[American Journal of Science, Vol. 255, February 1957, P. 104-114]

SEDIMENTARY CHARACTERISTICS OF DUST STORMS: II. VISIBILITY AND DUST CONCENTRATION

W. S. CHEPIL and N. P. WOODRUFF

ABSTRACT. Analysis of some dust storms in Kansas and Colorado during 1954 and 1955 indicates a relationship between visibility and atmospheric dust concentration when rules of Houghton are followed. Visibility varies inversely as some power of concentration, and concentration varies inversely as a certain power of height. The quantity of soil removed from any region for any storm or period of time can be estimated.

INTRODUCTION AND ACKNOWLEDGMENT

Visibility is often an indication of the concentration of dust in the atmosphere. Many weather observers in arid and semiarid regions record visibility to indicate the relative severity of dust storms. Such records are available for many years at different stations. Little information was found in the literature to indicate relationships between visibility and the actual quantity of dust carried by wind. The only available information of this nature is that of Langham, Foster, and Daniel (1938) giving visibilities associated with various dust concentrations at 30 inches above the ground at Goodwell, Oklahoma, during 1936 and 1937. Analysis of these data is included in this report. Such data used in conjunction with available records of intensity-frequency of occurrence of windstorms should be of potential value in estimating losses of soil from wind-eroded regions.

Estimations of soil losses also require information on the variation of dust concentration with height above the ground. Little of this type of information is available in the literature. While the data contained in this study do not include determinations to great heights, they do afford some opportunity for at least speculating on the concentrations above the heights of measurement. The previous paper (Chepil, 1957) of this series indicated the proportion of dust lost from various soil classes by the process of deflation. This paper presents an analysis of concentration of dust in the atmosphere and of the approximate rates of its removal from wind-eroded areas. The study was conducted on some dust storms in western Kansas and eastern Colorado in 1954 and 1955.

This paper is contribution no. 548, Department of Agronomy, Kansas Agricultural Experiment Station, Manhattan, and Agricultural Research Service, U. S. Department of Agriculture, Cooperative Investigations on the Mechanics of Wind Erosion.

PROCEDURE

Two grams of fine glass wool of 5-micron thickness of filaments packed in 1-1/8 inch inside diameter round aluminum tube was used to filter dust from the air. The apparatus consisted essentially of the glass wool filter, a 1-inch diameter connecting hose, an air meter and barometer to measure the volume of air intake as under standard temperature and pressure, an electric vacuum cleaner motor and fan to supply the necessary suction, a 110-volt generator, and a gasoline motor. Four filtering tubes were connected each to a separate manometer tube, and two such filtering tubes were connected to

548

each of the two vacuum cleaner units. Air intake in each tube was controlled by separate gas valves. The velocity of intake was the same as the velocity of the wind at corresponding height. A multiple alcohol manometer and Pitot tubes were used to measure wind velocity at each location of the filter tube. The basic unit with the exception of the filter tubes, air meters, and barometer, was similar to that of Zingg (1951) for measuring total quantities of soil eroded by wind. The controlled intake device was used to gauge air volume of samples in 1954. Air meters were added for the 1955 studies. With the exception of filtering tubes the apparatus was also similar to that of Langham and others (1938) for measuring total weight of dust in the air.

The assembly was mounted on a truck and hooded to give it and the operators partial protection from the dust storms (fig. 1). The filtering tubes were clamped to a vertical pole on the rear of the truck at various heights above the ground and facing into the direction of the wind. In 1954 the heights of measurement were 4, 6, and 8 feet, but in 1955 the heights of measurement were changed to 2, 5, 11, and 20 feet.

The filtering tubes were dried in an oven at 110°C before and after each exposure to determine the weight of dust caught. The tubes were stoppered when not in use. The efficiency of the filtering tube for catching dust was compared with that of the impinger tube of Langham and others (1938). On the average the filtering tube caught 97.5 percent of the dust collected by the impinger. An appropriate quantitative correction was, therefore, made. The impinger tube has one serious disadvantage over the filtering tube in that it is impossible to determine from the sample of dust caught in the water the actual size of particles carried through the air. The filtering tube, on the other hand, merely trapped the dry dust which was shaken out readily and its equivalent size distribution determined.

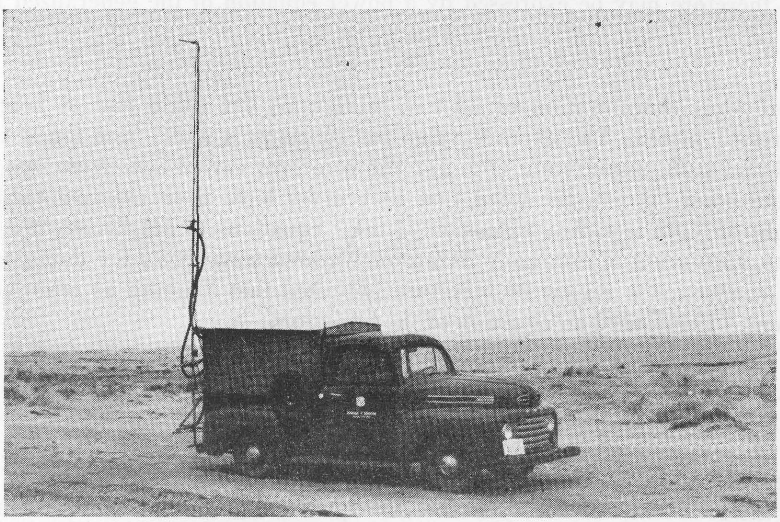

Fig. 1. Atmospheric dust-catching equipment as used in the field. Visibility in this case was 0.55 mile near Menno, Kansas, March 23, 1955.

The equivalent size distribution of dust particles was determined by sedimentation in carbon tetrachloride. Because this liquid is non-polar, it causes little or no breakdown of particles immersed in it. A weighed sample of dry dust first was wetted slowly by the liquid and then immersed in a definite volume of the liquid. The suspension was mixed thoroughly and allowed to settle for an appropriate period, depending on the equivalent diameter of the particles to be determined, depth of sampling, and temperature of the liquid. A 25 cc aliquot was then pipetted, using a uniform and appropriate air suction from a pump. The aliquot was evaporated to dryness, and the residue weighed and expressed in percentage of the total weight of sample.

Rules of Houghton (1945) for estimating daytime visibility were followed. Especially the following conditions were adhered to:

1. Measurements were made only on cloudless days between 9 A.M. and 5 P.M.
2. Objects for visibility marks were as dark as possible, silhouetted against the horizon sky. Glittering objects were avoided.
3. The sun was preferably not behind the observer but was in the field of vision.

Dull-colored approaching vehicles coming within the field of vision often served as a measure of visibility.

VARIATION OF DUST CONCENTRATION WITH HEIGHT ABOVE GROUND

Relationships between height above the ground surface and measured dust concentrations for 1954 and 1955 and the 1954-1955 average are shown in figure 2. The 1954 curve is based on 10 measurements at heights of 4, 6, and 8 feet and the 1955 curve is based on 12 measurements at heights of 2, 5, 11, and 20 feet. These relationships plot as a straight line on log-log paper and therefore may be expressed by a power equation of the generalized form

$$C_y = \frac{a}{y^{\eta}} \qquad (1)$$

where C_y is concentration of dust in milligrams per cubic foot at height y expressed in feet. The average value for constants a and η was found to be 12.4 and 0.28, respectively (fig. 2). The constants varied little from one year to the other. It will be noted that the curves have been extrapolated to a height of 5282 feet. Any extension of these equations to heights greater than 10 to 15 percent is extremely hazardous without some basis for doing so. In this connection a review of literature indicated that Schmidt as reported by Vanoni (1946) used an equation of the basic form

$$\log \frac{C}{C_a} = -W \int_a^y \frac{dy}{E_S} \qquad (2)$$

to express the concentration of dust in the atmosphere. If it is assumed that E_S, the sediment transfer coefficient, is equal to E_m, the momentum transfer coefficient, E_S can be expressed in terms of the shearing force τ, the depth of flow y_m, and any given height y, thus permitting integration of equation (2) to give

$$C = C_a \left[\frac{y_m - y}{y} \cdot \frac{a}{y_m - a} \right]^Z \qquad (3)$$

where

C = concentration at any height y
C_a = measured concentration at reference height a
y_m = depth of flow (taken as one mile)

$$Z = \frac{W}{k \sqrt{\frac{\tau}{\rho}}}$$

where
W = settling velocity of particle
$k = 0.4$
τ = wind shear
ρ = mass density of air

In analyzing the present data, attempts were made to use this equation as a basis of extension of data. Fortunately it also plots as a straight line on log-log paper and once determined can be reduced to the basic form of equation (1). Unfortunately, however, the degree of fit obtainable with this equation depends upon the determination of the mean equivalent diameter and the settling velocity of a representative sample of the suspended soil materials and on an accurate determination of wind shear and depth of flow.

In this study a rather thorough analysis of the equivalent diameter of dust particles in relation to height above ground surface was made for the data obtained during the 1955 season. This relationship and the equation expressing equivalent diameter d as a function of height y is shown in figure 2. Since the mean equivalent diameter of the particles varies with height and also since a larger concentration of particles would be located nearer the ground, both a weighted mean equivalent diameter and a mean equivalent diameter were determined by dividing the total height of 1 mile into 11 increments and integrating the two expressions for concentration and diameter, i.e.,

$$C = \frac{10.5}{y^{0.32}} \qquad (4a)$$

and

$$d = \frac{0.07}{y^{0.13}} \qquad (4b)$$

thus giving

$$\text{mean equivalent diameter} = \frac{\Sigma d_\Delta}{11} = 0.0384 \text{ mm}$$

and

$$\text{mean weighted equivalent diameter} = \frac{\Sigma C_\Delta d_\Delta}{\Sigma C_\Delta} = 0.0467 \text{ mm}$$

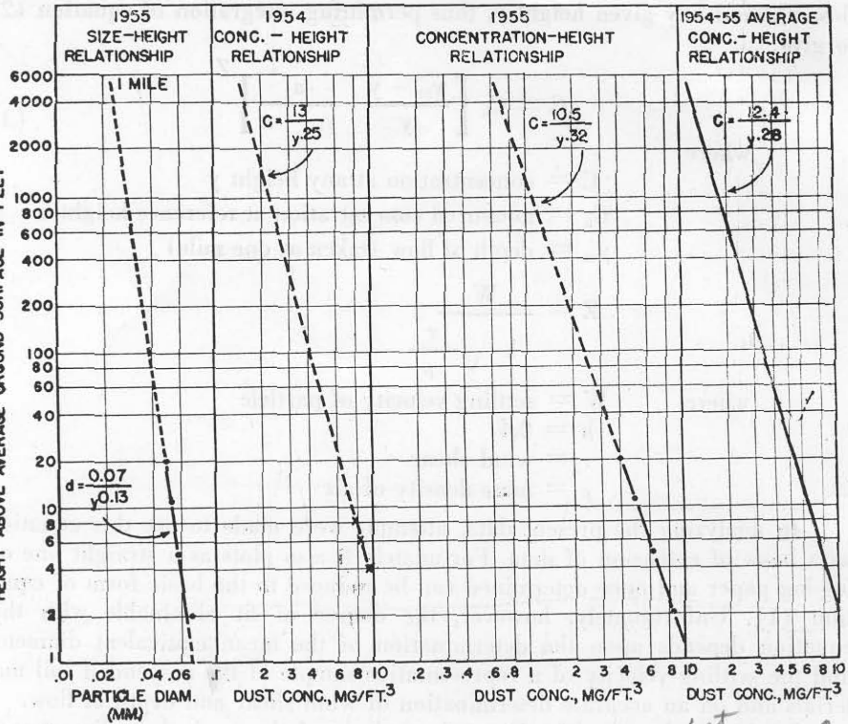

Fig. 2. Measured and projected average equivalent diameter and concentration of dust at various heights for some 1954 and 1955 dust storms in Kansas and Colorado.

Settling velocities W for the mean and the mean weighted equivalent diameters were taken as 12 and 15 cm/sec, respectively, from curves prepared by Rouse (1937) for the settling velocity of quartz spheres in air and water.

The degree of fit of the Schmidt equation was found to vary with the diameter used. When the mean weighted equivalent diameter (0.0467 mm) was used, the equation indicated a greater decrease in concentration with height than the plotted data and it gave the closest fit to the 1955 data. Some further investigation revealed that when the mean equivalent diameter (0.038 mm) was used, the Schmidt equation was identical to the 1955 derived equation and gave a reasonable fit to the combined 1954-1955 data. It would not, however, fit the 1954 data unless a mean equivalent diameter of 0.025 mm was used.

It is evident that there are some differences between the Schmidt equation and the empirical equations derived in this study. However, the agreement that can be obtained with proper selection of mean equivalent diameter of particles, a privilege which is augmented by a general lack of definition of Schmidt's "mean diameter of representative sample" and the fact that one of the diameters giving a reasonable fit is a mean calculated from the data, would indicate that the empirical equations probably are reasonably representative of conditions to a one-mile height. The one-mile average depth of flow appears to be reasonably valid. Occasionally dust clouds were reported to extend above 12,000 feet.

The total dust load in a cubic mile of the atmosphere can be found by determining the area under the height-concentration curves by integration. Values of the total dust load for each of the measurements made in 1954 and 1955 are shown in table 1. The average total load for each year and for the combined years is also given. All of these values were computed on the basis of the measured concentration at a 6-foot height and the 1954-1955 average concentration-height relationship. In general, the total dust loads and rates of removal were less in 1955 than in 1954. This is not surprising since variations in both soil and climatic conditions during the two years would account for great differences in dust load and its rate of removal.

RELATION BETWEEN VISIBILITY AND DUST CONCENTRATION

Pertinent data pertaining to this phase of the study are given in table 1. Functional relationships between measured dust concentration at the 6-foot height (lower abscissa) and visibility are shown in figure 3. The equation of the curve derived by the method of least squares is:

$$V = \frac{0.9}{C_a 0.8} \qquad (5)$$

where V is visibility in miles and C_a is dust concentration in mg/cu ft at the 6-foot elevation. Equation (5) is derived from data obtained in the present study and also from the data of Langham and others (1938) presented in figure 3 primarily to show the general agreement between the two studies.

Considerable data on visibility during dust storms are available from the Weather Bureau Stations. These visibility data probably could be used to determine dust concentrations. Information required would be a relationship similar to that of figure 3. The concentrations should be expressed, however, in terms of the quantity of material contained in a given volume of the atmosphere. The upper abscissa of figure 3 converts the average curve to units of total dust load in tons per cubic mile. This conversion was made on the basis of measured concentration at 6-foot height and the average proportionality of concentration to height, i.e., $C \propto y^{-0.28}$. The equation expressing this relationship is:

$$C_m = \frac{29.5}{V^{1.25}} \qquad (6)$$

where C_m is the concentration in tons per cubic mile of lower atmosphere and V is the visibility in miles. This equation provides a means of estimating dust concentrations from information on the visibility associated with a given dust storm.

Visibility and dust concentrations are generally proportional to wind velocity, but there are major exceptions. For example, the highest wind velocity of 32.5 mph at 8-foot height at Cheyenne Wells, Colorado, on April 27, 1955 actually was associated with a lower concentration than the wind of 25.6 mph at Syracuse, Kansas, on March 10, 1954. Such results are to be expected since it is known that high wind velocity is not always associated with dust storms. The soil texture, the condition of the soil, the wind direc-

TABLE 1
Relationship between Visibility and Quantity of Dust in Air*

Date	Location	Wind velocity at 2 ft	Wind velocity at 8 ft	Visibility	Concentration at 6-foot height	Total dust load	Average rate of soil removal
1954		mph	mph	miles	mg/cu ft	tons/cu mi	tons/hr/vertical sq mi
Mar. 4	Syracuse, Kansas	8.8	11.8	4.80	0.09	3.1	53
Feb. 25	Hugoton, Kansas	11.5	14.8	3.00	0.10	3.4	81
Mar. 4	Syracuse, Kansas	11.5	15.4	0.60	0.71	24.3	566
Apr. 15	Garden City, Kansas	19.5	26.4	0.87	0.91	31.2	1,180
Mar. 4	Syracuse, Kansas	13.1	18.3	0.50	0.72	24.7	682
Mar. 10	Syracuse, Kansas	13.0	18.6	0.30	1.71	58.6	1,571
Mar. 10	Syracuse, Kansas	15.6	22.2	0.15	8.83	303.0	10,566
Apr. 15	Garden City, Kansas	17.6	23.7	0.10	7.91	271.0	9,508
Mar. 10	Syracuse, Kansas	18.5	25.6	0.07	28.34	972.0	35,773
Mar. 10	Syracuse, Kansas	18.5	25.6	0.05	37.58	1,290.0	47,951
Mar. 12	Manhattan, Kansas	—	9.4	3.00	0.12	4.1	**
Mar. 12	Manhattan, Kansas	—	9.4	1.30	0.26	8.9	**
1954 Average		14.8	18.4	1.23	7.27	249.0	10,793
1955							
Mar. 22	Granada, Colorado	10.2	14.2	2.50	0.18	6.2	142
Mar. 23	Syracuse, Kansas	11.4	17.9	1.25	0.86	29.5	1,081
Mar. 23	Lakin, Kansas	13.7	21.0	0.80	1.95	67.0	1,559
Mar. 22	Granada, Colorado	12.1	18.0	0.50	1.52	52.2	2,481
Mar. 23	Menno, Kansas	16.7	24.2	0.55	2.70	92.7	3,801
Apr. 27	Meadow Lake, Colorado	13.7	21.7	0.44	3.00	102.9	4,091
Apr. 26	Midway, Colorado	18.0	23.3	0.42	6.60	226.0	7,823
Apr. 26	Elkhart, Kansas	14.8	21.3	0.31	8.00	275.0	9,788
Apr. 27	Cheyenne Wells, Colorado	20.1	31.0	0.38	5.50	189.0	13,403
Apr. 27	Cheyenne Wells, Colorado	23.2	32.5	0.20	10.00	343.0	17,785
Apr. 26	Midway, Colorado	14.2	22.0	0.12	13.20	453.0	17,412
Apr. 27	Cheyenne Wells, Colorado	23.7	32.5	0.12	16.50	566.0	29,815
1955 Average		16.0	23.3	0.63	5.82	200.0	9,098
1954-1955 Average		15.4	20.8	0.93	6.54	224.0	9,945

* Horizontal visibility on cloudless days between 10 A.M. and 4 P.M. Dust was of local origin except that at Manhattan, Kansas, which apparently came in from Oklahoma and Texas.

** Wind profile not measured.

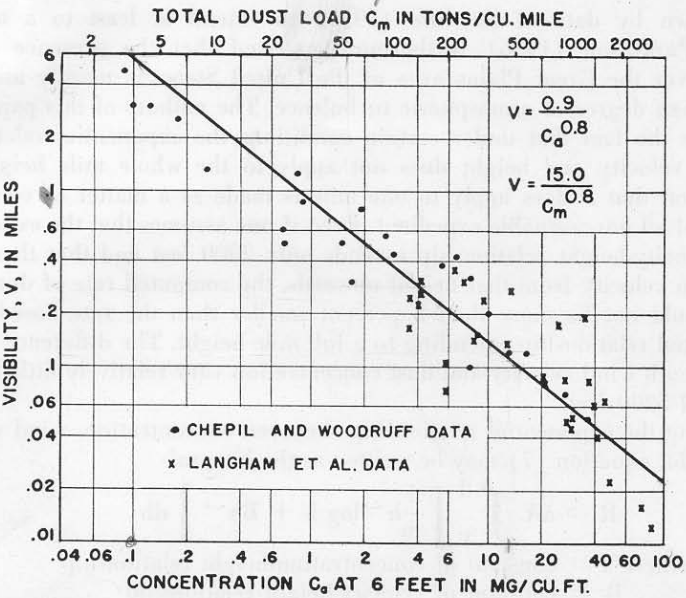

Fig. 3. Relation between visibility and dust concentration at 6-foot height.

tion, the proximity to or position within the eroded area, and the previous intensity of the wind and erosional history of the region are some of the other factors that influence the concentration of dust in the air.

SOIL REMOVAL IN RELATION TO DUST CONCENTRATION AND VISIBILITY

The dust concentration-visibility relationships when combined with wind velocity data can be used in estimating the rate of soil removal from wind-eroded areas. The rate of removal past a given vertical area normal to wind direction would be equal to the concentration multiplied by the wind velocity. Since both the concentration and the wind velocity vary with height, the actual rate of removal for a given storm would be expressed as

$$R = \Sigma(C_{\Delta} u_{\Delta}) A \quad (7)$$

where R = rate of removal

C_{Δ} = increment concentration

u_{Δ} = increment wind velocity

A = vertical cross-sectional area

The most accurate method of summing up the increment velocity-concentration products is to integrate the mathematical expressions for the variation of velocity and concentration with height. The type of relationship between concentration and height is given by equation (1). The wind velocity-height relationship can be expressed as an exponential type equation plotting as a straight line on semi-log paper. This relationship is characteristic of a gradient wind which during the daytime hours in a fully turbulent atmosphere was shown by data of Sutcliffe (1936) to extend at least to a one-mile height. Parkinson (1936) furthermore asserted that the presence of dust storms over the Great Plains area of the United States is usually associated with a high degree of atmospheric turbulence. The authors of this paper fully recognize the fact that under certain conditions the exponential relationship between velocity and height does not apply to the whole mile height. The assumption that it does apply to one mile is made as a matter of convenient but not at all unreasonable expedient. Even if one assumes that the exponential wind velocity-height relationship extends only 2000 feet and that there is no change in velocity from that height upwards, the computed rate of dust movement would not be more than 5 percent smaller than the rate based on the exponential relationship extending to a full mile height. The difference is small because both wind velocity and dust concentration vary relatively little between 2000 and 5280 feet.

Using the exponential relationships between concentration, wind velocity, and height, equation (7) may be written as the integral

$$R = aA \int_{c}^{d} \left[\frac{1}{m} h^{-n} \log h + Bh^{-n} \right] dh \tag{8}$$

where a = constant of concentration-height relationship
B = constant of velocity-height relationship
m = slope of velocity-height relationship (tangent of the angle the curve makes against the velocity axis)
n = slope of concentration-height relationship (0.28)
A = vertical cross-sectional area
h = height above ground

Assuming that the concentration-height and the wind velocity-height relationships represent conditions to a one-mile height, inserting proper conversion factors and choosing the mile to extend from 2 feet to 5282 feet, but ignoring the 2-foot limit because of its negligible influence on the total rate, equation (8) can be integrated and simplified to give

$$R = 20.4\, a \left[\frac{2.33}{m} + B \right] \tag{9}$$

where R is the rate of removal in tons/hour/vertical square mile area normal to wind direction.

Average rates of removal through a vertical square mile area for the individual measurements of this study are given in table 1. These values were calculated from equation (9).

While equation (9) permits estimates of rates of removal where both concentration and velocity profiles are measured, it does not permit calculations using variables that are more readily available from Weather Bureau records. Two of the variables usually available are the visibility and the wind velocity at a given height. If equation (6) of this study is used to provide an expression for concentration in terms of visibility, then equation (9) can be expressed as

$$R = \frac{29.5}{V^{1.25}} \left[\frac{2.33}{m} + B \right] \tag{10}$$

Solution of this equation would require values of the slope m and the constant B of the velocity-height profile. These values would, of course, vary somewhat with different wind storms. If, however, wind velocity were measured at one height and if the average value of Z_O, i.e., the intercept of the velocity-height semi-log relationship for a given type of land terrain were known, values of B and m could be determined. Analysis of the 22 profiles obtained in this study indicated that on the average the value of Z_O was approximately 0.07 feet, which is probably a representative value for the flat terrain over which these profiles were measured. Wind velocity at 60 feet was estimated from the velocity data up to 20 feet simply by extending the straight line curve of the plotted velocity-log height relationship to 60 feet. Values of B and m in terms of this value and the wind velocity at a height of 60 feet are as follows:

V_{60} (mph)	m	B
20	0.1477	7.82
25	0.1182	9.77
30	0.0984	11.74
35	0.0844	13.68
40	0.0738	15.65
45	0.0656	17.61
50	0.0591	19.54
55	0.0537	21.51
60	0.0492	23.47

These values used in conjunction with visibility measurements substituted into equation (10) would give an estimate of the rate of soil removal.

The next step in this type of analysis would be to determine the quantity of soil removal for any storm or period of time. While equation (10) provides a means of estimating rates of removal, it cannot give a total or actual removal without some knowledge of the width of the eroded area normal to wind direction and duration and number of dust storms occurring in a given length of time. Considerable data are available from Weather Bureau records on visibility, wind velocity, and duration of dust storms. This paper merely indicates how these data might be used in estimating the quantities of soil material removed from wind-eroded regions.

References

Chepil, W. S., 1957, Sedimentary characteristics of dust storms: I. Sorting of wind-eroded soil material: Am. Jour. Sci., v. 255, p. 12-22.

Houghton, H. G., 1945, Visibility: Handbook of meteorology: New York, McGraw-Hill Book Co. Inc.

Langham, W. H., Foster, R. L., and Daniel, H. A., 1938, The amount of dust in the air at plant height during wind storms at Goodwell, Oklahoma, in 1936-1937: Am. Soc. Agronomy Jour., v. 30, p. 139-144.

Parkinson, G. R., 1936, Dust storms over the Great Plains: Am. Meteorol. Soc. Bull., v. 17, p. 127-135.

Rouse, Hunter, 1937, Nomogram for settling velocity of spheres: Washington, D. C., Report of the Committee on Sedimentation, Exhibit D, National Research Council.

Sutcliffe, R. C., 1936, Surface resistance in atmospheric flow: Royal Meteorol. Soc. Quart. Jour., v. 62, p. 3-12.

Vanoni, V. A., 1946, Transportation of suspended sediment by water: Am. Soc. Civil Eng. Trans., v. 3, p. 67-133.

Zingg, A. W., 1951, A portable wind tunnel and dust collector developed to evaluate the erodibility of field surfaces: Agronomy Jour., v. 43, p. 189-191.

Western Soil and Water Management Section, S.W.C.R.B.
Agricultural Research Service, U.S.D.A.
Manhattan, Kansas