To the Graduate Council:

I am submitting herewith a thesis written by Margaret Wilson entitled "A Comparison Study of Atmospheric Stability Indicators." I have examined the final copy of this thesis for form and content and recommend its acceptance in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Wayne T. Davis

Wayne T. Davis, Major Professor

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A COMPARISON STUDY OF ATMOSPHERIC STABILITY INDICATORS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Margaret Wilson

December 1982

To my parents,

Albert J. and Ana M. Wilson

Happy 35th Anniversary

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NONENCLATURE

DT/DZ	Temperature change with height
g	Acceleration due to gravity
h	Vertical spread or height
H	Vertical Height of a point source
K	Constant, eddy-diffusivity coefficient
$[l_z]_\gamma$	Vertical step length in an arbitrarily-stratified atmosphere
$[l_z]_\Gamma$	Vertical step length in a neutrally-stratified atmosphere
Q	Source strength, total amount of material released from a point source
Q'	Emission rate of a point source
$\bar{q}$	Mean value of an air property per unit mass of air
R/M	Specific gas constant for dry air, 2.876E6 cm^2/sec^2 x deg
Re	Reynolds number
$\bar{u}$	Average wind speed in the downwind direction
x	Downwind direction
y	Crosswind direction
z	Vertical wind direction

Greek Letters

μ	Dynamic viscosity of air
ρ	Density of air
ν	Kinematic viscosity of air
λ	Lapse rate for an arbitrarily-stratified atmosphere

Γ'	Constant, 1° C/100 m (Dry Adiabatic Lapse Rate)
γ'	The ratio of specific heats for an ideal gas
θ	Angular spread
χ	Instantaneous value of concentration
$\bar{\chi}_p$	Peak or centerline concentration
γ	Subscript to denote an arbitrarily-stratified atmosphere
Γ	Subscript to denote a neutrally-stratified atmosphere
σ_y	Standard deviation of concentration profile in the lateral direction
σ_z	Standard deviation of concentration profile in the vertical direction
σ_θ	Standard deviation of the horizontal wind direction
σ_ϕ	Standard deviation of the vertical wind direction
μ'_γ	The ratio between an arbitrary and a neutral stratification

ABSTRACT

This study was conducted to investigate the relationships between three meteorological parameters commonly used to determine atmospheric stability for use in air quality modeling. The parameters compared were DT/DZ, σ_θ and σ_ϕ collected hourly for one year from a meteorological tower.

By employing the stability classifications proposed by the U. S. Environmental Protection Agency and the U. S. Nuclear Regulatory Commission, it has been shown that the methods are unreliable in determining stability during certain hours of the day. This suggests that pollutant concentration predictions as a result of air quality modeling during these periods will vary depending on the stability indicator used.

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INTRODUCTION

Purpose of the Study

A major effort towards achieving the objectives of the Clean Air Act has been to maintain the standards which protect the nation's air resources. The administrator of the Act, the U. S. Environmental Protection Agency (U. S. EPA), has determined that air quality monitoring and modeling are the procedures to be used in determining compliance with these standards. Under Title I Part C Section 165 of the Act, all major emitting facilities must determine the potential impacts of emissions prior to construction and must specify the air quality model to be used. Major emitting facilities are any of the stationary sources listed in Table 1 which emit, or have the potential to emit, one-hundred tons per year or more of any air pollutant [1].

Additional uses of air quality models include land-use planning, assessment of fuel substitution strategies, real-time alert warning systems, and real-time source emission control systems based on model estimates of air quality using meteorological conditions [2].

The most widely used model, providing the quantitative link between air quality and pollutant releases, is the Gaussian-Plume type. The mathematical expressions used in this model address the

Table 1. Stationary Sources of Air Pollutants [1].

Facility
Fossil-fuel fired steam electric plants of 250,000,000 BTU
Coal-cleaning plants
Kraft pump mills
Portland cement plants
Primary zinc smelters
Iron and steel mill plants
Primary aluminum ore reduction plants
Primary copper smelters
Municipal incinerators charging 250 tons of refuse/day
Hydrofluoric, sulfuric and nitric acid plants
Petroleum refineries
Lime plants
Phosphate rock processing plants
Coke oven batteries
Sulfur recovery plants
Carbon black plants
Primary lead smelters
Fuel conversion plants
Sintering plants
Secondary metal production facilities
Chemical processing plants
Petroleum storage with a capacity of 300,000 barrels
Taconite ore processing plants
Glass fiber processing plants
Charcoal production facilities

dispersion of air pollutants in a manner which can be directly related to visual observation. Practical application of the model lies in the ability to quantify diffusion from on-site meteorological data. Though useful information is provided by air quality models, there are limitations to their accuracy. The determination of atmospheric stability is a significant factor contributing to the inaccuracies in model predictions.

For regulatory purposes, the U. S. EPA has sought to standardize air quality models and their application by means of a guideline issued in 1978. When no wind fluctuation data are available the guideline recommends using the Pasquill-Gifford scheme of stability determination which is based on low-level releases of smoke under varying conditions of wind speed, time of day, and cloud cover. The relationship of stability to varying meteorological data is shown in Table 2. Based on a Gaussian form of concentration in the horizontal and vertical, Pasquill compiled all available data from diffusion experiments carried out in the 1950's in terms of a lateral spread angle (θ) and a vertical spread (h) of the plume which was published in 1961. Following this article, Gifford published graphs which expressed (θ) and (h) in terms of dispersion coefficients (σ_y) and (σ_z) for direct use in the Gaussian model equations. As such, a classic scheme for determining stability, referred to as the Pasquill-Gifford (P-G) technique, was incorporated into the guideline procedures.

Presently, an attempt to use more site-specific wind fluctuation data is being considered. Proponents of this option are

Table 2. Relation of Turbulence Types to Weather Conditions [3].

Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or >4/8 cloudiness†	<3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

*Applicable to heavy overcast, day or night.

†The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

A-Extremely unstable conditions; B-Moderately unstable conditions; C-Slightly unstable conditions; D-Neutral conditions*; E-Slightly stable conditions; F-Moderately stable conditions.

meteorologists in the nuclear regulatory industry. Their efforts are aimed at determining worst-case conditions of meteorology for low-level releases for safety reasons. Initial guidelines for determining stability were issued by the U. S. Nuclear Regulatory Commission (U. S. NRC) in 1972.

Revisions to both the U. S. EPA Guideline on Air Quality Models and the Nuclear Regulatory Guide 1.23 have been proposed in 1980. The objective of the stability criteria presented in these guides is to relate meteorological data to stability for regulatory and safety purposes. These revisions are presented in Tables 3 and 4 for the U. S. EPA and U. S. NRC, respectively.

The purpose of this study is to evaluate certain characteristics of the atmosphere for use in determining stability. The objectives are listed below.

1. To examine and review the P-G scheme of stability determination.
2. To determine the precision of the association between various stability indicators from on-site meteorological measurements collected for one year.
3. To compare the consistency between stability classification guidelines when applied to actual data.

Table 3. Proposed Revisions to the Guideline on Air Quality Models [4].

P-G Stability Category	*Standard Deviation of Vertical Wind Direction, σ_ϕ
A	$\sigma_\phi > 12^o$
B	12^o
C	10^o
D	7.8^o
E	5^o
F	$\sigma_\phi < 2.4^o$

P-G Stability Category	**Standard Deviation of Horizontal Wind Direction, σ_θ
A	$\sigma_\Theta > 22.5^o$
B	22.5^o
C	17.5^o
D	12.5^o
E	7.5^o
F	$\sigma_\Theta < 3.8^o$

*Adjust for surface roughness by multiplying σ_ϕ by $(z_0/15cm)^2$ where is the average surface roughness length within a 1 to 3km radium of the source.

**Adjust for surface roughness by multiplying σ_θ by $(z_0/15cm)^2$ where is the average aerodynamic roughness within 1 to 3 km of the source.

Table 4. Proposed Revisions to the U.S. NRC Guide 1.23 [5]

Stability Classification	Pasquill Categories	Temperature Change with Height (°C/100 m)	σ_θ degrees
Extremely unstable	A	$\Delta T/\Delta z \leq -1.9$	$\sigma_\theta \geq 22.5$
Moderately unstable	B	$-1.9 < \Delta T/\Delta z \leq -1.7$	$22.5 > \sigma_\theta \geq 17.5$
Slightly unstable	C	$-1.7 < \Delta T/\Delta z \leq -1.5$	$17.5 > \sigma_\theta \geq 12.5$
Neutral	D	$-1.5 < \Delta T/\Delta z \leq -0.5$	$12.5 > \sigma_\theta \geq 7.5$
Slightly stable	E	$-0.5 < \Delta T/\Delta z \leq 1.5$	$7.5 > \sigma_\theta \geq 3.8$
Moderately stable	F	$1.5 < \Delta T/\Delta z \leq 4.0$	$3.8 > \sigma_\theta \geq 2.1$
Extremely stable	G	$4.0 < \Delta T/\Delta z$	$2.1 > \sigma_\theta$

CHAPTER II

LITERATURE REVIEW

Characteristics of the Atmosphere for Use in Determining Stability

In an effort to assess the air quality impacts of new and existing source facilities, both for permitting and compliance purposes, dispersion modeling is required. As recommended by the U. S. EPA and U. S. NRC, on-site meteorological data should be used. In order to quantitatively define the concentration downwind of an effluent source it is necessary to account for the diffusion of material that ensues once the effluent is released. A suitable means of doing this is to determine the stability of the atmosphere from on-site meteorological parameters.

At present, the stage of technology is such that continuous recording of meteorological parameters can be taken and used directly in the calculation for downwind concentration. This has not been the case in the past. For a distance $\leq$ 100 m above the earth's surface distinguishing characteristics of the atmosphere have been used as the primary means of determining stability.

Wind Speed and Wind Direction in the Surface Layer

According to Sutton [3], the surface boundary layer does not exceed 100 m above the earth's surface. This region is characterized by a constant shearing stress and a wind structure that is determined by the vertical temperature. The region extending from the surface to not more than 1000 m is the planetary boundary layer and is characterized by a variable shearing stress and a wind structure that is influenced by surface friction and the earth's rotation.

In order to obtain the nature of wind flow in the surface layer (the layer into which most sources emit effluents) it is necessary to define a reference length to be 10 m in depth from the surface, and assuming a typical velocity in this layer to be 1 m/sec the Reynolds number can be determined in the following manner as presented by Slade [6]. Define the Reynolds number as

$$\text{Re} = (\text{reference length}) \times (\text{flow velocity}) \times (\text{dynamic viscosity/density})^{-1} \quad (2.1)$$

At 101,326 N/m^2 pressure and 298K temperature the properties of dry air are

$$\mu = 1.84\text{E-}5 \text{ kg/m-s}$$

$$\rho = 1.185 \text{ kg/m}^3$$

$$\nu = \mu/\rho = 1.55\text{E-}5 \text{ m}^2\text{/s}$$

Substituting the length, velocity, and ν into Eq.(2.1), and considering flows at Re > 2000 to be turbulent, the flow regime in the surface layer is

$$\text{Re} = 645{,}000 \quad .$$

Hence a turbulent flow is normally associated with the surface layer.

Influence of the diurnal variations in density associated with changes in the temperature structure is a source of difficulty in characterizing the surface layer.

In the daytime, due to surface heating effects, turbulent mixing in the surface layer is enhanced. In the nighttime, due to the loss of longwave radiation to space, the air nearest the ground is cooler than air above. Such a situation reduces the turbulent mixing in the surface layer. Above this region, the average wind speed may be higher at night than during the day [6] . Variation of the wind speed profile as a result of diurnal temperature effects [6] is shown in Figure 1. Figure 2 shows a vector diagram indicating the wind direction and magnitude for both day and night conditions. During daytime conditions, the low-level wind (16 m) approaches that of the upper-level wind in both speed and direction. Nighttime conditions show variable wind speeds and direction with height.

Temperature Structure

In the atmosphere, the density, pressure, and temperature are dependent on height, however, there is an equilibrium state which the atmosphere tries to return to. This state has been noted by Sutton [7] and Singer and Smith [8].

An equation is derived to obtain the definition of this equilibrium state. Qualitative estimates of stability will be discussed in relation to the theoretical equilibrium value.

Define the linear decrease of temperature with altitude in the atmosphere as

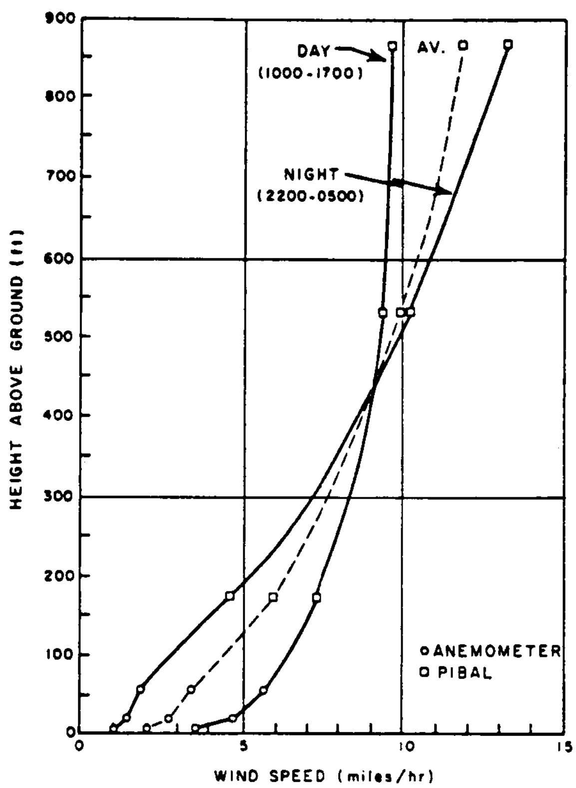


Figure 1. Average wind speed profiles constructed from measurements made during a 1-year period [6].

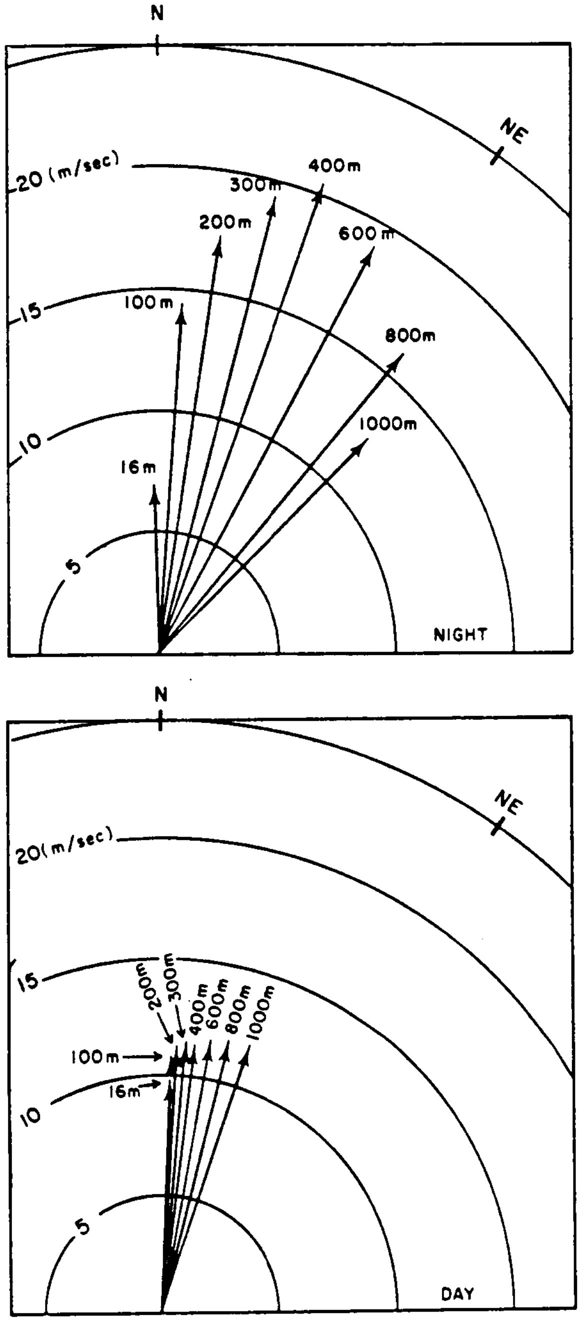


Figure 2. Average vectors of wind direction and magnitude constructed from observations in Central Nebraska [6].

$$\frac{dT}{dz} = - \lambda \tag{2.2}$$

where λ = the lapse rate.

Note the pressure variation with height from the hydrostatic equation to be

$$\frac{dP}{dz} = -g\rho \tag{2.3}$$

For an ideal gas, the equation of state is given by

$$P = \rho RT \tag{2.4}$$

Differentiate Eq. (2.4) with respect to z, the vertical height

$$\frac{dP}{dz} = RT\,\frac{d\rho}{dz} + \rho R\,\frac{dT}{dz} \tag{2.5}$$

By using Eq. (2.2) and Eq. (2.3), Eq. (2.5) reduces to

$$-g\rho = RT\,\frac{d\rho}{dz} + \rho R(-\lambda) \tag{2.6}$$

Dividing Eq. (2.6) by RT and rearranging terms results in the vertical gradient of ambient density

$$\left(\frac{d\rho}{dz}\right)_{atm} = \frac{\rho}{T}\left(\lambda - \frac{g}{R}\right) \tag{2.7}$$

To calculate the vertical gradient of an air parcel introduced into this atmosphere we will assume an adiabatic process for the system. In this case the following thermodynamic relationship is

$$PV^{\gamma'} \text{ is a constant} \tag{2.8}$$

To find $d\rho/dz)_{par}$, the $d\rho/dz$ of a parcel of air, we note that

$$(\frac{d\rho}{dz})_{par} = (\frac{d\rho}{dP})_{par} (\frac{dP}{dz}) \quad , \qquad (2.9)$$

and since dP/dz is imposed by the atmosphere it is equal to $-g\rho$. The quantity $(d\rho/dp)_{par}$ is found by differentiating Eq. (2.8) which allows Eq. (2.9) to be evaluated as follows

$$(\frac{d\rho}{dz})_{par} = - \rho g \left(\frac{1}{TR\,\gamma'}\right) \qquad (2.10)$$

The criterion for stable equilibrium will be that the density of the air parcel must be higher than the ambient density i.e.

$$(\frac{d\rho}{dz})_{par} > (\frac{d\rho}{dz})_{atm} \qquad (2.11)$$

Substituting the two vertical gradients from Eq. (2.7) and (2.10) into Eq. (2.11) gives the range of lapse rates corresponding to stable conditions as follows

$$\lambda < \frac{g}{R/M} \frac{\gamma' - 1}{\gamma'} \qquad (2.12)$$

where $\gamma' = 1.4$

$g = 981.0$ cm/s^2

$R/M = 2.876E6$(cm^2/sec^2 x deg)

The lapse rate defined in Eq. (2.12) is known as the dry adiabatic lapse rate (Γ') and has a value

$$\Gamma' = \frac{g}{R/M} \frac{\gamma' - 1}{\gamma'} = 9.75E\text{-}5° \text{ C/cm} \qquad (2.13)$$

$$\Gamma' \simeq 1^{o} \text{ C/100 m} \qquad (2.14)$$

Relative states of stability determined by relating values of λ to the dry adiabatic lapse rate (Eq. 2.14) are listed below.

For $\lambda < \Gamma'$, the parcel density is greater than that of the surrounding air, hence a stable environment.

For $\lambda = \Gamma'$, the parcel density is equal to that of the surrounding air, hence a neutral stability.

For $\lambda > \Gamma'$, the parcel density is less than that of the surrounding air, hence, unstable conditions.

Stability Determined from Visual Observation of Vertical Dispersion

Observations of ground-level smoke releases made by Pasquill have led to a classic scheme for determining the diffusive action of the atmosphere under various meteorological conditions. A key to stability categories based on qualitative assessments was shown in Table 2, page 4.

Defining the plume concentration to be normally distributed horizontally and vertically, Pasquill noted that a vertical spread (h) and angular spread (θ) of the cloud plume could be determined by the concentration distribution [9].

Assuming the visible edge of a diffusing plume to be the point at which the axial concentration decreases to 10% of its value, (h) and (θ) can be defined by ordinate values of the normal distribution curve [6] as

$$h = 2.14\ \sigma_z \qquad (2.15)$$

$$\theta = \frac{4.28\ \sigma_y}{x} \qquad (2.16)$$

Referring to an orthogonal coordinate system in which x is downwind, y is crosswind, and z is vertical wind, the distribution of concentration [χ (x,y,z)] from a source of strength (Q) at location (0,0,H) is

$$\chi\ (x,y,z) = \frac{Q}{2\Pi\sigma_y\sigma_z\bar{u}}\left[\exp\ -\frac{(z-H)^2}{2\sigma_z^2} + \exp - \frac{(z+H)^2}{2\sigma_z^2}\right] \tag{2.17}$$

Assuming σ_y/σ_z = constant, the maximum ground-level concentration downwind (χ(x,0,0)), can be defined in terms of (h) by differentiating Eq. (2.17) with respect to σ_z. χ(x,0,0) is a maximum when

$$\sigma_z = \frac{H}{\sqrt{2}} \tag{2.18}$$

Eq. (2.17) is one solution to the Fickian diffusion equation which governs the heat transfer in a stationary fluid. The form of this equation, when applied to the atmosphere is

$$\frac{\partial\bar{q}}{\partial t} = K\,\frac{\partial^2\bar{q}}{\partial x^2}\ , \tag{2.19}$$

where K is a constant eddy-diffusivity coefficient which may be expressed in terms of the concentration profile i.e. K = σ_z^2.

Considering a grid placed perpendicular to a plume axis with step lengths varying according to the thermal stratification, the random motion of diffusion particles can be expressed as a function of step length on the grid [10]. Under the influence of thermal stratification, the vertical steplengths will be smaller in a stable-stratified layer than in an adiabatic layer. By relating steplengths to diffusivity coefficients in the form of a ratio between an arbitrary stratification and a neutral stratification the following relationships are stated

$$\mu'_{\gamma} = \frac{[l_z]_{\gamma}}{[l_z]_{\Gamma}} \tag{2.20}$$

$$\mu'_{\gamma} \quad \frac{[K_z]_{\gamma}}{[K_z]_{\Gamma}} \tag{2.21}$$

Since $K = \sigma_z^2$ Eq. (2.21) can be written as

$$\mu'_{\gamma} = \frac{[\sigma_z]_{\gamma}}{[\sigma_z]_{\Gamma}} \tag{2.22}$$

Eq. (2.22) is useful in determining the magnitude of the turbulent fluctuations simulated by grid lengths with variable spacing according to the thermal stratification of the atmosphere.

Based on available data collected by Pasquill in various conditions of stability, Wippermann has used Eq. (2.22) to define stability classes [10]. By selecting arbitrary ranges of lapse rate from the data, Wippermann has categorized stability classes as listed below.

Stability	Range of $^{o}C/100$ m
A	< -3.1
B	(-3.1) - (-1.9)
C	(-2.5) - (-1.2)
D_1	(-1.7) - (-0.3)
D_2	(-1.3) - (-0.1)
E	(-0.1) - (1.1)
F	(1.6) - (2.8)

For a downwind distance of 2500 m, the vertical spread of a cloud plume, under adiabatic conditions is 150 m (see Figure 3). From Eq. (2.15), the standard deviation of the concentration profile in a neutrally-stratified atmosphere is 70.1 m. Values of the standard deviation of the concentration profile in arbitrarily-stratified atmospheres (i.e. (A-F) stabilities) calculated from Eq. (2.15) are listed below.

Stability	h (at 2500 m)	$[\sigma_z]_\gamma$
A	-	-
B	640	300
C	310	145
D_1	145	68
D_2	123	57
E	82	38
F	53	24

From Eq. (2.22), the values of the ratio between the arbitrary stratifications and the neutral stratification (i.e. μ'_γ) are listed below.

Stability	μ'_γ
A	-
B	4.3
C	2.0
D_1	1.0
D_2	0.81
E	0.54
F	0.35

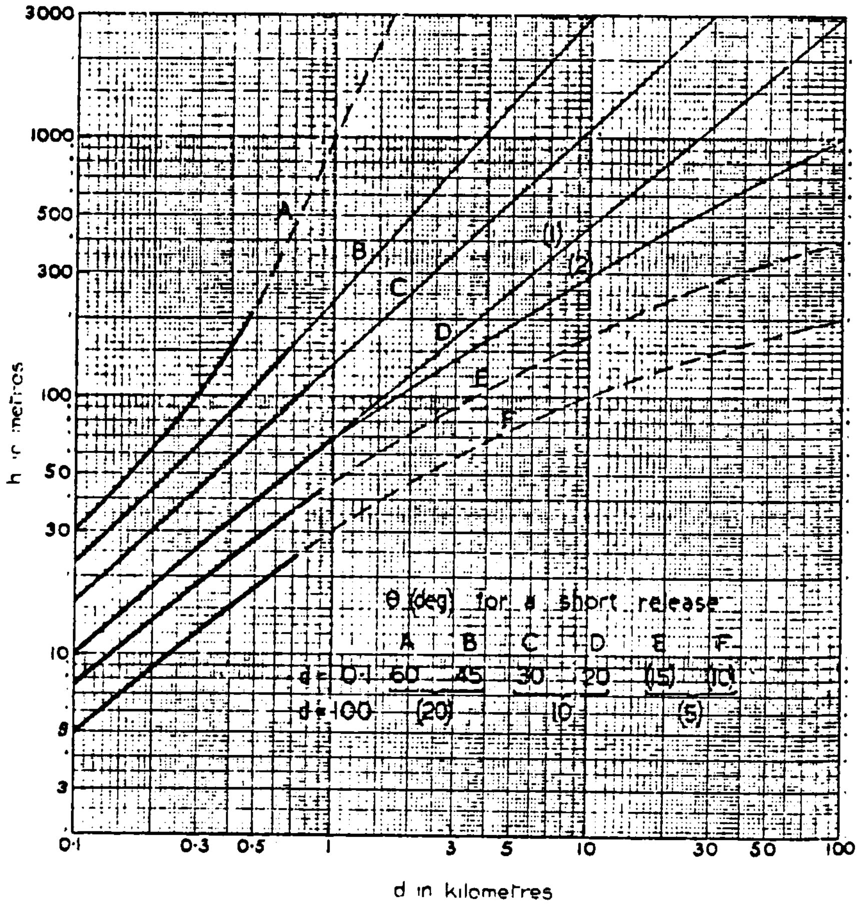


Figure 3. Tentative estimates of vertical height (h) and lateral spread (θ) [9].

By plotting μ'_γ on a semi-log scale (step length versus lapse rate), the relationship between $[\sigma_z]_\gamma$ and $[\sigma_z]_\Gamma$ as a function of thermal stratification at x = 2500 is shown in Figure 4 [10]. At distances > 1 km, the curves in Figure 5 [11] can be produced according to the transformation in Eq. (2.15) for the data in Figure 3 and the relationship developed by Wippermann in Eq. (2.22).

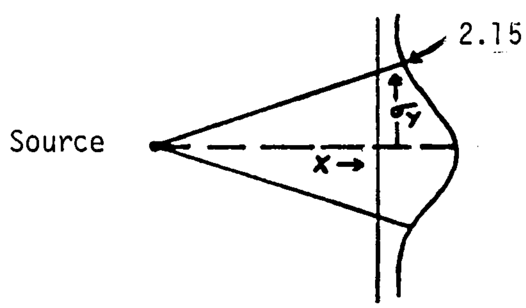
It has been shown that a systematic relationship for (σ_z) versus (x) does exist. The treatment of (σ_y) versus (x) has had significantly less data to rely on. The main reasons for the tentative estimations of (θ) beyond 1 km is due to the uncertainty of the wind shear effects on (θ). As noted by Pasquill [12], further reexamination of the data collected for ground-level smoke releases has not led to the determination of the wind shear effect on (θ).

Horizontal Dispersion

In order to relate (θ) to (σ_y), Gifford has used values of (θ) collected at limited downwind distances. According to Gifford [13], (θ) can be expressed as

$$\text{Tan}\left(\frac{\theta}{2}\right) = \frac{2.15\ \sigma_y}{x} \qquad (2.23)$$

The constant 2.15 is the 10% ordinate value of the normal distribution curve with the geometry of this distribution curve as the following



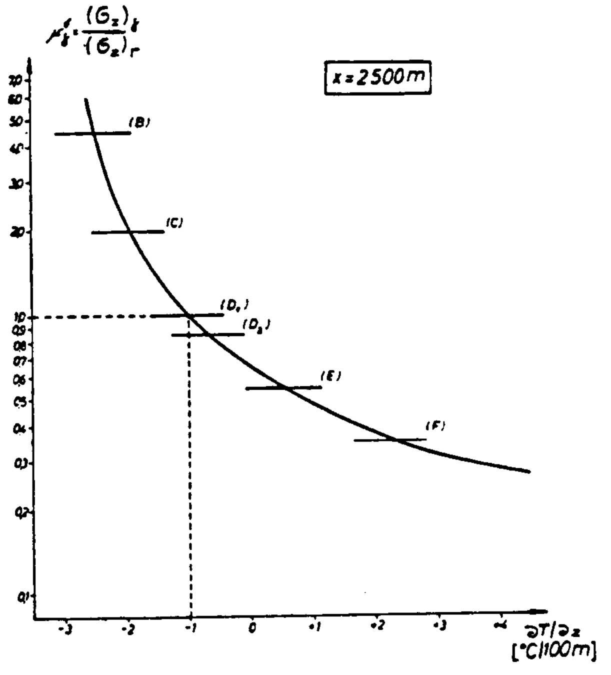


Figure 4. The relationship between standard deviations of concentration profile as a function of thermal stratification for Pasquill stability classes (B-F) [10].

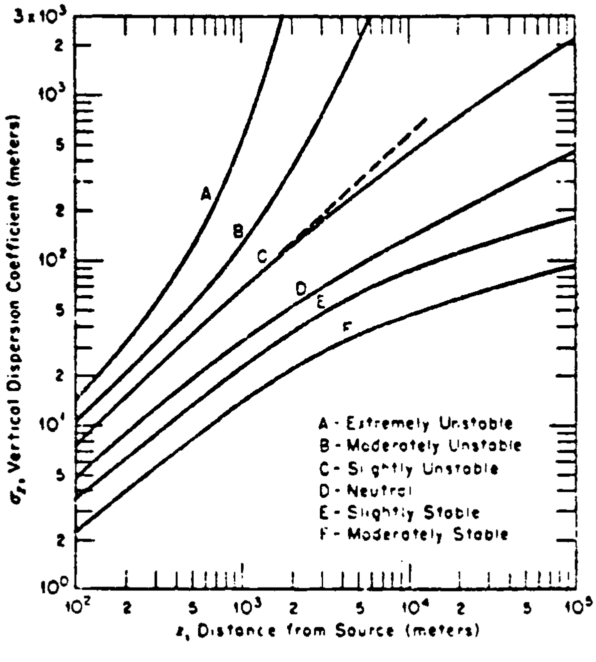


Figure 5. Vertical dispersion parameter, (σ_z) versus downwind distance, (x) [11].

Evaluating Eq. (2.23) for (σ_y) in terms of x, for x = 100 m, and substituting the values of (θ) for stabilities (A-F) from Figure 3, results of the (σ_y) values are listed below.

Stability	θ (degrees)	σ_y (m)
A	60	26.85
B	45	19.26
C	30	12.46
D	20	8.20
E	15	6.12
F	10	4.07

An extension of these points over three intervals of distance (i.e. 1 km, 10 km, 100 km) has been done by interpolation based on the assumption that θ is a constant over these intervals. A back calculation on Gifford's representation of (σ_y) versus (x) [11] shown in Figure 6 was performed by Tadmor and Gur [14]. Representing σ_y in the form of

$$\sigma_y = ax^p \tag{2.24}$$

where $p = \frac{d\ (\log \sigma_y)}{d\ (\log \sigma_x)}$ is a constant

and taking p = .9031 from back calculations, Eq. (2.24) can be solved for the unknown (σ_y) at a distance of 1 km as follows

$$p = \frac{\log \sigma_{y\,(1)} - \log \sigma_{y\,(.1)}}{\log x_{(1)} - \log x_{(.1)}} \tag{2.25}$$

where subscripts denote distances in km.

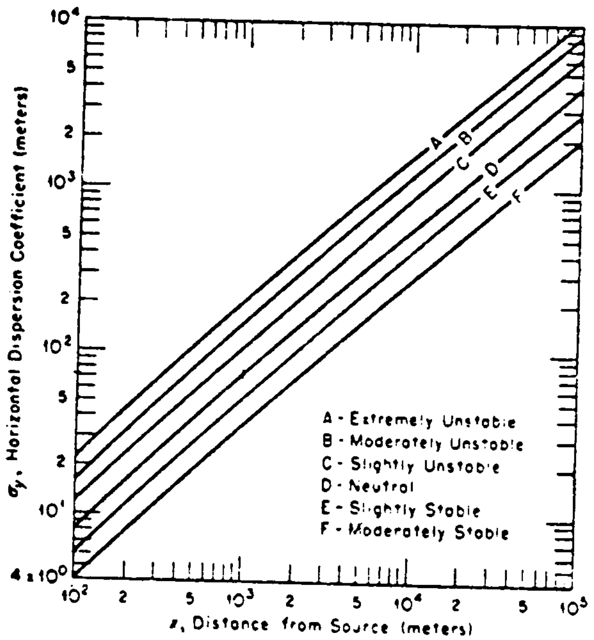


Figure 6. Horizontal dispersion parameter, (σ_y) versus downwind distance, (x) [11].

By substituting p = .9031 and log 1 - log .1 = 1, Eq. (2.25) becomes

$$\log \sigma_{y(1)} = .9031 \times \log (\sigma_y)_{(.1)} \qquad (2.26)$$

Evaluating Eq. (2.26) for the unknown σ_y results in the following values at x = 1km for stabilities (A-F).

Stability	σ_y (m) @ x = .1 km	σ_y (m) @ x = 1 km
A	26.85	215
B	19.26	154
C	12.46	100
D	8.20	66
E	6.12	49
F	4.07	33

Further interpolation leads to Figure 6.

Stability Determined from Diffusion Experiments

One of the objectives of the diffusion experiments carried out in the years between 1956-1964 was to relate on-site meteorological measurements to diffusion estimations. Studies conducted on continuous source releases in the surface layer have resulted in numerous methods of data analysis. For comparison purposes, the relation between normalized-axial concentration $(\overline{\chi}_p)$ and (x) is selected from Slade [6].

Method of Normalizing the Average Centerline Concentration from a Continuous-Point Source

The centerline concentration from a continuous surface source, for which y=z=0, and the geometric factor,

$$\frac{1}{2}\left[\exp\ -\frac{(z-H)^2}{2\ \sigma_z^{\ 2}} + \exp\ -\frac{(z+H)^2}{2\ \sigma_z^{\ 2}}\right] = 1 \qquad (2.27)$$

is the following from Eq. (2.17)

$$\overline{\chi}_p = \frac{Q'}{\pi\sigma_y\sigma_z\overline{u}} \qquad (2.28)$$

The normalized concentration is defined as

$$\frac{\bar{\chi}_p\bar{u}}{Q'}\ (m^{-2}) = \frac{1}{\Pi\sigma_y\sigma_z}\ (m^{-2}) \qquad (2.29)$$

From Figures 5 and 6, the values of (σ_z) and (σ_y) at x = .1 km for stability (A) are

$$\sigma_z = 14\ m \qquad (2.30)$$

$$\sigma_y = 26.85\ m \qquad (2.31)$$

Evaluating Eq. (2.29) by substitution of Eq. (2.30) and (2.31) results in

$$\frac{\bar{\chi}_p\bar{u}}{Q'} = 8.5E\text{-}4\ (m^{-2}) \qquad (2.32)$$

For stability (F) at x = .1 km, the values of (σ_z) and (σ_y) from Figures 5 and 6 are

$$\sigma_z = 2.2 \text{ m} \tag{2.33}$$

$$\sigma_y = 4.07 \text{ m} \tag{2.34}$$

by evaluating Eq. (2.29) by substituting Eq. (2.33) and (2.34) results in

$$\frac{\bar{\chi}_p \bar{u}}{Q'} = 3.6E\text{-}2 \ (m^{-2}) \tag{2.35}$$

By grouping the normalized concentrations from available data collected from 200 diffusion experiments and taking the median values of these concentrations corresponding to values of wind fluctuation data (σ_θ), a summary diagram from Slade [6] is presented in Figure 7. Aside from the possibility of cloud deposition during stable conditions (hence lower concentrations) as postulated by Slade, the experimental data fits within the range of normalized concentration from stabilities (A-F) calculated in Eq. (2.32) and Eq. (2.35) from Pasquill's categories.

From these data, wind fluctuation measurements have been used as stability indicators corresponding to Pasquill's categories [6] as shown in Table 5.

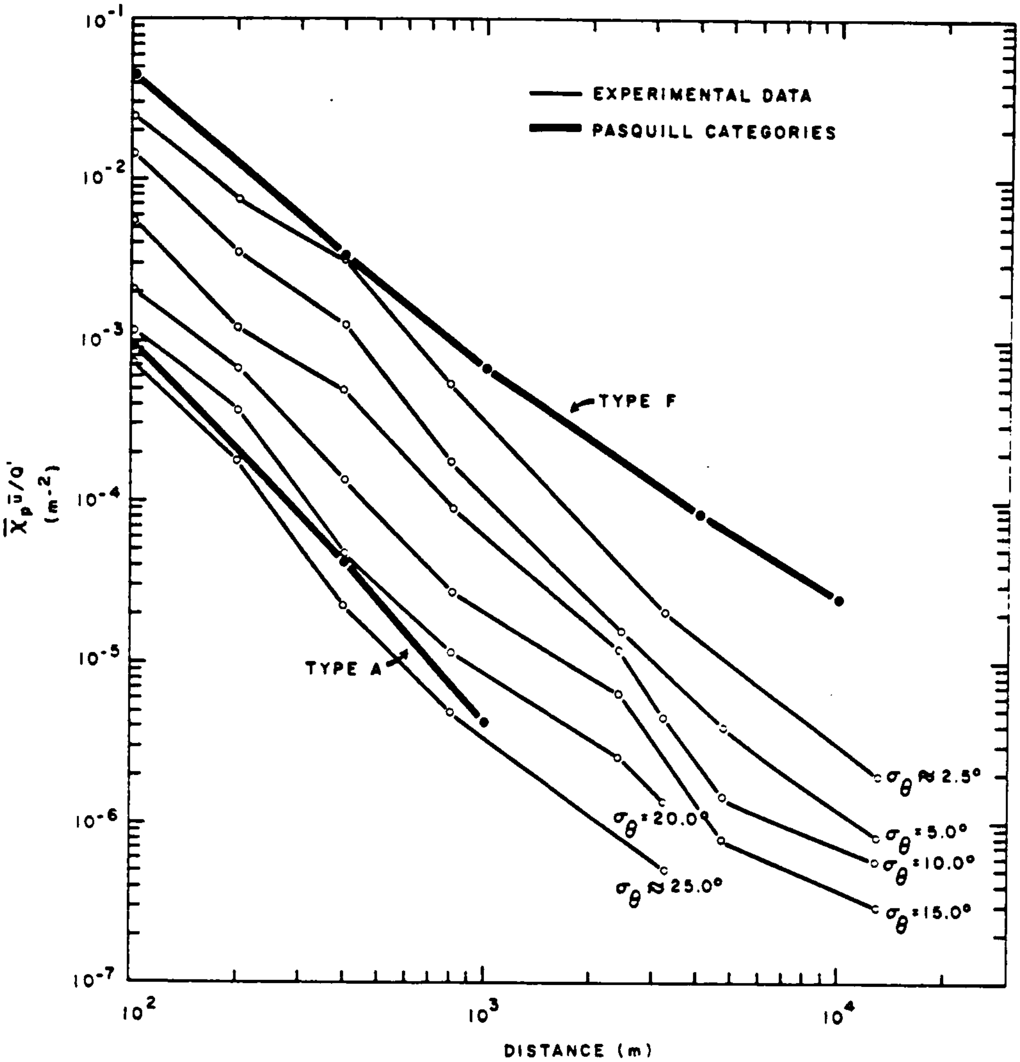


Figure 7. Summary diagram of observed normalized-axial concentration measurements versus downwind distance [6].

Table 5. Pasquill Stability Categories [6].

Pasquill Categories	Stability Classification	Standard Deviation of Horizontal Wind Direction, σ_θ
A	Extremely Unstable	25.0^o
B	Moderately Unstable	20.0^o
C	Slightly Unstable	15.0^o
D	Neutral	10.0^o
E	Slightly Stable	5.0^o
F	Moderately Stable	2.5^o

CHAPTER III

INSTRUMENTATION AND METHODOLOGY

Instrumentation

The data for this study have been collected at the Shawnee meteorological tower located approximately 1.6 kilometers south of the Ohio River in McCracken County, Kentucky. These data have been made available by the Tennessee Valley Authority (TVA) Data Acquisition System.

The site of the meteorological tower at Shawnee and surrounding area south of the Ohio River can be characterized as flat to gently rolling countryside. The area north of the River, approximately 3.2 kilometers from the tower, is more hilly.

The meteorological tower site includes a 61-meter tower equipped with conventional instrumentation. At the 61-meter level, measurements of the instantaneous air temperature and wind direction were collected at 1-sec and 5-sec intervals, respectively. Standard deviations of wind directions in the horizontal and vertical were calculated during 5-min intervals from the readings collected every 5-secs. The hourly standard deviations are recorded as the average of twelve 5-min standard deviations. At the 10-meter level, measurements of the wind direction (horizontal only) and air temperature were recorded. Average values of the parameters were output hourly.

The reporting period of data for this study is 1 January 1981 - 31 December 1981.

Methodology

Statistical Analysis of Meteorological Parameters

The magnetic tape files containing one year of data of temperature, σ_θ, and σ_ϕ were received from TVA for statistical analysis. The hourly average measurements of temperature were converted to values of (DT/DZ) in degrees centigrade per 100 m. As the usual convention for classifying stability, classes A, B, and C are considered to be unstable, class D is to be neutral, and classes E, F, and G are considered to be stable.

The statistics indicated in subsequent figures and tables were assembled using standard procedures. Inspection of Figures 8, 9 and 10 provided the means for determining the transformations to be made on the variables when defining the functional relationships between the dependent and independent variables. The following functional forms of the dependent variable were used in correlating the data and provided the best fit curve to the data:

$$DT/DZ \text{ vs } k_1/\sigma_\theta + k_2/\sigma_\theta^{\,2} + k_3 \quad (3.1)$$

$$DT/DZ \text{ vs } k_1/\sigma_\phi + k_2/\sigma_\phi^{\,2} + k_3 \quad (3.2)$$

$$\sigma_\phi \text{ vs } k_1\ (\sigma_\phi) + k_2 \quad (3.3)$$

Table 6 contains the constants for each of the functional forms (k_1 to k_3), the correlation coefficient, r^2, resulting from correlation of the data to the functional relationship, and n, the number of observations used in the analysis.

Scattergram plots of hourly observations of data using the best-fit curve equations (shown in Table 6) along with the specified ranges of DT/DZ, σ_θ, and σ_ϕ proposed by the U. S. NRC and U. S. EPA (see Tables 3 and 4, pages 6 and 7) will be discussed.

Table 6. Results of Regression Analysis on Stability Indicators.

Parameters	r^2	n
DT/DZ vs $f(\sigma_\theta)$	.629	7934
DT/DZ vs $f(\sigma_\phi)$	.579	8371
σ_ϕ vs σ_θ	.846	7859

where $f(\sigma_\theta) = k_1/\sigma_\theta + k_2/\sigma_\theta^2 + k_3$

and $k_1 = 9.974$

$k_2 = -5.949$

$k_3 = -1.395$

$f(\sigma_\phi) = k_1/\sigma_\phi + k_2/\sigma_\phi^2 + k_3$

$k_1 = 6.724$

$k_2 = -3.265$

$k_3 = -1.132$

$\sigma_\theta = k_1(\sigma_\theta) + k_2$

$k_1 = .865$

$k_2 = -.041$

CHAPTER IV

RESULTS AND DISCUSSION

Analysis of Stability Classification Guidelines When Applied to Actual Data

In an effort to see how well the federally proposed classifications are able to describe the relationship between stability parameters, the ranges of DT/DZ versus σ_θ, DT/DZ versus σ_ϕ, and σ_ϕ versus σ_θ, as proposed by Federal guidelines (Tables 3 and 4), have been superimposed on the data. The best-fit curve to this data yielding the maximum association between the dependent and the functional form of the independent variable has also been superimposed on the data shown in Figures 8, 9, and 10.

A comparison of the best-fit curve of DT/DZ versus σ_θ and the relationship proposed by the U. S. NRC (Table 4) shows a marked similarity in describing the relationship between these two stability indicators as shown in Figure 8. A similar comparison for DT/DZ versus σ_ϕ, shown in Figure 9, indicates some discrepancy between the actual best-fit curve and the relationship proposed by the U. S. EPA (Table 3, page 6). In all but the moderately unstable category, the data is best described by larger DT/DZ values in correspondence with values of σ_ϕ rather than the ranges proposed by the U. S. EPA. The plot of σ_ϕ versus σ_θ, for which r^2 = .846, shown in Figure 10,

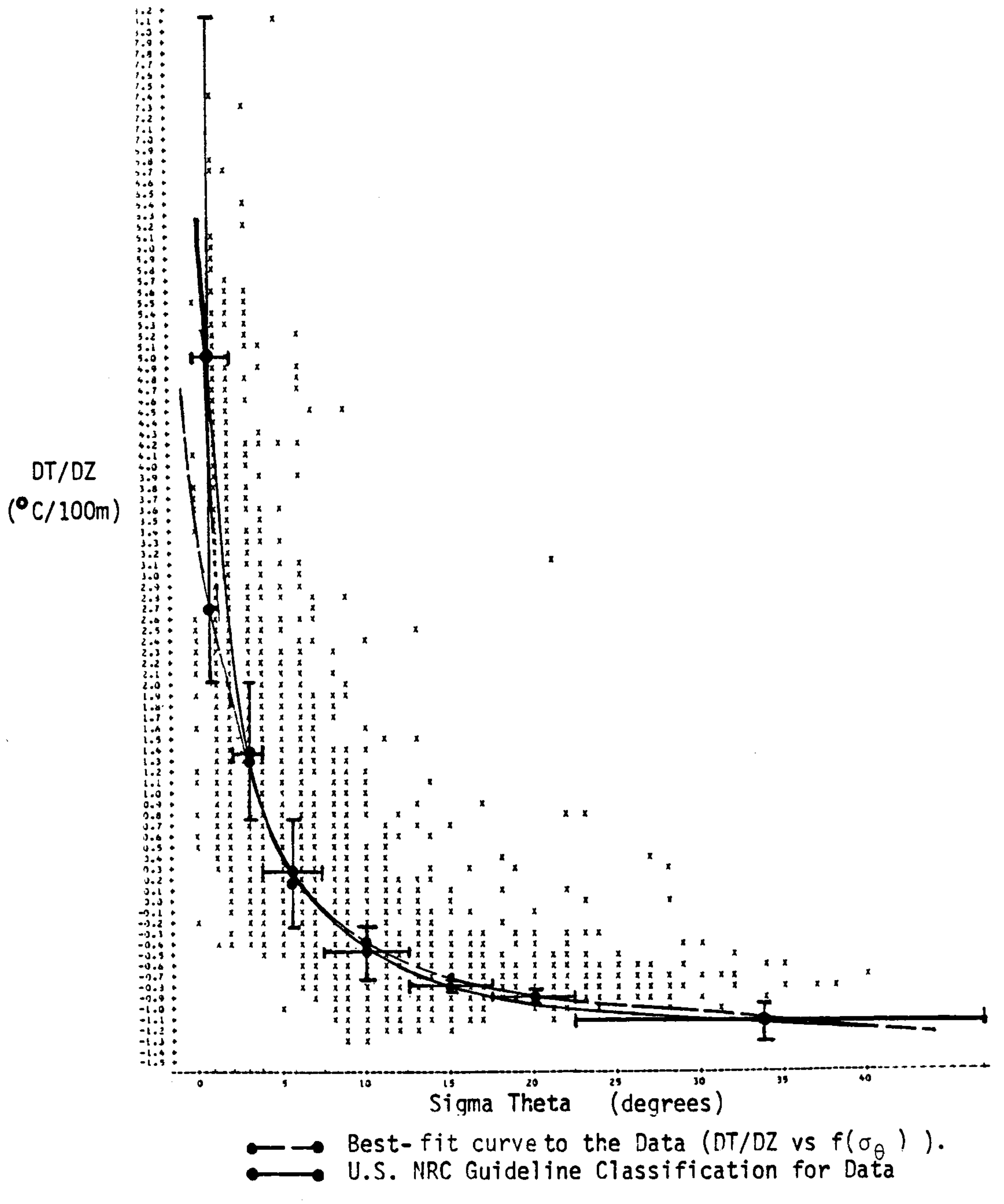


Figure 8. DT/DZ versus σ_θ (Best-fit curve and U. S. NRC fit).

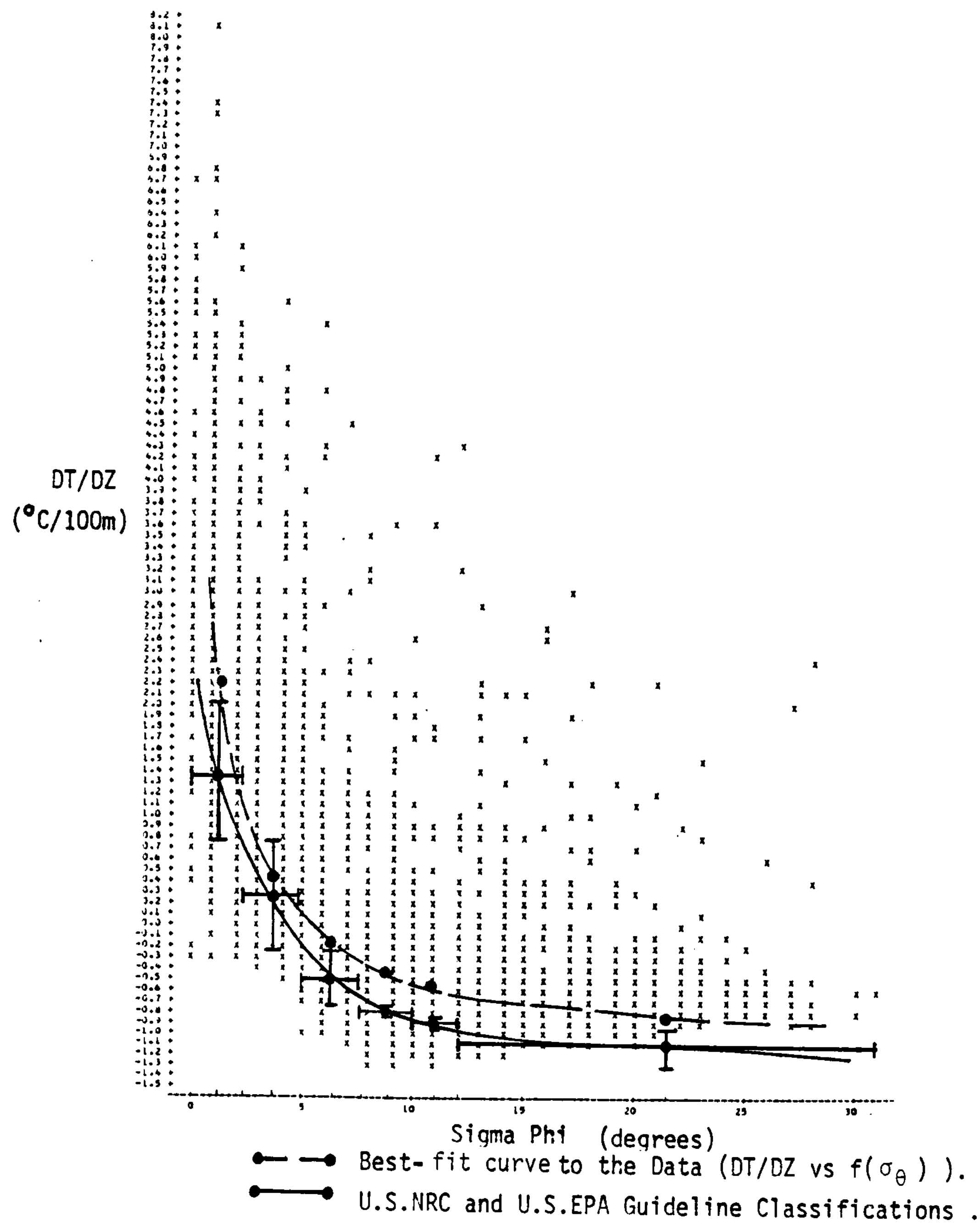


Figure 9. DT/DZ versus σ_ϕ (Best-fit curve and U. S. EPA-U. S. NRC fit).

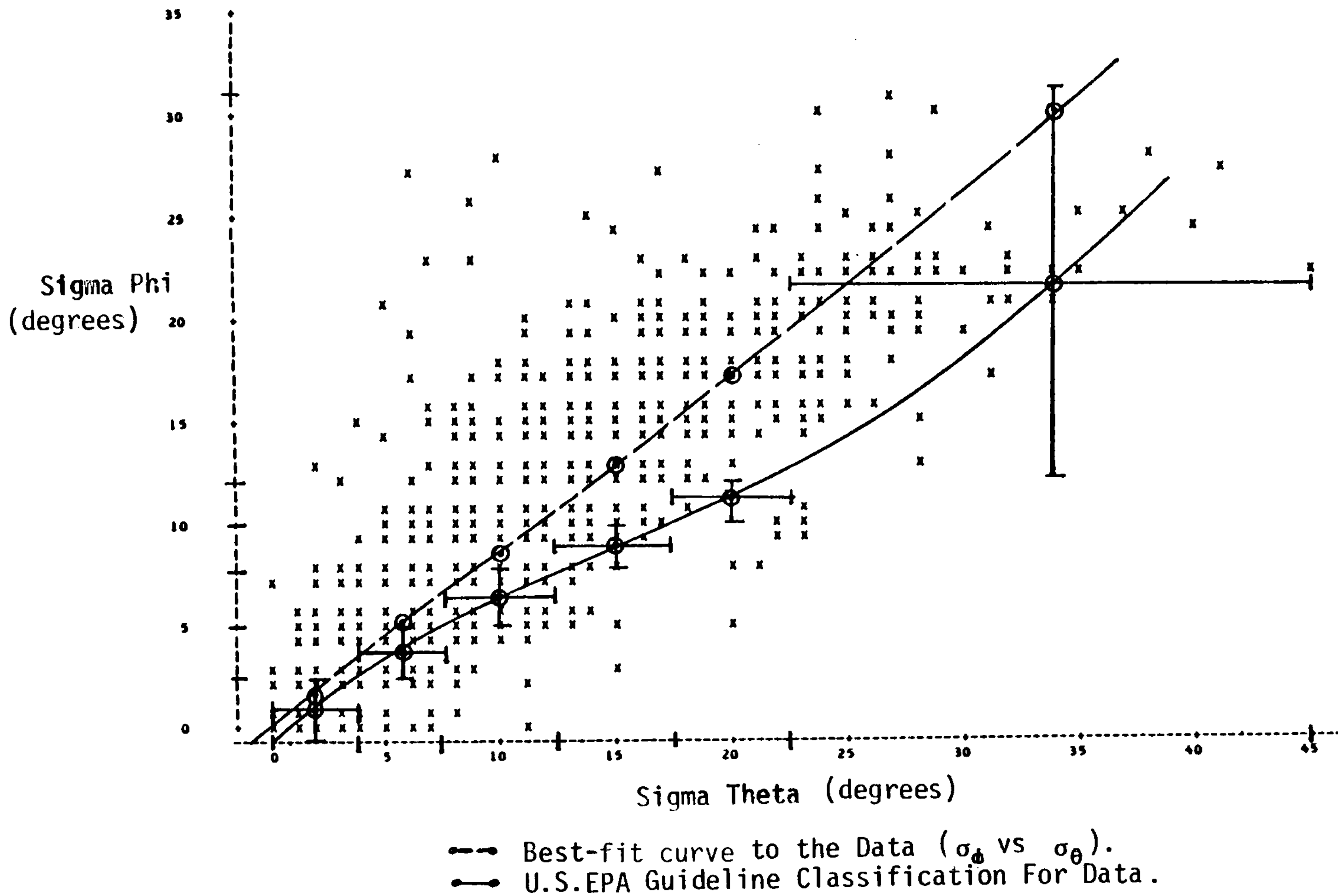


Figure 10. σ_ϕ versus σ_θ (Best-fit curve and U. S. EPA fit).

indicates that the U. S. EPA classifications of σ_ϕ and σ_θ do not adequately describe the relationship between the measured stability parameters.

Regression Analysis on Data by Hour

Regression analyses were also conducted on the relationship between DT/DZ, σ_θ, and σ_ϕ in which the data set was restricted to each hour of the day rather than lumping all 24 hours of observations into one equation. By allowing the constants in equations (3.1 to 3.3) to adjust to provide the maximum r^2 value for each hour, model equations were determined for the dependent and independent variable by hour of the day. The functional form of the independent variable under this condition is designated as $f_1(\sigma_\theta)$ or $f_1(\sigma_\phi)$. The resulting r^2 values by hour of the day for DT/DZ versus $f_1(\sigma_\theta)$, DT/DZ versus $f_1(\sigma_\phi)$, and σ_ϕ versus σ_θ are shown in Figure 11.

Irregularities in the r^2 values for σ_ϕ versus σ_θ occurred between two time periods in a day as shown in the top of Figure 11. A near-steady value of $r^2=0.8$ was maintained throughout the day with the exception of the hours 7 a.m. to 9 a.m. and 5 p.m. to 9 p.m. It is suggested that these deviations are due to the variable influence of inversion breakup and inversion formation on σ_ϕ and σ_θ.

The general trend of r^2 values for DT/DZ versus $f_1(\sigma_\theta)$ and DT/DZ versus $f_1(\sigma_\phi)$ appears to be similar. Between the hours of 10 a.m. to 1 p.m., both associations did not correlate well as shown in Figure 11. High values of σ_θ and σ_ϕ associated with small DT/DZ values resulted in near zero correlations for these hours.

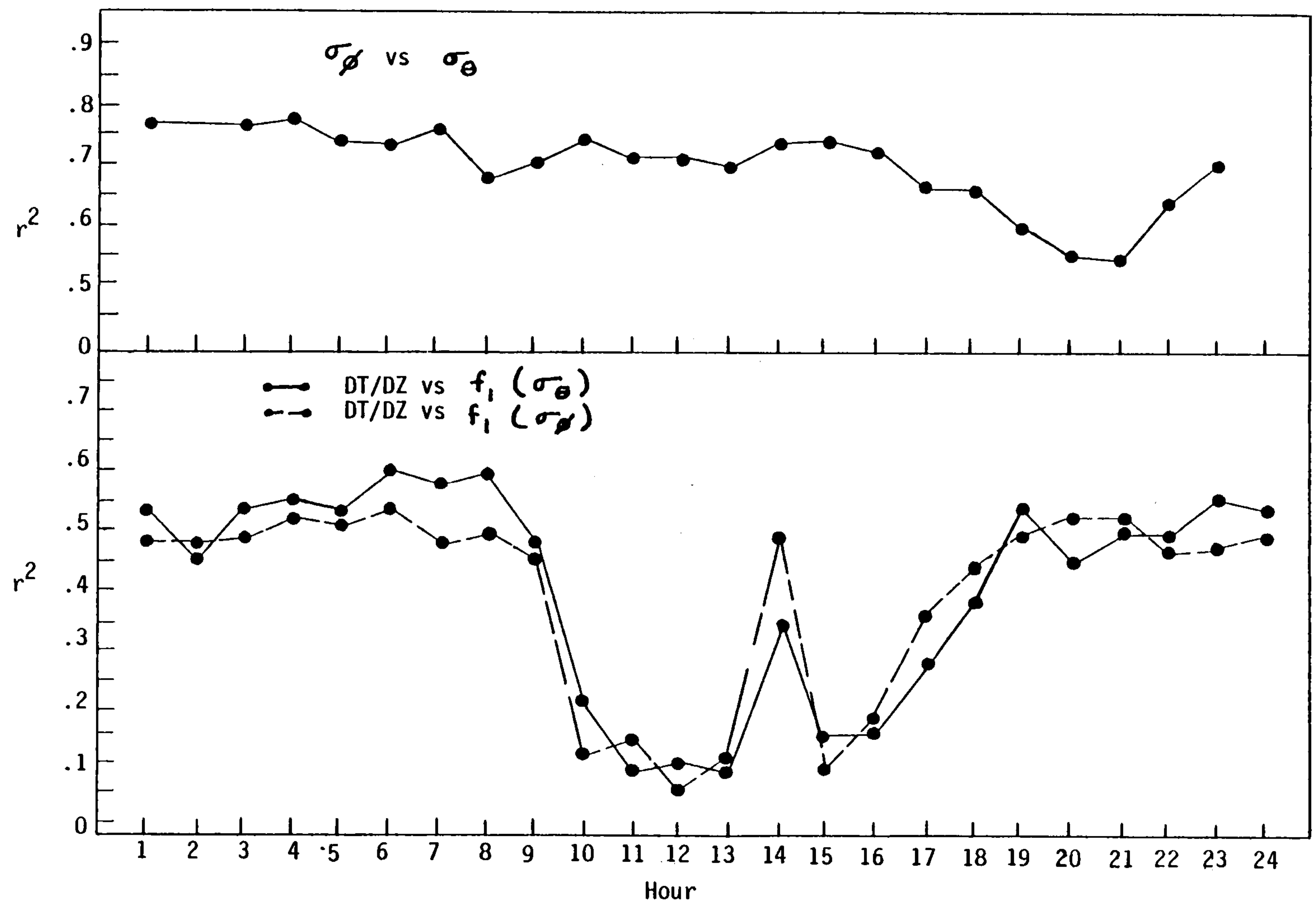


Figure 11. Regression analysis with adjustable constants for maximum r^2 by hour.

Scattergram plots of DT/DZ versus $f_1(\sigma_\theta)$ and DT/DZ versus $f_1(\sigma_\phi)$ at 12 noon and 1 p.m. are presented in Figures 12 through 15, respectively.

Parameter Distributions by Hour

The distributions of DT/DZ, σ_θ, and σ_ϕ by hour of the day are shown in Figures 16, 17, and 18, respectively. The mean value of the range is indicated by a horizontal tick mark for each hour of the day. All data sets show the normal diurnal variation of average parameter value versus hour.

The DT/DZ data (Figure 16) changed sign twice during the 24-hour period. This occurred between 8 a.m. to 9 a.m. and 5 p.m. to 7 p.m. The large DT/DZ values shown from 8 p.m. to 7 a.m. are an indication of the relatively greater stability of the atmosphere during this period when compared to the other periods. Between 9 a.m. and 5 p.m., the atmosphere is characterized by small DT/DZ values (i.e. DT/DZ < 0).

The σ_θ and σ_ϕ data have a similar distribution of mean values over a 24-hour period as shown in Figures 17 and 18, respectively. Low mean values of σ_θ and σ_ϕ occur between 8 p.m. and 7 a.m. and are indicative of stable nighttime conditions. The mean values of σ_θ and σ_ϕ increase from 8 a.m. until a peak average of 12.5^o is reached between 12 noon and 1 p.m. After 1 p.m., σ_θ and σ_ϕ decrease in value until 7 p.m.

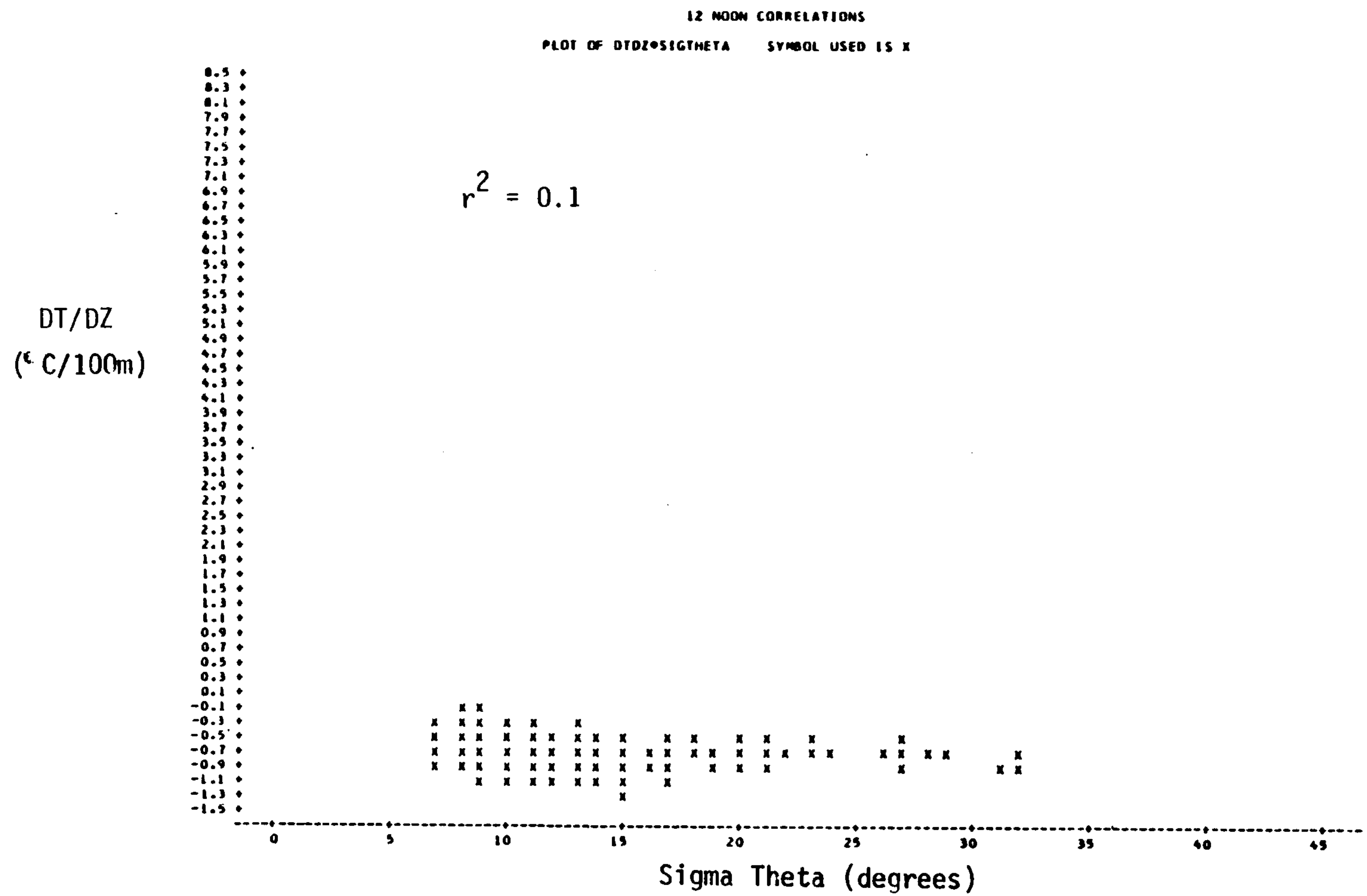


Figure 12. DT/DZ versus f_1 (σ_θ) at 12 noon.

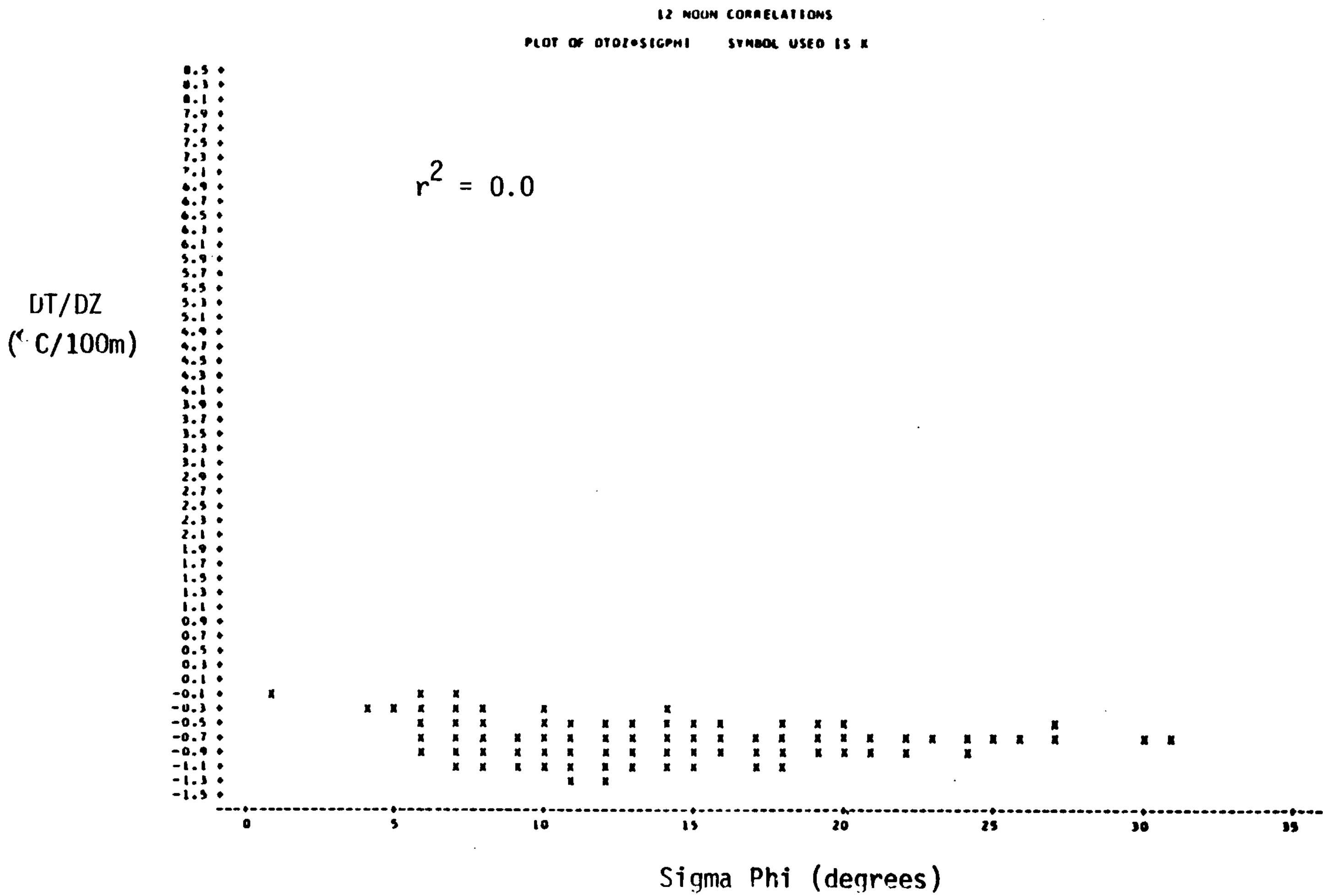


Figure 13. DT/DZ versus f_1 (σ_ϕ) at 12 noon.

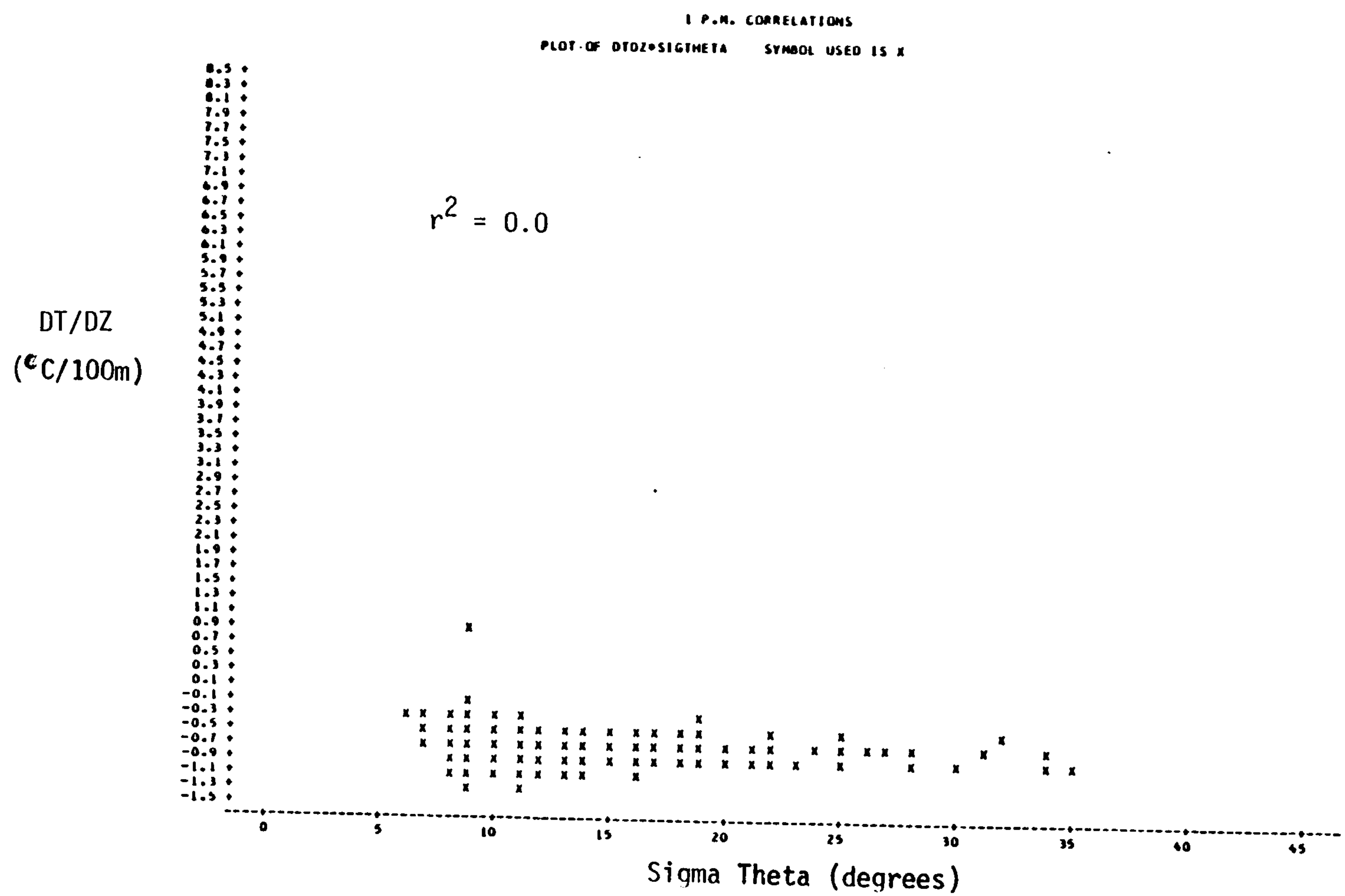


Figure 14. DT/DZ versus f_1 (σ_θ) at 1 p.m.

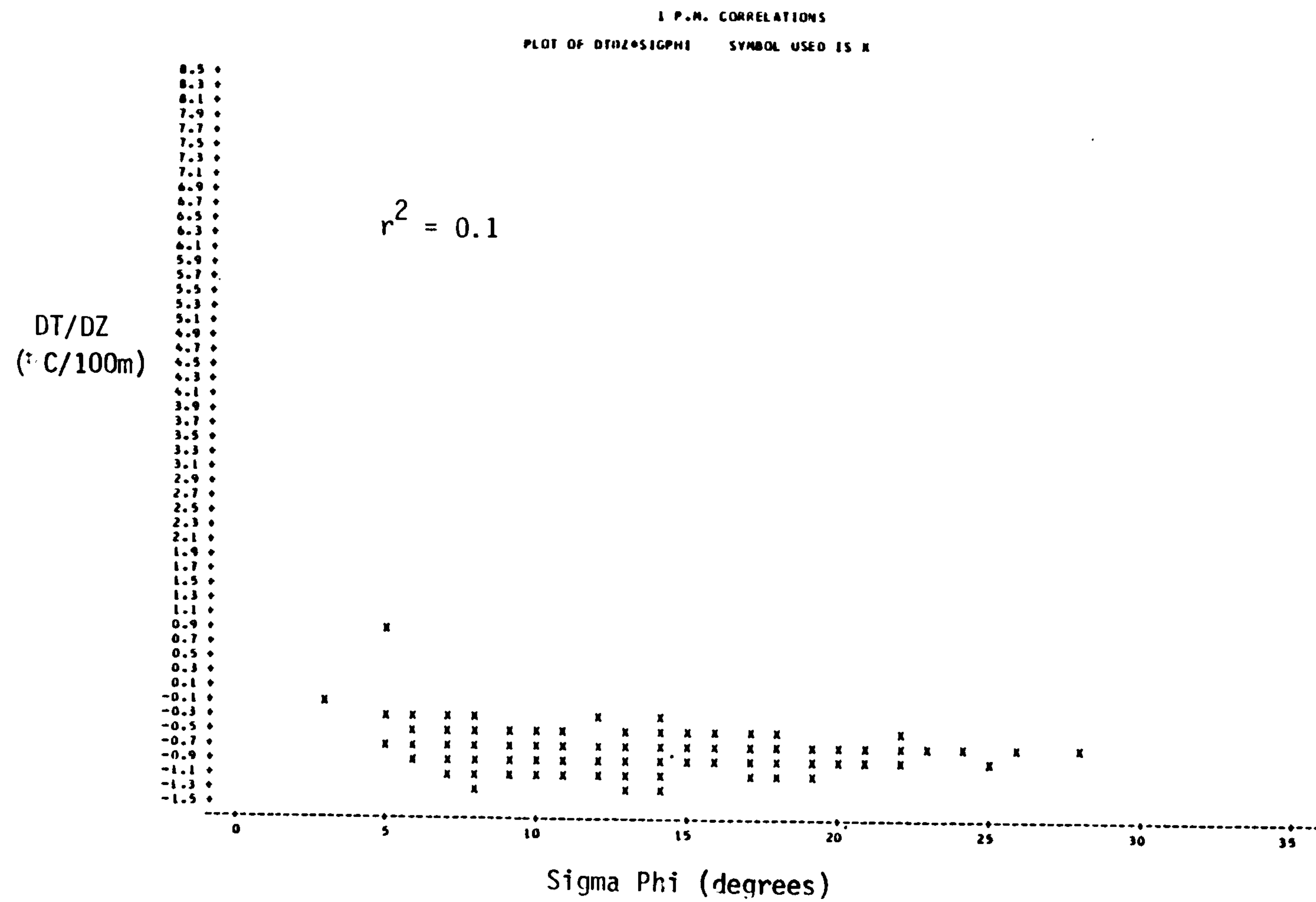


Figure 15. DT/DZ versus f_1 (σ_ϕ) at 1 p.m.

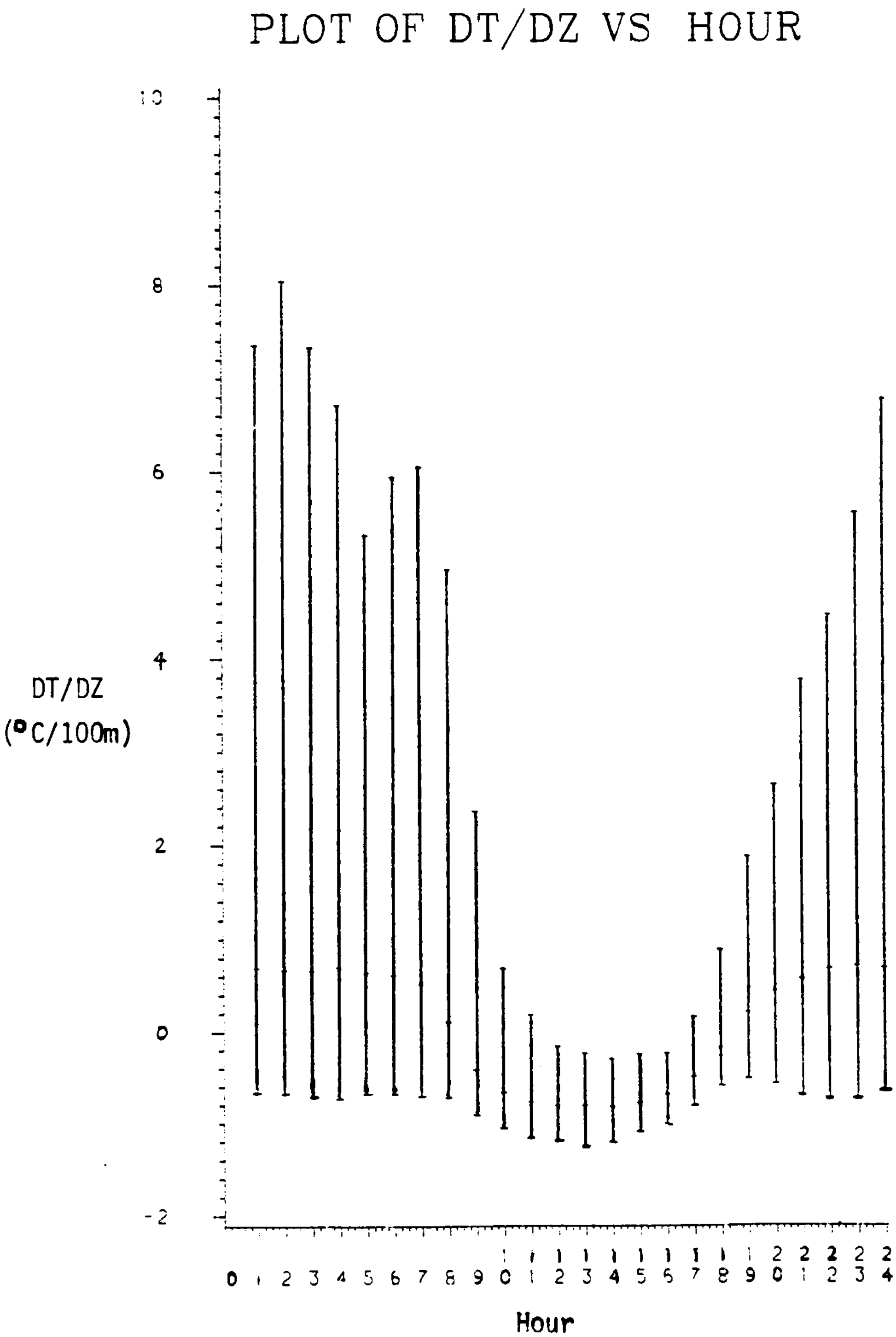


Figure 16. Distribution of DT/DZ versus hour of the day.

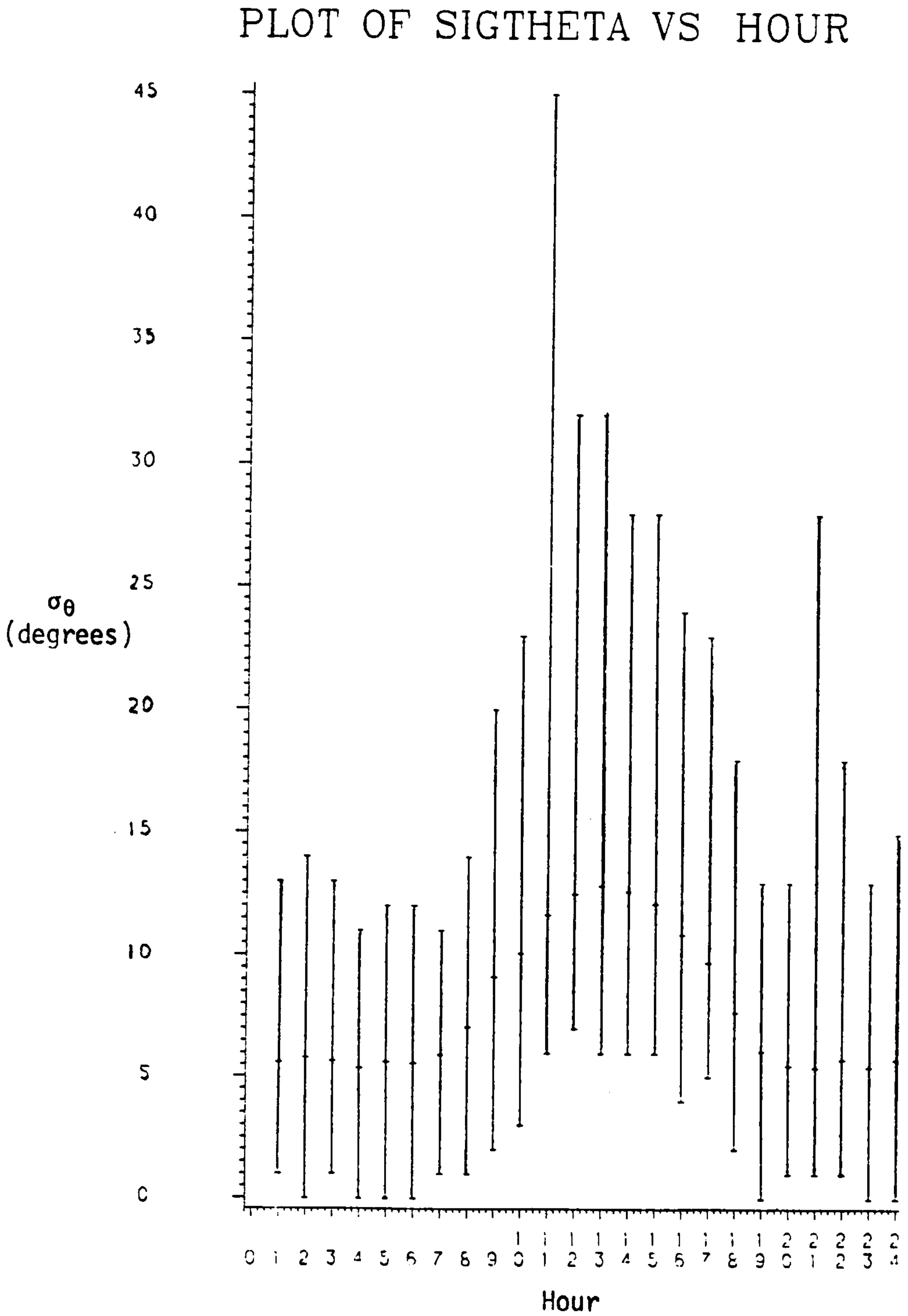


Figure 17. Distribution of σ_θ versus hour of the day.

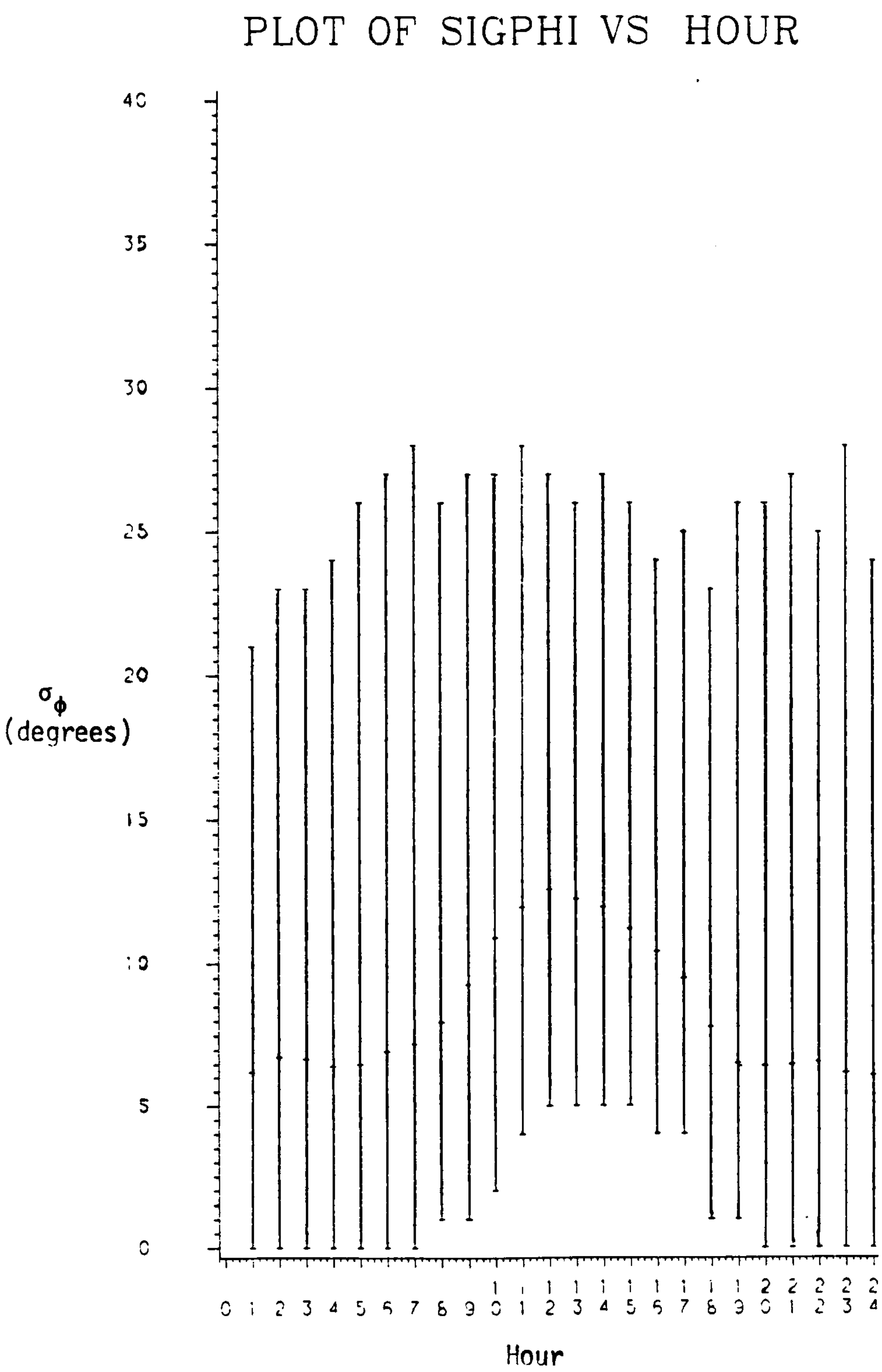


Figure 18. Distribution of σ_ϕ versus hour of the day.

Frequency Analysis of Data Categorized by Stability Classification Guidelines

Table 7 shows the frequency analysis for the U. S. NRC classification of DT/DZ and σ_θ and the U. S. EPA classification of σ_ϕ. According to the U. S. NRC classification guidelines (Table 4, page 7), the DT/DZ method, when corrected to DT in degrees centigrade per 100 m, categorized 14% of the Shawnee data as being unstable, 37% as neutral, and 49% as stable. Classification by the σ_θ resulted in 12% of the data categorized as unstable, 41% as neutral, and 47% as stable.

The U. S. EPA classification of σ_ϕ resulted in 40% of the data categorized as unstable, 31% as neutral, and 29% as stable. It can be noted from the frequency analysis that DT/DZ and σ_θ are the most closely related parameters in measuring the dispersive action of the atmosphere. Figure 8, page 35, provides additional evidence to this fact by the similarity in the actual best-fit curve and the relationship prescribed by the U. S. NRC. Although σ_ϕ and σ_θ are highly related (i.e. r^2=.846) DT/DZ versus σ_θ gives a better fit to the data than DT/DZ versus σ_ϕ.

The frequency analysis of the σ_θ method shows 12% of the data being classified as unstable as compared to 40% by the σ_ϕ method. A 20% differential is shown in classifying the stable categories by these two methods. The large discrepancy between the actual best-fit curve and the relationship prescribed by the U. S. EPA, shown in Figure 10, page 37, is an indication that the guideline definitions

Table 7. Frequency Analysis of Data Categorized by Stability Classification Guidelines.

Stability Indicator	Stability Classification		Frequency	Percent
DT/DZ (^oC/100 m)	Extremely Unstable	(A)	356	4.064
	Moderately Unstable	(B)	364	4.155
	Slightly Unstable	(C)	514	5.868
	Unstable		1234	14.087
	Neutral	(D)	3211	36.655
	Slightly Stable	(E)	2653	30.285
	Moderately Stable	(F)	1000	11.416
	Extremely Stable	(G)	662	7.557
	Stable		4315	49.258
σ_θ (degrees)	Extremely Unstable	(A)	108	1.354
	Moderately Unstable	(B)	195	2.444
	Slightly Unstable	(C)	669	8.386
	Unstable		972	12.184
	Neutral	(D)	3268	40.958
	Slightly Stable	(E)	2427	30.417
	Moderately Stable	(F)	517	6.480
	Extremely Stable	(G)	795	9.964
	Stable		3739	46.861
σ_ϕ (degrees)	Extremely Unstable	(A)	1315	15.382
	Moderately Unstable	(B)	743	8.691
	Slightly Unstable	(C)	1378	16.119
	Unstable		3436	40.192
	Neutral	(D)	2647	30.963
	Slightly Stable	(E)	1170	13.686
	Moderately Stable	(F)	1296	15.160
	Stable		2466	28.846

of σ_θ and σ_ϕ do not provide consistent estimations of atmospheric dispersal. If stability were to be determined by the σ_ϕ method in lieu of σ_θ data the resulting concentration predictions would tend to be lower than those predictions made using σ_θ. Similarly, lower concentration predictions would result if DT/DZ data were not available and σ_ϕ was used instead. It was shown from the regression analysis that DT/DZ correlated with $f(\sigma_\phi)$ to an r^2 value of .579 which was the least associated relationship among the parameters. The relationship prescribed by the guideline classifications indicates an even lesser association.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It can be concluded that DT/DZ and σ_θ are the most closely related methods of measuring the dispersive action of the atmosphere. Use of DT/DZ or σ_θ in estimating stability will not significantly alter concentration predictions. This is not the case for σ_ϕ. Use of σ_ϕ when σ_θ and DT/DZ are not available will result in lower concentration predictions than predictions made using either σ_θ or DT/DZ. As such, not all of the federally proposed methods of classifying stability provide consistent results. This is especially true for certain hours of the day. It has been shown that small DT/DZ values and large wind fluctuations, typical of daytime hours, do not correlate well from 12 noon - 1 p.m., hence, concentration predictions will vary depending on the stability indicator in use.

While σ_θ and DT/DZ tend to estimate similar classes of stability and σ_ϕ does not provide similar classification with either σ_θ or DT/DZ, it has not been possible in this effort to determine which of the three parameters provides the most realistic estimate of stability.

Recommendations

Further research on the work described here could be extended into the areas summarized below.

1. A universally acceptable method for determining stability from meteorological data should be developed. Instead of specifying the stability class by a specific range of values, the classes should be determined by actual data collected at the site of interest.
2. Diffusion experiments should be conducted during daytime conditions in an effort to determine which stability indicator provides the most accurate description of the diffusion process.
3. An investigation into the effect of inversion break up and formation on σ_θ and σ_ϕ data should be made.

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VITA

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