Atmospheric Environment Vol. 10, pp. 813–825. Pergamon Press 1976. Printed in Great Britain.

FREQUENCY AND DIURNAL VARIATION OF DUST STORMS IN THE CONTIGUOUS U.S.A.*

M. M. ORGILL and G. A. SEHMEL
Atmospheric Sciences Department, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, U.S.A.

(*First received* 8 *January* 1976 *and in final form* 19 *March* 1976)

Abstract—Studies of regional wind erosion and the translocation of suspended particles are important for accurate surveys of air pollution. This category of investigation has nationwide implications for planning and regulatory purposes. However, most regional studies of wind suspension (airborne dust) have centered around the Great Plains without much consideration given to other areas of the country.

The purpose of this study is to quantitate the wind translocation problem throughout the contiguous United States by using visibility as an index. National Weather Service and military surface observations on dust were analyzed for annual, monthly and diurnal periods. Frequency of dusty periods were based on hourly weather observations from stations recording dust, blowing dust, and blowing sand when visibility was 7 miles or less.

Mountainous, forested, and predominantly maritime regions are generally free from major dust storms. The highest dust frequency is in the Southern Great Plains. Secondary dust frequency maxima occur in the Western States, Northern Great Plains, southern coastal Pacific and inland valleys and the Southeast.

Maximum dust frequency occurs in early and late spring months for most regions but some regions experience additional dust in summer or fall. Hourly observations show higher dust frequencies occur in the afternoon between 12.00 and 20.00 LST, or during the period of maximum thermal instability.

Regional dust frequency patterns are discussed in relation to the principal factors which govern natural wind-caused suspension, i.e. (1) surface properties, (2) particle properties, and (3) meteorological conditions.

INTRODUCTION

Studies concerning regional wind translocation of soil particles are important to better understanding of air pollution processes. Selection of sites for future energy installations and related facilities must include thorough consideration of the location's potential for wind resuspension of pollutants. There are diverse regions in the United States subject to varying degrees of suspended dust. The regional processes of particulate resuspension should be understood. Planning for the nation's energy needs should incorporate all possible strategies for control of environmental impacts through competent regulatory and design criteria. Thus it is vital that the frequency, duration and intensity of suspended dust episodes be determined for candidate sites, as well as existing locations of energy-related activity.

Most wind translocation dust studies have centered around the Great Plains (Hagen and Woodruff, 1973) with little attention given to other regions of the country. Other regions are generally known to experience significant dust storms (Clements *et al.*, 1963; Orgill *et al.*, 1974) but there are no comprehensive reports concerning the frequency and regional distributions of suspended dust for the entire country. Consequently, the major purpose of this research was to quantitate the relative frequency and location of wind translocation regions throughout the contiguous United States.

Two methods were considered for analyzing the existing data for regional dust frequency. The first required examination and analysis of actual airborne particulate-concentration data from national and local air pollution monitoring stations during suspended dust episodes. Although this method would probably be best quantitatively, it was not selected for this initial study because of the time and expense of collecting and analyzing the vast amounts of data.

The second method, which was ultimately used, utilized the National Weather Service and Armed Services summarized surface hourly observations of dust and prevailing visibility to define regional dust frequencies. This method was more qualitative, but the data base for a 15–30 y period could be handled more economically and analyzed easily. Consequently, National Weather Service, Air Force, Navy, Army and Marine summarized surface hourly observations on blowing dust and sand were analyzed for annual, monthly, and diurnal periods.

In weather observing practice (Huschke, 1969) a dust storm is only reported if blowing dust reduces visibility below 5/8 mile (1 km). However, in this study we will use the term "dust storm" to include all dust events that reduced the prevailing visibility below 7 miles (11.3 km).

The frequency and spatial distribution of dusty periods were based on summarized hourly weather

* This paper is based on work performed under U.S. Atomic Energy Commission Contract No. AT(45-1)-1830.

observations from 343 weather observing stations that recorded dust, blowing dust, and sand when the visibility was less than 7 miles (11.3 km). This distance is a standard weather observing procedure (NOAA, 1970). The collected and analyzed data showed, with some exceptions, most regions of the continental U.S.A. are susceptible to airborne dust due to wind translocation.

PROCEDURES

Visibility, as a measure of atmospheric opacity, is perceived by an observer to be an indicator of the quantity of pollution (in this case, dust) in the air. Prevailing visibility is the greatest visibility equaled or exceeded throughout one-half of the horizon circle (NOAA, 1970). It is a subjective measurement which depends upon individual ability to both detect and recognize distant objects seen against the horizon sky by day or to detect distant lights at night. Prevailing visibility is taken routinely at National Weather Service observation stations and military installations that have observers on duty.

Charlson (1969) has shown that prevailing visibility and particulate concentrations are approximately related when the particle size distribution remains constant and the relative humidity is less than 70% or deliquescent particles are not present in significant numbers.

A theoretical visibility-concentration relationship (Hagen and Woodruff, 1973) can be derived by assuming: (1) visibility is reduced only by scattering; (2) airborne particles are of uniform size; and (3) the scattering area coefficient is constant. In this case,

$$C = \frac{57.2}{V} (\mathrm{mg\ m^{-3}}), \tag{1}$$

where V is prevailing visibility in km. A nearly identical empirical visibility-concentration relationship at 1.8 m above the surface was found by Chepil and Woodruff (Hagen and Woodruff, 1973)

$$C = \frac{56.0}{V^{1.25}} (\mathrm{mg\ m^{-3}}). \tag{2}$$

This empirical concentration-visibility relation agrees with the theoretical relation when V is about 1 km, but has a smaller concentration than the theoretical one for visibilities greater than 1 km.

National Weather Service and military surface observations of dust are only reported when the prevailing visibility is less than 7 miles (11.3 km). If the assumptions are met, substitution of 11.3 km into equations (1) and (2) gives a dust concentration from 2.7 to 5.1 mg m^{-3}. Unfortunately, this criteria eliminates any consideration of dust storms with visibility greater than 7 miles or with dust concentrations between 75 μg m^{-3} (ambient air standard) and 2700 μg m^{-3}. If these data could be included they would increase the relative frequency of dust storms, but it is not known whether the relative frequency distributions of the >7 mile dust storms are the same as the <7 mile dust storms. We suspect not, but we don't have the data on hand to verify it. Therefore, dust frequency data based on prevailing visibility refer only to dust storms when the dust concentration is from 3 to 5 mg m^{-3} or greater. Measured dust concentrations in dust storms have been reported from 0.1 to 176 mg m^{-3} depending on stage of storm development (Gillette *et al.*, 1972; Shinn *et al.*, 1974; Viletto and Ohman, 1972).

Hourly observations of prevailing visibility and occurrence of dust have been collected over several years and are available either from tabulated summaries (Part A) or magnetic tapes at the National Climatic Center in Asheville, North Carolina. Tabulated summaries were obtained for 249 weather stations and an additional 94 summaries were specially processed for this research program by the National Climatic Center. Hence, tabulations for 343 weather stations were utilized in this study. Figure 1 shows the distribution of stations.

The data for individual weather stations were tabulated in terms of percentage frequency of occurrence for various weather elements for annual, monthly, and 3-h periods. Data pertaining to percentage frequency of dust were extracted, plotted and analyzed.

The country was divided into seven different regions (Fig. 1) depending partially on relative dust frequency, spatial dust frequency patterns and geography. To quantify the dustiness in these seven regions a simple regional average dust frequency was defined as follows:

$$\mathrm{RADF} = \sum_{i=1}^{i=N} \frac{f_i}{N}, \tag{3}$$

where RADF is the annual or monthly regional average dust frequency; f_i is the annual or monthly percent frequency of dust occurrence for the ith station in each region, and N is the total number of stations for each region.

RESULTS

Annual distribution of suspended dust and sand

The frequency of occurrence of suspended dust or sand from major dust storms on an annual basis for the country (excluding AK and HI) is shown in Fig. 2. In this figure, frequency isopleths approximate the regional dust frequency. The isopleths were drawn subjectively with the goal of delineating dust frequency on a broad regional basis. These isopleths range from N (none)* to 3% of the total hourly observations.

* The shaded regions of Figs. 2, 5a–d represent regions where no hourly observations were found with visibility <7 miles due to dust, etc. If dust storms with visibility >7 miles were to be included, the relative dust frequency would be higher but the location of dusty areas should not change significantly.

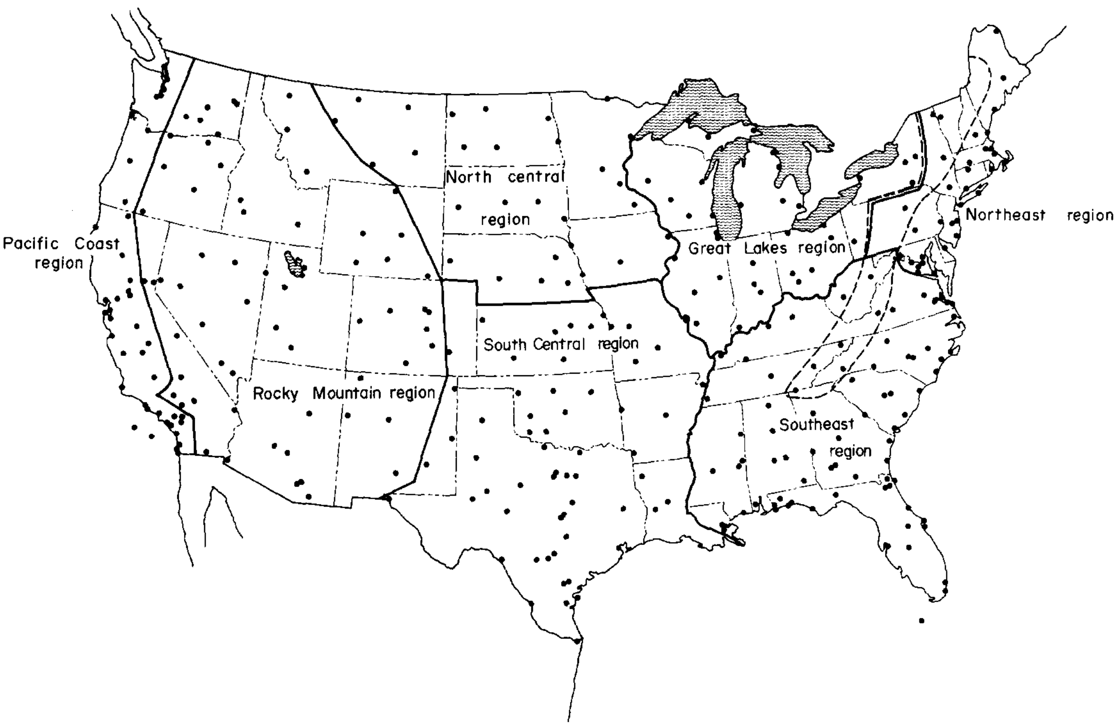


Fig. 1. Distribution of 343 weather observation stations used in study and seven defined dust regions of the country. Dash lines represent the Appalachian Mountains.

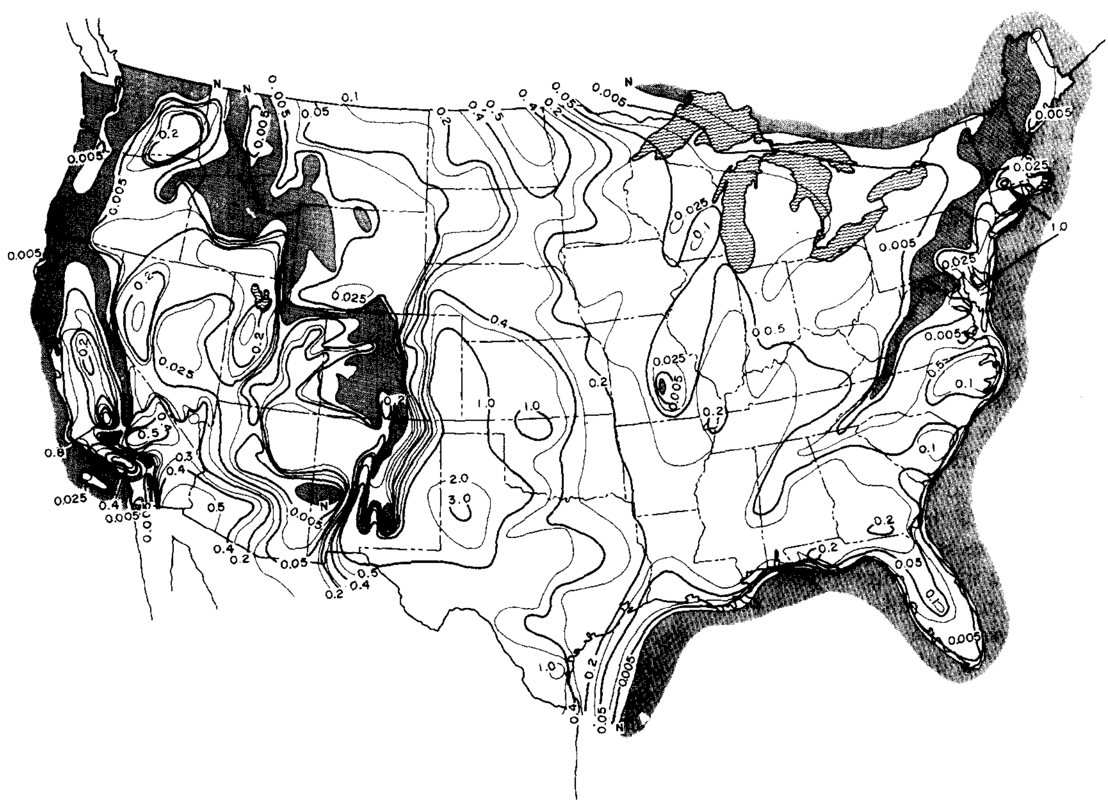


Fig. 2. Annual % frequency of dusty hours based on hourly observations from 343 weather observation stations that recorded dust, blowing dust and sand when prevailing visibility was less than 7 miles (11 km). Shaded areas (*N*) represent no observations of dust. Total period between 1940 and 1970, approx.

The occurrence of suspended dust is relatively infrequent. For example, the maximum annual percentage frequency for the country is 3.1% at Lubbock, TX. This amounts to a total of 5 133 h in a 23-y period (105 580 h of observation) or 223 dust h y^{-1} on the average.

A general description of the distribution of annual dust frequency in the seven general regions of the country as shown in Fig. 2 follows:

Pacific coast region. Coastal and inland valley regions (west of the Cascade Mountains) of WA and OR have very few occurrences of major dust storms because of the prevailing onshore winds and frequent precipitation, although, strong winds ($>7\ m\ s^{-1}$) do occur at times. The major areas of relatively high incidence are found in the San Joaquin Valley (0.2–0.8%) and Los Angeles basin of CA (0.1–0.4%. In central and Southern CA, dust frequency gradients are very steep, due in part to the mountain ranges.

Rocky Mountain Region. Dust frequency is highest in the broad river valleys, deserts, and leeside areas of mountain ranges, such as the Mojave Desert in southern CA and AZ (0.7–0.8%), Great Salt Lake Desert (0.3%), western NV (0.3%), eastern WA (0.1–0.2%) Snake River Valley (0.1%), southern Rio Grande Valley (0.6–> 1%), and the higher desert plateaus of AZ (~0.2%) and WY (~0.05%).

Southern central region. The highest annual dust frequency (1–3%) in the country is located along a north–south axis, through west TX, OK, KS, and eastern CO, approx. 300 km east from the crest of the Rocky Mountains. Further east, the frequency of dust (~0.1%) decreases by a factor 10–30 in the states of MO, AR and LA.

North central region. The north–south axis of high dust frequency from the south central region also extends through central NB and eastern S and ND, but with lower frequencies. A secondary maximum (0.6%) is located in eastern ND. An eastward extension of high dust frequency extends from this area through MN toward MI.

Great Lakes region. The northern Great Lakes area has a very low dust frequency (0.05% to *N*) but areas south of the Great Lakes in IL, IN, and OH have an increased incidence (0.025–0.1%) of dust. Evidently, a major part of the suspended dust that occurs in the Great Lakes area are due to "dust fronts" moving east from the south central region and north central region (Cohen and Pinkerton, 1966).

Southeastern region. The southern states, as well as TN, KY, WV, and VA have annual dust frequencies (0.1–0.2%) comparable to some western mountain regions. Frequencies are low along the Applachian Mountains, but maximum frequency (0.1–0.2%) areas occur through TN, KY, GA, and the Carolinas. Again, "dust fronts" from the south central region contribute to the dust frequency in this area.

Northeastern region. Dust frequency is very low (0.005–0.01%) in the northeastern portion of the country, and especially along the Applachian Mountains. The urban area between Boston and Washington, D.C., indicates a minor high frequency (0.005–0.1%) area of dustiness. The authenticity of this feature may be questionable and requires further verification.

Table 1. Annual average regional dust frequency for seven regions of the U.S.A.

	Annual RADF (%)
South central region	0.61
Rocky Mountain region	0.17
North central region	0.17
Pacific coast region	0.07
South eastern region	0.06
Great Lakes region	0.04
North eastern region	0.01

A comparison of relative average dustiness of the seven regions was made by computing an annual average regional dust frequency from equation (3) for each region. These are shown in Table 1.

Comparison of the annual average dust frequency for the seven regions shows that the south central, Rocky Mountains, and north central regions of the country have the highest relative dust frequency. The northeast and Great Lakes regions the lowest frequency. The relatively high frequency of dustiness for the Pacific coast region is due solely to the influence of Central and Southern CA. The coastal regions of OR, WA, and NC have one of the lowest (if not the lowest) dust frequency in the nation.

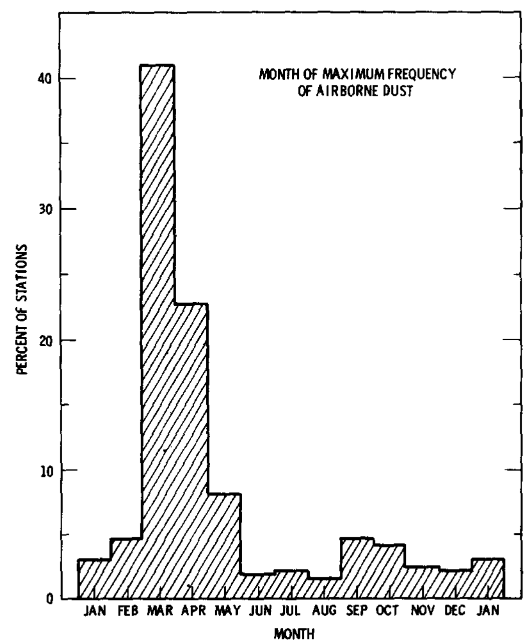


Fig. 3. The % of observation stations that have a maximum frequency of airborne dust during a particular month.

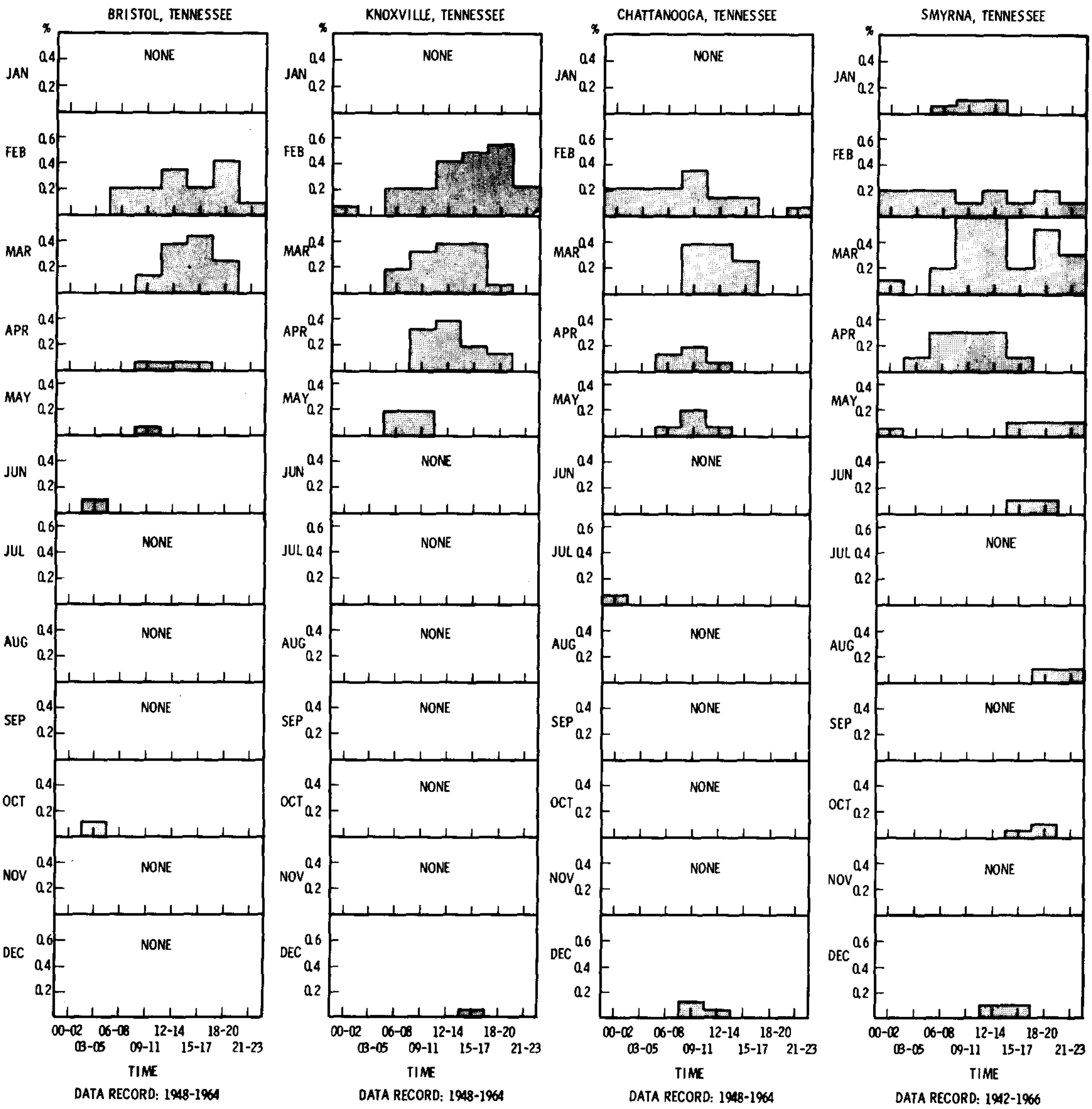


Fig. 4. Four stations in TN showing a definite dust frequency maxima during the Spring months as well as diurnal variations.

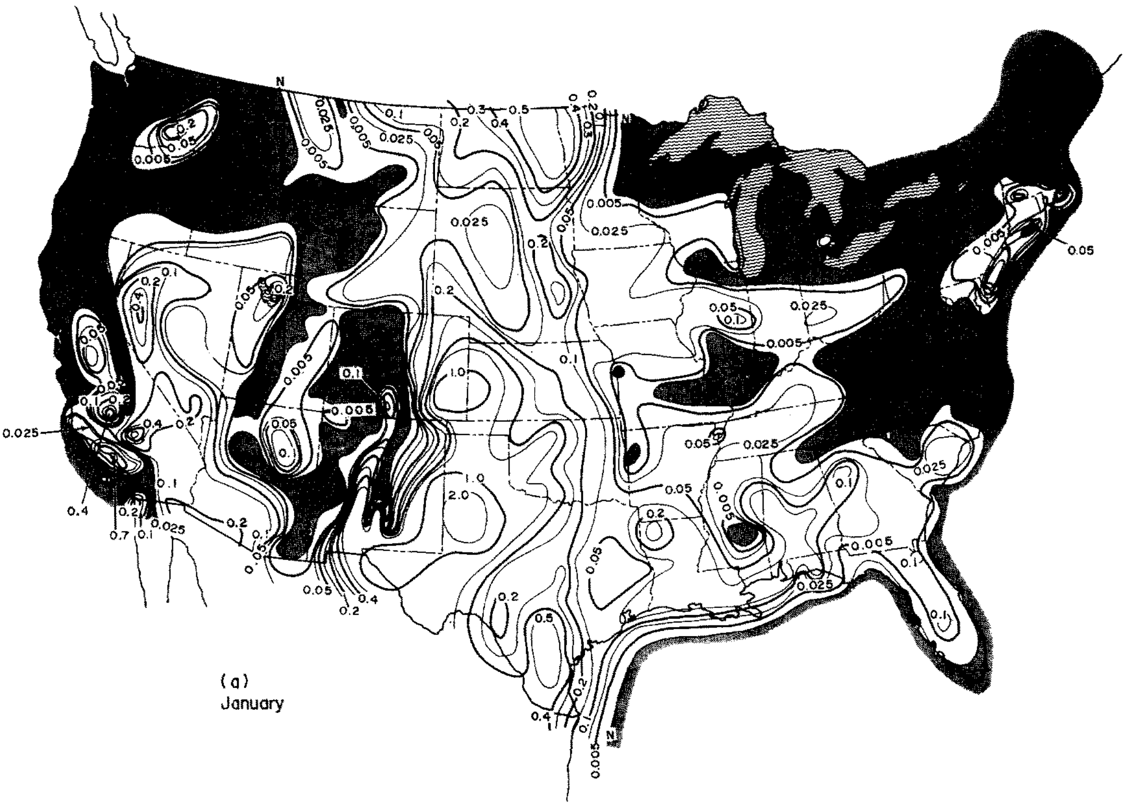
Seasonal and monthly variation of suspended dust and sand

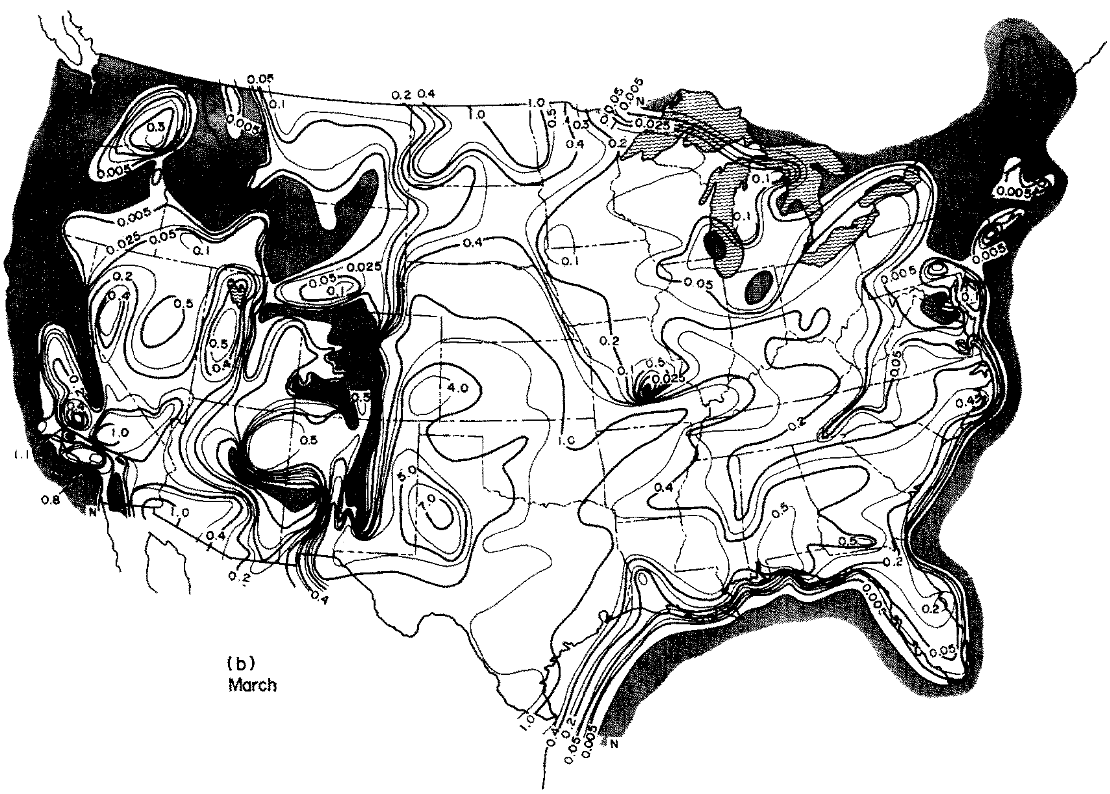
The maximum frequency of suspended dust for the country occurs during the months of March, April and May. Figure 3 shows that during this period around 72% of the stations showed maximum monthly dust frequencies. In March, 41% of the stations indicated monthly maximum dust frequencies. Figure 4 shows four observation stations in TN that illustrate a definite spring maximum in dustiness. This spring maximum in dustiness is largely the result of strong winds ($>7\ \mathrm{m\,s^{-1}}$) associated with spring cyclonic and convective storm activity. A definite afternoon maximum in dust frequency is often observed in the spring but this feature will be discussed later.

A much smaller secondary maximum in dust frequency (4–5% of the stations) occurs during the months of September and October. This is the result of several stations in the Pacific Coast and Rocky Mountain regions having their monthly maximum dust frequency during the fall months. This is the case in eastern WA and the San Joaquin–Sacramento Valleys of CA.

The spatial distribution of the monthly dust frequency for the country are shown in Fig. 5(a–d). One of the distinguishing characteristics of the monthly dust frequency patterns is the persistence of dust source regions west of Mississippi River. The spatial dust frequency patterns are generally fixed to certain regions of available soil, e.g. Mojave Desert, Great Salt Lake Desert, and South Great Plains.

Regions east of the Mississippi River show intermittent and variable regional dust frequency patterns from month to month. During the spring months, when the frequency of dust generally increases over


(a)
January


(b)
March

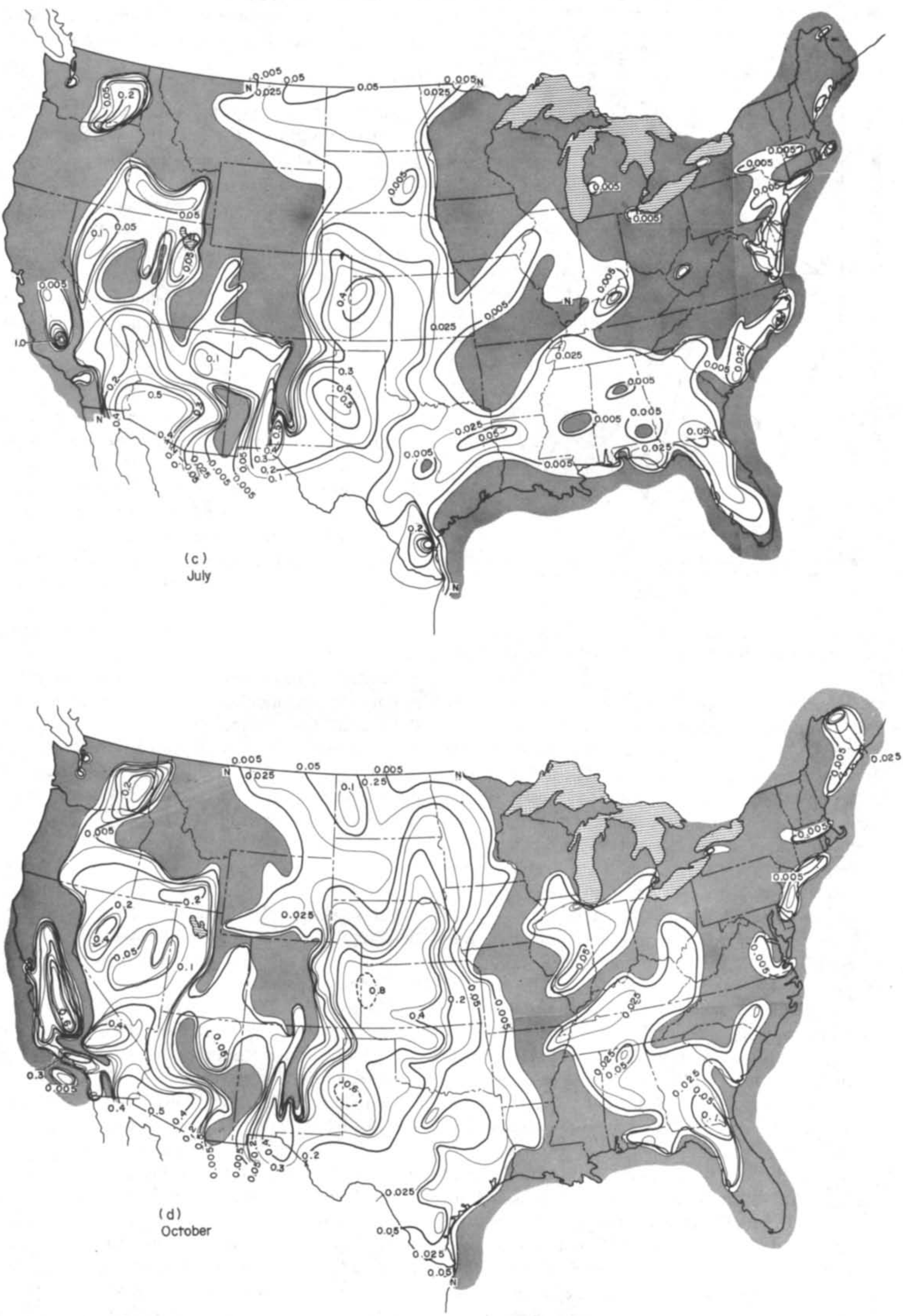


Fig. 5. Monthly % frequency of dusty hours for January (a), March (b), July (c) and October (d) based on hourly observations from 343 weather observation stations that recorded dust, blowing dust and sand when prevailing visibility was less than 7 miles (11 km). Shaded areas (*N*) represent no observations of dust. Other months available from authors.

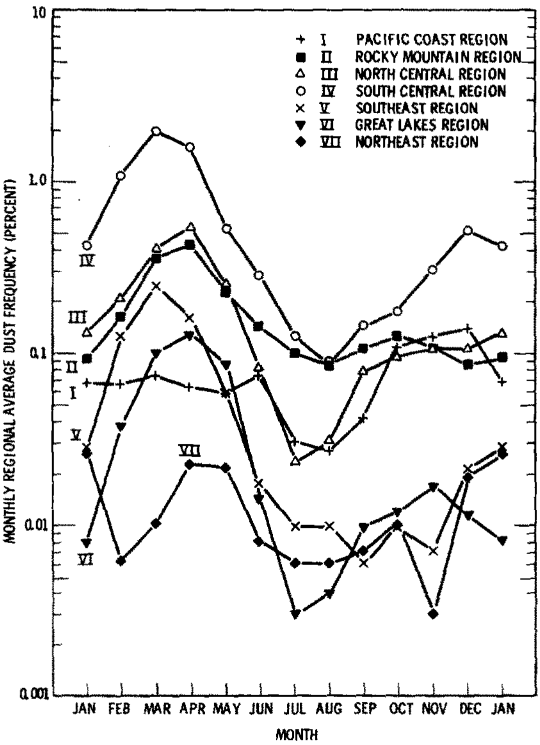


Fig. 6. Monthly regional average dust frequencies for seven defined dust regions in the contiguous U.S.A.

the eastern section of the country, fairly persistent maximum dust frequency areas appear in the southeast region including TN and KY. Another maximum area occurs through the northern Great Lakes area and appears to originate from the north central region. By the month of June, these maximum dust frequency areas have reduced in magnitude and become more variable in location, but still have a tendency to persist in the southeast and southern Great Lakes region throughout the year.

A monthly regional average dust frequency was computed for each of the seven regions of the country for each month by equation (3). The results are presented in Fig. 6. One of the most distinguishing characteristics of Fig. 6 is the definite maximum in dustiness during the spring months for all areas except the Pacific Coastal region. In this latter case, the maximum occurs during the fall and early winter months. All the regions show a definite decrease during the summer months.

At least three of the regions, south central, Great Lakes, and Rocky Mountain, have a seasonal bimodal distribution in dust frequency with a primary maximum in the spring months and a secondary maximum in the fall or early winter months. Also, a number of stations in some of the other regions show bimodal dust frequency distributions. Four selected stations that show bimodal seasonal dust frequencies are shown in Fig. 7. Each station shows the characteristic dust frequency maxima in the spring months, the decrease during the summer months, another maxima in dustiness during the fall months and then another decrease during the winter months.

Diurnal variation of dust frequency

Three-hour dust frequency data were examined for a number of stations. The diurnal dust frequency was generally classified into four types. These are: (1) the afternoon maximum; (2) random; (3) mixed; and (4) late afternoon and evening. Examples of these four diurnal dust frequency types are presented in Fig. 8.

The afternoon maximum in dust frequency is very common and occurs at many locations. Lubbock, TX, as well as the stations in Fig. 7 illustrate this diurnal variation. The highest dust frequencies occur during afternoon hours when the atmospheric boundary layer is normally deep and turbulent mixing is more pronounced.

The random diurnal dust pattern is illustrated by Lufkin, TX. The dust frequency variation is devoid of any significant peaks in dust frequency. In this case the dust distribution is probably due to the random occurrence of strong winds ($>7\ m\ s^{-1}$) associated with frontal or thunderstorm activity.

The mixed diurnal dust pattern is illustrated by Hanford, WA, and Fig. 4. In this case, the random occurrence of storm activity is superimposed on an afternoon maximum resulting in peak dust frequencies at different local times depending on the month.

The late afternoon and evening diurnal dust pattern is not very common. It appears best developed at Bakersfield, CA, between April and August. Apparently, during these warm months a strong sea-breeze front invades the Bakersfield area and, at times, produces late evening dust storms of varying degrees (U.S. Dept. of Commerce, 1971).

DISCUSSION

The suspended dust potential of a region depends on several closely interrelated factors. Factors which may influence soil particle translocation are generally divided into particle properties, surface properties, and meteorological factors (Hilst and Nickola, 1959). These factors and their components have been the subject of extensive research by soil scientists and others for several years.

Past studies (Viletto and Ohman, 1972; Ohman *et al.*, 1972) have attempted to evaluate the potential dustiness of an area by examining the particle distribution and physical characteristics of soil. It was concluded that soils with potential dust particles are very common on a world basis so other factors such as surface cover properties and meteorological factors must be factored in to predict dust suspension. Techniques have been developed by soil scientists for estimating soil loss by wind erosion (Woodruff and Siddoway, 1965; Skidmore and Woodruff, 1968), but the problem of particle suspension under various surface and meteorological conditions has not been completely solved.

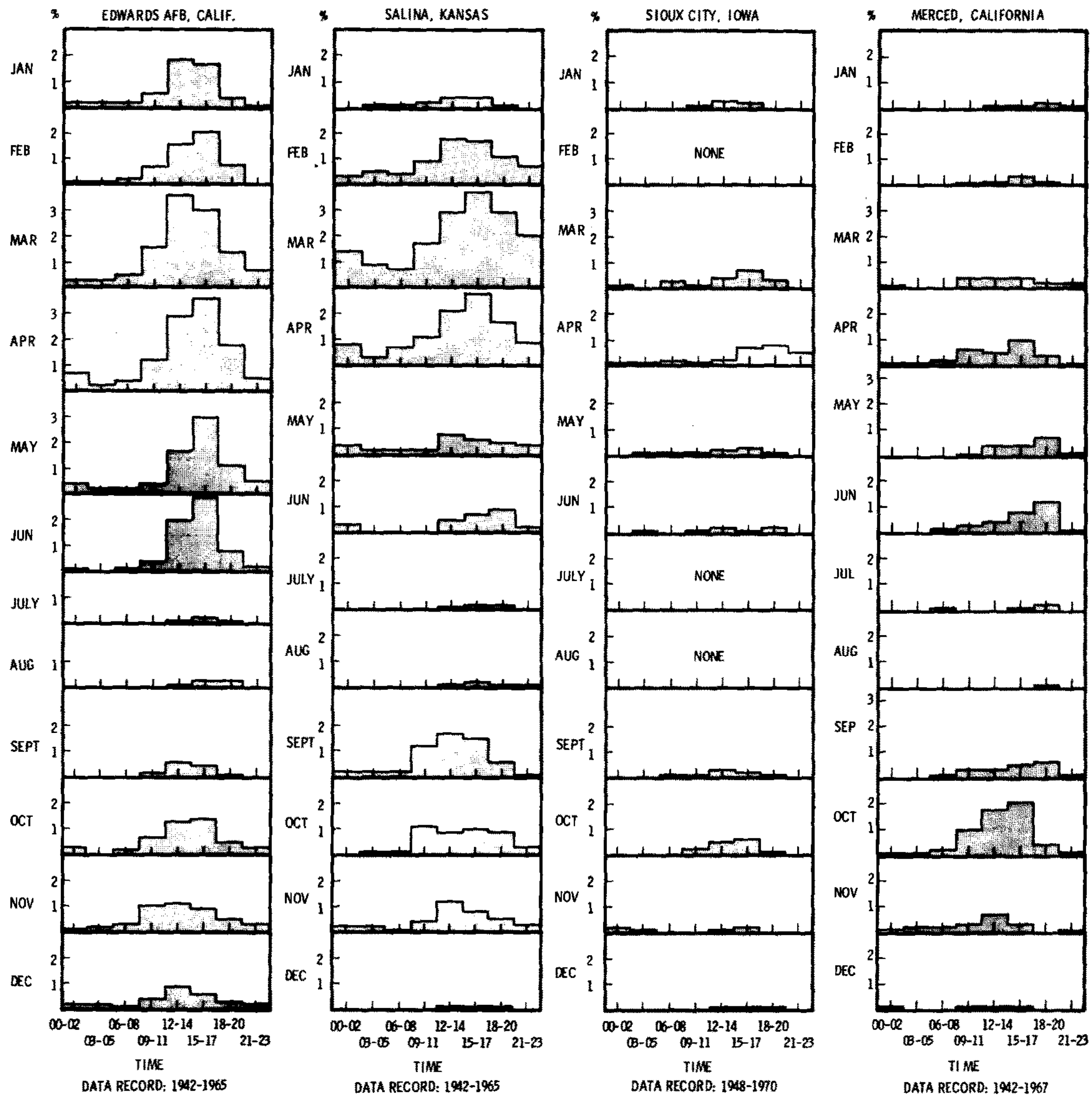


Fig. 7. Monthly and diurnal dust frequency variations at four locations that have a seasonal bimodal distribution of dust frequency.

An important factor in assessing the dust potential of a region is the presence or absence of protective vegetation cover. Dense vegetation which is often found in the high mountains and in regions of moderate to high precipitation provides excellent protection from strong wind movement. Thus, a large share of the coastal Pacific northwest, Rocky and Appalachian Mountains, the Great Lakes region, and the northeast region have very low dust frequencies. However, dust may be transported from other regions. Table 2 shows monthly dust frequencies in mountainous regions for the available stations. Table 2 generally indicates dust frequencies are quite low in mountainous terrain, but dust is not totally absent. Apparently, a large share of the reported airborne dust originates and is transported from local surrounding dust source regions.

When the vegetative cover is disturbed by mechanical means, such as construction, plowing, strip-mining, etc. the regional dust potential is expected to increase. Since the early spring and fall months are normally the time period in which farmland is prepared for future crops, vast areas of disturbed soil become available for wind translocation. Apparently, agricultural activity is a factor that may explain the high frequency of dustiness for the whole country during the spring months and possibly again during the fall months as indicated in Figs. 3 and 6.

The ground surface characteristics also changes during the winter. In the northern states and in the mountanous areas the ground may freeze or become covered with snow at times. Dustiness is nearly nonexistent during this time, but the snow cover itself will be subjected to wind translocation. Blowing

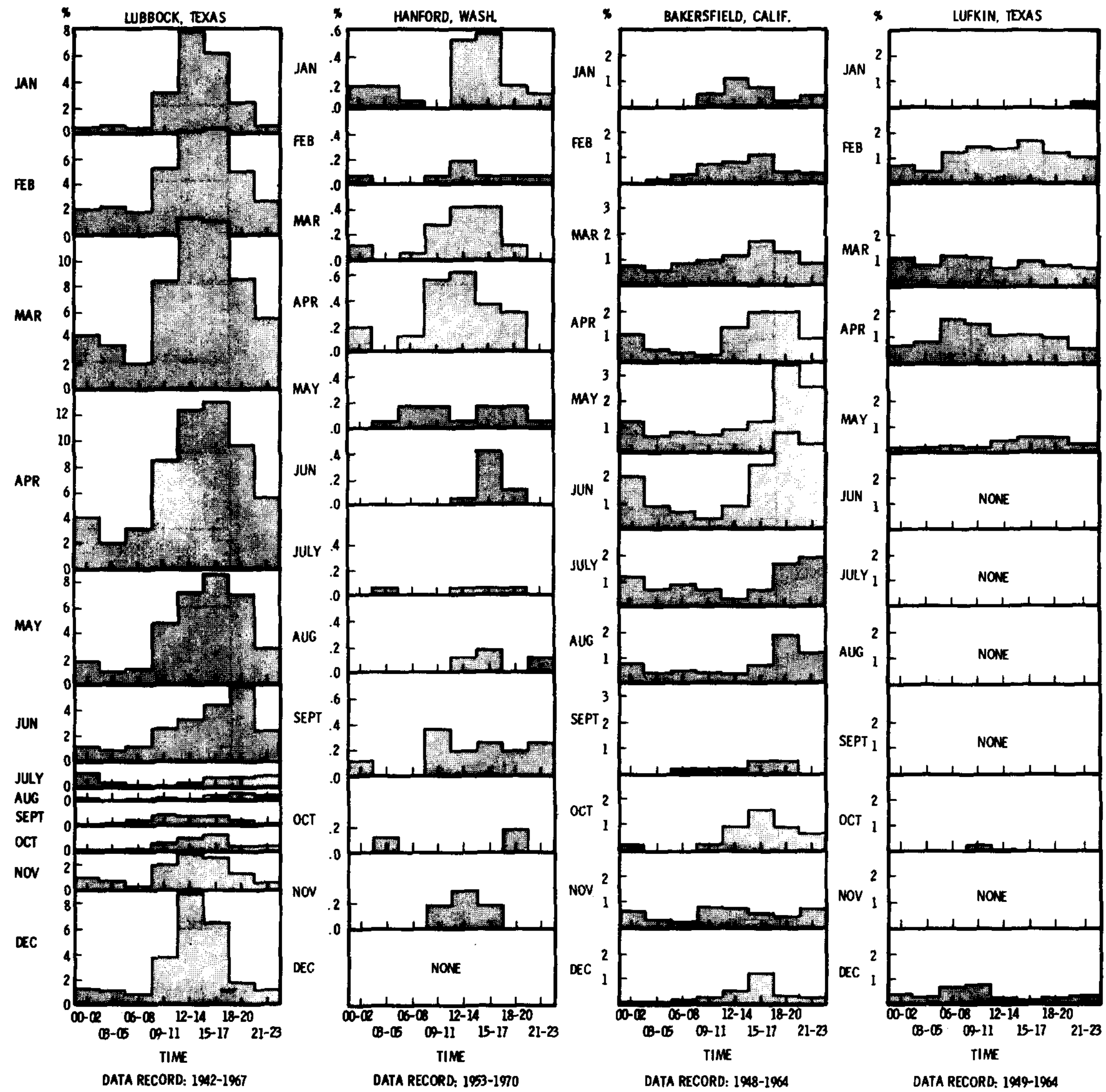


Fig. 8. Four types of diurnal dust frequency variations; afternoon maximum: Lubbock, TX; random: Lufkin, TX; mixed: Hanford, WA; late afternoon and evening maximum (warm season): Bakersfield, CA.

Table 2. Monthly dust frequency for stations in mountainous areas (% of total monthly or annual hourly observations)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Montague, CA					None								None
Blue Canyon, CA					None								None
Donner Summit, CA					None							0.1(?)	0.01(?)
Baker, OR			0.008	0.016					0.049		0.016		0.007
Ely, NV	0.036	0.038	0.053	0.254	0.018	0.018	0.053		0.019	0.055	0.019	0.081	0.056
Bryce Canyon, UT			0.126							0.008			0.011
Flagstaff, AZ						0.068 ·	0.030						0.008
Ft. Huachuca, AZ		0.1	0.2	0.1			0.01					0.1	0.035
Dillon, MT		0.009	0.008		0.016								0.003
Kalispell, MT		0.016	0.015	0.015					0.031				0.006
Eagle, CO				0.065	0.063	0.008					0.008		0.012
Asheville, NC		0.035	0.166	0.008	0.024								0.019
Roanoke, VA		0.026	0.079		0.047								0.013
Elkins, WV		0.104	0.040		0.008								0.012
Plattsburgh, NY						None							None
Burlington, VT				0.015									0.001

snow, during the winter, is more common than dust. Winter monthly frequencies of blowing snow may vary between 1 and 12% of the total hourly observations. These frequencies are substantially higher than dust frequencies. However, the role of blowing snow in the translocation of radioactive particles or other potentially hazardous materials has not been investigated.

Meteorological systems or events that can cause major dust suspension throughout the country are:

1. Convective weather systems, i.e. squall lines, thunderstorms, tornadoes.
2. Warm and cold frontal passage.
3. Cyclogenesis.
4. Low-level winds associated with upper-level jet streams.
5. Diurnal winds.
6. Mountain katabatic winds, e.g. Chinook and Santa Ana.

An interesting climatological feature this study has revealed is that many relatively high-dust frequency areas in the Rocky Mountain region are located in the lee of mountain ranges where katabatic winds often occur. The phenomenon is well known east of the Rocky Mountains and Sierra Nevadas, and also occurs in varying degrees in other locations, such as eastern WA, western NV, western and eastern UT, the WY desert and the southern Rio Grande Valley. This climatic feature is not so apparent east of the Mississippi River unless the dust frequency maximum which occurs during the spring months in eastern S and NC is the result, in part, to the leeside effects of the Appalachian Mountains.

The Los Angeles Basin and southern San Joaquin Valley is also another region where katabatic winds cause dusty conditions. Warm, dry and dusty Santa Ana winds blow from the Mojave Desert westward into this region, causing severe dust conditions at times. The maximum dust frequency during the late

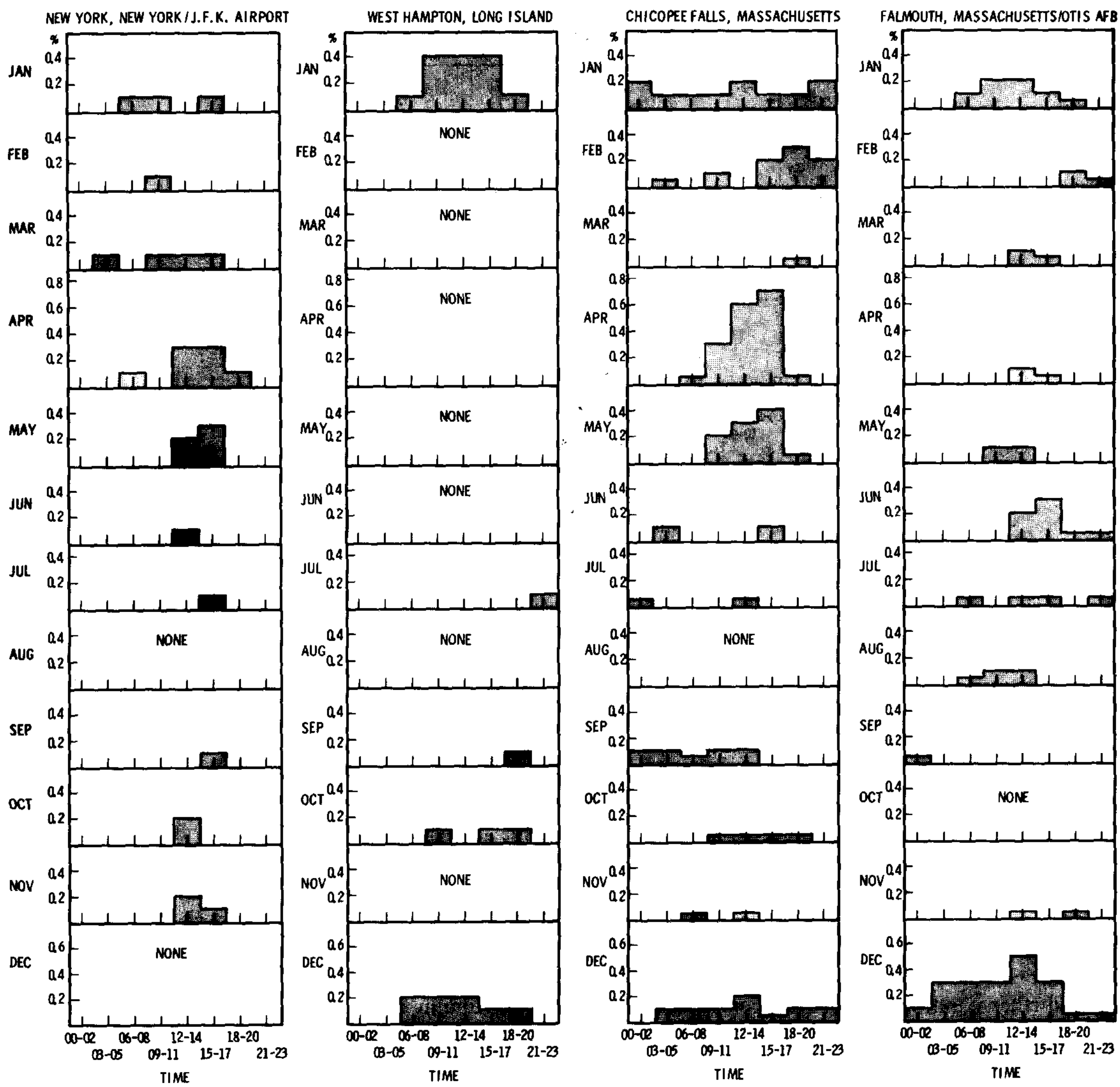


Fig. 9. Monthly and diurnal dust frequency at selected east coast locations.

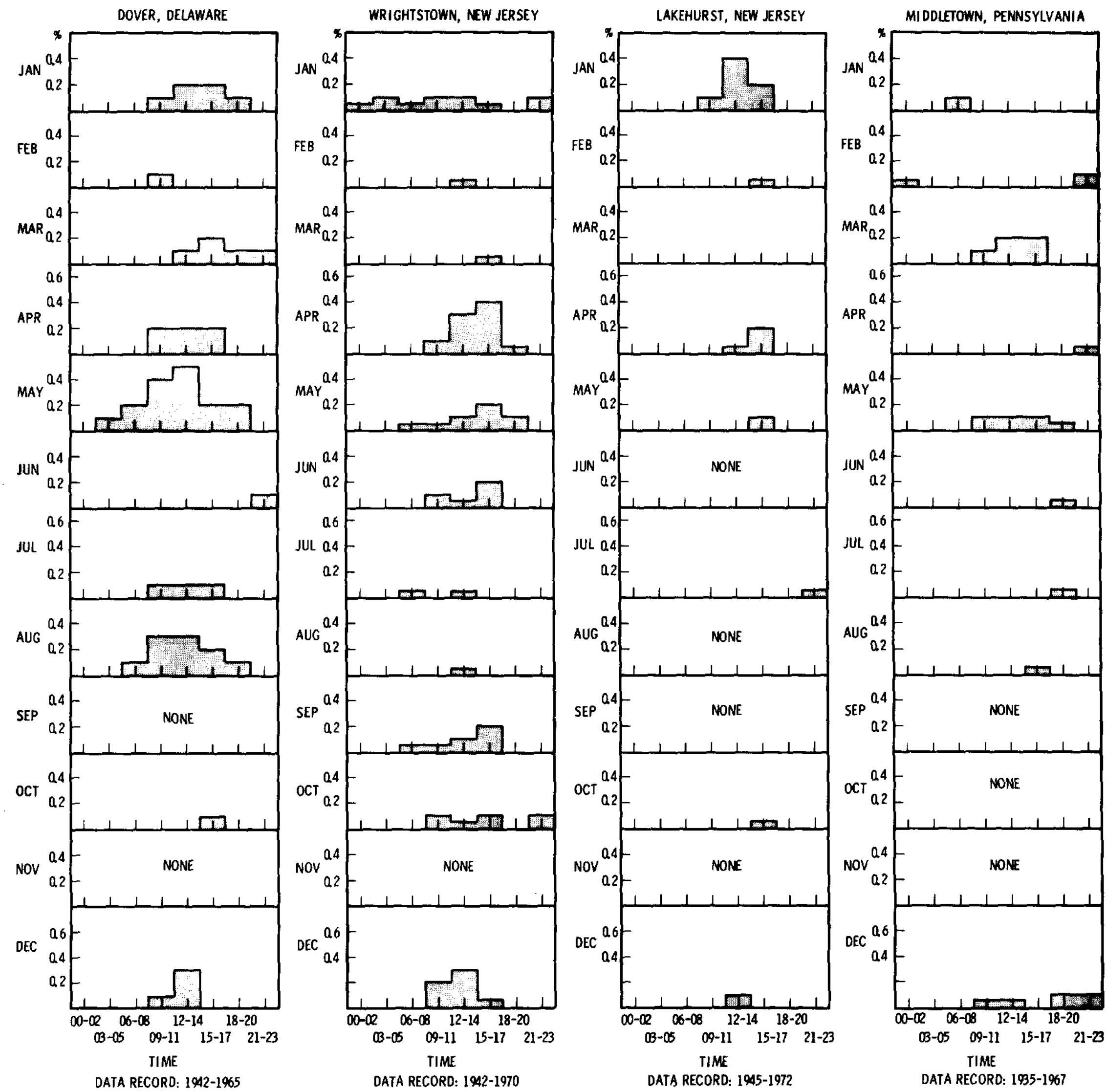


Fig. 10. Same as Fig. 9, but for 4 different locations.

fall and early winter months (Fig. 6) within the Los Angeles Basin is the result, in part, to these dusty Santa Ana events.

A surprising aspect of this study was the presence of dust events in the eastern section of the country, especially between Washington, D.C. and Maine. Figures 9 and 10 are a selection of observation stations in this region that indicated dust episodes but at infrequent periods. The origin of the airborne dust, if it is actually dust (possibly observers could confuse haze and smoke with dust in these relatively high polluted regions), is not known at this time. Even though eastern dust events are not particularly significant, further confirmation of these episodes may be of interest, but would require a detail examination of the hourly observation records of several eastern stations and the synoptic charts during suspected dust episodes.

CONCLUSIONS

This study has shown that many diverse regions of the country, such as urban, agricultural, desert, valley, plain and forested areas are subject to suspended dust in varying degrees. Regions of the country that are mountainous, forested and predominantly maritime are generally free from major "dust storms" (visibility less than 11 km). The highest frequency of dust is observed in the southern Great Plains. Secondary dust frequency maxima are observed in the western states, northern Great Plains, southern coastal Pacific and inland valleys and the southeast.

Maximum dust frequency occurs in the early and late spring months for most regions of the country, but some areas experience additional dust in the summer or fall. Observations show that the higher frequencies of airborne dust occur in the afternoon period between 12:00 and 20:00 LST or during the period of maximum thermal instability.

Details on the different regional patterns of dust frequency would require additional studies on the principal factors which govern natural wind-caused suspension, i.e. (1) soil particle properties, (2) surface properties, and (3) meteorological conditions.

REFERENCES

Charlson R. J. (1969) Atmospheric visibility related to aerosol mass concentration: A Review. *Environ. Sci. Technol.* **3**, 913–918.

Clements T., Mann J. F., Stone R. O. and Eymann J. L. (1963) A study of windborne sand and dust in desert areas. Technical Report ES-8, Earth Sciences Div., I/S, Army National Laboratories.

Cohen J. M. and Pinkerton C. (1966) Widespread translocation of pesticides by air transport and rain-out. *Organic Pesticides in the Environment, Advances in Chemistry Series* 60, pp. 167–168. American Chemical Society.

Gillette D. A., Blifford J. H., Jr. and Fenster C. R. (1972) Measurements of aerosol size distributions and vertical fluxes of aerosols on land subject to wind erosion. *J. appl. met.* **11**, 977–987.

Hagen L. J. and Woodruff N. P. (1973) Air pollution from dust storms in the Great Plains. *Atmospheric Environment* **7**, 323–332.

Hilst G. R. and Nickola P. W. (1959) On the wind erosion of small particles. *Bull. AMS* **40**, 73–77.

Huschke R. E. (Editor) (1959) *Glossary of Meteorology*, pp. 183–184. American Meteorological Society, Boston, MA.

NOAA—National Weather Service (1970) *Federal Meteorological Handbook* No. 1. Government Printing Office, Washington, D.C.

Ohman H. L., Viletto J., Jr., Ackerson K. T. and Miller L. L. (1972) Potential sand and dust source areas. Report ETL-SR-72-1, U.S. Army Engineers Topographic Labs., Ft. Belvoir, VA.

Orgill M. M., Sehmel G. A. and Bander T. J. (1974) Regional wind resuspension of dust. BNWL-1850, Pt. 3, UC-11, Pacific Northwest Laboratory Annual Report for 1973, to the USAEC Div. of Biomedical and Environment Research, Atmospheric Sciences, 214–219.

Shinn J. H., Kennedy N. C., Koval J. S., Clegg B. R. and Porch W. H. (1974) Observations of dust flux in the surface boundary layer for steady and non-steady cases. Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants Symposium, CONF-740921, Richland, WA.

Skidmore E. L. and Woodruff N. P. (1968) Wind erosion forces in the United States and their Use in predicting soil loss. *Agriculture Handbook* No. 346, U.S. Dept. of Agriculture, Manhattan, KS.

U.S. Dept. of Commerce (1971) Narrative Climatological Summary. Bakersfield, CA, Local Climatological Data, NOAA.

Viletto J. and Ohman H. L. (1972) Particulate matter considerations in the design of V/STOL Aircraft. Special Report ETL-SR-72-2, U.S. Army Engineers Topographic Laboratories, Ft. Belvoir, VA.

Woodruff N. P. and Siddoway F. H. (1965) A wind erosion equation. *Soil Sci. Soc.* **29**, 602–608.