
Air Pollution Climatology

Climatology refers to averaged meteorology over a period of record, usually several years. Air pollution climatology involves meteorological variables that are important in air pollution. Alternatively, it is the interpretation of air pollution data from a meteorological perspective.

I. SOURCES OF DATA

There are numerous sources of meteorological data. Hourly observations, primarily to support forecast programs and aviation operations, are made 24 h a day. Observations throughout the world, including those of over 200 stations in the contiguous United States, are also made at other intervals, when the weather is changing significantly. Since January 1, 1966, when archiving of each hourly US observation in a computer-compatible form was discontinued as an economy move, only every third hour (00 GMT plus every 3 h) has been readily accessible. The other observations are available as reproductions of manually recorded observations and may be specially prepared on magnetic tape at cost for computer use. The US archive for such data is the National Oceanic and Atmospheric Administration's (NOAA)

National Climate Center in Asheville, North Carolina. The data available from the hourly observations are listed in Table 23.1.

Other data, gathered primarily once each day by cooperative observers, consist mostly of temperature and precipitation readings. These are of limited usefulness for air pollution analysis because wind data are generally lacking.

Other sources of data, especially wind data, may be routinely measured by industrial or commercial establishments. Availability of these data must be ascertained through contact with each data collector.

Many city and regional agencies responsible for air pollutant measurements also measure wind and temperature at some of their air pollutant sampling stations. Because exposure at air quality stations is generally considerably less ideal than at airport stations, the data may be representative of extremely local conditions.

Radiosonde balloons are released twice daily, approximately at 00:00 h and 12:00 h GMT. Measurements of temperature and humidity, alternated by a pressure switch, are transmitted by radio signals from the instrument package, which is also tracked by ground-based radio direction-finding equipment at the point of release. This allows computation of wind direction and wind speed at numerous heights above ground. Figure 23.1 shows the

TABLE 23.1

Hourly Surface Observation Variables

Station number, five digits ^a
Date—year, month, day, six digits ^a
Hour, two digits ^a
Ceiling height, hundreds of feet, three alphanumeric characters ^a
Sky condition, up to four layers, four alphanumeric characters
Visibility, miles, three digits (coded)
Weather and/or obstructions to vision, eight alphanumeric characters
Sea-level pressure, millibars, four digits
Dew point, °F, three digits
Wind direction, tens of degrees azimuth, two digits ^a
Wind speed, knots, two digits ^a
Station pressure, inches of mercury, four digits
Dry bulb temperature, °F, three digits ^a
Wet bulb temperature, °F, three digits
Relative humidity, percent, three digits
Clouds and obscuring phenomena
Total amount, tenths, one coded alphanumeric character ^a
Following for up to four layers:
Amount, tenths, one coded alphanumeric character
Type, one coded alphanumeric character
Height, hundreds of feet, three alphanumeric characters
Amount of opaque cloud cover, tenths, one alphanumeric character ^a

^aOf particular interest in air pollution work.

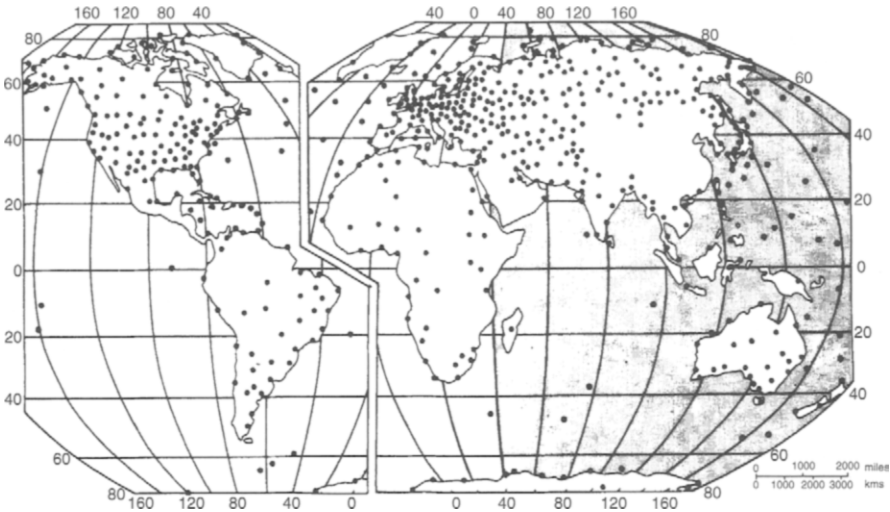


Fig. 23.1. World network of radiosonde stations. Ten stations, one in the Atlantic and nine in the Pacific, are not shown. Each dot represents a station at which an upper-air sounding is made each day at 00:00 h GMT, at 12:00 h GMT, or both. *Source:* The Secretary-General, World Meteorological Organization, Geneva.

locations of radiosonde stations throughout the world, including over 60 locations in the contiguous United States.

Numerous analyses of data routinely collected in the United States have been performed by the US National Climatic Center, results of these analyses are available at reasonable cost. The joint frequency of Pasquill stability class, wind direction class (primarily to 16 compass points), and wind speed class (in six classes) has been determined for various periods of record for over 200 observation stations in the United States from either hourly or 3-hourly data. A computer program called STAR (STability ARray) estimates the Pasquill class from the elevation of the sun (approximated from the hour and time of year), wind speed, cloud cover, and ceiling height. STAR output for seasons and the entire period of record can be obtained from the Center. Table 23.2 is similar in format to the standard output. This table gives the frequencies for D stability, based on a total of 100 for all stabilities.

Additional tables are furnished for the other stability classes. Note that calms have been distributed among the directions. Such joint frequency data can be used directly in climatological models such as the climatological dispersion model (CDM) [1]. The CDM calculates seasonal or annual concentrations at each receptor by considering sources in each wind sector (1/16 of the compass), performing a calculation for each wind speed–stability combination occurring for that sector, and weighting the calculation by the frequency for this combination. For annual concentrations, this saves a considerable number of calculations compared with simulating the period hour by hour.

TABLE 23.2

Relative Frequency of Winds for D Stability (O'Hare Airport, Chicago, 1965–1969)

Direction	Speed (knots)						Total
	0–3	4–6	7–10	11–16	17–21	>21	
N	0.0885	0.7123	1.3492	1.2670	0.1301	0.0411	3.5882
NNE	0.0646	0.5342	1.0547	1.1712	0.2123	0.0959	3.1328
NE	0.0605	0.4589	1.3972	1.0958	0.0959	0.0411	3.1494
ENE	0.0258	0.2123	0.9246	0.7260	0.0616	0.0068	1.9571
E	0.0521	0.3013	0.9109	0.8972	0.0342	0.0068	2.2027
ESE	0.0847	0.5068	0.9109	0.4794	0.0205	0.0068	2.0093
SE	0.0829	0.4726	0.6575	0.3150	0.0137	—	1.5417
SSE	0.0714	0.5274	0.9383	0.5890	0.0616	—	2.1877
S	0.1818	1.1095	2.7190	2.4245	0.2534	0.0479	6.7361
SSW	0.1495	0.7739	1.8423	2.2670	0.2397	0.0548	5.3272
SW	0.0985	0.6301	1.5889	1.4520	0.1781	0.0342	3.9818
WSW	0.1368	0.6712	1.2328	1.1712	0.2603	0.0822	3.5544
W	0.2485	1.0068	1.7191	2.0273	0.3698	0.0753	5.4467
WNW	0.1477	0.7397	1.4109	1.4794	0.2534	0.0274	4.0584
NW	0.1292	0.6643	1.3013	0.9999	0.0753	0.0068	3.1769
NNW	0.0349	0.3835	0.9109	1.0205	0.1781	0.0274	2.5553
Total	1.6574	9.7048	20.8684	19.3822	2.4382	0.5548	54.6058
Relative frequency of occurrence of D stability ^a							
Relative frequency of calms distributed above with D stability = 0.5753							

^a Total frequency of all stability classes is 100.

Mixing heights for each day can be calculated from the radiosonde data. Such data for a 5-year period of record, 1960–1964, were calculated and used in a study by Holzworth [2]. Figure 23.2 shows the mean annual afternoon mixing height variation across the contiguous United States.

II. REPRESENTATIVENESS

The term *representativeness* in air pollution meteorology usually means the extent to which a particular parameter is measured by instrumentation sited in such a way and with sensitivity and accuracy such that it is useful for the designated purpose. For normal climatological purposes, wind measurements are made at locations relatively free from observation; thus, they are not influenced in different ways by winds coming from different directions and consequently present an unbiased record. A parameter such as wind, which varies with height above ground, must have the height of the measurement reported along with the data.

The use of a measurement generally dictates the circumstances of data collection. For example, to provide a best estimate of plume transport direction,

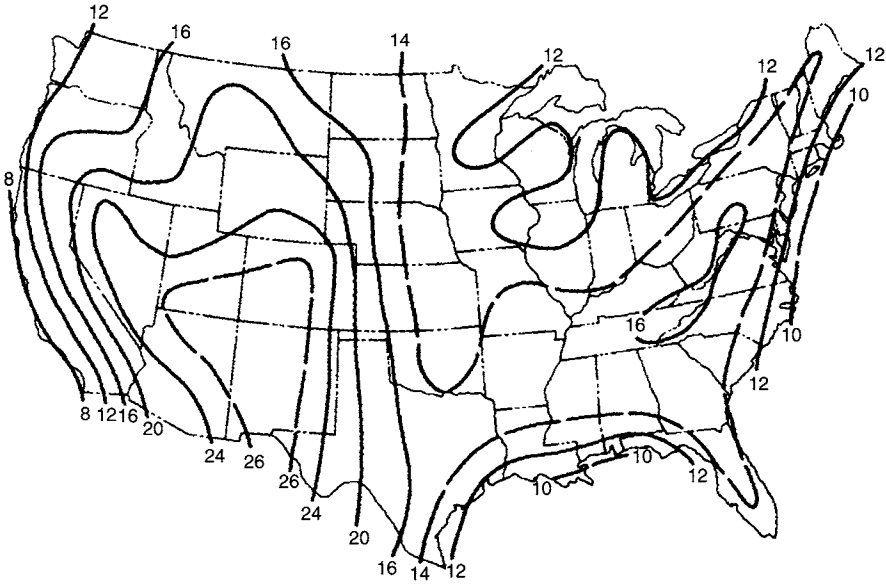


Fig. 23.2. Mean annual afternoon mixing height, in hundreds of meters. *Source:* Adapted from Holzworth [2].

hour by hour, of a release from a 75-m stack, a wind vane at the 100-m level of a tower will probably provide more representative wind direction measurements than a vane at 10 m above ground. If the release has buoyancy so that it rises appreciably before leveling off, even the 100-m measurement may not be totally adequate.

If one is studying the transport of material through the tree canopy of a forest, it is most desirable to disturb the natural environment as little as possible in making a wind measurement in the canopy. An extremely sensitive wind system is necessary because one would expect the winds to be extremely light. Also, it may be necessary to make supporting measurements both above and below the canopy, so that a wind speed profile is obtained.

Frequently, it is necessary to determine whether a record made at one location can be used to infer values of a particular parameter at another location. Many factors help to determine whether one location's measurements of a parameter are similar to those made at another location, such as the parameter in question, distance between sites, intervening topography, local topography, surface roughness, local vegetative cover, and the height above ground of the measurement. Generally, no measurements are made at both sites to check for comparability; if there were, there would be little need to use measurements at one site as a substitute for those at the other.

The foregoing factors are not independent. Two sites 50 km apart in Kansas, a state with large expanses of quite flat terrain largely planted in field crops, may be much more representative of one another than two sites

5 km apart in more rugged mountainous, wooded terrain, e.g. in the western part of North Carolina.

Data for one full year (1964) for Nashville, Tennessee, and Knoxville, Tennessee, 265 km (165 miles) apart, were compared to determine the extent to which the frequencies of various parameters were similar. Knoxville is located in an area with mountainous ridges oriented southwest-northeast; Nashville is situated in a comparatively flat area. The data available are the number of hours during which each of 36 wind directions (every 10° azimuth) occurred, the average wind speed for each direction, the number of hours of each Pasquill stability class for each direction, and the mean annual wind speed.

Table 23.3 indicates that average wind speeds are lower in Knoxville, where the average wind is 0.86 of that at Nashville. Considering the difference in topography, it is surprising that the difference is not greater. The percentage of calms, slightly greater at Knoxville, is entirely consistent with the wind speeds.

Because of the slight difference in average wind speed, one might expect this to cause a greater frequency of both stable and unstable conditions at Knoxville compared to Nashville. The stability comparisons are given in Table 23.4. The frequencies are very nearly the same, with only A and B stabilities being slightly greater at Knoxville at the expense of the D stability. Stability G is more stable than Pasquill's F.

TABLE 23.3

Average Wind Speed and Frequency of Calms

	Nashville	Knoxville
Average wind speed	3.79 m s ⁻¹	3.26 m s ⁻¹
Percentage of calms	9.21	9.77

TABLE 23.4

Occurrence of Pasquill Stability Classes

Stability class	Nashville		Knoxville	
	Percent	Cumulative	Percent	Cumulative
(G)	7.64	7.64	7.35	7.35
F	14.15	21.79	15.57	22.92
E	14.18	35.97	14.67	37.59
D	45.14	81.11	41.42	79.01
C	12.37	93.48	12.32	91.33
B	5.75	99.23	7.21	98.54
A	0.77	100.00	1.46	100.00

The maximum number of hours of each stability class in a single wind direction is given in Table 23.5. The total hours for A, C, and D stabilities are nearly the same. The maximum number of hours of B stability, with winds from a single direction, is about 50% higher at Knoxville. For all three stable cases, E, F, and (G), the maximum number of hours at Knoxville is about two-thirds that at Nashville.

The frequency of occurrence of winds from each of the 36 directions for the two sites is given in the second and third columns of Table 23.6. Knoxville has its maximum from 240°, with frequent winds also from adjacent points. There is a secondary maximum across the compass (in the vicinity of 60°). Nashville, on the other hand, seems to have only one principal maximum (from 180°). To explore the magnitude of the differences, the fourth column is the difference for each direction. Summing the absolute values of the differences and expressing them as a percentage of the total number of hours of observations shows that the differences constitute 62% of the total.

It is noted that backing the Knoxville frequencies by 60° would result in the maxima occurring together. This is tabulated in the fifth column of Table 23.6. The difference between Nashville and this artificial frequency is then obtained (the sixth column). The sum of the absolute values of the differences expressed as a percentage of the total is 30.2; the differences have been reduced by more than half. This does *not* prove that the frequencies are similar except that the winds at Knoxville are channeled by the major topographical features in the vicinity, but it does imply that this is an explanation.

Certainly the directional frequencies of these sites cannot be considered as representative of each other. However, this comparison would seem to indicate that the percentage of the stability categories may be more conservative over distance than the direction frequencies.

TABLE 23.5

Maximum Hours of Each Stability in One Direction

Stability	Nashville			Knoxville		
	Number of hours	Total for direction	Direction	Number of hours	Total for direction	Direction
A	7	184	22	8	{ 220 364	{ 12 20
B	25	252	16	38	616	6
C	79	736	36	81	616	6
D	324	736	36	332	616	6
E	123	736	36	82	431	22
F	118	736	36	79	342	25
(G)	66	736	36	45	174	31

TABLE 23.6

Number of Hours of Wind from Each Direction (Calms Are Distributed)

Direction (tens of degrees)	Hours from this direction		Nashville– Knoxville	Knoxville backed 60°	Nashville– Knoxville backed 60°
	Nashville	Knoxville			
1	140	279	–139	342	–202
2	201	364	–163	204	–3
3	158	295	–137	213	–55
4	184	431	–247	119	65
5	138	413	–275	104	34
6	165	426	–261	158	7
7	187	342	–155	174	13
8	134 ^a	204	–70	157	–23
9	202	213	–11	81	121
10	146	119	27	86	60
11	167	104	63	67	100
12	170	158	12	137	33
13	155	174	–19	110	45
14	262	157	105	152	110
15	245	81	164	212	33
16	527	86	441	389	138
17	478	67 ^a	411	410	68
18	736 ^b	137	599	616	120
19	348	110	238	442	–94
20	303	152	151	302	1
21	226	212	14	343	–117
22	283	389	–106	209	74
23	243	410	–167	240	3
24	257	616 ^b	–359	220	37
25	195	442	–247	174	21
26	182	302	–120	129	53
27	215	343	–128	129	86
28	174	209	–35	181	–7
29	231	240	–9	187	44
30	231	220	11	289	–58
31	338	174	164	279	59
32	300	129	171	364	–64
33	212	129	83	295	–83
34	252	181	71	431	–179
35	157	187	–30	413	–256
36	242	289	–47	426	–184
	8784	8784	Sum		Sum
			absolute		absolute
			5450 =		2650 =
			62.0%		30.2%

^a Minimum.

^b Maximum.

III. FREQUENCY OF ATMOSPHERIC STAGNATIONS

At times when the surface pressure gradient is weak, resulting in light winds in the atmosphere's lowest layers, and there is a closed high-pressure system aloft, there is potential for the buildup of air pollutant concentrations. This is especially true if the system is slow-moving so that light winds remain in the same vicinity for several days. With light winds there will be little dilution of pollutants at the source and not much advection of the polluted air away from source areas.

Korshover [3] studied stagnating anticyclones in the eastern United States over two periods totaling 30 years. He found that for stagnation to occur for 4 days or longer, the high-pressure system had to have a warm core. Korshover's criteria included a wind speed of 15 knots or less, no frontal areas of precipitation, and persistence of these conditions for 4 or more days.

The numbers of occurrences of 4 days or more over the 30-year period (1936–1965) peak in October and September and reach a minimum in February and March. The total number of stagnation days for each part of the study area is shown in Fig. 23.3.

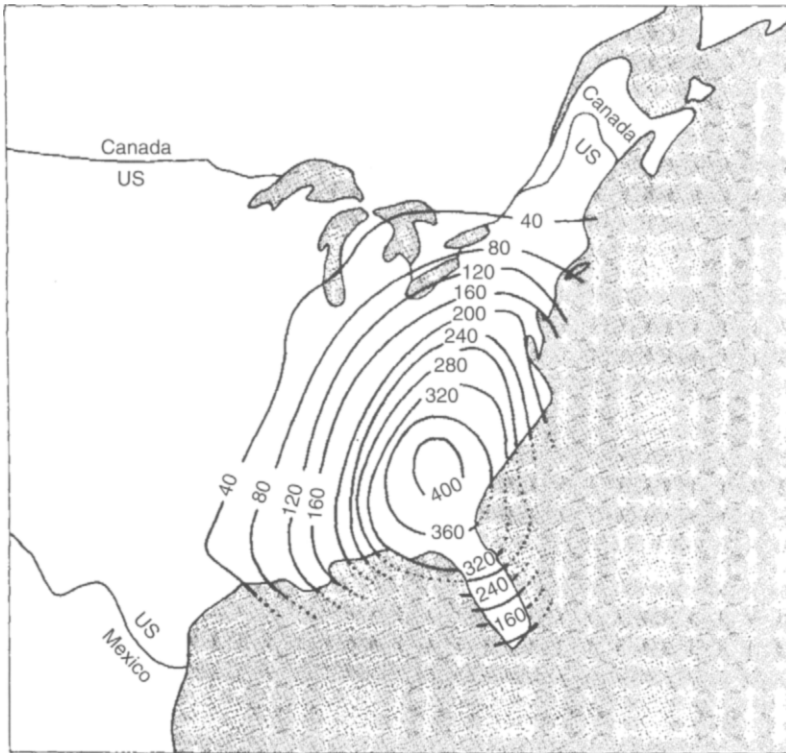


Fig. 23.3. Total number of extreme stagnation days during 1936–1965 east of the Rocky Mountains. Source: Korshover [3].

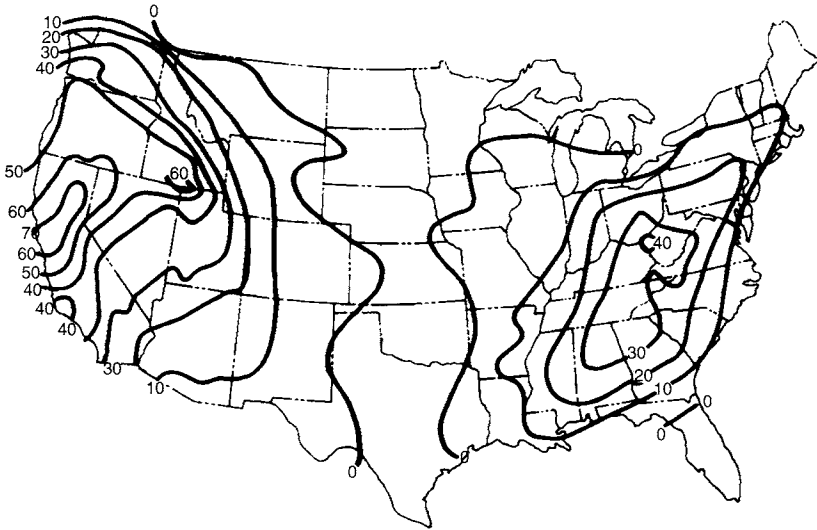


Fig. 23.4. Number of forecast days of high air pollution potential per 5 years (1960–1964). *Source:* Adapted from Holzworth [2].

Using criteria of mixing heights of 1500 m or less, with average speed through the mixing height of 4 m s^{-1} or less, no precipitation, and persistence of these conditions for at least 2 days, Holzworth [2] tabulated high air pollution potential for the contiguous United States expressed as the number of days per 5 years (1960–1964) (Fig. 23.4). The pattern over the eastern United States is very similar to that of Korshover. It also shows no occurrences through the central plains. The number of days in the West exceed those in the East, with the maximum in central California.

IV. VENTILATION CLIMATOLOGY

Hosler [4], through study of radiosonde data for the lowest 500 ft at over 70 locations in the United States, determined inversion frequencies. The values were used to draw isolines of inversion frequency percentages on US maps for annual values and the four seasons. The percent of total hours of inversions for the annual period is shown in Fig. 23.5. Conditions frequently associated with radiation inversions—light winds and slight cloud cover at night—were also examined in terms of frequency. Both display maxima over the desert Southwest.

The study by Holzworth [2] also examined several other parameters in addition to mixing height. For example, because pollutants are diluted by the wind and mixing height limits the vertical dispersion of pollutants, Holzworth used the radiosonde data to determine the average wind speed through the mixing height for each season and annually. Figure 23.6 shows the distribution of mean annual wind speed averaged through the afternoon mixing layer.

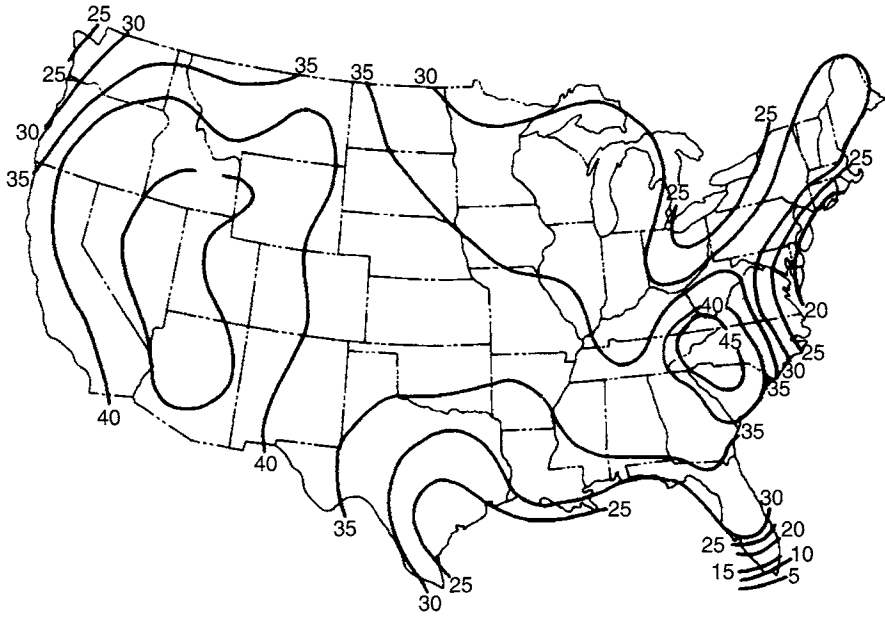


Fig. 23.5. Annual inversion frequency, percent of total hours. Source: Adapted from Hosler [4].

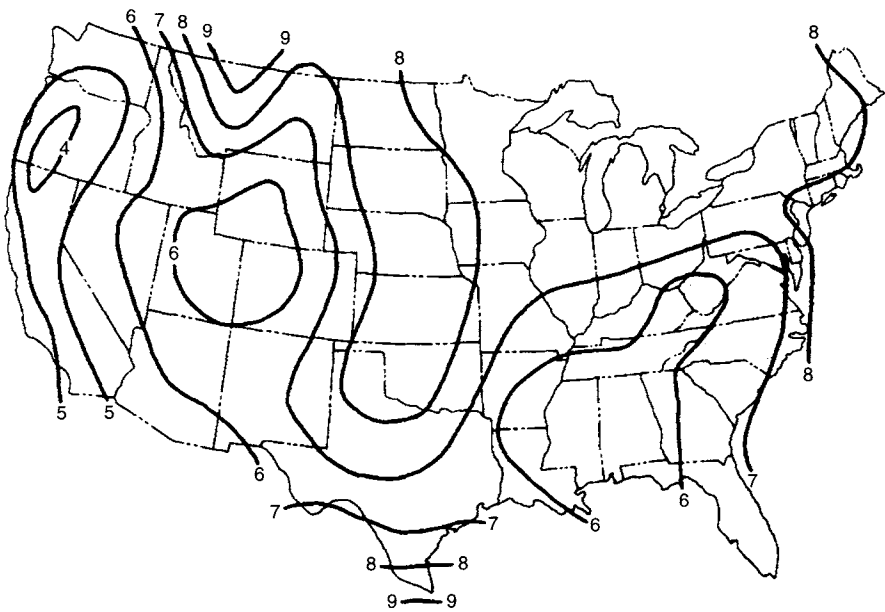


Fig. 23.6. Mean annual wind speed averaged through the afternoon mixing layer. Speeds are in meters per second. Source: Adapted from Holzworth [2].

Using the urban model of Miller and Holzworth [5], which requires wind speed and mixing height, Holzworth [2] used the mixing height and wind speed data to calculate concentrations for the median, upper quartile, and upper decile for hypothetical alongwind city lengths of 10 and 100 km. Results for the upper decile for the 10-km city for both the morning and the afternoon are shown in Fig. 23.7.

Another climatological study is of interest. Radiosonde observations for the 5-year period 1960–1964, used previously [2], were analyzed by Holzworth [6] to determine plume rise through the atmosphere's structure for two different stack heights, 50 and 400 m. This encompasses the range of stack heights normally encountered. The annual average effective height for the morning radiosonde ranged from less than 150 to 200 m for 50-m stacks and from less than 650 to greater than 750 m for 400-m stacks. The frequency of effective heights from 400-m stacks of the morning radiosonde that are exceeded by the afternoon mixing heights ranges from 50% to 60% near coastlines and from 70 to more than 90% throughout the rest of the contiguous United States.

Taylor and Marsh [7] investigated the long-term characteristics of temperature inversions and mixed layers in the lower atmosphere to produce an inversion climatology for the Los Angeles basin. In this area, the cooler ocean currents produce an elevated inversion that is nearly always present

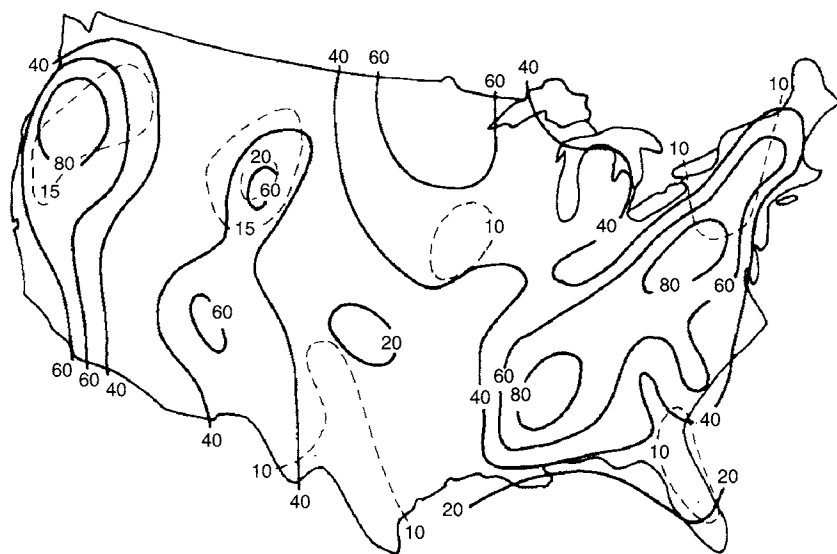


Fig. 23.7. Relative concentration in seconds per meter (s m^{-1}) exceeded in a 10-km city on 10% of all mornings (solid lines) and 10% of all afternoons (dashed lines). Source: After Holzworth [2].

and traps the pollutants released over the area within a layer seldom deeper than 1200 m and frequently much shallower.

V. WIND AND POLLUTION ROSES

Since wind is circular, it is frequently easier to interpret and visualize the frequency of wind flow subjectively by displaying a wind rose, that is, wind frequencies for each direction oriented according to the azimuth for that direction. Figure 23.8 is a wind rose showing both directional frequencies and wind speed frequencies by six classes from 3-hourly observations for a 5-year period (1965–1969) for O’Hare Airport, Chicago. The highest frequencies are from the south and west, the lowest from the southeast and east.

Figure 23.9 is a stability wind rose that indicates Pasquill stability class frequencies for each direction. For this location, the various stabilities seem to be nearly a set proportion of the frequency for that direction; the larger the total frequency for that direction, the greater the frequency for each stability.

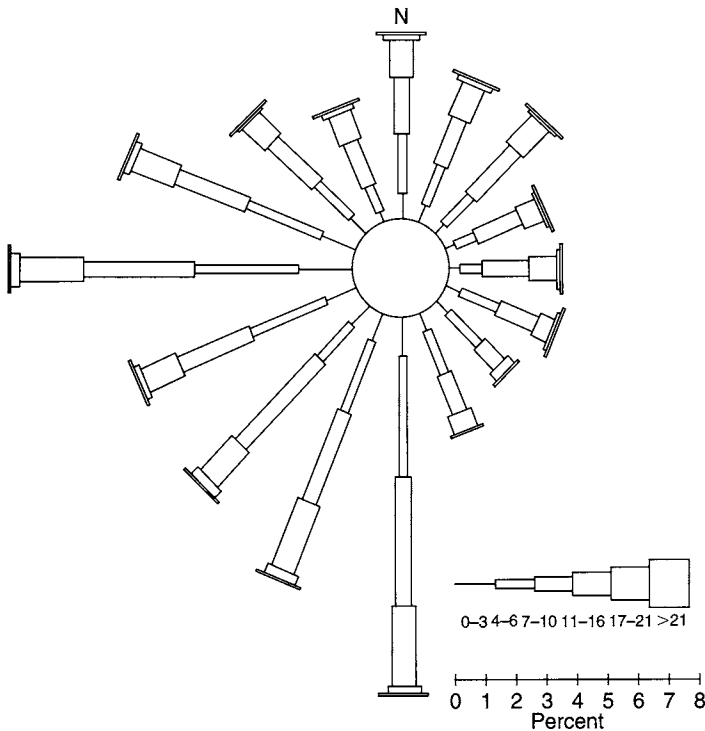


Fig. 23.8. Wind rose (direction–speed) for O’Hare Airport, Chicago, 1965–1969.

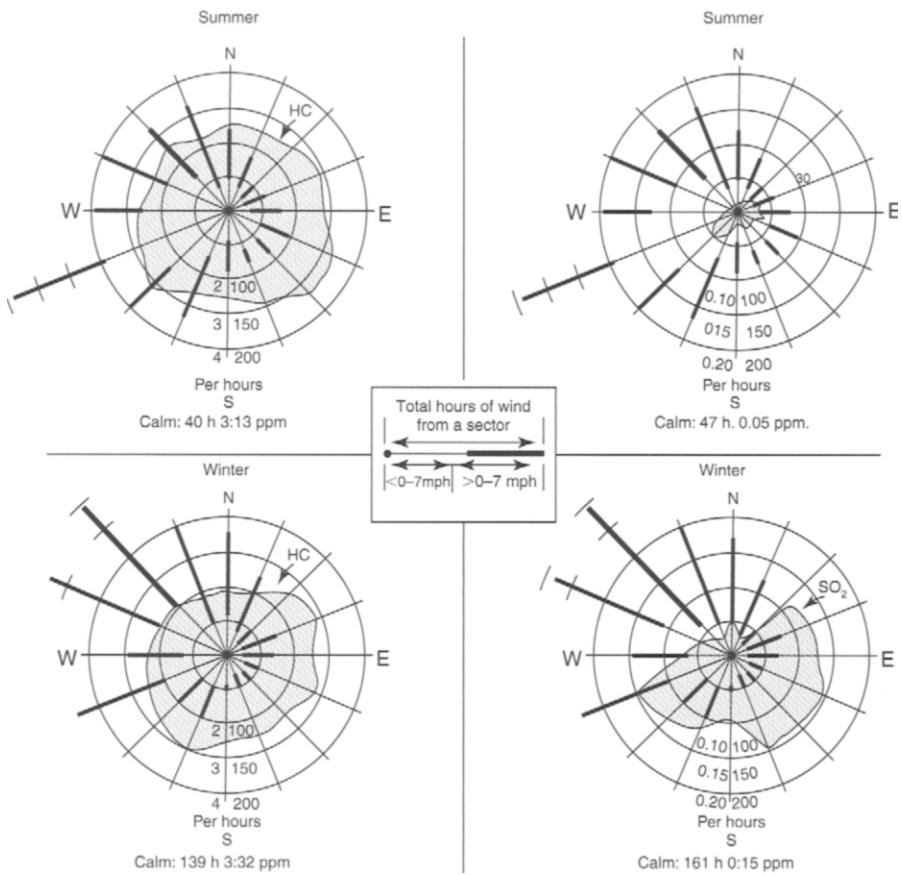


Fig. 23.10. Average concentrations of hydrocarbons and sulfur dioxide for each wind direction and wind direction frequency in two classes ($0-7$ miles h^{-1} and greater than 7 miles h^{-1}), Philadelphia, 1963. Source: US Department of Health, Education and Welfare [8].

The behavior of these pollution roses is intuitively plausible, because considerable hydrocarbon emissions come from motor vehicles which are operated in both winter and summer and travel throughout the urban area. On the other hand, sulfur dioxide is released largely from the burning of coal and fuel oil. Space heating emissions are high in winter and low in summer. The SO_2 emissions in summer are probably due to only a few point sources, such as power plants, and result in low average concentrations from each direction as well as large directional variability.

Concentrations resulting from dispersion models can also be depicted using a form of pollution rose. Figure 23.11 is a concentration rose for a measurement station in New York City for the SO_2 concentration estimates

from the CDM [1]. The number in the circle is the total estimated annual SO_2 concentration from the model. The radial values represent the contribution to the annual concentration from each direction, with the length of the line proportional to the concentration resulting from area sources and the length of the rectangle proportional to the concentration resulting from the point sources. For the monitoring station in Fig. 23.11, the estimated annual concentration is $240 \mu\text{g m}^{-3}$. The maximum annual contribution from area sources is from the south ($39 \mu\text{g m}^{-3}$); the maximum annual contribution from point sources is from the southwest ($7.1 \mu\text{g m}^{-3}$). The minimum concentration is from the east-southeast.

An example of frequencies of wind direction when the concentration exceeds a particular value is shown in Fig. 23.12. For this example, the concentration threshold is 0.1 ppm ($262 \mu\text{g m}^{-3}$). Although the maximum frequency from any one direction is only about 1%, this can be significant. Munn [9] is careful to point out that "The diagram suggests but, of course, does not prove that a major source of SO_2 is situated between the sampling stations" (p. 109).

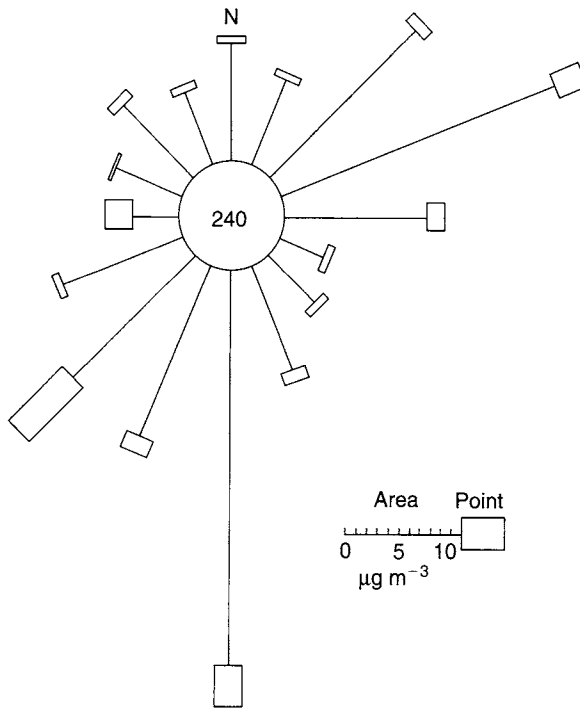


Fig. 23.11. Contributions to the annual sulfur dioxide concentration from each direction at a receptor in New York by area sources (lines) and point sources (rectangles) for 1969 using the CDM.

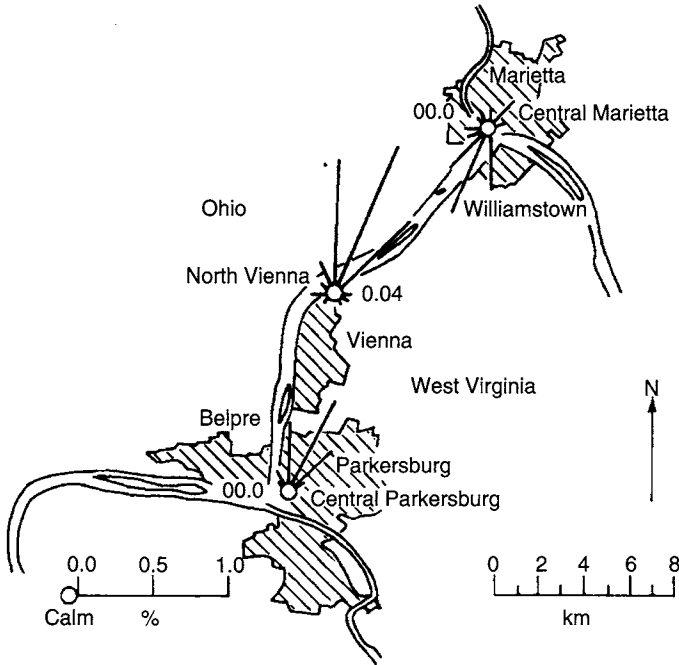


Fig. 23.12. Frequency of wind direction when sulfur dioxide exceeds 0.1 ppm near Parkersburg, West Virginia. Source: Munn [9].

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QUESTIONS

1. What geographical or climatological conditions seem to be associated with the lowest mean annual mixing heights shown in Fig. 23.2? With the highest mixing heights?
2. In attempting to determine the air pollution impact of a small town containing several industrial facilities in a mountainous river valley about 1 km wide with sloping sides extending 400–500 m above the river, what meteorological measurement program would you recommend and what facts would you try to determine before finalizing your recommendation?
3. Over relatively flat terrain, which of the following measurements would be expected to represent conditions most closely at a second site 10 km away: wind velocity or total amount of cloud?
4. What areas of the contiguous United States have the least air pollution potential as defined by mixing heights of less than 1500 m with wind speeds of less than 4 m s^{-1} through the mixing height? Which areas have the greatest air pollution potential?
5. What is the variation in relative concentration exceeded 10% of the time in a 10-km city over the contiguous United States for mornings? For afternoons?
6. From Fig. 23.10, what wind directions are related to highest average winter sulfur dioxide concentrations at this sampling station?
7. If one considers a contribution to the annual concentration from point sources as significant when it exceeds $2 \mu\text{g m}^{-3}$, using Fig. 23.11, what wind directions account for significant point source contributions at this station?