Atmospheric Environment Vol. 26A, No. 15, pp. 2845–2852, 1992.
Printed in Great Britain.

0004–6981/92 $5.00+0.00

AN IMPROVED METHOD FOR PREDICTING SEASONAL AND ANNUAL SHADOWING FROM COOLING TOWER PLUMES

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(*Received 5 September* 1990 *and in final form* 10 *May* 1991)

Abstract—An improved model developed at Argonne National Laboratory and the University of Illinois (ANL/UI) for predicting long-term shadowing due to cooling tower plumes is presented, and its assumptions are compared with those used in previous models. The model is based on a method for the selection of representative categories of similar plumes developed by Dunn and Policastro (Dunn, 1980, *Proc. IAHR Cooling Tower Workshop*, San Francisco; Policastro *et al*., 1984, Report EPRI CS-3403-CCM). At a given site this method reduces the large number of meteorological data cases in a season or year to a much smaller number (≈35) of representative cases, each of which will have a predicted plume substantially different from the others. Plume predictions for the reduced set of category representative cases are then made with the validated ANL/UI plume model. With category representative plume shape, wind speed, wind direction and sun angles available for each hour, full effects of sun angles for the latitude and longitude of the site to be studied are included. The ANL/UI model yields seasonal and annual isopleths of hours of additional shadowing or of percentage reduction in total and direct solar energy arriving at the ground on a horizontal surface. Results for two hypothetical sites with 500 MWe generating capacity are presented and contrasted, one at Syracuse, NY, and the other at Spokane, WA.

Key word index: Electrical energy generation, plume shadowing, solar radiation.

1. INTRODUCTION

In the past 20 years, natural-draft cooling towers (NDCTs) and mechanical-draft cooling towers (MDCTs) have been used extensively as a means of reducing the thermal impact of electrical energy generation on water bodies. A variety of environmental effects of these towers have been studied, both from the theoretical and the experimental viewpoints. One important effect that has been measured in the field (Berge *et al*., 1975; Ryznar, 1978) is the shadowing of ground areas by the plume. However, what has yet to be determined is whether cumulative annual shadowing from a group of cooling towers will have an adverse impact on crop growth in nearby agricultural fields, on solar energy production capacity from neighboring solar collectors or on recreational uses of contiguous lands (e.g. a bathing beach).

For plume shadowing (as for other plume environmental effects), it is desirable to have an inexpensive, easily usable, validated model to predict seasonal and annual plume shadowing at a proposed power plant site in order to make intelligent siting decisions. Because adequate seasonal and/or annual shadowing data are not available, a shadowing model cannot be fully validated at present. However, reasonable models for calculating plume shadowing by using validated plume-rise methods have been constructed and can be strengthened theoretically.

This paper presents an improved model for predicting seasonal and annual shadowing. The model was developed as part of a larger project sponsored by the Electric Power Research Institute (EPRI) to embed the validated ANL/UI plume and drift models into a system of codes for easily predicting a variety of seasonal and annual cooling tower effects.

Section 2 considers the usefulness of several measures of plume shadowing, and Section 3 reviews the two previously existing methodologies for computing shadowing effects from cooling towers. Section 4 describes the new ANL/UI model approach, including a brief review of the Dunn–Policastro category scheme used for associating plume predictions with hourly meteorological data (Dunn, 1980; Carhart *et al.*, 1981; Policastro *et al.*, 1984). Finally, Section 5 presents model results for two hypothetical sites: Syracuse, NY, and Spokane, WA.

2. MEASURES OF SOLAR INSOLATION REDUCTION

2.1. *Physics of solar insolation*

At the Earth's surface, visible sunlight is composed of a direct (beam) and a diffuse (scattered) component. A flat-plate solar collector accepts both components, but a focusing collector accepts primarily the direct component. Vegetation utilizes both components of the sun's energy flux. However, a natural cloud or a plume from a cooling tower removes primarily the direct component, and thus has minimal effect on the diffuse component. Some of the absorbed direct component is not converted to other wavelengths, such as infrared, but is scattered in other directions. For example, measurements of the solar energy flux just beyond the edge of the plume shadow have yielded values higher than those that would have been obtained if the plume were not present (Berge *et al.*, 1975; Ryznar, 1978). Presumably, such results are due to side-scatter from the visible plume. Similar increases have also been noted when natural cumulus clouds are present (Weseley and Lipschutz, 1976).

2.2. *Measures of shadowing*

Three measures of shadowing have received some theoretical or experimental attention:

(a) *Hours per season or year when the visible plume is overhead*, although not a direct measure of shadowing, can be correlated with shadowing to some extent. As used by Dunn and Policastro (1978) in a study of alternate sites for the Seabrook nuclear power plant in New Hampshire, the measure included both day and night hours, because plume overhead at night was deemed to be an undesirable impact for some recreational uses of nearby land.

(b) *Hours of shadow per season or year* is a useful measure if the presence of any shadows is known to have a detrimental effect. As usually employed, it includes daylight hours when the sky is heavily overcast, and shadows block only about 20% of the solar energy flux (Berge *et al.*, 1975).

(c) *Reduction in solar energy flux per season or year on a horizontal surface* has not previously been calculated in models for plume shadowing, even though all anticipated environmental impacts besides interference with recreational use, depend on the change in energy flux. A breakdown of this measure into reduction in direct and diffuse solar components is very helpful in quantifying the loss of sunlight available both for energy and for crop production purposes.

The ANL/UI model discussed in this article provides users with three measures of shadowing: (1) hours of shadowing, (2) reduction in total solar flux on a horizontal surface ($\mathrm{MJ\,m^{-2}}$), and (3) reduction in direct solar flux on a horizontal surface ($\mathrm{MJ\,m^{-2}}$).

3. MODELS AND METHODS FOR COMPUTING SEASONAL AND ANNUAL SHADOWING

3.1. *Hourly computations with a highly simplified model*

The earliest method for computing the seasonal or annual environmental impacts of cooling tower plumes involved making plume predictions for each hourly meteorological record. The well-known Oak Ridge Fog and Drift (ORFAD) model (LaVerne, 1976) uses this approach. Because of the sheer number of hourly records in a year, or even a season, it is too costly to use a detailed plume model for each hour. Therefore, in this method the hourly plumes are calculated with a highly simplified set of plume and drift models. This method seems to make maximum allowance for hourly variations in specific plume configurations and in sun angles. Unfortunately, in ORFAD the sun is always assumed to be directly overhead during daylight. Furthermore, validation studies (Policastro *et al.*, 1979) have shown the relative inaccuracy of the ORFAD model, and other highly simplified models, for individual plume cases.

3.2. *Computation of typical plumes with a detailed model*

A better method was developed by Motor Columbus Consulting Engineers of Baden, Switzerland, in their KUMULUS model (Fuchs and Hofman, 1980). They assumed that, except for wind direction, only a limited number of significantly different plumes occur at a particular site. Therefore, a more realistic, validated plume model was used to predict a small set of representative plume cases. The categories were established by fixed ranges in relative humidity, temperature and wind speed. An average set of tower conditions and meteorological data was chosen for each category, and detailed model predictions were made for each category. Category representative cases were selected so that their combined wind rose equals the seasonal site wind rose. Because the European twice-daily upper-air soundings are used for impact studies by Motor Columbus, the set of meteorological conditions for a category representative was assumed to apply to an entire day. Practical experience in applying the KUMULUS model has shown the need for about 200 categories to predict shadowing and other impacts.

The probability of occurrence of each category by season was calculated from the hourly data tape records. In a given direction, seasonal and annual results for plume length, drift deposition, shadowing and other effects were then computed by adding the resulting effect from each category-representative prediction, as weighted by its probability of occurrence in that wind direction. Although the computed plume was assumed constant throughout a day, for cumulative shadowing the shadow of the plume was computed at hourly intervals. The plume was assumed to be opaque, with the complex shape of the shadow approximated. This approach clearly included the effect of variable sun angles. For example, in the Northern Hemisphere the shadowing pattern was shifted toward the north side of the site, because the sun spent most of the time in the southern sky.

4. THE ANL/UI METHOD

The assumptions behind the ANL/UI model are similar to those of the KUMULUS model, but major improvements have been made in four main areas: choice of categories, hourly idealized plumes, average solar insolation and partial absorption by the plume.

4.1. *Choice of categories*

In the ANL/UI model, as in the KUMULUS model, each hourly reading is assigned to a category. However, in the ANL/UI model categories are defined by selecting ranges in three non-dimensional parameters that correlate well with visible plume length and rise: (1) composite plume length parameter (Dunn, 1980; Carhart *et al.*, 1981), (2) stability class, and (3) wind speed-to-exit velocity ratio. In the KUMULUS model, categories are chosen based on fixed ranges in humidity, temperature and wind speed. As a result, some categories contain a wide range of plume lengths (Juersch, 1978), and the category populations can vary widely, thereby placing undue emphasis on certain categories at the expense of others. Alternatively, the parameter ranges for each category in the ANL/UI model are allocated dynamically so that all categories have roughly equal populations, and the choice of parameters guarantees that all plumes in a category are similar.

Instead of the KUMULUS model's 200 categories, the ANL/UI model methodology requires only about 35 categories for each independent wind direction needed to capture the effects of source geometry. Because the ranges of parameters defining the categories more closely correlate with physical differences in predicted plumes, this decrease in the number of categories in the ANL/UI model is accompanied by an improvement in the model's accuracy. In addition, by decreasing the number of categories needed the ANL/UI model allows the use of 35 categories for several representative wind directions for the same cost as running the KUMULUS model's 200 categories. In this way the effects of multiple-source geometry can be predicted with better accuracy.

As in the KUMULUS model, each hourly record in a suitable averaging period (e.g. 5 years) is assigned to a category, and frequency of occurrence tables are accumulated by wind direction. The validated ANL/UI plume model is then used to make detailed plume and drift predictions for the category. For all plume environmental effects except shadowing, the effects calculated for the category representatives are combined according to the frequency-of-occurrence tables as a function of wind direction.

This first improvement in the model affects all of the environmental impacts. For shadowing, however, the information retained for each category includes height of rise of the visible plume above the tower, visible plume length and final visible plume radius. Three additional improvements are made in the calculation of average shadowing.

4.2. *Hourly idealized plumes*

The second major improvement in the model involves a more realistic representation of the effects of sun angles on shadow location. The ideal, but excessively expensive, method would be for each hour with the actual sun angles to map out fully the complex shadow shape for that hour's category-representative case, including the detailed plume trajectory and the radial growth. The KUMULUS model avoids excessive cost by simplifying the shape of the shadow of the plume, and by assuming that a single category applies to all hourly meteorological conditions present in a single day. In the model, the sun is allowed to rise, move across the sky and set, while hours of shadowing are accumulated in sectors on the ground. During the entire day, the plume is assumed to be the same size and shape, and to lie in the same direction. Using these assumptions one cannot account for possible correlations between wind direction and plume length, nor correlations between times of day and considerably longer or shorter plumes, such as long plumes early in the morning during cooler, more humid conditions in general.

By contrast, with the ANL/UI model, ground-sector shadowing is calculated for every hour on the data tape using the plume parameters, the prevailing sun angles and the wind direction unique to that hour. Extensive computation time is avoided by simplifying the shadow geometry. The plume is approximated by a section of a cone, as shown in Fig. 1. A line is drawn from the center of the outlet at the exit plane to the centerline of the plume at the point where it disappears. This line becomes the cone axis and the length of the truncated section is the segment length. The smaller radius of the section is taken as the tower outlet radius, and its larger radius is the maximum visible plume radius. Such an object will approximately cast a quadrilateral shadow, as drawn in Fig. 2, with its proportions, location and size determined by the plume height and final radius, and the sun's azimuth and declination angles.

In another geometrical simplification, the shadow for a single hour is assigned to standard subsectors formed from the intersection of 16 angular rays (16 wind directions, every 22.5°), with 50 circles, spaced

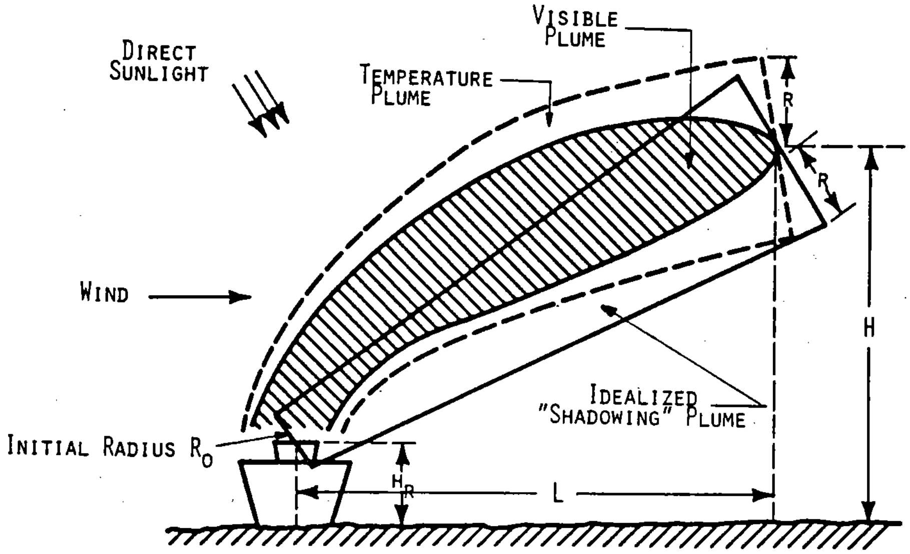

Fig. 1. Simplified plume shape assumed in the ANL/UI model for shadowing.

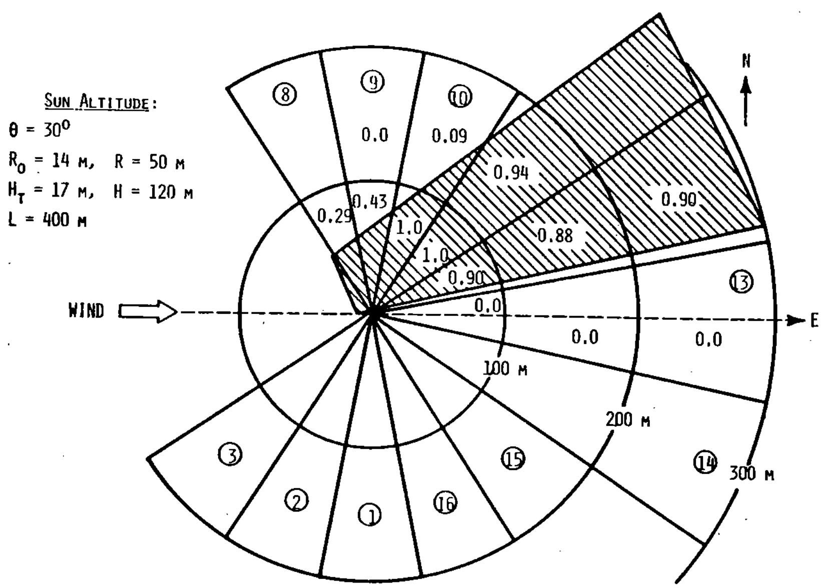

Fig. 2. Simplified ground shadow shape assumed in the ANL/UI model as a result of the assumed plume shape illustrated in Fig. 1. The fractions of an hour of shadowing assigned to several subsectors due to this shadow are indicated.

every 0.2 km out to 10 km. The center of each subsector is checked with a simple algorithm to determine if it lies in the parallelogram shadow. If so, the entire subsector is considered to be shadowed; if not, no shadow is included in that subsector for that hour. For individual plumes, this procedure can distort the calculated location of the shadow somewhat. However, our sensitivity tests carried out by further subdividing all subsectors (into four and nine pieces) have shown that the seasonal and annual isopleths change very little. The ANL/UI model makes such subdivision into $M \times M$ smaller subsectors a user-selectable option.

4.3. *Average solar insolation*

The third improvement contained in the model involves estimating the solar insolation on a ground-level horizontal surface and its balance between diffuse and direct components from the hourly meteorological data.

At present, reliable average hourly direct (beam) and diffuse (scattered) components of the solar flux at ground level cannot be predicted from data contained in commonly available weather tapes. However, in solar energy design work, considerable progress has been made in predicting reliable long-term average daily and hourly values of direct and diffuse solar energy flux (Collares-Pereira and Rabl, 1979; Liu and Jordan, 1969). Such predictions require a site's latitude and longitude, the monthly clearness indices (K_i), and the average daily total solar flux on a horizontal surface at sea level for each month of the year (H_i). As a result of the SOLMET program (NCC, 1978), monthly values of K and H are available at about 200 sites across the continental United States, Canada and Alaska. (These values vary smoothly with location, thereby allowing interpolation to most intermediate sites.)

Using the formulas of Collares-Pereira and Rabl (1979), which are extensions of the work by Liu and Jordan (1969), and the SOLMET values of K_i and H_i, we have defined the average diffuse and direct solar flux for each day on an hourly basis. Although these hourly fluxes do not represent the actual solar fluxes for that date and hour, they accurately represent climatological average fluxes for that date and hour.

4.4. *Plume absorption*

The final improvement to previously used methods included in the ANL/UI model involves estimating the fraction of the direct component of solar insolation absorbed as it traverses the plume, instead of assuming that the plume is opaque as does the KUMULUS model. In the ANL/UI model the absorption of the diffuse component of solar insolation is neglected, because this component is radiated toward the ground from all angles, and the plume will intercept only a small fraction of it. The partial absorption of the direct solar flux by the plume is accounted for approximately by assuming that all rays intersecting the plume pass through a thickness of plume material equal to the final visible plume diameter. This approximation is clearly conservative, because it overestimates the energy reduction. The fraction of direct solar energy absorbed will depend on the liquid water content of the plume, as well as on the path length through plume cloudwater droplets. This absorption is fairly well known for natural clouds, and could be included in the model. However, the added complexity and expense introduced by accounting for droplet content and varying path length do not seem justified given the other approximations made in the model and the uncertain accuracy of model predictions of plume liquid water content.

Instead, therefore, we have chosen to assume that the visible plume has a standard optical thickness, calibrated from actual plume solar absorption data (Berge *et al.*, 1975). The assumed fraction, f, of direct solar energy absorbed in passing through a thickness, d, of plume material is

$$f = 1 - \exp(-0.0165\ D),$$

where D is the maximum visible plume diameter (m). The 65 m thickness of the visible plume on which the measurements were made absorbed about 65% of the incident direct flux on a horizontal surface at the center of the shadow when the sun was directly overhead, fixing the coefficient as 0.0165.

When the assumptions made in the four areas discussed above are combined in the ANL/UI model, the resulting isopleths of hours of shadow and of percentage reduction for direct and total solar energy deposition are expected to contain the effects of time of day, time of year, plume length, wind direction and partial absorption of sunlight in the plume. Except very close to the tower, the estimates are expected to be conservative, since most of our assumptions overestimate shadowing. Within 100–200 m of the tower, however, the model could underestimate shadowing, because the reduction in sunlight due to the tower's own shadow is not included.

5. RESULTS

The ANL/UI seasonal/annual plume shadowing prediction model was applied to two hypothetical sites with hourly meteorological data for the 5 years, 1983–1987: one site in Spokane, WA, and the other in

Table 1. Comparison of average (1983–1987) meteorological and solar insolation data between the Spokane and Syracuse sites

Meteorological parameter	Spokane	Syracuse
Average dry bulb temperature (°C)	8.6	8.8
Average relative humidity (%)	67.1	74.5
Average wind speed (m s^{-1})	4.4	4.2
Percentage of calm hours	5.7	6.8
Average stability class (1–7)	4.2	4.3

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Clearness index												
Syracuse	0.410	0.430	0.470	0.470	0.520	0.560	0.580	0.550	0.530	0.490	0.360	0.370
Spokane	0.470	0.560	0.560	0.610	0.600	0.610	0.700	0.670	0.640	0.470	0.460	0.350
Average total daily solar energy deposition												
Syracuse	5.40	8.08	12.14	15.66	20.26	23.11	23.36	19.72	14.99	10.09	5.19	4.31
Spokane	4.94	8.91	13.26	19.53	23.25	25.30	27.73	23.17	17.02	8.62	5.48	3.18

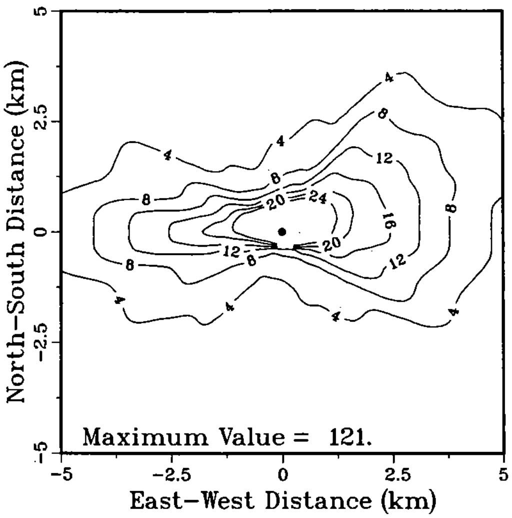

Fig. 3. Isopleths of average annual horizontal surface energy loss (MJ m^{-2}) for Syracuse using meteorological data for the years 1983–1987 and assuming a single NDCT dissipating heat from a 500 MWe generating unit.

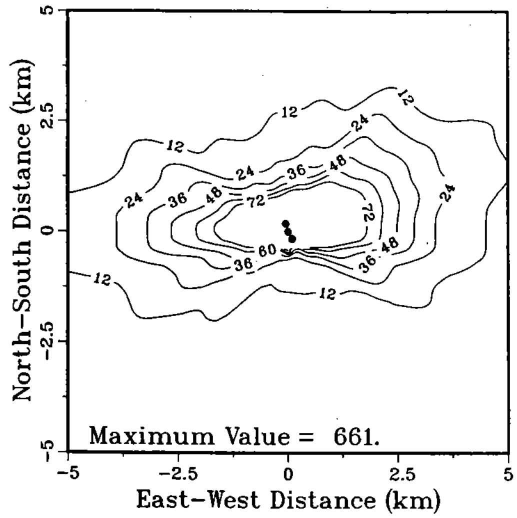

Fig. 5. Isopleths of average annual horizontal surface energy loss (MJ m^{-2}) for Syracuse using meteorological data for the years 1983–1987 and assuming three NDCTs, each dissipating heat from a 500 MWe generating unit. The NDCTs are assumed to lie approximately in a line, as indicated by the dark circles.

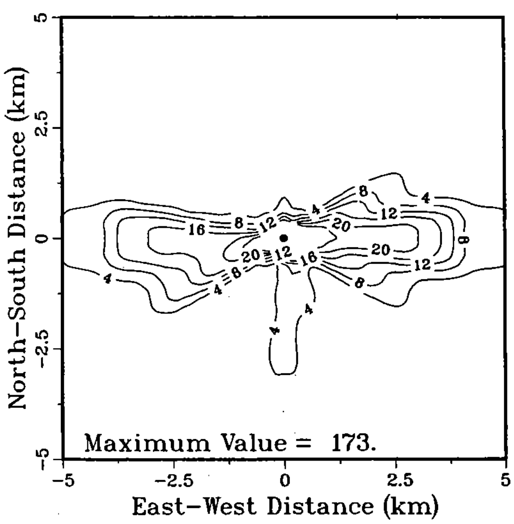

Fig. 4. Isopleths of average annual horizontal surface energy loss (MJ m^{-2}) for Syracuse using meteorological data for the years 1983–1987 and assuming a single NDCT dissipating heat from a 500 MWe generating unit. For this figure the sun is assumed to be directly overhead during all daylight hours.

Syracuse, NY. The predominant winds at Spokane are primarily from the southwest, and secondarily from the northeast, while at Syracuse they are predominantly from the west, and secondarily from the east. The differences between these wind roses are substantial, and clearly show up in the shadowing predictions.

In Table 1 the annual average values of dry bulb temperature, relative humidity, stability class and wind speed are presented. The two sites have similar average wind speeds, temperatures and stability classes. The relative humidity averages 7.4% higher at Syracuse than at Spokane. The two sites also share similar values of the percentages of cases in each range of the meteorological variables (not shown), except for relative humidity. Also given in Table 1 are the clearness indices and the total average daily solar insolation values for the two sites for each month. The more northerly location of Spokane (47.4°N, 76.1°E) shows up in its higher daily insolation values in the summer months and its lower values in the winter. The tendency toward greater cloudiness at Syracuse (43.1°N, 117.7°W) shows up in its lower clearness indices, which also contribute to reduced summer total solar insolation. The main differences, then, are in the directional aspects of the wind roses and in the somewhat clearer and drier conditions at Spokane.

Figure 3 shows the results of the ANL/UI model run for hourly meteorological data from 1983 to 1987 at Syracuse. The isopleths show average annual total solar energy loss on a horizontal surface in MJ m^{-2} due to plumes from a hypothetical NDCT dissipating heat from a 500 MWe generating unit. The effects are distributed mainly along an east–west direction, with shadowing stronger to the north of the tower. The dominance of easterly and westerly winds at Syracuse confirms this behavior. The maximum loss was 121 MJ m^{-2}. The mean daily insolation values from Table 1 indicate that the annual average total at Syracuse is 4950 MJ m^{-2}, resulting in a maximum loss of only 2.4%. The 24 MJ m^{-2} contour, which reaches points 1.3 km from the tower, represents a 0.48% loss. Thus, the overall environmental impact due to energy loss is quite small outside of probable plant boundaries, although the recreational and aesthetic impacts might be deemed more significant.

In Fig. 4, the effects of including realistic hourly sun angles are shown. The same Syracuse meteorological

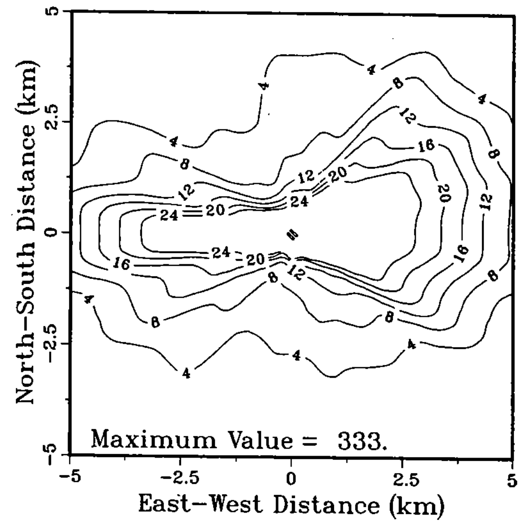

Fig. 6. Isopleths of average annual horizontal surface energy loss (MJ m^{-2}) for Syracuse using meteorological data for the years 1983–1987 and assuming two 9-cell LMDCTs each dissipating heat from a 260 MWe generating unit. The long axes of the side-by-side towers are parallel and lie in a northwest–southeast direction, as illustrated.

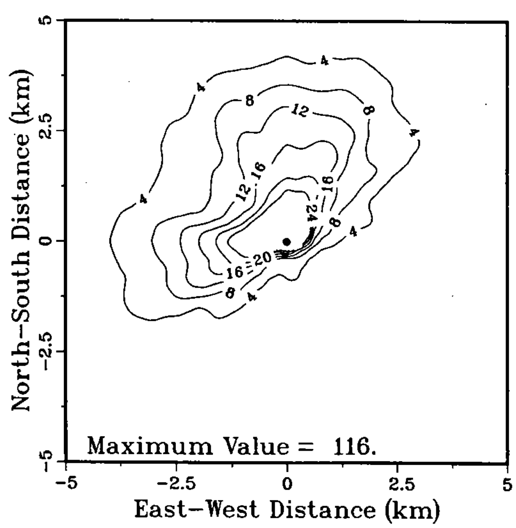

Fig. 7. Isopleths of average annual horizontal surface energy loss (MJ m^{-2}) for Spokane using meteorological data for the years 1983–1987 and assuming a single NDCT dissipating heat from a 500 MWe generating unit.

and source data were used to obtain the isopleths, but the sun was assumed always to lie overhead during daylight hours. With this assumption, the energy loss pattern does not show the expected northward shift of shadowing in the mid-latitudes of the Northern Hemisphere. In general, the pattern is more compact and more closely aligned with the predominant winds. Making this assumption would lead to higher energy-loss predictions mainly near the tower, and less shadowing predicted in the northward and southward directions.

Figure 5 shows that three such towers lead to more than a tripling of the energy loss. The energy loss isopleths have a similar shape, but at a given ground location, they are increased by a factor of about 4, while the maximum is increased by a factor of 5.5. The larger and longer merged plumes, along with the presence of multiple plumes near the towers, apparently lead to a more substantial solar energy loss per MWe of generating capacity. Under these conditions, the predicted 1% energy loss contour (about 48 MJ m^{-2}) reaches 2.5 km from the tower to the east and west.

A pair of linear mechanical draft cooling towers (LMDCTs) dissipating heat from a total of 520 MWe generating capacity, about the same as for the NDCT case shown in Fig. 3, also leads to much more near-field shadowing, as shown in Fig. 6. The maximum energy loss is about 6.7%, up by a factor of 2.8, while the 0.5% contour reaches 2.5 km, nearly twice as far. The increase by about 50% in shadowing at any given point is also evident. This increase happens partly because plumes produced by LMDCTs lie much closer to the ground than those produced by NDCTs, and would therefore cause more near-field shadowing.

Finally, the results for a single NDCT, also cooling 500 MWe, at the Spokane site are illustrated in Fig. 7. The average annual insolation is 5500 MJ m^{-2} at Spokane, compared with 4950 MJ m^{-2} at Syracuse. The drier and clearer conditions at the more northern Spokane site are represented by this increase. For the same reason, the maximum energy loss is about 4% less. The predominant wind directions at Spokane, mentioned above, suggest that plumes should be more common along a northeast–southwest axis. Indeed, Fig. 7 confirms this expectation, and also exhibits the general northward shift of the whole pattern expected in the Northern Hemisphere. Although it appears that a given isopleth of average annual loss at Spokane stays closer to the tower by a factor of about 0.7, differences other than those due to predominant wind direction variations between the sites are not large.

Some shadowing data has been collected by European investigators for two sites in West Germany (Berge *et al.*, 1975; Frank, 1977), and for three sites in France and Switzerland (Biscay *et al.*, 1986). Unfortunately, in each case there are factors that prevent a direct comparison with predictions made by the ANL/UI model. Taken as a whole these data support the order-of-magnitude of the shadowing effects predicted by the ANL/UI model, and give preliminary evidence that the model is realistic.

6. CONCLUSION

An improved ANL/UI model to calculate seasonal and annual solar energy flux reduction from visible plumes has been described and applied at two typical cooling tower sites in the northern United States, each with 500 MWe hypothetical generating capacity. The category scheme used to reduce the distinct predicted plume cases has been strengthened relative to methods based on simple ranges in the meteorological parameters. Sun-angle effects are more fully represented in the present model than in other existing models, and the prediction of energy flux reduction (in addition to hours of shadow) affords a more precise physical measure of plume shadowing.

The present study demonstrates that, with the sun-overhead assumption and within a typical plant boundary (2.5 km from the towers) a maximum of about 20 $MJ\,m^{-2}$ of solar energy flux (0.40% of the total) would be lost at the Syracuse site, given a single NDCT dissipating about 970 MWt. When the effects of sun angles were included, the maximum amounts of predicted shadowing decreased outside the 2.5 km boundary, and a given percentage of shadowing was spread over a wider angle around the predominant wind directions in a region closer to the towers. Thus, prediction of hours of shadowing or loss of solar energy flux with sun-angle effects included is a more conservative and accurate method for predicting shadowing than prediction of hours of shadowing with the sun always overhead during daylight.

Maximum shadowing occurred to the northwest of the Syracuse site. Actual energy loss isopleths for the Syracuse site with a single NDCT dissipating about 970 MWt showed less than 0.1% total energy reduction beyond 4 km from the towers. By contrast, for the same heat release at the less-humid Spokane site, the solar flux reductions were moderately less at a given distance from the tower. The spatial distribution of shadowing was consistent with the differences in wind rose with a northward shift from the tower due to north latitude. Three such NDCTs caused proportionately greater shadowing by a factor of 4 to 5.5 at a given spot due to multiple near-field plumes, longer far-field plumes and exponential absorption through thicker plumes. Two LMDCTs dissipating the same heat as one NDCT caused an increase in shadowing by about 50% at a given spot due to the presence of two plumes, each wider, emitted closer to the ground. Each of these cases was run for 5 years of hourly data in less than an hour on a 20 MHz 80386-based microcomputer with an 80387 mathematical processor chip, 640K of RAM and approximately 8 Mb of disk storage.

At the present time, the greatest barrier to further modeling progress for shadowing is the absence of good field data for long-term energy loss. The acquisition of such data should be made a priority. In the meantime, reasonable theoretical methods are available to predict long-term average solar energy loss, which appears not to be a very severe environmental impact in most situations.

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