CHAPTER 15

THE SHEAR STRESS OF SEA BREEZE ON A SWASH ZONE

By Shih-Ang Hsu
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT

Measurements of shear stress under the effect of a sea breeze were made by simultaneous wind and temperature profiles over a shore near Fort Walton Beach, Florida It was found that the sea breeze in the surface boundary layer is in the atmospheric free-convection regime The measured shear stress coefficient is in conformity with that obtained by other investigators by the sea surface tilt method under the unstable condition For coastal applications, the result is found to be more reliable than those assumed coefficients obtained under neutral stability for this localized coastal wind system

INTRODUCTION

In coastal areas, especially on tropical, subtropical, and marine desert coasts, and on the shores of relatively large lakes, we can observe in the course of a day the reversal of onshore and offshore winds, called sea breeze and land breeze, respectively Perhaps the most lucid synopsis of the main features of these local wind systems has been presented by Defant (1951) Baralt and Brown (1965) have compiled an excellent annotated bibliography on this subject It should be noted that whereas a hurricane or storm may cause extensive damage to coastal structures, the sea breeze is a persistent phenomenon and may, in the long run, be more important For instance, loss of beach sand into the backshore area as a result of sea breeze is an urgent engineering problem, examples are found especially in coastal Peru, Libya, Florida, and the Cape Hatteras National Seashore

The mesoscale structure as a function of space and time and particularly the hypothesis of land- and sea-breeze systems which are governed by the circulation theorem have been observed and verified on the Texas coast by Hsu (1970) Some of the microstructure of the frontal characteristics and the diurnal clockwise rotation of the system with time owing to the Coriolis effect have been observed and presented elsewhere (Hsu, 1969a), this paper will study the surface shearing stress aspect of the sea breeze

The sea breeze is effective in generating waves and currents (Murray, personal communication), which in turn transport sediments in the littoral environment (Sonu, personal communication) Also, eolian sand transport (Sonu, personal communication) and air pollution (Neiburger, 1969) in the coastal zone are closely controlled by this localized wind system Since in the nearshore areas that are frequently affected by diurnal local wind systems the lapse rate is rarely adiabatic and buoyancy forces must be considered, the wind shear stress coefficients obtained under the near-neutral condition (see, e g , Wu, 1969) cannot be used under these local wind conditions, as previously pointed out by Hsu (1969b) It is hoped that this study will fulfill the need for coefficient values under the sea breeze situation

THEORETICAL CONSIDERATION

The following derivation for the sea breeze regime in the surface boundary layer is due to McPherson (1968) and is an expanded version of that presented by Estoque (1961)

It is presumed that in the layer immediately above the surface the viscous forces acting on a fluid element are much larger than the inertial forces, thus the horizontal momentum equations and the thermodynamic equation for the layer become

$$\frac{\partial}{\partial Z}\left(K \frac{\partial u}{\partial Z}\right) = 0 \tag{1}$$

and

$$\frac{\partial}{\partial Z}\left(K \frac{\partial \theta}{\partial Z}\right) = 0 \tag{2}$$

where K is an eddy exchange coefficient, assumed to be the same for both heat and momentum transfer, u is the magnitude of the horizontal wind, and θ is the potential temperature If K is known as a function of height Z, the equations can be integrated to obtain u and θ in the boundary layer

Under conditions of free convection--that is, when the buoyant forces dominate the mechanical forces--the expression of K used is

$$K = \lambda Z^2 \left(\frac{g}{\bar{\theta}} \left| \frac{\partial \theta}{\partial Z} \right|\right)^{1/2}, \quad Ri < -0\ 03, \tag{3}$$

as discussed by Priestley (1959) Here λ is an empirical constant, g is the acceleration of gravity, and $\bar{\theta}$ is a layer-mean potential temperature in the layer in which the Richardson number (Ri) is evaluated Eqs (1) and (2) may be written as

$$K \frac{\partial u}{\partial Z} = U_*^{\,2} \tag{4}$$

and

$$K \frac{\partial \theta}{\partial Z} = \theta_* U_*, \tag{5}$$

where U_*, θ_* are termed the "friction velocity" and "friction temperature" respectively From Eqs (4) and (5) we obtain

$$\frac{\partial u}{\partial Z} = \frac{U_*}{\theta_*} \frac{\partial \theta}{\partial Z} \tag{6}$$

and

$$\frac{\partial \theta}{\partial Z} = \frac{\theta_*}{U_*} \frac{\partial u}{\partial Z} \tag{7}$$

For the free-convection regime, we use Eqs (3) through (7) and obtain

$$\frac{\partial u}{\partial Z} = \left[\frac{U_*^{\,5}\ \bar{\theta}}{\lambda^2 g |\theta_*|} \right]^{1/3} Z^{-4/3} \tag{8}$$

and

$$\frac{\partial \theta}{\partial Z} = \left[\frac{U_*^{\,2}\ \theta_*^{\,2}\ \bar{\theta}}{\lambda^2 g} \right]^{1/3} Z^{-4/3} \tag{9}$$

Eqs (8) and (9) can be integrated to give

$$U = -3 \left[\frac{U_*^{\,5}\ \bar{\theta}}{\lambda^2 g |\theta_*|} \right]^{1/3} Z^{-1/3} + \text{Constant} \tag{10}$$

$$\theta = -3 \left[\frac{U_*^{\,2}\ \theta_*^{\,2}\ \bar{\theta}}{\lambda^2 g} \right]^{1/3} Z^{-1/3} + \text{Constant} \tag{11}$$

The expressions for turbulent shear stress (τ) and surface shear stress (τ_o) are

$$\tau = \rho U_*^2 \tag{12}$$

and

$$\tau_o = \rho C_z U_z^2 \tag{13}$$

where ρ is the density of air and C_z is a dimensionless "shear stress" or "drag" coefficient for the height Z

Combining Eqs (12) and (13) gives

$$C_z = \left(\frac{U_*}{U_z}\right)^2 \tag{14}$$

Thus, from simultaneous temperature- and wind-profile measurements in the atmospheric boundary layer and from Eqs (8) through (14), the values of C_z and τ_o are obtained

FIELD EXPERIMENT AND DATA ANALYSIS

Field Site and Experiment

The experiment site (see Figs 1 and 2) was located on the Gulf Coast near Fort Walton Beach, Florida The site (86°43'W, 30°24'N) has an approximate east-west shoreline orientation It has been used to study the local wind system (Hsu, 1969a) The experiment related to the present study was designed to measure the temperature and wind profiles in the surface boundary layer as shown in Eqs (8) through (11) and was performed during the month of May 1970

Instrumentation

The main instrument used for this study was a Thornthwaite Wind Profile Register System (Model 106) with 6-unit, 3-cup fast response mounted 20, 40, 80, 160, 240, and 320 cm above the beach surface (Fig 1) The anemometers have a distance constant of better than 1 meter and are rugged enough to withstand limited exposure to a marine atmosphere (Seesholtz, 1968) Note that the system is portable so that during the experiment it is quickly and easily moved to a desired location

Temperatures were measured at 170, 360, and 550 cm above a grass-

Fig. 1. Cup anemometer array located in the swash on the coast of the Gulf of Mexico near Fort Walton Beach, Florida. Hot-wire anemometer, also part of the instrumentation, is shown in the background.

free berm surface by three identical recording hygrometry systems (Taylor Instrument Company, Series 76J, having readings within ± 1 percent of any given chart range). The sensors were mounted on a 10-meter meteorological tower. An all-purpose wind-recording system (Science Associates, Inc., No. 162) at the 10-meter level above the surface made wind speed and direction measurements as the reference level. For detailed information about these instruments and their installation, relevant manuals should be consulted.

Data Reduction

Wind velocities measured by the Thornthwaite Wind Profile Register System were recorded by a Thornthwaite's Digital Printout Recorder (system model 706), which uses the well-known Polaroid reproduction process. A system of mirrors and mechanical level movements moves the image of a row of counters by small increments along the length of the film card. During the experiment an exposure of the register image is made on command from a timer after each movement of the image. A 15-minute time interval was used for the present study. The readings of the counters are then entered on the film card at the start of the period and again at the end. The difference is obtained and the corresponding wind speed in centimeters per second is determined from the appropriate conversion table supplied by the manufacturer.

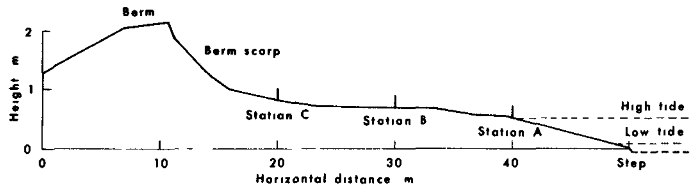

Fig 2 Beach profile on the coast of the Gulf of Mexico near Fort Walton Beach, Florida, during the experimental period, between May 20 and May 26, 1970

Method of Data Analysis

Our immediate concern is to examine the validity of Eq (10) under sea breeze conditions First, by integrating Eq (10) between any two heights a and b, we have

$$U_b - U_a = 3\left[\frac{U_*^5\,\bar{\theta}}{\lambda^2 g|\theta_*|}\right]^{1/3} (a^{-1/3} - b^{-1/3}) \tag{15}$$

This may be written

$$y = a_o + a_1 x \tag{15a}$$

where

$$y = U_b - U_a$$

$$a_o = 0$$

$$a_1 = 3\left[\frac{U_*^5\,\bar{\theta}}{\lambda^2 g|\theta_*|}\right]^{1/3} \tag{15b}$$

$$x = a^{-1/3} - b^{-1/3}$$

We plot the observations for each run in the form y against x, plotting on point for each available pair of heights Eq (15a) shows that, if the data do follow the free-convection form, the points lie on a straight line This method is similar to that used by Webb (1970) Eqs (15a) and (15b) have also been obtained by the least-squares technique Table 1 gives as an example the least-squares values of each correlation

Table 1 Sea Breeze Wind Profiles on the Swash near Fort Walton Beach, Florida

May 22, 1970	Measured Wind Profiles (Speed vs Height)						Least-Squares Values# (Eqs 15, 15a, and 15b)	
15-Minute Ending Time Hr Min CDT	Wind Speed at 20 cm cm/sec	Wind Speed at 40 cm cm/sec	Wind Speed at 80 cm cm/sec	Wind Speed at 160 cm cm/sec	Wind Speed at 240 cm cm/sec	Wind Speed at 320 cm cm/sec	Correlation Coefficient r	Y Axis Intercept a_o, cm
800*	139	154	168	196	226	267	61	25 1
15*	152	169	185	213	248	276	69	21 8
30*	138	149	164	189	216	244	66	19 7
45*	130	144	158	181	200	227	73	15 6
900*	160	176	192	209	223	242	86	9 6
15**	190	211	227	247	254	262	98	2 6
30**	209	235	258	282	291	300	99	2 6
45**	240	272	303	341	361	377	96	9 1
1000	266	304	336	367	382	395	99	4 1
15	282	323	360	393	410	426	99	5 1
30	297	340	380	416	431	447	99	4 1
45	300	346	379	406	421	435	99	2 2
1100	337	389	424	455	466	480	99	- 0 0
15	354	407	443	472	484	499	99	0 1
30	369	428	465	493	507	523	99	- 0 2
45	374	431	468	501	518	535	99	2 4
1200	347	413	448	478	494	511	99	0 1
15	322	382	417	444	456	471	99	- 1 4
30	312	381	421	447	462	477	99	- 2 6
45	298	362	394	419	434	448	98	- 1 4
1300	326	395	431	460	472	488	98	- 2 6
15	270	324	353	374	385	398	98	- 1 6
30	250	301	326	345	352	361	98	- 3 8
45	233	279	300	316	324	332	97	- 2 8
1400	213	252	270	284	291	299	98	- 1 8
15	205	242	261	275	282	290	98	- 1 6
30	202	240	258	273	280	287	98	- 1 9
45	190	231	249	262	267	275	96	- 3 1

Table 1 continued

May 22, 1970	Measured Wind Profiles (Speed vs Height)						Least-Squares Values# (Eqs 15, 15a, and 15b)	
15-Minute Ending Time Hr Min CDT	Wind Speed at 20 cm cm/sec	Wind Speed at 40 cm cm/sec	Wind Speed at 80 cm cm/sec	Wind Speed at 160 cm cm/sec	Wind Speed at 240 cm cm/sec	Wind Speed at 320 cm cm/sec	Correlation Coefficient r	Y Axis Intercept a_o, cm
1500	201	238	256	271	278	286	98	- 1 3
15	198	240	260	277	285	294	98	- 1 5
30	216	263	290	307	317	326	98	- 2 3
45	230	280	310	330	342	352	99	- 1 7
1600	265	319	355	374	386	396	99	- 3 2
15	276	335	374	401	414	428	99	- 1 5
30	266	318	358	383	396	406	99	- 2 0
45	230	280	312	332	345	355	99	- 1 5
1700	246	300	332	351	363	373	98	- 2 8
15	230	277	313	332	343	352	99	- 2 5
30	237	291	323	342	351	360	98	- 4 2
45	213	259	291	307	316	322	98	- 4 2
1800	216	264	298	317	328	336	99	- 2 9
15	232	286	326	346	356	364	98	- 4 8
30	222	270	302	320	327	335	98	- 4 3
45	216	265	301	321	332	340	99	- 3 1
1900	227	277	314	335	345	353	99	- 3 7
15	237	289	328	349	361	369	99	- 3 5
30	224	277	314	335	345	352	99	- 4 6
45	217	265	301	321	332	339	99	- 3 3
2000	204	252	285	302	310	315	98	- 5 2
15	200	247	279	296	305	311	98	- 4 2
30	193	238	268	282	291	296	98	- 4 4
45	176	215	243	257	264	268	98	- 4 2
2100	166	205	231	245	251	256	98	- 4 0
15	174	214	242	255	262	267	98	- 4 2
30	167	204	230	244	249	254	98	- 4 0
45	159	192	216	228	233	237	98	- 3 7

Table 2 continued

May 22, 1970	Measured Wind Profiles (Speed vs Height)						Least-Squares Values# (Eqs 15, 15a, and 15b)	
15-Minute Ending Time Hr Min CDT	Wind Speed at 20 cm cm/sec	Wind Speed at 40 cm cm/sec	Wind Speed at 80 cm cm/sec	Wind Speed at 160 cm cm/sec	Wind Speed at 240 cm cm/sec	Wind Speed at 320 cm cm/sec	Correlation Coefficient r	Y Axis Intercept a_o, cm
2200	163	190	212	231	236	241	99	- 1 0
15**	111	127	143	163	174	187	92	6 8
30**	44	48	59	74	88	135	40	21 9

#Least-squares values are obtained from Eqs 15, 15a, and 15b for the atmospheric free-convection regime, which has pronounced nonlogarithmic wind profile

*For reference only land breeze regime

**Sea breeze and land breeze fronts, for reference only coefficient (r), as well as the y-axis intercept (a_o) It can be seen from this table that, in the whole sea breeze range from 1000 to 2200 CDT, r > 96 and -5 2 cm < a_o < 5 2 cm, which is within the experimental error In other words, these observations verify that the sea breeze is in the atmospheric free-convection regime and that its wind profile in the surface boundary layer can be represented by Eq (10)

Similar analyses were made for temperature profiles under sea breeze conditions whenever wind profiles were measured Thus, the U_* and θ_* values are obtained from these observations, as mentioned previously Note that, on the basis of the findings by Priestly (1959), Deardorff and Willis (1967), and Dyer (1967), the value of λ was chosen to equal unity and was used in the present analysis

SURFACE SHEAR STRESS OF THE SEA BREEZE

Since the main purpose of this paper is to provide the shear stress coefficient (C_z) under the sea breeze condition, and since usually Z = 10 meters is taken as reference level, Figure 3 shows the required results It can be noted immediately from this figure that the $C_{10} \times 10^3$ value for a given wind speed is greater than that under neutral and stable conditions (e g , Roll, 1965) This is not surprising inasmuch as the sea breeze itself is set up by the differential heating between land and water (Hsu, 1970) Thus the buoyancy forces must play the dominant role, as demonstrated in Table 1

The result is consistent with the findings by J and M Darbyshire (1955), who showed that atmospheric stability has a very marked effect on the tilt of the water surface in response to the wind In measuring the surface slope of a lake under different thermal conditions, they obtained stress coefficients that, for a given wind speed, were twice as great in unstable cases as in stable ones According to Roll (1965), the Darbyshires' result is also in conformity with the findings of several authors in different regions of the world (see references given by Roll, 1965)

Since the shear stress coefficient may also be affected by the fetch of the wind (e g , J and M Darbyshire, 1955, and Roll, 1965), the annotated bibliography compiled by Baralt and Brown (1965) for the sea breeze structure in various parts of the world and a summary of local winds by Defant (1951) may be consulted Furthermore, since the land and sea breeze systems, which are governed by the circulation theorem, have been verified by Hsu (1970), the fetch may be estimated from wind observations (see Eq 8 in Hsu, 1970), provided that the value of the coefficient of friction can be estimated on the basis of accurate geomorphological survey of the coastal area in question (see also the discussions by Haurwitz, 1947) An example of the mesoscale structure, including the fetch study of the sea breeze, is given by Hsu (1970)

As for coastal applications, Murray (personal communication) found that the computed shear stress value based on Figure 3 for a given wind speed fits his wind-induced current prediction and observation under the

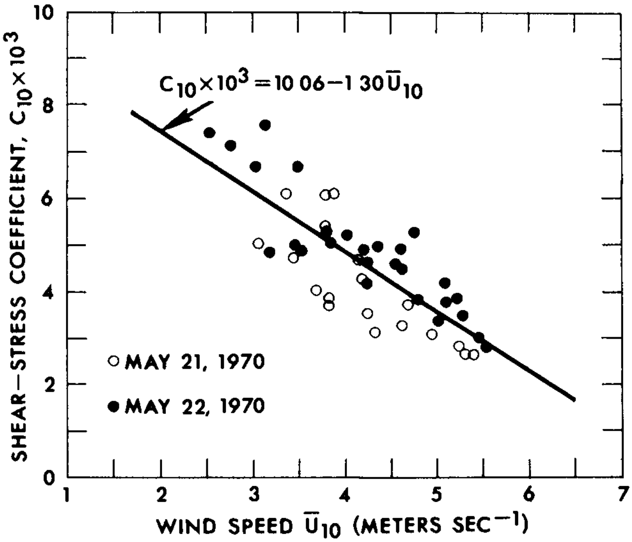

Fig 3 Measured shear stress coefficients under the sea breeze condition Each point is calculated from a 15-minute time average from both air temperature and velocity profiles Correlation coefficient of the least-squares fit for the straight line is 0 80

sea breeze condition more reliably than that based on the neutral stability coefficient (e g , Wu, 1969)

CONCLUDING REMARKS

While this study is intended to provide the shear stress coefficient under the sea breeze condition, caution should be exercised in applying the result, which may not be applicable to other coastal winds, such as the land breeze, coastal mountain and valley winds, and other synoptic and subsynoptic wind systems It is suggested that before this result can be applied some knowledge of sea breeze meteorology may be needed In this connection, papers by, among others, Defant (1951), Baralt and Brown (1965), and Hsu (1969a and b and 1970) may be consulted

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