Mixing Depths, Wind Speeds and Air Pollution Potential for Selected Locations in the United States[1]

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ABSTRACT

Daily estimates of morning and afternoon mixing depths and average wind speeds through the mixing layers were calculated and summarized for seven locations in several climatic regions of the contiguous United States. Mixing depth and wind speed estimates were based on regular surface (airways) and upper air (rawinsonde) observations of the Weather Bureau and on the assumption of a dry-adiabatic lapse rate in the mixing layer. Monthly averages of morning and afternoon mixing depth and wind speed are presented graphically. The frequency of occurrence of various combinations of mixing depth and wind speed classes were used in an urban diffusion model to calculate theoretical values of relative pollutant concentration for four major cities. These relative pollutant concentrations, which also depend upon city size, are compared among the cities on the bases of their current sizes and a common size.

1. Introduction

Meteorologists at the National Center for Air Pollution Control are developing a quantitative air pollution potential climatology for the contiguous 48 states. Two parameters considered basic to this climatology are 1) the depth above the surface through which pollutants are mixed vigorously, and 2) the average wind speed through the mixing layer. Typically, these parameters undergo significant seasonal and diurnal variations, with values highest in the afternoon and lowest in the morning.

For community air pollution considerations, primary interest is in mixing depths and wind speeds over urban areas; usually, however, meteorological observations are made only at airports in rural or suburban surroundings. Since, in many respects, cities create their own climates (Kratzer, 1956; Landsberg, 1956), especially at night, there are problems in estimating meteorological conditions over cites on the basis of observations made in rural areas.

The mixing-depth concept is based upon the principle that heat transferred to the atmosphere at the earth's surface results in convection, vigorous vertical mixing, and establishment of a dry-adiabatic lapse rate. The depth through which such mixing extends depends primarily upon the initial vertical temperature structure and the heat input at the surface. Neglecting temperature advection, afternoon mixing depths were calculated from temperatures aloft observed at 1200 GMT and maximum surface temperatures observed from 1200 to 1600 local standard (LST).

Afternoon mixing depths in urban and nearby rural areas usually do not differ significantly; however, the differences between nocturnal mixing depths in urban and rural areas are often highly significant. For example, on a clear calm night with an inversion at the surface in a rural area, vertical mixing in the inversion layer cannot be described for the purposes of this study as anything like vigorous; in fact, vertical mixing is practically nonexistent. In such a case there is no mixing layer as defined here. On the other hand, in a nearby city the effect of the nocturnal urban "heat island" (Mitchell, 1962) is to *create* a mixing layer (Duckworth and Sandberg, 1954; DeMarrais, 1961; Summers, 1967).

Since upper-air soundings are made at 1200 GMT, which is near sunup in the United States, morning mixing depths over an urban area were estimated for the time interval of the morning "rush" hours. Additional reasons for selecting this time were that pollutant emission rates and concentrations of nonreactive pollutants both are usually greatest around morning rush hours. A value for the morning urban mixing depth was calculated by adding 5C to the minimum airport surface temperature observed from 0200 to 0600 LST and assuming a dry-adiabatic lapse rate to the intersection of the observed 1200 GMT temperature sounding. Urban-rural minimum temperature differences vary considerably and appear to depend at least in part upon city size, topography, state of ground, wind speed and direction, sky condition, etc. Based on some comparisons of urban-rural minimum temperature differences, an overall average value of 5C may be

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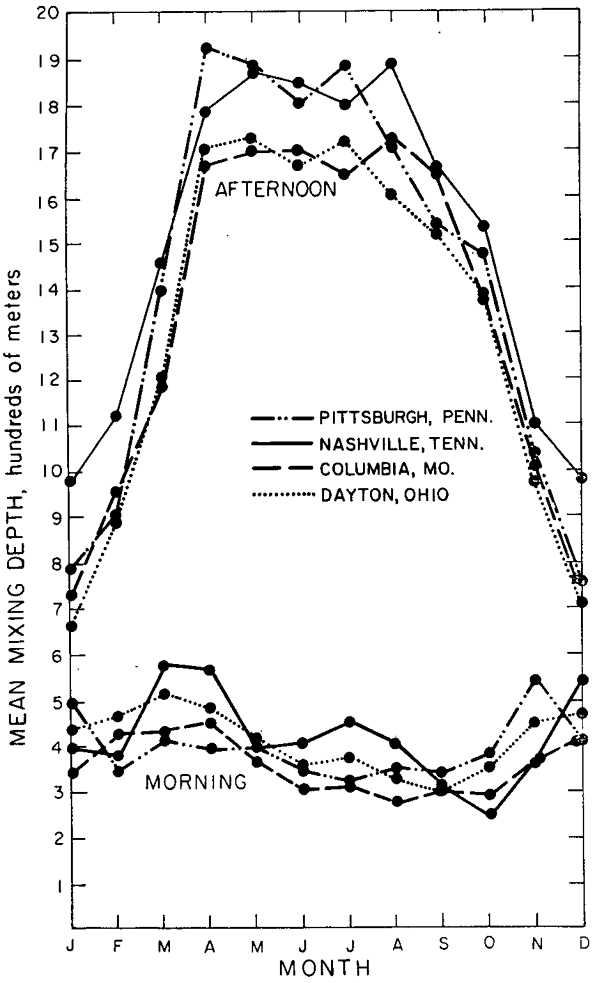

FIG. 1. Monthly mean mixing depths at Pittsburgh, Pa.; Nashville, Tenn.; Columbia, Mo.; and Dayton, Ohio: 1960–1964.

somewhat excessive, even for large cities. The "+5C" factor was established arbitrarily to allow for urban-rural differences in morning surface temperature *and* for some solar heating of the surface after sunrise. Admittedly, daily calculations of urban morning mixing depth are rough estimates, but they are considered adequate for the climatological purposes of this paper.

The other parameter considered important in this study was the wind speed averaged vertically through the mixing depth. This value was calculated as a simple arithmetic average of wind speeds aloft and at the surface. The levels of winds aloft were 150 and 300 m above station elevation, 500, 1000, 1500, 2000, 2500, 3000, 4000 m, etc., above MSL. To insure that wind speeds near the same level were used only once, the third reported level was not used if it was within 150 m of the first two reported levels. Calculations of morning values were based on speeds aloft at 1200 GMT and average speeds at the surface from 0200 to 0600 LST. Afternoon average speeds were based on winds aloft at 0000 GMT and average surface speeds from 1200 to 1600 LST.

If precipitation occurred during specified 12-hr periods that included a morning or afternoon mixing depth computation, those cases were not included in the present study because of the assumption of a dry-adiabatic lapse rate in the mixing layer. Non-precipitation cases accounted for about 80% of all cases. For the main purpose of the present study, the climatology of air pollution potential, the non-precipitation data are considered to be adequately representative of all cases. All data presented in this paper are for the 5 years 1960–1964.

2. Mixing depths[3]

Fig. 1 shows monthly mean mixing depths for morning and afternoon, calculated for Pittsburgh, Nashville, Columbia and Dayton. These data are plotted together because of their similarity. Among the four stations mean afternoon mixing depths differ by less than 300 m in most months; mean morning mixing depths differ by less than 200 m in all months.

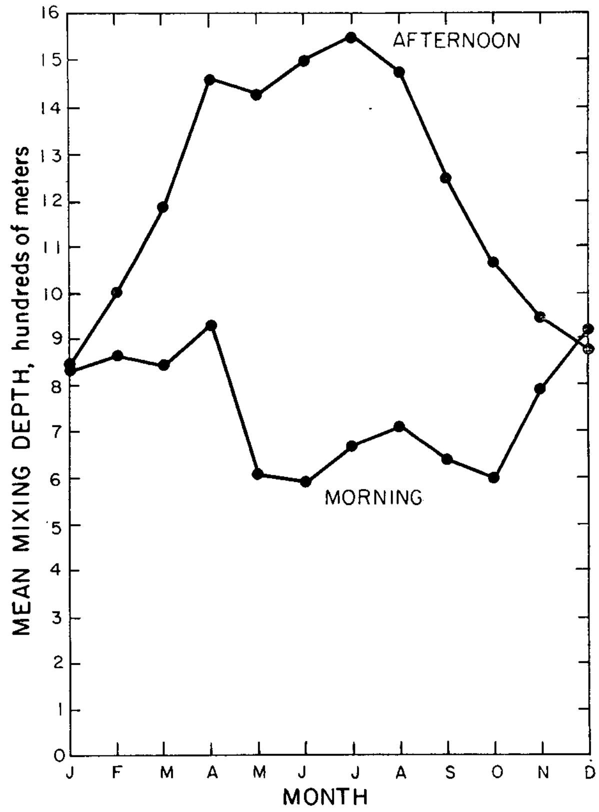

FIG. 2. Monthly mean mixing depths at New York: 1960–1964.

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[3] Previous estimates of monthly mean afternoon mixing depths in the United States have been given by Holzworth (1964). Since the estimates of 1964 were based upon less detailed data than in the current study, the latter are considered more reliable. Climatological data on morning (or nocturnal) mixing depths over urban areas are unknown, but a study by Hosler (1961) has shown a high frequency of low-level inversions at night and early morning at most rawinsonde stations in the United States.

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Values for afternoon mixing depths show large variations during the year. They are deepest, about 1650–1900 m, during April through August, and shallowest, about 700–1000 m, in December and January, with rapid changes in transition months. Values for morning mixing depths vary throughout the year at most of these locations by only about 200 m; in general, maxima occur in March and April and minima occur from July through October.

At New York (Fig. 2) afternoon mixing depths are much like those in Fig. 1, except that from April through October the depths are a few hundred meters shallower at New York. The main feature that distinguishes New York from the locations in Fig. 1 is that morning mixing depths are several hundred meters deeper in New York. The cause of this phenomenon has not been found but it is believed to be due to influences of nearby water masses and perhaps the urban heat island.

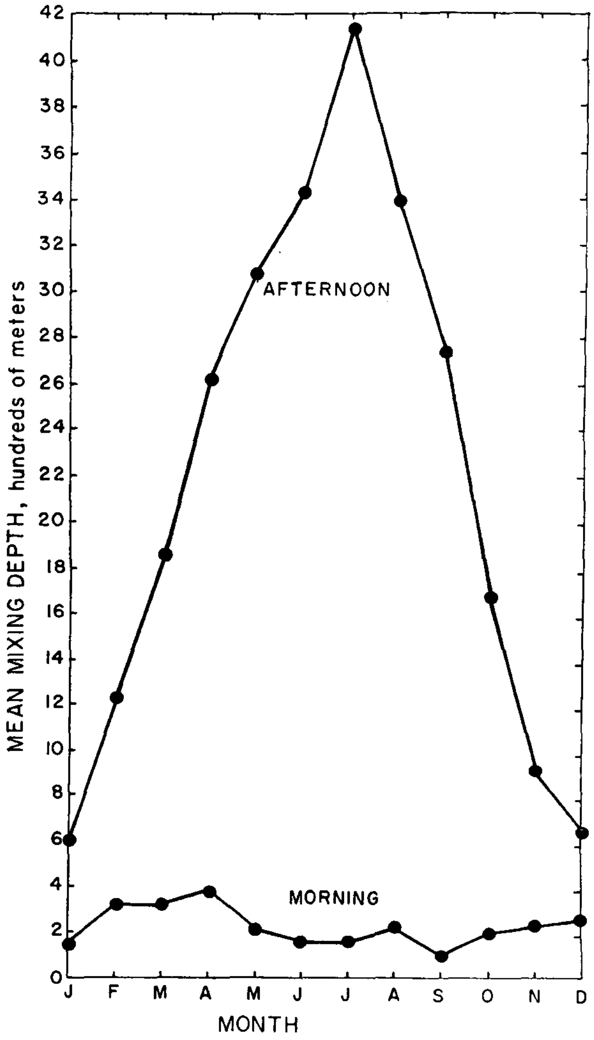

FIG. 3. Monthly mean mixing depths at Salt Lake City, Utah: 1960–1964.

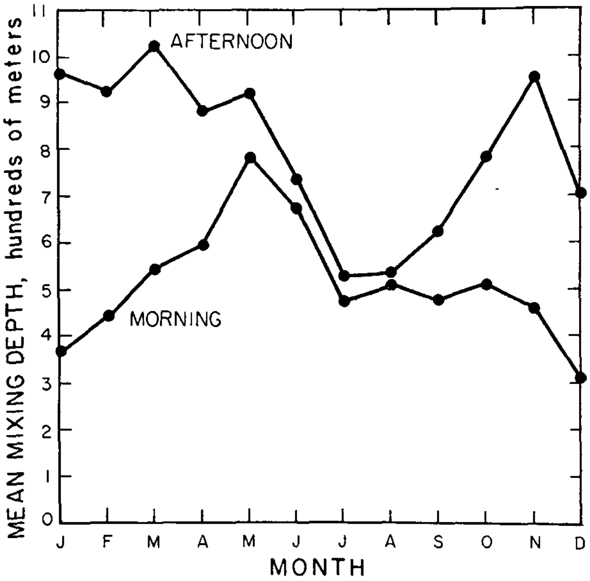

FIG. 4. Monthly mean mixing depths at Los Angeles, Calif.: 1960–1964.

Fig. 3 shows mean mixing depths at Salt Lake City. These morning and afternoon curves differ markedly from those for any of the other stations in this study. In particular, afternoon mixing depths at Salt Lake City change significantly from month to month, varying from 600 m in January to 4150 m in July. Relative to curves for other locations, the afternoon curve indicates an almost continuous transition state.

Morning mixing depths at Salt Lake City differ from those at other locations in being shallower; they vary from only 130 to 400 m, being deepest from February through April. The fact that morning mixing depths are so shallow attests to the frequent occurrence of intense radiation inversions, e.g., as shown by Hosler (1961).

Fig. 4 shows mean mixing depths for Los Angeles; these morning and afternoon curves are distinctly different from those for any of the other six stations. Afternoon depths are shallowest from July through September and deepest from January through May and in November. The annual range of monthly mean afternoon values, however, is only about 500 m. Morning mixing depths, on the other hand, are distinguished by a comparatively large range between monthly extremes, from 310 m in December to 785 m in May. The rather small differences between morning and afternoon mixing depths from May through September also consititue a unique feature of the Los Angeles data.

3. Wind speeds

Average wind speeds through morning and afternoon mixing depths (hereafter referred to as wind speeds) are shown in Fig. 5 for Pittsburgh, Nashville, Dayton

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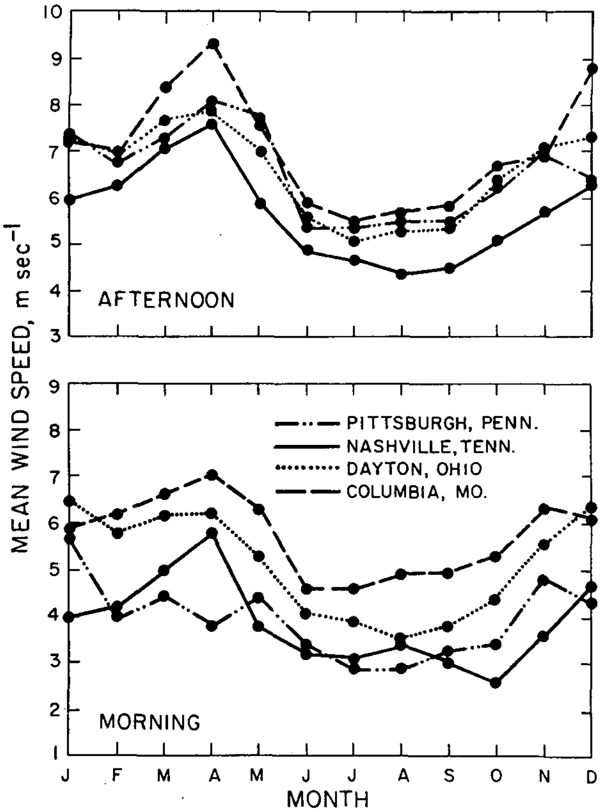

FIG. 5. Monthly mean values of the average wind speed through the mixing layer at Pittsburgh, Pa.; Nashville, Tenn.; Columbia, Mo.; and Dayton, Ohio: 1960–1964.

and Columbia. Data for these stations are fairly similar, especially in the afternoon. Except for extremes, afternoon speeds range from about 4½ to 8 m sec^{-1} and morning speeds range from about 3 to 6½ m sec^{-1}. Like mixing depths, wind speeds are greater in afternoons than in mornings. Annual variations in the morning and afternoon curves are similar; generally, faster speeds occur from November through April and slower speeds from June through October.

The wind speed data for New York, shown in Fig. 6, display an annual variation that is quite similar to that shown for the four stations in Fig. 5, except that speeds at New York are somewhat faster than at the other locations.

At Salt Lake City (Fig. 6) afternoon speeds vary regularly between 3.5 m sec^{-1} in January and 6.3 m sec^{-1} in May. Morning speeds vary rather irregularly during the year, with extremes of 3.1 m sec^{-1} in January and 5.1 m sec^{-1} in April. In general, the annual variation of wind speed at Salt Lake City is quite different from that for New York and other locations to the east.

Fig. 6 also shows wind speeds for Los Angeles; for afternoons these values are similar to those for Salt Lake City, except that speeds in Los Angeles in summer are somewhat slower. Morning values at Los Angeles are characterized by extraordinarily slow speeds, ranging from only about 2 m sec^{-1} from June through October to near 3 m sec^{-1} from January through April.

4. Air pollution potential

Up to this point it has been shown that mean mixing depths and wind speeds vary more or less from place to place, from month to month, and from morning to afternoon. In addition, there are often significant variations from day to day. These parameters, mixing depth and wind speed, are potentially useful in various meteorological specialties. Although they have been recognized as highly important in appraising the meteorological potential for community air pollution, their combined effect has seldom been studied quantitatively. This can be accomplished now by application of an atmospheric diffusion model for metropolitan areas, a model recently tested against observed pollutant data with good results (Miller and Holzworth, 1967). In this model the relative pollutant concentration[4] averaged over an urban area is a function of the mixing depth, wind speed and physical size of the city. The model assumes that the pollutants are stable or non-

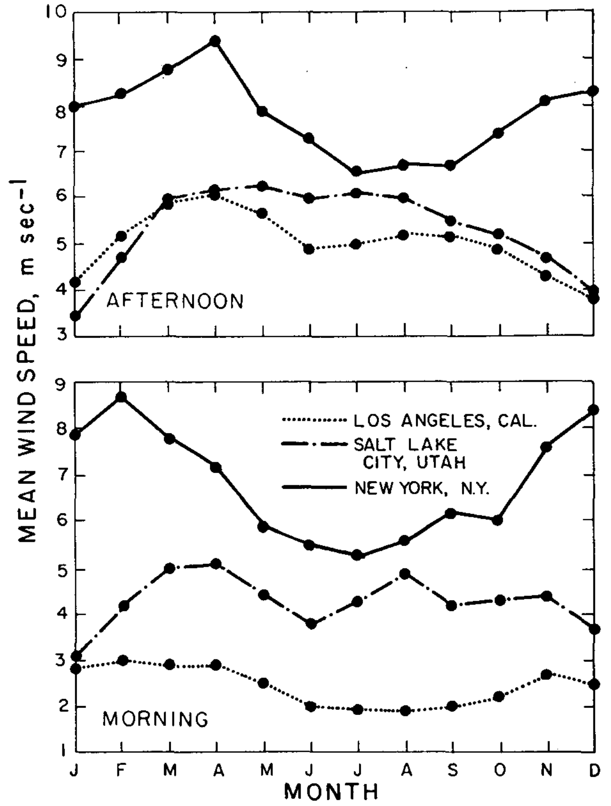

FIG. 6. Monthly mean values of the average wind speed through the mixing layer at New York; Salt Lake City, Utah; and Los Angeles, Calif.: 1960–1964.

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[4] Units of relative concentration, χ/Q_A, are sec m^{-1} since units of concentration χ are gm m^{-3} and those of area emission rate Q_A are gm m^{-2} sec^{-1}.

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TABLE 1. Theoretical relative concentrations (sec m^{-1}) averaged over each city area expected to be equalled or exceeded 10%, 50% and 90% of the time annually, based on current city sizes.

	Morning			Afternoon		
	10%	50%	90%	10%	50%	90%
Salt Lake City—16 km	43	23	15	16	11	10
St. Louis—32 km	70	23	15	16	12	10
New York—45 km	66	19	16	18	13	12
Los Angeles—60 km	206	55	25	35	18	14

reactive and diffuse vertically from a continuous series of cross-wind line sources until they reach the top of the mixing layer; thereafter, a uniform vertical distribution of pollutants is assumed. The total concentration at a receptor due to all cross-wind line sources located up-wind is the sum of concentrations from each line source and is determined by integration. Emission rates for each city are assumed uniform and, by integration, line sources are treated as area sources. Vertical diffusion coefficients appropriate for morning and afternoon mixing layers are specified arbitrarily. The model predicts that the average relative concentration will increase as mixing depth and wind speed decrease, and as city size increases. For small cities with deep mixing layers and, especially, with fast winds the average relative concentrations vary only slightly, due largely to the fact that by the times the pollutant plumes from the up-wind line sources diffuse to the top of the mixing layer they have been transported beyond the downwind edge of the city. For large cities with shallow mixing layers and slow winds, however, the average relative concentrations are highly sensitive to the values of mixing depth and wind speed. These results are in qualitative agreement with physical interpretations of atmospheric dispersion over urban areas.

Calculations of daily values (1960–1964) of morning and afternoon mixing depth and wind speed were used in the diffusion model to derive frequencies of relative concentrations for several cities. To reduce the number of calculations of relative concentration, the frequencies of various combinations of mixing depth and wind speed classes were obtained and the median value of each class was used in the diffusion model.

Fig. 7 shows the annual cumulative percent frequency of theoretical relative concentrations averaged over Los Angeles, whose size was assumed to be 60 km. City size was defined as the mean distance across the urban area. The figure shows clearly that high relative concentrations are expected more frequently in the morning than in the afternoon, reflecting the diurnal variation of mixing depths and wind speeds. At the low-frequency ends of the curves the highest relative concentrations, about 330 sec m^{-1} or greater, are expected on only about 0.1% of the afternoons but on about 5% of the mornings. Similarly, at the 50-percentile frequency the relative concentration for afternoons is 18 sec m^{-1}, while that for mornings is 55 sec m^{-1}.

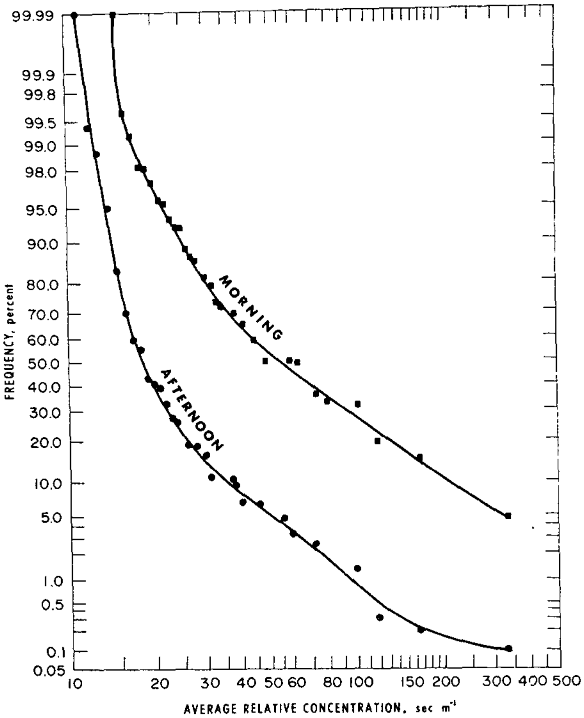

FIG. 7. Annual frequency of theoretical relative pollutant concentrations (averaged over the Los Angeles area) equal to or greater than abcissa values.

Curves like those in Fig. 7 for Los Angeles were also prepared for Salt Lake City, New York and St. Louis, the latter based on meteorological data at Columbia, Mo. Table 1 shows average relative concentrations expected to be exceeded 10, 50 and 90% of the time, based on current city sizes. Thus, at Salt Lake City, city size 16 km, an average relative concentration of 43 sec m^{-1} or greater is expected on 10% of the mornings. Although values in Table 1 may be compared among the different cities, it should be emphasized that these values represent theoretical concentrations *relative* to emission rates. Pollutant concentrations in each city will depend critically upon the *appropriate* emission rates. The only comparisons offered in this paper concern the dilution effects due to meteorological conditions and effects due to city size.

For current city sizes the highest relative concentrations for morning and afternoon at all percentiles occur at Los Angeles; these high concentrations are due in part to the large size of that city. Los Angeles values are especially high in the morning; e.g., at Los Angeles 206 sec m^{-1} or greater is expected on 10% of the mornings, while the next highest value at any of the locations is 70 sec m^{-1} at St. Louis. It is interesting that at the morning 10-percentile level, relative concentrations at St. Louis and New York are almost equal, although the size used for New York is almost half again as large as that for St. Louis. Similarly, in the morning at the 50- and 90-percentile frequencies, relative concentra-

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tions for Salt Lake City and St. Louis are equal although the city-size values differ by a factor of 2. In the afternoon at all percentiles the relative concentrations differ only slightly among the locations, except at Los Angeles, where they are highest.

It is interesting to consider what the relative concentrations would be like if the other cities were all the same size as Los Angeles. Table 2 is the same as Table 1 except that all city sizes are the same as for Los Angeles, 60 km. In the morning at the 10-percentile frequency the highest relative concentration, 206 sec m^{-1}, still would occur at Los Angeles but the next highest value, 147 sec m^{-1}, now would occur at Salt Lake City and the lowest value, 94 sec m^{-1}, would occur at New York. In the morning at the 50-percentile or mean-value level, the highest relative concentration, 71 sec m^{-1}, would occur at Salt Lake City, the second highest, 55 sec m^{-1} would occur at Los Angeles and the lowest, 21 sec m^{-1}, would occur at New York. On an annual basis the mean of average relative concentrations in the morning would be highest at Salt Lake City. At the 90-percentile frequency, morning relative concentrations would be highest at Los Angeles but almost as high at Salt Lake City; values for St. Louis and New York would be somewhat lower.

In the afternoon at the 10-percentile frequency the highest relative concentration, 37 sec m^{-1}, would occur at Salt Lake City but would be only slightly higher than the Los Angeles value, 35 sec m^{-1}. At the 50-percentile frequency the highest afternoon relative concentration still would occur at Los Angeles but values for the other cities would be only slightly lower. Table 2 indicates that for 60-km size cities the annual dispersion conditions at Salt Lake City are generally almost as poor as at Los Angeles; in some respects they are worse. Dispersion conditions at New York generally are better than at any of the other three cities considered.

It should be noted that the foregoing comparisons of frequencies of relative concentrations are made on an annual basis in the interest of space economy. As may be expected from the monthly data on mixing depths and wind speeds, significant variations occur in the seasonal frequencies of relative concentrations.

5. Summary

Monthly mean values of mixing depth and average wind speed through the mixing depth have been shown to vary more or less from place to place in the United States, from month to month, and from morning to afternoon. Frequencies of these parameters together with city sizes have been used in a model of atmospheric diffusion over metropolitan areas to estimate annual cumulative frequency curves of average relative pollutant concentrations for four major cities of various sizes. On the basis of the 50-percentile frequencies and current city sizes, the highest relative concentration in the morning occurs at Los Angeles; values at Salt Lake City and St. Louis are about one-half the Los Angeles values and at New York, about one-third. In the afternoon relative concentrations are lower than in the morning for all cities; relative concentrations are highest at Los Angeles, roughly half again as high as at the other cities. If all cities were the size of Los Angeles, 60 km, the highest relative concentration at the 50-percentile frequency in the morning would be at Salt Lake City, followed in order by Los Angeles, St. Louis and New York; in the afternoon the highest average relative concentration would be at Los Angeles, with only slightly lower values at the other cities. Thus, from meteorological considerations dispersion conditions at Salt Lake City are almost as poor as at Los Angeles. Of the four cities considered the best dispersion occurs at New York.

It is planned to further develop and extend this air pollution potential work to other locations in the United States, ultimately providing an urban air pollution potential climatology for the United States.

TABLE 2. Theoretical relative concentrations (sec m^{-1}) averaged over each city area expected to be equalled or exceeded 10%, 50% and 90% of the time annually, based on a common city size of 60 km.

	Morning			Afternoon		
	10%	50%	90%	10%	50%	90%
Salt Lake City—60 km	147	71	22	37	16	13
St. Louis—60 km	127	37	17	22	15	12
New York—60 km	94	21	16	22	14	12
Los Angeles—60 km	206	55	25	35	18	14

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