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SENSITIVITY OF C_n^2 TO RANDOM VARIATIONS OF WINDSPEED, SENSIBLE HEAT FLUX, AND LATENT HEAT FLUX

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13. ABSTRACT *(Maximum 200 words)*

The optical turbulence structure parameter, C_n^2, is a primary parameter in expressions used to characterize electromagnetic energy and image propagation through the atmosphere. Examples of these expressions include the receiver coherence diameter and the atmospheric modulation transfer function. In this analysis the authors write C_n^2 in terms of windspeed (V), sensible heat flux (H), and latent heat flux (L′E) assuming that their values are measured or modeled. Then the authors consider the effect on 2 C_n^2 if estimates of H. L′E, and V are assumed to be in error or vary (that is, due to sensor error and/or natural atmospheric variations). Micrometeorological data from Davis, California, are used to comprise two case studies. The results presented include bar charts of the modeled distributions of H; L′E; the surface friction velocity, U^*; the temperature and specific humidity scaling parameters, T^* and q^*; the Obukhov scaling length, L; the reference level (1 m) windspeed, V_r; and finally C_n^2 for each case.

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1. INTRODUCTION

The optical turbulence structure parameter C_n^2 is a primary parameter in expressions used to characterize electromagnetic energy and image propagation through the atmosphere. Examples of these expressions include the receiver coherence diameter, the atmospheric modulation transfer function, the isoplanation effective path length, and the scintillation average length (Miller and Ricklin, 1990).

A basic form of the equation often used for computing C_n^2 is given by Tatarski (1961) as

$$C_n^2 = b\left(\frac{K_h}{\epsilon^{1/3}}\right)\left(\frac{dn}{dz}\right)^2 \quad , \tag{1}$$

where

b = a constant = 3.2 (obtained from Wyngaard (1973), Hill (1989), and Andreas (1988)),

z = height above ground,

$K_h = u^* \dfrac{kz}{\phi_H}$ = turbulent exchange coefficient for heat,

ϕ_H = dimensionless lapse rate = $\left(1 - 15\dfrac{z}{L}\right)^{-1/2}$, L < 0 (Hansen, 1980),

k = von Karman's constant,

ϵ = energy dissipation rate = $\left(\phi_m - \dfrac{z}{L}\right)\dfrac{u^{*3}}{kz}$ (Panofsky, 1968),

$\phi_m = \left(1 - 15\dfrac{z}{L}\right)^{-1/4}$, L < 0 (Hansen, 1980),

n = real index of refraction,

L = Obukhov length,

$\dfrac{dn}{dz}$ = height derivative of n,

u^* = friction velocity.

In addition, $\dfrac{dn}{dz}$ is a function of the height derivatives of potential temperature and specific humidity, that is, $\dfrac{d\theta}{dz}$ and $\dfrac{dq}{dz}$. As such, a critical question would be how can we best approximate these derivatives. In our approaches, we assume that the environment is in a steady, horizontally homogenous state so that

$\frac{d\theta}{dz} = \frac{\partial\theta}{\partial z}$, and $\frac{dq}{dz} = \frac{\partial q}{\partial z}$. Furthermore, we assume that the derivatives are expressible in similarity form. For instance, for unstable conditions, the derivatives of potential temperature θ, specific humidity q, and windspeed v are written as

$$\frac{\partial\theta}{\partial z} = \frac{\theta^*}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/2} , \tag{2}$$

$$\frac{\partial q}{\partial z} = \frac{q^*}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/2} , \tag{3}$$

$$\frac{\partial v}{\partial z} = \frac{u*}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/4} , \tag{4}$$

(Hansen, 1980; Businger, 1973; Hoffert, 1979)

where the integrated forms of equations (2) through (4) are

$$\theta = \theta_r + \frac{\theta^*}{k}\left\{\ln\left(\frac{y - 1}{y + 1}\right)\right\}\Bigg|_{y_r}^{y} , \tag{5}$$

$$q = q_r + \frac{q^*}{k}\left\{\ln\left(\frac{y' - 1}{y' + 1}\right)\right\}\Bigg|_{y'_r}^{y'} , \tag{6}$$

$$v = \frac{u*}{k}\left\{\ln\left(\frac{x - 1}{x + 1}\right) + 2\tan^{-1}x\right\}\Bigg|_{x_o}^{x} , \tag{7}$$

$$y = \left(1 - 15\frac{z}{L}\right)^{1/2} , \tag{8}$$

$$y' = \left(1 - 15\frac{z}{L}\right)^{1/2} \quad , \tag{9}$$

$$x = \left(1 - 15\frac{z}{L}\right)^{1/4} \quad , \tag{10}$$

$$x_o = \left(1 - 15\frac{z_o}{L}\right)^{1/4} \tag{11}$$

Z_o = roughness length ,

$$L = \frac{u*^2 T_{vr}}{kg\theta_v^*} = \text{Obukhov length} \quad . \tag{12}$$

(Lumley and Panofsky (1964); Van Boxel et al., 1989)

θ^* - temperature scaling length.

q^* - specific humidity scaling length.

u^* - friction velocity.

T_{vr} - T_r $(1 + 0.61q_r)$.

T_r - temperature at the reference height.

q_r - specific humidity at the reference height.

g - acceleration due to gravity.

$$\theta_v^* = \theta^* + 0.61\theta^* q \quad . \tag{13}$$

Furthermore, since these expressions are based on the notion that the atmosphere is in steady state and horizontally homogeneous, then for unstable conditions appropriate time averages are on the order of 20 to 30 min (Hansen, 1991*). This is an important requirement; that is, we are working with average values.

Andreas (1988) expressed $\frac{dn}{dz}$ in terms of potential temperature and "absolute" humidity scaling lengths θ^* and Q^*. Tunick and Rachele (1991) prefer $\frac{dn}{dz}$ in terms of potential temperature and "specific" humidity to be consistent with Tatarski (1961). For example at a wavelength of 0.55 μm (Tunick and Rachele, 1991)

$$\frac{dn}{dz} = -7.9 \times 10^{-5} \frac{P}{T^2} \frac{\partial\theta}{\partial z} + \left(1.97 \times 10^{-5} \frac{P}{T} \frac{\partial q}{\partial z}\right) , \tag{14}$$

where

P = pressure in millibars,

T = temperature in degrees kelvin.

There are several ways of determining θ^* and q^* for equation (12) when $\frac{\partial\theta}{\partial z}$ and $\frac{\partial q}{\partial z}$ are expressed in similarity form using equations (2) and (3). Conceptually, the simplest approach is to evaluate equations (5) through (7) using wind, temperature, and relative humidity data measured at two heights using sensitive, but conventional sensors (Rachele and Tunick, 1991). However, experience has shown (Hansen, 1991*) that measurements from only two heights generally are not sufficient due to natural variability of the parameters and due to sensor errors. Furthermore, a disadvantage of this approach is that the measurement, logging, and processing of these data are not operationally trivial. Even so, this method was used to establish distributions of H and L'E for this study. Therefore, to clarify, the windspeed variations that are input are normally distributed with a constant value used for their variance. The H and L'E inputs, although seemingly normal with respect to their distributions (see figures 1 to 18 discussed in section 6), were modeled by the two-level method discussed immediately above. Later in section 6 we discuss the standard deviations of the derived distributions for H and L'E.

Another approach, which is theoretically more basic, makes use of turbulent fluctuation covariances and their relationship to the scaling constants, that is,

$$u^{*2} = -\overline{w'u'} , \tag{14a}$$

$$u^*\theta^* = \overline{w'T'} , \tag{14b}$$

$$u^*q^* = \overline{w'q'} , \tag{14c}$$

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*Frank V. Hansen, 1991, personal communication, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM where u', w', and q' are deviations (fluctuations) from their mean values. The overbar indicates an average of the fluctuation covariances.

The advantage of this approach is that it only requires measurements at one height. However, the disadvantage is that the sensors and logging equipment suitable for making these measurements are delicate and sophisticated, requiring highly skilled technicians for their operation.

Still another approach for determining the scaling contents is based on the measurement or modeling of the fluxes of sensible heat and latent heat since these fluxes are related to the scaling constants θ^* and q^* as follows:

$$H = -C_p \rho u^* \theta^* \quad , \tag{15a}$$

$$L'E = -L' \rho u^* q^* \quad , \tag{15b}$$

where

H - sensible heat flux,

$L'E$ - latent heat flux,

L' - heat of vaporization,

ρ - density of air.

The friction velocity u^* in equation (15) can be approximated using the similarity relations given by equations (4), (7), and (12).

The modeling method for estimating H and L'E is based on the energy balance equations as follows. The amount of solar energy reaching the ground is modeled considering the position of the sun relative to the site of interest; the amount of energy scattered, absorbed, and transmitted by atmospheric gases and water vapor; and the longwave transmission toward the ground. Next, one considers energy reflected by the ground surface (albedo); the longwave emission from the surface; the energy absorbed by the ground, which, in turn, is either stored in the ground, used to evaporate moisture (resulting in latent heat); and finally energy that heats the air (sensible heat). The advantage of this approach is that it is heavily model oriented; the disadvantage is that it is very complex physically. In any event, the purpose of this report is not to explore the energy balance approach per se. Our question at this point is the sensitivity of H, L'E, and V in estimating C_n^2. Or, put a different way, how well must we estimate H, L'E, and V in our model to provide "acceptable" values of C_n^2. The question of whether we can do this well enough, using the energy balance approach, will be addressed in a separate study.

In this study, then, we write C_n^2 in terms of windspeed, sensible heat flux, and latent heat flux, assuming that their values are measured or modeled. We then consider the effect on C_n^2 if estimates of H, L'E, and V are assumed to be in error or vary for whatever reason. Furthermore, we assume that the variations are approximately normally distributed as found in a separate study (Rachele and Tunick, 1991) using the first method, that is, the two-level method discussed earlier.

2. PRIMARY EQUATIONS

We write C_n^2 ($\lambda = 0.55\ \mu$m) for damp unstable conditions (Tunick and Rachele, 1991) as

$$C_n^2 = A'\theta^{*2} + B'\theta^{*}q^{*} + C'q^{*2} \quad , \tag{16}$$

where

$$A' = b\,(6.241\ x\ 10^{-9})\frac{P^2}{T^4}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \quad , \tag{17}$$

$$B' = b\,[3.11\ x\ 10^{-9}]\ \frac{P^2}{T^3}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \quad , \tag{18}$$

$$C' = b\,(3.88\ x\ 10^{-10})\frac{P^2}{T^2}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \quad , \tag{19}$$

and where

$$\{\,\} = \left\{\frac{\left[1 - \gamma\frac{z}{L}\right]^{1/2}}{\left[\left(\left[1 - \beta\frac{z}{L}\right]^{-1/4} - \frac{z}{L}\right)\right]^{1/3}}\right\} \quad ,$$

b = constant = 3.2,

k = von Karman's constant (0.4),

z = height.

θ^* - scaling constant for temperature,

q^* - scaling constant for specific humidity,

We determine θ^* and q^* in terms of sensible and latent heat fluxes from equation (15); that is,

$$\theta^* = -\frac{H \times 10^3}{C_p \rho u^*} , \tag{20}$$

$$q^* = -\frac{(L'E) \times 10^3}{L' \rho u^*} , \tag{21}$$

where

H = sensible heat flux (W m^{-2}),

$(L'E)$ = latent heat flux (W m^{-2}),

C_p = gas constant = 1×10^7 (c.g.s. units),

ρ = density of moist air = 10^{-3} g cm^{-3},

u^* = friction velocity (cms^{-1}),

L' = latent heat of vaporization = 2.5×10^{10} (c.g.s. units).

Substituting equations (20) and (21) into equation (16) gives

$$C_n^2 = A'\left(\frac{H^2 \times 10^6}{C_p^2 \rho^2 u^{*2}}\right) + B'\left(\frac{H(L'E) \times 10^6}{C_p L' \rho^2 u^{*2}}\right) + C'\left(\frac{(L'E)^2 \times 10^6}{L^2 \rho^2 u^{*2}}\right) . \tag{22}$$

The friction velocity, u^*, is a function of H and the Obukhov length L, and L is functionally related to V. Hence, u^* in equation (22) can implicitly be replaced by V.

From equations (17), (18), and (19) we note that the expressions for A', B', and C' contain the Obukhov length L, which, in turn, is a function of H, (L'E), and u^*, that is,

$$L = -\frac{u^{*3} T_{vr} \rho_v C_p}{kg(H - 0.61 C_p T_r (L'E)/L')} , \tag{23}$$

where

T_r - reference level temperature,

T_{vr} - reference level virtual temperature,

g - acceleration due to gravity,

$$\rho_v - \text{density of moist air} - \frac{P}{R_d T_v} \,. \tag{24}$$

3. SECONDARY EQUATIONS

For unstable conditions we write a relationship between V and L as

$$V = \frac{u*}{k}\left\{\ln\left(\frac{x-1}{x+1}\right) + 2\ tan^{1}x\right\}\Bigg|_{x_o}^{x} \quad , \tag{25}$$

where

$$X_o = \left(1 - 15\frac{z}{L}\right)^{1/4} \quad , \tag{26a}$$

$$x_o = \left(1 - 15\frac{z_o}{L}\right)(1/4 \quad , \tag{26b}$$

z_o = roughness length.

The differential of V in terms of u^* and x is

$$dV = \frac{\partial V}{\partial u^*}du^* + \frac{\partial V}{\partial x}dx \quad , \tag{27}$$

where

$$\frac{\partial V}{\partial u*} = \frac{1}{k}\left\{\ln\left(\frac{x-1}{x+1}\right) + 2\ tan^{-1}x\right\}\Bigg|_{x_o}^{x} \quad , \tag{28a}$$

$$\frac{\partial V}{\partial x} = \frac{u*}{k}\left\{\frac{2}{(x-1)(x+1)} + \frac{2}{1+x^2}\right\} \,. \tag{28b}$$

However, from equation (26a)

$$dx = \frac{15z}{4L^2}\left(1 - 15\frac{z}{L}\right)^{-3/4} dL \quad . \tag{29}$$

From equations (28) and (29) we obtain

$$\begin{aligned} dv = {} & \frac{1}{k}\left\{\ln\left(\frac{x - 1}{x + 1}\right) + 2\tan^{1}x\right\}\Big|_{x_o}^{x} du^* \\ & + \frac{30zu^*}{4kL^2}\left\{\frac{1}{x^2 - 1} + \frac{1}{x^2 + 1}\right\}\left(1 - 15\frac{z}{L}\right)^{-3/4} dL \quad . \end{aligned} \tag{30}$$

Equation (30) is written as

$$dv = \alpha_3 du^* + \alpha_4 dL \quad . \tag{31}$$

We use equation (23) to determine the differential of L, that is,

$$dL = \frac{\partial L}{\partial u^*} du^* + \frac{\partial L}{\partial \theta_v^*} d\theta_v^* \quad , \tag{32}$$

where

$$\frac{\partial L}{\partial u^*} = \frac{2u^* T_{vr}}{kg\theta_v^*} \quad , \tag{33a}$$

$$\frac{\partial L}{\partial \theta_v^*} = -\frac{u^{*2} T_{rp}}{kg\theta_v^{*2}} \quad . \tag{33b}$$

However, since

$$\theta_v^* = \theta^* + 0.61\theta_r q^* \quad , \tag{34}$$

$$d\theta_v^* = d\theta^* + 0.61\theta_r dq^* \quad , \tag{35}$$

and

$$dL = \frac{2u^* T_{vr}}{kg\theta_v^*} du^* - \frac{u^{*2} T_{vr}}{kg\theta_v^* 2}\left(d\theta^* + 0.61\theta_r dq^*\right) \quad . \tag{36}$$

Knowing H and L′E, and having the equations to compute u^*, we can determine the differential forms of θ^* and q^*, that is,

$$d\theta^* = -\frac{-dH}{C_p \rho u^*} + \frac{\theta^* du*}{u^*} \quad , \tag{37a}$$

$$dq^* = \frac{-d(L'E)}{L' \rho u^*} - \frac{q^* du^*}{u^*} \quad . \tag{37b}$$

4. CALCULATION PROCEDURE

For this calculation procedure we assume that the values of H, L′E, V_r, T_r, P_r, and f_r (reference level relative humidity) are known. We also assume that T_r, P_r, and f_r are precise. The only parameters that vary are H, L′E, and V_r.

1. L and u^* are computed interatively using equations (23) and (25).

2. Substituting $d\theta^*$ and dq^* of equation (37) into equation (36) gives dL in terms of du^*. Solving equations (36) and (31) gives random variations in u* and L for random errors in H and (L′E).

3. Variations in C_n^2 are computed using equation (22) for errors in H, L′E, and u^*.

5. DATA SETS

The two cases considered in this study are based on field data collected at Davis, California, during the summer of 1966 (Stenmark and Drury, 1970). The Davis field site, a flat, 5-hectare area at 17 m elevation above sea level is located about 2 km west of the main portion of the University of California at the Davis Campus, 24 km west of Sacramento, and 113 km northeast of San Francisco. The data were taken during periods when the surrounding fields, for the most part, were crop covered and well irrigated, giving, in effect, homogeneous surface conditions with respect to temperature and moisture. Advection effects were considered to be negligible. Profiles of wind, temperature, and specific humidity (moisture) were measured at nine levels from 25 to 600 cm. Raw data were processed to give 1/2-h average profiles. Table 1 gives the reference level (1 m) values for windspeed (V_r), pressure, (P_r), relative humidity (f_r), and temperature (T_r), as well as the derived values for the sensible heat flux (H) and latent heat flux (L′E), for each of these cases.

TABLE 1. MICROMETEOROLOGICAL DATA FROM DAVIS, CALIFORNIA

	Case 1	Case 2
Date	6-22-66	6-3-66
Time (PST)	1430	1200
V_r (cm/s)	447.9	207.7
P_r (mbar)	1000	1000
f_r (%)	37.6	35.6
T_r (K)	294.35	294.58
H (W/m^2)	66.57	37.92
L′E (W/m^2)	515.43	307.73

6. RESULTS

We alert the reader to a possible pitfall of misinterpretation and application of the data presented in this report. The so-called natural variations used in this study were not determined from field data; instead they are creations on our part of what we felt were reasonable. In particular we not only required that the distributions of the fluctuations be normally distributed, but we also specified the values of the variances. (Note however that the mean values were determined from field data--see section 5.) For example, the standard deviation for the windspeed distributions was 3.33 cm/s. For this study we did not try to adjust the windspeed variance to changes in the magnitude of the windspeed itself. For temperature we chose a standard deviation about the mean of 1/3 of 0.1 K. For relative humidity the standard deviation used to generate its normal distribution was 1/2 of 1 percent relative humidity. The standard deviation used for the pressure distribution was 1/3 of 1 mbar.

As far as the variances for the derived distributions for H and L′E are concerned, they (not unexpectedly) varied from case to case. For L′E the standard deviations changed from 8.0 to 11.3 W/m^2, for cases 1 and 2, respectively. Similarly, the change in standard deviations for H was approximately 8.1 to 6.0 W/m^2.

The results of two cases are presented in this section and as such are at best representations of the sensitivity of C_n^2 to the input parameters, as specified, and should not be interpreted as real world solutions.

Figure 1* shows the two-level model, derived distributions of H, L′E, and U* for Case 1. Additionally, the normal distributions for V_r are presented to show the fidelity of the normal distributions generated and used as input parameters.

Note that the range of the distribution of sensible and latent heat for this case is approximately 50 W/m^2. The distribution for U* shows a narrow range and relative insensitivity to variations in the input parameters used.

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*Figures are presented at the end of the text.

Figure 2 shows the derived distributions for T^* (θ^*), q^*, and L. The range for these distributions is approximately a factor of 2. Note that for this case, since U^* is relatively large and T^* is small, the mean value for the Obukhov scaling length is quite large, representing weakly unstable atmospheric conditions.

Figure 3 illustrates the random distribution for C_n^2 resulting from variations in H, L'E, and V_r. The range for the random distribution of C_n^2 is approximately a factor of 3. Additionally a cumulative distribution for C_n^2 is shown. It suggests that about 47 percent of the time C_n^2 will have a value equal to or less than its mean value.

Figures 4 through 6 show the distributions of H, L'E, V_r, U^*, T^*, q^*, L, and C_n^2 for Case 2. Note here that mean values for T^* and q^* are slightly greater in magnitude than those from Case 1, and the mean value for U^* is small. This results in L values lower in magnitude for this case, representing more moderately unstable atmospheric conditions. C_n^2 is significantly larger in magnitude (that is, on the order of 10^{-13}) and its range is approximately a factor of 5.

7. SUMMARY AND CONCLUSIONS

In this study we wrote C_n^2 in terms of windspeed, sensible heat flux, and latent heat flux. Recall that our goal was to consider the effect on C_n^2 if estimates of V_r, H, and L'E were assumed to be in error or contained natural variabilities. We used micrometeorological data from Davis, California, to evaluate distributions for H, L'E, and finally C_n^2. These figures were discussed in section 6.

We found that by constraining the variations for windspeed to a $\sigma = 3.33$ cm/s and with a range of approximately 50 W/m^2 for both sensible and latent heat that for these two cases, C_n^2 could be determined within a factor of 3 or 5.

Now the question remains as to what are acceptable ranges or values for C_n^2. The answer lies wholly with their use, or, that is, it depends on the application for C_n^2. In a separate study (Rachele and Tunick, 1991), we found that r_o, the receiver coherence diameter, can vary (in one case) from 1.26 to 3.76 cm, causing, in turn, a significant effect upon the near- and far-field slow modulation transfer function. Other cases resulted in similar findings.

In conclusion we feel confident that our methodology was sound and that our results have the potential to suggest how well we must estimate H and L'E in our models.

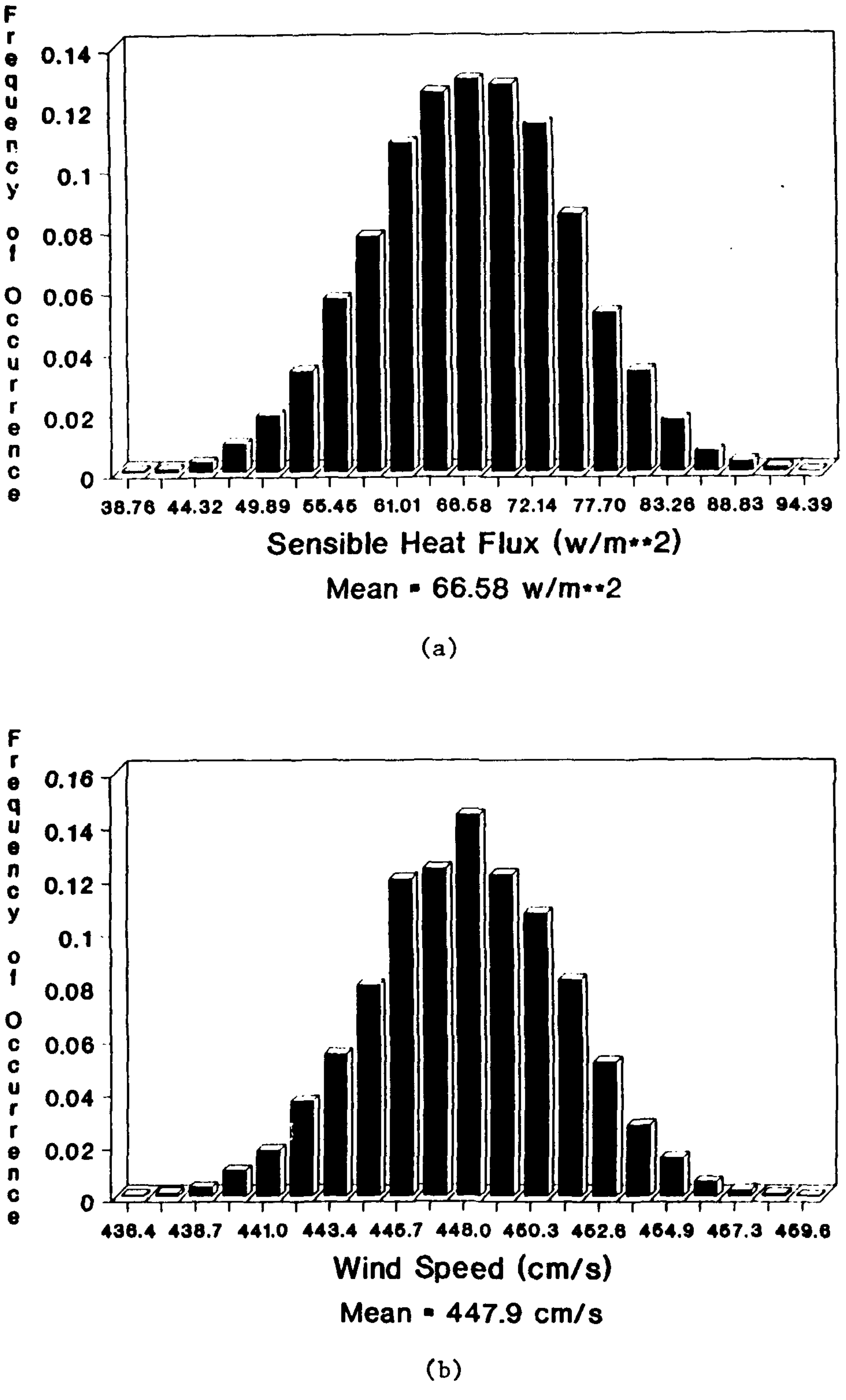
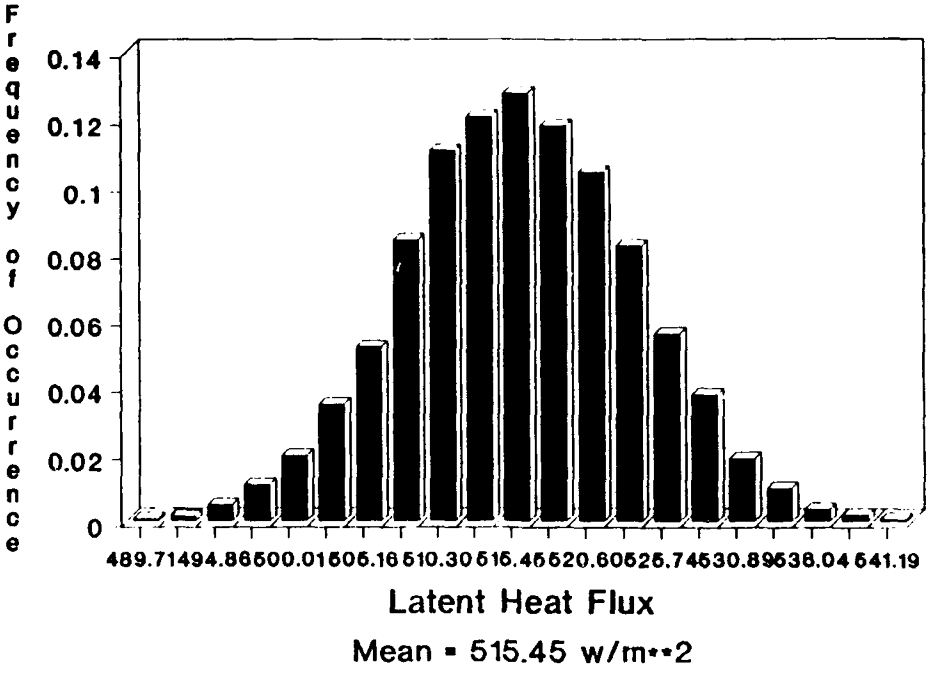


Figure 1. Case 1 - Random distribution for: (a) H, (b) L'E, (c) u*, and (d) normal distribution for V_r.



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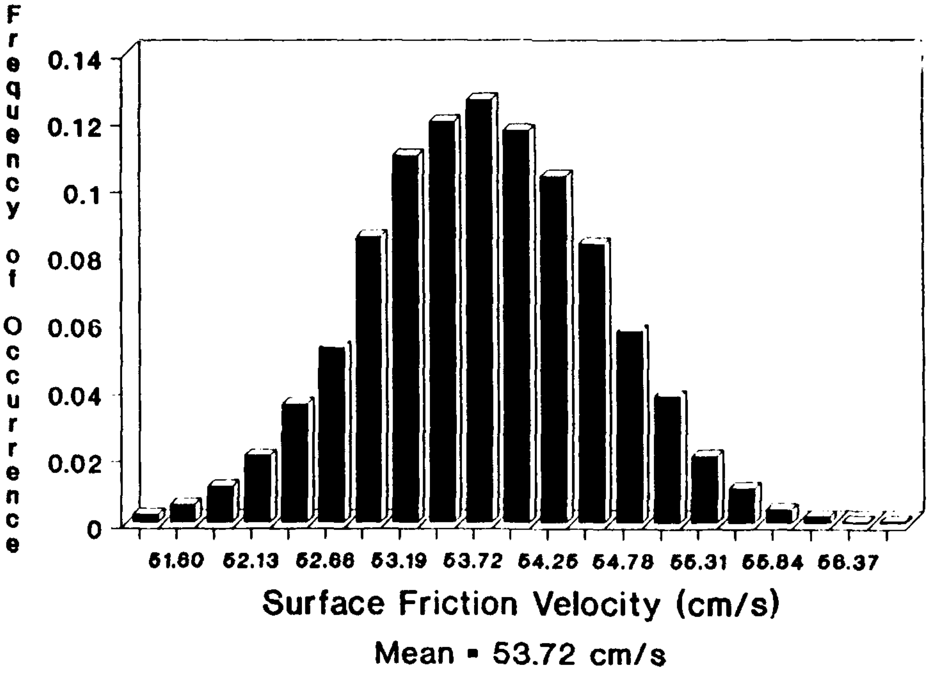

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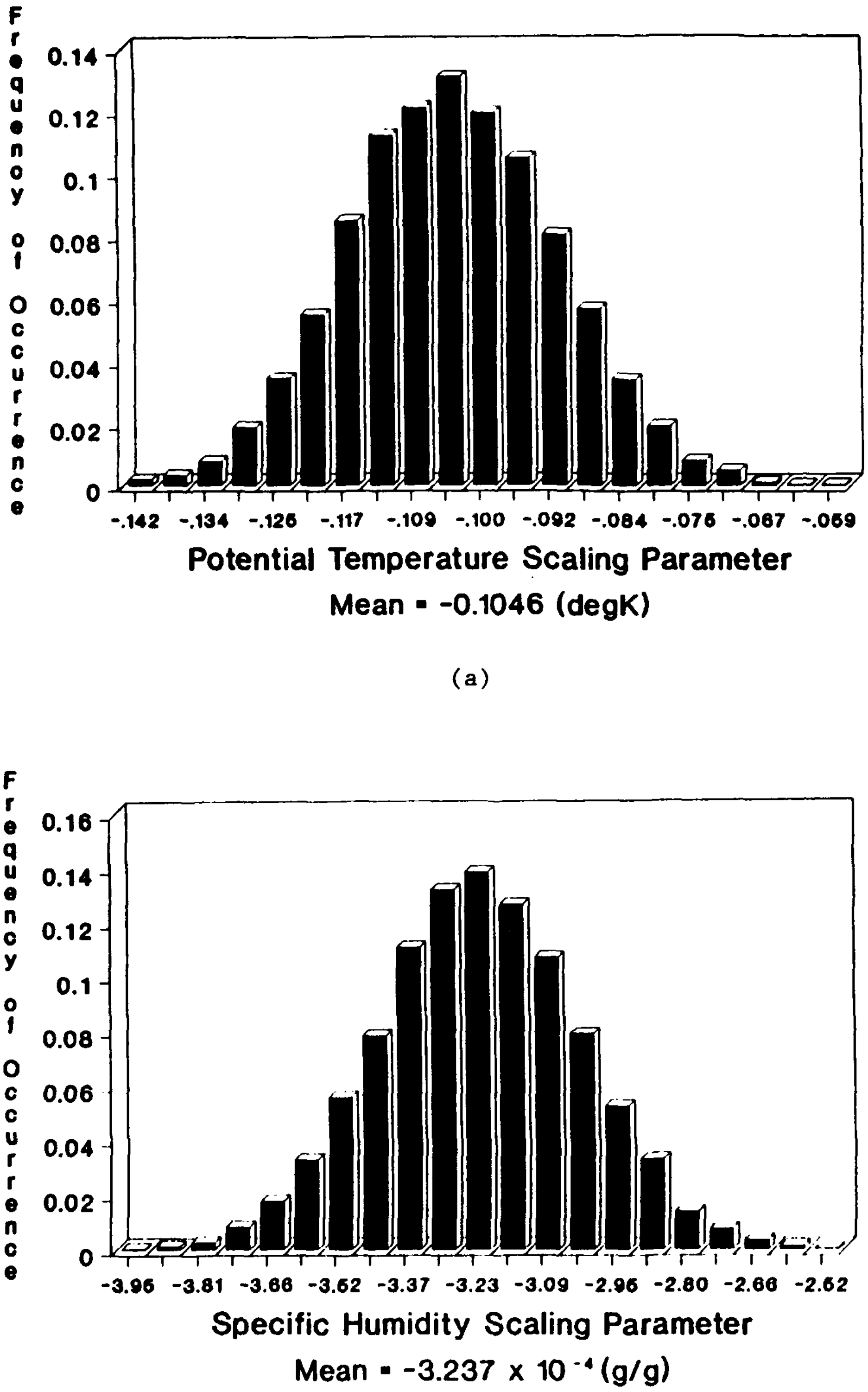
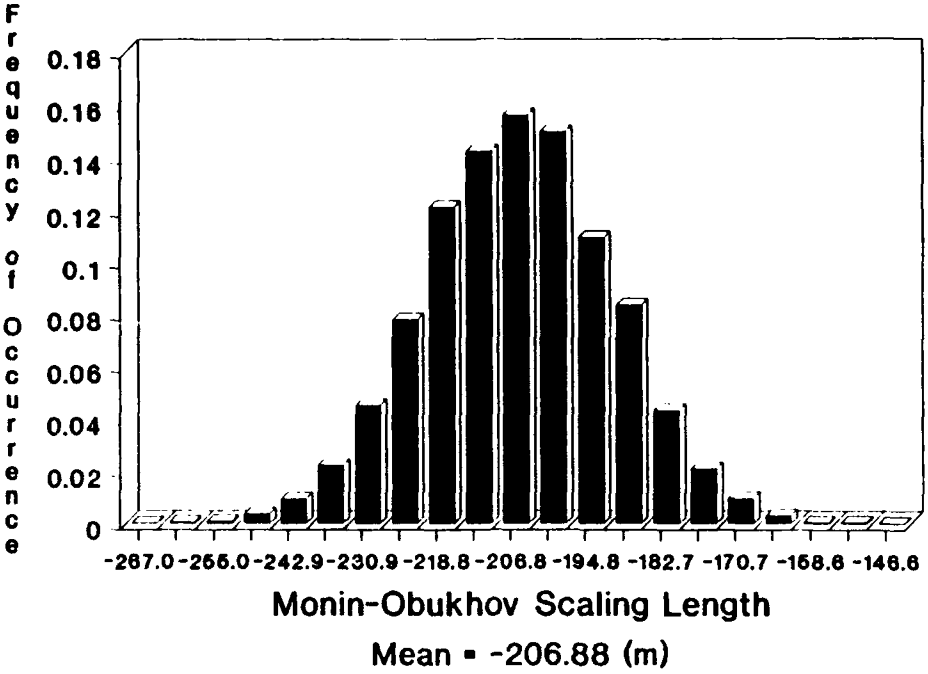
Figure 1 (cont)



(a)

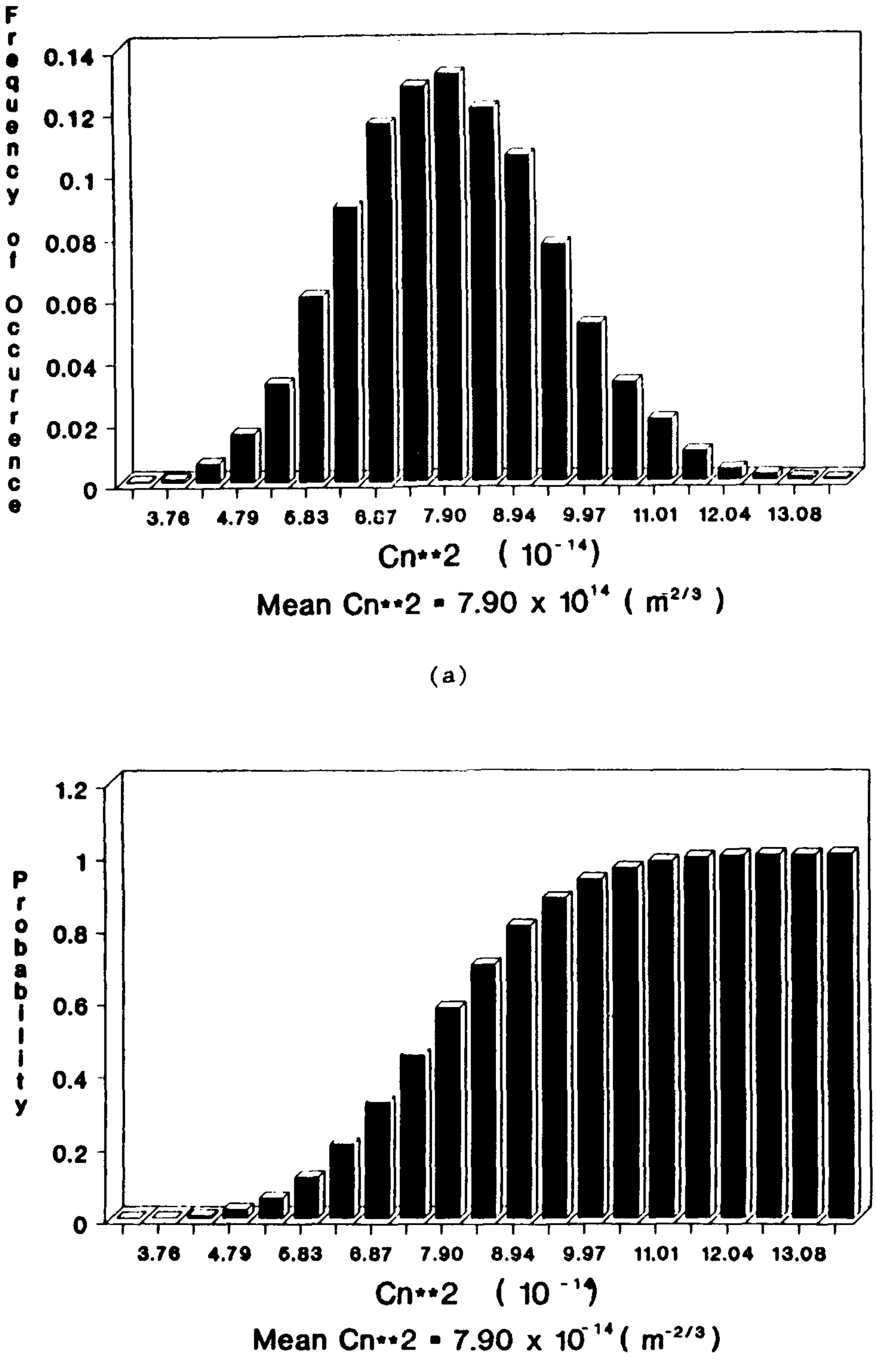
(b)

Figure 2. Case 1 - Random distribution for: (a) T*, (b) q*, and (c) L.



(c)

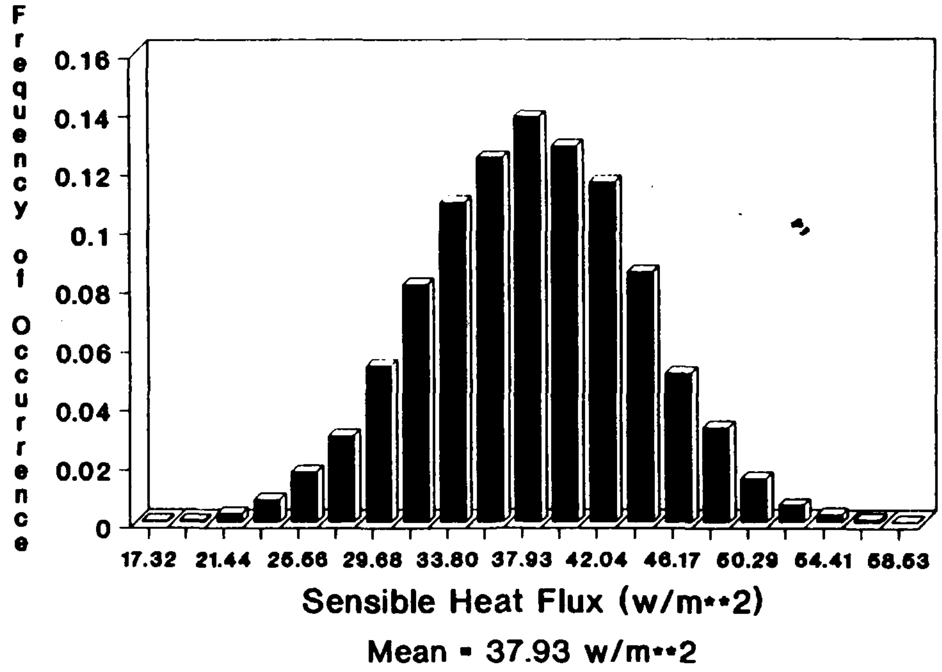
Figure 2 (cont)



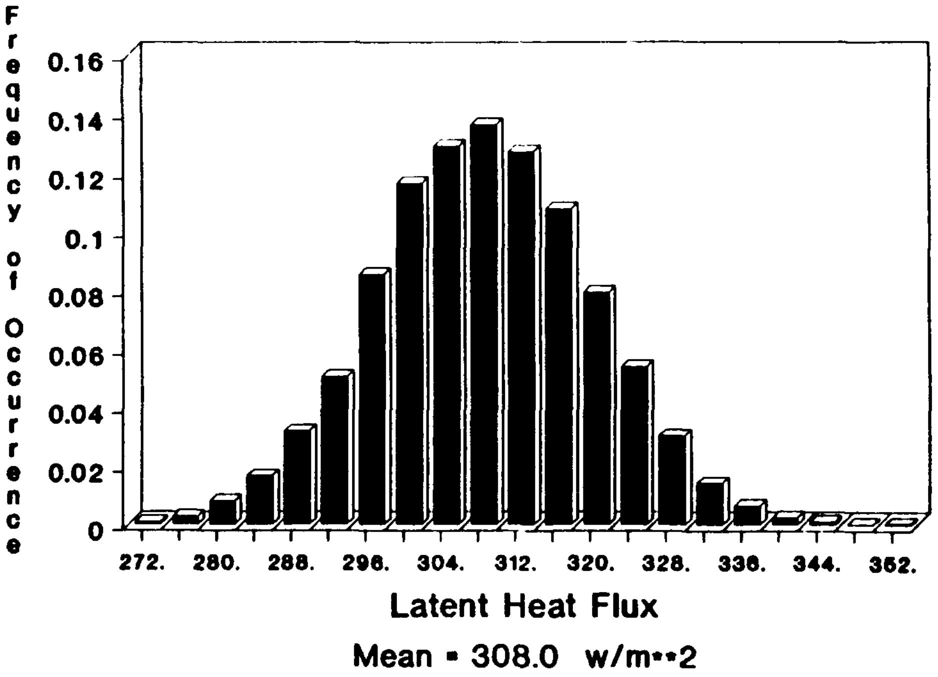
(a)

(b)

Figure 3. Case 1 - Distribution for C_n^2: (a) random and (b) probability.

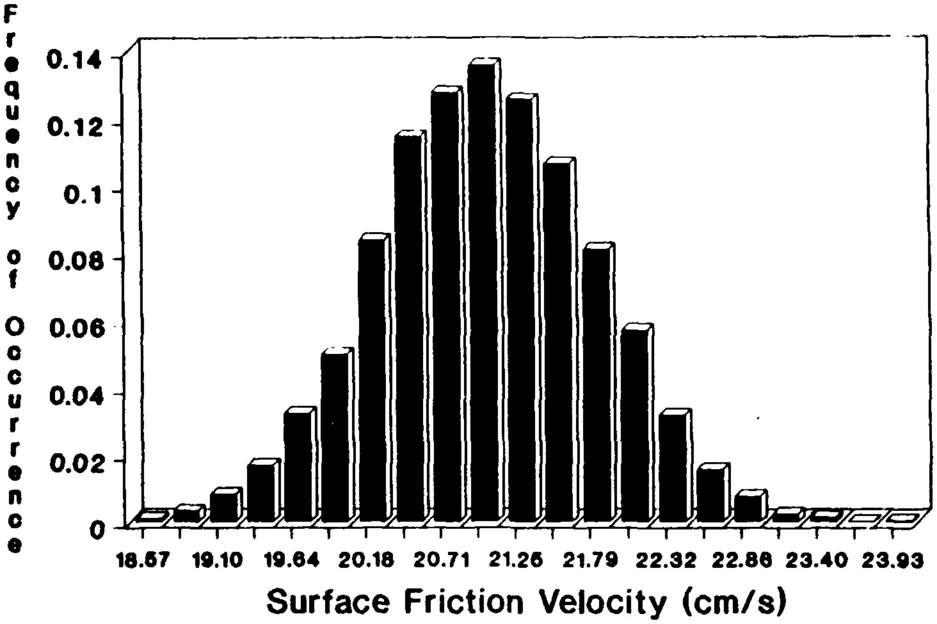


(a)



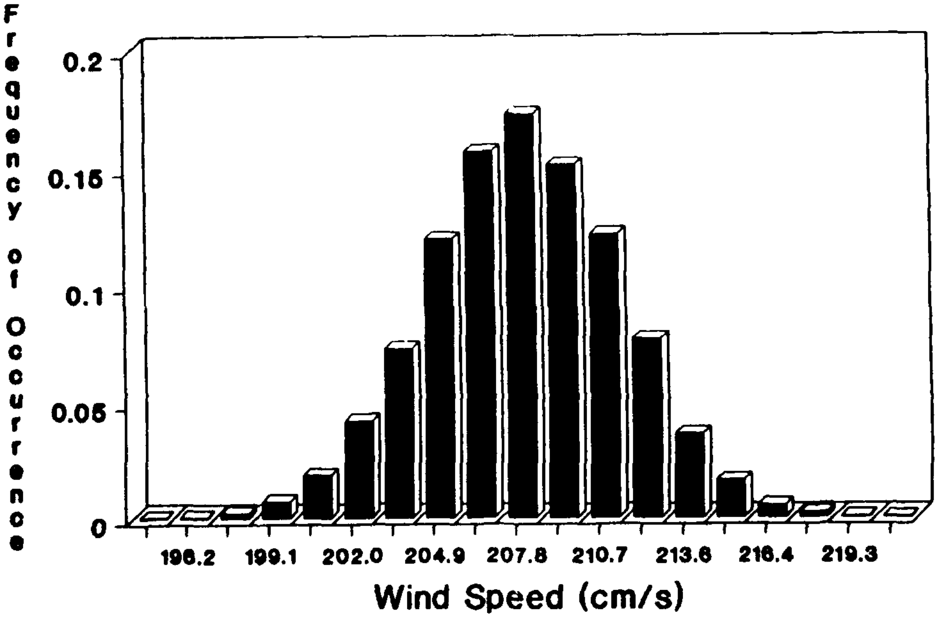
(b)

Figure 4. Case 2 - Random distribution for: (a) H, (b) L'E, (c) u*, and (d) normal distribution for V_r.



Mean = 20.98 cm/s

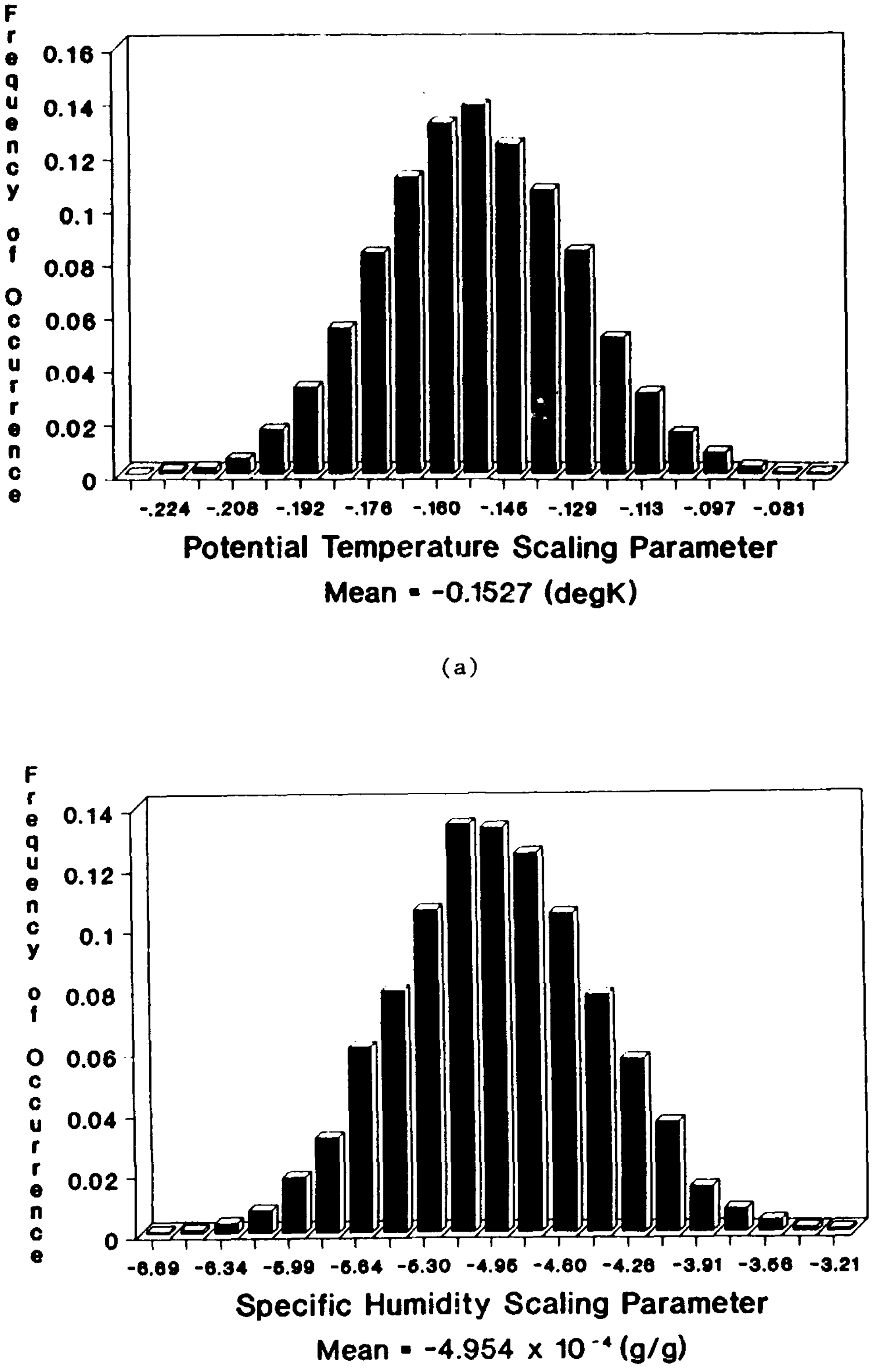
(c)



Mean = 207.7 cm/s

(d)

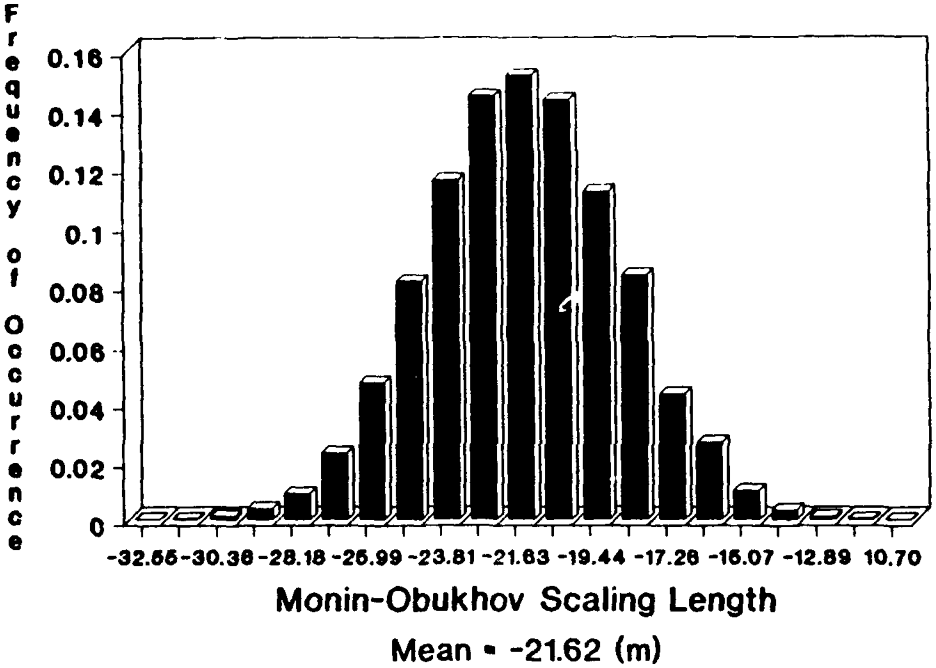
Figure 4 (cont)



(a)

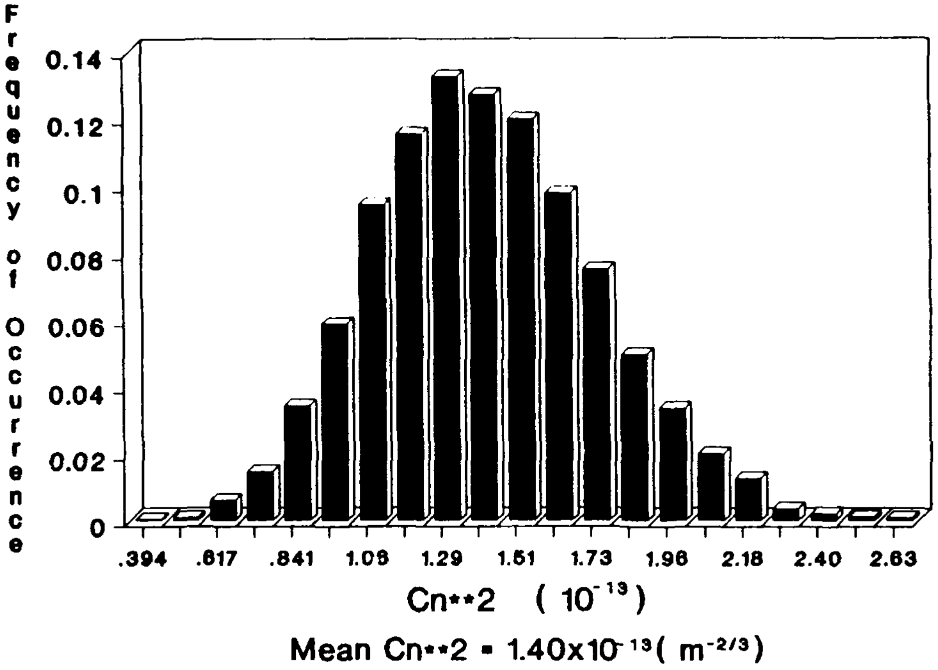
(b)

Figure 5. Case 2 - Random distribution for: (a) T*, (b) q*, and (c) L.

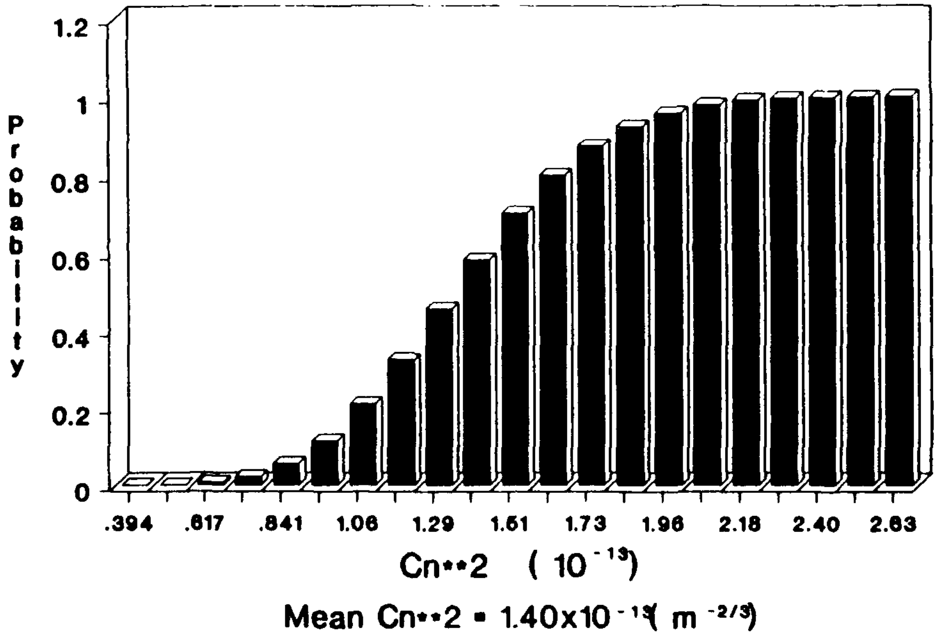


(c)

Figure 5 (cont)



(a)



(b)

Figure 6. Case 2 - Distribution for C_n^2: (a) random and (b) probability.

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