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A MODEL FOR SEASONAL AND ANNUAL COOLING TOWER IMPACTS*

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Abstract—The Argonne National Laboratory/University of Illinois Seasonal/Annual Cooling Tower Impacts model provides predictions of seasonal, monthly, and annual cooling tower impacts from any number of mechanical- or natural-draft cooling towers. The model typically requires five years of hourly surface meteorological data and concurrent twice-daily mixing heights in addition to basic data on the thermal performance of the cooling tower. The model predicts average plume length, rise, drift deposition, fogging, icing, and shadowing.

The model uses a category scheme in which the five years of hourly surface data are placed into about 100 categories based on a special plume-scaling relationship. With this reduced number of cases to be run for long-term impact evaluations, advanced state-of-the-art models for plume impacts are then applied. For multiple plumes, the methodology includes variation of the merging patterns and of the wake effects from tower housings for different wind directions.

The main advantage to this model over previous models is its advanced theoretical development and extensive model validation with experimental data for its component submodels. From studies in the United States of America and Europe, an extensive database on cooling tower plumes and drift was accumulated and analysed to assist in the identification of superior theoretical assumptions. Other data, not used in model development, provided for independent model verification. The validation of each submodel is presented, and typical results are given for a representative natural-draft cooling tower installation and for a typical linear mechanical-draft cooling tower arrangement.

Key word index: Environmental impacts of energy generation, cooling tower, plume model, drift deposition, fogging, icing, shadowing.

1. INTRODUCTION

The design and licensing of nuclear and fossil-fired electric generating stations in the United States of America requires that the potential environmental impacts be assessed. Nearly every environmental report and environmental impact statement must evaluate cooling towers, either as the proposed cooling system or as a reasonable alternative system. The potential adverse impacts of cooling towers that must be considered include (1) aesthetic impact of the visible plume (spatial extent), (2) ground deposition of drift droplets containing high concentrations of dissolved or suspended solids that are emitted by the cooling towers, (3) ground-level fogging and icing, (4) shadowing by the plume, and (5) ground-level humidity increase. Because all of these impacts are related to the dispersion of the cooling tower plume, prediction of the plume has become the primary consideration in conducting environmental assessments of the cooling towers in the United States of America.

Some environmental impacts are functions of the average behavior of the plume (such as sunshine reduction on crops or drift deposition). In other cases, the impact depends on "worst-case" behavior (such as a long plume over a resort beach, for example). Thus, the assessment methodology must provide reliable numerical predictions of both average and worst-case behaviors. The model presented in this paper is suitable for determining average impacts, rather than worst-case impacts. The normal requirement for an environmental impact evaluation is the quantitive prediction of the potential effects averaged over at least five years using representative meteorological

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conditions for the site. The problem is how to use this large database to make affordable computer calculations of climatological averages of the environmental impacts. It would be desirable to make detailed calculations for every hourly record, but the large number of records to be processed makes this procedure too expensive with integral-type (or more complex) models.

The earliest method developed, embodied in the Oak Ridge Fog and Drift Model (ORFAD), employed simple formulas to calculate gross plume properties for each measurement record (Laverne, 1976). The hourly results were added to running totals, and averages were then computed and presented in tabular or graphical form. The ORFAD methodology was an improvement over previous subjective methods in that it gave quantitative predictions. However, the large number of records to be processed required the use of only the simplest plume and drift models. Moreover, the results of these formulas were shown (Policastro *et al.*, 1980a; Carhart *et al.*, 1982) to compare poorly with plume observations. Therefore, the reliability of the end results of an ORFAD-type computation is questionable.

Recognizing these limitations, the developers of the Swiss model KUMULUS (Moore, 1977) sought to limit computations to a set of typical meteorological conditions. This decision was based on the widely accepted observation that only a limited number of significantly different plumes occur at a given site. For the reduced set of typical conditions, a validated integral plume and drift submodel was run. The results were then summed and averaged with respect to a frequency table of the occurrence of the typical cases by wind direction. To obtain the typical meteorological input, each data record was classified according to range in wind speed, humidity, temperature, and lapse rate. In one application of this method (Moore, 1977), the total number of plume categories was 400, but because of the infrequent occurrence of many categories, the number was reduced to 80 typical cases and 10 extreme cases.

Although the KUMULUS model approach represented a significant advancement in technique, it still suffered from several deficiencies. First, the range in behaviors within a given category differs from category to category and is generally unknown *a priori*. No assurance exists that two plumes from different categories will be any less similar than two from the same category. Second, the selection of parameter ranges is difficult, and our experience shows that plume categories depend on tower characteristics (not included in the category scheme) and the particulars of the site.

The present model—The Argonne National Laboratory/University of Illinois Seasonal and Annual Cooling Tower Impact (ANL/UI SACTI) model—is similar to the KUMULUS model approach in that a small number of detailed plume computations are performed with a validated plume model (whose limits of applicability are established) for categories of hourly cases that correspond to significantly different plume size and behavior (Dunn, 1980). Average and idealized sets of input data are used to produce these representative plumes. The use of an integral model is important in predicting the detailed plume environment within which the drift droplets are falling and evaporating, as well as in predicting any fogging or icing. The present method differs from the previous approach in that categories are based on nondimensional parameters that have been shown to correlate well with plume length and rise, rather than on fixed ranges in the dimensional meteorological data. Category ranges are also dynamically allocated to ensure nearly equal population in each category. For richly populated plume length categories, a further breakdown by wind speed and, if needed, by stability class range is used to define a category. The improvements, then, are that the hourly cases assigned to a category correspond to nearly the same plume size and behavior, while different categories have significantly different plume predictions. Thus, there will be no biases or lack of resolution introduced by using sparsely populated categories. Furthermore, the categories are selected by scanning the entire meteorological database, and the specific tower thermal behavior is modeled for each hourly record in evaluating the nondimensional parameters. Thus, site-specific category selection is achieved.

To implement this method, the ANL/UI SACTI model contains three separate programs, which are run sequentially. The first, called PREP, is a preprocessor that examines the overall meteorological database, using it to set up the categories to be used and to prepare input data for the representative cases for detailed computation. The second, named MULT, performs the detailed plume and drift computations for the representative cases. The final program, identified as TABLES, merges the outputs of the preprocessor step and the plume/drift computation step to produce predictions of environmental impacts for each ground subsector surrounding the installation.

In addition to requiring a reliable method for assigning hourly records to categories of similar plumes, accurate prediction requires a plume and drift model with the state-of-the-art submodels available. These submodels include those for (1) single plumes; (2) multiple plumes, including realistic merging and tower wake effects; (3) single plume drift deposition; (4) multiple plume enhancements of drift deposition; (5) ground fogging and ground ice deposition; and (6) shadowing.

At present, no long-term average validation data exist for the environmental impacts listed above, except for shadowing. Because the overall model cannot be validated directly, strong validation of the core submodels is necessary for the results to be considered reliable. Among alternative formulations for each submodel, the one selected should be the best-performing among the available options. The

ANL/UI model embodies state-of-the-art submodels in each of these categories. The calibration and verification of each submodel was done with all available data, including a large body of European data that had not previously been catalogued and presented in the literature in the United States (Policastro and Wastag, 1981). Table 1 details the nature of this extensive database for calibration and verification. The submodels used in the detailed plume model and the validation procedures and results for each one are described next.

2. SUBMODELS

The plume model MULT is composed of six submodels: (1) single-plume, (2) multiple-plume, (3) single-plume drift, (4) multiple-plume drift, (5) fogging and icing, and (6) shadowing. The formulation of these submodels has been presented previously as referenced in each submodel discussion. Only brief summaries are included here. Instead, we want to focus primarily on the validation with field and laboratory data of each submodel to demonstrate the predictive accuracy that has been achieved with each of the model components. In making plume predictions for measured data cases, we used the full measured meteorological profiles, not the simplified boundary layer assumptions shown in Fig. 1 that are based upon the hourly surface data. When we are forced to work from surface data, these simplifying assumptions are needed, but for determining the accuracy of the model's predictions, fully measured field cases are used.

2.1. *The single plume submodel*

For simplicity in this section, the single-plume submodel will be referred to simply as the ANL/UI model or "the model". A plume model of the integral

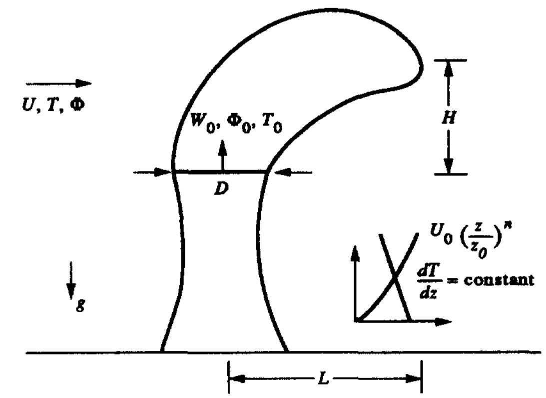
Table 1. Summary of data used in submodel calibration and verification for natural-draft cooling tower (NDCT) and linear mechanical-draft cooling tower (LMDCT) examples

Single and multiple tower plume submodels

No. towers (cells)	Type	Field or lab.	Site or laboratory	No. of cases	References
Calibration					
1	NDCT	Field	Lünen	12	Bremer *et al.*, 1973
1	NDCT	Field	Chalk Point	14	Meyer, 1975 Meyer and Jenkins, 1977
1	NDCT	Field	Paradise	13	Slawson and Coleman, 1978
1	NDCT	Lab.	EDF	6	Viollet, 1977
2	NDCT	Lab.	EDF	3	Viollet, 1977
4	NDCT	Lab.	EDF	8	Viollet, 1977
1 (6)	LMDCT	Lab.	Kannberg/Onishi	6	Kannberg and Onishi, 1978
2	NDCT	Lab.	EDF	3	Viollet, 1977
4	NDCT	Lab.	EDF	8	Viollet, 1977
1 (6)	LMDCT	Lab.	Kannberg/Onishi	6	Kannberg and Onishi, 1978
Verification					
1	NDCT	Field	Chalk Point	2	Meyer and Stanbro, 1977
1	NDCT	Field	Gardanne	5	Viollet, 1977
1	NDCT	Field	Philippsburg	13	Brog *et al.*, 1984
1	NDCT	Lab.	EDF	15	Viollet, 1977
1	NDCT	Lab.	Pryputniewicz	3	Pryputniewicz and Bowley, 1975
1	NDCT	Lab.	Davis *et al.*	3	Davis *et al.*, 1977
3	NDCT	Field	Neurath	7	Caspar *et al.*, 1974 Baer *et al.*, 1974
3	NDCT	Field	Amos	19	Kramer *et al.*, 1976a, b
2 (8)	LMDCT	Field	Benning Road	10	Meyer *et al.*, 1974
2 (9)	LMDCT	Field	Gaston	10	Slawson *et al.*, 1979
3 (6)	LMDCT	Lab.	Kannberg	6	Kannberg, 1978
7	LMDCT	Lab.	Gregoric	7	Gregoric, 1979
1(1–7)	LMDCT	Lab.	Gregoric	5	Gregoric, 1979

Single and multiple tower drift submodels (verification only)

No. towers (cells)	Type	Field or lab.	Site or laboratory	No. of cases	References
1	NDCT	Field	Chalk Point	26	Meyer and Stanbro, 1977/8 Env.Sys. Corp., 1977
2 (13)	LMDCT	Field	Pittsburg, CA	86	Laulainen *et al.*, 1979 Webb, 1978



D = exit diameter
W_0 = exit velocity
Φ_0 = exit mixing ratio
T_0 = exit temperature
U = average ambient wind speed
T = average ambient temperature
Φ = average ambient mixing ratio
g = acceleration of gravity
n = wind exponent
dT/dz = temperature lapse rate
L = visible plume length
H = visible plume rise

Fig. 1. Definitional sketch of typical plume problem, showing the usual boundary-layer meteorology assumptions made in this paper.

type was chosen as the best compromise between accuracy and cost. The use of more detailed models seemed inconsistent with the less detailed input data available from state-of-the-art tower performance models and surface-layer meteorological models. The ANL/UI integral model is able to solve the simultaneous equations for development of plume properties averaged over a cross section. The model has been described and discussed more fully elsewhere (Carhart *et al.*, 1981; Carhart and Policastro, 1991).

The variables included in the system of eight coupled ordinary differential equations as a function of centerline distance are (1) mass, (2) two components of momentum, (3) enthalpy, (4) total water, (5) liquid water, and (6) two components of centerline position. The key entrainment rate assumption made in this model uses two parameters to include the mixing effects of both plume rise and plume shear along the centerline relative to the ambient wind.

State-of-the-art refinements have been included in the ANL/UI single-plume model in the following areas:

- Initial zone of flow establishment,
- Tower wake suction or drag,
- Increased turbulent mixing in the wake,
- Freezing and thawing of the plume water droplets,
- Leveling-off of the plume within a stable layer of sufficient depth,
- Mixing by ambient turbulence for leveled-off plumes,
- Visible plume extent determined by equivalent Gaussian distributions, and
- Initial liquid water content.

The model development effort grew out of an earlier model validation study in which we compared the predictions of 15 models (Policastro *et al.*, 1980a; Carhart *et al.*, 1982) with an extensive database from laboratory and field studies. The original 39 single-plume data cases had fully measured profiles of temperature, wind speed, and humidity, and included measured plume outlines averaged over periods of 15–30 min. An additional 20 data cases of the same type have since been added for model verification. Key theoretical assumptions identified in the validation study were then tested systematically in many combinations to identify the most accurate set. However, the formulation of the wake effects we introduced (more rapid mixing and an added downward drag force near the wake) had no parallel in other single-plume models (Halitsky, 1977; Hosker, 1979). By using a large database for calibration purposes, we were able to identify a clearly superior set of physically plausible assumptions and to obtain the best calibration of model parameters. When examined theoretically, these assumptions also seemed to agree best with what was known about plume structure, behavior, and parameter calibration. The single-plume model maintained its predictive excellence when results were compared with a large laboratory and field verification database.

Figures 2 and 3 show typical model/data comparisons for a field data case and a laboratory case, including the predictions of several other good models (Carhart *et al.*, 1981; Carhart and Policastro, 1991). For 59 field data cases, the single-plume model is able to predict visible plume rise within a factor of 2.0 in 75% of cases and visible plume length within a factor of 2.5 in 70% of cases. For laboratory data, the mean error in trajectory predictions is 20% of rise, and the mean error in dilution predictions is 30%. These levels of predictive accuracy are state-of-the-art for one-dimensional integral single-plume models.

A set of performance-evaluation statistics for each of 15 models was compiled for the model validation study. The statistics included the evaluation of $\rho_{\log} = \text{antilog}(N^{-1}\Sigma_i \log|P_i/O_i|)$, where P_i and O_i were corresponding predicted and observed values for the ith case. For laboratory data, the ANL/UI model yielded $\rho_{\log}$ values of 1.20 (trajectory) and 1.29 (dilution). The model making the next-best predictions achieved values of 1.32 and 1.27, respectively. For prediction of plume rise in the field cases, the $\rho_{\log}$ value for ANL/UI was 1.45, with a ratio of 1.53 for the next-best performing model. For visible plume length, three models gave comparable means, with $\rho_{\log}$ values of

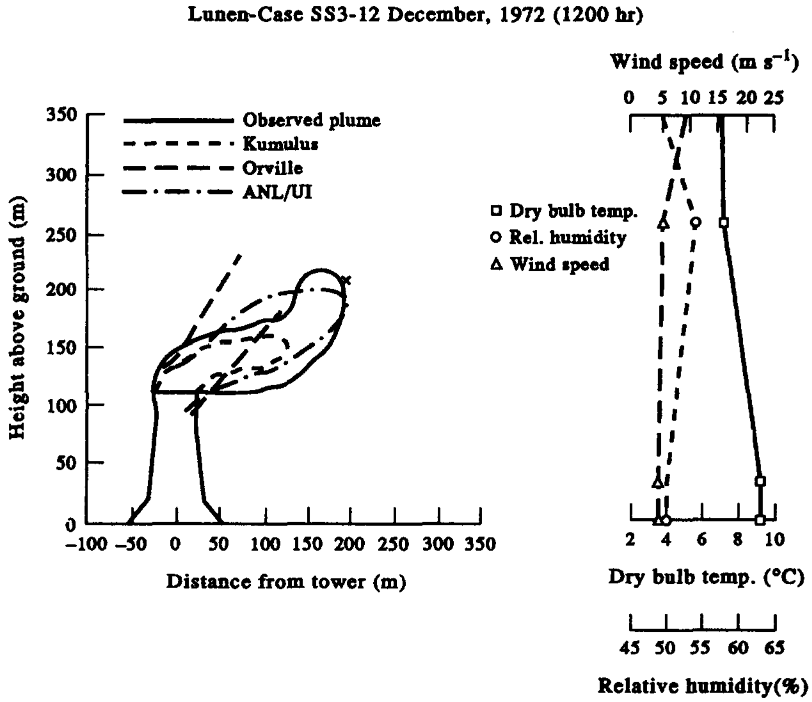


Fig. 2. Comparison of predictions of KUMULUS (Moore, 1977), Orville *et al.* (1980), and ANL/UI models for a calibration field data case at the Lünen power plant (Case SS3). The X indicates the end of the visible plume for the Orville model, which does not give outline predictions beyond the point of subsaturation of mean properties.

1.57, 1.68, and 1.79, while the ANL/UI model yielded a value of 1.81. However, the number of plume lengths predicted within a factor of 2.5 was greatest for the ANL/UI model. The model's tendency to overpredict length is also conservative when applied to impact evaluation.

Overall, the ANL/UI model had the best predictive accuracy by a small margin within the group of best-performing models, although the differences in predictive accuracy within this group may not be statistically significant.

2.2. *The multiple-plume submodel*

The multiple-plume submodel is a straightforward extension of the single-plume submodel. It is designed to describe the merging process of two or more single plumes and to embody more complex wake effects. The multiple-plume submodel has been carefully validated with an extensive set of 46 field data cases (see Table 1) containing full meteorological profiles and averaged plume outlines. In addition, the model was tested with a number of laboratory multiple-plume measurements. Overall, its predictions are more accurate than any other model of its class tested.

A multiple plume occurs with multiple natural-draft towers as well as at any mechanical-draft tower. The most important improvement in our multiple-plume model is its ability to treat a large number of separate plumes, whether separate natural-draft towers or cells of mechanical-draft towers. The towers can be arranged in any geometrical configuration, and that configuration can be examined in any orientation to the wind direction. Distinctive physical effects that have been observed in the field and in the laboratory are modeled by treating each source individually, including the merging of separate plumes. For example, plumes from a line of sources rise higher if the wind direction lies along the line (in line) than if the wind direction lies perpendicular to the line (crossflow). Plumes in line with the wind merge rapidly, enhancing the effects of the buoyancies of individual plumes. In addition, the effects of downwash from the tower structures are minimized for in-line plumes.

In our validation study of multiple-plume models (Dunn *et al.*, 1980) we identified those theoretical aspects of multiple-plume models that are most in need of improvement. These enhancements were realized in the multiple-plume submodel by adding (1) a description of two merging plumes during the merging process when the merged cross section cannot be approximated as circular with full dependence on wind direction, (2) an entrainment formula for plumes with elongated cross sections that produces growth toward circularity, and (3) a wind-direction-dependent formulation of tower downwash effects (downward suction due to lowered wake pressure and increased mixing due to higher wake turbulence) for typical

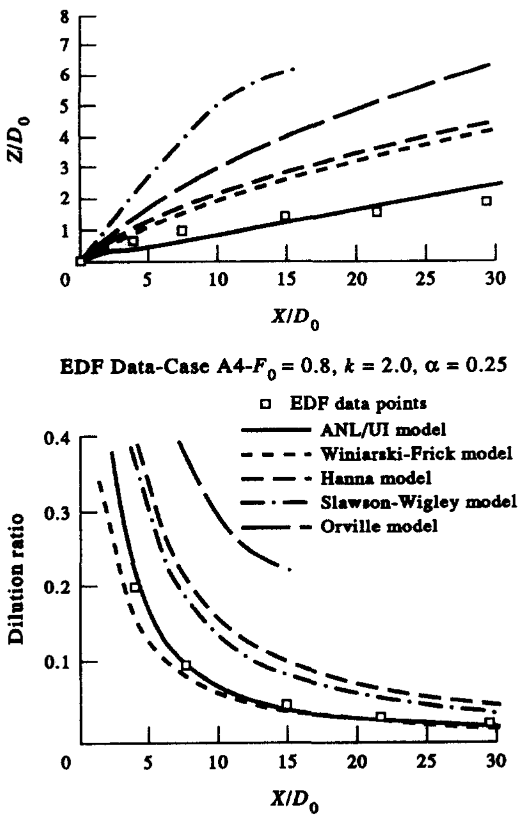


Fig. 3. Comparison of predictions of ANL/UI, Winiarski–Frick (1978), Hanna (1975), Slawson–Wigley (1975), and Orville *et al.* (1980) models for Electricité de France (EDF) laboratory data; calibration case A4, (top) centerline trajectory, (bottom) centerline dilution.

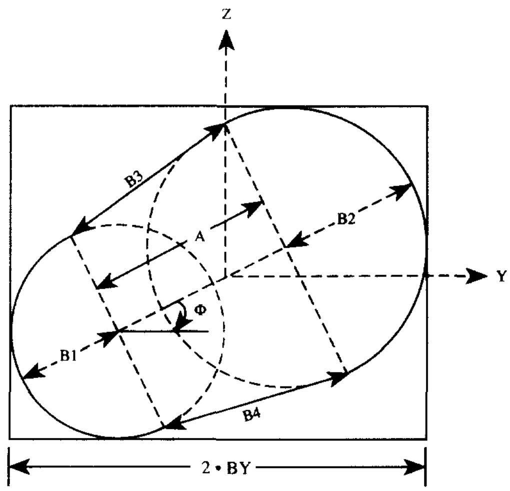


Fig. 4. Merging of two round jets to form a slot jet with half-round ends.

tower housings encompassing natural-draft, circular mechanical-draft, and linear mechanical-draft towers.

Several existing models that can handle multiple plumes either do not incorporate these effects or do so in a very simplified manner (Dunn *et al.*, 1980). Most available multiple-plume models handle plume merging by defining an effective source representing the total flux of plume properties either (1) initially or (2) when the initial single plume grows to satisfy some predetermined size criterion. Although these effective-source methods do model the enhanced buoyancy of merging plumes, the results lack realism because they are independent of wind direction and because they generally overestimate plume rise and length. All models except the KUMULUS model neglect wake effects, which also results in long and high plume predictions.

The merging methodology used in the ANL/UI model is a further development of methods first introduced by Wu and Koh (1977). Here we will only summarize the method, referring the reader to a fuller description (Policastro *et al.*, 1981a). The model begins by integrating the single plume located farthest upwind, initiating new plumes as the first plume passes other cell locations. At each time step, the model checks in three dimensions whether any two plumes have overlapped enough to qualify as merged. A single elongated plume is then defined in a way that preserves the basic cross-sectional shape and orientation and conserves all fluxes. An example for the merging of two round plumes is illustrated in Fig. 4.

The versatility and realism of this methodology is evident. For example, for a linear mechanical-draft tower in line with the wind, the plumes from separate cells will gradually merge to form a plume with a vertically elongated cross section near the tower, while for the same tower in crossflow to the wind, the individual cell plumes will all rapidly merge to form a plume with a horizontally elongated cross section. As the merged plume travels downwind the cross section will grow toward circularity for either orientation.

Downwash effects are handled just as for a single natural-draft tower, except that wakes are defined for each tower housing (or each cell for in-line wind directions). Wakes for other significant buildings or structures are also allowed.

The submodel was verified by using seven field data cases from Neurath, West Germany. The data were collected for three natural-draft towers that are situated in an equilateral triangle and that cool a total of 900 MWe. Three model predictions for one of these cases, with the surface wind directed perpendicular to one side, are shown in Fig. 5. The Orville *et al.* (1980) model predicts a plume that is far too high and somewhat long. The initial prediction of the KUMULUS model, which was partly calibrated to this data, gives a reasonable approximation to the plume, but it also predicts a reappearance of visible plume from 1.5 to 3.0 km, which was not observed. The ANL/UI model prediction is the closest representation of the actual data.

A verification field data case for two linear mechanical-draft towers at the Gaston steam plant in

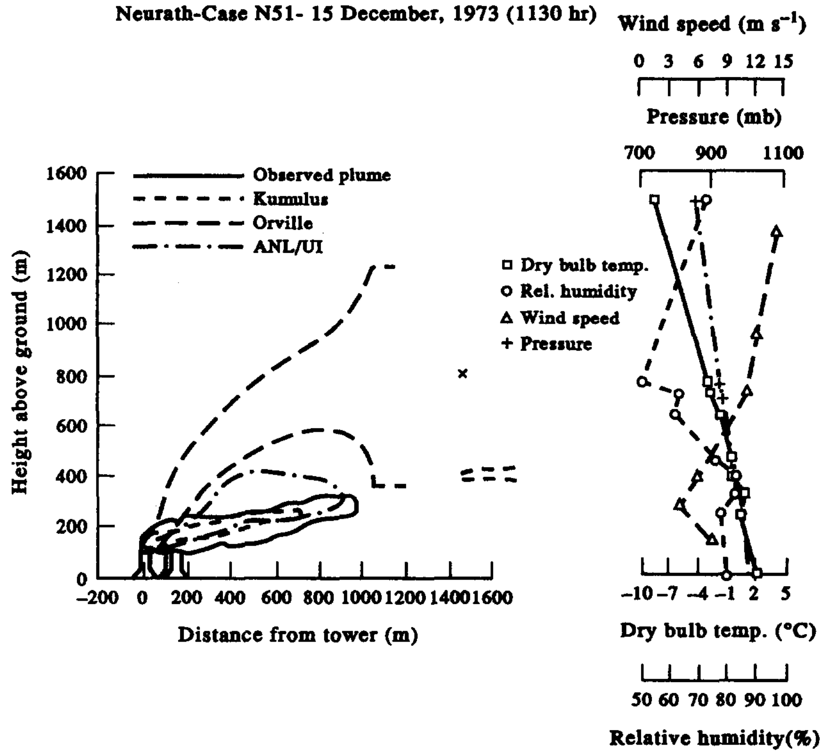


Fig. 5. Comparison of predictions of the KUMULUS (Moore, 1977), Orville *et al.* (1980), and ANL/UI models with a verification field data case for the Neurath power plant, West Germany, involving three natural-draft towers in an equilateral triangle with the wind direction perpendicular to one side (Case N51). The KUMULUS model predicted a visible plume out to 3 km. The X indicates the end of the visible plume for the Orville model, which produces no outline predictions beyond the point of subsaturation of mean properties.

Alabama, U.S.A., which cool a total of 800 MWe, is shown in Fig. 6. KUMULUS model predictions were not available for Gaston data, so those of another effective-source model, the Slawson–Wigley model (1975), are shown. The wind direction for this case is perpendicular to the long axes of the towers. Downwash effects are quite pronounced, and the ANL/UI model predictions show the realism of its merging and downwash logic. As expected, the effective-source models (Orville and KUMULUS) for this case show plumes that have high trajectories. These two models predict short plumes because the elevated air is drier than the air near the ground.

The entrainment coefficients were not altered, and the entrainment rate for the elongated cross section was taken, as calibrated, from Wu and Koh (1977). The wake formulas underwent some additional calibration, principally to lessen the cumulative effect of several tower housings relative to a simple sum of effects. Part of the multiple-plume laboratory data available was used for this calibration (Policastro *et al.*, 1981a).

All the 46 field data cases encompassing two sets of three natural-draft towers (Amos [19 cases] and Neurath [7 cases]) and two pairs of linear mechanical-draft towers (Benning Road and Gaston [10 cases each]) were used for model verification. The remaining laboratory data were also used. The log-mean values for the ANL/UI model of 1.57 for rise and 1.55 for length were considerably closer to 1.0 than those of both the Orville model (1.66, 1.88) and of the Slawson–Wigley model (1.80, 2.47). The accuracy of plume rise for multiple plumes is a little worse than for single plumes, but the length log-mean predicted-to-observed ratio of 1.55 produced by the ANL/UI model is much more accurate than its 1.81 value for single plumes. The ANL/UI model predicts multiple-plume rise still within a factor of 2.0 in 75% of the cases, and within a factor of 2.5 in nearly 80% of the cases. The laboratory data case predictions also verify the model's superior accuracy. The ANL/UI model's advantages are most clearly seen in the multiple-plume data.

2.3. *The single-plume drift submodel*

Cooling towers emit both large and small droplets of water. The large ones (diameter > 20 μm), called drift droplets, are formed from cooling water containing dissolved solids and are carried by the plume updraft out of the tower. The drift droplets, whose number spectrum by size is an important initial condition, are subsequently deposited in the environment as

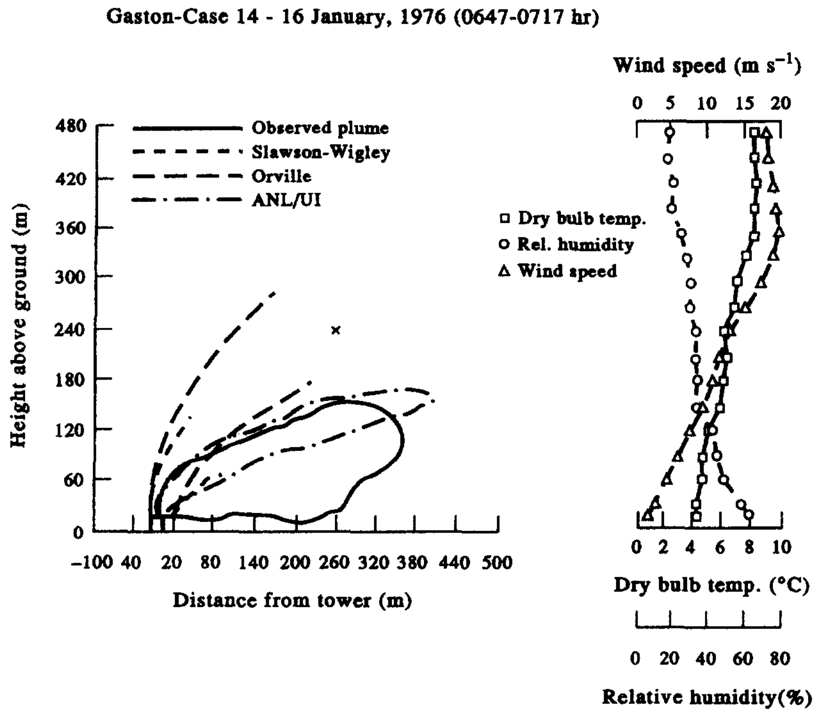


Fig. 6. Comparison of predictions of Slawson–Wigley (1975), Orville *et al.* (1980), and ANL/UI models with a verification field data case for the Gaston power plant, involving two 9-cell linear mechanical-draft towers. Each tower is 100 m long. The two towers are placed parallel to one another and separated by 140 m (Case G14). The X indicates the end of the visible plume for the Orville model, which does not give outline predictions beyond the point of subsaturation of mean properties.

partially evaporated drops or as dry particles of the dissolved solids. Plume liquid water droplets are pure recondensate droplets less than 20 microns in diameter which are included in the overall water budget of the dispersing plume.

The single-plume drift model is dependent upon the velocity and humidity field predicted by the plume model. A set of 10 drift models was included in a model validation study (Policastro *et al.*, 1980b) that used drift data from the Chalk Point dye tracer study, conducted 16–17, June, 1977 (Meyer and Stanbro, 1977). State-of-the-art model accuracy was established as prediction within a factor of three of sodium deposition flux, liquid mass deposition rate, number drop deposition flux, and average droplet diameter. Also, model performance was correlated with theoretical formulation. Four key elements of a drift model were identified: (1) plume dispersion model, (2) droplet evaporation formulation, (3) droplet breakaway criteria, and (4) drift deposition methodology. Sensitivity studies identified the most critical parts of the model.

The ANL/UI model was then formulated to use the single-plume model for plume dispersion to calculate the velocity, temperature, and humidity environment for drift drops (Dunn *et al.*, 1981). Temperature gradients and concentration gradients are taken into account in drop evaporation, along with ambient condition profiles as the drop moves. This droplet evaporation formulation has no adjustable parameters and includes results from new laboratory studies (Gavin, 1978, 1983). These and previous laboratory studies have established that the final state of a fully evaporated drop is not, as previously assumed, a solid sphere of solute. Instead, the final state is a "porous cap" or spherical shell of solid solute with well-determined inner and outer radii dependent on conditions during evaporation. Thus, a given drop will have a lower settling velocity with mass in the larger-radius cap configuration than it would in the smaller-radius solid sphere geometry. Drops will be predicted to fall farther out for the cap scenario for fully evaporated drops. These studies verified the nature of the final state and the predictions of the droplet evaporation formulation for drop sizes characteristic of typical drift spectra.

Five breakaway criteria have been used to determine where and when each drop size will cease advecting within the plume environment and begin to fall freely in the ambient atmosphere. Method 1 assumes that drops break away when their settling velocity becomes just greater than the updraft velocity at the plume centerline. Method 2 postulates that drops break away when their fall away from the centerline becomes larger than the local plume radius measured vertically. Method 3 pictures drops breaking away when their displacement from the plume centerline equals the initial plume radius. Method 4 treats plume properties as Gaussian-distributed, and has no sudden breakaway condition. Method 5 assumes a formula for the breakaway of each droplet size range depending on settling velocity, wind speed, and local plume radius. The criterion adopted for the ANL/UI model was to allow the droplet to break away suddenly when it has fallen a distance equal to the plume's momentum radius below centerline (Method 2).

Several methods for depositing drops that had evaporated either partially or to a dry particle were investigated. We selected the ballistic method, in which the central drop size droplet in each size range is advected with the wind and its vertical velocity is computed on the basis of the drop's varying size and mass as evaporation proceeds. From the velocities, the coordinates are integrated until the droplet is found to impact the ground. The impact points of the extreme drop sizes in the range are also computed and used to distribute the drop contents for the entire size range.

The Chalk Point study produced eight sampler values of sodium deposition flux, as well as values of droplet number flux, average droplet diameter, and liquid mass deposition flux at 0.5 km from the cooling tower. At 1.0 km there were 12 sampler values plus the other three data values. Thus, the study provides a total of 26 data values for model comparison. General model predictive accuracy is measured as a "factor of three", which means that a value between 0.33 and 3.0 times the predicted value lies within the error bars of the measured value. The most accurate models by this measure were the ANL/UI model and the Wolf model, which provided 25 of 26 predicted values within a factor of three. Given the predictive accuracy of the best plume rise models mentioned earlier and the dependence of drift predictions on the plume rise submodel, the prediction of drift values with less accuracy is understandable. Figure 7 compares the model's predictions to the data at the arc of 0.5 km samplers. The model/data agreement is seen to be reasonably good.

Because the ANL/UI model contains advanced droplet evaporation physics, it should be more accurate than other models in the 1–10 km region, where the smaller drops (including fully evaporated ones) are deposited. This region is of greatest concern for impact prediction, because it lies generally outside plant boundaries. Verification of the expected accuracy improvement must await the measurement of drift data for distances beyond 1 km.

2.4. *The multiple-plume drift submodel*

Because a detailed treatment of the multiple-plume drift submodel has been published (Policastro *et al.*, 1981b), we discuss only the highlights here. The droplet breakaway criteria, the motion of the drop up to breakaway, and the treatment of deposition parameters in the single-plume drift submodel were extended to predict drift from multiple plumes. Drops in each size range from each cell are followed to determine the horizontal and vertical coordinates of break-

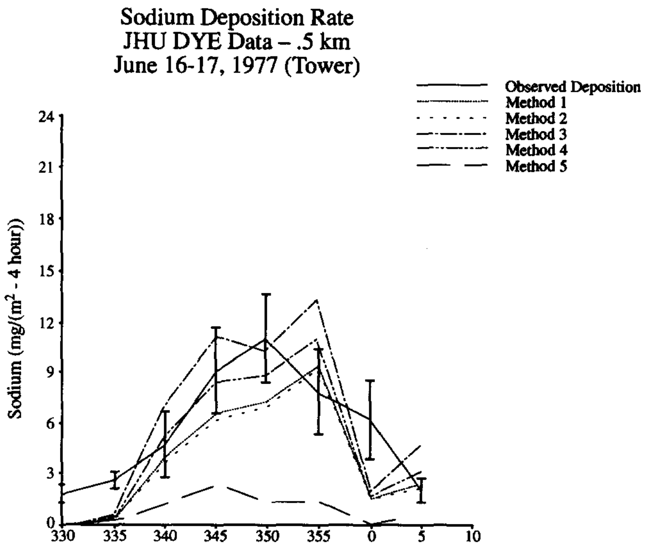


Fig. 7. Comparison of ANL/UI model predictions to measurements of sodium deposition flux from the single natural-draft tower alone (excluding stack drift) at fixed locations along an arc located 0.5 km from the cooling tower at Chalk Point, MD, on 16–17 June, 1977 (Meyer and Stanbro, 1977; Dunn *et al.*, 1981). Methods 1–5 refer to different assumptions for the droplet breakaway criterion as described in the text.

away relative to the dimensions of the partially or fully merged plume. Only drops from the upwind cell are modeled after breakaway. When a drop breaks away from the plume, its subsequent trajectory from the breakaway point and location of ground impact and deposition are computed by exactly the same methods as in the single-plume drift submodel. The ground deposition coordinates for drops of a given size from other cells are found from those for the first and from the actual breakaway coordinates by an interpolation/extrapolation procedure to decrease code execution time. To account for lateral displacement of deposition from cells other than the upwind one, a Gaussian distribution in angle is employed to spread the droplet deposition from that cell laterally to subsector or sampler locations.

The model was verified by using drift deposition data collected at Pittsburg, California (Webb, 1978; Laulainen *et al.*, 1979) in June 1978 from two 13-cell linear mechanical-draft towers oriented nearly along a common axis and separated by the length of a tower housing. On five different test days, sodium deposition data were collected on parts of seven arcs within 0.75 km of the geometrical center of the tower array. No adjustable parameters are used in the single-plume or multiple-plume drift deposition submodels. Figure 8 shows model/data comparisons for an entire arc. No other model was available that could handle the complexity of the Pittsburg towers. The ANL/UI model predictions were within a factor of three for 50% of the 58 reliable sampler values obtained in the experiment, which establishes the current state-of-the-art for multiple-plume drift deposition predictions.

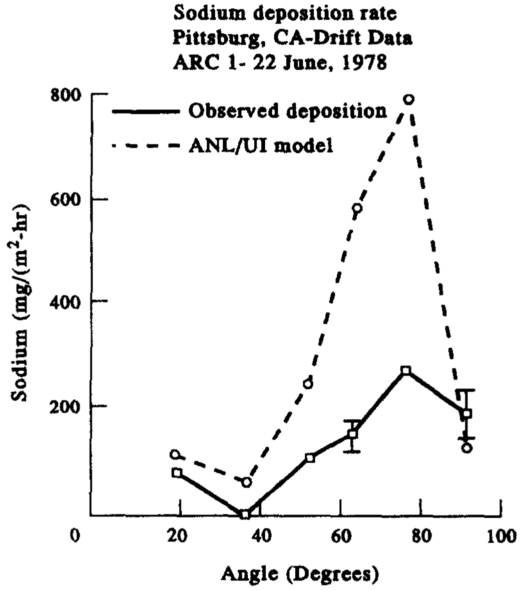


Fig. 8. Comparison of ANL/UI model predictions to measurements of sodium deposition flux from the two 13-cell linear mechanical-draft cooling towers on arc No. 1 at Pittsburg, California, for 22 June, 1978 (Webb, 1978; Laulainen *et al.*, 1979; Policastro *et al.*, 1981b).

2.5. *The fogging/icing submodel*

Ground fogging and rime icing have been observed for mechanical-draft towers. Persistent fogging or icing has not been observed for a natural-draft tower, but transient contact between plume puffs and the ground has been seen. (Snow falling from a plume has been documented several times at the Amos plant, but present models cannot predict snowfall.) Therefore, fogging and icing computations are excluded for natural-draft towers. When the ambient temperature is below freezing, ground fogging leads to deposition of rime ice on the ground and on elevated structures. The other documented form of icing, in which drift droplets impact on the ground or on structures and freeze, is not included in the model. Of available models, only the FOG model (Iaccarino, 1991) can predict ground-level humidity increases and fogging and icing resulting from the plume. Because reliable long-term data for these impacts do not exist, we must rely on the demonstrated accuracy of the plume model to justify the accuracy of the predictions.

To compute average hours of fogging and icing, 10 special categories were identified on the basis of fixed ranges of temperature, windspeed, and dewpoint depression (Carhart *et al.*, 1981). (Fogging and icing are heavily wake-dependent, and new categories should be established by users applying the model to towers of markedly different size or shape.) The categories are defined differently for linear than for circular mechanical-draft towers, because the downwash from the former is much stronger. The plume model is run for a representative case from each fogging/icing category, and the region of plume contact with the ground is determined in the near field out to 1.5 km. The 10 characteristic patterns are then distributed according to the frequency table of category by wind direction to obtain the number of hours of fogging/icing in each of the 240 sectors.

2.6. *The shadowing submodel*

Plumes cast shadows during daylight hours, thus reducing the solar energy reaching the ground. The model computes seasonal and annual averages of the following four measures of energy deposition loss on a horizontal surface: (1) hours of plume shadowing, (2) total (beam plus diffuse) solar energy, (3) percentage of total solar energy, and (4) percentage of beam energy (Carhart *et al.*, 1992).

Shadowing must be computed on an hourly basis and cannot be predicted using a plume category scheme, because even with a steady plume, the sun angles and resulting shadow positions vary continuously throughout a day. For each hour, the category-representative computed plume is used to obtain the shadowing, but the location on the ground of the simplified trapezoidal shadow is determined from the actual sun angles for that hour. Measured climatological averages of hourly cloudiness and the optical path length through the computed plume are combined to establish the solar intensity. The shadows cast by the cooling tower structure or by nearby buildings are not included in the predictions.

The method used in the ANL/UI model is more realistic than earlier methods in that it accounts for hourly changes in plume shape and direction, includes plume optical thickness, predicts physical measures of shadowing (energy loss), and accounts for hourly variation of sun angles. Typical correlations between time of day and plume length (e.g. long plumes tending to occur in the early morning) that may be site-specific are reflected in results obtained by this method. Although long-term average data do not exist in any form useful for integral modeling, some isolated values obtained in European impact studies verify the order-of-magnitude accuracy of the ANL/UI model predictions (Carhart *et al.*, 1992).

3. THE SEASONAL/ANNUAL SCHEME

In the United States of America, usually only hourly surface (10 m) meteorological data is available for long-term environmental impact assessment. Sometimes twice-daily mixing heights can also be obtained. Therefore, idealized boundary-layer profiles must be assumed to provide vertical profiles of meteorological variables for the detailed integral plume model. A simple schematization of the typical plume problem from a natural-draft cooling tower was shown in Fig. 1. In the ANL/UI model, we assume a power-law wind profile with stability-dependent exponent n, a linear temperature profile with stability-dependent lapse rate γ, and a uniform mixing ratio. The boundary layer conditions are assumed to hold up to the height of the capping inversion, obtained as an estimated mixing height. No attempt is made to calculate cloud base from the surface data and adjust plume length when the plume reaches the cloud layer. Thus the model overestimates plume visibility and therefore is conservative.

The following four nondimensional parameters were identified as most important in correlating with measured plume lengths:

- *The Richardson Number*, Ri, is the ratio of buoyancy flux in the plume relative to the momentum flux in units of the characteristic time (diameter/exit velocity). A large Ri value indicates a highly buoyant plume.
- *The Crossflow Velocity Ratio*, k, is the ratio of wind speed at the tower top to the exit velocity. A large k value means the wake has more effect on plume dispersion.
- *The Atmospheric Stability Class*, IS, has integer values from 1 to 7 that measure the relative convective stability or instability of the atmosphere. Unstable conditions occur for $IS<4$, and stable for $IS>4$.
- *The Plume Length Parameter*, L (divided by D), is a prediction of the plume length obtained by closed-form solution of the ANL/UI plume model assuming further simplified meteorological conditions and using a simplified entrainment formula (Carhart *et al.*, 1981). It depends on Ri, k, the ambient temperature, the assumed entrainment rate constant, and the saturation deficit.

The values of these parameters are site-specific, since they include exit temperature and velocity values predicted by the tower performance submodel for the hourly meteorological record. We determined that L, k, and IS were the parameters that most closely correlate with plume height and length for the available test cases. The correlation of the computed length parameter with observed plume length, for example, is illustrated in Fig. 9 for 39 cases used in previous single-tower validation work (Carhart *et al.*, 1981). These plume data cases had fully measured profiles of temperature, wind speed, and humidity, and included measured plume outlines. We have also checked the correlation for the idealized boundary layer meteorology assumed from the hourly surface measurements for one year of surface data, and the plume length predicted by the integral model correlates even more strongly with the plume length parameter.

As the meteorological data file is scanned by the preprocessor code, each hourly record is assigned to one of 864 bins on the basis of 96 ranges of L and 3 ranges each of k and IS. All meteorological data are averaged within a given bin. When the entire file has been scanned, the category-representative cases are calculated. Successive bins out of the 864 are lumped together until a percentage close to $100/N$ is obtained to form a category, where N is the user-specified number of detailed cases to be considered for each distinct wind direction. If a range in the length parameter already contains too large a percentage of hourly records, the three ranges in the k parameter are next used to subdivide the bin, which tends to associate cases with similar tower wake effects. If still more discrimination is needed within the k ranges, then the stability class ranges are used. For densely populated plume length regions, this division associates plumes with similar rise heights. This method ensures use of categories that are approximately equally populated.

Average output conditions and average meteorological data are available for each of the 864 bins. Each category now contains a collection of the original bins, and a further weighted average of output and meteorological data is performed within the category to define the meteorology and tower exit data for that category. If the user specifies fogging/icing calculations, then an additional 10 categories are provided for each significant wind direction, as discussed above, to allow detailed computation of fogging and icing.

The detailed plume model code, which receives most of its input from the preprocessor code, computes the category-representative plume and drift

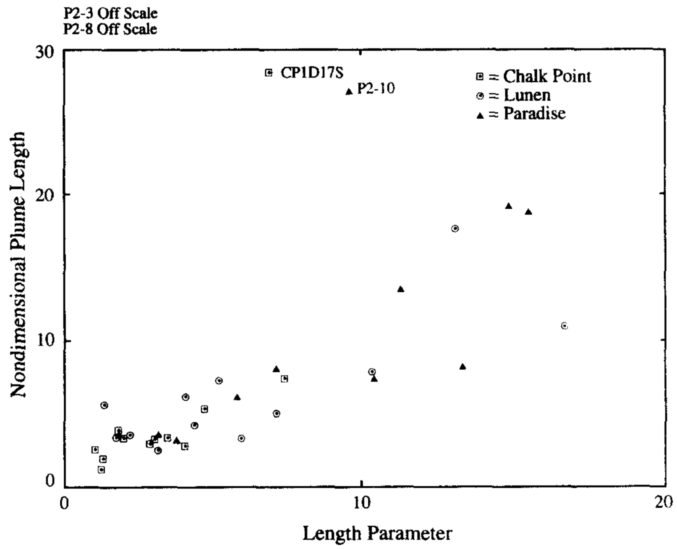


Fig. 9. Comparison of predicted plume length based on length parameter (length prediction of simplified model in diameters) with observed plume length (in diameters) for 39 plume rise data cases for single natural-draft towers.

cases for each significant wind direction. The plume rise for a given category, especially for fogging/icing cases, can depend significantly on wind direction. The simplest natural-draft example would be a set of towers along a line (as for the three towers at Amos), where the plumes will merge differently for wind along the line of towers than for wind at right angles to the line of towers. The same observation applies to a single linear mechanical-draft tower or a set of several.

For a single circular mechanical-draft tower, the symmetry of the tower suggests little wind-direction dependence, but for two such towers, there would be a difference between crossflow and in-line orientations of the wind. However, the three natural-draft towers at Neurath, which form an equilateral triangle, have considerable symmetry. For this case, one wind direction would probably give nearly the same results as two or three. The user can decide how many unique wind directions to define and must indicate which wind directions (out of the 16 usual meteorological directions) will be equivalent. For example, for a single linear mechanical-draft tower, there are two in-line directions and two crossflow directions, and the directions on each side of in line might be considered equivalent to in line. A number of examples of these choices are given in the user's manual (Policastro *et al.*, 1984). Each category is computed for each user-specified wind direction, so that the effective number of detailed runs of the plume rise model is N times the number of wind directions. Three unique wind directions are usually enough, and two often capture much of the directionality.

The TABLES code provides the final stage in predicting average impacts. It relies on the expanded meteorological record that was produced by the preprocessor by adding to each hourly record such other useful data as the plume length parameter, k, and IS. The hourly records are scanned in this expanded form to accumulate frequency tables by bins (864). These frequency tables are combined using the categories defined by the preprocessor code to produce frequencies of category by wind direction. Then the tables are merged with the detailed category plume and drift predictions to distribute the various environmental impacts in the 16 directional sectors and into the radial subsectors. The averaging method is straightforward and obvious for all effects except shadowing, which was covered earlier.

4. EXAMPLES OF SEASONAL/ANNUAL AVERAGE IMPACTS

In the absence of seasonal or annual average impact data for model/data comparison, two hypothetical installations are used to illustrate typical results. Both installations are assumed to be located in Syracuse, New York, which was chosen because it has a climate sufficiently cold to produce ground icing and sufficiently humid to produce longer than average plumes. Our first example is a pair of parallel 9-cell linear mechanical-draft towers, each cooling about 350 MWe (a common configuration). Our second example, for comparison, is a single natural-draft tower of typical height. Such a tower normally cools only 500 MWe, while the two hypothetical mechanical-draft towers together cool 700 MWe. For the comparison to be valid, the diameter, heat release rate, and drift rate of the natural-draft tower had to be increased by 40%.

A full analysis of the linear mechanical-draft example requires from 1 to 6 h on a typical (1992) 386- or 486-based personal computer, depending on processor and disk-access speeds. The runs we made exercised all computation options, including the use of an hourly surface meteorology tape and a mixing height tape from the U.S. National Weather Service. The towers were assumed to be parallel, aligned NW to SE, and separated by 1.5 housing lengths. Three wind directions were used: (1) NW and SE, (2) NE and SW, and (3) N, S, E and W. The other eight directions were considered equivalent to direction (1) or (2), depending on which is adjacent. The measured drift spectrum from Pittsburg, California, (Webb, 1978; Laulainen *et al.*, 1979) was used, along with the cooling water characteristics from that experiment.

The natural-draft tower example was much simpler than the mechanical-draft tower case and required only one-fourth the computer time. All wind directions were equivalent, and no fogging/icing calculations were done. For this example, the drift spectrum, the salt concentration, and the salt density were taken from the Chalk Point experiment (Meyer and Stanbro, 1977).

The system provides a variety of outputs. We focus here on contour plots of environmental impacts. The five-year average wind rose for Syracuse is shown in Fig. 10 as an aid to interpreting the contour plots.

Figure 11 shows the contour plots of the annual average plume length frequency. The contours largely align with the wind rose. However, southerly winds tend to be associated with shorter predicted plumes: the low frequency of plumes predicted to extend beyond 200 m north of the sources is much less than the 13% expected from the wind rose for winds from the SSE, S, and SSW. This tendency means that for southerly winds, the relative humidity tends to be low and the temperature high, which can be verified from the tables of temperature frequency by wind direction generated in the preprocessor step. While similar in shape, the contour plots for the two sources differ in that the natural-draft tower produces more plumes in the mid-lengths beyond 2.5 km in all directions except S, SSW, and SSE. This reflects the fact that the merging cell plumes from the linear mechanical-draft towers provide more early mixing, as does the additional turbulence in the wake of the large housings. The linear mechanical-draft plume dilutes more rapidly and tends to be shorter, although these effects are moderate.

Figure 12 shows contours of drift deposition. The site wind rose clearly influences the areas where salt is deposited. The subsectors east and west of the towers receive the greatest deposition. For the linear mechanical-draft towers, the deposition beyond 2 km is quite small—less than 5 kg over a square kilometer per month. The corresponding value for the natural-draft

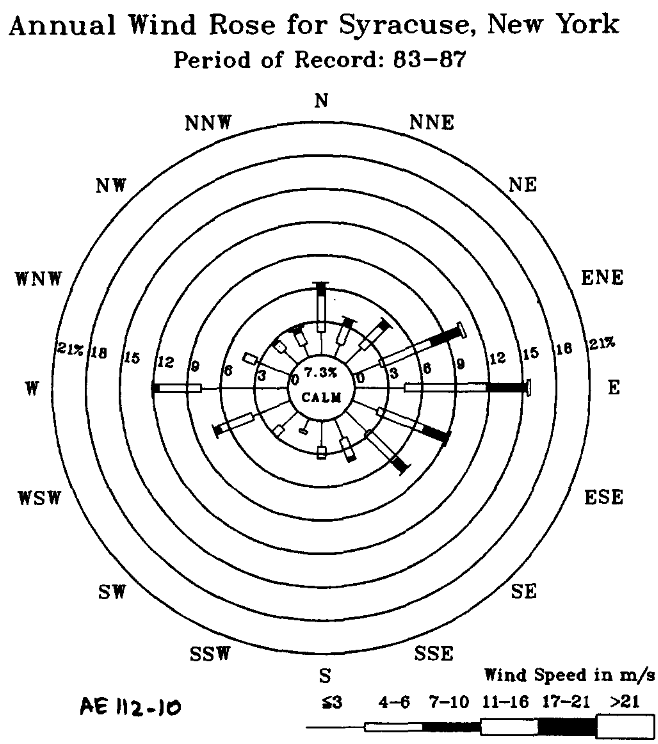


Fig. 10. Average wind rose for Syracuse, New York, for 1983–1987. The bars lie in the direction toward which the wind is blowing.

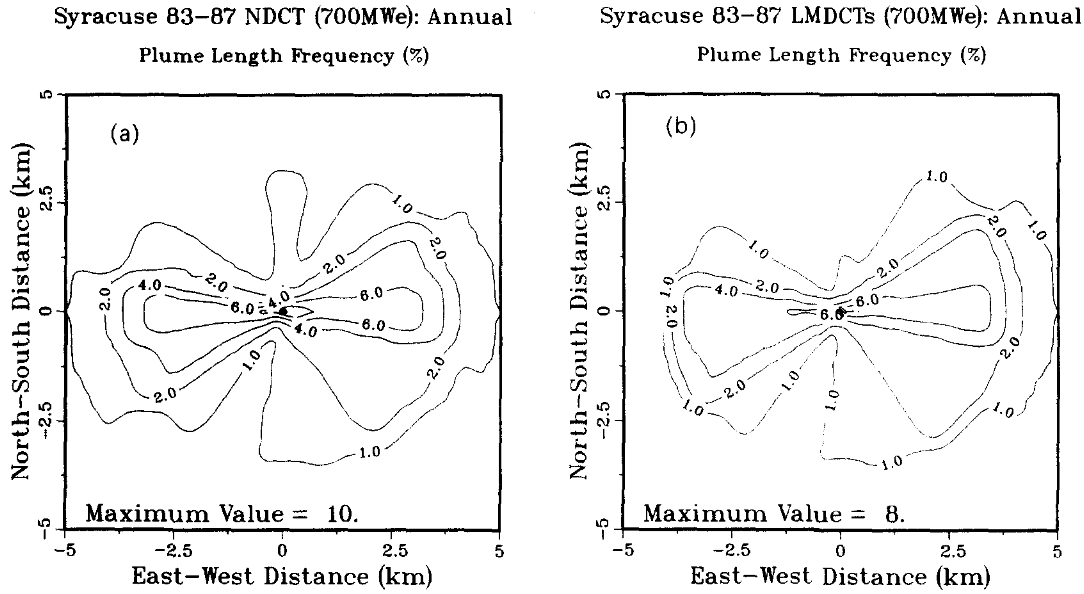


Fig. 11. Plume length frequency contours in percent for (a) the natural-draft tower example and (b) the linear mechanical-draft towers example.

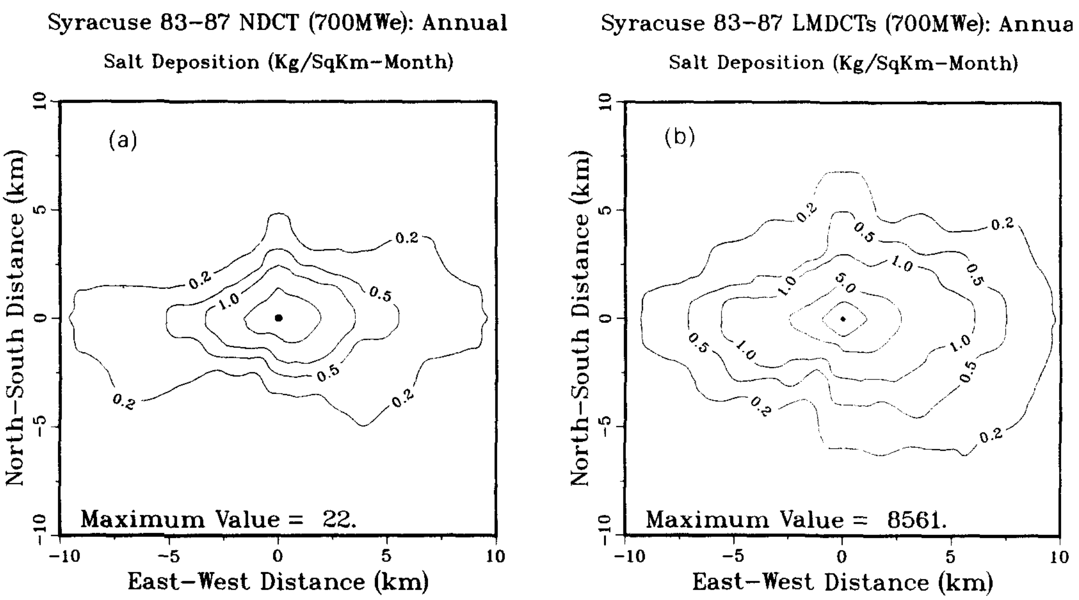


Fig. 12. Ground salt deposition in kg/km^2-month for (a) the natural-draft tower example and (b) the linear mechanical-draft towers example. The quoted maximum values occur very close to the towers. Unlabeled contours are 2.0 (NDCT) and 10.0 (LMDCT).

tower is less than 2 kg per month over a square kilometer. The drift from the natural-draft tower is spread over a larger area farther from the towers than the drift from the linear mechanical-draft towers, as expected from the fact that the drop spectrum of the natural-draft tower is skewed toward smaller diameters than that of the linear mechanical-draft tower. Also, the total natural-draft tower drift rate is only two-thirds that of a comparable linear mechanical-draft tower, mainly as a result of lower exit velocities. The lower drift rate is reflected in the smaller areas of the higher contours for the natural-draft tower plot.

Figure 13 illustrates predictions of annual average total solar energy loss on a horizontal surface. For both source types, less than 1% of solar energy is lost outside of plant boundaries (beyond 1 km from the towers). Because the natural-draft tower emits plumes of a smaller radius located at a greater height, it

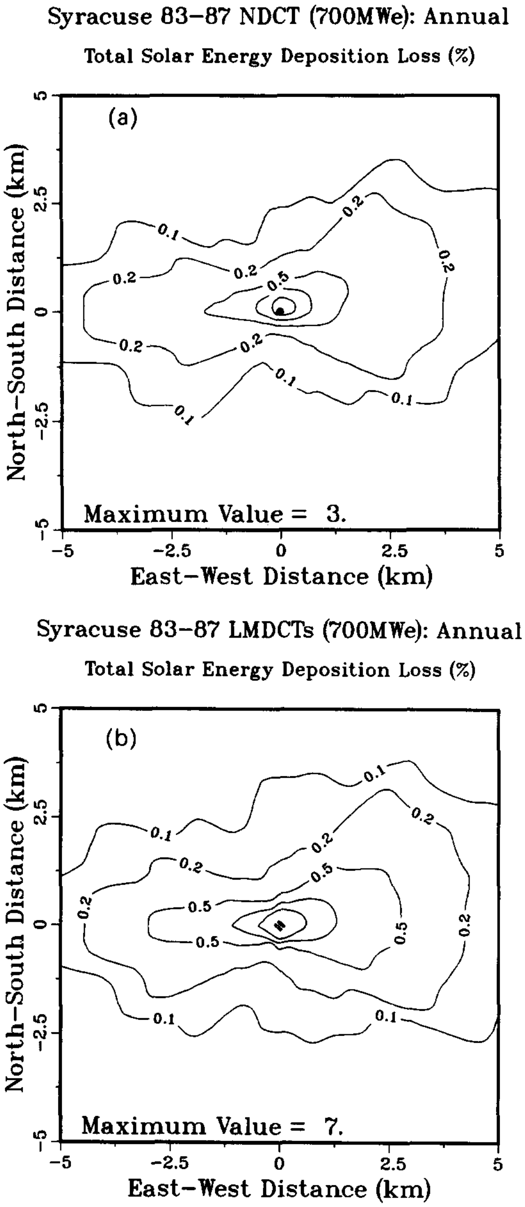


Fig. 13. Ground contours of percentage of total annual solar energy lost as a result of shadowing for (a) the natural-draft tower example and (b) the linear mechanical-draft towers example. Unlabeled contours are 1 and 2%.

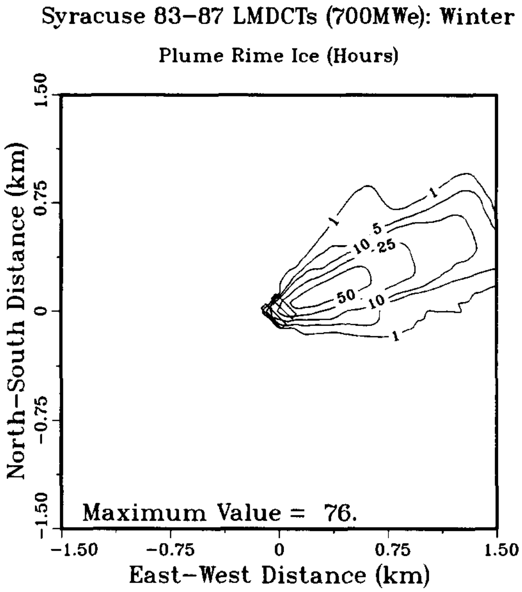


Fig. 14. Ground contours of hours of rime icing for the linear mechanical-draft towers example averaged over the winter season (Julian days 355–059). The innermost contour is 50 h.

produces less shadowing than the linear mechanical-draft towers at all distances, but especially near the towers.

Finally, Fig. 14 shows the predicted hours of rime icing at ground locations surrounding the towers for the linear mechanical-draft example for the winter season. The model predicts a few hours of icing during the spring as well, but none during summer or fall. It is of interest that icing is predicted to occur only with winds from the W, WSW, and SW directions at Syracuse. Ground icing requires a conjunction of high winds and below-freezing temperatures, which only occurs with these winds. Near the towers the maximum number of icing hours is predicted to be 76, and the 50-h contour reaches only 0.5 km from the center. The 1-h contour lies within 1.5 km of the towers, which normally would fall within plant boundaries. For this site and tower installation, icing might be a problem within the plant boundaries in winter, but would probably never impact the surrounding community. Fogging would be more frequent, however, and could cause difficulty if the towers were too near a public roadway or other transportation corridor.

5. CONCLUSIONS

The ANL/UI system of codes for modeling seasonal and annual cooling tower environmental impacts embodies an efficient and reliable methodology for predicting the physical impacts of cooling tower emissions. The system can be run on widely available microcomputer systems. The codes and sample input data for test cases are available for a nominal fee from the Electric Power Research Institute (EPRI, 3412 Hillview Ave., Palo Alto, CA 94304).

Our use of extensive U.S. and European data in the calibration and validation of the model is the main reason for the theoretical advances embodied in the model and for its accurate predictive performance. Because each submodel has been calibrated and validated with the data available, each represents state-of-the-art predictive accuracy. Basic physical principles have been emphasized in each submodel. The drift submodels are particularly complete in their physical basis, containing no adjustable parameters. In these submodels, all coefficients have a direct physical and experimental basis.

The category scheme allows state-of-the-art submodels to be combined into a detailed integral model that can be used with reasonable computer resource requirements. The system meets the requirements of most regulatory bodies. It has been extended for small towers for the U.S. Environmental Protection Agency (USEPA) by adding an improved tower performance submodel and taking into account the effects of turbulent atmospheric dispersion (as opposed to ballistic deposition) on the distribution of drift droplets (Policastro *et al.*, 1988). The USEPA has used the model in evaluating the relative environmental impacts of hexavalent chromium emitted from refinery cooling towers. These improvements to the model are, however, not included in the version available from EPRI.

To make further progress in modeling seasonal/annual cooling tower impacts, it will be necessary to obtain long-term average data for impacts such as drift deposition, shadowing, and plume frequencies. Data on fogging and icing near towers would assist in validating those particular submodels in the ANL/UI system, and would also provide a stringent test of the plume submodel downwash formulation.

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