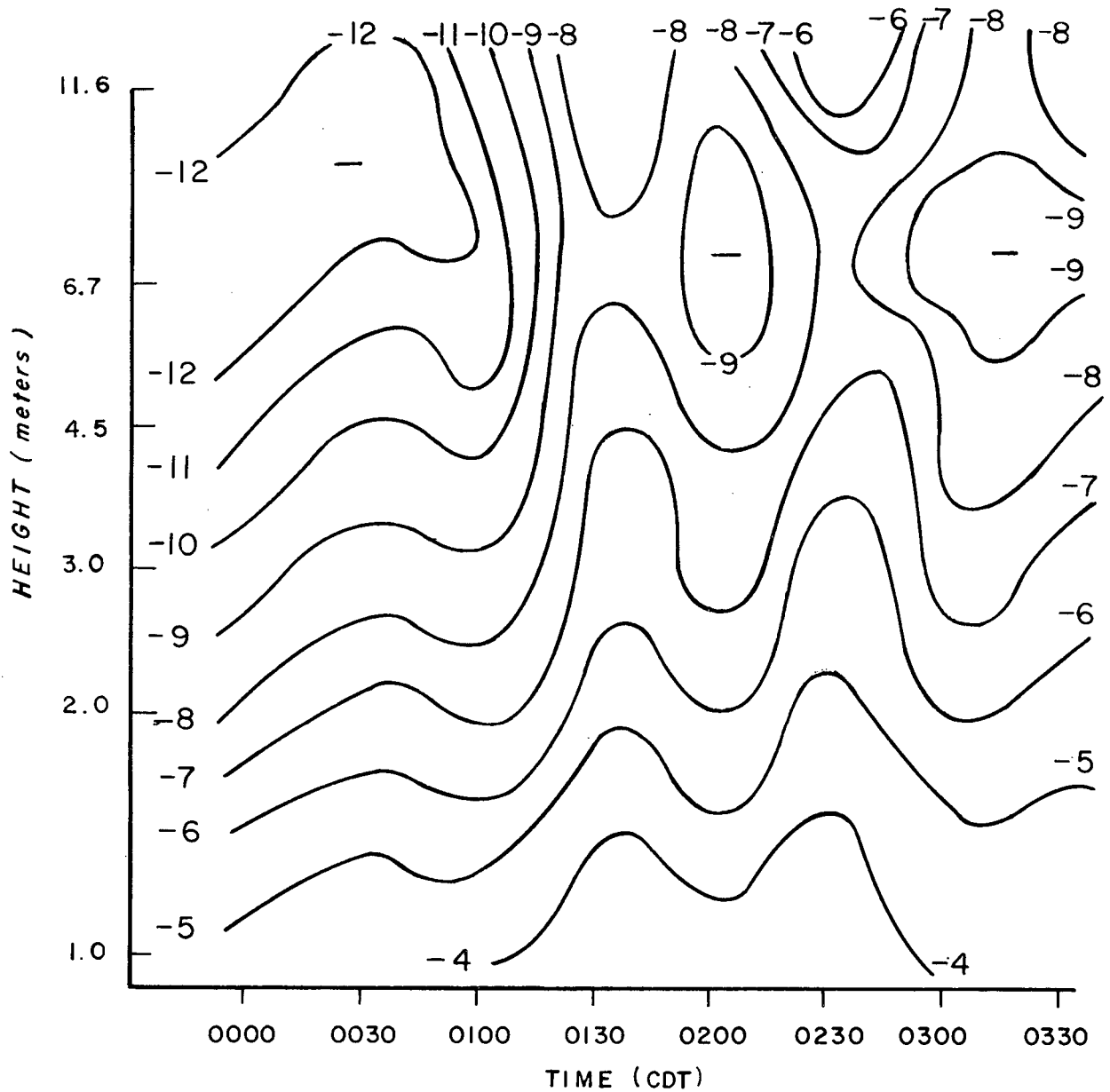


Fig. 16 Vertical distribution of kinetic energy change in joules/kg between the beach site and canal site (night)

in the lower levels in the first 90 m of overland flow. Per unit distance, the greatest reduction in kinetic energy occurs in this first 90 m for Yu's data. The tower data can be used to synthesize a theoretical over-water profile using the top three levels at the beach. Since the linear variation of wind speed with the logarithm of height was assumed for the over-water profiles, the three wind speed values at the top of the tower can be extrapolated downward to the four levels below to give theoretical over-water wind speed values at these levels. The kinetic energy difference between the theoretical and observed overland values can be calculated giving an estimate of the kinetic energy loss as the air passes from water to 90 m inland.

The profiles used for this estimate will be the representative profiles previously chosen to determine the height of the internal boundary layer (Fig. 14). These were chosen because both day and night cases are included, a reasonable wind speed spread is represented, and each profile represents a long term mean within its velocity band. The day case includes profiles from both 14 and 16 June with the night case from after midnight on the 16th.

Figs. 17 and 18 show the vertical distribution of kinetic energy loss from water to land as a function of the 27 m mean wind speed. The top level wind speed was chosen as a reference because it is farthest removed from the internal boundary layer and should reflect the undisturbed flow over water. The day case (Fig. 17) shows that the largest kinetic energy loss occurs at the lowest level with decreasing loss in the vertical. The greatest loss between the beach and canal towers for the day case (Fig. 15) occurred near the 6.7 m level. The difference suggests that the largest kinetic energy loss between two sites after an increase in surface roughness coincides with the lowest level to which the undisturbed flow extends at the upwind site. Fig. 17 also shows that, in general, kinetic energy loss at all levels increases with

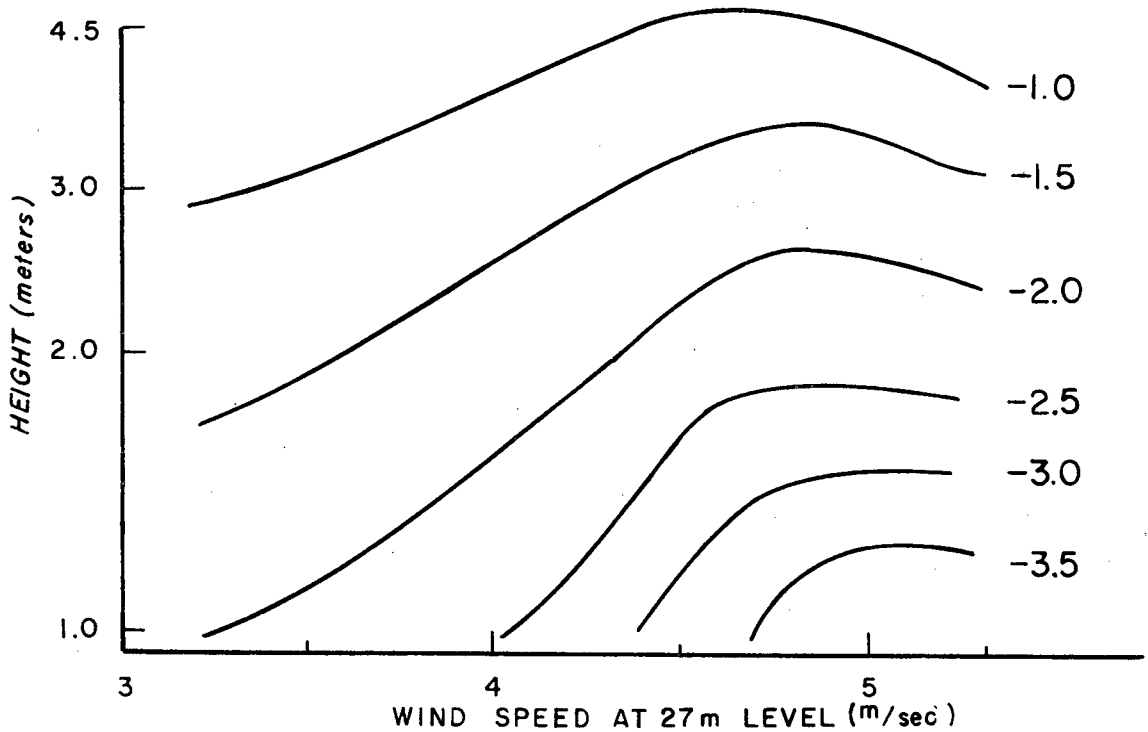


Fig. 17 Vertical distribution of kinetic energy change in joules/kg from water to beach site (day)

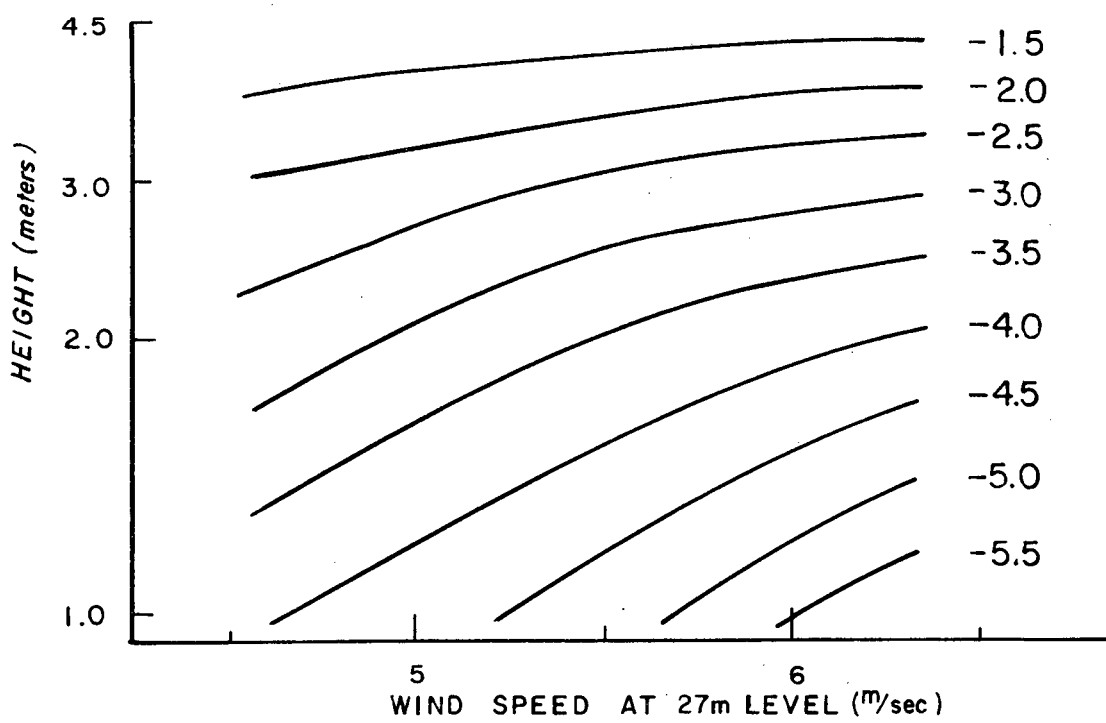


Fig. 18 Vertical distribution of kinetic energy change in joules/kg from water to beach site (night)

increasing wind speed at the top level, producing a larger gradient of  $\Delta KE$  in the vertical. The exception in this analysis is near the 5 m/sec speed where decreases in kinetic energy loss occur above the one meter level. The reason for this decrease is not clear, although it may be related to a conversion of internal energy to kinetic energy during the late afternoon resulting in higher wind speeds than expected in the lower levels.

Fig. 18 shows the nighttime case for  $\Delta KE$  at the beach site. The wind speeds are higher than during the day with overlap near 5 m/sec. Kinetic energy loss continues to increase with increasing wind speed. The  $\Delta KE$  values at all four levels for the nighttime case are larger than during the day for similar wind speeds. This suggests that some conversion of internal to kinetic energy occurs during the day in this first 90 m, reducing the observed kinetic energy loss. As noted for the  $\Delta KE$  values between the beach and canal sites, the largest vertical gradient occurs at night. Also, at night the kinetic energy difference decreases with height between the Gulf and beach station and increases with height between the beach and canal stations.

As Yu (1970) has found, this analysis shows that the greatest kinetic energy loss per unit distance occurs in the first 90 m with nighttime losses larger than during the day. The largest vertical gradient of kinetic energy loss occurs at night for both the beach theoretical estimates and beach to canal site calculations. Considering both of these estimates we may conclude that the largest discontinuity in the wind speed and kinetic energy occurs very near the ground at the coastline and increases in height with increasing distance inland from the change in surface roughness for onshore flow.

#### E. Some observed turbulence characteristics.

As mentioned previously, the manner in which the tower wind data were

obtained and averaged allows easy computation of such parameters as standard deviation of wind speed and direction. The results led to some interesting conclusions concerning the observed turbulent characteristics. To obtain some meaningful numbers from the standard deviations of wind speed, the longitudinal and lateral intensities of turbulence were calculated as described by Munn (1966), Swanson and Cramer (1965), and others. These parameters, sometimes called the level of turbulence or gustiness, are defined by  $G_x = \sigma_x / \bar{U}$  for the longitudinal component and  $G_y = \sigma_y / \bar{U}$  for the lateral component, where  $\sigma_x$  and  $\sigma_y$  are the standard deviations of wind speed for the longitudinal and lateral components, respectively. The longitudinal direction is defined as the mean direction of the wind for the averaging period. The standard deviation  $\sigma_x$  is calculated using the sum of the deviations from the mean wind such that for N observations

$$\sigma_x = \frac{1}{\sqrt{N}} \left[ \sum_{i=1}^n (U'_i)^2 \right]^{1/2}$$

where  $U'_i = U_i - \bar{U}$ . Because the x-coordinate axis has been rotated to lie along the mean wind direction,  $\bar{V} = 0$  so that for the lateral component

$$\sigma_y = \frac{1}{\sqrt{N}} \left[ \sum_{i=1}^n (V'_i)^2 \right]^{1/2}$$

The standard deviation of wind direction (azimuth)  $\sigma_A$  is calculated similarly with deviations given in degrees (deg).

The resulting values from the computations were identified with the mean wind speed for each period. The data were then grouped according to the same limits placed on the second level at each site (as in the wind profile section). Averages were obtained at each level for the different intervals of wind speed at the second level. This yielded profiles of lateral and

longitudinal intensities of turbulence and standard deviation of azimuth for various wind speeds referenced to the second level. Considering that day and night data were available we can also consider the changes in  $G_x$  and  $G_y$  with stability. Of the points considered for each plotted mean, ninety percent lie within the limits shown in Figs. 19 to 24.

Although the four minute average was too short for adequate mean wind profile description, it is felt that this averaging time is sufficient to describe turbulence characteristics. Longer averages would contain more of the very long wave disturbances and long lived perturbations in the flow, tending to mask the variations due to mechanical or thermal mechanisms. Thus, the 8 and 12 min averages would be expected to give somewhat higher values for gustiness than the 4 min averages, and this was verified. Smith and Abbott (1961), measuring lateral gustiness at the 16 m level, used averaging times of 5, 30, and 180 sec and also found that the average value of  $\sigma_A$  increased and had a greater spread in values as the averaging time increased.

The daytime beach data from 14 and 16 June shows a decrease with height in values of  $G_x$  and  $G_y$  up to the 11.6 m level with little change above. Panofsky and Deland (1959) state that the variances of lateral ( $\sigma_y^2$ ) and longitudinal ( $\sigma_x^2$ ) components of wind velocity are nearly independent of height for unstable thermal stratification but decrease rapidly with height for stable stratification. But wind speed increases with height so that both  $G_x$  and  $G_y$  decrease for both stable and unstable conditions, but more rapidly under stable stratification. The daytime beach values were obtained under neutral to slightly unstable conditions in the lower levels and neutral stability in the upper levels. Lower level  $G_x$  and  $G_y$  values ranged near 0.2 with an approximate 0.1 decrease in the vertical to the top level. For the same wind speed limits, profiles from the two days are very similar (Figs. 20a and 21a).

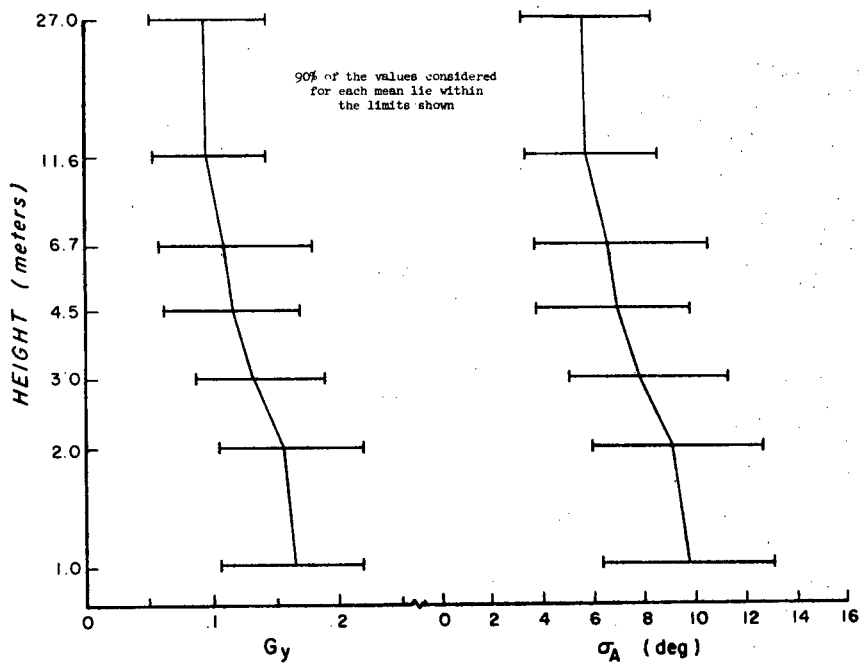


Fig. 19a Comparison of lateral intensity of turbulence ( $G_y$ ) to standard deviation of wind direction ( $\sigma_A$ ) for speed range of 3.0 to 3.5 m/sec

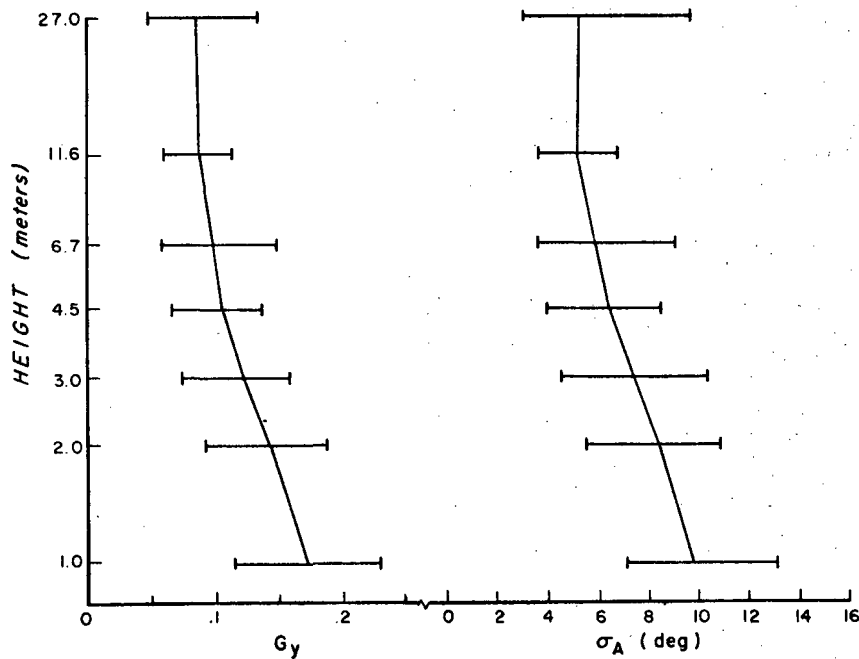


Fig. 19b Comparison of lateral intensity of turbulence ( $G_y$ ) to standard deviation of wind direction ( $\sigma_A$ ) for speed range of 3.5 to 4.0 m/sec

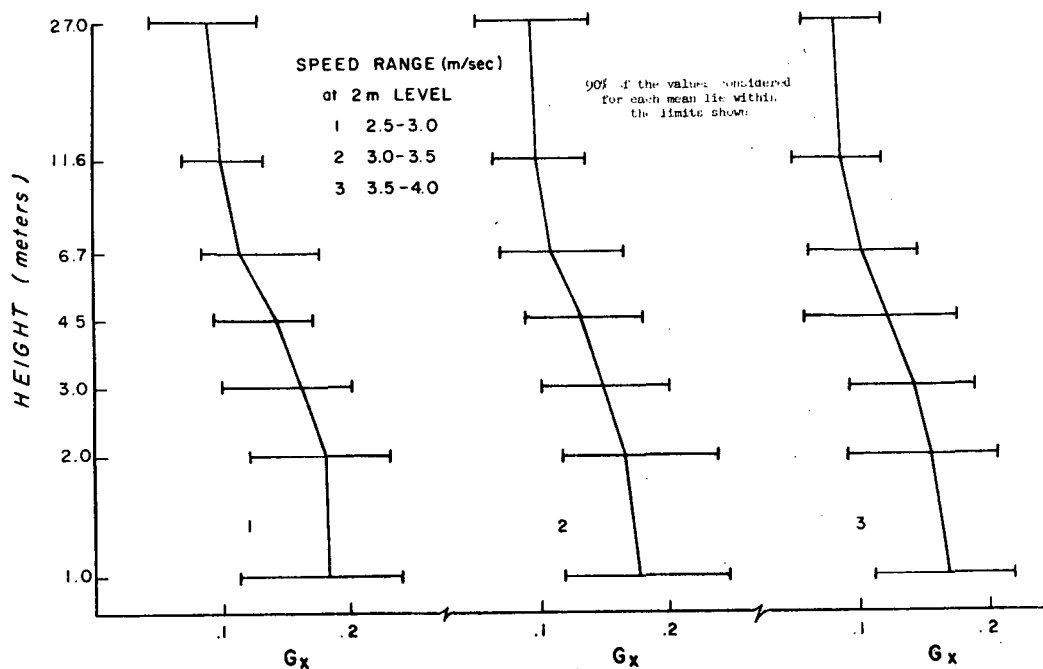


Fig. 20a Longitudinal intensity of turbulence ( $G_x$ ) profiles for beach site 14 June (day)

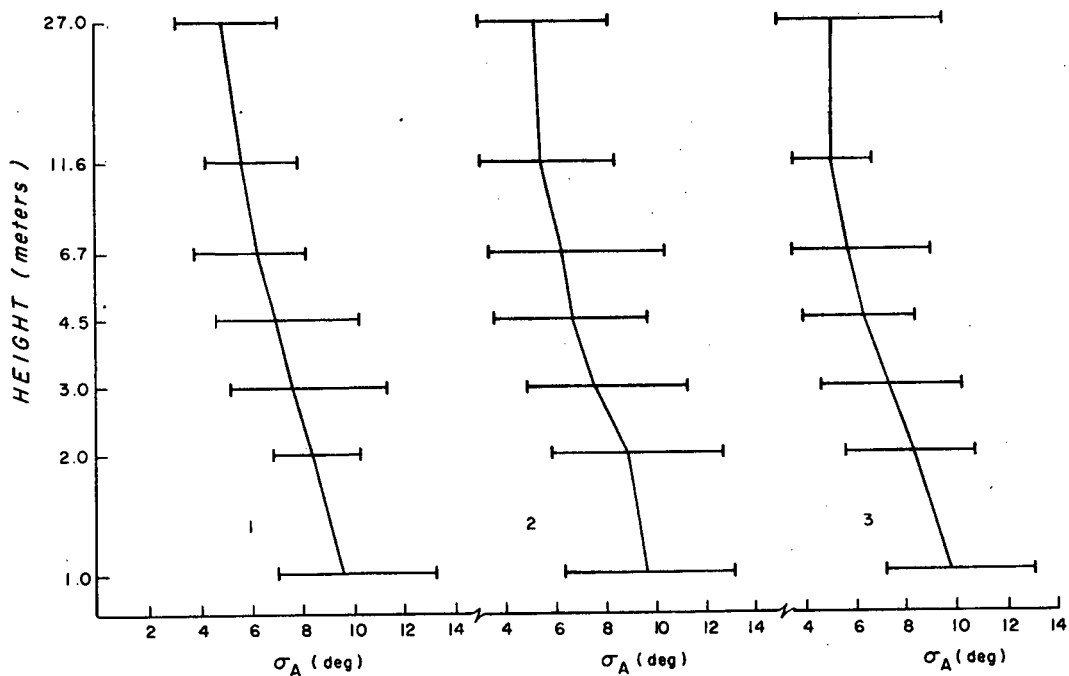


Fig. 20b Standard deviation of wind direction ( $\sigma_A$ ) profiles for beach site 14 June (day)

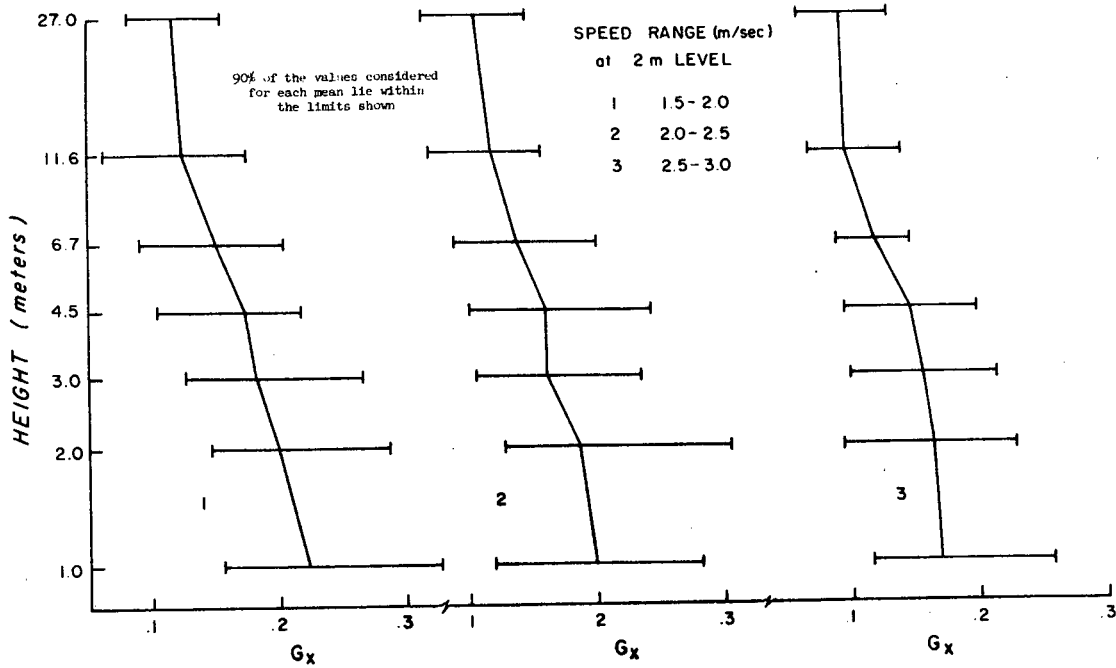


Fig. 21a Longitudinal intensity of turbulence ( $G_x$ ) profiles for beach site 16 June (day)

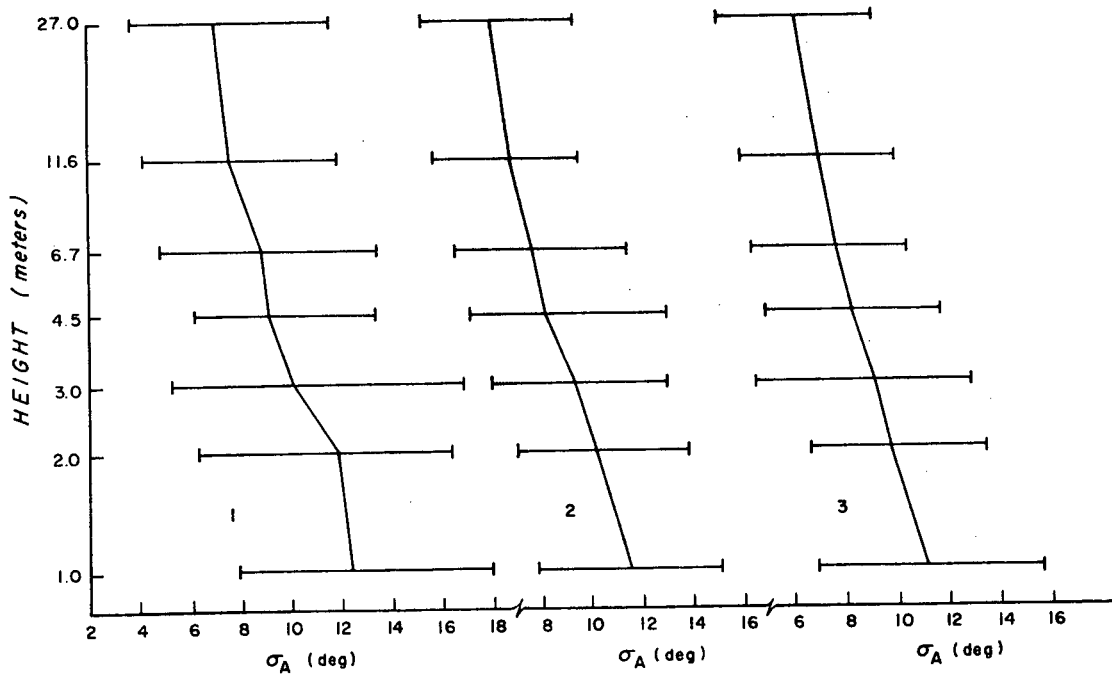


Fig. 21b Standard deviation of wind direction ( $\sigma_A$ ) profiles for beach site 16 June (day)

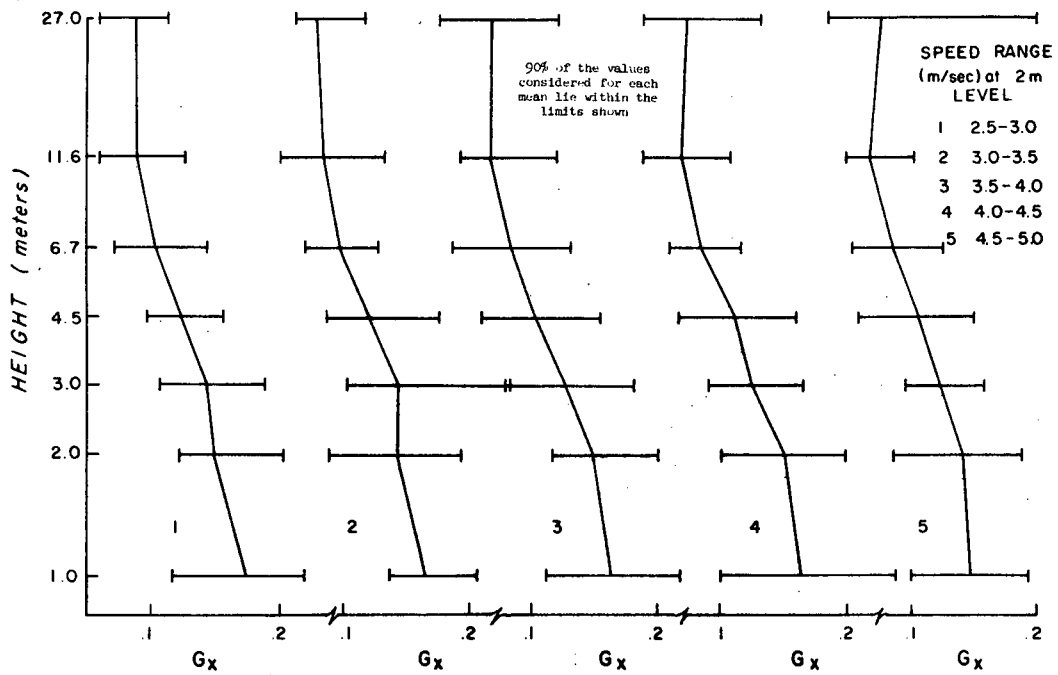


Fig. 22a Longitudinal intensity of turbulence ( $G_x$ ) profiles for beach site 16 June (night)

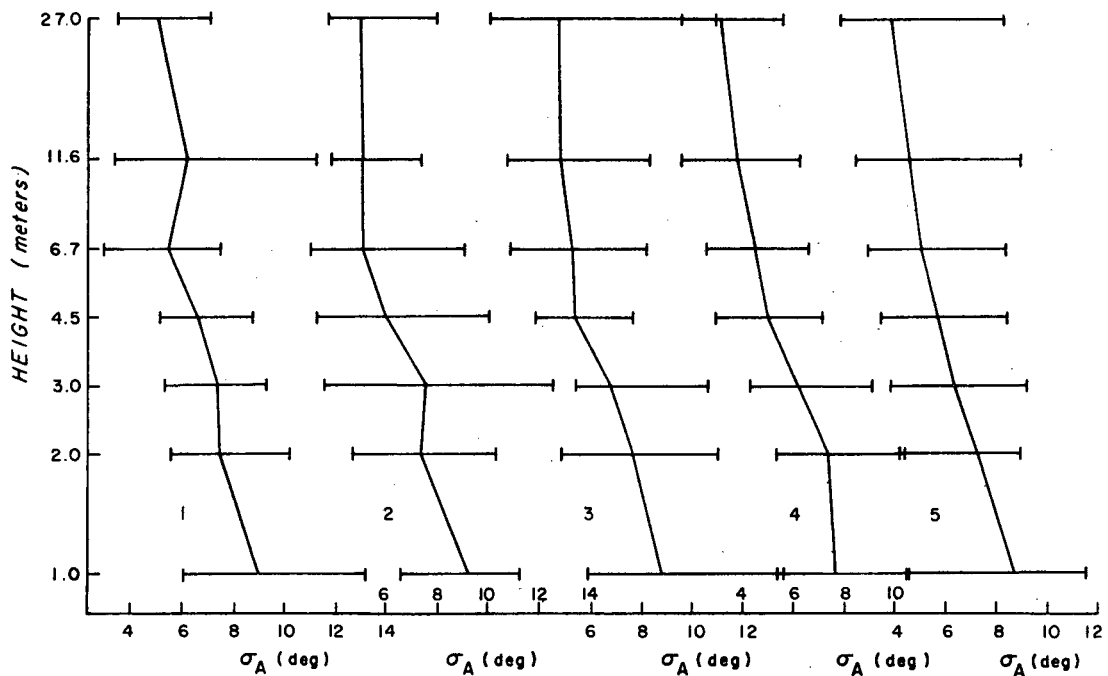


Fig. 22b Standard deviation of wind direction ( $\sigma_A$ ) profiles for beach site 16 June (night)

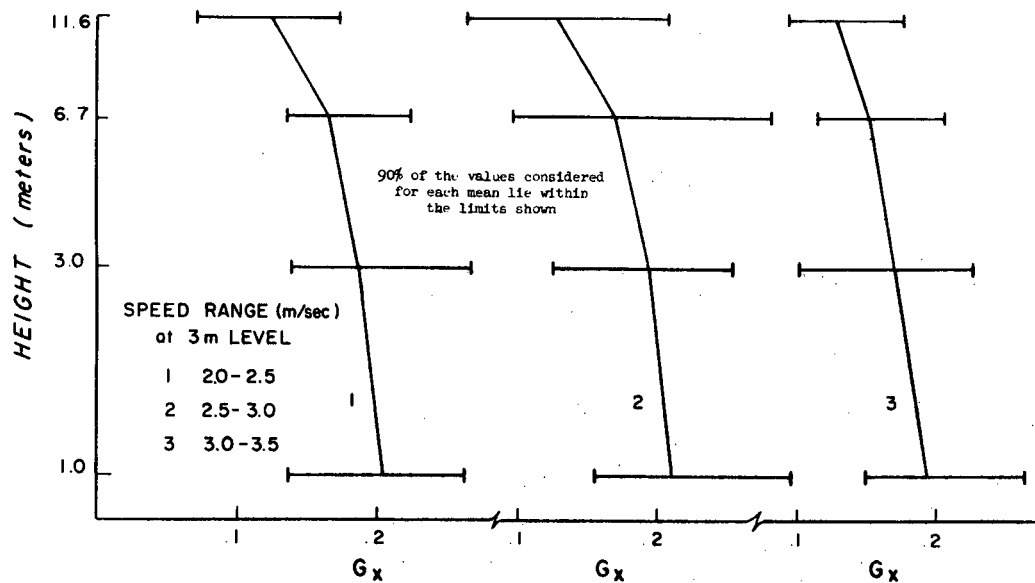


Fig. 23a Longitudinal intensity of turbulence ( $G_x$ ) profiles for canal site 16 June (day)

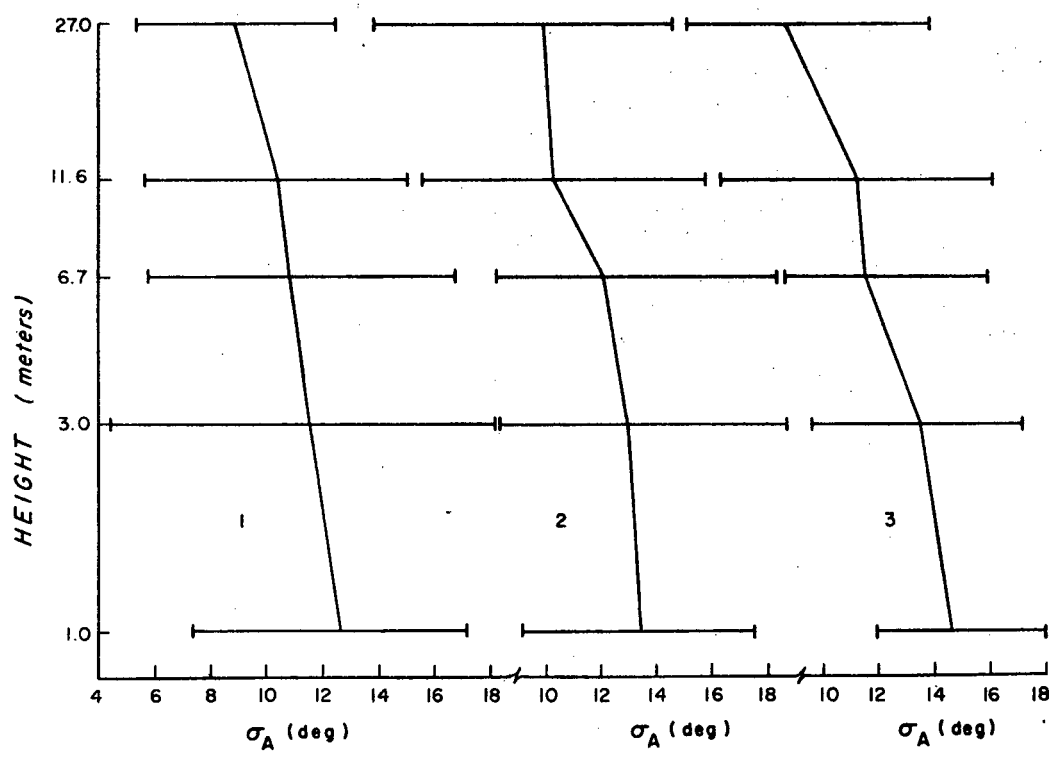


Fig. 23b Standard deviation of wind direction ( $\sigma_A$ ) profiles for canal site 16 June (day)

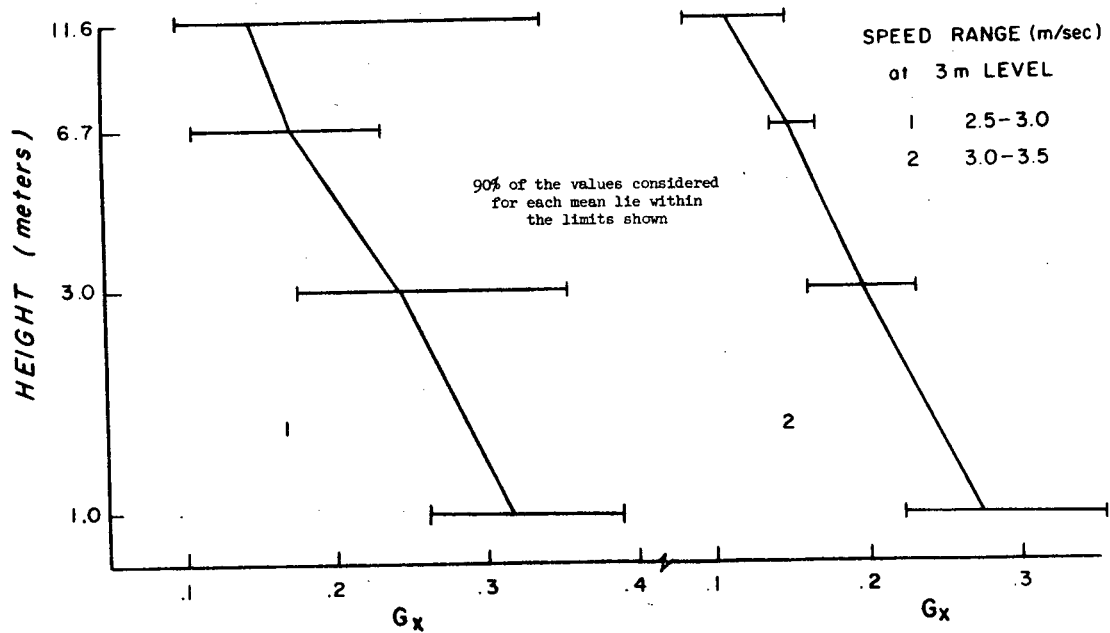


Fig. 24a Longitudinal intensity of turbulence ( $G_x$ ) profiles for canal site 16 June (night)

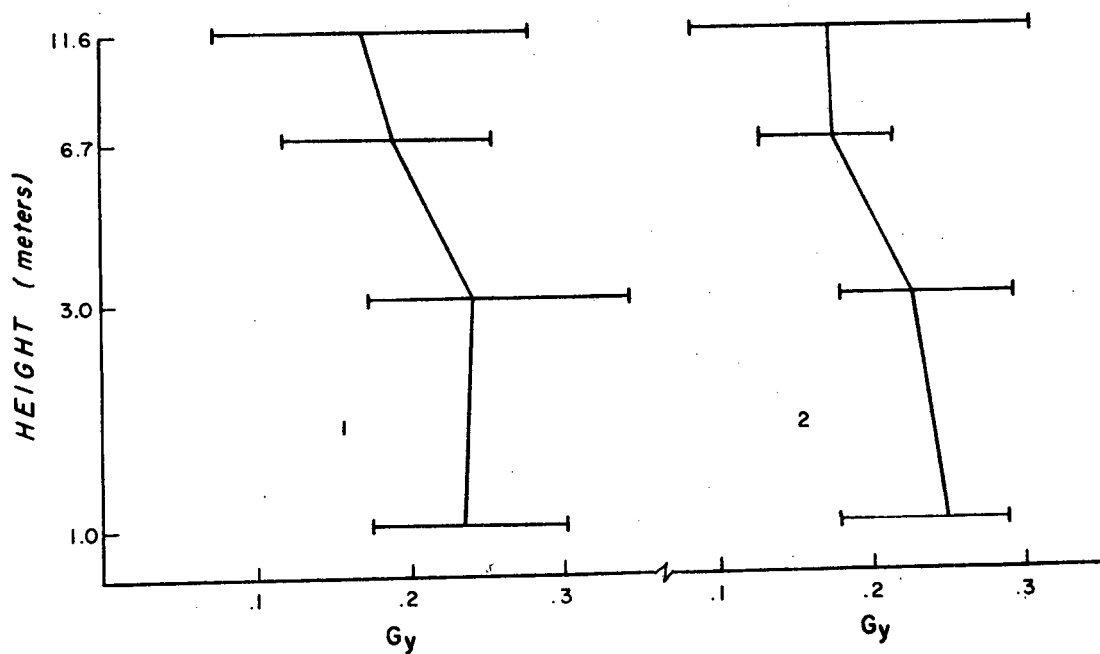


Fig. 24b Lateral intensity of turbulence ( $G_y$ ) profiles for canal site 16 June (night)

Swanson and Cramer (1965) made computations in New Mexico of the vertical distribution of  $G_x$  and  $\sigma_A$  for various stabilities and wind speeds using 10 min averages. They concluded that both lateral and longitudinal intensities of turbulence decrease with increasing stability, wind speed, and height above the surface. The approximation of  $G_y \approx \sigma_A$  was made, using  $\sigma_A$  as a measure of the lateral component of intensity of turbulence. Comparison of the  $G_y$  and  $\sigma_A$  profiles for both beach and canal sites indicate marked similarity between these parameters. Fig. 19 shows this for profiles on 14 June. Because of this similarity  $\sigma_A$  will generally be used in the analysis for the lateral component of turbulence. Swanson and Cramer's data indicates approximately the same rate of decrease of  $G_x$  in the vertical as observed at the beach tower. Their values are higher because of their longer averaging times and rougher surrounding terrain. Another reason for lower values of  $G_x$  and  $\sigma_A$  at the beach is that turbulence is not yet fully developed in its 90 m travel over land. A theory advanced by Peterson (1969) indicates that the turbulent energy adjusts much more slowly to new boundary conditions than does the velocity profile. His theory submits that only about the bottom ten percent of the transition layer is in equilibrium with the new roughness. For afternoon lapse conditions and similar wind speed limits, Swanson and Cramer's values ranged from 0.27 at 4.6 m to 0.22 at 26.6 m while afternoon neutral conditions give values of 0.25 to 0.17. No values were computed below 4.6 m. The  $G_x$  values for the 4.5 m level at the beach range from 0.12 to 0.14 and are approximately 0.03 to 0.05 lower than at one meter. This yields a rate of decrease from 4.5 to 27 m of 0.07 to 0.05, in the same range as Swanson and Cramer's computations. A decrease in  $G_x$  at the beach site is also observed for increasing wind speeds.

The standard deviations of azimuth at the beach during the day (Fig. 20) give values ranging from near 12 deg for low wind speeds to 9 deg for the

higher wind speeds at the one meter level. At the top level  $\sigma_A$  ranged from 7 deg at low wind speeds to 4 deg for the higher. These calculations are low for Swanson and Cramer's afternoon lapse conditions but are in good agreement for afternoon neutral conditions. A wider spread is also observed in the points making up the average of  $\sigma_A$  for the lower wind speeds.

The nighttime beach profiles of  $G_x$  and  $\sigma_A$  vary only slightly from the daytime case (Fig. 22). The values tend to be slightly lower with the greatest decrease with height through a more shallow layer than during the day. This small difference between day and night was expected since near-neutral thermal stratification also prevailed at night. Decreases in  $G_x$  and  $\sigma_A$  were observed for increasing wind speed.

The canal site is more representative of the conditions under which Swanson and Cramer obtained their data in that the flow is more horizontally homogeneous than at the beach. The flow reaching the canal will have approached an equilibrium with the new surface roughness and turbulence will be characteristic of this surface. No wind speed data were available for the top level but wind direction was available, giving  $\sigma_A$  computations at that level. No  $\sigma_A$  values were calculated for the nighttime case. The  $G_y$  values will be used in place of  $\sigma_A$  for this case.

Several major differences are obvious when comparing the daytime canal (Fig. 23a) and beach profiles of  $G_x$ . The values at one meter are larger at the canal with a less rapid decrease with height in the lower levels. A marked decrease is evident from the 6.7 to 11.6 m levels, possibly indicating thorough mixing with thermal convection below the 6.7 m level. The spread in points is greater at the canal than at the beach with greatest spread associated with lower wind speed. The corresponding  $\sigma_A$  profiles (Fig. 23b) exhibit these same tendencies. While little difference was observed between the  $G_x$  and  $G_y$

profiles at the beach the  $G_y$  profiles at the canal during the day are consistently greater in value than  $G_x$  at all levels by 0.05 or more. This would indicate greater variations in wind direction inland and larger values of  $\sigma_A$  which are observed. The canal values of  $G_x$  are lower than Swanson and Cramer's calculations by an amount less than at the beach while  $\sigma_A$  values are lower by 2 to 3 deg.

No four-minute averages were available for the nighttime case at the canal. The 8 min average will be used, recalling that slightly higher values of the intensities of turbulence are to be expected with the longer averaging time. The  $G_x$  values (Fig. 24a) are much higher in the lower levels than during the day with a rapid but smooth decrease in the vertical to values of  $G_x$  equivalent to the daytime regime. The rapid decrease with height is expected for this stable flow. The  $G_y$  values (Fig. 24b) decrease less rapidly in the vertical with lower values at the one meter level as compared to  $G_x$  and higher values at the top. The nighttime canal site computations for  $G_x$  are less than Swanson and Cramer's values for nighttime stable conditions but differ less than the daytime canal values and significantly less than the beach site values.

The beach site profiles for this nighttime period give significantly smaller values of  $G_x$  and  $G_y$  than at the canal, especially in the lower levels. These observations tend to substantiate Peterson's theory (1969). This large increase in  $G_x$  and  $G_y$  between the beach and canal indicates mechanically driven turbulence increases with the overland distance from the beach and is more pronounced near the surface. A slight decrease in the longitudinal component of intensity of turbulence at the canal site is observed for increasing wind speed with little change in the lateral component.

#### IV. SUMMARY AND CONCLUSIONS

The basic purpose of this study was to investigate the change in wind structure in the lower 30 m of the atmosphere after encountering an abrupt change in surface roughness with air flow from water to land. Wind speed measurements at several levels on one tower 90 m from the beach and another 4.8 km inland were obtained for both daytime and nighttime cases. These measurements, with the assumption of the logarithmic wind profile under neutral conditions, allowed estimates to be made of the aerodynamic roughness of the land surface near the beach and at the inland site. The daytime profiles yielded values of 3 to 4 cm for the roughness at the beach site and 0.8 to 1.5 cm at the inland canal site. These values agree well with estimates by other authors for similar terrain. Nighttime roughness values were somewhat higher than daytime values at each site. This is attributed to an incomplete description of the profiles in the layer below 1 m under stable conditions. Similar future experiments at such a micrometeorological site should include measurements as near the surface as is practicable if roughness parameter evaluations are to be made by the above method.

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 below 7 m/sec (referenced to

the 10 m level).

The surface roughness change of four orders of magnitude implies that the new internal boundary layer should be detectable by the previously mentioned kink in the profile (as predicted by Peterson, 1969). Using the logarithmic wind profile assumption, the slope of the profile was calculated at the various levels. The slope is constant below the estimated top of the internal boundary layer but changes abruptly to a new constant value above that height. This analysis, in conjunction with visual evaluations of the profiles, indicates that the top of the internal boundary layer lies near the 6.7 m level at this experimental site for onshore winds. A small increase and decrease in the height of the layer at the beach is observed for day and night profiles, respectively. The average height of the layer is lower than predicted by several authors for measurements made 90 m downwind of an increase in surface roughness. No such discontinuity was observed in the slope of the wind profile at the canal tower which is expected to be well within the new layer.

The vertical profiles of horizontal velocity at each site were used to compute the kinetic energy loss due to increased surface friction in the onshore flow between the two sites. Daytime calculations indicate small kinetic energy loss, especially during the early part of the study period when the largest solar heating was occurring. This suggests conversion of internal to kinetic energy inland (a conclusion also made by Yu, 1970). Increased kinetic energy loss was observed in the daytime data as solar heating decreased. Night-time data indicated much larger kinetic energy loss than during the day with a larger vertical gradient of  $\Delta KE$  values. The effect of friction is more evident at night since no internal energy source was available to replace kinetic energy lost through frictional dissipation. The maximum kinetic energy loss occurs for both day and night cases near the 6.7 m level (height of internal boundary

layer at the beach site).

Estimates of the kinetic energy loss from over water to the beach tower were made using over-water profiles of wind speed synthesized from the top levels of the beach site profiles. The calculations indicate that the greatest kinetic energy loss per unit distance occurs just downstream from the roughness change. Increasing wind speed at the top level implied increasing kinetic energy loss at all levels within the internal boundary layer with maximum loss at the lowest measured level. Nighttime estimates gave larger loss values with larger vertical gradients of  $\Delta KE$ . These estimates of kinetic energy loss with onshore flow from water to the beach site and beach site to the canal verified that the largest discontinuity in wind speed and kinetic energy occurs very near the ground at the coastline. The discontinuity increases in height with increasing distance inland from the change in surface roughness and would seem to be coincident with the height of the internal boundary layer.

Intensity-of-turbulence computations were made for each site. At the beach site lateral and longitudinal components of turbulence were found to be nearly equal for both day and night cases. The turbulence decreases rather rapidly in the vertical up to the 11.6 m level but is nearly constant above. This implies that turbulence is being generated in the lower levels as the air passes from water to land. The rate of decrease in the vertical is similar to measurements by Swanson and Cramer (1965) but the initial values are less. These lower values indicate that turbulence is not fully developed in this newly developing layer while equilibrium has apparently been established in these turbulence parameters for flow over the Gulf.

Daytime turbulence computations for the canal site yielded values larger than at the beach site. No rapid decrease in values was observed in the vertical except at the top level, indicating that equilibrium is nearly esta-

blished in the lower levels. The lateral component of turbulence was observed to be larger than the longitudinal at this inland site. Nighttime measurements gave larger values in the lower levels than during the day but decreased smoothly and rapidly in the vertical to values at the top near those observed during the day. This smooth decrease reflects the stable nighttime flow inland. For both sites a decrease in turbulence intensity values was observed for increasing wind speeds and decreasing averaging times. As predicted by Peterson (1969) a larger increase in turbulence was observed inland with largest values near the surface. Future studies should use faster sampling rates in data acquisition making averaged wind profiles more representative of instantaneous values and allowing shorter averaging times in turbulence computations.

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