Estimated Effective Chimney Heights Based on Rawinsonde Observations at Selected Sites in the United States[1]

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ABSTRACT

The plume rise equations of Briggs (1975) for variable vertical profiles of temperature and wind speed are described and applied for hypothetical short and very tall chimneys at five National Weather Service rawinsonde stations across the United States. Annual average effective chimney heights are presented and from other available data additional information on plume behavior is deduced. For example, based on the 0515 CST soundings at Nashville, 61% of the effective plume heights for 50 m chimneys were in a temperature inversion, but only 21% of the plumes for 400 m chimneys were so constrained. Ordinarily, such plumes would be in a fanning configuration. Most of the plumes from tall chimneys (60%) were above an inversion, practically isolated from the ground. Overall, 98% of the short-chimney plumes were reached by the afternoon mixing height, but only 85% of the tall-chimney plumes were reached. Such information supports the obvious presumption that the effluent from tall chimneys remains airborne longer than that from short chimneys, is transported over greater distances, and has more opportunity to undergo chemical transformations before reaching the ground.

1. Introduction

In order to ameliorate ground-level concentrations of pollutants from large individual sources, the effluents are usually emitted from chimneys. It is usually found that the maximum concentrations at ground level are roughly inversely proportional to the square of the plume height above the ground. The plume height commonly exceeds the chimney height because most plumes are warm and buoyant. Only warm plumes are considered in this paper, and aerodynamic effects are neglected. After the plume rises, its height, or the "effective chimney height" for diffusion purposes, may be defined as that height where the plume essentially becomes horizontal, i.e., where the plume density is practically equal to that of the adjacent atmosphere. Throughout this paper the terms "effective chimney height" and "plume height" refer to the centerline of the plume.

The density of a buoyant plume approaches that of the surrounding air mainly because of entrainment of that air and adiabatic cooling. Accordingly, plume rise is inhibited by faster winds and more stable temperature profiles; it is enhanced by slower winds and less stable temperature profiles. The ultimate plume rise is dependent upon the various combinations of wind and temperature or stability structure through which a plume rises. Nevertheless, either explicitly or implicitly, practically all of the many plume rise equations assume uniform profiles of wind and stability (e.g., see the 15 equations summarized by Carson and Moses, 1969). The two main reasons for this approach are that 1) vertical profiles of wind and temperature are rarely available for the times, places, and elevations for which they are needed, and 2) the equations for a uniform layer are more tractable than for a non-uniform layer. Undoubtedly the assumption of uniform wind and stability profiles contributes to the disparity between calculated and observed plume rises. This paper presents some climatological estimates of effective chimney heights based on observed vertical profiles of temperature and wind (National Weather Service rawinsonde data) and on hypothesized physical chimney heights, effluent volume emission rates, and effluent temperatures.

2. Formulation

Although the matter of determining the most appropriate formulations of plume rise has made considerable progress lately, it remains a matter of some controversy. Yet atmospheric scientists are routinely faced with making such calculations. They use those equations which they believe to be most suitable. Since the early

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1970's (Turner, 1973) the Environmental Protection Agency has been using the formulations of Briggs (1969, 1975), whose 1969 work clarified and simplified the matter considerably. His more recent monograph updates the subject and presents formulae for rise through vertically varying profiles of temperature and wind speed (Briggs, 1975, see Section 4.4). Those formulations are used in this study. Some of the important assumptions are that 1) buoyancy dominates the plume rise, 2) buoyancy is conserved so that motion is adiabatic, 3) mass and momentum are conserved, 4) plumes are either nearly vertical or nearly horizontal, and 5) entrainment velocity is proportional to shear velocity between plume and atmosphere.

Briggs' method of calculating effective chimney heights for plume rise through variable temperature and wind speed profiles consists of following the buoyancy flux of a plume segment through successive layers, where it is depleted (or enhanced), to the level where the flux is zero. The initial buoyancy from the chimney (F_0, m^3 s^{-1}), assuming standard conditions,[3] is

$$F_0 = 3.7 \times 10^{-5} Q_H, \tag{1}$$

and Q_H, the heat emission rate, is determined by

$$Q_H = 83.45 Q_v P_0 \frac{T_s - T_0}{T_s} [\text{cal s}^{-1}], \tag{2}$$

where Q_v is the gas volume emission rate from chimney (m^3 s^{-1}), P_0 the atmospheric pressure at top of chimney (mb), T_s the effluent temperature at top of chimney (K) and T_0 the air temperature at top of chimney (K). Q_v and T_s are specified, while P_0 and T_0 are determined from the rawinsonde data. Each rawinsonde observation is divided into successive layers in which the change of temperature with height [$\Delta T/\Delta Z$(°C m^{-1})] and wind speed [$\Delta U/\Delta Z$(s^{-1})] both are constant and linear. The height above the chimney top of the bottom of each such layer is specified as Z_{n-1} and the top as Z_n. Thus, the chimney top is the bottom of the lowest layer, where $Z_{n-1}=0$ and F_0 becomes F_{n-1}. The buoyancy flux at the top (F_n) of each successively higher layer is calculated until it becomes negative. For the layer immediately above the last level where the buoyancy flux was positive, F_n is set equal to zero and the equation is solved for the plume rise (Z_e) above the physical chimney height. The effective chimney height equals the physical chimney height plus the plume rise.

There are two sets of equations for calculating F_n and Z_e. The first set is for no-wind conditions, e.g., nearly vertically rising plumes,

$$F_n = F_{n-1} - \frac{0.265 F_0^{1/3}}{273 + 0.5(T_n + T_{n-1})} \left(\frac{T_n - T_{n-1}}{Z_n - Z_{n-1}} + 0.01 \right) \times (Z_n^{8/3} - Z_{n-1}^{8/3}), \tag{3}$$

$$Z_e = \left\{ Z_{n-1}^{8/3} + 3.77 \left(\frac{F_{n-1}}{F_0^{1/3}} \right) (273 + T_{n-1}) \times \left[\frac{Z_n - Z_{n-1}}{T_n - T_{n-1} + 0.01(Z_n - Z_{n-1})} \right] \right\}^{3/8}, \tag{4}$$

where T (°C) is air temperature and Z (m) is height above the top of the chimney. In Eq. (4) $273 + T_{n-1}$ is used instead of $273 + 0.5(T_n + T_{n-1})$. Notice that Eq. (4) evolves from Eq. (3) by setting $F_n = 0$ and $Z_n^{8/3} = Z_e^{8/3}$, but the Z_n notation is retained in the ratio $(T_n - T_{n-1})/(Z_n - Z_{n-1})$, since the value is by definition constant through the entire layer. The numerical constant, 0.265, in the first equation includes the appropriate entrainment coefficient and gravity (see Briggs, 1975).

The second set of equations is for with-wind conditions, i.e., nearly horizontally rising plumes,

$$F_n = F_{n-1} - \frac{0.523}{273 + 0.5(T_n + T_{n-1})} \left(\frac{T_n - T_{n-1}}{Z_n - Z_{n-1}} + 0.01 \right) \times [0.5(U_n + U_{n-1})](Z_n^3 - Z_{n-1}^3), \tag{5}$$

$$Z_{e1} = \left\{ Z_{n-1}^3 + \frac{1.91 F_{n-1}(273 + T_{n-1})}{U_{n-1}} \times \left[\frac{Z_n - Z_{n-1}}{T_n - T_{n-1} + 0.01(Z_n - Z_{n-1})} \right] \right\}^{1/3}, \tag{6}$$

$$Z_e = \left\{ Z_{n-1}^3 + \frac{1.91 F_{n-1}}{0.5(U_{n-1} + U_{e1})} [273 + 0.5(T_{n-1} + T_{e1})] \times \left[\frac{Z_n - Z_{n-1}}{T_n - T_{n-1} + 0.01(Z_n - Z_{n-1})} \right] \right\}^{1/3}, \tag{7}$$

where U is wind speed (m s^{-1}). In Eq. (6) $273 + T_{n-1}$ is used instead of $273 + 0.5(T_n + T_{n-1})$ and U_{n-1} is used instead of $0.5(U_n + U_{n-1})$. Z_{e1} is a preliminary estimate of the plume rise above the chimney top. This step is necessary because Eq. (7) can be sensitive to the wind speed (U_{e1}) at the plume-rise height (i.e., at Z_{e1}). Note that again the ratio $(T_n - T_{n-1})/(Z_n - Z_{n-1})$ is necessarily constant for the entire layer.

Specification of sufficiently slow winds for use of the no-wind equations is somewhat arbitrary in some cases and is based on the personal recommendation of Briggs. For layers with $U = 0.0$, there is no ambiguity and the no-wind equations are used. For all other layers we

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[3] This assumption results in a somewhat conservative estimate of F_0 for high-altitude stations, since it neglects rarification of the air. The correction factor is $(1000/P_0)$.

interpolate to the level Z_{ub} at which the critical wind speed (U_b) occurs, i.e.,

$$U_b=\left(\frac{0.18F_0}{Z_n+Z_{n-1}}\right)^{\frac{1}{3}}. \tag{8}$$

If U_b occurs in the particular layer, the no-wind equations are used in the sublayer with $U\leqslant U_b$ and the with-wind equations are used in the sublayer with $U\geqslant U_b$. If, in the particular layer, all $U>U_b$, the with-wind equations are used for the entire layer; if all $U<U_b$, the no-wind equations are used. Ordinarily U_b is <1.5 m s^{-1}, even for chimneys with very large values of F_0.

3. Application

Effective chimney heights have been calculated for various specified values of physical chimney height, volume emission rate, and effluent temperature, using National Weather Service rawinsonde observations scheduled for 0000 and 1200 GMT during 1960–1964. Additional useful information on plume behavior has been obtained by considering other readily available data. For example, the main features of the temperature structure in the lower 3000 m of each rawinsonde observation have been determined (Holzworth, 1974b), and were used to infer the behavior of the plume. Also, the effective chimney heights at the sounding times were compared with the afternoon mixing heights (Holzworth, 1972) to infer plume behavior during the intervening period. This paper focuses on annual results for postulated short (50 m) and tall (400 m) chimneys at five National Weather Service rawinsonde stations. Corresponding average values of volume emission rate (Q_v) and effluent temperature (T_s) were based on a summary of United States power plant characteristics (Tikvart, 1976) and were as follows:

Chimney height (m)	Q_v (m^3 s^{-1})	T_s (K)
50	110	445
400	2000	410

The rawinsonde data were also processed on a seasonal basis for additional stations and intermediate chimney sizes (for publication by the Environmental Protection Agency), but available space here limits the presentation to annual results for 50 and 400 m chimneys at five locations. Although actual chimney heights are only approaching 400 m now, the trend has been clearly to larger sizes. The comparison of results for the two chimney sizes should be indicative of behavior trends for any sources of comparable chimney height and heat emission rate.

4. Results

Annual results are presented here based on 5 years (1960–64) of twice-daily rawinsonde observations at five stations located in different sections of the contiguous United States. The following descriptions of these data are in greater detail for the initial stations in order to avoid redundancy. As stated earlier, the effective chimney height calculations in this paper are for plume centerlines, but in some configurations the plumes may extend through considerable depths. Thus, only some part of a particular plume may penetrate into an inversion and/or through an inversion top. The problem and possible solution have been discussed by Briggs (1975), although the details seem more complex than warranted by the current state of plume-rise verification and the general purposes of this paper.

TABLE 1. Annual statistics on calculated effective chimney heights (H_e) and comparisons to afternoon mixing heights (H_a), Oakland Calif., 1960–1964.

	Rawinsonde release			
	0315 PST		1515 PST	
Physical chimney size (m)	50	400	50	400
Average heat emission (10^6 cal s^{-1})	3.3	49.2	3.2	47.9
Average effective height (m)	215	687	266	737
Below inversion (%)	42	13	49	25
In inversion (%)	41	52	33	38
Above inversion (%)	10	28	1	20
No inversion (%)	7	7	17	17
Total cases, $H_a>H_e$ (%)	97	55	95	49

a. *Oakland, California*

Table 1 shows that at Oakland the average heat emission rates for the specified short and tall chimneys differ by a factor of about fifteen. Although average effluent temperature decreases slightly with increasing chimney size, the volume emission rate increases tremendously and is the main reason for the difference in heat emission. Notice also that, assuming constant effluent temperature and volume emission rate, the heat emission rates in the morning for both short and tall chimneys are slightly larger than those in the afternoon, reflecting differences between constant effluent temperatures and diurnally varying air temperatures. Obviously, many plants do not follow such a rigid operating schedule. The aforementioned characteristics of heat emission rates for Oakland are generally true for the other stations included in this paper.

Table 1 indicates that at Oakland at 0315 PST for a 50 m chimney the overall average effective chimney height was 215 m above ground level.[4] The plume *rise*, therefore, averaged 165 meters, a factor of roughly three over the actual chimney height. In the early morning, and probably throughout much of the preceding night, the plume from the short chimney was in

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[4] Ordinarily rawinsondes were released 45 min before the scheduled observation times of 1200 and 0000 GMT.

a temperature inversion in 41% of the observations; this suggests a fanning type of plume. Since practically all (97%) of the short-chimney plumes at 0315 PST were reached by the afternoon mixing height (at the time of maximum surface temperature), practically all of the fanning plumes would be expected to go through the fumigation process during some part of the intervening period. At 0315 PST the short-chimney plume was below an inversion in 42% of the observations. In such cases the temperature structure below the plume centerline (and below the inversion) would be subadiabatic for the most part. Although it is difficult to specify, the accompanying plume behavior would most likely be weak fanning. Continuing in Table 1, at 0315 PST the small plume from the short chimney was above an inversion, indicating optimum conditions for inhibiting plume contact with the ground in 10% of the observations. The configuration of these plumes was probably weak fanning or lofting, or some combination thereof, depending on the plume height above the inversion top and the lapse rate. Finally, there was no inversion (within 3000 m of the surface[5]) in only 7% of the observations. In the early morning (and at night) these plumes were probably behaving like those below an inversion, although later in the morning coning or looping plumes could develop, depending on wind speed and solar radiation intensity. Notice in the table that for short chimneys at 0315 PST their effective height was reached by the afternoon mixing height in a total of 97% of the observations. This is not surprising since the average effective chimney height is 215 m and the average afternoon mixing height has been estimated to be about 800 m (Holzworth, 1972). Accordingly, around the middle of the day a high frequency of coning or looping plumes is expected in association with near-neutral and unstable lapse rates.

Turning now to 400 m chimneys and the 0315 PST rawinsondes (Table 1), there are some marked differences compared to the features previously described for 50 m chimneys. For 400 m chimneys the average effective height is 687 m; the plume rise is considerably less than a factor of one above the physical chimney height. For tall chimneys the incidence of effective chimney heights in and above inversions both increase at the expense of those effective heights below an inversion. Thus at 0315 PST, the plumes from tall chimneys are within an inversion in a fanning mode in 52% of the observations, and they are above an inversion in 28% of the observations. These optimum conditions for inhibiting dispersion of the plume to ground level at 0315 PST, and probably throughout much of the night, occur in a total of 80% of the observations for tall chimneys compared to 51% for short chimneys. More favorable conditions for dispersion to ground level characterize the remaining cases, 20% for tall and 49% for short chimneys. Notice also that for tall chimneys the morning effective heights are reached by the afternoon mixing heights in only 55% of the observations, compared to 97% for short chimneys.

For short chimneys and the 1515 PST soundings at Oakland the average effective height was 266 m, somewhat higher than that for short chimneys at 0315 PST. Also, in the afternoon the frequencies of effective short-chimney plume heights in and above an inversion were less than in the morning, and the frequencies of plumes below an inversion and with no inversion were greater than in the morning. These comparisons follow from the general diurnal variation of low-level temperature structure: fewer ground-based, but more elevated and no-inversions in the afternoon than in the morning. The 95% frequency that the afternoon mixing height exceeded the effective height of short chimneys at 1515 PST reinforces a previous statement that earlier, around mid-day, many plumes are expected to be in a coning or looping configuration.

If the Table 1 data for 400 m chimneys are compared with those for 50 m chimneys, both based on the 1515 PST soundings, the relative differences are similar to such a comparison based on the 0315 PST soundings. That is, in the afternoon the frequencies of effective chimney heights in and above an inversion are greater, and the frequency of effective heights below an inversion is less for tall than for short chimneys. At 1515 PST tall-chimney plumes would be in an unfavorable configuration for rapid dispersion to ground level in 58% of the observations and in a more favorable configuration in 42% of the observations, compared to 34% and 66%, respectively, for short-chimney plumes.

After 1515 PST the effective chimney height statistics are expected to revert to those at 0315 PST. These changes would probably be rapid around sunset and then more gradual later in the night, especially for short chimneys.

b. Denver, Colorado

Table 2 shows that at Denver at 0415 MST the average effective height for 50 m chimneys is only 146 m. These plumes are in a temperature inversion in 74% of the observations, suggesting a very high frequency of radiation inversions (Hosler, 1961). For 400 m chimneys at 0415 MST, only 12% of the effective heights are in an inversion, but 77% are above an inversion. These statistics are due undoubtedly to the fact that many of the inversions do not extend much above the physical chimney height of 400 m. Notice that a total of 98% of the short-chimney morning plumes and 84% of the tall-chimney morning plumes are reached by the afternoon mixing heights. Although this indicates a high frequency of fumigating-type plumes in the forenoon, the average duration of the phenomenon is likely

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[5] The analyzed rawinsonde data (Holzworth, 1974b) used in this paper only considered the temperature structure in the first 3000 m of each sounding, which is considered adequate for the practical purposes of this study.

TABLE 2. Annual statistics on calculated effective chimney heights (H_e) and comparisons to afternoon mixing heights (H_a), Denver, Colo., 1960–1964.

	Rawinsonde release			
	0415 MST		1615 MST	
Physical chimney size (m)	50	400	50	400
Average heat emission (10^6 cal s^{-1})	2.8	40.7	2.6	39.4
Average effective height (m)	146	741	344	913
Below inversion (%)	9	6	17	12
In inversion (%)	74	12	12	6
Above inversion (%)	12	77	8	19
No inversion (%)	5	5	63	63
Total cases, $H_a > H_e$ (%)	98	84	94	81

to be relatively brief since the average afternoon mixing height of more than 2500 m (Holzworth, 1972) is so great with respect to the average effective chimney height—for 400 m as well as 50 m chimneys. Accordingly, during afternoons many of the Denver plumes would be in a coning or looping mode through a deep layer.

For the 1615 MST Denver soundings there was no inversion within 3000 m of the surface in 63% of the observations, suggesting that on many days coning and looping continued into the late afternoon (and substantiating the large average afternoon mixing height). As would be expected in late afternoon the frequencies of plumes in and below inversions both are less for tall than for short chimneys and the frequency of plumes above an inversion is greater for tall chimneys. Around sunset conditions are expected to begin changing rapidly toward those at 0415 MST.

c. *Nashville, Tennessee*

Table 3 summarizes the data for Nashville. For the morning soundings the percentages are rather similar to those for Denver. However, at Nashville short-chimney plumes at 0515 CST are in and above inversions somewhat less often and are below inversions more often than at Denver. On the other hand, at Nashville tall-chimney plumes at 0515 CST are in and below inversions more often, and are above inversions less frequently than at Denver. The total frequency that the afternoon mixing height exceeds the morning effective height is 98% for short and 85% for tall chimneys. The average afternoon mixing height for Nashville is almost 1600 m (Holzworth, 1972) and is much less than the 2500-m value for Denver.

For the 1715 CST soundings at Nashville the frequency of effective heights below an inversion is rather high, 49% for short and 39% for tall chimneys. Apparently in the late afternoon (and perhaps around mid-day) the frequency of elevated inversions and the potential for limited mixing conditions are considerably greater at Nashville than at Denver. This is further confirmed by a difference in average afternoon mixing heights of almost 1 km and a large difference in no-inversion frequencies between the two locations.

d. *Pittsburgh, Pennsylvania*

The data in Table 4 for Pittsburgh are remarkably similar to those for Nashville. Furthermore, the average afternoon mixing heights differ by only 50 m, being lower at Pittsburgh. Thus, the data in Tables 3 and 4 appear to be representative of a large region and require no further discussion.

e. *New York, New York*

Table 5 indicates that in New York at 0615 EST the effective chimney height for 50 m chimneys is below a temperature inversion in almost half the observations. This suggests a relatively high frequency of elevated inversions with probably weak fanning and some coning plumes during the pre-dawn hours. These conditions are in concert with the fact that for short chimneys the morning soundings have the lowest frequency of effective heights in an inversion and the highest frequency of no-inversion conditions, compared to the other sta-

TABLE 3. Annual statistics on calculated effective chimney heights (H_e) and comparisons to afternoon mixing heights (H_a), Nashville, Tenn., 1960–1964.

	Rawinsonde release			
	0515 CST		1715 CST	
Physical chimney size (m)	50	400	50	400
Average heat emission (10^6 cal s^{-1})	3.1	46.3	3.0	44.8
Average effective height (m)	179	723	331	895
Below inversion (%)	24	12	49	39
In inversion (%)	61	21	9	12
Above inversion (%)	8	60	8	15
No inversion (%)	7	7	34	34
Total cases, $H_a > H_e$ (%)	98	85	98	79

TABLE 4. Annual statistics on calculated effective chimney heights (H_e) and comparisons to afternoon mixing heights (H_a), Pittsburgh, Penn., 1960–1964.

	Rawinsonde release			
	0615 EST		1815 EST	
Physical chimney size (m)	50	400	50	400
Average heat emission (10^6 cal s^{-1})	3.1	46.7	3.0	45.6
Average effective height (m)	166	703	275	827
Below inversion (%)	28	16	51	39
In inversion (%)	58	17	11	13
Above inversion (%)	6	59	7	17
No inversion (%)	8	8	31	31
Total cases, $H_a > H_e$ (%)	98	80	96	75

TABLE 5. Annual statistics on calculated effective chimney heights (H_e) and comparisons to afternoon mixing heights (H_a), New York, N. Y., 1960–1964.

	Rawinsonde release 0615 EST		1815 EST	
Physical chimney size (m)	50	400	50	400
Average heat emission (10^6 cal s^{-1})	3.2	48.5	3.2	47.4
Average effective height (m)	193	704	236	794
Below inversion (%)	49	27	53	40
In inversion (%)	31	24	24	14
Above inversion (%)	5	34	3	26
No inversion (%)	15	15	20	20
Total cases, $H_a > H_e$ (%)	96	72	95	65

tions presented in this report. These statistics, particularly for small chimneys, may be influenced by the proximity of the sounding site at J. F. Kennedy Airport to the nearby metropolis. Analyses of rawinsonde data from adjacent stations (Holzworth, 1974a) suggest that the New York urban heat island, perhaps enhanced by local patterns of water temperature and atmospheric humidity, destabilizes the lower atmosphere in the morning, as indicated by the soundings from J. F. Kennedy Airport. Such effects may also occur to some degree at other locations and, although they are difficult to detect from available information, their potential should not be overlooked.

For tall-chimney plumes in the early morning 27% are below an inversion, 24% are in an inversion, and 34% are above an inversion. A total of 96% of the short-chimney morning plumes are reached by the afternoon mixing heights, compared to only 72% for tall-chimney morning plumes. The estimated afternoon mixing heights average almost 1300 m (Holzworth, 1972).

For soundings at 1815 EST the effective heights for short chimneys are below and in an inversion more frequently than those for tall chimneys; however, tall chimneys have far more effective heights above an inversion. Such optimum conditions for inhibiting plume contact with the ground occur in 26% of the afternoon observations. The conditions at 1815 EST are expected to change during the night to those at 0615 EST. This tendency appears to be rather gradual since the statistics in Table 5 for short and tall chimneys are rather similar at both observation times.

5. Summary and conclusions

This paper presents plume rise equations, which were initially formulated by Briggs (1975), for use with variable vertical profiles of temperature and wind speed. Although further work on plume rise is called for, the variable profile method is considered to be more relevant than the usual method, which assumes that a constant temperature gradient (or stability class) and wind speed (usually at the chimney height) are representative of the layer(s) through which a plume rises. The equations are applied for hypothesized short (50 m) and tall (400 m) chimneys using rawinsonde observations at five National Weather Service stations across the contiguous United States to determine effective chimney heights above ground level. In addition, the incorporation into the data processing of existing analyses of rawinsonde temperature lapse rates and calculated afternoon mixing heights permits inferences about plume behavior.

The data summaries indicate that the annual average effective chimney heights are fairly variable among the five coast-to-coast stations considered in this report, but are within reasonable bounds for short and tall chimneys. For example, the ranges of annual average effective chimney heights for the five stations are as follows:

Sounding time	1115 GMT	2315 GMT
50 m chimneys	146–215 m	236–344 m
400 m chimneys	687–741 m	737–913 m

Obviously, the plume rise is greater for tall chimneys than for short chimneys, and it is also greater in the late afternoon and early evening (2315 GMT) than in the morning near sunrise (1115 GMT). For stations in the Pacific and Mountain Time Zones the 2315 GMT sounding data appear to give a reasonable indication of the diurnal maximum in effective chimney heights. However, in the Central and Eastern Time Zones the diurnal maximum probably is somewhat underestimated because of the low-level cooling that ordinarily begins before sunset. This effect is especially true for short chimneys and during the winter season.

The statistics on temperature structure at the effective chimney heights show considerable variation among the five stations. For short chimneys and the 1115 GMT soundings most stations show a large fraction of the observations with the effective chimney height in a temperature inversion, but the values range from 31 to 74%. This situation suggests that at 1115 GMT these plumes are in a fanning configuration. Since at all stations the afternoon mixing heights almost always exceed the effective heights of the short chimneys at 1115 GMT, fumigating plumes are likely during some part of the intervening period. The occurrence of short-chimney plumes at 1115 GMT below an inversion (to some extent in a trapping configuration) ranges from 9 to 49%, above an inversion (optimum for inhibiting contact with the ground) from 5 to 12%, and no inversion below 3000 m (probably weak fanning plumes) from 5 to 15%. A relatively high frequency of short-chimney plumes below an elevated inversion at 0615 EST at New York suggests some influence of the metropolitan heat island.

For tall chimneys at 1115 GMT most stations show, with respect to short chimneys, fewer plumes below and

TABLE 6. Comparison between 50 and 400 m chimneys of the percentage frequencies that calculated effective chimney heights (H_e) are in or above a temperature inversion, and that the afternoon mixing height (H_a) exceeds the effective chimney heights. Data based on rawinsonde observations for 1960–1964.

	1115 GMT		2315 GMT	
Physical chimney height (m)	50	400	50	400
Oakland, Cal.				
In or above inversion	51	80	34	58
$H_a >$ all H_e	97	55	95	49
Denver, Col.				
In or above inversion	86	89	20	25
$H_a >$ all H_e	98	84	94	81
Nashville, Tenn.				
In or above inversion	69	81	17	27
$H_a >$ all H_e	98	85	98	79
Pittsburgh, Pa.				
In or above inversion	64	76	18	30
$H_a >$ all H_e	98	80	96	75
New York, N.Y.				
In or above inversion	36	58	27	40
$H_a >$ all H_e	96	72	95	65

in an inversion, and more plumes above an inversion—as would be expected generally from the preponderance of low-level inversions at 1115 GMT. At all five stations the frequencies of short- and tall-chimney plumes below a temperature inversion are greater at 2315 GMT than at 1115 GMT.

Although there are some large inter-station variations in the effective chimney height statistics for the stations included in this report, the data are believed to be *generally* representative of the climatic region in which each station is located. Nevertheless, it should be appreciated that the results are *most* applicable at the places where the rawinsonde observations were made. While the data should be of considerable use in evaluating existing and potential air pollution problems, they also confirm an obvious but unseen phenomenon that is highly important in the dispersion of large quantities of pollutants emitted from chimneys. This phenomenon is that the total percentage of effective chimney heights in and above a temperature inversion is greater for tall than for short chimneys, for 1115 and 2315 GMT rawinsonde observations, and for all stations—as shown in Table 6. This means that the plumes from tall chimneys are inhibited from readily diffusing to ground level more often than from short chimneys. Table 6 also shows that the afternoon mixing heights exceed both the 1115 and 2315 GMT effective heights for tall chimneys somewhat less often than for short chimneys. Plumes from tall chimneys remain airborne longer than those from short chimneys, may be transported over longer distances, and have more time to undergo atmospheric transformations. The general trend toward taller chimneys indicates a trend toward longer range pollutant transport and associated problems. The impact of these trends is amplified by the fact that taller chimneys typically emit greater quantities of pollutants.

While the technique described in this paper has generated much practical information, it does include some uncertainties that deserve mention. For example, the calculations of effective chimney height were based on *all* the archived temperature and wind data for each rawinsonde observation, but the soundings themselves sometimes omit details that could be important in specific cases. The analyses of rawinsonde temperature structure (Holzworth, 1974b), which were used to infer plume behavior, retained only the major features of the lower 3 km of each sounding. Afternoon mixing heights were calculated (Holzworth, 1972) under the assumption that surface heating resulted in a dry adiabatic lapse rate from the afternoon maximum temperature to the intersection with the observed morning (1115 GMT) temperature profile. In cases where the temperature profile was changing due to processes aloft (e.g., cold or warm advection, subsidence, etc.) the calculated mixing heights would be in error. Another difficulty that arises in calculating mixing heights as well as plume rise is the occurrence of precipitation. The impact of this problem is not included in the methodology of this paper under the assumption that such occurrences are relatively infrequent. Another simplification in this study is that the plume rise calculations consider only the center line of the plumes, neglecting their finite size. From these caveats it is clear that the data presented in this paper are most appropriately interpreted as climatological in which the statistical summaries have balanced out the anomalies associated with specific situations. Accordingly, the application of techniques used in this paper to specific situations should not be done without attention to the inherent uncertainties.

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