Predicted Climatology of Cooling Tower Plumes from Energy Centers

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ABSTRACT

A one-dimensional plume and cloud growth model is applied to four months of radiosonde observations from Nashville, using as initial conditions the plume from single large cooling towers with waste heat outputs of 10^3, 10^4 and 10^5 MW, and a complex of cooling towers with a total waste heat output of 10^5 MW. Estimates of average annual plume rise from the four energy sources are 580, 1180, 2460 and 780 m, respectively.

The predicted plume rise, visible plume length and cloud formation are given as functions of time of day, year and weather type. For example, a cloud forms at the top of the plume from the 10^3 MW tower in 65% of the morning soundings during which ground level fog was observed. A cloud is predicted to occur 95% of the time at the top of the plume from the single 10^5 MW tower. It is found that if the towers in an energy center are separated by a distance greater than the average plume rise from one tower, then plume merging is minimized. Observations from TVA's Paradise steam plant are used to test the predictions of visible plume length from a single 10^3 MW tower.

1. Introduction

The potential environmental effects of cooling towers include increases in cloudiness and precipitation and shading of the sun by long visible plumes. These problems are intensified as the size of power plants and energy centers increases (see Hanna and Gifford, 1975). Currently operating power plants, such as Paradise, Keystone or Amos, are approaching energy productions of about 3000 MWe. Minor environmental effects, such as light snowfall (Kramer *et al.*, 1976), have occasionally been observed at these power plants, but there do not appear to be any major effects. It is clear that as the energy releases from power plants increase, at some level there will be serious and unacceptable atmospheric effects. It is desirable to determine this critical point while energy centers are still on the drawing boards. For example, drawings exist for a proposed energy center in Louisiana in which dozens of 1000 MW cooling towers are squeezed into an area of a few square kilometers. The atmospheric scientists can provide specific input to this project by suggesting a minimum spacing between cooling towers, based on calculations of the conditions under which plumes merge.

There have been no comprehensive studies of the climatology of plume types at existing large cooling towers. Even the well-funded Chalk Point Cooling Tower Program (Pell, 1974) does not have climatology as one of its subprojects, although evidently the necessary daily observations are being made. A series of daily observations of visible plume geometry at TVA's Paradise plant will be described below, but it will develop that there are many serious limitations to these observations. Therefore, a good climatological data set for comparison with model predictions is very desirable. Such a data set, which should include at least one year's observations, would include the following:

1) Accurate morning and evening rawinsonde soundings.
2) Plant operating characteristics at the time of the rawinsondes (total power output, towers operating, temperature and vertical speed at tower opening).
3) Visible plume geometry (from photographs).
4) Reports of cloud formation by plume, and of precipitation falling from plume.
5) Current weather (cloud cover and height, fog, precipitation).
6) Aircraft measurements of temperature and mixing ratio in the plume to downwind distances of about 10 km.

All these measurements are necessary to exercise and test a cooling tower plume and cloud growth model.

2. A modeling approach to plume climatology

Since such comprehensive climatological data sets for cooling towers do not exist, reliance must be placed at present on modeling studies to simulate the plume properties. The plume model that is used in this paper is based on Briggs' (1975) plume rise theory and Weinstein's (1970) one-dimensional cloud growth model, and has been fully described by Hanna (1976a). It is a steady-state model in which the cloud variables (vertical speed, radius, temperature, water vapor content, cloud water content and hydrometeor water content) are functions only of height. The model has been validated using observations of cooling tower plumes at the John E. Amos Plant (Kramer *et al.*, 1975), the Chalk Point Plant (Meyer, 1976; Environmental Systems Corporation, 1976), and the Rancho Seco Plant (Gifford *et al.*, 1976). It also successfully simulated the cloud that formed over an oil refinery near St. Louis (Auer, 1976; Hanna, 1976b).

This model was applied using data from 241 radiosonde observations made at Nashville, Tenn., during the months of January, April, July and October 1974, in order to determine the effects of seasonal changes on plumes. This location was chosen because it is close to the TVA Hartsville power plant (under construction), the TVA Paradise power plant (where studies of cooling towers are underway), and the hypothetical Land-between-the-Lakes energy center site (Gray *et al.*, 1976).

a. Source characteristics

Four types of sources were assumed, covering the energy range from typical current power plants to large future energy centers. Their characteristics are the following.

A. 10^3 MW SINGLE TOWER

This tower, with radius 30 m, is typical of natural draft cooling towers currently in operation. Initial vertical speed is 4.4 m s^{-1} and initial plume temperature is calculated from the environmental temperature and relative humidity using a table published by Kramer *et al.* (1975). The plume is initially saturated and initial cloud water and hydrometeor water contents are both equal to 1 g kg^{-1}.

B. 10^4 MW SINGLE TOWER

The waste heat output is slightly larger than that from the largest existing power plants. The extra energy is obtained by keeping all parameters except initial plume radius the same as in the first case. Initial plume radius is increased to 91 m.

C. 10^5 MW SINGLE TOWER

The waste heat output is equal to that proposed for a large energy center. The additional energy is obtained by keeping all parameters except initial plume radius the same as in the first case, but increasing the initial plume radius to 300 m. Since the energy flux is so concentrated, the results of this analysis represent the "worst case."

D. 10^5 MW ENERGY PARK

There are 100 cooling towers each with the characteristic of case A, divided into 25 groups of four. The groups are assumed to be spaced on a square grid, 1 km apart. The four towers in each group are in a square array, 200 m apart. Merging of plumes is assumed to occur when the radius of a plume equals one-half the distance between the sources. At that point, the energies of the plumes add linearly, which is accomplished by increasing the plume radius to equal $RN^{\frac{1}{2}}$, where N is the number of plumes merging and R the radius of a plume before merger.

TABLE 1. Nashville atmospheric sounding for 2315 GMT 2 July 1974. Initial plume temperature is 313.4 K.

Height above surface (m)	Dry bulb temperature (K)	Dew point temperature (K)	Wind speed (m s^{-1})
0	302.9	296.6	2.5
127	301.7	296.0	3.0
1 393	291.2	289.3	3.0
1 827	289.4	284.4	3.5
2 214	286.0	283.0	3.5
2 446	285.3	279.6	3.5
2 974	282.3	278.0	5.0
3 033	282.1	276.1	5.0
3 285	279.8	275.2	5.5
4 041	275.9	264.4	5.0
4 441	273.1	266.0	6.0
4 931	271.4	241.4	4.0
5 193	271.0	241.0	4.0
5 509	268.4	238.4	4.0
5 742	269.0	239.0	4.0
6 113	267.7	237.7	3.5
7 465	256.1	226.1	4.5
8 307	248.8	218.8	6.0
8 704	246.8	216.8	7.5
9 098	244.1	233.4	5.5
9 143	244.2	242.2	13.5
9 233	244.1	244.0	16.5
9 371	243.5	241.9	17.0
9 559	242.5	236.3	18.5
10 070	238.6	232.5	20.5
10 377	236.6	226.2	16.5
10 640	234.0	227.1	15.0
10 829	232.2	202.2	15.5

b. Model properties

The model follows the plumes until the vertical speed w drops to zero, at which point the maximum final plume rise has been achieved. The major characteristics of the calculated plumes that are used in the following analysis are visible plume height and length (determined by the end of the condensed portion of the plume), final plume rise, and liquid water concentrations at the tops of plumes which are condensed at the final plume rise height. The occurrence or nonoccurrence of clouds at the top of the simulated plume are compared for the following six major observed weather types:

1) Clear
2) Precipitation
3) Cloud height $\geqslant$ 20 000 ft (no precipitation)
4) 10 000 $\leqslant$ cloud height $\leqslant$ 20 000 ft (no precipitation)

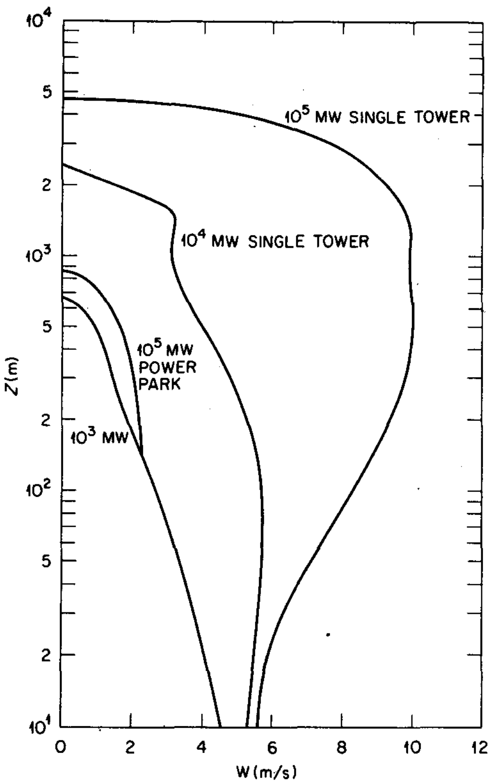

FIG. 1. Plume vertical velocity w predicted by the model using the sounding in Table 1.

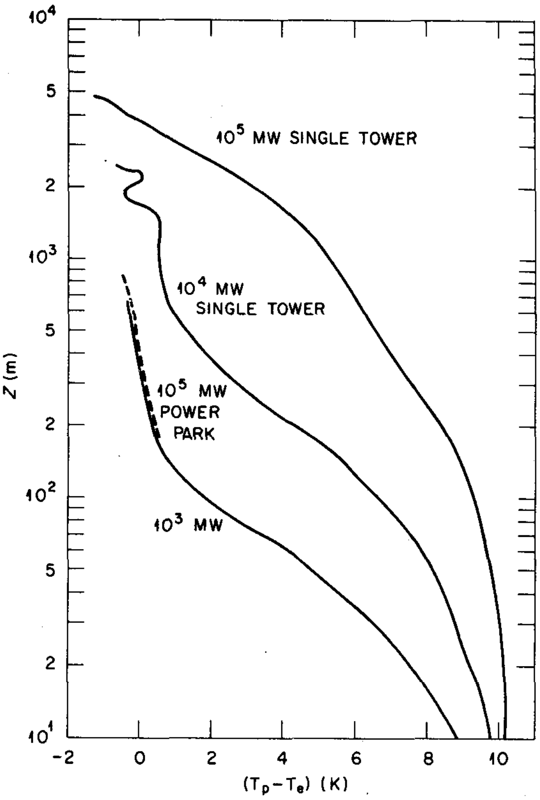

FIG. 2. Temperature difference between plume T_p and environment T_e, predicted by the model using the sounding in Table 1.

5) Cloud height $\leqslant$ 10 000 ft (no precipitation)
6) Fog (no precipitation).

In this manner a climatology of visible plume lengths, plume rise and cloud formation is developed.

3. Results

a. *Plume rise*

If condensation occurs in the plume, the resulting release of latent heat can increase the plume rise. For about one-third of the model runs for the single 10^3 MW tower, a cloud is predicted to exist at the height of final plume rise. This fraction increases to 95% for the case of the single 10^5 MW tower. Examples of the differences in the calculated plumes from the four different sources, based on the particular radiosonde profile shown in Table 1 (2300 GMT, 2 July 1974), are given in Figs. 1–3. For this sounding, the profiles of vertical speed of rise, temperature difference between the plume and the ambient air and cloud water turn out to be the same at heights below 150 m for the 10^3 MW tower and 10^5 MW power park. Above 150 m, the groups of four plumes in the power park merge and the combined plume rises about 200 m higher than for the 10^3 MW plume. The 10^4 and 10^5 MW single-tower plumes rise quite high and always contain liquid water, whereas the plumes from the 10^3 MW single tower and the 10^5 MW power park evaporate at a height of 130 m.

The average plume rises for all 241 soundings, by months and for the four different sources, are listed in Table 2. The calculated increase in plume rise with increase in source strength for the first three types of sources is in approximate agreement with Briggs' (1975) theory for plume rise, which predicts that the plume rise for bent-over plumes is proportional to source strength raised to the one-third power. The figures in Table 2 for average annual plume rise show that the ratio of the 10^4 MW plume rise to the 10^3 MW plume rise is 2.04 and the ratio of the 10^5 MW plume rise to the 10^3 MW plume rise is 4.25. Briggs' theory predicts that these ratios will be $10^{1/3}$ or 2.15, and $100^{1/3}$ or 4.65, respectively.

The 10^5 MW power park yields an average plume rise that lies generally between those calculated for the single 10^3 MW tower and the single 10^4 MW tower. Occasionally, all 100 plumes of the power park will combine and yield a plume rise close to that calculated for the single 10^5 MW tower. In about 90% of the runs, plumes in the group of four towers merge, and in about 15% of the runs, the 25 groups of four all merge. But since merging generally occurs near the top of the plume, it doesn't result in much additional rise. Based on this, a general rule for avoiding plume merging can

TABLE 2. Average plume rise estimated using Nashville radiosonde observations. The range in plume rise of the numbers used in calculating each average is given in parentheses.

Month (1974)	Morning rise (m)				Evening rise (m)				Average rise (m)			
	10^3 MW	10^4 MW	10^5 MW	10^5 MW*	10^3 MW	10^4 MW	10^5 MW	10^5 MW*	10^3 MW	10^4 MW	10^5 MW	10^5 MW*
January	500 (160–1340)	880 (320–1450)	1470 (650–3600)	610 (160–1390)	660 (240–1360)	970 (400–1690)	1590 (750–4010)	740 (240–1530)	580 (160–1360)	920 (320–1690)	1530 (650–4010)	670 (160–1530)
April	490 (170–1430)	1030 (300–1920)	2340 (780–4500)	610 (170–1740)	890 (120–1600)	1410 (190–2160)	2550 (420–4300)	1090 (120–1880)	690 (120–1600)	1220 (190–2160)	2440 (420–4500)	850 (120–1880)
July	470 (200–1590)	1530 (340–3110)	3130 (1260–4950)	890 (210–3620)	730 (240–1800)	1590 (520–2710)	3570 (1690–5460)	1130 (240–2980)	600 (200–1800)	1500 (340–3110)	3250 (1260–5460)	1010 (210–3620)
October	360 (190–990)	850 (320–3160)	2410 (850–4790)	420 (230–1200)	550 (260–1140)	1140 (500–2160)	2610 (1500–4600)	770 (210–2300)	450 (190–1140)	1000 (320–3160)	2510 (850–4790)	600 (210–2300)
Annual average	450 (160–1590)	1030 (300–3160)	2340 (650–4950)	630 (160–3620)	710 (120–1800)	1280 (190–2710)	2580 (420–5460)	930 (120–2980)	580 (120–1800)	1180 (190–3160)	2460 (420–5460)	780 (120–3620)

* This represents the power park, a group of 100 towers whose total output is 10^5 MW. All other power outputs represent individual towers.

be stated. The cooling towers should be spaced a distance apart greater than the average plume rise from a single tower. In this way, the edges of the plumes from adjacent towers do not touch, since the radius ($\propto 0.4z$) of each plume at its height of final rise is less than half the distance between the towers.

Enhancement of plume rise due to the merging of multiple plumes was studied by Briggs (1974). In his study the ratio of the enhanced plume rise from N sources to the plume rise from one source, which is denoted by E_N, is a function of the number of sources N the plume rise from one source H and the distance between the sources s, i.e.,

$$E_N=[(N+S)/(1+S)]^{\frac{1}{3}}, \tag{1}$$

where

$$S=6[(N-1)s/N^{\frac{1}{3}}H]^{\frac{3}{2}}.$$

The model results in Table 2 show that the average annual plume rise from a single 10^5 MW tower is 580 m. For the small groups in our hypothetical power park ($N=4$ and $s=200$ m), $E_N=1.20$. For the entire power park ($N=100$ and $s=1000$ m), $E_N=1.02$. In this case the enhancement factors for the groups of four and the entire power park should probably be multiplied together. On this basis the plume rise enhancement factor E_N from Eq. (1) would be about 1.22 for our hypothetical power park. The plume and cloud growth model yields the result that the average annual ratio of plume rise for the 10^5 MW spaced power park to the plume rise for the single 10^3 MW cooling tower is 780 m/580 m, or 1.35, in fair agreement with Eq. (1).

The seasonal variation of plume rise shown by Table 2 is about what would be expected intuitively. The lowest plume rise usually occurs during winter when the lower atmosphere is more stable. Similarly, afternoon plume rises are 10–80% greater than morning plume rises. The diurnal variation is less for large sources, since the morning inversion is usually limited to a layer about 100–200 m deep near the ground. However, the annual variation is greatest for the large sources, presumably due to the influence of the deep isothermal or inversion layers which exist during the winter. Also, it should be stressed that this "climatology" is based on plume rise calculations made from meteorological observations during a period of only four months. Ideally, observations during at least ten years

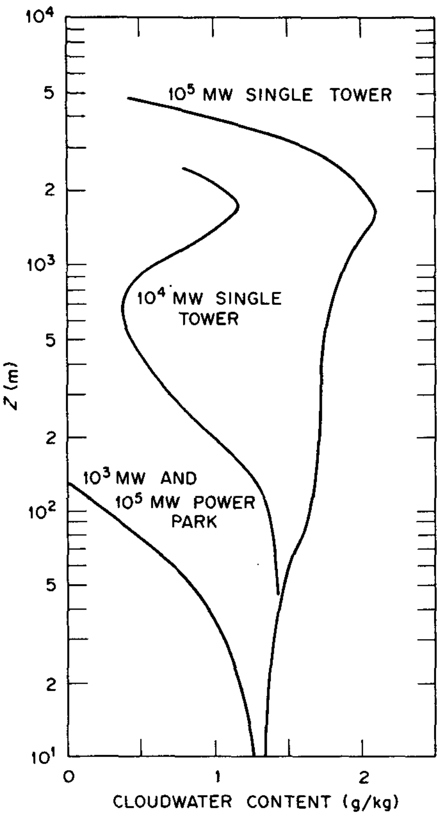

FIG. 3. Cloud water content predicted by the model using the sounding in Table 1.

TABLE 3. Predicted frequency of cooling tower cloud occurrence (liquid water content greater than zero at height of final rise) for 10^3 MW tower at Nashville.

Weather class	Observed class frequency AM	PM	Frequency of cooling tower cloud occurrence within class AM	PM
1. Clear	0.09	0.15	0.32	0
2. Precipitation	0.18		0.60	
3. Cloud height ≥ 20 000 ft (no precipitation)	0.05	0.07	0.23	0
4. 10 000 ≤ cloud height < 20 000 ft (no precipitation)	0.09		0.14	
5. Cloud height < 10 000 ft (no precipitation)	0.24		0.53	
6. Fog (no precipitation)	0.13		0.65	
All	1.00		0.39	

should be used to establish stable climatological estimates.

b. *Cloud at top of plume*

In many of the model calculations, liquid water is predicted to be present in the plume at the height of final rise. Either a cloud persists from the tower opening through the entire depth of the plume, or else it forms just above the lifting condensation level. The frequencies of cloud occurrence predicted by the model for the six weather classes are given in Table 3, in the case for which the source is the single 10^3 MW, 30 m radius tower. On the average, a cloud is predicted to occur at the top of the plume 39% of the time. During precipitation, fog, or cases when the natural cloud height is less than 10 000 ft., a cloud at the top of the plume is predicted about 60% of the time. The reason why the percentage is not 100% during precipitation conditions is that sometimes precipitation falls into relatively dry air near the surface; this occurs, for instance, when warm frontal rain is just beginning or snow flurries are occurring. Clouds at the top of the plume are very unlikely during afternoons that are clear or have high natural clouds. Such high occurrences of clouds are not usually reported from operating cooling towers, since on foggy days or days with precipitation, it is difficult to see the plume. It should be remembered that the model calculates plumes on all days, instead of just sunny days when the plume is easily visible.

The frequency of cloud occurrence is predicted to increase as source size increases, as shown in Table 4. For the 10^5 MW power park the frequency of cloud occurrence is roughly halfway between those for single 10^3 MW and 10^4 MW cooling towers, just as (see Table 2) is true for the plume rise for the power park. A cloud forms nearly all the time (frequency 0.95) over the single 10^5 MW cooling tower. This is a good argument against clustering the waste heat sources as close together as possible. This model predicts that a cloud averaging 2500 m deep would exist nearly continuously over an area with radius 300 m dissipating 10^5 MW of heat.

c. *Liquid water content of cloud formed by cooling tower*

The liquid water content of a cloud determines the visibility in the cloud and the rainfall rate from the cloud. The removal of large raindrops from the plume has been calculated using a scheme developed by Simpson and Wiggert (1970). It is uncertain whether the estimated rainfall rate at the ground is realistic, because a cooling tower cloud is unlike a natural cloud, in that its base is stationary rather than drifting with the wind.

The average liquid water contents predicted by the model are listed in Table 5. These refer only to those cases when a cloud formed at the top of the plume. The average liquid water contents range between 0.29 and 0.63 g kg^{-1}, in agreement with typical values reported by Fletcher (1962) of the liquid water content in natural clouds. The largest liquid water value is 1.49 g kg^{-1}. The average liquid water content for the larger sources is significantly greater than that for the 10^3 MW source, but there is no significant seasonal variation. In most cases the liquid water content at the top of the plume is less than that in the middle sections of the cloud.

d. *Relation of plume rise to inversion height*

Based on observations of cooling tower plume rise on cold winter mornings at the John E. Amos power plant, Brennan *et al.* (1976) state that the capping inversion height or mixing-layer depth determines the final plume rise. Hanna (1976a) has pointed out that this conclusion is not likely to be valid during the summer when the capping inversion is much higher than it is in the winter. Consequently the 241 Nashville soundings were analyzed to determine the relation between predicted plume rise from the 1000 MW cooling tower and observed inversion height.

A well-defined capping inversion occurs in 89 of the Nashville soundings; the average plume rise and inversion height for these runs are 690 and 1250 m,

TABLE 4. Frequency of cooling tower cloud occurrence estimated using Nashville radiosonde observations.

Month (1974)	10^3 MW	10^4 MW	10^5 MW	10^5 MW*
January	0.41	0.70	0.97	0.59
April	0.34	0.59	0.96	0.43
July	0.51	0.76	0.97	0.59
October	0.31	0.54	0.89	0.39
All runs	0.39	0.64	0.95	0.50

* Power park.

TABLE 5. Predicted average and peak concentration of cloud water at the top of plumes which are condensed at the height of final rise, estimated using Nashville radiosonde observations.

Month (1974)	Average concentration ($g\ kg^{-1}$)				Peak concentration ($g\ kg^{-1}$)			
	10^3 MW	10^4 MW	10^5 MW	10^5 MW*	10^3 MW	10^4 MW	10^5 MW	10^5 MW*
January	0.40	0.54	0.62	0.47	0.72	0.96	1.49	0.98
April	0.44	0.60	0.61	0.54	0.82	1.15	1.19	1.00
July	0.29	0.63	0.44	0.49	0.91	1.03	0.77	1.25
October	0.33	0.39	0.44	0.36	0.62	1.02	1.09	0.90
All runs	0.36	0.54	0.53	0.47	0.91	1.15	1.49	1.25

* Power park.

respectively. Capping inversion heights and plume rise for these soundings are summarized in Table 6. The correlation between plume rise and inversion height is very high for the group of runs for which the estimated plume rise is greater than or equal to the inversion height. If the plume has enough buoyancy to bring it to the capping inversion, the plume will in all likelihood stop there. But, in general, a knowledge of the height of the capping inversion permits only an upper limit to be estimated for plume rise.

e. *Visible plume length*

The analysis of visible moisture plumes can be conducted with confidence only in the case of plumes that evaporate before they reach the height of final rise. Downwind of this point passive diffusion governs the distribution of excess water, and very little is known about cooling tower plumes in this region. Keeping in mind this limitation, in the case of the single 10^3 MW source the average annual visible plume height predicted by the model is 150 m and the average annual visible plume length is 190 m.

Seasonal variations of predicted visible plume length and height for the 10^3 MW source are given in Table 7. It can be seen that the average resultant visible plume length is about 40–75% greater in January than in July, and that the morning length is about twice the afternoon length. Furthermore, the angle of the plume with the horizontal, which is easily calculated from these values, is about 30° less in the winter than in the summer, presumably due to the greater wind speeds in the winter ($8.0\ m\ s^{-1}$ in January compared to $3.4\ m\ s^{-1}$ in July). The shortest plumes are predicted to occur on hot dry days in July, when the visible plume length is only about 50 m, or about one tower diameter.

TABLE 6. Predicted plume rise and observed capping inversion height for the 1974 Nashville soundings. The number of runs in each category is given in parentheses.

Month (1974)	Average capping inversion height (m)	Average model plume rise (m)	Correlation coefficient between capping inversion height and plume rise	
			All runs with inversion	Runs with plume rise ≥ inversion height
January	920	640	0.31 (39)	0.99 (14)
April	1640	760	0.20 (25)	0.99 (5)
July	1700	1250	0.78 (5)	(0)
October	1280	570	0.15 (20)	(2)
All runs	1250	690	0.33 (89)	0.99 (21)

The model predictions of Table 7 can be compared with observations of visible plume geometry at TVA's Paradise Steam Plant (Hanna and Pike, 1976) where there are three large natural draft cooling towers. Morning observations of surface weather conditions and plume geometry and plume photographs were analyzed for the year 1974, with the results given in Table 8. It is seen that the agreement between model predictions and observations is fair. The model underpredicts visible plume height by about 24% and visible plume length by about 32%. This comparison may be biased by the fact that the predicted plume lengths are restricted to cases when the plume is not visible at its height of final rise. Furthermore, the total energy output of the three cooling towers at Paradise is about twice as great as the output assumed in the model.

4. Limitations of the model

Because the plume and cloud growth model is one-dimensional, i.e., variables are functions of height only, it cannot account for horizontal variability in the source, the plume or the environment. Plume size is parameter-

TABLE 7. Visible plume length and height predicted using Nashville radiosonde observations for plumes which are not visible at their final height of rise. The resultant plume length is the hypotenuse formed by the visible plume length and height. The 10^3 MW source is used.

Month (1974)	Height (m)		Length (m)		Resultant (m)	
	AM	PM	AM	PM	AM	PM
January	230	130	430	170	490	210
April	180	90	330	130	380	160
July	240	120	140	90	280	150
October	240	80	210	110	310	140
All runs	220	100	280	130	360	160

TABLE 8. Observed morning visible plume geometry at TVA's Paradise steam plant, 1974, compared with model predictions from Table 7.

Season	Average visible plume height (m) Observed	Average visible plume height (m) Predicted	Average visible plume length (m) Observed	Average visible plume length (m) Predicted
Winter	340	230	580	430
Spring	250	180	200	330
Summer	260	240	330	140
Fall	310	240	550	210
Average	290 m	220 m	410 m	280 m

ized by making the radius a function of height, and mixing with the environment is parameterized by assuming a value for the entrainment coefficient. The distributions of temperature, moisture, etc., in the plume are assumed to be uniform within a cross section perpendicular to the axis of the plume. These limitations are not serious for the study of single plumes, as shown by the success of Briggs' (1975) plume rise theory. However, at many existing power plants, such as Paradise, Amos, Rancho Seco or Keystone, there are more than one cooling tower on the site, and the plumes from these towers are often observed to merge. Interactions of these plumes cannot in all respects be accurately simulated by a one-dimensional model. As discussed above, it has been necessary to resort to gross parameterizations, such as assuming that the plumes completely combine at the point that their edges first touch. Planned energy centers will contain many individual cooling units, and a detailed understanding of their atmospheric effects will require two- or three-dimensional models, similar to the multi-cloud model proposed by Hill (1974).

The calculations in this paper for 10^4 and 10^5 MW energy sources represent the extreme case for which all the energy comes from a single source. The 10^5 MW power park assumes a distribution of cooling towers, but plume merging is treated in a highly parameterized way. In a model in which interactions between the plume and the environment can occur, it is expected that the high density of cooling towers would cause the environmental air to be gradually warmed and moistened as it passes over the energy center and through or between the plumes. At the height of final plume rise, it is expected that a broad cloud consisting of the upper portions of all the plumes would drift off downwind.

Another major modeling difficulty is the lack of adequate parameterization for the precipitation rate from relatively narrow, bent-over plumes. According to Simpson and Wiggert (1969), precipitation should fall from a cloud whose liquid water content is 1 g kg^{-1}. Several of the plumes in this study have liquid water content greater than 1 g kg^{-1}, but the effect of precipitation cannot yet be adequately modeled. A research program is needed in which plume microphysics parameters are measured in detail.

The climatology predictions of this model have been compared with a limited set of observations from the Paradise Steam Plant. Further observations should be made of plume climatology, especially the variation of visible plume length and cloudiness with the six weather classes. If models can be satisfactorily validated with measurements from existing power plants, we can be more confident of their extrapolation to large energy centers.

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