**Atmospheric Effects of Nuclear Energy
Centers (AENEC) Program
Annual Technical Progress Report for
Period July 1975 – September 1976**

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H. W. Hoffman

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ATMOSPHERIC EFFECTS OF NUCLEAR ENERGY
CENTERS (AENEC) PROGRAM
ANNUAL TECHNICAL PROGRESS REPORT FOR
PERIOD JULY 1975 - SEPTEMBER 1976

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ABSTRACT

This Technical Memorandum is the Annual Technical Progress Report of the Atmospheric Effects of Nuclear Energy Centers (AENEC) Program for the period July 1975 - September 1976. It contains information of a preliminary nature from the six participants of the Program describing their activities and presenting the results obtained during the above-mentioned period.

The birth of the Program, its definition and evolution are described in the Introduction, and a complete breakdown of responsibilities and tasks assigned to the six AENEC participants is presented.

1. INTRODUCTION

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General Information

The Atmospheric Effects of Nuclear Energy Centers (AENEC) Program came into official being at the beginning of FY 1976 (July 1, 1976) under the sponsorship of the ERDA Division of Nuclear Research and Applications (NRA), Advanced Concepts Evaluation Branch, and with the involvement and support of the ERDA Division of Biomedical and Environmental Research (BER). The initial structure of the program thus formed consisted of the joining of a number of relevant studies already being funded by BER with new work to be supported by NRA under the technical management of the Oak Ridge National Laboratory. It was the objective of this program to develop and verify methods (analytical or experimental) for predicting the maximum amount of energy that can be dissipated to the atmosphere (through cooling towers or cooling ponds) from proposed nuclear energy centers (NEC's) without affecting (adversely or beneficially) the local and regional environment (weather).

Program Definition

Studies during the past decade have led to an awareness that the level of man-produced heat, moisture, and particulate emissions to the atmosphere are sufficiently high to effect meteorologic and climatic changes. Particularly pertinent has been the documentation by Peterson¹ and by Huff and Changnon² that the natural atmospheric processes can be altered by the presence of such sources as the "urban heat island." With the proposed clustering of nuclear reactors into energy centers (for reasons of safety, security, fuel economy, and land use effectiveness), the effects already noted could be further exaggerated. Thus,

¹O. Peterson, The Climate of Cities: A Survey of Recent Literature, U.S. Department of Health, Education, and Welfare, Public Health Service, Raleigh, North Carolina, October 1969.

²F. A. Huff and S. A. Changnon, Jr., Climatological Assessment of Urban Effects on Precipitation at St. Louis, J. Applied Meteorology, 11(5), August 1972, pp. 825-843.

Hanna and Swisher³ pointed out that significant influences on local meteorology could be present at distances of up to 20 to 30 km from typical power plants existing in 1971 and that the length scale would undoubtedly increase as energy production at a site became more concentrated.

In consequence of this concern, as voiced by an ad hoc gathering of prominent meteorologists in 1975, four general areas of needed research were identified by NRA:

- (1) Development and verification of models for predicting the off-site effects of NEC atmospheric waste heat discharges on local and regional meteorology and climatology
- (2) Assessment of the impact of such NEC atmospheric waste heat discharges on the design of nuclear energy centers
- (3) Prediction of the effect of NEC atmospheric waste heat discharges on the diffusion and deposition of radioactivity discharged from such centers
- (4) Assessment of the public acceptability of predicted offsite effects of NEC atmospheric waste heat dischargers.

The program assembled to address these concerns is outlined in Table 1.1 in its original embodiment; evolution throughout the year has effected priorities and scopes of the listed tasks. Notable was the decision to postpone any substantive work under Tasks 4 and 5 until predictive capability (through models or field data) was more firmly established. Further, activity under Tasks 2.1.2, 2.1.5, and 2.1.6 were reduced or postponed, while Tasks 2.1.7 and 2.3.4 were added. This culminated by the end of the fiscal Transition Quarter (September 30, 1976) in movement of the program toward a more applied attitude, with emphasis on early response to NRC needs and stronger coordination with other agencies (governmental or private) having similar interests.

³S. R. Hanna and S. D. Swisher, Meteorological Effects of the Heat and Moisture Produced by Man, Nuclear Safety, 12(2), March-April, 1971, 114-122.

Table 1.1

Task 1: Management (ORNL)

Develop program elements and priorities; coordinate activities of organizations carrying out technical tasks; establish and maintain interface with other governmental agencies and the technical community engaged in similar activities; represent ERDA sponsor and carry out delegated administrative functions.

Task 2: Model Development and Verification

Construction and verification of models describing atmospheric phenomena arising from heat and mass releases from cooling towers and cooling ponds.

2.1.1 Near-Field Plume and Cloud Growth (ATDL)^a

Examine, modify, develop, and verify plume growth and merger models and extend into cloud growth domain; predict effects of tower spacing and configuration.

2.1.2: Plume Diffusion with Phase Change (ATDL)^a

Examine effects of latent heat release on plume growth and rise characteristics.

2.1.3: Drift Deposition Models (ORNL)

Survey and critically compare existing models; improve and extend models; test models against available field data; delineate plume interaction effects.

2.1.4: Mesoscale Cloud Growth Models (Rand)^b

Survey natural analogs of massive heat and mass inputs to atmosphere; identify meteorological and climatological effects; test against available models.

2.1.5: Deep Convection Model (PNT)^c

Survey data on occurrence, frequency, mechanism, generation, and dissipation of convective vortices; establish applicability of existing model to thunderstorm intensification and vorticity concentration.

^aNational Oceanographic and Atmospheric Administration-Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, Tennessee.

^bRand Corporation, Santa Monica, California.

^cBattelle Pacific Northwest Laboratory, Hanford, Washington.

Table 1.1 (Cont'd.)

Task 2: Model Development and Verification (Cont'd.)

2.1.6: Diffusion-Advection Dynamic Model (PSU)^d

Assemble 2-D dynamic model and test against observations from aircraft plume measurements.

2.1.7: Model Applications (ORNL)

Develop periodic state-of-the-art description of predictive models; define "effects" and assist in developing standards.

2.2.1: Wind Tunnel Experiments (ATDL)^a

Investigate existing facility availability; develop plan and carry out experiments on plume motion near towers (downwash-lift-off), point-source assumption, etc.

2.2.2: Water Flume Experiments (PNL)^c

Establish applicability of water flumes for defining plume interactions, tower spacing criteria, terrain effects, etc.; pursue appropriate measurements.

2.2.3: Plume Merger Studies (ORNL)

Carry out experiments with buoyant plumes at laboratory scale to identify controlling mechanisms for multiple plume interaction and growth.

2.3.1: Cooling Tower Plume Characterization (PNL, PSU)^{c,d}

Designate appropriate sites for aircraft or ground-based measurement of cooling tower plume parameters; collate such field data and issue for project utilization.

2.3.2: Cooling Pond Surface Heat Exchange (ANL)^e

Correlate existing Dresden Pond measurements; test correlation of alternate sites and modify models as necessary; consider effects of pond aeration (sparging).

^d Pennsylvania State University, University Park, Pennsylvania.

^e Argonne National Laboratory, Argonne, Illinois.

Table 1.1 (Cont'd.)

Task 2: Model Development and Verification (Cont'd.)

2.3.3: Cooling Tower Drift Characterization (ORNL)

Assist Chalk Point Project in reduction, evaluation, and correlation of drift deposition data; identify alternate sites for drift measurement and carry out or participate in measurements; develop improved drift measurement techniques.

2.3.4: Cooling Tower Case Studies (ORNL, PNL, PSU)^{c,d}

Develop data base for statistical evaluation of "effects" at selected sites; establish inventory of U.S. power plants as to location and cooling mode.

Task 3: Effects of NEC Design

3.1: Vorticity Enhancement (ATDL)^a

Collate and correlate available data on vorticity generation in association with strong jets or thermal sources; carry out model development and appropriate experimentation.

3.2: Tower Spacing Interference (ATDL, ORNL)^a

Survey existing data and models to establish preliminary criteria on spacing; carry out measurements as appropriate (see 2.2.1 and 2.2.2).

3.3: Noise (ORNL)

Survey potential noise sources in an NEC; establish possible effects; investigate solutions.

Task 4: Diffusion and Deposition of Radioactivity

4.1: Radioactivity Dispersal (ORNL)

Survey current state-of-information on radioactivity release and atmospheric dispersal; generate guide for needed studies.

Task 5: Public Acceptance

Identify relevant cases on public reaction to environmental/safety considerations arising from anthropogenic activities; develop an appropriate survey instrument.

Workshops

An important function of the AENEC Program is to serve as a focus for the diverse technical efforts in this area. Accordingly, "the workshop" was proposed as an appropriate format for bringing together active workers in the university, industrial, and research institute communities with the AENEC "staff" to discuss in depth specific problems relevant to AENEC interests. The first such workshop (held June 16-18 at ORNL) concentrated on the interface between cooling-tower plume model development and field measurement efforts; thus, considered were:

- (1) the analyst's requirements for field data (type, range, and accuracy) necessary to verify the models being developed to describe cooling-tower plume behavior and
- (2) the experimenter's capabilities (instrumentation and technique type, limitations, and accuracy) for supplying this needed data through aircraft and ground-based measurements of cooling-tower plumes.

A summary of this workshop appears in Appendix A; while answers to the questions of what data does the modeler want and what data can the experimenter provide were not completely developed, a useful summary of accuracies currently practical in tower and plume observation programs did result. Future workshops on cooling ponds, laboratory studies, and drift and fog are planned.

2. MODEL DEVELOPMENT AND VERIFICATION

2.1 Model Development

2.1.1 Near-Field Plume and Cloud Growth

S. R. Hanna

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Oak Ridge, Tennessee 37830

Introduction

Single cooling towers emit as much as 1000 MW of sensible and latent heat to the atmosphere. Planned energy centers or power parks may contain clusters of cooling towers which emit a total of 100,000 MW. As shown by Hanna and Gifford¹ heat releases of this magnitude have the potential to significantly alter local weather. Cooling towers can also alter the local environment by the production of fog and clouds and the deposition of drift salts.

There are several models available for estimating drift deposition and visible plume length from single cooling towers.² However, there are no data suitable for testing the drift deposition models and very few data suitable for testing the visible plume models. Currently a drift deposition experiment³ is underway at Chalk Point, Maryland, as part of a comprehensive study of the salt water natural draft cooling tower at that site. A few measurements of visible plume length are available,^{4,5} and there are several more sets of measurements that are

¹S. R. Hanna and F. A. Gifford, "Meteorological Effects of Energy Dissipation at Large Power Parks," Bull. Am. Meteorol. Soc., 56, 1975, 1069-1076.

²G. E. McVehil and K. E. Heikes, Cooling Tower Plume Modeling and Drift Measurement. A Review of the State-of-the-Art, prepared for ASME (Contract G-131-1) by Aerospace Division, Ball Brothers Research Corporation, Boulder, Colorado 80302, 1975.

³Environmental Systems Corporation, Chalk Point Cooling Tower Project Seasonal Test Data for the period December 15-19, 1975, Report No. PPSP-CPCTP-8, Prepared by ESC, Knoxville, Tennessee, for the Maryland Power Plant Siting Program, Chalk Point Cooling Tower Project, 1976, 157 pp.

⁴P. R. Slawson, J. H. Coleman, and J. W. Frey, "Some Observations on Cooling Tower Plume Behavior at the Paradise Steam Plant," in Cooling Tower Environment-1974, ERDA Symposium Series, CONF-740302, Nat. Tech. Information Service, U.S. Department of Commerce, Springfield, Virginia 22161, 1974, 147-160.

⁵J. H. Meyer, T. W. Eagles, L. C. Kohlenstein, J. A. Kagan, and W. D. Stanbro, "Mechanical Draft Cooling Tower Visible Plume Behavior: Measurements, Models, Predictions," in Cooling Tower Environment-1974, ERDA Symposium Series, CONF-740302 Nat. Tech. Information Service, U.S. Dept. of Commerce, Springfield, Virginia 22161, 1974, 307-352.

just being published. Three of the new sets of visible plume observations are compared with model predictions in this report. These are the observations of cooling tower plumes at the John E. Amos fossil power plant,⁶ the Rancho Seco nuclear power plant,⁷ and a refinery plume near St. Louis.⁸

The basic model presented in this report is a simple one-dimensional model (variables are functions only of height). Since the cooling tower emissions are usually constant with time, at least over time periods less than four or five hours, the steady-state assumption is good. Phenomena such as multiple plume merging and changes in the environmental air surrounding the plume are accounted for only by crude parameterization. According to our plan, this model is only the first in a series of models, and future models will be multidimensional and able to handle plume-environment interactions. Other members of our research group, S. Rao⁹ and C. Nappo,¹⁰ are developing second-order closure and fully turbulent models of multiple plumes.

⁶M. L. Kramer, D. E. Seymour, M. J. Butler, R. N. Kempton, P. J. Brennan, J. J. Conte, and R. G. Thomson, John E. Amos Cooling Tower Flight Program Data, December 1974-March 1975, by Smith-Singer Meteorologists, Inc., 134 Broadway, Amityville, New York 11701 for American Electric Power Service Corporation, P.O. Box 487, Canton, Ohio 44701, 1975.

⁷M. A. Wolf, "Natural Draft Cooling Tower Plume Characteristics Determined with Airborne Instrumentation," Pacific Northwest Lab. Annual Rep. for 1975 to the USERDA DBER. Part 3 Atmospheric Sciences, BNWL-2000 PT3, 1976a, 281-288.

⁸A. H. Auer, Jr., "Observations of an Industrial Cumulus," J. Appl. Meteorol., 15, 1976, 406-413.

⁹K. S. Rao, "3-D Subgrid Turbulence Enclosure Models - A Critical Review," in ATDL Annual Report to the Atmospheric Effects of Nuclear Energy Centers Program, ATDL-NOAA, Oak Ridge, Tennessee, 1976.

¹⁰C. J. Nappo, "The Detailed Numerical Simulation of Vorticity Concentration Downwind of Large Heat Sources," in ATDL Annual Report to the Atmospheric Effects of Nuclear Energy Centers Program, ATDL-NOAA, Oak Ridge, Tennessee, 1976.

A thorough description of the one-dimensional numerical model for plume and cloud growth that is used in the analyses in later sections is given in Section 2 of the paper by Hanna,¹¹ to be published in Atmospheric Environment.

John E. Amos Cooling Towers

During the winter of 1974-1975, Smith-Singer Meteorologists, Inc., obtained measurements with a light aircraft around the three cooling tower plumes at the John E. Amos power plant in West Virginia.⁶ Experiments were performed only on cold, humid mornings when long visible plumes were expected. The aircraft measured vertical profiles of temperature and dew point and roughly estimated the wind speed. Photographs of the visible plume were taken, but the aircraft did not penetrate the plume. Plant personnel provided data on the load of the cooling towers.

The plant ran close to its rated capacity of 2900 MW during most of the experiments. In the model, the plume from a single tower is followed until its radius, R , equals one-half of the distance, s , between the towers ($s = 200\text{m}$). The initial plume radius, R_o , and vertical speed, w_o , equal 40m and 4.4m/s, respectively. To insure continuity of the momentum flux, the effective initial plume radius for bent-over plumes is calculated from the equation

$$R_{\text{eff}} = R_o (w_o/U)^{1/2}, \quad (1)$$

where U is the wind speed. Using the specifications given by Kramer et al.,⁶ the initial plume temperature, T_{po} , at full load is assumed to be given by the relation:

$$T_{po} = \left[297.4 + 0.635 (T_d - 273) \right] [1 + 0.01 (1 - RH)], \quad (2)$$

¹¹S. R. Hanna, "Predicted and Observed Cooling Tower Plume Rise and Visible Plume Length at the John E. Amos Power Plant," to be published in Atmos. Environ., 1976, and "Observed and Predicted Cooling Tower Plume Rise at the John E. Amos Power Plant, West Virginia," Proceedings of the Third Symposium on Atmospheric Turbulence Diffusion and Air Quality, American Meteorological Society, Raleigh, North Carolina, 1976.

where T_d is the ambient dew point and RH is the ambient relative humidity. For power outputs less than full load, initial plume temperature is calculated from:

$$\frac{T_{po} - T_{eo}}{T_{po} [\text{Eq. (2)}] - T_{eo}} = \frac{\text{actual load}}{2900 \text{ mw}}, \quad (3)$$

where T_{eo} is the ambient temperature. Initial plume cloud water, Q_c , and hydrometeor water, Q_H , are arbitrarily set equal to 0.001 g/g, on the basis that fog or cloud is obviously present at the tower mouth. This estimate could be made more accurate if observations of liquid water at the tower mouth were taken.

About half of the sets of observations could not be used because of uncertainties in the temperature profiles or plume photographs. Of the 27 sets that were used, the input data for four are given in the papers by Hanna.¹¹ Kramer, et al.,⁶ give complete listings of all the data.

Plume rise at Amos: In 19 of the runs studied, the observed visible plume passed through the point of maximum plume rise. A comparison of observed and predicted plume rise is given in Table 2.1.1, showing that the average predicted plume rise (670m) is close to the average observed rise (750m). The correlation coefficient is 0.49, which is only fair. The last column of the table contains Briggs¹² analytical plume rise prediction, where the initial buoyancy flux is assumed to equal the sensible heat flux from the largest tower. The average predicted rise is 540m, and the correlation with observations is 0.37. Column five in the table contains the observed height of the base of the capping inversion or mixing layer, which is seen to be well correlated (0.90) with the observed plume rise. Brennan et al.,¹³

¹²G. A. Briggs, Plume Rise Predictions, Lectures on Air Pollution and Environmental Impact Analyses, American Meteorol. Soc., 45 Beacon Street, Boston, Massachusetts, 1975, 59-111.

¹³p. T. Brennan, D. E. Seymour, M. J. Butler, M. L. Kramer, M. E. Smith, and T. T. Frankenburg, "The Observed Rise of Visible Plumes from Hyperbolic Natural-Draft Cooling Towers," Atmos. Environ., 10, No. 6, 1976, 425-431.

Table 2.1.1 Observed and calculated plume rise at John E. Amos power plant

Run	$\bar{U}$ (m/s)	Ambient tower top saturation deficit (g/kg)	$\Delta\theta/\Delta Z$ over depth of plume (°C/m $\times 10^3$)	Inversion height above tower (m)	Observed plume rise (m)	Model plume rise (m)	Analytical plume rise sensible one unit (m)
1	14	0.43	13.5		560	260	250
6	11	0.13	3.0		850	820	430
8a	9	0	9.8		370	350	250
10a	5	0.60	2.1	720	820	820	590
11	0	1.34	6.1	660	880	900	980
12	6	1.25	1.2	1140	1060	1200	720
15	3	0.28	10.7		1120	790	780
16	6	0.41	7.2	1200	1160	700	380
17a	8	0.29	6.7	360	360	430	410
18	6	0.78	5.6		910	720	410
19	0	1.07	6.9	840	800	970	910
24	6	0.60	4.0	750	760	630	500
28a	5	0.52	21.8		360	400	310
31	0	1.02	11.6		500	900	780
35a	3	0.87	9.8	390	360	590	480
44	8	1.16	1.9	960	910	420	510
45	7	1.16	5.6	1200	910	370	390
47	0	1.44	3.8	900	800	1020	910
48a	<u>7</u>	<u>1.46</u>	<u>7.6</u>	<u>750</u>	<u>670</u>	<u>360</u>	<u>340</u>
Avg.	5.6	0.76	7.4	820	750	670	540

have analyzed these data and find that when a capping inversion is present the plume will level off after striking it. This rule is probably not valid in the summer when the height of the capping inversion is much higher and the plume is likely to reach final rise before striking the inversion.

Some examples of vertical profiles of Q_c , w , and $T_p - T_e$ are given in Figs. 2.1.1, 2.1.2, and 2.1.3. The predicted cloud water content, Q_c , is generally about 0.5 to 1.5 g/kg, which agrees with observations in natural cumulus clouds. The maximum vertical speed, w , is between 4 and 10 m/s. The temperature excess, $T_p - T_e$ is seen to decrease almost linearly with $\log z$ for the runs plotted. Unfortunately, there were no in-plume measurements during this experiment that could be used to test these predictions.

Visible plume length at Amos: There are seven runs in which the visible plume is moderately long but does not reach the point of maximum plume rise. These runs are summarized in Table 2.1.2. The results of a simple analytical model¹⁴ are also given, where it is assumed that the tip of the visible plume occurs when the initial flux of excess water, $w_o R_o^2 Q_{po}$, in the plume equals the saturation deficit flux, $UR^2(Q_{eos} - Q_{eo})$:

$$h = 2R_o (w_o/U)^{1/2} \left\{ \left[2Q_{po}/(Q_{eos} - Q_{eo}) \right]^{1/2} - 1 \right\} \quad (4)$$

$$\ell = 1.4 \left(R_o^{3/2} U^{3/4} w_o^{3/4} / F^{1/2} \right) \left\{ \left[2Q_{po}/(Q_{eos} - Q_{eo}) \right]^{1/2} - 1 \right\}^{3/2} \quad (5)$$

In these equations h is visible plume height, ℓ is visible plume length, subscripts p , e , o , and s refer to plume, environmental, initial, and saturated variables, respectively, and F is the initial buoyancy flux:

$$F = (g/T_{po}) w_o R_o^2 (T_{po} - T_{eo}) \quad (6)$$

¹⁴S. R. Hanna, "Meteorological Effects of the Mechanical-Draft Cooling Towers of the Oak Ridge Gaseous Diffusion Plant, in Cooling Tower Environment-1974, ERDA Symposium Series, CONF-740302, Nat. Tech. Information Service, U.S. Dept. of Commerce, Springfield, Virginia 22161, 1974, 291-306.

Fig. 2.1.1. Variation of calculated vertical speed, w , with height for runs 1, 10, and 15.

Fig. 2.1.2. Variation of calculated cloud water content, Q_c , with height for runs, 1, 10, and 15.

Fig. 2.1.3. Variation of calculated temperature difference, $(T_p - T_e)$ with height for runs 1, 10, and 15.

Table 2.1.2 Visible plume dimensions for plumes whose visible portion does not reach the point of maximum rise, for John E. Amos power plant

Run	$\bar{U}$ (m/s)	<u>Ambient saturation deficit (g/kg)</u>		<u>Observed</u>		<u>Numerical model</u>		<u>Analytical model</u>		Ambient RH at plume level
		Tower top	plume level	Visible plume height (m)	Visible plume length (m)	Visible plume height (m)	Visible plume length (m)	Visible plume height (m)	Visible plume length (m)	
2	13	3.0	3.9	100	200	75	290	100	370	0.4
3	10	2.6	2.7	150	500	120	350	140	400	0.65
13	10	0.86	1.8	100	300	150	480	210	730	0.6
20	10	2.8	3.9	200	400	70	250	120	290	0.45
27	20	1.5	2.0	390	600	120	450	110	800	0.55
39	15	2.9	3.6	240	450	140	240	100	430	0.45
41	<u>16</u>	<u>3.5</u>	<u>3.2</u>	<u>50</u>	<u>300</u>	<u>55</u>	<u>290</u>	<u>80</u>	<u>360</u>	<u>0.35</u>
Avg.	13	2.5	3.0	180	390	100	340	120	450	0.50

The factor 2 in front of Q_{po} in Eqs. (4) and (5) is the so-called "peak factor," accounting for the observation that a visible plume can persist past the point at which the average plume becomes unsaturated. Saturated parcels of air persist in the midst of unsaturated air. The empirical peak factor was first used in the analyses by Meyer et al.,⁵ Slawson et al.,⁴ and Briggs.¹²

It is seen in Table 2.1.2 that the numerical and analytical models are equally capable of estimating the visible plume height and length. The average observed and estimated visible plume length and height agree within 20% and 80%, respectively.

St. Louis Refinery Cloud

While measuring cumulus clouds in the vicinity of St. Louis with an instrumented light aircraft, Auer⁸ noticed a cumulus cloud that was obviously forming in the plume from a refinery complex. He made several passes through the cloud, measuring temperature excess, vertical speed, and excess water. He also obtained vertical soundings of dry-bulb temperature, dew point, and wind speed. Unfortunately, the source details are sketchy in his report, and it is necessary to arbitrarily choose parameters such as the initial plume radius. Auer states that the refinery gives off 7×10^{11} cal h^{-1} (about 800 MW), divided about equally between sensible and latent heat. For the model calculations the initial plume temperature, relative humidity, radius, and vertical speed are assumed to equal 302.3K, humidity 76%, 250 m, and 1 m/s, respectively. Initial values of cloud and rainwater content are set equal to zero. The environment profiles are given in Table 2.1.3.

The comparison of observations with model output are summarized in Table 2.1.4 (all heights are in meters above the surface). The height of the cloud base and top are quite well predicted by the model. There is a slight inversion above about 2100 m which causes the plume to level off. The predicted vertical speed w is about a factor of two too low at all heights, and the predicted liquid water content is a factor of three to ten too high. The observed and predicted temperature differences are

Table 2.1.3 Profiles of temperature, dewpoint, and windspeed
for the St. Louis refinery cloud on 10 August
1973 (after Auer, 1976)

<u>z(m)</u>	<u>Temperature (°K)</u>	<u>Dewpoint (°K)</u>	<u>U(m/s)</u>
0	300.5	296.0	1.1
250	298.0	295.5	1.1
450	296.5	295.0	1.3
600	295.0	294.5	1.8
750	293.5	292.8	1.9
900	292.5	291.0	3.0
1050	291.8	285.0	2.5
1200	290.6	288.5	2.0
1350	289.4	288.5	2.0
1500	288.5	286.5	1.1
1650	287.5	286.5	2.0
1850	286.0	284.2	3.8
2000	285.0	282.0	3.8
2100	284.8	278.0	3.8
2250	284.0	277.5	3.8
2350	283.3	277.8	3.8

Table 2.1.4 Comparison of observations
and predictions for St.
Louis refinery

	<u>Observed</u>	<u>Predicted</u>
Cloud base	700 m	650 m
Cloud top	2050 m	2350 m
<hr/>		
<u>z(m)</u>	<u>Liquid water content observed (g/m³)</u>	<u>Liquid water content predicted (g/m³)</u>
930	0.046	0.56
1270	0.10	0.75
1860	0.44	1.30
<hr/>		
<u>z(m)</u>	<u>Observed w(m/s)</u>	<u>Predicted w(m/s)</u>
500	3	2.0
1500	4	2.0
2000	3	2.3
<hr/>		
<u>z(m)</u>	<u>Observed (T_p - T_e) (°K)</u>	<u>Predicted (T_p - T_e) (°K)</u>
500	0.2	0.1
1500	-0.5	0.3
2000	-0.2	0.5

within 1°K of each other. Because of the differences in water vapor content between the plume and the environment, the virtual temperature difference ($T_{pv} - T_{ev}$) is positive even though the observed actual temperature difference is negative at heights of 1500 and 2000 m.

Auer calculated the entrainment rate based on his measurements of temperature in the cloud. He finds that the entrainment rate is between 33 and 91%/km for eight different passes through the cloud. In the numerical model the entrainment rate $(1/V) (dV/dz)$ equals $0.8/R$, where V is the volume flux, UR^2 . Thus, the theoretical entrainment rate is about 160% at cloud base and about 75% at a height of 2000 m (using $R = R_0 + 0.4z$). There is a great deal of uncertainty among the cloud modelers with respect to their recommendations of entrainment rate for cumulus clouds.¹⁵ It is measurements such as Auer's which will allow modelers to better specify the entrainment rate.

Rancho Seco Cooling Towers

The plumes from the two natural-draft cooling towers at the Rancho Seco, California, nuclear power plant were sampled by Wolf⁷ using a light aircraft. Environmental data from the three days of measurements are listed in Table 2.1.5.

The two towers have radii of 30 m, and their centers are separated by 140 m. In the model a single plume is followed to a height where its radius equals 70 m, or one-half of the distance between the towers. Beyond this point, the plumes are assumed to merge and the fluxes of all parameters increase by a factor of two. The measured initial velocities, w_0 , on the three days 2/17, 2/18, and 2/20, are 4.4, 3.6, and 3.9 m/s, respectively. Wolf suggests that the initial liquid water content should be less than we have been using previously, since he has measured liquid water concentrations no greater than 0.0001 g/g at a distance of 125 m from the tower exits. Therefore, for these three runs, it is

¹⁵W. R. Cotton, Theoretical Cumulus Dynamics, Reviews of Geophysics and Space Physics, 13, 1975, 419-447.

Table 2.1.5 Environmental data from Rancho Seco, California (from Wolf, 1976b)

Height above tower (m)	2/17/75		$\underline{U}^{(3)}$	$\underline{T_e}$	2/18/75		$\underline{T_e}$	2/20/75	
	$\underline{T_e}^{(1)}$	$\underline{T_d}^{(2)}$			$\underline{T_d}$	$\underline{U}$		$\underline{T_d}$	$\underline{U}$
0	280.0	270.9	5.0	283.0	274.4	3.4	283.2	275.4	9.1
44	279.5	270.6	5.0	--	--	--	282.8	274.8	9.0
120	278.8	270.9	5.0	281.5	273.7	2.8	282.0	274.7	8.8
197	278.2	270.0	5.0	--	--	--	--	--	--
273	278.9	268.9	5.6	280.4	272.3	2.2	280.6	273.4	8.2
425	279.2	265.3	7.2	279.5	269.9	1.9	279.2	271.2	7.1
578	278.4	266.8	9.4	278.5	267.1	1.5	277.9	271.3	6.0
654	--	--	--	277.8	267.2	1.8	--	--	--
730	278.0	264.7	11.0	278.0	268.6	2.4	276.6	270.1	5.0
807	--	--	--	278.1	267.7	2.9	--	--	--
883	--	--	--	278.0	266.5	3.0	276.1	269.0	4.5

(1) Dry-bulb temperature, °K.

(2) Dewpoint, °K.

(3) Wind speed, from pilot balloons (m/s).

assumed that Q_{CO} equals 0.0005 and $Q_{HO} = 0.0001$ g/g. Equations (2) and (3), based on the John E. Amos towers, were used to estimate the initial plume temperatures.

The estimated visible plume length and height are compared with observations in Table 2.1.6. It is seen that the model underestimates visible plume length and height by a factor of three to five. However, Wolf reports that he observed visible plumes when the average plume relative humidity was as low as 60%. Either the plume is far lumpier than we think, or the measured relative humidities are too low. If the former is true, the model could be improved by increasing the peak factor.

The observed and estimated excess temperature and ~~excess water~~ content are in better agreement than the visible plume parameters, as seen in Table 2.1.7. The observed temperature excess is about twice the estimated excess, on the average. The observed and estimated excess water content are generally quite close. The paradox exists that visible plume length is not estimated very well, while excess water content is estimated quite well. Adjustments in the peak factor cannot simultaneously improve predictions of visible plume length and excess water content at Rancho Seco.

Climatology of Plume Types

Since the plume and cloud growth model is relatively simple and each computer run costs only a few cents, it is feasible to apply the model to large numbers of input data. The statistics of the resulting plume predictions can be calculated and a climatology of plume types developed. The average plume rise and visible plume length and height for a year and for various seasons can be included in the climatology. Plume characteristics for weather categories ranging from clear to precipitation can be estimated.

Upper air and surface observations from the Nashville weather service office for the months January, April, July, and October, 1974, were obtained. Since observations are taken twice each day (morning and evening), a total of 241 sets of input data are used. The Nashville station was chosen because of its proximity to the proposed TVA Hartsville

Table 2.1.6 Observed and estimated visible
plume length and height at
Rancho Seco

	Feb. 17		Feb. 18		Feb. 20	
	<u>Obs.</u>	<u>Model</u>	<u>Obs.</u>	<u>Model</u>	<u>Obs.</u>	<u>Model</u>
Plume length (m)	vert.	170	500	130	1000	250
Plume height (m)	350	110	800	160	420	75

Table 2.1.7 Observed and estimated temperature and
water content excesses at Rancho Seco

<u>Date</u>	<u>Height above tower (m)</u>	<u>$(T_p - T_e)$ ($^{\circ}\text{K}$)</u>		<u>$(q_p + Q_c + Q_H - q_e)$ (g/kg)</u>	
		<u>Obs.</u>	<u>Model</u>	<u>Obs.</u>	<u>Model</u>
Feb 17	120m	7.2 $^{\circ}\text{K}$	2.3 $^{\circ}\text{K}$	5.1 g/kg	3.3 g/kg
	136	5.6	2.0	3.6	3.1
	151	5.0	1.6	3.1	2.8
	181	1.9	1.2	1.8	2.5
	273	2.3	-0.3	2.1	1.8
	349	0.7	top at 340m	1.1	
Feb 18	197m	2.2 $^{\circ}\text{K}$	1.3 $^{\circ}\text{K}$	2.2 g/kg	3.2 g/kg
	273	2.1	0.7	2.4	2.4
	425	0.8	-0.1	1.8	1.9
	578	-0.3	-0.5	0.8	1.7
	730	-0.5	top at 610m	0.4	
	883	-2.1		0.4	
	974	-3.8		0	
Feb 20	120m	3.0 $^{\circ}\text{K}$	1.3 $^{\circ}\text{K}$	1.9 g/kg	2.6 g/kg
	151	3.0	0.9	2.0	2.0
	181	1.4	0.7	0.8	1.7
	273	0.9	0.4	0.6	1.2
	425	0	0.1	0.4	1.1
	486	1.0	0	0.7	0.9
	730	-0.4	top at 720m	-0.1	

power park, the surrogate nuclear energy center site at Land-Between-the-Lakes and the existing TVA Paradise steam plant.

The four different types of sources used as input to the model are listed in Table 2.1.8. Because the model is one-dimensional, plume merging in the 100,000-MW power park with 100 cooling towers must be completely parameterized. It is assumed that the four plumes in a group merge if the plume radius equals 100m (one-half of the distance between the towers) and the groups merge if the plume radius equals 500m (one-half of the distance between the groups). The other source types in the table are treated as if all the heat were from one cooling tower. This is unrealistic for the 10,000- and 100,000-MW sources but will provide estimates of the worst possible cases of weather modification.

Plume rise: Final plume rise is defined as the height at which the vertical speed of the plume, w , reaches zero. In about one-third of the runs for the single 1000-MW tower, a cloud exists ($Q_C + Q_H > 0$) at the height of final plume rise. This fraction increases to 95% for the single 10^5 MW tower. The average plume rise for the four different months and four different sources are listed in Table 2.1.9. The numbers in parentheses are the range of plume rise for that class.

The increase in plume rise with increase in source strength for the first three types of sources is in approximate agreement with Briggs' theory¹² 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 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 spaced 10^5 MW energy center yields an average plume rise between those for the single 10^3 MW tower and the single 10^4 MW tower. Occasionally, the plumes will combine and yield a plume rise close to that for the single 10^5 MW tower. In about 90% of the runs, the four towers in a group merge, and in about 15% of the runs, the 25 groups merge; but since merger generally occurs near the top of the plume, it does not give the plume much additional boost. A general rule for

Table 2.1.8 Source input for plume climatology study

<u>Approximate power</u>	<u>Number of cooling towers</u>	<u>w_c (m/s)</u>	<u>T_o (°K)</u>	<u>R_o (m)</u>	<u>Characteristics</u>
1,000 MW	1	4.4	Eq. (2)	30	Typical natural draft tower
10,000 MW	1	4.4	Eq. (2)	92	Same, but larger diameter
100,000 MW	1	4.4	Eq. (2)	300	Same, but much larger diameter
100,000 MW	100	4.4	Eq. (2)	30	Square grid; groups of four towers, with the towers spaced 200m apart; groups are spaced 1 km apart

Table 2.1.9 Average plume rise estimated using Nashville radiosonde observations. The range in plume rise for that class is given in parentheses.

Month (all 1974)	Morning rise (m)				Evening rise (m)				Average rise (m)			
	<u>10³ MW</u>	<u>10⁴ MW</u>	<u>10⁵ MW</u>	<u>10⁵ MW spaced</u>	<u>10³ MW</u>	<u>10⁴ MW</u>	<u>10⁵ MW</u>	<u>10⁵ MW spaced</u>	<u>10³ MW</u>	<u>10⁴ MW</u>	<u>10⁵ MW</u>	<u>10⁵ MW spaced</u>
Jan.	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)
Apr.	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)
Oct.	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)
Avg. annual	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)

avoiding plume merger is to space the cooling towers a distance apart equal to the average plume rise from a single tower. In this way, the plume radii, which grow roughly as $0.4z$, do not reach the critical value for plume merger (one-half the distance between the towers).

The enhancement of plume rise due to the merging of multiple plumes has been predicted theoretically by Briggs.¹⁶ 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 .

$$E_N = [(N + S)/(1 + S)]^{1/3} \quad (7)$$

where

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

From the results in Table 2.1.9, it can be assumed that H is 580m. For the small groups in our hypothetical power park ($N = 4$ and $s = 200\text{m}$), E_N equals 1.43. For the entire power park ($N = 100$ and $s = 1000\text{m}$), E_N equals 1.14. In this case the enhancement factors for the groups of four and the entire power park should probably be multiplied together. Thus, the theoretical enhancement E_N is predicted to be about 1.4 or 1.5 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 780m/580m, or 1.35.

The seasonal variation of plume rise in Table 2.1.9 is what would be expected intuitively, with the lowest plume rise usually occurring during the winter when the lower atmosphere is more stable. Similarly, the afternoon plume rises are 10 to 80% greater than the morning plume rises. The diurnal variation is less for the large sources, since the morning inversion is usually limited to a layer about 100 to 200m 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

¹⁶G. A. Briggs, "Plume Rise from Multiple Sources," in Cooling Tower Environment-1974, National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161, 1974, 161-179.

stressed that this "climatology" is based on observations during only four months. Ideally, observations during at least ten years should be used to establish a stable climatology.

Cloud at top of plume: In many model calculations, liquid water exists 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 it forms just above the lifting condensation level, with clear air beneath it. The frequencies of cloud occurrence for the six weather classes are given in Table 2.1.10, where the source is the single 1000 MW, 30m radius tower. On the average, a cloud is predicted at the top of the plume 39% of the time. During precipitation, fog, or cases when the cloud height is less than 10,000 ft, a cloud is predicted about 60% of the time. Clouds are very unlikely during afternoons which are clear or have high clouds. The reason that such high occurrence of clouds are not reported from operating cooling towers is that on foggy days or days with precipitation it is hard to see the plume. The model calculates plumes on all days, instead of just sunny days when the observer can easily see the plume.

The frequency of cloud occurrence is predicted to increase as source size increases, as shown in Table 2.1.11. For the 10^5 MW spaced power park the frequency of cloud occurrence is roughly halfway between those for single 10^3 MW and 10^4 MW cooling towers. As seen in Table 2.1.9, the plume rise for the spaced power park occupies the same relative position between that for the single 10^3 MW and 10^4 MW towers. 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 2500m deep would exist nearly continuously over an area with radius 300m dissipating 10^5 MW of heat.

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 is calculated using a scheme developed by Simpson and Wiggert,¹⁷

¹⁷J. Simpson and V. Wiggert, "Models of Precipitating Cumulus Towers," Mon. Wea. Rev., 97, 1970, 471-489.

Table 2.1.10 Frequency of cloud occurrence (QC0 + QH0 > 0
at height of final rise) for 1000 MW tower
at Nashville

<u>Weather class</u>	<u>Observed class frequency</u>		<u>Frequency of cloud occurrence within class</u>	
	<u>a.m.</u>	<u>p.m.</u>	<u>a.m.</u>	<u>p.m.</u>
1. Clear	0.09	0.15	0.32	0
2. Precipitation	0.18		0.60	
3. Cloud height $\geq$ 20,000 ft (no prec.)	0.05	0.07	0.23	0
4. 10,000 $<$ cloud height $<$ 20,000 ft (no prec.)	0.09		0.14	
5. Cloud height $<$ 10,000 ft (no prec.)	0.24		0.53	
6. Fog (no prec.)	0.13		0.65	
All	1.00		0.39	

Table 2.1.11 Frequency of cloud occurrence
estimated using Nashville
radiosonde observations

<u>Month (all 1974)</u>	<u>10³ MW</u>	<u>10⁴ MW</u>	<u>10⁵ MW</u>	<u>10⁵ MW spaced</u>
Jan.	0.41	0.70	0.97	0.59
Apr.	0.34	0.59	0.96	0.43
July	0.51	0.76	0.97	0.59
Oct.	<u>0.31</u>	<u>0.54</u>	<u>0.89</u>	<u>0.39</u>
Total	0.39	0.64	0.95	0.50

but it is uncertain whether the estimated rainfall rate at the ground is realistic. 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 listed in Table 2.1.12 refer to only those cases when a cloud formed at the top of the plume. The average liquid water contents range between 0.29 and 0.63, in agreement with typical values reported by Fletcher¹⁸ of the liquid water content in natural clouds. The peak liquid water content is 1.49 g/kg. It is seen that the average liquid water content for the larger sources is significantly greater than that for the 10³ MW source but that 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.

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,¹³ state that the capping inversion height, or mixing layer depth, determines the final plume rise. In the paper by Hanna¹¹ it is 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 runs were analyzed to determine the relation between plume rise from the 1000 MW cooling tower and inversion height.

A well-defined capping inversion is found in 89 of the runs, with the average plume rise and inversion height during these conditions equal to 690m and 1250m, respectively. All the runs are summarized in Table 2.1.13. The correlation coefficients between plume rise and inversion height are seen to be very high for the group of runs where 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, it will in all likelihood stop there.

Visible plume length: The model calculations stop after the vertical speed of the plume falls to zero. Downwind of this point, where passive

¹⁸N. H. Fletcher, The Physics of Rainclouds, Cambridge University Press, London, 1962, 386pp.

Table 2.1.12 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 (all 1974)	Average concentration (g/kg)				Peak concentration (g/kg)			
	10^3 MW	10^4 MW	10^5 MW	10^5 MW spaced	10^3 MW	10^4 MW	10^5 MW	10^5 MW spaced
July	0.40	0.54	0.62	0.47	0.72	0.96	1.49	0.98
Apr.	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
Oct.	<u>0.33</u>	<u>0.39</u>	<u>0.44</u>	<u>0.36</u>	<u>0.62</u>	<u>1.02</u>	<u>1.09</u>	<u>0.90</u>
Total	0.36	0.54	0.53	0.47	0.91	1.15	1.49	1.25

diffusion governs the distribution of excess water, very little is known about cooling tower plumes. It is better to wait for the results of measurement programs than to go ahead with a completely arbitrary model of passive diffusion. Consequently, this section on visible plumes is concerned only with plumes which evaporate before they reach the height of final rise. With this restriction, for the single 1000-MW source, the average annual visible plume height is 150m, and the average annual visible plume length is 190m. These estimates are about a factor of two less than the observations of visible plume geometry at the Paradise cooling towers, where the average annual visible plume length is 390m. At Paradise there are three cooling towers with a total energy output of more than 2000 MW. Our analysis of the daily Paradise observations is continuing in order to compare the model predictions of plume rise and visible plume length with the observations for the classes of weather conditions listed in Table 2.1.10.

Seasonal variations of predicted visible plume length and height are given in Table 2.1.14. It is seen that the average resultant visible plume length is about 40% to 75% longer in January than in July and that the morning length is about twice as long as the afternoon length. Furthermore, the angle of the plume with the horizontal 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 in January compared to 3.4 m/s in July). The shortest plumes occur on hot, dry days in July, when the visible plume length is only about 50m, or about one tower diameter.

Table 2.1.13 Plume rise and capping inversion height for the 1974 Nashville Soundings. The number of runs in each category is given in parenthesis.

<u>Month</u>	<u>Avg. capping inversion height</u>	<u>Avg. model plume rise</u>	<u>Correlation coefficient between capping inversion height and plume rise</u>	
			<u>All runs with inversion</u>	<u>Runs with plume rise ≥ inversion heights</u>
Jan.	920m	640m	0.31(39)	0.989(14)
Apr.	1640	760	0.20(25)	0.998(5)
July	1700	1250	0.78(5)	(0)
Oct.	<u>1280</u>	<u>570</u>	<u>0.15(20)</u>	<u>(2)</u>
Total	1250	690	0.33(89)	0.993(21)

Table 2.1.14 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.

<u>Month</u>	<u>Height(m)</u>		<u>Length(m)</u>		<u>Resultant(m)</u>	
	<u>am</u>	<u>pm</u>	<u>am</u>	<u>pm</u>	<u>am</u>	<u>pm</u>
Jan.	230	130	430	170	490	210
Apr.	180	90	330	130	380	160
July	240	120	140	90	280	150
Oct.	<u>240</u>	<u>80</u>	<u>210</u>	<u>110</u>	<u>310</u>	<u>140</u>
Average	220	100	280	130	360	160

2.1.2 Vorticity Enhancement

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Introduction

Intense vortex structures have been observed downwind of strong, area-extended heat sources such as volcanoes or fire storms. These observations have been reported on by Hanna and Gifford¹ and have been analyzed by Briggs.² It is felt that large power parks may also produce such motions. Consider the thermal plume created by such a power park by heat rejection. It will be bent over and highly buoyant, and this buoyancy will tend to create areas of horizontal convergence immediately below the plume as shown in Fig. 2.1.4. If the air which is being horizontally entrained has some horizontal circulation or vorticity, then one can expect this vorticity to be concentrated and, perhaps, lead to intense swirling motions beneath the plume. The details of the vortex-stretching mechanism are discussed by Rao.³ Accepting the above as a viable explanation of the observed phenomena, one is left with the question of the origin of the ambient vorticity which is being concentrated. Dr. Briggs suggests two possible sources: (1) the vorticity is produced by vortex shedding as a result of the flow around the plume and (2) the vorticity is produced naturally in the mixed layer by the action of convective overturning. The first mechanism is expected to operate at all times while the second will be dependent upon the degree of instability of the mixed layer. It is quite possible that intense vortex structures might exist at all times downwind of a large power park. An analysis of these processes may be accomplished through mathematical modeling. The nature of the problem requires a 3-dimensional turbulence numerical model similar to that developed by Deardorff.⁴

¹S. R. Hanna and F. A. Gifford, Meteorological Effects of Energy Dissipation at Large Power Parks, Bull. Amer. Meteor. Soc., 56, 1975, 1069-1076.

²G. A. Briggs, Plume Rise from Multiple Sources, in Cooling Tower Environment-1974, Springfield, Virginia, NTIS, 1975, pp. 161-179.

³K. S. Rao, Three-Dimensional Subgrid Turbulence Closure Models — A Critical Review, ARATDL internal note, April 30, 1976.

⁴J. W. Deardorff, Three-Dimension Numerical Modeling of the Planetary Boundary Layer, Workshop in Micrometeorology, D. A. Haugen, editor, American Society, Boston, Massachusetts, 1973.

Fig. 2.1.4. Schematic diagram of vorticity concentration below a buoyant plume.

On April 29, 1976, I discussed with Dr. Deardorff several points concerning the development of a 3-dimensional turbulence model capable of simulating a buoyant plume in a turbulent boundary layer. The results of this meeting are presented here in the form of a detailed analysis of the problems which must be overcome in this modeling effort. This report concludes with an outline of the approach to model development and suggestions for possible future applications of the turbulence model.

Preliminary Data Analysis

Before numerical experiments begin, it is necessary to have some knowledge of the scale of the natural vorticity patterns resulting from convective overturning in the mixed layer. Dr. Briggs has made some estimates of these scales by a subjective analysis of the velocity perturbation fields presented in Deardorff;⁵ however, a more detailed analysis must be performed. Data from the 1972 numerical experiment are not available; however, data from the 1974 Wangara simulation⁶ are available on magnetic tapes. These data are described in detail in Deardorff and Drake.⁷ Briefly, the three velocity components, virtual potential temperature, specific humidity, and subgrid turbulence kinetic energy and pressure fluctuations from 12:29 to 13:21 local time of the numerical simulation of day 33 of the Australian Wangara data⁸ are available. These variables are located at 64,000 points within a computational grid 5×5 km in the horizontal and 2 km in the vertical direction. The subgrid resolution is $\Delta x = \Delta y = 125$ m and $\Delta z = 50$ m. The time step in this simulation is 8 seconds.

⁵J. W. Deardorff, Numerical Investigation of Neutral and Unstable Planetary Boundary Layers, J. Atmos. Sci., 29, 1972, pp. 91-115.

⁶J. W. Deardorff, Three-Dimensional Numerical Study of the Height and Mean Structure of a Heated Planetary Boundary Layer, Boundary Layer Meteorol., 7, 1974, pp. 81-106.

⁷J. W. Deardorff and M. A. Drake, Boundary Layer Data from a Numerical Integration in Three Dimensions. National Center for Atmospheric Research, Boulder, Colorado, 1974.

⁸R. H. Clarke, A. J. Dyer, R. R. Brook, D. G. Reid, and A. J. Troup, The Wangara Experiment: Boundary Layer Data, CSIRO Div. of Meteorol. Phys. Tech. Paper No. 19, 1971, 340 pp.

As a first step in this study, it is suggested that ATDL obtain these tapes and perform the necessary analysis before proceeding too far on the turbulence model development. This analysis will not only offer a good opportunity to become familiar with the quality and quantity of the high resolution data but also will enable us to develop I/O routines and graphics packages which will be needed in the computer code.

The Model

The form of the governing equations is:

$$\begin{aligned} \partial \bar{U}_i / \partial t = & -\partial(\bar{U}_i \bar{U}_j) / \partial X_j - \partial(\overline{u'_i u'_j}) / \partial X_j - 2\epsilon_{ijk} \Omega_j \bar{U}_k - \rho_o^{-1} \partial \bar{P} / \partial X_i \\ & + \delta_{i3} g \left[-1 + (\bar{\theta}_v - \langle \bar{\theta}_v \rangle) / \theta_{vo} \right] \end{aligned} \quad (1)$$

$$\partial \bar{\theta}_v / \partial t = -\partial(\bar{U}_j \bar{\theta}_v) / \partial X_j - \partial(\overline{u'_j \theta'_v}) / \partial X_j + (d\theta_v / dt)_{\text{RAD}} \quad (2)$$

$$\partial \bar{q} / \partial t = -\partial(\bar{U}_j \bar{q}) / \partial X_j - \partial(\overline{u'_j q'}) / \partial X_j \quad (3)$$

$$\partial \bar{U}_j / \partial X_j = 0 \quad (4)$$

Here, the overbars denote grid-volume averaged quantities, and the primes denote deviations from the grid-volume averages. Indices i and j run from 1 to 3 with $X_1 = x$, $X_2 = y$, and $X_3 = z$. U is the wind speed, P is pressure, and θ_v is the virtual potential temperature defined as

$$\theta_v \approx \theta + 0.61 \theta_0 q \quad (5)$$

where q is the specific humidity, θ the potential temperature, and subscript zero refers to averages within a grid layer. ϵ_{ijk} is the alternating tensor, and Ω_j is the j th component of the Earth's angular velocity. Brackets denote horizontal averages. The last term in Eq. (2) refers to the estimated temperature changes as a result of the divergence of long-wave radiation flux.

Deardorff suggests that we use the following form for the subgrid Reynolds stresses and fluxes:

$$\overline{u'_i u'_j} = -K_m \left(\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right) \quad (6)$$

$$\overline{u'_i \theta'_v} = -K_h \left(\partial \bar{\theta}_v / \partial x_i \right) \quad (7)$$

$$\overline{u'_i q'} = -K_h \left(\partial \bar{q} / \partial x_i \right) \quad (8)$$

where the eddy coefficients are given by

$$K_m = 0.12 \ell E^{1/2} \quad (9)$$

$$K_h = (1 + 2\ell/\Delta) K_m \quad (10)$$

$$\Delta = (\Delta x \cdot \Delta y \cdot \Delta z)^{1/3} \quad (11)$$

where ℓ is a subgrid mixing length scale and E is the turbulence kinetic energy on the subgrid scale,

$$E = 1/2 \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right). \quad (12)$$

For stable conditions

$$\ell = 0.5 \left[E / \left(g / \theta_v \partial \theta_v / \partial z \right) \right]^{1/2} \quad (13)$$

while for neutral and unstable stratifications

$$\ell = \Delta. \quad (14)$$

The subgrid turbulence kinetic energy is estimated from

$$\begin{aligned} \partial E^{1/2} / \partial t = & -\nabla \cdot (\bar{v} E^{1/2}) + 0.06 \ell \left[\partial \bar{u}_i / \partial x_j \left(\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right) \right. \\ & \left. - K_h / K_m g / \theta_{v0} \partial \bar{\theta}_v / \partial z \right] + \partial \left(2 K_m \partial E^{1/2} / \partial x_i \right) / \partial x_i - \epsilon / 2 E^{1/2}. \end{aligned} \quad (15)$$

The dissipation rate ϵ is given by

$$\epsilon = G(z) \left[0.19 + 0.51 \ell / \Delta \right] E^{3/2} / \ell \quad (16)$$

where $G(z)$ is an empirical wall correction term given by

$$G(z) = 1 + 2 / \left[(z / \Delta z + 3/2)^2 - 3.3 \right]. \quad (17)$$

The subgrid closure (6) to (8) along with the subgrid turbulence energy Eq. (15) is to be preferred over the more detailed time-dependent subgrid flux and stress formulations⁶ for several reasons. First of all, the simpler closure results are a 2/3 savings of computer time, i.e., a 6-sec time step requires 20 sec instead of 60. The more complicated closure, moreover, requires several constants whose values are critical

but uncertain. The uncertainty in these constants leads to results that cannot be considered more accurate or realistic than the results from the use of Eqs. (6) to (8) and (15). It is felt that of the subgrid quantities, the most is known about the turbulence energy. Inclusion of Eq. (15) in the closure introduces second order with a minimum number of unknowns. In his experience with the more complicated closure, Deardorff found more cases of lack of realizability with it than with the simpler scheme. A lack of realizability is indicated by negative subgrid variances or energies. These situations are often attributed to noise produced by truncation error or computer round-off or computational instabilities; however, the larger instances of these errors in the more complicated closure were felt to be due to the uncertainties in the values used for the constants.

A potential source of difficulty is the inability of the numerical model to simulate the actual vortex stretching process since this is occurring on the subgrid scale. In reality, the vorticity will be concentrated into vortex tubes with diameters on the order of 10 m. In these structures the concentrated energy (vorticity) is rapidly destroyed by vortex stretching (energy cascade to smaller scales) and finally viscous dissipation. The simulation of the entrainment of ambient vorticity is expected to proceed normally on the scales resolvable by the model. This process will continue to ever smaller scales until the subgrid scale is reached. At this point, an anomalously high flux of turbulence energy might enter the subgrid scale to be dissipated. One is faced with the question of what if the energy cascade and dissipation parameterization is not able to admit these high inputs of energy. If the subgrid energy sink in Eq. (15) is not strong enough, will there result a kind of pile-up of energy within one or two grid cells? What effect would such a pile-up have on stability or realizability? These points cannot be answered now; however, they must be kept in mind during model development and testing.

Finite Differencing

Perhaps the most difficult problem to overcome in this development program is the formulation of an appropriate finite differencing scheme. The replacement of continuous derivatives by finite differences introduces truncation errors into the numerical results. These errors appear as a high frequency noise which interferes with the correct solution. If unchecked or not minimized, truncation errors will eventually overcome the computation leading to a physically unrealizable result. Truncation errors are related to the grid cell size and the time step size, and these quantities are related through the Courant-Friedricks-Lewy condition for linear stability of the solution, which is

$$\Delta t \leq \min \left(\Delta x / \bar{U}_{1\max}, \Delta y / \bar{U}_{2\max}, \Delta z / \bar{U}_{3\max} \right). \quad (18)$$

If we consider the mean flow to be in the x-direction we can write Eq. (18) as

$$\Delta t \leq \Delta x / \left(\langle \bar{U}_1 \rangle + \bar{U}_{\max} \right) \quad (19)$$

Where $\langle \bar{U}_1 \rangle$ is the globally averaged x-component of the wind velocity and $\bar{U}_{\max}$ is the maximum perturbation of $\langle \bar{U}_1 \rangle$ throughout the grid. In order to minimize truncation errors and ease the restriction on Δt , a common technique⁹ is to uniformly translate the computational grid with a velocity $\langle \bar{U}_1 \rangle$. This Galilean transformation allows a larger time step to be used than would otherwise be allowed from Eq. (19). While Eq. (19) insures stability of the solution, Deardorff⁴ has found that in practice Δt must be about 1/2 to 1/4 of its required value to insure proper minimization of the truncation errors. Typically, Δt has a value of from 6 to 8 sec.

In the present problem, this Galilean transformation cannot be made because the power park we are investigating is fixed to the ground surface. A 5-km-long computational grid traveling, say, at 5 m/sec would pass over the source in about 20 min. There would not be enough time for the plume

⁹J. W. Deardorff, A Three-Dimensional Numerical Investigation of the Idealized Planetary Boundary Layer, Geophys. Fluid Dyn., 1, 1970, pp. 377-410.

to establish itself — let alone begin to interact with any ambient vorticity fields. Two alternatives exist: either translate a very long computational grid or fix the grid to the ground surface. Practical considerations require the use of a stationary grid; however, in the absence of a Galilean transformation, the size of the time step is reduced. To retain advective stability and keep truncation errors small, a time step of one or two seconds may be necessary, which of course is completely unreasonable. From Eq. (19) it would seem that Δt can be increased by increasing Δx ; however, Deardorff has found through experience that unless

$$\Delta x < h_1/8 \quad (20)$$

where h_1 is the depth of the mixed layer, the convective turbulence is overcome by truncation error. Normally, h is about 1000 m so that Δx must be less than about 125 m. We see that the grid cell size is fixed by computational stability requirements. If in our case we expect to have local speeds of about 10 m/sec, then our time steps would have to be less than 3 sec. This value comes from taking 1/4 of Eq. (19) with $\Delta x = 125$ m and $\langle \bar{U}_1 \rangle + \bar{U}_{\max} = 10$ m/sec.

To retain reasonable time steps and yet minimize the truncation errors a more accurate finite differencing scheme must be used. Typically a second-order scheme¹⁰ is used. Molenkamp¹¹ investigated several differencing schemes for the advection equation. This study shows that the 4th order scheme of Roberts and Weiss¹² is the most accurate of the several schemes tested. The Arakawa-Adams Bashforth

¹⁰D. G. Fox and J. W. Deardorff, Computer Methods for Simulation of Multidimensional, Nonlinear, Subsonic, Incompressible Flow, J. Heat Transfer, Nov., 1972, pp. 337-346.

¹¹C. R. Molenkamp, Accuracy of Finite-Difference Methods Applied to the Advection Equation, J. Appl. Meteor., 7, 1968, pp. 160-167.

¹²K. V. Roberts and N. O. Weiss, Convective Difference Schemes, Math. Comp., 20, 1966, pp. 272-299.

scheme used by Deardorff, which is second order, produces large-phase errors relative to the Roberts-Weiss scheme; however, the Roberts-Weiss scheme requires about 28 times as much computer time as the Arakawa-Adams-Bashforth scheme. Obviously, the use of such a time-consuming scheme is not practical.

Recently, the use of third- and fourth-order splines in finite differencing schemes for differential equations have been investigated. Briefly, the procedure consists of constructing continuous functions (spline) of the variables assuming continuous first or second derivatives at the grid points. The continuous derivative of these functions at the grid points then replaces the finite differencing of the former method. Truncation error is introduced by the approximation of the real functions by their spline interpolation; however, the more exact the interpolation is, the less will be the truncation errors. Purnell¹³ has demonstrated that upstream interpolation with a cubic spline as a means of finite differencing the advection equations gives much better results than realized with second-order conservative, centered differencing. His spline method takes about 1/3 the computer time of an Arakawa-type scheme and requires about 1/8 the computer memory space. Rubin and Khosla¹⁴ have developed spline methods which are fourth-order accurate in the first and second derivatives but require 25% more computer time than finite differencing. Dr. Deardorff feels that these methods have potential and should be investigated.

Another approach is to solve the advection equation using Galerkin methods as is done by Orszag.¹⁵ Such a method makes use of the Fourier expansion of the flow variables and the subsequent solution of the advection equation in spectral form. The technique is quite free of truncation or aliasing errors and new developments in fast-Fourier transforms make its use in large problems practical. The main disadvantage is that the method requires periodic boundary conditions.

¹³D. K. Purnell, Solution of the Advection Equation by Upstream Interpolation with a Cubic Spline, Mon. Weath. Rev., 104, 1976, pp. 42-48.

¹⁴S. G. Rubin and P. K. Khosla, Higher-Order Numerical Solutions Using Cubic Splines, NASA Contractor Rpt. CR-2653, 1976.

¹⁵S. A. Orszag, Numerical Simulation of Incompressible Flows within Simple Boundaries: Accuracy, J. Fluid Mech., 49, 1971, pp. 75-112.

Boundary and Initial Conditions

Lateral boundaries: Perhaps the second most important part of this program will be the proper specification of lateral inflow and outflow boundary conditions. In almost all turbulence models currently in use, the assumption of horizontal homogeneity and the absence of sources of pollutants or heat allows the use of cyclical boundary conditions on the lateral boundaries. The introduction of a large source of heat and turbulence energy due to a nuclear energy center would make the outflow conditions quite different from the inflow conditions. Two alternatives are available for fixing these boundary conditions: (1) keep cyclic boundary conditions but place the outflow boundary sufficiently away from the heat source so that its presence is not seen and (2) use non-periodic boundary conditions.

If cyclic boundary conditions are to be used, then an estimate of the minimum distance to the downwind boundary can be made by assuming that at this point the plume is uniformly mixed through the mixed layer. For a passive plume in a convectively unstable boundary layer, the laboratory experiments of Deardorff and Willis¹⁶ suggest that the plume is uniformly mixed in the vertical when

$$(w_*/z_i)(x/U) = 4.2 \quad (21)$$

where w_* is the mixed layer convective velocity scale, z_i is the mixed layer depth, x the downwind distance, and U the wind speed. Typically, z_i varies between 1000 and 1500 m, w_* between 1.0 and 2.5 m/sec, and U between 2 and 10 m/sec. With these extremes, we can expect that the minimum distance from the heat source to the outflow boundary must be between 6000 and 18,000 m. To ensure that the effects of the heat source are dissipated before the outflow boundary is reached, a computational grid at least 20 km long should be used. This, of course, cannot be done because the demands on computer time and storage are too great.

¹⁶J. A. Deardorff and G. E. Willis, A Parameterization of Diffusion into the Mixed Layer, J. of Appl. Meteor., 14, 1975, pp. 1451-1458.

It appears that the only course left is to assume non-cyclic lateral boundary conditions. In this case, more heat and turbulence kinetic energy would pass through the downstream boundary than would enter the upstream boundary. For this case, Deardorff⁴ suggests that the inflow boundary conditions be specified at each time step and the first or second derivatives be specified at the outflow boundary. An example of the latter boundary condition is

$$\partial^2 \bar{\theta} / \partial x^2 = -4\pi^2 / L^2 (\bar{\theta} - \langle \bar{\theta} \rangle) \quad (22)$$

where L is a characteristic wavelength which must be specified and $\langle \bar{\theta} \rangle$ is the horizontal average of $\bar{\theta}$. The inflow boundary conditions must be known before the start of the integration. This can be easily done by running the turbulence model without a heat source and storing the output from selected points on magnetic tape. This tape can then be used to update the inflow boundary of the turbulence model when it is run with the heat source. Of course, this same input data can be used to run the turbulence model for other applications.

Horizontal boundaries: At the lower boundary, the following conditions are imposed:

$$\begin{aligned} \bar{w} = 0 = \overline{\partial u'^2 / \partial z} = \overline{\partial v'^2 / \partial z} = \partial E / \partial z = \partial (\overline{u'v'}) / \partial z = \partial (\overline{u'_i \theta'_v}) / \partial z \\ = \partial (\overline{u'_i q'}) / \partial z = \overline{\partial \theta'^2 / \partial z} = \overline{\partial q'^2 / \partial z} = \partial (\overline{q' \theta'_v} / \partial z). \end{aligned} \quad (23)$$

Vertical fluxes of heat, water vapor, and momentum are given by:

$$\overline{u'w'} (x, y, 0, t) = -c_p \bar{s} \bar{u} (x, y, z_1, t) \quad (24a)$$

$$\overline{v'w'} (x, y, 0, t) = -c_d \bar{s} \bar{v} (x, y, z_1, t) \quad (24b)$$

$$\overline{\theta'w'} (x, y, 0, t) = c_H s [\bar{\theta}_g (x, y, t) - \bar{\theta}_v (x, y, z_1, t)] \quad (25)$$

$$\overline{q'w'} (x, y, 0, t) = c_Q s [\bar{q}_g (x, y, t) - \bar{q} (x, y, z_1, t)] \quad (26)$$

where $s = (\bar{U}^2 + \bar{V}^2)^{1/2}$, z_1 is the first computational level above the ground surface, c_d is a horizontally averaged drag coefficient, and c_H and c_Q are the horizontally averaged exchange coefficients for vertical potential temperature and specific humidity, respectively. $\bar{\theta}_g$ and $\bar{q}_g$ are the subgrid averaged surface values of vertical potential temperature and specific humidity, respectively. In the calculations to be done, all surface values will be held constant, i.e., there will be no diurnal trend in the input or surface data.

At the upper boundary we impose the following conditions:

$$\begin{aligned} \bar{W} = 0 = \partial \bar{U} / \partial z = \partial \bar{V} / \partial z = \partial \bar{q} / \partial z = \partial (\overline{u'_i u'_j}) / \partial z = \partial (\overline{u'_i \theta'}) / \partial z \\ = \partial (\overline{u'_i q'}) / \partial z = \partial \overline{\theta'^2} / \partial z = \partial \overline{q'^2} / \partial z = \partial (\overline{q' \theta'}) / \partial z . \end{aligned} \quad (27)$$

The addition of the large heat source may prohibit the assumption of zero heat flux at the top boundary. It is not clear at this time how this case would be treated; however, an expedient would be to ensure that the model depth is large compared to the mixed-layer depth. It is also expected that the heated plume will tend to entrain the elevated inversion capping the mixed layer faster than normal. This effect, however, is expected not to be of great significance.

Initial conditions: Initial conditions can be taken from field observation studies such as the Australian Wangara experiment⁸ or the more recent Minnesota experiment.¹⁷ Mean profiles of horizontally averaged quantities can also be specified. To initialize the subgrid averaged values, these input data must be randomized so that a desired level of horizontal variability is achieved. Such a condition, if realistically imposed, can speed up the time required for the turbulence model run without a heat source to reach a steady state in its mean quantities. When running with the heat source, we shall initialize all points with data from the source-free run. In this way, the plume will develop in a turbulent field, i.e., the heat source will be turned on

¹⁷J. C. Kaimal, J. C. Wyngaard, D. A. Haugen, O. R. Cote, Y. Izumi, S. J. Caughey, and C. J. Readings, Turbulence Structure in the Convective Boundary Layer, to appear in J. Atmos. Sci., 1976.

at the start of the simulation. It is not known how much computer time will be required for the plume to reach a steady, developed state; however, an estimate can be made using Eq. (21) by replacing X/U by t (the advection time) to get

$$t = 4.2z_1/w^* . \quad (28)$$

Using typical values for z_1 and w^* as before, the time required ranges from about 45 to 70 minutes. If we assume that a 6-sec time step will take about 20 sec, then an outside estimate of the computer time needed to establish a developed plume is about 4 hrs.

Program Development

The preceding discussion dealt with some of the technical problems involved in the development of a turbulence model capable of simulating the detailed processes of vorticity concentration in the presence of large heat sources. In this section, we shall outline a plan for the development of such a model.

Dynamic modeling: The development of this program requires the simultaneous actions of numerical modeling and analysis of the physical problem. These actions will often complement each other in a bootstrap fashion or indicate where potential problems lie. While what has to be done in numerical modeling is clear, the question of analysis of the problem (vorticity concentration) is not. Dynamic modeling as discussed by Rao³ offers a means of performing this necessary analysis. In this case, the exact physical processes are not simulated but rather their ensembled averages. This type of modeling can then afford a statistical analysis of the problem, indicating the scales of the disturbances, frequency of occurrence, etc. Dynamic modeling is not computer intensive, and so a number of cases can be run such as varying boundary layer conditions and source strengths and configurations. In this way, a "window" of boundary layer and source parameters can be established wherein vorticity concentration may or may not be expected to occur.

Software: Software must be developed for the computer code. These include I/O packages, graphic displays, the logical disposition of the computational grid, and the use of computer memory both direct and indirect. Optimization of the computer code must be performed at each step, always keeping in mind the saving of computer and wall clock time. This task will require the help of computer experts experienced in handling large volumes of data. A data set is needed for this development, and it is suggested that we obtain the Wangara simulation data discussed previously.⁷ With this data, the preliminary data analysis and software development can be done simultaneously.

Finite differencing: From the discussion of lateral boundary conditions, we can conclude that non-cyclic conditions are needed. This precludes the use of Galerkin techniques in solving for the advection terms but admits the use of spline interpolation techniques. It is suggested that these techniques be used; before incorporating them into a complex turbulence model, however, they should be used in a more familiar environment where they could be more easily understood. This could be done by expanding the ATDL 1-dimensional PBL model into a 3-dimensional mesoscale model using these spline techniques to solve for the advection terms. The mesoscale model will not only be a convenient vehicle with which to test these differencing schemes but also satisfy a long-standing need for such a modeling capability.

Initial running: With the completion of the turbulence model, we should like to duplicate some of the experiments of Deardorff, for instance his simulation of day 33 of the Wangara experiment.⁶ The agreement between his results and ours (using an entirely different numerical treatment) will serve to validate our model. Being satisfied that our model is sound, we can begin an extensive run which will generate inflow boundary conditions needed for the heat source simulation or other problems. In this initial run we can assume cyclic boundary conditions.

Final experiment: Having finished the above tasks, the final experiment can begin. Initially this should consist of several short

runs in which key parameters, i.e., conserved, globally averaged quantities such as potential temperature or energy, are monitored very closely. This cautious running will quickly spot errors or other "bugs" in the code and save a great deal of wasted computations. If errors are caught quickly enough, the integration may be saved with only slight back stepping. Once satisfied that the code is error-free, longer running times can be used.

2.1.3 Drift Deposition

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A Review of Cooling Tower Drift Deposition Models

Congress is looking into the conglomeration of nuclear reactors into energy centers of limited area for the purpose of, among others, plutonium safeguards. The program entitled "Atmospheric Effects of Nuclear Energy Centers" is intended to centralize research on model development and verification in regard to weather modification and its local and regional effects. As a part of this effort, a state-of-the-art review¹ dealing with ground-level salt deposition from cooling tower drift is studied.

Drift from cooling towers can corrode and damage structures in the immediate vicinity of the towers, cause a public nuisance if located near parking lots or high-density traffic areas, and endanger local vegetation. To date, however, the determination of salt deposition has relied primarily on predictions from a variety of models, with very few direct measurements. One of the major efforts in the study is to evaluate assumptions, limitations, and applicabilities of various analytical models for deposition prediction. To quantify the cooling tower contributions, a common set of input parameters — an essential element for model evaluation — is provided for the model comparison.

When a small amount of the circulating water in a cooling tower is entrained and carried aloft by the air stream in the form of droplets that contain chemicals in roughly the same concentration as in the cooling water, the droplets, which vary from a few to several hundred microns in diameter, are referred to as drift. In a modern cooling tower system, with efficient drift eliminators, the ratio of drift rate to circulating water rate can be as low as 0.001%.

The drift deposition problem is a complicated one which involves several interrelated processes: the dynamics and thermodynamics of drops in a rising plume, the point at which the drops break free, dispersal by atmospheric turbulence, and evaporation in an unsaturated atmosphere. To make deposition estimates possible, the source characteristics of the tower, such as tower geometry, amount of water circulated, effluent speed, droplet emission spectra, drift rate, and salt concentration, must be known.

¹N. C. J. Chen, "A Review of Cooling Tower Drift Deposition Models," ORNL/TM-5357 (1976).

Calculations must be made of the plume rise which, in part, depends on initial momentum and buoyancy flux and on the ambient atmospheric conditions. Droplet transport, which depends on meteorological conditions such as atmospheric relative humidity, turbulence, temperature and its gradient, and wind vector, should be studied. Further complications in making deposition estimates may arise if the plume is bifurcated.

Ten models available have been reviewed; it is found that each model employs some simplifying assumptions to make deposition prediction mathematically tractable. As a result, their predictions are not yet exact. Certain parameters within each require tuning before reliable predictions are possible.

Models are compared (Table 2.1.15) by a means of some prominent characteristics, with no attempt made to examine all details. Basically, there are two methods in the deposition prediction. First, in the ballistic method, the trajectory is determined by the droplet fall velocity and the wind vector. Second, the tilted Gaussian plume model, the axis of the gravity of a given class of droplet, falls in proportion to the settling velocity of the mean droplet, with respect to the gas plume. The atmospheric diffusion is simulated by a Gaussian distribution, with the use of Pasquill σ values. Some of the models involve a combined method; that is, the trajectory technique for the large droplets and the Gaussian plume technique for small droplets. The majority of models use plume-rise equations derived by Briggs. Assumptions in breakaway points vary from model to model. The treatment of evaporation differs among models, but most of them apply the Hosler et al. method.

As stated earlier, before long-term field data becomes available to verify models, a valuable and effective way is to study the behavior and range of predictions of all current models by a set of identical input parameters. A set of meteorological conditions, as shown in Table 2.1.16, to simulate as close as possible a natural-draft cooling tower is chosen. The six drift-drop-size distribution is arbitrary, guided by data from environmental reports.

Given the input data, most of the models estimate that the cooling tower plume will level at about 500 m above ground at a distance of

Table 2.1.15 Summary of model characteristics on ground deposition rate prediction^a

Investigator	Method	Atmospheric turbulence diffusion	Plume rise formula	Breakaway point	Evaporation
Hosler, et al. ² May 1972	Ballistic	No	Ns ^b	Drop fall velocity exceeds updraft	Three categories: no evapora- tion, saturated solution, and dry particles
Roffman & Grimble ³⁻⁵ Jan. 1973	K-theory	Yes, constant K used	Briggs	Max. plume rise	Same as Hosler, et al.
Wistrom & Ovard ⁶ Jan. 1973	Ballistic - large drops: Gaussian - small drops	Yes, PG ^c	Ns ^b	Tower top	Yes
Slinn, ⁷ Mar. 1974	Ballistic - large drops: Gaussian - small drops	Yes, PG ^c	Briggs	Tower top - large drops; max. plume rise - small drops	No
Laskowski ⁸ Mar. 1974	Ballistic-Gaussian	Yes, PG ^c	Briggs or Slawson & Csanady	Amount of drop fall exceeds plume radius	Yes
Israel & Overcamp ⁹ Mar. 1974	Gaussian	Yes, BNL ^d or PG	Briggs or Slawson & Csanady	Drop fall velocity exceeds updraft	Same as Hosler, et al.
Hanna, ¹⁰ Mar. 1974	Ballistic	No	Briggs	Amount of drop fall exceeds plume radius	Yes
Wolf, ^e Mar. 1974	Ballistic	No	Briggs		Yes
Tsai & Johnson ¹¹	Ballistic	Ns ^b	Extension of Morton, Fan, Taylor, & Turner ^f model	Fall velocity exceeds updraft	Yes
ORFAD ¹²⁻¹³ Jan. 1975	Ballistic	No	Briggs	Ns ^b	Same as Hosler, et al.
Rao, et al. ¹⁴	Ballistic-Gaussian	Yes	Extension of Morton, Taylor, & Turner ^f model	Ns ^b	Empirical formula

^aEffects of downwash and washout are accounted for only by Laskowski.

^bNo specification is given in the model.

^cPasquill-and-Gifford stability class.

^dBrookhaven National Laboratory stability class.

^eWolf's model is not reviewed in this report.

^fB. R. Morton, G. Taylor, and J. S. Turner, "Turbulent gravitational convection from maintained and instantaneous sources," Proc. Roy. Soc. (London) Ser. A234, 1956, 1-23.

^gOak Ridge fog and deposition model.

²C. Hosler, J. Pena, and R. Pena, "Determination of Salt Deposition Rates from Drift from Evaporative Cooling Towers," Trans. ASME, Ser. A: J. Eng. Power, 96(3), 1974, 283.

³A. Roffman and R. E. Grimbale, "Predictions of Drift Deposition from Saltwater Cooling Towers," paper presented at the annual meeting of the Cooling Tower Institute, January 29-31, 1973, Houston, Texas.

⁴A. Roffman, et al., The State of the Art of Saltwater Cooling Towers for Steam Electric Generating Plants, USAEC Report WASH-1244, February, 1973.

⁵A. Roffman and Lowell D. Van Vleck, "The State-of-the-Art of Calculating and Predicting Cooling Tower Drift and Its Deposition," J. Air Pollu. Control Assoc., 24(9), 1974, 855-859.

⁶G. K. Wistrom and J. C. Ovard, "Cooling Tower Drift; Its Measurements, Control, and Environmental Effects," paper presented at the annual meeting of the Cooling Tower Institute, Jan. 29-31, 1973, Houston, Texas.

⁷W. G. N. Slinn, "An Analytical Search for the Stochastic-Dominating Process in the Drift Deposition Problem," p. 483 in Cooling Tower Environment - 1974, TIC-ERDA, CONF-740302, 1975.

⁸S. M. Laskowski, "A Mathematical Transport Model for Salt Distribution from a Saltwater Natural-Draft Cooling Tower," p. 598 in Cooling Tower Environment - 1974, TIC-ERDA, CONF-740302, 1975.

⁹G. W. Israel and T. J. Overcamp, "Drift Deposition Model for Natural-Draft Cooling Towers," p. 614 in Cooling Tower Environment - 1974, TIC-ERDA, CONF-740302, 1975.

¹⁰S. R. Hanna, "Meteorological Effects of the Mechanical-Draft Cooling Towers of the Oak Ridge Gaseous Diffusion Plant," p. 291 in Cooling Tower Environment - 1974, TIC-ERDA, CONF-740302, 1975.

¹¹Y. J. Tsai and D. H. Johnson, "Cooling Tower Drift Model," paper presented at the Fifth Annual Pittsburgh Conference on Modeling and Simulation, April 24-26, 1974.

¹²J. V. Wilson, ORFAD, A Computer Program to Estimate Fog and Drift from Wet Cooling Towers, ORNL/TM-4568, January 1975.

¹³M. E. LaVerne, Oak Ridge Fog and Drift Program (ORFAD) User's Manual, ORNL/TM-5021 (in preparation).

¹⁴K. S. Rao, J. S. Lague, and B. A. Egan, "Cooling Tower Drift Model Description," Appendix B of A Study of Environmental Impacts Associated with Cooling Tower Operation at the Proposed Pleasant Prairie, Wisconsin, Power Plant, ERT/P-1235, 1975.

Table 2.1.16. Parameters used in the calculations

Saturated plume initially

Plume temperature at exit from tower, $T_{po} = 305^{\circ}\text{K}$

Ambient temperature near exit from tower, $T_{eo} = 275^{\circ}\text{K}$

Tower height = 100 m

Tower exit diameter = 60 m

Efflux velocity = 4.3 m/sec

Amount of circulating water = $31.5 \text{ m}^3/\text{sec}$

Drift rate = 2×10^{-5}

Water salinity = 3.45%

Wind speed = 4.3 m/sec

Calculated salt deposition rate for sector of 22.5°

Frequency of wind direction which blows toward the sector = 1

Ambient relative humidity = 70% (constant with height)

Isothermal ambient atmosphere (slightly stable atmosphere)

Drop size distribution

Diameter interval (μm)	Mass mean diameter for interval (μm)	Mass fraction
0-100	50	0.05
100-200	150	0.3
200-300	250	0.4
300-400	350	0.15
400-500	450	0.075
500-600	550	0.025

about 550 m from the tower. Most models applied the plume-rise formula derived by Briggs. For the sake of clearance, results of the model calculations are shown in Figs. 2.1.5, 2.1.6, and 2.1.7. Curves (A) and (B) in Fig. 2.1.5 are the result of models which bracket the other curves in the figure. Curve (A) is obtained using the trajectory method, assuming that all droplets break away at the tower top and that no evaporation occurs. The resulting deposition pattern has a larger maximum deposition but covers a shorter distance than any of the other models. Curve (B) is obtained by applying the Gaussian diffusion model, assuming that all droplets break away at the height of maximum plume rise and that they evaporate completely. The resulting deposition pattern has a smaller deposition but covers a broader distance than any of the other models in the range of downwind distance considered. Any model prediction on the maximum deposition falling out of these two extremes indicates that a certain error in physical processes involved would have occurred.

The curves in Figs. 2.1.5, 2.1.6, and 2.1.7 group into three categories, depending on the assumptions involved in the models: (1) histograms with six steps corresponding to six classes of droplet size, where ground deposition is assumed to be uniform over the particle size range; (2) curves representing the superposition of six isolated bell-shaped Gaussian curves, where turbulent mixing causes overlap in ground deposition between particle-size classes and, hence, smearing of interface; and (3) curves resulting from a combination of the above two methods — the trajectory technique for large droplets and the Gaussian diffusion model for small droplets. For some models in which the trajectory method without dispersion is applied, the step function is smoothed by increasing the groups of droplet-size distribution. In the near field (for example, at about 1 km), comparison between the models shows disagreements of at least two orders of magnitude in the predicted deposition rates and a wide range in peak locations. Some of this variance can be identified with differing assumptions of the effective height of particle emission and/or the extent of droplet evaporation. While the deposition rates fall off rapidly with increasing distance from the tower (effect of area increase rather than mass decrease), the discrepancy between predictions in the far field (for example, at about 100 km) shows little improvement. Results in the far field obtained by applying

Fig. 2.1.5. Histograms with six steps corresponding to six classes of droplet size, where ground deposition is assumed to be uniform over the particle-size range.

Fig. 2.1.6. Curves representing the superposition of six isolated bell-shaped Gaussian curves, where turbulent mixing causes overlay in ground deposition between particle-size classes.

Fig. 2.1.7. Curves resulting from a combination of the trajectory technique for large droplets and the Gaussian diffusion model for small droplets.

Pasquill-Gifford σ curves should be viewed cautiously because the σ values have been extended to distances greater than those for which they were derived.

Whichever method is used, the salt mass should be conserved — one of the essential elements for model evaluation. For the parameters provided, total mass emission of NaCl from the tower is 22 g/sec. By integrating the sector-averaged deposition rate ($\text{kg}/\text{km}^2/\text{month}$), it is found that total salt deposition (kg/month) predicted from the trajectory method equals approximately the amount emitted as expected; whereas, surprisingly, total salt deposition predicted from the Gaussian diffusion model is about twice the amount emitted.

Model-predicted maximum deposition rate, downwind location, and rate of NaCl deposited to that emitted is tabulated in Table 2.1.17. The ratio in the last column for all models are computed by integrating the averaged deposition ($\text{kg}/\text{km}^2/\text{month}$) over a $22\frac{1}{2}^\circ$ sector from 0.1 to 100 km. However, the integration interval for the model K is from 0.1 to 10 km and for the model L from 0.5 to 2 km.

Some general suggestions to improve the model are listed as follows:

Effects of Centrifugal Force. The centrifugal force of the vortex motion in a bifurcated plume might be of some importance for droplet removal and in determining the ground deposition rate and the deposition pattern. For instance, the centrifugal force might cause droplets to be thrown out normal to the axis of the plume and enhance the ground deposition rate laterally near the tower and reduce it offsite. Field data are needed to verify this prediction.

A rough comparison of the centrifugal force to the gravity force of a bifurcated plume from typical cooling towers and smoke stacks is presented in Table 2.1.18. If the vortex angular speed is one-quarter that of the effluent speed ($v_t/w_o = 1/4$), the ratio of the centrifugal force to the gravity force is 0.01, 0.3, and 0.96 for typical natural-draft cooling towers, mechanical draft cooling towers, and smoke stacks, respectively. The ratio of centrifugal-to-gravity forces increases proportionally to the square of the angular speed and is inversely proportional to the diameter of the tower. The ratio increases rapidly with angular speed and becomes 0.17, 4, and 15 for natural-draft cooling

Table 2.1.17. Summary of model predicted maximum deposition rate, location, and ratio of NaCl deposited to that emitted

Model	Maximum deposition rate (kg/km ² /month)	Location from source (km)	NaCl deposited (gm/sec) ^a NaCl emitted (gm/sec) ^a
C	4000	From 2.3 to 3.4	1.03
D	4800	From 0.6 to 1.4	1.02
E	24000	1.1	1.88
F	260000	From 0.29 to 0.41	0.95
G	29400	1.1	0.87
H	31000	From 0.6 to 0.8	0.91
I	44000	0.9	0.95
J	16400	1.2	1.16
K	24500	1.0	0.41
L	20000	0.7	0.11

^aThe rate of NaCl deposited to that emitted in all models are computed by integrating the averaged deposition (kg/km²/month) over a 22 1/2° sector from 0.1 to 100 km. However, the integration interval for the model K is from 0.1 to 10 km and for the model L from 0.5 to 2 km.

Table 2.1.18. Comparison of the centrifugal force to gravity for a bifurcated plume from cooling towers and from smoke stacks

	NDCT ^a	MDCT ^b	Stoke stacks
D, m	60	10	6
$R_v = D/4$	15	2.5	1.5
w_o , m/sec	5	10	15
$\frac{v_t^2/R_v}{g}$			
$v_t = w_o/4$	0.011	0.26	0.96
$v_t = w_o/2$	0.043	1.02	3.83
$v_t = w_o$	0.17	4.08	15.31

^aNDCT = Natural-draft cooling tower.

^bMDCT - Mechanical-draft cooling tower.

towers, and smoke stacks, respectively, if the vortex angular speed is comparable to the effluent speed. More theoretical studies about a bifurcated plume and measurements of vortex angular speeds are required before the impact in drift deposition enhancement due to the secondary flow can be assessed with certainty.

Multiple Plumes. There are usually several cooling towers at any site. If mechanical-draft cooling towers are used, there can be several tower units, each containing 10 or 20 individual cells. Groups of three or four natural-draft towers are in use, for example, at Paradise, Kentucky, Keystone, Pennsylvania, and the John E. Amos plant in West Virginia. Because a future 50,000-MWe energy center would require at least 50 natural-draft towers, it is obviously important to know how plumes from these multiple sources will interact. The merged plume may enhance plume rise and reduce the drift deposition but increase the chance of cloud and rainstorm generation.

Unfortunately, there are no adequate observations of the interaction among cooling tower plumes. The only method available derived by Briggs¹⁵ for estimating the enhancement to plume rise due to multiple sources is based on a few observations at TVA smoke stacks. Since the full-scale field observations will not be available until Nuclear Energy Centers are in operation, clearly, the study of multiple plume interaction must be done in the laboratory. This seems to be the only method in which the important physical mechanisms can be examined.

Observation programs at multiple cooling towers are needed to verify Briggs' prediction. Also necessary so that the physical mechanism of plume merger can be understood are laboratory experiments and aircraft penetrations of the plumes from the point at which the plumes begin to merge to some point downwind at which they are completely merged.

Downwash. Downwash from rectangular mechanical-draft towers is a severe problem due to the towers' low height and large cross-sectional

¹⁵G. A. Briggs, "Plume Rise from Multiple Sources," p. 161 in Cooling Tower Environment - 1974, TIC-ERDA, CONF-740302 (1975).

area. Hanna¹⁰ estimates that downwash (the plume reaching the ground) occurs about 40% of the time at the mechanical-draft towers in Oak Ridge. A rough estimating criterion is that the plume will downwash if the wind speed exceeds the vertical speed of the plume. If the plume is very buoyant, that is, the initial Froude number $Fr = w_0^2 / g(\Delta T/T)D$ is 1 or less, the buoyant forces may be sufficient to balance some of the adverse pressure force and perhaps the criterion could be relaxed. Overcamp and Hoult,¹⁶ based on laboratory simulation, suggest that the critical value decreases to 0.5 at $Fr = 0.25$ and decreases further to 0.2 at $Fr = 0.01$.

At natural-draft towers the plume seldom reaches the ground during downwash conditions, due to the towers' height and smooth aerodynamic shape. Correction factors are introduced into the plume rise equations to account for the slight downwash.

Terrain Effects. Very little is known about the effects of terrain on cooling tower plumes and drift deposition. The diffusion of the plume after final rise is attained will be increased due to the mechanical mixing generated by rough terrain. This increase will be greater than would be expected from measures of stability such as the Pasquill-Gifford classes. As an indirect effect, the terrain can channel the winds¹⁷ and thus influence the direction of the plume. If the terrain discontinuity is close enough to the cooling towers (less than about ten tower heights), vertical motions induced by the terrain can influence plume rise. For example, observers at the Indiana, Pennsylvania, towers report that the plume dips toward the ground when the wind blows over a hill upwind of the

¹⁶T. J. Overcamp and D. P. Holt, "Precipitation in the Wake of Cooling Towers," Atmos. Environ., 5: 751-765 (1971).

¹⁷D. H. Slade (ed.), Meteorology and Atomic Energy 1968, USAEC Report TID-24190.

towers. Furthermore, the plume may impact the side of a hill during stable conditions and cause local fogging and local maximum deposition. Since most terrain is site-specific and cannot be represented in a general way, it is recommended that terrain effects be studied at any particular site using a physical modeling facility (wind tunnel or water flume).

In the following, a summary and recommendations are given. Most of the models use the stack-plume-rise formulas derived by Briggs. Whether the formulas can be adequately applied to cooling tower plumes has never been proven and should be determined by measurements. In some models, it is assumed that the droplets escaped from the plume at a height where the droplet fall velocity exceeds the updraft. Various updraft have been assumed, but they should be tested by aircraft measurements. In practice, the plume centerline vertical velocity derived from the 2/3 law of plume rise derived by Briggs is recommended. The effective height of emission used by Israel and Overcamp⁶ is recommended. In this method, the effective height of emission is bounded by the cooling tower height for the largest droplets and the maximum plume rise for smaller droplets. The method for calculating the rate of droplet evaporation as a function of droplet size, salinity, and the ambient relative humidity used by Hosler, Pena, and Pena⁷ is recommended. In the absence of adequate verification, the combined method for deposition calculation is recommended on the basis of physical reasonableness. The trajectory method is more proper for those large droplets (with diameter larger than 100 μm) free from turbulent effects near the rising plume where the application of the Gaussian diffusion model has a limitation. The diffusion method is more appropriate for small droplets (with diameters less than 100 μm) which are influenced by turbulence at a distance from the source where the plume becomes passive.

The present understanding of droplets breakaway points is limited. The dispersal of the droplets by the plume-induced turbulence in the rising plume needs to be studied. Downwash and terrain effects, two very important site-dependent factors, are absent from nearly all of the models. In addition, effects of the centrifical force on deposition when the plume is bifurcated are not accounted for. Whichever method is used, the total amount of salt emitted should be conserved.

The main findings in this study are that the discrepancy in predicted maximum deposition differs by almost two orders of magnitude (from 4,000 to 260,000 kg/km²/month, with two extreme cases excluded) and an order of magnitude in the downwind location of peak deposition (from 0.2 to 3 km). Some of these discrepancies are attributed with different assumptions of the height variation in the plume centerline vertical velocity, the droplet effective height of emission and the extent of evaporation. The fact that a given droplet may or may not reach equilibrium size is affected by many factors, such as where the droplet breaks free, the plume updraft, droplet size, salt concentration, and relative humidity. Among them the effective height of emission is crucial in determining the impact distances and the subsequent deposition.

No model can claim superiority over any other model without field-data verification. Thus, no new models are needed, but field data, especially measurements of ground salt deposition, are needed. It is found that the maximum deposition and its location is very sensitive to the mass fraction in larger droplets for all present models. Thus the measurement of droplet-emission-spectrum in both size and mass fraction should be as accurate as possible.

There are other sources, such as background due to natural salt spray and interference from nearby smokestacks, for deposition besides cooling towers. Thus, it is necessary to establish the background and distinguish smokestack contribution from cooling towers before predicted deposition against measurements can be made.

To verify the different deposition models, it is suggested that simultaneous measurements be made of salt concentration in the tower basin, drift-droplet distribution at the tower exit, drift rate, onsite weather conditions, and ground deposition rate distribution. Since the amount of salt to be measured is small, the results will be very sensitive to the instruments and methods used.

The receptors should be suitably located at 500-m intervals from the tower to a point 10 km in the downstream direction of the persistent wind. It is also suggested that more than one collector (sensor) be placed at a given station to provide a necessary redundancy.

Deposition depends on, among other things, the joint frequency distribution of wind vector and ambient relative humidity. Thus, onsite hourly averaged wind and relative humidity as a function of height from ground surface to the maximum plume rise are necessary.

Because almost all the models reviewed are of the integral, empirical, or phenomenological plume model, the sampling period should be longer than the time scale of the plume meandering.

An hourly sampling frequency is reasonable for detailed studies of plume trajectory and its correlation with deposition rate; diurnal variation will smear the maximum and minimum deposition value if measurements are obtained only daily. For ecological concerns or environmental impact assessments, integrated results from monthly and yearly measurements are reasonable.

Finally, more important, it is recommended that a time-lapse movie camera system with high resolution should be equipped to study vortex structure of a bifurcated plume so the influence of the secondary flow on deposition can be assessed.

2.1.4 Mesoscale Cloud Growth

2.1.4.1 Perturbations in Atmospheric
Thermal Convection Modeling

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Introduction

Thermal convection in the atmosphere has one distinguishing feature that sets it apart from many other types of thermal convection that are frequently studied, namely, the destabilizing effect of the condensation of water vapor. Typically, the free atmosphere is characterized by an upward increase of potential temperature (that is, temperature referred to standard pressure), which indicates that it is statically stable. Ordinarily, potential temperature is a conservative property, so a parcel that is displaced upward will become cooler and more dense than its surroundings, and hence will tend to return to its original level. If, however, the parcel is lifted a sufficient distance for it to be adiabatically cooled to its dew point, condensation will occur, and the release of latent heat will increase the potential temperature of the parcel. Should this increase be sufficient, the parcel will become warmer and less dense than its surroundings and so will freely continue its ascent. This is known as conditional instability.

In many climates and seasons the atmosphere is characterized by conditional instability. The release of conditional instability is visibly manifested by the appearance of cumulus clouds. For each convective cell that grows into a cumulus cloud there must be an impulse sufficient to lift a parcel of air to its condensation level without similarly lifting all the air about it; that is, there must be a perturbation.

In nature, the perturbation lies in the inherent horizontal inhomogeneity of the atmosphere. Small horizontal differences in temperature (resulting, for instance, from different thermal properties of the underlying surface) or in humidity (resulting, for instance, from different rates of evaporation from the underlying surface) can produce the necessary horizontal gradient of density, or an updraft forced by an underlying hill can provide the required lifting. In any given instance the precise origin of the perturbation is not usually known, but the existence of inhomogeneities of this type is well documented by observation.

Perturbations, however, do not necessarily occur only by chance. Some are produced anthropogenically, such as the introduction of heat and moisture to the atmosphere by cooling towers that dissipate waste from power-generating facilities, and the characteristics of these perturbations are well known. Since the air leaving such towers is hot and saturated, the slight cooling it experiences on rising to the exit will cause condensation to water droplets, making a visible plume. Under some circumstances the water drops may fall out as drizzle or be converted to ice crystals that fall out as snow. The primary concern here, however, is that the perturbation of warm, moist (and, hence, less dense) air might release the conditional instability present in the atmosphere and allow one or more large clouds to grow, perhaps resulting in significant amounts of liquid or solid precipitation. This precipitation is not merely water that came from the cooling tower but is water that was already present in the atmosphere in much larger amounts as water vapor.

When atmospheric thermal convection is modeled numerically, horizontal homogeneity is usually assumed for the basic atmosphere, and some type of perturbation of temperature, humidity, or vertical wind (or a combination thereof) is arbitrarily assumed over a limited volume of the atmosphere. In some instances an instantaneous perturbation is introduced initially, and in others the perturbation is continued over a finite length of time, perhaps over the entire simulation period. The latter could be representative of some natural terrain feature or it could describe a continuing influx of energy from a cooling tower. In any case, if the atmospheric structure is suitable and if the perturbation is sufficiently large, the conditional instability will be released, and the convective cloud element can continue to grow on its own, independent of the impulse that originated it.

That independence should not be taken too literally. It is reasonable to suspect that a larger perturbation will lead to a larger cloud. Also, a continued perturbation must continue to affect the related cloud. The latter is illustrated in nature by the stationary

clouds that continually form and dissipate where air flows over a mountain ridge. Time-lapse photographs show that the same can occur over a cooling tower.

Although the requirement of a perturbation to initiate free convection can be determined theoretically, it is not so easy to demonstrate how the size, shape, intensity, and duration of the perturbation will quantitatively affect the course of the convection. The equations describing the hydrodynamics and thermodynamics of the atmosphere are too complicated for analytic solution. The phenomena cannot properly be modeled in the laboratory, and observation of the real atmosphere on the necessary scale, including a full range of perturbations and atmospheric structures, is impractical. The approach that is suggested, therefore, is numerical modeling.

Types of Perturbations

Three types of perturbations are in general use in cloud modeling. They are perturbations of sensible heat (temperature), latent heat (humidity), and kinetic energy (updraft). The first two act by producing a horizontal gradient of density, hence, regions of positive and negative buoyancy. The third provides mechanical lifting, which under appropriate circumstances releases conditional instability. Sometimes combinations of these types of perturbation are used.

Perhaps the perturbation in most widespread use for the modeling of natural clouds is that of temperature. It is easily applied and is physically associated with solar heating. Its drawback, however, is that if the temperature of a parcel of air is raised, its relative humidity is lowered. Thus, even though a parcel now has positive buoyancy, it must rise an extra distance before condensation can start. This situation, however, is physically correct for modeling a dry cooling tower. The addition of an updraft to the temperature perturbation will help the parcel to rise to the condensation level, but it may well be that this kind of tower is less prone to induce freely convective cumuli than is a wet tower, which puts out warm saturated air.

The Rand cloud model has been run rather extensively with humidity perturbations. This has a great advantage in that the air in the perturbed buoyant bubble starts at or near saturation, so only a minimal rise is necessary for condensation, which makes for worthwhile economies in computer time. The humidity perturbation is also in keeping with observations of nature, although it is less easily related to a precise antecedent as in the case of solar heating and the temperature impulse. Since a wet cooling tower releases on the order of 80 percent of its waste energy in the form of latent heat, the humidity impulse is appropriate to study it. In particular, a combination of humidity and temperature in the perturbation is indicated, and the combination may be more effective than either alone. If the temperature is increased, and simultaneously the humidity is increased enough to reach saturation at the higher temperature, both effects increase the buoyancy, and the slightest lifting causes condensation, which further increases the buoyancy.

A motion perturbation has also been found suitable for use with the Rand cloud model. Its particular virtue is that it does not alter the atmospheric sounding. As applied to the simulation of natural clouds, the perturbation is specified at initial time and then allowed to change as it will in response to the dynamics of the model. Before conditional instability is released, the motion perturbation decays, and if its magnitude is properly chosen in the first place, it will practically vanish before free convection takes over. Hence, the later simulation is virtually decoupled from the perturbation, in contrast with the temperature and humidity perturbations that permanently alter the sounding. Cooling towers, of course, produced updrafts, so an appropriate perturbation for simulating their effects would be a combination of three types. For reasons that are discussed below, however, it is probable that the motion part of the perturbation is much less important than the other two parts, and so may possibly be omitted in some cases.

Shape, Size, and Intensity of the Perturbation

The aim in any sort of numerical modeling is to simulate the actual phenomena as closely as possible. The type or the shape, size, and intensity of perturbations that give rise to natural clouds are not known with any great precision. In particular, the perturbation associated with a specific cloud is rarely known at all. However, the perturbation introduced by a man-made facility such as a power plant or an oil refinery can be determined with reasonable accuracy, and if a cloud results in the atmosphere, it can be measured and compared in detail with the computed cloud. Thus, the problem of whether any given installation will affect the atmosphere in an important way is amenable to study by numerical modeling.

Shape: There is ample evidence that the shape of the perturbation has an important bearing on the results of the simulation. Consider a buoyancy perturbation (temperature, humidity, or a combination of them) for simplicity. A parcel will have an upward acceleration if its density is less (i.e., its temperature or humidity greater) than that of its environment. In an actual case, the question is what constitutes the environment. According to the differential equations, if the curve of temperature or humidity anomaly (difference between perturbed and reference value) plotted against radial distance is convex upward, the buoyancy is positive. Typically in application of the Rand cloud model the temperature or humidity anomaly will have a maximum at the axis and drop off according to a half cycle of a cosine curve to zero at some specified radial distance. As a result the buoyancy will be positive out to the inflection point, negative beyond that to the zero point, and then neutral. The magnitude of the buoyancy depends on the slope of the anomaly curve. This effect was demonstrated in practice when Murray¹ showed that with a steep perturbation curve early cloud development was rapid.

¹F. W. Murray, "Humidity Augmentation as the Initial Impulse in a Numerical Cloud Model," Monthly Weather Review, Vol. 99, No. 1, 1971, pp. 37-48.

Size: The size of the perturbation certainly should have some bearing on the nature of the induced cloud, but at least as regards horizontal size, this seems to be more related to shape. If the intensity is the same, a broader perturbation will have a gentler slope and so will lead to slower development. However, such a perturbation will affect the atmospheric sounding over a wider area, and if it is a perturbation of humidity, it will give the ensuing cloud more fuel (in the form of warm moist air) on which to grow. Thus, the eventual cloud development will be greater than in the case of the narrow perturbation.

The cloud induced by a wide perturbation will also have a large radius, and the area-volume relationship states that the relative entrainment of a broad cloud is less than that of a narrow one. Consequently, with less mixing it will grow taller. If, however, the perturbation is too broad, the average horizontal gradient of density must be negligible unless the central intensity is unreasonably large. This kind of perturbation would not be expected to be effective in initiating convection. Even if the density gradient were concentrated near the edges of the perturbation the atmosphere would tend to "see" this as two narrow perturbations separated by a wide, almost neutral zone.

The vertical size of the perturbation has the effect one might expect: the larger fuel supply results in a larger and more vigorous cloud. Murray¹ showed that this could easily override the horizontal shape and size conditions.

Intensity: The intensity is related to the other two criteria. If the intensity is large and the horizontal size is small, the development will be rapid; but correspondingly, a downdraft will develop just beyond the cloud edge, and entrainment of this warm, dry air will inhibit growth and hasten the decay of the cloud. If the intensity and horizontal size are both large, the shape factor will make for slow development, but the large amount of fuel will contribute to strong development.

Total energy: The total energy introduced into the atmosphere by the perturbation might be expected to have a strong influence on the development of clouds, but at least in the types of perturbations considered here it does not seem to. In the experiments mentioned above, a humidity perturbation was used which added energy (latent heat) to the atmosphere. The subsequent cloud growth was, in a general way, related to the amount of energy added. However, in another series of experiments,² perturbations were used that added energy to one part of the domain and took an equal amount away from another part. Because growth is more closely related to shape in a local neighborhood than to overall size, the net-zero perturbations gave results similar to the positive energy perturbations when they had the same shape in the positive buoyancy region near the axis. Moreover, a kinetic-energy impulse applied to the same sounding gave almost the same results as the net-zero humidity impulse. This suggests that the sounding exerts greater control than the perturbation, which is as it should be.

Complex Perturbations

All the perturbations mentioned to this point have been of simple shape and have been applied only at initial time. Such a perturbation should give rise to a single convective cell. There have been experiments with more complex perturbations.

Sweet and Lowe³ used a version of the Rand cloud model with perturbations applied simultaneously in more than one part of the domain, leading to two or more interacting convective cells. Not surprisingly, they found that the closer the cells were, the greater the interaction. Typically, a developing cell will have an updraft on its axis and a somewhat weaker downdraft at its edge a few hundred meters out. If two cells of similar strength are moderately close, the downdrafts will

²L. R. Koenig and F. W. Murray, "Cumulus Cloud Energetics as Revealed in a Numerical Model of Cloud Dynamics: Part II, Computational Results," Pure and Applied Geophysics, Vol. 113, No. 5/6, 1975, pp. 925-947.

³Sweet, Wayne, and Paul Lowe, An Investigation of Interactions Between Double Clouds Using a Two-Dimensional Numerical Model, Naval Environmental Prediction Research Facility, Technical Paper 2-75, 1975, 110 pp.

reinforce each other, and cell growth will be inhibited. If one cell is much stronger, it can suppress the other. This is also observed in nature.

On the other hand, it is also observed that on occasion two clouds can merge, resulting in an area-volume relationship that supports less relative entrainment, and so permitting greater cloud growth. This can also be modeled. For example, Hill⁴ used a model similar in many ways to the Rand model, but having for its impulse a continuous surface heating function with random perturbations, each having a duration of several hundred seconds. In several instances cloud mergers resulted.

Modeling of banks of cooling towers would have some of the elements of each of the experiments. The impulse would be continuous, as in Hill's experiment, but without the random perturbation. It would probably include latent heat as well as sensible heat. On the other hand, the impulse would have fixed geometry as in the experiment of Sweet and Lowe, that being determined by the geometry of the cooling tower site. The object would be to determine whether and under what conditions the ensemble of towers enhances or suppresses the effect of a single tower.

The impulse may also be complex in time as well as space. Murray and Hollinden⁵ applied a new sensible heat impulse at intervals of ten minutes throughout a simulation. The object was to see whether a large cloud might grow from a series of convective cells each ascending through an atmosphere made more conducive to free convection by the passage of the previous cells. As it turned out, the impulse was of sensible heat only, which lowered the relative humidity, causing evaporation and a temporary suppression of development rather than a new spurt.

⁴Geoffrey E. Hill, "Factors Controlling the Size and Spacing of Cumulus Clouds as Revealed by Numerical Experiments," Journal of the Atmospheric Sciences, Vol. 31, No. 3, 1974, pp. 646-67 .

⁵F. W. Murray and A. B. Hollinden, The Evolution of Cumulus Clouds: A Numerical Simulation and Its Comparison Against Observation, Douglas Aircraft Company Report SM-49372 (AD 630-660), 1966, 147 pp.

If this experiment were repeated with an appropriate latent heat impulse, it might have a bearing on the cooling tower problem. As the time between the repeated impulses is diminished, a steady-state impulse, as in a cooling tower, is approached. If, however, the interval is kept long, it could simulate an atmosphere with an existing storm moving over an energy source, and the augmentation of the storm due to the energy source can be determined. There is reason to believe that the greatest effect that energy sources such as cooling towers have occurs in disturbed conditions when natural clouds abound. There is a question, then, of whether the main effect is initiation of new clouds or augmentation of existing natural clouds.

Finite-Difference Considerations

In numerical modeling a number of different — sometimes conflicting — factors must be balanced off against each other. First, a scale must be decided on, for this will determine not only the particular form of the equations to be used but also the type of finite-difference net and the appropriate time interval to use. The grid spacing should be of the order of one-fourth the characteristic length of the smallest phenomenon to be studied. A larger mesh length will give insufficient resolution, whereas a smaller one will be wasteful, particularly if, as is frequently the case, smaller features are filtered out by the chosen governing equations. The mesh length, then, determines the maximum domain size through storage limitations in the available computer or practical limitations on running time. Thus, with fixed mesh length it is probably not feasible to model a nuclear energy center of 10 km or more on the side with the resolution of an individual cooling tower. There can be some relaxation of this restriction if an expanding grid or nesting grids are used, but this technique is useful only if there is a limited region requiring high resolution and a much larger region in which low resolution is satisfactory.

Thus, somewhat different models are indicated depending on whether one wants to resolve a single cooling tower, a bank of towers, or several

banks of towers. The shape, size, and intensity of the perturbations are different in each of the cases, and the resolution with which the perturbation can be described also differs.

For a single cooling tower a simple perturbation of the type used for single cloud cells can be prescribed. The mesh length can be less than the tower diameter, and the resulting plume and cloud can be described with some detail. The perturbation should probably include sensible heat, latent heat, and kinetic energy, and it should be applied to those grid points closest to the tower exit.

For a bank of cooling towers it might be feasible to use high resolution, as above, and develop a plume and cloud for each of the towers, as in the natural-cloud experiments of Sweet and Lowe. This approach might illuminate the problem of plume merger; but if a larger scale is used in order to be able to model the larger and more remote cumulus clouds that might be expected to occur in connection with this moderately large source of energy, individual plumes could not be resolved.

The line of reasoning in developing the perturbation for this version is as follows: The bank of cooling towers is continually pumping heat and moisture into a volume of the atmosphere that lies just over the towers. Normal mixing will occur, but one should not expect homogeneity throughout that volume. On the other hand, any value assigned to a grid point is not representative of a spot measurement at that point but of an average over the entire volume represented by that grid point. In other words, the limit of resolution of a finite-difference grid requires formal treatment as though there had been complete mixing throughout the individual volume elements that are one mesh length on the side.

The appropriate perturbation, therefore, would be a continual addition of heat and moisture to a selected group of grid points at a rate such that the total energy added to the volume of air represented by these grid points is equal to the total energy released through the cooling towers. The assignment to the grid points need not be uniform;

it could depend on site configuration and other factors. Kinetic energy was not mentioned in connection with this perturbation. Presumably, the mass of air exiting from the towers is so small in comparison with the mass of air represented by the grid points that the addition of kinetic energy to the grid points would be negligible. If this were found not to be so in a particular case, kinetic energy could be included. In any case it is possible that the tower updraft might be strong enough to justify perturbing grid points at more than one level above the towers. This would also be advantageous to the finite-difference computations.

For several banks of cooling towers (that is, a full-fledged energy center) it will almost certainly be impossible to have resolution fine enough to describe a single plume. Each bank must be treated as a single source in the manner just described, but different banks can interact with each other as in the experiments of Sweet and Lowe. Judging by extrapolation from smaller scale experiments already made, the interactions between the banks of towers may be of as great significance in inducing the development of large clouds and storms as the total amount of energy released.

Conclusions

The atmosphere is often characterized by conditional instability such that if a parcel is lifted a certain critical amount, condensation will occur, and the consequent release of latent heat will cause the parcel to be more buoyant yet and continue to rise. In a horizontally uniform atmosphere, such as is usually assumed initially in modeling, there is nothing to release the conditional instability, hence the need for a perturbation.

Cloud modeling has generally made use of three kinds of perturbation: sensible heat, latent heat, and kinetic energy. Any of them is capable of initiating free convection provided the atmospheric structure and the shape, size, and intensity of the perturbation are all favorable. An evaporative cooling tower provides a continuous perturbation of all three kinds simultaneously. The function of modeling is

to determine whether under given atmospheric conditions that perturbation is sufficient to set off free convection that can result in large clouds, storms, or significant precipitation.

Experience in cloud modeling shows that with a density perturbation (heat or moisture) the rapidity of development depends mainly on the shape of the perturbation (assuming, of course, the same favorable atmospheric structure in all cases). A steep horizontal gradient of density leads to strong updrafts and early onset of condensation. Over the long run, however, the size of the perturbation exerts strong control. A density perturbation modifies the sounding, and if it is broad or deep it provides more "fuel" (warm, moist air) for the convection. Moreover, a broad convective current has less relative entrainment of dry air from the side and so will tend to develop a taller, more vigorous cloud. The latter consideration applies also to a perturbation of motion — a forced updraft.

For modeling the atmospheric effects of cooling towers the characteristics of the perturbation are all specified. It is usually a combination of specific and latent heat in given proportions plus some kinetic energy, and the shape, size, and intensity are known. Moreover, it is steady state. Because of the latter circumstance, the speed with which free convection can be set off is of lesser importance than the eventual magnitude of the convective clouds. Hence, the volume of atmosphere affected by the perturbation becomes important. For that reason a bank of closely situated cooling towers should have more effect than the same number of towers dispersed enough so that there is a separate perturbation for each rather than a combined perturbation for all. An aim of modeling should be to determine quantitatively the effects of different degrees of separation. This also becomes a problem of interaction between neighboring convective cells, which still needs much study.

On the larger scale — that of the nuclear energy center — the problem is similar except that each bank of towers can be considered to contribute a single perturbation, and the interaction between these larger systems must be studied. It may be that the geometry of the site will exercise strong control over the results.

It should be kept in mind that the main interest is not in the water vapor that comes from the cooling tower and then may condense and possibly fall to earth. More towers would, of course, provide more water of this sort, but even a nuclear energy center would not be expected to evaporate enough water to produce major rainfall. Rather, it is the trigger effect of the perturbation of heat and water vapor that can release instability already latent in the atmosphere. The resultant interaction of dynamics and microphysics can, under appropriate conditions, produce atmospheric effects of far greater magnitude than the perturbation. Water vapor present in a large volume of the atmosphere can be collected and condensed to fall out as heavy rain, snow, or hail, and large amounts of kinetic energy can be generated.

Whether and to what extent a given configuration of cooling towers could set off major convective activity is the aim of the modeling. Previous work with cloud modeling, using hypothetical perturbations based on general knowledge of atmospheric variability suggests that perturbations of the type and approximate magnitude of cooling tower emissions can indeed have such an effect. This should now be verified in detail using models and perturbations more specifically related to the cooling tower problem. Models of different scales are indicated, from the single cooling tower to the nuclear energy center, but interest centers on the larger scales because there is now less experience to draw upon at those scales and because the expected large perturbations may have effects that are rather different than those experienced to date with small perturbations. In particular, much work is needed on interactions between systems generated by separate perturbations.

2.1.4.2 Analogs for Waste Heat Dissipation Effects

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Introduction

For the past several years there has been an attempt to alert utility planners and regulators to the possibility that the dissipation of waste heat directly into the atmosphere from the large electric power generating facilities might cause undesirable modification of cloudiness, rainfall distribution, and related phenomena. Hanna and Gifford¹ have prepared one of the more recent discussions on this matter. Since the primary concern is directed to facilities larger than those already constructed, experience could not be directly applied to test the validity of the prophecies. Theoretical calculations only apply in a peripheral way, for none are capable of addressing the question meaningfully. For these reasons analogs have been an important means to garner some notion concerning the effects that might be caused. At present, a program is underway to predict waste heat effects on the atmosphere, and the purpose of the work reported here is to look more critically at the applicability of certain analogs to this matter. These analogs include: fires, volcanoes, and industrial operations, particularly petroleum refineries. Our intention is to discuss other analogs in additional reports.

Forms of Heat Dissipation

Useful analogs might be found that closely match the heat dissipating characteristics of the power plant cooling system, or they might be fitted by proper scaling. In any case some data on the characteristics of the heat rejection system are required. For the present purposes we can distinguish two basic ways to dissipate (reject) unwanted heat from power plants directly into the atmosphere. One method involves a broad warm area source rejecting heat to the atmosphere with no forced convection — that is, the cooling pond. On the scale of phenomena of interest,

¹S. R. Hanna and F. A. Gifford, "Meteorological Effects of Energy Dissipation at Large Power Works," Bulletin of the American Meteorological Society, Vol. 56, 1975, pp. 1069-1076.

the cooling pond is probably best regarded as an area source. The second method involves much smaller source areas and the creation of a vertical force of such magnitude that the resulting air currents carry the heat mechanically to a significant height into the atmosphere even under stable air conditions — that is, the cooling tower. Cooling towers, being about 50 m in diameter, may act as point sources on the scale of interest, although in aggregate it may be possible to treat them as an area source. Other systems, such as spray ponds, lie between these extremes. Heat dissipation rates for cooling ponds are on the order of 10^6 W per acre ($4,047 \text{ m}^2$) or $2.5 \times 10^2 \text{ W m}^{-2}$, whereas a cooling tower heat dissipation rate is on the order of $0.42 \times 10^6 \text{ W m}^{-2}$. A 40-unit power center (48,000 MWe) might require a single cooling pond of about 96,000 acres or $3.9 \times 10^8 \text{ m}^2$ in area, whereas examples of cooling tower arrangements shown by the Nuclear Regulatory Commission² shows towers in arrangements occupying between 18 and 65 sq mi ($4 \times 10^7 \text{ m}^2$ and $1.7 \times 10^8 \text{ m}^2$). The average energy dissipation across the cooling pond might be $2.5 \times 10^2 \text{ W m}^{-2}$ and across the tower complex 2.4×10^3 to $5.6 \times 10^2 \text{ W m}^{-2}$, but individual towers would have fluxes three orders of magnitude greater. These energy flux values combined with the energy dissipation rates are important in selecting useful analogs from other phenomena. Table 2.1.19 summarizes these source and flux data together with corresponding data from the analogs that will be discussed.

Fires

Fires have often been mentioned in connection with analogs to power centers. The heat of combustion of most wildfire fuels on a dry basis are similar, so the heat release rate is mainly a function of the rate of burning, a function of the condition of the fuel, its density on

²Nuclear Regulatory Commission, Nuclear Energy Center Site Survey — 1975, Part III, NUREG-0001 (available from NTIS, Springfield, Virginia), 1976.

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Table 2.1.19 Some heat flux and source strength value of phenomena discussed in this note

Situation	Area (m ²)	Source strength (W)	Flux (W m ⁻²)
Cooling pond (assuming 1 MW/acre)	--	--	2.5×10^2
For 48,000-MWe power center	3.9×10^8	9.6×10^{10}	2.5×10^2
Cooling tower (assuming 10 MW dissipated in tower 55 m in diameter)	2.4×10^3	1.0×10^9	4.2×10^5
For 48,000-MWe power center, treat aggregate of towers as an area source occupying either 18 or 65 sq mi	4.0×10^7 1.7×10^8	9.6×10^{10} 9.6×10^{10}	2.4×10^3 5.6×10^2
Large petroleum refinery cooling towers	2.2×10^3	4.9×10^8	2.2×10^4
Dispersed sources	2.6×10^6	1.1×10^9	4.23×10^2
Total	2.6×10^6	1.6×10^9	6.13×10^2
Los Angeles basin refinery complex	1.2×10^8	8.0×10^9	6.7×10^1
Large experimental fires ^a	2.0×10^5	1.0×10^{10}	5.0×10^4
Bushfire ^b (total area and average source strength)	4.0×10^7	1.5×10^{11}	3.6×10^3
Volcano ^c (average values during first three months of the eruption producing Surtsey Island)	2.0×10^5	1.0×10^{11}	5.0×10^5

^aFrom Palmer and Northcutt.

^bFrom Taylor, et al.

^cFrom Thorarinnsson and Vonnegut.

³T. Y. Palmer and L. I. Northcutt, "Convection Columns Above Large Experimental Fires," Fire Technology, Vol. 11, 1975, pp. 111-118.

⁴R. J. Taylor, S. T. Evans, N. K. King, E. T. Stevens, D. R. Packham, and R. J. Vines, "Convective Activity Over a Large-Scale Brushfire," Journal of Applied Meteorology, Vol. 12, 1973, pp. 1144-1150.

⁵S. Thorarinnsson and B. Vonnegut, "Whirlwinds Produced by the Eruption of Surtsey Volcano," Bulletin of the American Meteorological Society, Vol. 45, 1964, pp. 440-444.

the land, and atmospheric conditions.⁶ Experimental fires provide the best source of quantitative data. According to Palmer³ the heat fluxes from large fires that were engineered during a series of mass fire experiments were of the order of 10^5 W m^{-2} . Plots were from 30 to 50 acres (1.2×10^5 to $2 \times 10^5 \text{ m}^2$) in size. Thus, the source strengths were of the order of 10,000 MW. A cluster of five power units (somewhat small for present purposes would have a similar value for its rate of waste heat rejection. In these fires heat fluxes were about those of a cooling tower but were much greater than that anticipated from a power center treated as an aggregate. Thus, in some respects the flux and strength of these fires are relevant individually to certain aspects of the question of atmospheric effects of prospective power centers but not together.

Data from these fires indicate that one can exercise control over the tendency for large-scale rotation of the convective column by varying the placement or sequence of ignition of the fuel.^{7,8} For example, Fig. 2.1.8 illustrates an arrangement that produced anticyclonic rotation.⁷ Another form of vortex motion in fire situations is the commonly observed firewhirl.⁹ According to Graham¹⁰ these fire-containing whirlwinds have been observed to be as large as 1200 ft (365 m) in

⁶K. P. Davis, Forest Fire: Control and Use, New York, McGraw-Hill Book Company, Inc., 1959, 584 pp.

⁷T. Y. Palmer, "Convergence and Vorticity in a Mass Fire Experiment," Paper C1 in Collected Papers, Mass Fire Symposium, Vol. 2, Maribyrnong, Victoria, Australia, Defence Standards Laboratory, 1969.

⁸T. Y. Palmer, communication.

⁹C. M. Countryman, Mass Fires and Fire Behavior, Berkeley, Pacific Southwest Forest and Range Experiment Station, Research Paper PSW-19, 1964, 53 pp.

¹⁰H. E. Graham, "Fire Whirlwinds," Bulletin of the American Meteorological Society, Vol. 36, 1955, pp. 99-103.

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Fig. 2.1.8. Large-scale cyclonic air flow counteracted by fuel pattern causing anticyclonic flow. Air flow is jet-like downward into the fuel with maximum inflow at about 4.5 ft. After Palmer.⁷

diameter and to extend to 4000 ft (1220 m) in height. Wind speeds approaching those associated with tornadoes have been observed, but of course, lesser phenomena are more common. Apparently the turbulence and stability of the air mass are important in determining whether or not the whirling motion will occur. Lee slopes of mountainous terrain favors the occurrence, apparently encouraging the required turbulence and wind shear¹¹ (see Fig. 2.1.9). However, whirls have occurred in flat terrain, and it is of note that although a large heat source favors firewhirls, they often form just after ignition, and the largest one produced during an experimental fire devised to induce whirls occurred after the fuel had been nearly all consumed.^{9,11} Firewhirls seem to contradict the criteria tentatively proposed by Briggs¹² to anticipate situations in which vorticity concentration might occur and thus produce small-scale but intense and destructive circulations. The appearance of the largest whirl well after the most intense heat release and when the maximum area was presumably a heat source is in the proper trend to support Briggs' criteria, however.

Measurements of air flow around experimental fires indicate that most of the air entering the convective column comes not from the surface layer of air but rather higher. Apparently there are strong drafts bringing air into the flames at low level. The column some distance above the flame front itself is occasionally observed to become constricted. This implies strong entrainment from the sides. A similar necking-in of multiple cooling tower plumes has been observed and will be discussed in the section on petroleum refineries. Intense convective columns apparently block the large-scale air flow, acting in many respects as if they were a solid obstacle. Taylor, et al.⁴ hypothesize that this blocking reduces entrainment into the convective column, thus causing more buoyancy than would be the case if the entrainment were as vigorous as occurs in normal cumulus cloud bubbles or plumes.

¹¹C. M. Countryman, Project Flambeau — An Investigation of Mass Fire (1964-1967), Final Report, Vol. 1, Berkeley, California, Pacific Southwest Forest and Range Experiment Station, 1969, 68 pp.

¹²G. A. Briggs, "Plume Rise from Multiple Sources," in Cooling Tower Environment — 1974 (Proceedings of a symposium held at the University of Maryland Adult Education Center, March 4-6, 1974), USERDA Technical Information Center, Oak Ridge, Tennessee, CONF-740302, 1975, pp. 147-160.

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Fig. 2.1.9. Most fire whirls in the Flambeau tests developed on lee slopes. They resulted from an unstable condition in which thermal wind and the fire blocked incoming cool air. From Countryman.¹¹

There is ample evidence that convection associated with large fires (such as wildfires in forested or brush land and experimental fires) can be strong enough to carry air currents above their condensation level and thus produce a dark smoke-filled column topped by a white, water-particle cloud. These observations are sufficiently commonplace so that research has been carried out to investigate the efficacy of artificially stimulating rain production from these clouds to assist in extinguishing the fire.

Perhaps one of the more pertinent observations of cloudiness and rain associated with a fire has been made by Morris and Ulbrich.¹³ Using 3-cm radar having a 60-mi (97-km) range, they observed only one cluster of clouds during an 8-hr period. The cloud echoes were recorded photographically through their formative and dissipating stages. By reconstructing the probable trajectory of the clouds prior to the development of a radar echo, Morris and Ulbrich were able to argue convincingly that the origin of the clouds was a fire 21 mi (34 km) from the location of the first cloud echo. The fire originated at a smelter and spread into nearby grassland. It began approximately 1 hr prior to the appearance of the first cloud echo — that is, prior to the development of precipitation-size drops. The largest echo reached a maximum height of 23,000 ft (7 km). These observations are of particular interest for several reasons:

1. The precipitation required about 1 hr to develop. This is perhaps a little longer than what one might expect from natural clouds. High cloud condensation nuclear concentrations ingested from the fire would probably slow microphysical processes, converting small droplets to precipitation-size drops. This effect would be different in the power-center case.
2. In spite of a rather stable atmosphere, the clouds once initiated were able to grow, not dissipate, after leaving the source of the perturbation.
3. The rain area occupied a region about 5 mi (8 km) wide and 25 mi (40 km) long, displaced 21 mi (34 km) from its origin. No rain amounts were reported. The 125-sq-mi (320-km²) area that was affected is not small, yet it is contained within an angular segment of 10°. In other words, a

¹³T. R. Morris and C. W. Ulbrich, "Radar Observations of Fire-Induced Rain Clouds," Journal of Applied Meteorology, Vol. 12, 1973, pp. 551-553.

shift of wind of only this amount would cause the rain to fall in an entirely different location.

4. The formation of rain, first appearing 1 hr and 21 mi (34 km) downwind of the initiating perturbation, indicates that the effects of strong convective perturbations such as would result from large power centers may be felt at a substantial distance from the source.

Implications. The use of fire data to aid in power center design is tenuous due to the differences in heat flux. However, the control that can be exerted on the rotation of the convective column and the occurrence of firewhirls suggest that this knowledge might be of use in the design of the pattern of the cooling towers on a large center. The interaction of the ambient wind flow with the air flow into the tower should be examined from the point of view of possible shear situations that could lead to the encouragement of whirls. The pattern created during the building phase of the center, when plants and towers gradually come on stream, should also be evaluated for possible creation of undesirable wind flow patterns. The same concern for tower configurations is indicated when certain cooling towers are shut down during the routine operation of the center.

The information on the rain clouds caused by a fire 21 mi upwind points out the great difficulty that should be expected in identifying certain weather phenomena caused by a small power center due to the variability of the location of the impact of the phenomena in time and space. In other words, the total atmospheric modification may be substantial, but it will be so spread out that it will be difficult to determine unless a carefully designed program is mounted to measure effects.

Volcanoes — Geysers

Volcanoes. Volcanoes and geyser areas are local heat sources at the earth's surface that have been suggested as pertinent for gaining insight into the atmospheric phenomena that might be associated with power centers. The heat released by these phenomena range over the

values of interest, but quantitative data of their effect on the atmosphere is sparse.

The recent submarine eruption giving birth to the island of Surtsey, 150 km from Reykjavik, Iceland, was extensively observed. Of importance to the subject in hand is the estimate⁵ that during the first ten days of practically continuous eruption the heat injected into the atmosphere averaged about 200,000 MW. During the first three months of activity the heat injection averaged about 100,000 MW. The diameter of the volcano orifice was about 500 m. Thus, the source flux was on the order of 0.5 to 1 MW m⁻². A cooling tower dissipating 1200 MW, having a diameter of 55 m, has a similar (0.5 MW m⁻²) source flux (but, of course, not an equal source strength). The average heat dissipated is on the order of that which would be rejected from the largest proposed power centers (those having electrical power outputs of 50,000 MW) (but, of course, the average flux over the power center is much less than over the volcano). Nevertheless, it is reasonable to note the atmospheric phenomena related to the volcano. The information reported below relates to the first few months of volcanic activity and is extracted from Anderson, et al.,¹⁴ Thorarinsson and Vonnegut,⁵ and Thorarinsson.¹⁵

Atmospheric phenomena were variable, being functions of volcanic activity and atmospheric stability. At maximum activity, lava bombs were generally confined to altitudes lower than 1000 m. The eruption clouds on occasion rose to about 9 km, pulsations having maximum rise rates of about 12 to 5 m/sec near the top, with a spreading out of cloud material into a stratiform layer upon the collapse of the turret. The lower column of the eruption under these conditions rose almost vertically, and the material was being ejected at the volcano orifice with velocities

¹⁴R. Anderson, S. B. Björnsson, D. C. Blanchard, S. Cathman, J. Hughes, S. Jónasson, C. B. Moore, H. J. Survilas, B. Vonnegut, "Electricity in Volcanic Clouds, Science, Vol. 148, 1965, 1179-1189.

¹⁵S. Thorarinsson, Surtsey, New York, The Viking Press, 1967, 54 pp.

up to about 100 m s^{-1} . During less violent conditions, periodic cloud formation was observed with the production of well-defined individual clouds ranging in height from about 3 km to 6 km. Other cloud phenomena included cloud streets with rolls in the form of cylinders 0.5 km in radius, of 3 to 4 km in height, and having clear air separation of about 1 km between rolls. There is suggestive evidence that thunderstorms were initiated by the volcano, but on occasion the plume was confined below stable layers as low as 600 m in height. Thus, a wide variety of behavior was observed.

Electrification of the steam cloud occurred when the vent was open to the sea and when molten lava ran into the ocean. Electrification of the eruption cloud was sufficiently great to produce lightning-like discharges within the plume and between the plume and earth. Also of interest is the occurrence of whirlwinds extending from the eruption cloud. They were observed downwind from the crater, their frequency being a function of volcanic activity (heat release to the atmosphere). During periods of great activity they were common, and multiple vortices were observed. No observations were reported under calm conditions, but no critical relation was noted between the wind speed and the character and number of vortices — there is some suggestion that whirlwinds were more frequent when the eruption column was swayed by the wind. This is in agreement with the association of firewhirls and wind shear or turbulence as discussed earlier. The wind speed in the vortices were estimated to reach 90 m s^{-1} . These observations of frequent whirlwinds on occasions of great buoyancy seem to contradict Briggs' vorticity concentration criteria,¹² for the characteristic vertical speed of the buoyant source would be expected to be too large. Perhaps since forces other than buoyancy are involved in developing the plume, the criteria of Briggs should not be applied. However, the strong and confined buoyancy perturbation in the case of cooling towers is not a natural phenomenon and has certain characteristics similar to the expulsion of volcanic material.

It is clear that a volcano of the size that formed Surtsey can produce unacceptable weather modification effects. (At this point it

may be well to note that the energy release of that volcano at its most active phase did not exceed the energy released as latent heat of condensation within moderately large thunderstorms.)

Both the total average heat dissipation rate and the heat flux of this volcano had some relationship to proposed power centers and their cooling towers (see Table 2.1.19). Of course, the average heat flux over a power center would be vastly different than that from the cooling towers or the volcano.

Implications. These observations of phenomena associated with volcanic activity suggest the following:

1. Cloud electrification — The electrification associated with the entrance of lava into the ocean supports a mechanism for electrification (charge separation) observed by Blanchard¹⁶ by breaking bubbles in water. A similar process of disrupting water surfaces and bubbling probably occurs in cooling towers, so we might expect charge separation in cooling towers. If so, it should be easily measured in operating towers. If this does occur, it may result in some modification of the electrification of cumulus clouds in the vicinity of the power center. This could affect microphysical processes involved in rain formation (if so, probably the time to develop rain-size drops would be shortened). Overall, however, electrification is judged to be nonconsequential to the practical aspects of the program.

2. Tornadoes — The possibility of whirlwinds was found to be a function of the rate of heat release. It undoubtedly is also a function of energy flux. There were indications (but not necessarily conclusive ones) that vortex generation required an ambient wind and possibly that the deflection of the wind by the island was instrumental in vortex development. The clustering of cooling towers to effect high heat flux (in order to reduce the entrainment of low-level air) seems inadvisable from the standpoint of vortex formation. While heat flux approximating that from the volcano when whirlwinds were frequent is essentially

¹⁶D. C. Blanchard, "Electrification of the Atmosphere by Particles from Bubbles in the Sea," in Progress in Oceanography, Oxford, 1963, pp. 73-202.

impossible to obtain, we see little reason to encourage whirlwind occurrence, and on this basis would encourage wide dispersion of the cooling towers on the power center site. Note, however, if the criterion of Briggs¹² is correct and the volcano data are not applicable to the power center situation, then clustering may be advisable to reduce vorticity concentration.

3. Cloud formation — A wide variety of cloud formations were obviously formed by the volcano. The vertical structure of the atmosphere and volcano activity controlled the specific characteristics of the atmospheric response. It should be noted that the volcano heat dissipation rate, even at the height of activity, was less than that of a thunderstorm of moderate size at its most intense period. The large-scale atmospheric structure has a major influence on natural cloud behavior. The volcano did not overwhelm the natural atmosphere, and we conclude that the response of the atmosphere to the nuclear energy center will be largely controlled by the ambient atmospheric structure.

Geysers. Geyser and associated thermal regions are another example of geological phenomena where abnormally large quantities of heat and moisture are input into the atmosphere. Geyser plumes are larger, taller, and more persistent in cold weather than in warm weather due to the decreased evaporation of plume droplets and the formation of droplets by condensation that occurs as the hot, water-saturated air within the plume cools. We know of no studies indicating modification of the dynamics of clouds (formation, etc.) due to thermal areas other than fog formation in cold weather. However, it is possible that more extensive weather modification occurs and is not recognized (see subsequent discussion dealing with perceptions of weather modification).

Petroleum Refineries

Recently attention has been directed to cloud formation associated with large petroleum refineries. Auer¹⁷ has made an extensive analysis

¹⁷A. H. Auer, Jr., "Observations of an Industrial Cumulus," Journal of Applied Meteorology, Vol. 15, 1976, pp. 406-413.

of the properties of a cloud formed over the Shell Oil Company refinery in Wood River, Illinois. Stinson and Brown¹⁸ have ground-based observations that clearly indicate cloud development associated with refineries in the vicinity of the Palos Verdes Peninsula within the Los Angeles basin. Our independent study of the Los Angeles basin supports their conclusions.

Heat dissipation from petroleum refineries. Comparison of petroleum refinery heat rejection and that from power plants is useful. We understand that overall about 5 to 10 percent of the input to refineries is dissipated as heat in one form or another. The overall efficiency of a refinery depends on the processes used. The larger domestic refineries tend to have more complex energy-consuming (and wasting) processing (such as catalytic cracking and reforming processes) than the smaller refineries, which may simply process the crude by fractional distillation. Thus, the largest refineries are probably the least efficient as far as an overall heat balance is concerned. Electrical energy consumed (ultimately dissipated into the atmosphere as heat) can be separated from the petroleum-derived energy, but it is smaller in amount, and in view of the uncertainty in the energy wasted from petroleum sources, it will be ignored.

We can estimate the heat rejection from these installations as follows:

1. One bbl of crude contains 42 gal having a mass of 7.7 lb per gal and a heat of combustion of 19,000 Btu per lb. Hence, the crude petroleum contains:

$$42 \times 7.7 \times 19,000 = 6.14 \times 10^6 \text{ Btu/bbl} .$$

2. One Btu/min = 17.58 W. Hence, the input to the refinery (in terms of watts) is:

$$\frac{6.14 \times 10^6 \text{ Btu}}{\text{bbl}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{17.58 \text{ W}}{\text{Btu/min}} = 7.5 \times 10^4 \text{ W (per bbl per day input)}$$

¹⁸J. R. Stinson and C. Brown, Inadvertent Cloud Formation and Modification by Refineries, California State College, Dominguez Hills, Geography Department Report 76-1, 1976, 7 pp.

3. Assuming 10 percent of the input goes to waste heat, the assumed waste heat rejection is:

$$\frac{100,000 \text{ bbl}}{\text{day}} \times \frac{7.5 \times 10^4 \text{ W}}{\text{bbl/day}} \times \frac{1 \text{ MW}}{10 \text{ W}} \times 0.1 = 750 \text{ MW per } 100,000 \text{ bbl/day refinery throughput.}$$

According to these estimates a 200,000 bbl/day refinery rejects about the same amount of heat as a 750-MWe electric power plant (1/3 efficient). The heat from the refinery contains more sensible heat than the power plant, for some heat is rejected by cooling products, and direct sensible heat transfer to air by means of heat exchanges similar to automobile radiators is used. Another difference is that at the refinery heat rejection is more dispersed, the process equipment covering a larger area than cooling towers of power plants.

The refinery over which Auer observed the "first cloud" of the day has a rated capacity of 283,000 bbl per calenday day.¹⁹ This approximates the 230,000 bbl/day of the Standard Oil of California refinery at El Segundo (in the Los Angeles basin) — the refinery which we can observe without difficulty. Both refineries have extensive facilities for restructuring the petroleum into various commercial products and are probably relatively inefficient insofar as a total energy balance is concerned.

Specific information was obtained on the Standard Oil of California refinery at El Segundo. On the average, a total of 130×10^9 Btu/day (1.6×10^9 W) is dissipated to the atmosphere, of which 40×10^9 Btu/day (4.9×10^8 W) is rejected by cooling towers; 40×10^9 Btu/day (4.9×10^8 W) is rejected by hot products held in storage, and the remainder, 50×10^9 Btu/day (6.1×10^8 W) is dissipated by means of thin fan air coolers. The air coolers are relatively small, being associated with individual pieces of equipment, and therefore in aggregate can be considered as an area source. Also, the cooling product in storage is essentially an area source. The cooling towers are located in groups at several different parts of the refinery complex. The effects of each group are distinguishable, and therefore each group should be considered a point

source. The quantity of water evaporated from the towers averages 3600 gal per min. The refinery area is approximately 1 sq mi (2.59 km²). Thus, the heat flux over the entire area is 618 W/m². From these data the efficiency of the refinery may be computed as follows:

$$100 - \frac{130 \times 10^9 \text{ Btu/day wasted}}{(6.14 \times 10^6 \text{ Btu/bbl})(230,000 \text{ bbl/day}) \text{ throughput}} \times 100 = 90.8\% .$$

The ratio of sensible to latent heat may be found as follows:

$$3600 \text{ gal/min} \times 3785 \text{ cm}^3/\text{gal} \times 1 \text{ g/cm}^3 \times 1440 \text{ min/day} = 2 \times 10^{10} \text{ g/day} .$$

This amounts to:

$$580 \text{ cal/g} \times 2 \times 10^{10} \text{ g/day} \times \frac{1}{252 \text{ cal/Btu}} = 4.6 \times 10^{10} \text{ Btu/day}$$

and the ratio of sensible to latent heat is:

$$\frac{130 \times 10^9 \text{ Btu/day} - 46 \times 10^9 \text{ Btu/day}}{46 \times 10^9 \text{ Btu/day}} = 1.8 .$$

The efficiency value is in accordance with the estimates used above. The ratio of sensible to latent heat is substantially greater than the value Auer¹⁷ estimated for the Wood River, Illinois, refinery. Because of variations in cooling methods this ratio will vary from refinery to refinery. Older installations made more use of once-through cooling than newer installations and therefore would place relatively little moisture into the atmosphere. Other factors will cause difference among plants, but for the purposes at hand the El Segundo data will be used as typical of complex refineries.

It will be noted that these refineries are comparable in heat output to power facilities that are now in operation. The heat flux at the forced draft cooling towers is probably similar to that from natural-draft towers. However, the average flux over the entire refinery is lower than that anticipated for power centers. The special value of petroleum refineries as an analog to power centers is the fact that there is a tendency for the industry to group refineries (and petrochemical plants). These groupings provide opportunities to observe effects of

abnormal heat flux within areas that are similar to the areas envisioned for power centers. Some groups of interest are shown in Table 2.1.20.

Los Angeles basin. The complex of petroleum refineries in the Los Angeles basin is of particular interest to us. As shown in Fig. 2.1.10 the oil refineries in this region are located in a cluster, many within a circle of 5 km radius. Their capacities are shown in Table 2.1.21. The largest refineries are within about 17 km (about 10 mi) of one another. If winds are blowing from the northwest or southeast, the heat perturbations from the largest refineries can influence one another. Flow from north or south encourages plume interactions within the densest concentrations of refineries. The refineries are located on substantially flat ground, but elevated terrain at the Palos Verdes Peninsula provides opportunities for the observation of nearly all the refineries simultaneously from several convenient locations. Shadows of clouds on the ground can be used to locate their positions and for more precise data stereophotogrammetry may be used.

Cloudiness over the ocean is often suppressed relative to that over the land; thus, it is often possible to have a clear line of sight from coastal sites across Santa Monica Bay to the Standard Oil refinery at El Segundo. This provides the distance necessary to properly view effects, but precise knowledge of location is less easily obtained than from elevated sites on the peninsula.

The proximity of the ocean and land causes local wind effects that are useful in providing a predictable daily variation in wind pattern. Strong large-scale pressure patterns can dominate at any time of the day to upset the general diurnal wind pattern. Generally, however, in the early morning wind flows from land to the ocean, and as the sun warms the land the air flow reverses, with the flow from ocean to land. Thus, a given site within this regime at some time or another is influenced by converging but substantially calm horizontal winds. The Palos Verdes Peninsula blocks low-level winds; thus, air associated with on-shore flow has a tendency to converge behind the peninsula, the region in which many of the refineries are located. The peninsula itself can serve as a cloud generator because of orographic lifting. Strong winds encourage

Fig. 2.1.10. Locations of petroleum refineries in the Los Angeles basin.

Table 2.1.20 Some large petroleum refinery clusters of interest

Location	Refinery capacity (bbl/day)	Electric Power Plant Equivalent ^a (MWe)
Los Angeles basin (California)	1,058,000	4,000
Wood River (Illinois)	388,000	1,500
Chicago Metropolitan Area (Illinois, Indiana)	486,000	1,800
Baton Rouge (one refinery) (Louisiana)	449,000	1,700
Lake Charles (one refinery) (Louisiana)	268,000	1,000
Houston	386,000	1,400
Texas City	474,000	1,800
Bay Town (one refinery)	400,000	1,500
Beaumont	325,000	1,200
Port Arthur (Texas)	802,000	3,000
Marcus Hook	308,000	1,200
Philadelphia (Pennsylvania)	359,000	1,400
Point-à-Pierre (one refinery) (Trinidad)	361,000	1,400
Fawley (one refinery) (England)	363,000	1,400
Milazzo, Sicily (Italy)	505,000	1,900
Pernis	761,000	2,900
Rotterdam (one refinery) (Netherlands)	490,000	1,800
Aruba (one refinery)	440,000	1,700
Curacao (Netherlands Antilles W.I.)	460,000	1,700
Amuay (one refinery)	630,000	2,400
El Cardon (one refinery)	348,000	1,300
Combined (Venezuela)	978,000	3,700
Virgin Islands (one refinery)	590,000	2,200
Antwerp (Belgium)	579,000	2,200
Freeport (Bahamas)	500,000	1,900
Singapore	845,000	3,200

^aBased on refinery efficiency of 90% and power plant efficiency, 33%.

Table 2.1.21 Capacity of refineries located in the Los Angeles Basin (in bbl per calendar day)

Name and symbol on Fig. 3	Crude	Catalytic cracking	catalytic reforming	Electric power plant equivalent ^a (MWe)
Atlantic Richfield Co. Carson [A]	185,000	57,000	34,000	1,400
Champlain Petroleum Co. Wilmington [C]	30,600	--	--	230
Douglas Oil Co. of Ca. Paramount [D]	35,000	--	6,400	260
Edgington Oil Co. Long Beach [E]	29,500	--	--	220
Fletcher Oil & Refining Co. Carson [F]	19,200	--	4,700	140
Golden Eagle Refining Co. Carson [GE]	12,350	--	--	93
Gulf Oil Co. Santa Fe Springs [G]	51,500	13,500	19,000	390
Lunday-Thagard Oil Co. South Gate [L]	5,400	--	--	41
MacMillan Ring-Free Oil Co. Signal Hill [MR]	11,590	--	--	87
Mobil Oil Corp. Torrance [A]	123,500	56,000	36,000	930
Powerine Oil Co. Santa Fe Springs [P]	46,000	11,000	6,300	350
Shell Oil Co. Wilmington [S]	96,000	35,000	21,000	720
Standard Oil Co. of Ca. El Segundo [SOC]	230,000	43,500	60,000	1,700
Texaco, Inc. Wilmington [T]	75,000	28,000	38,879	560
Union Oil Co. of Ca. San Pedro [U]	108,000	45,000	29,000	810

SOURCE: International Petroleum Encyclopedia, 1975.^a Assuming power plant has an efficiency of 33-1/3% and the refinery, 90%.

orographic effects, and under some circumstances a standing wave to the lee of the peninsula is evident. Thus, the peninsula serves not only as an excellent vantage point for observation but also introduces factors that vary the air flow around the refineries (and, therefore, their effects on the atmosphere). The general meteorological situation in the Los Angeles region is dominated by a large-scale inversion that tends to inhibit interesting meteorological effects. However, this system is interrupted by other weather patterns and substantially all meteorological circumstances of interest are realized at one time or another, the exceptions being cold weather and phenomena associated with severe convective storms.

Observations of heat effects. During the spring of 1976, observations were made of the petroleum refineries in the Los Angeles basin for the purpose of obtaining information on effects of their heat rejection to the atmosphere. Data were gathered by time-lapse photography (8 mm) and other photographic methods. This was a qualitative, idea-gathering survey, not a quantitative assessment. Furthermore, other heat sources exist in the general area of the refineries; and consequently, the effects noted may not be solely attributable to refinery operations. In particular, two power plants exist adjacent to the Standard Oil of California refinery at El Segundo; and although they are once-through cooled by ocean water, effects of the heat from the stacks are often observable when effects from the refinery are noticeable. Additionally, heavy industry is located near the center of the refinery cluster. These operations also reject heat to the atmosphere.

Detection of heat effects. This writer, who daily views the El Segundo region from about a distance of 15 mi across the Santa Monica Bay, has been aware of the fact that the Standard Oil Refinery has the ability to generate clouds. An associate, also a meteorologist, who lived in the Palos Verdes Peninsula, was aware of what he described as small (unimportant) clouds that occasionally were associated with the refineries. The extent of the modification was unknown to both of us but was generally considered unimportant. Professor J. R. Stinson of the California State College at Dominguez Hills first brought our attention

to the possibility that the refineries are important weather producers. The College is located on gently rising ground about 4 mi NE of the center of the concentric circles shown in Fig. 2.1.10. This is an excellent position to observe any effects caused by the refineries. The Palos Verdes Peninsula sites, being much higher in elevation and generally upwind of events, offers advantages over the generally downwind location of the College, but from the point of view of logistics, the ability to observe at a moment's notice, Stinson's position is unsurpassed. He has claimed that the refinery plumes make very significant alterations in local weather, even speculating that a localized hailfall was caused by the refinery effluents.¹⁹ He believes that the chemical effluents, acting as precipitation nuclei, are an important factor in determining the inadvertent weather phenomena associated with the refineries.

Personal conversation with Auer of the University of Wyoming (who published the observations pertaining to cloud initiated by a refinery at Wood River, Illinois) and Ackerman of the Illinois State Water Survey [an investigator on the same National Science Foundation program designed to unravel urban influences on weather ("Metromex")] indicated that both were of the opinion that the first convective clouds of a given day were often associated with heat sources such as power plants and refineries but that there was no specific evidence to suggest that later in the day these sources produced the clouds that generated significant weather (rain, etc.). Auer's flights operated out of an airport near the refinery. Metromex investigators have documented the general area around Wood River by radar and raingauge data to be a weather producer. A comprehensive analysis of Metromex data by Changnon, et al.,²⁰ indicates rain anomalies in the St. Louis urban area are caused by (1) thermodynamic effects leading to instability, (2) thermodynamics and mechanical effects leading to cloud initiation, and (3) enhancement of coalescence due to microphysical

¹⁹International Petroleum Encyclopedia, 1975.

²⁰S. A. Changnon, Jr. R. G. Semonin, and F. A. Huff, "A Hypothesis for Urban Rainfall Anomalies," Journal of Applied Meteorology, Vol. 15, pp. 544-560.

changes. Auer believes it more likely that the marshy area near the confluence of the Mississippi and Missouri Rivers near Wood River is more instrumental than the industrial area in producing important rain-bearing clouds.

It is useful to point out that casual observations in the Los Angeles basin did not reveal the extent of modification that Stinson claims. However, as a result of our independent survey, we believe the local modification effects are sufficiently great as to be useful analogs to the power center situation. This difference between assessment based on casual and systematic observations points out the difficulty of observing atmospheric effects caused by man-produced perturbations. Factors that lead to confusion in identifying natural and modified effects include:

1. Generally speaking, if no other clouds are present (initiated from "natural" sources) the cloud associated with a specific refinery heat source will be small and of little practical consequence. This situation accounts for the writer's casual observations of clouds caused by the El Segundo refinery, probably for the "first" cloud observations noted of Auer and Ackerman and also for most other casual associations of waste heat sources and cloud development.
2. Except in cases where there is a continuous column of condensate from the cooling tower to the condensation level, it is difficult, on casual inspection, to directly attribute a cloud to a source, even if it is isolated.
3. Casual observation only records "snapshots" of situations. The time sequence of events is not captured. Since natural convective clouds generally occur in many locations, sizes, and characteristics at a given instant, the artificially produced cloud is substantially indistinguishable from natural ones.
4. On the other hand, if an observer is looking for an association between heat sources and clouds, he can easily imagine telling characteristics; for example, a cloud located over the heat source, a cloud having a peculiar, ragged, or funnel-shaped bottom, a cloud that is darker than

the others, etc. Some of the characteristics are more likely to be associated with the artificial cloud than the natural one; however, in attempting to discover this type of association between heat source and cloud, it is very important to note characteristics of accompanying clouds that cannot be associated with the heat source. Most of the imagined unique characteristics will be observed in natural clouds. In particular, optical properties (how dark or light) and microphysical properties (for example, rain or ice production) are extremely variable, and any distinction between natural and artificial clouds based on these characteristics should be viewed with caution.

Time-lapse photography has been found to be an inexpensive and useful tool to do exploratory studies to determine possible connections between heat sources at the ground and cloud behavior. The special advantage of time-lapse information is that sequential characteristics that require a lengthy period to evolve are restructured in a period of time more suitable for comprehension. A time compression of 1:64 (1 frame every 4 sec) has been found to be generally satisfactory. Distant vantage points having clear lines of sight such as across the Santa Monica Bay and from the Palos Verdes Peninsula, have been found more useful than sites close to the refineries. The ease of determining the proper direction to point the camera to obtain useful records attests to the fixed sites of cloud production associated with ground-level heat sources. Time-lapse photography of natural clouds from their birth to death is difficult because of the continuous variation in the location of their initiation and their movement during their life cycle.

At the present time we have data on about 15 days during which some influence of the refineries on local cloudiness was observed. Only a few of these produced phenomena of much interest insofar as large area effects are concerned, and in general we would suspect that casual observation would not have revealed a connection between cloudiness and heat source in these instances. Since each day of significant effect was in a sense unique, we feel that more observations of this nature will be useful.

The primary key that reveals cloudiness as being artificially born by a continuous heat source located at the ground is the relatively fixed position in space of these clouds in comparison with neighboring naturally induced clouds. The latter drift along with the prevailing winds, they grow and decay as they move along, and no portion appears rooted in one location. The artificial cloud has many characteristics of orographically induced natural clouds. The upwind edge is likely to be the scene of a series of buoyant bubbles, one following the path of another, the older bubbles being carried downstream to quickly evaporate, or, if conditions permit, continuing to grow into large clouds which then evolve in a more or less natural way. There is an attempt by the cloud to remain rooted to the ground source. The conditions dictating whether or not a cloud forms at all, whether it quickly evaporates or grows large, apparently are mainly functions of: (1) the strength and other characteristics of the source and (2) the temperature, humidity, and wind structure of the atmosphere. It should be pointed out that observations indicate that abnormal cloudiness generally will be located downwind of the heat source — not directly over it. The first appearance of substantial cloudiness attributable to the anthropogenic perturbation will occur at a distance equal to the height of the condensation level divided by the rate of rise of the perturbation multiplied by the prevailing wind. The stronger the wind, the further downstream the initial effects and, since the perturbation becomes more mixed with ambient air when the wind is stronger, there is an inverse relationship between the likelihood of an effect and the strength of the wind.

Some observed effects. In spite of the fact that heat transfer to the atmosphere is more or less continuous, often the effect of the cooling towers (more or less point sources) is to produce a bubbling form of heat transfer. The bubbling seems to consist of smaller, more frequent impulses than those attributable to natural perturbations. Furthermore, the pulses can frequently be seen to rise through the natural condensation level and penetrate up to the summit of the cloud. This effect is particularly apparent if the cloud is carried downwind at speeds such that

the bubbling activity occurs on the upwind edge of the cloud. Under calm conditions the bubbling mode of convection occurs but is less obvious, for the cloud hangs stationary over the source, and the activity takes place more toward the center of the cloud rather than the edge. Occasionally the flow of heat from the source to the cloud base appears to be substantially continuous. Calm winds promote the creation of one cloud, whereas stronger winds promote a series of clouds giving rise to cloud "streets."

The heat release from cooling towers of a refinery constitutes only about one-third of the total heat dissipated into the atmosphere. The larger remaining portion amounts to an area source having little or no initial upward momentum. It is useful to attempt to distinguish the effects of this kind of areal heat rejection from more concentrated forms having greater buoyancy and initial upward momentum. This information may be used in assessing the advantages of cooling ponds or otherwise spreading the heat burden to the atmosphere.

At El Segundo, when the point sources from the power plant stacks and the refinery cooling towers are visible as a continuous umbilical-cord-like filament carrying heat and moisture to the cloud, there occasionally is observed a larger, offset cloud mass having a convex-shaped base but no striking evidence of the injection of new material. This separate cloud is not always apparent, and its association with the refinery is based on its quasi-steady state existence for periods exceeding one hour, for natural clouds would pass through a growing and dissipating life-cycle in this time period. The differences in behavior are caused by the presence of a continuous initiating impulse in the artificial cloud and the transitory nature of impulses causing natural clouds (with exceptions). The displacement of the area source cloud from the point source cloud is believed to be caused by the differences in rise velocity of the perturbations. The point source, having more buoyancy, rises more quickly, and the resulting cloud is closer to its source than the area source cloud — the perturbation being carried further downwind before condensation occurs. Under calm winds the two clouds merge, the point source perturbation bubbling into the broad base of the merged cloud. They will also merge if the atmosphere is sufficiently unstable for the artificial perturbations

to cause the development of convective clouds that grow larger by feeding on the moisture supplied from the surrounding air. Observations have shown the combination of heat source from the cluster of refineries near the center of the concentric circles in Fig. 2.1.10 feeding two cumulus congestus clouds. This amounts to a broad area plume merger.

The quasi-steady state nature of the artificial clouds continues as long as the external atmospheric conditions remain substantially constant. Wind shifts or changes in temperature and humidity structure can alter the behavior of the clouds. The local effects are particularly dependent on changes in the low-level moisture supply (saturation deficit). Generally, visually obvious but meteorologically unimportant cloud effects are more pronounced in the early morning, before the near-ground air becomes dryer due to solar heating. On the other hand, conditions that produce important cloud and rain are dependent on the characteristics of a greater depth of atmosphere, and therefore there is relatively less diurnal influence. Rather, the degree of influence is governed by the timing of the larger scale meteorological processes. Effects are most apparent in the unstable air mass that exists during general clearing after the passage of a front, or upper level disturbance, but it is likely that this is more of a matter of the ability of our detecting devices (restricted to visual observations) rather than a true reflection of the influences of the heat sources themselves.

The refineries tend to have more than one aggregate of cooling towers. Observations often show that the plumes from the towers, separated as much as a mile, tend to converge (not merge). This indicates that they affect a larger scale of motion than might be suspected from the area of the towers. Plumes from adjacent refineries also have been observed to interact in this manner.

Rain augmentation. The Los Angeles County Flood Control District has rainfall records from a dense network of gauges. They have prepared a 90-year (1872-1962) average rainfall distribution map and also yearly maps. Comparison of the long-term average (which should not be greatly affected by industrialization) with maps of recent rainy seasons does not indicate an obvious redistribution of rainfall caused by the refineries.

Since good sources of data are available, however, it is believed warranted to look at this question in a systematic way. As outlined in Fig. 2.1.11, rain augmentation or suppression can be a product of either changes in the dynamics of clouds or in their microphysical behavior (that is, the small-scale processes that cause small condensate particles with essentially no fall speed to grow and become sufficiently large to precipitate).

It is reasonably clear that the refineries have the capability to promote the formation of clouds by affecting convective dynamics. Whether or not the artificially induced clouds are large enough to have some effect on rainfall is not obvious, but both local visual observations and data from Metromex studies in the St. Louis urban region suggest that it would be unwise to reject without further consideration the hypothesis that refineries have an ability to alter rainfall amounts and patterns. Metromex data primarily addresses the distribution of cloudiness and rainfall around an industrialized region, whereas the visual observations focus on individual events.

Aside from dynamical changes, there is a question of the influence that the refinery effluents have on the natural precipitation mechanism. That is, given two "identical" clouds, one natural, the other infected with effluents, would one be more likely to rain (or to hail) than the other? Our observations do not provide much information in this regard. Clouds apparently associated with refineries have been observed to rain, while others have not. A typical, confused example is an observation that on a generally non-rainy day having a low stratified overcast, when a rather shallow plume under the overcast passed overhead, light drizzle was observed, but other drizzling clouds were in the region at the time, and whether or not a natural cloud of similar characteristics would have produced drizzle is not known. On showery days, rain was often observed in the vicinity of the refineries, but probably the same statement could be made of the occurrence of rain at any given location.

Stinson and Brown¹⁸ are of the opinion that material other than water vapor present in the refinery effluent is very important in determining the effects on the atmosphere. They believe the material acts as

Fig. 2.1.11. Factors influencing cloud initiation and growth and the resulting effects on the atmosphere.

abnormal condensation nuclei, producing a visible cloud at humidities lower than natural nuclei would require. Furthermore, they believe that the effluents contain material that causes abnormal cloud glaciation; they have observed a very localized but intense shower of small hail at the college, downwind of the refinery complex. They attribute this to the refinery's heat rejection processes. Their data is totally visual with no measurements. Changnon, et al.,²⁰ express a similar point of view on the efficacy of abnormal condensation nuclei concentrations in producing abnormally high rainfall amounts.

On the other hand, from a large number of observations on power plant plumes, Kramer²¹ found that temperatures must be below -12°C before glaciation takes place. This implies no abnormal effects caused by these cooling towers. Auer¹⁷ has made extensive airborne measurements within a refinery-initiated cloud that maintain a quasi-steady state during a 45-min period of observation. The measurements included factors important to microphysical processes such as condensation nucleus counts and drop-size spectra. The cloud base was at 0.85 km (2800 ft) MSL ($\sim 21^{\circ}\text{C}$), and the summit extended to 2.2 km (7200 ft) MSL ($\sim 7^{\circ}\text{C}$). The cloud did not produce rain (it is unlikely that a natural cloud of these characteristics would have produced rain, but if the drizzle observations noted earlier in connection with a local refinery and Stinson and Brown's conclusions are correct, one would expect to find larger drops than found by Auer). The refinery was a copious source of small aerosols, which infested the cloud, giving it more cloud condensation nuclei than the surrounding air. High concentrations ($\sim 2000\text{ cm}^{-3}$) of small size (1-20 μm in diameter) drops were found. This apparently inhibited the growth of cloud droplets toward precipitation particle sizes and contradicts ideas that the cloud would abnormally produce rain by an all-liquid process.

The observations and interpretations may seem to be in conflict, but this need not necessarily be the case. What is required is more information on the physical characteristics of these clouds.

²¹Kramer, 1976 Personal Communication.

Concluding remarks. This Working Note is in the nature of a report of work in progress, and therefore, it is somewhat premature to draw many conclusions. However, we tentatively conclude:

1. The three-dimensional structure of the atmosphere, winds, temperature, and moisture distribution (with the vertical properties of primary importance) will dictate the extent of anomalous weather caused by power plant heat rejection to the atmosphere.

2. Cooling tower plumes will interact with one another and act in concert to perturb the ambient air flow. Different patterns of towers, causing different inflow characteristics, can probably locally concentrate or change the vorticity of the ambient atmosphere. A simple hydrodynamic model of sinks (representing inflow to the tower) and sources (representing outflow) in a flow field might be useful in estimating the extent of control that the towers might have.

3. Of the analogs discussed herein, the oil refinery complexes are the most pertinent to the question of the effects of power centers on atmospheric processes. From observations within the Los Angeles basin we tentatively conclude:

a. It is likely that presently operating power plants have the capability of significantly altering weather under certain circumstances. The detection of these changes is difficult, however, due to the variability of weather and the likelihood that rainfall changes occur at a sufficiently great distance from the plants that the anomaly is not recognized as such and therefore not attributed to the power plant. A careful investigation would be required to quantify the effect.

b. The substantial point sources of heat produced by cooling towers cause a more obvious environmental modification than the broad sources. This may be an artifact of the relative ease by which the concentrated plume may be seen and the difficulty in associating the invisible broad perturbation with a specific effect. Again, careful measurements are necessary if the effects of the perturbations are to be understood.

c. The more obvious effects of heat rejection occur during periods of relatively low wind speed. This may be primarily a consequence of relative detectability, not a true measure of environment impact with respect to meaningful weather modification effects.

2.1.5 Deep Convection

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Introduction

Certain economic, health, safety, and environmental considerations favor the location of multiple energy production, and related facilities, at the same site. However, available meteorological information suggests that the concentration of waste heat sources may cause significant and potentially severe weather effects; current knowledge is not adequate to assess these effects. Thus, the objective of the PNL study was to help develop the technical bases required for assessing these potential effects and determining their importance as limiting factors in the grouping of large sources of waste heat.

The technical approach that PNL employed to develop this data base was twofold: a deep convection modeling study and a field program for the characterization of cooling tower plumes. The modeling work was a generic study of the initiation and enhancement of convective activity due to the release of waste heat from NEC's.

In the second section of this report we describe the results obtained from the deep convection model. These results include the description of a study of thunderstorm enhancement due to moisture releases from a NEC and cloud formation due to heat and moisture releases under various ambient conditions.

The Deep Convection Modeling Study

Model description. The complete description of the deep convection model used in this study is given in Hane.¹ In Fig. 2.1.12, we show the domain of computation (vertical slab) and the finite difference grid used in the solution of the governing equations of the model.

The basic equations of the model include the time-dependent equations for vorticity, temperature, and the mixing ratios of water vapor, cloud-water and rainwater. The other basic equation relates the vorticity to the stream function.

The processes and characteristics that are included in the model are as follows:

1. An ambient wind profile possessing strong vertical shear.
2. Ambient profiles of temperature and dew point.

¹Hane, C. E., 1973, J. Atm. Sci., 30, pp. 1672-1690.

Fig. 2.1.12. Domain of computation and the finite-differencing used in this study.

3. Condensation and evaporation processes and their associated temperature changes.

4. Liquid water is included "in bulk," assuming a Marshall-Palmer² distribution of raindrops. The fall velocities of the raindrops are taken into account.

5. The autoconversion, accretion and fall velocity expressions follow the work of Kessler et al.³

6. Turbulent mixing by scales of motion not resolvable by the 400 m grid (the value of Δ in Fig. 2.1.12) are parameterized in terms of known grid-scale variables.⁴ In addition, the rate of mass exchange between updrafts (and downdrafts) and the environment due to small-scale eddy motions is considered and an expression for the model equations is found.

7. The sizes of the domain of computation in Fig. 2.1.12 are $L_z = 12.8$ km by $L_x = 25.6$ km and 38 km.

Processes and characteristics that are not included are as follows:

1. Variations in the y-direction of Fig. 2.1.12 are neglected, hence, a vertical slab model.

2. The ice phase is neglected.

3. Horizontal and temporal changes in air density are not taken into account, except implicitly in the buoyancy term in the vorticity equation.

4. Radiation effects are neglected.

5. Surface effects are neglected, including surface evaporation and frictional effects, to the extent that they are not taken into account explicitly in the boundary conditions.

For a more complete description of the model, one should refer to Hane.¹

²Marshall, J. S. and W. McK. Palmer, 1948, J. Meteor., 5, 165-166.

³Kessler, E. E., E. Newburg, P. Feterig, and G. Wickham, 1961-64, Relationships between Tropical Precipitation and Kinematic Cloud Models, Repts. 1-5, Contract DA36-039 SC 89099, Travelers Research Center.

⁴Leith, C. E., 1968, Proc. WMO/IUGG Symp. Numerical Weather Prediction, Tokyo, Japan, 1-41 to 1-44.

Relationship between the model and the NEC. The NEC that was postulated for this study is a 36-unit center, spaced on a square mesh with a cell size of 1 km, see Fig. 2.1.13. Further, we assumed that the total rated capacity of the system is 48 GWe. If this system is totally cooled by evaporative cooling towers, the estimated consumptive water use of the NEC is 2.52×10^7 gm/sec.

The orientation of the vertical slab model with reference to the assumed NEC is shown in Fig. 2.1.13 (plan view) and Figs. 2.1.14 and 2.1.16 (vertical profile). It is assumed that the width of the vertical slab is 1 m. Hence, the moisture perturbation in the vertical slab due to the NEC is given as 5.04×10^3 gm/sec/5000 m². This moisture perturbation assumes that all of the waste heat is in the latent form.

As we look at the relationship of the model to the NEC in Figs. 2.1.13, 2.1.14, and 2.1.16, we could postulate an initial three-dimensional inflow into the region described by the vertical slab. Hence, this two-dimensional model may initially underestimate the convective activity generated by the NEC. However, as the convective activity increases in intensity and becomes more mature, we would expect that the two-dimensional model would overestimate the activity. Thus, we feel that the model will eventually (as time increases) give conservative answers for most of the computer runs.

Thunderstorm enhancement due to moisture releases from a NEC. A schematic of the enhancement of an existing thunderstorm by moisture releases as the storm passes over a NEC is given in Fig. 2.1.14. It is assumed that the moisture release from the NEC is fed into the storm's updraft from an altitude of 200 m to an altitude of 1400 m, see Fig. 2.1.14. For the 1 m wide slab, the excess moisture contributed to the storm through this vertical "window" is 0.8 gm/kg.

The storm that was simulated in the model was a large, squall line type thunderstorm that occurred in the St. Louis area on August 21, 1972. This storm was simulated for a time period of 60 minutes for the case of no water vapor enhancement and for the case of water vapor enhancement from a NEC for the time period of 35 minutes to 60 minutes after the start of the simulation. The results of these two runs are shown in Fig. 2.1.15.

From Fig. 2.1.15, we note that the NEC perturbations produce the following results:

Fig. 2.1.13. The orientation of the "vertical slab" model with respect to the orientation of the 48-GWe NEC.

Fig. 2.1.14. Schematic representation of the enhancement of existing thunderstorms by moisture releases from a NEC.

Fig. 2.1.15. The enhanced vertical velocity and rainfall mixing ratio of a thunderstorm as it passes over a NEC.

Fig. 2.1.16. Schematic representation of the initiation of a convective cloud due to the releases of latent and sensible heat from a NEC.

1. The storm's vertical velocities were increased by 1 mps in the period from 45 to 60 minutes after the start of the simulation, and

2. The storm's rainwater mixing ratio was increased by 0.7 g/Kg during the same time period. This increase can be translated into a rainfall increase of 5 to 10%.

Initiation of corrective clouds by latent and sensible heat emissions from NEC's. We ran four computer simulations for the purpose of analyzing the potential for a NEC to initiate and promote cloud development. In these runs we used actual atmospheric soundings or actual soundings that were somewhat modified. Even though actual soundings were used, we feel that our results are generic in nature because of our choices of soundings and the manner in which we modified them. If this phase of the program were to continue and more selected soundings were considered in the study, the complete set of calculations would constitute a generic study of the generation of cumulus clouds by NEC's. In addition, the comparisons between the modified and unmodified soundings represent a set of sensitivity tests of the model and of the response of the real atmosphere to NEC's.

In Fig. 2.1.16, we show a schematic of the way in which latent and sensible heat emissions from a NEC will produce cumulus clouds. In the vertical slab model, the excess latent and sensible heat are added to the atmosphere along a horizontal strip positioned over the cooling towers at an elevation of 400 m from the surface of the earth. The perturbation is along a horizontal strip in this case (it was a vertical strip earlier) since there are no strong updrafts formed prior to cloud development.

In Fig. 2.1.17, we show the soundings of temperature and dew point (a modified skew-T diagram) vs pressure for Runs 2, 3, and 4. In addition, the wind speed is given as a function of height. In Fig. 2.1.22, we show the ambient soundings for Run 5.

The sounding for Run 2 is a Nashville sounding taken on July 14, 1973, at 23 z. During this time period there were several thunderstorms in the area; however, at the location of the Nashville sounding, it appears that the atmosphere is influenced by the subsiding circulations of the neighboring thunderstorms. The sounding for Run 3 is a modified form of that for Run 2. The original moisture and wind profiles were retained while changing the temperature structure in the lower levels. The new temperature

Fig. 2.1.17. Vertical soundings of temperature, dewpoint and wind for the ambient atmospheres used in the computer simulations, Cases 2, 3, and 4.

profile starts with a surface temperature of 91°F and decreases along a dry-adiabat until the original profile is intersected. Then, the temperature profile for Run 3 becomes identical to Run 2. Thus, Run 3 is the same as Run 2, except for an unstable lower layer of air.

Run 4 has a sounding identical to Run 2, except for a modification of the lower levels of the temperature profile. In this case, a surface temperature of 77°F was assumed with the low level temperature sounding merging into the original sounding at 800 m. The rationale behind this example was the simulation of the nocturnal "heat-island" effect of a NEC. Finally, the sounding for Run 5 represents the atmospheric conditions at a high-latitude site such as the Hanford Site in Washington. This sounding is rather stable and thus reduces the convective activity produced by NEC's.

In Fig. 2.1.18, we have a graph showing the maximum vertical velocity vs time for Cases 2 to 5. From this figure we note that the relatively stable sounding in Case 2 does not produce a very active circulation. However, in Fig. 2.1.19, we do note that a small low level cloud was formed. Shown in this figure is the cloud outline and the vertical motion field in mps after 1.08 hr of simulated time.

When the sounding in Case 2 is modified by adding an unstable lower layer (Case 3), the convective activity triggered by the NEC is greatly increased. This is easily seen from the increased vertical motion in Fig. 2.1.18 and the cloud development in Fig. 2.1.20. Figure 2.1.20a shows the cloud outline, the streamlines and the direction of the air currents, mixing ratio of rain below the cloud, and the location of rain on the surface. The zero on the horizontal scale is the downwind edge of the NEC. Figure 2.1.20b shows the cloud outline, the vertical motion in mps, and the temperature anomaly in °C.

The "nocturnal" modification (Case 4) of Case 2 suppresses the convective activity for the first 1 1/2 hr of simulated time; but after that period, the activity begins to increase and a sizable cloud is formed, see Figs. 2.1.18 and 2.1.20. In Fig. 2.1.21, we show the cloud outline and temperature anomaly downwind of the NEC after 3.79 hr of simulated time.

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Fig. 2.1.18. The maximum vertical velocity generated by the convective activity in Cases 2, 3, 4, and 5.

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Fig. 2.1.19. The cloud outline and vertical motion field after 1.08 hr of simulated time for Case 2.

Fig. 2.1.20. The cloud outline, streamlines, rainfall mixing ratio, amount of rain below the cloud, vertical motion field, and temperature anomaly after 0.63 hr of simulated time for Case 3.

Fig. 2.1.21. The cloud outline and temperature anomaly after 3.79 hr of simulated time for Case 4.

From Figs. 2.1.18 and 2.1.23, we note that the Hanford type (Case 5) sounding promoted very little convective activity. Figure 2.1.23 shows the streamlines, direction of wind currents, and vertical motion field in mps. The pattern in this figure is basically steady state. Thus, the effect of the NEC is to produce a perturbation in the ambient flow field, but no clouds are formed.

Conclusions. Using a vertical slab, time-dependent, deep convection model, we have studied the feasibility of a NEC triggering cloud formation and precipitation, and intensifying the activity of a passing thunderstorm. Our model shows that both of these phenomena are possible under the proper ambient conditions. Using the five cases discussed in this report along with a new set of selected cases, we could construct a reasonable climatology of the effects of NEC's on cloud formation, the production of precipitation, and the enhancement of thunderstorm activity.

Fig. 2.1.22. Vertical soundings of temperature, dewpoint, and wind for the ambient atmosphere used in the computer simulation, Case 5.

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Fig. 2.1.23. The stream function and vertical motion field in mps after 0.84 hr of simulated time for Case 5.

2.1.6 Turbulence Closure Models

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Vortex Stretching

The motion in weather systems is very much constrained in the vertical; the effective thickness of the atmosphere is much smaller than its horizontal extent. The atmospheric turbulence is a quasi-two-dimensional turbulence. Charney¹ calls it geostrophic turbulence. Theoretical studies and computer simulations of 2-D turbulence are, therefore, of great significance in the continuing efforts to find answers to many atmospheric problems.

A chaotic flow field, however, can be called "turbulent" only if it is intrinsically three-dimensional. An important feature of turbulence is the amplification of vorticity fluctuations by the mechanism called "vortex stretching." The vorticity vector, defined as the curl of the velocity vector ($\bar{\omega} = \bar{\nabla} \times \bar{v}$), is a measure of the angular velocity of a fluid volume. From the principle of conservation of angular momentum, we conclude that vorticity grows when angular momentum is compressed into a smaller cross section.

The basic distinction between 2-D and 3-D turbulence models is the constraint on vorticity. In 2-D flows, the mean squared modulus of the vorticity vector ($|\bar{\omega}|^2$), which is called "enstrophy," is a conserved property except for the effects of external torque and viscous dissipation. The enstrophy is not a conserved property in 3-D flows since a constant enstrophy implies that the vortices are not able to stretch in all three directions.

Vortex stretching, the mechanism that gives hurricanes and tornadoes their destructive force, is absent in 2-D flows. A 2-D flow cannot turn or stretch the vorticity vector.² In turbulence, as vortex stretching proceeds, the size of active vortices decreases. This occurs over a wide range of scales, with ever smaller vortices feeding on the strain

¹J. G. Charney, J. Atmos. Sci., 28, 1971, 1087.

²H. Tennekes and J. L. Lumley, A First Course in Turbulence, MIT Press, 1972.

rates of larger ones. Extremely large values of enstrophy could be created at ever increasing wave numbers (small wavelengths). In reality, this catastrophe is prevented by the fluid's viscosity which limits the wave number range over which random motion can be maintained. The smallest wavelength in turbulence is called the Kolmogorov micro-scale (η). In atmosphere, $\eta \simeq 1$ mm.

Energy Spectrum

In turbulence, there is a balance between the equipartition of energy over all modes of motion and the viscosity. When energy input to a fluid system takes place only on very large scales and viscous dissipation occurs only on very small scales, an inertial range of scales between these two extremes is said to exist. This scale range, referred to as the "inertial subrange," occurs only in high Reynolds number flow, such as in the atmosphere ($Re \simeq 10^7$). In the inertial subrange (IS), energy is neither produced from mean flow or potential energy sources, nor destroyed by molecular viscosity in significant amounts, but there is a rapid transfer of energy from larger to smaller scales of motion. This constant "spectral energy cascade" (at a rate ϵ equal to the mean viscous dissipation rate) is driven by the random vortex-stretching mechanism. The theoretical models of this process are all formulated for the asymptotic case in which the Re tends to infinity.³ A schematic 3-D spectrum with scales characteristic of various ranges is shown in Fig. 2.1.24 where $k = |\vec{k}|$, the 3-D wave-number vector.

Kolmogorov's⁴ hypothesis holds that in turbulence of sufficiently large Re , the fine structure is isotropic, determined only by ϵ and the kinematic viscosity ν , and independent of the large scale flow. (The large scale features of turbulent flows do not change with Reynolds

³H. Tennekes, Physics Today, 27, 1974, p. 52.

⁴A. N. Kolmogorov, Compt. Rend. (Dokl.) Akad. Sci. USSR 30, 1941, p. 301.

Fig. 2.1.24. Energy spectrum.

number, if boundary and initial conditions are fixed independent of Re.⁵ The Kolmogorov microscale defined as

$$\eta = (\nu^3/\epsilon)^{1/4} \quad (1)$$

is the largest scale that can be neglected in a turbulent flow simulation.

Much of the modern turbulence theory is based on the notion of an inertial subrange in the turbulent energy spectrum. In this range, the statistics are determined solely by ϵ , the rate at which energy is cascaded through this region to be dissipated by viscosity. The scalar energy spectrum function $E(k)$ of the scalar wave number k is

$$E(k) = \alpha \epsilon^{2/3} k^{-5/3} \quad (2)$$

where $\alpha \approx 1.5$ is a universal constant. Somewhere in the inertial subrange, the turbulence structure becomes statistically isotropic.

Kraichnan⁶ pointed out that while in the 3-D flow, the energy is cascaded down the scale towards the large wave numbers and dissipated in the smallest scales, the 2-D flow allows a cascade of energy upward into large scale (small wave number) and leads to a separation of energy spectrum from the dissipation scales. Then, all energy resides in large scales which are not affected by viscosity, and the flow becomes more energetic while vorticity patterns tend to become small scale dominated since only enstrophy is cascaded in the usual sense at high wave numbers.

The absence of vortex-stretching and the reverse energy cascade in the 2-D flow indicate that an adequate model for vorticity should be 3-dimensional, such as Deardorff's subgrid scale modeling⁷ or Orszag's numerical simulations by spectral (Galerkin) methods.⁸ The latter have

⁵J. R. Herring, et al., J. Fluid Mech., 66, 1974.

⁶R. Kraichnan, Phys. Fluids, 10, 1967, 1417.

⁷J. W. Deardorff, Appl. Mech. & Fluids Engy. Conf., ASME Paper 73-FE-21, Atlanta, Georgia, 1973.

⁸S. A. Orszag, Report No. 52, Flow Research, 1974.

severe Re limitations ($Re \simeq 10^4$ only realized so far), difficulties in obtaining adequate statistics to compute accurate statistical averages and in the imposition of boundary conditions on the flow, and rapidly recede beyond economic reach as Re increases.⁹ Deardorff's subgrid scale approach is outlined and examined below with a view to adopting it to model the possible concentration of vorticity resulting from the injection of large amounts of heat and moisture over a small region by the proposed energy parks. It is hoped that the other effects of energy parks, such as the merging of individual plumes and the cumulus cloud growth could be more suitably studied by dynamical modeling, for example the second-order closure models of Lumley¹⁰ and others, which predict only ensemble-averaged statistics of the turbulent structure rather than the instantaneous details of the randomly fluctuating fields. This could be justified since the merging plumes can be in a stochastic steady-state, while the concentrated vortices may be short-lived.

3-D Subgrid Turbulence Closure Modeling

Rationale of approach: There are two ways to simulate turbulent fluid motions:

1. Compute all possible scales of motion down to that of viscous dissipation. Corrsin¹¹ pointed out the futility of such a program, showing that it would require some 10^{12} grid points to simulate even a fairly low Re of 10^4 . As Re increases, the computing requirements increase as $(Re)^3$. Such numbers are well beyond our present computing capabilities of 1-10 MIPS (millions of instructions per second) with CDC-6600, 7600, IBM 360-195, or near future capabilities of 10-100 MIPS

⁹D. G. Fox and D. K. Lilly, Rev. Geophys. & Space Phys., 10, 1972, 51.

¹⁰J. L. Lumley and B. Khajeh-Nouri, Adv. Geophys. 18A, Academic Press, 1974, 73.

¹¹S. Corrsin, American Scientist, 49, 1961, 300.

(e.g., CDC STAR, Illiac, TI ASC, Cray Research). So, we may regard such complete simulation for atmospheric flows as hopeless in the near future.

2. Calculate the larger energy-containing (explicitly resolvable) scales only and approximate in some way the effect of smaller (non-resolvable) scales.

The latter provides a practical approach for useful geophysical computations since it recognizes that it is economically impossible to carry in the computation the smallest scales at high Re. The grid scale, made as small as is economically feasible, is defined as

$$\Delta = (\Delta x \cdot \Delta y \cdot \Delta z)^{1/3} \quad (3)$$

and chosen such that it lies in the inertial subrange. Since $\Delta \gg \eta$, it is necessary to approximate the motion on scales below the grid scale Δ (but above η , which is the largest scale that can be neglected in turbulence simulations) such that the profound but indirect effects that molecular viscosity and diffusion exert on a real fluid are accounted for, without actually computing the motions on all of the interacting scales. Such an approach is justified by the well-supported property of turbulence dynamics that the precise nature of the dissipative mechanism does not influence the large scales of the motion, if Re is high enough.²

Since the grid scale Δ lies within the inertial subrange, the relatively simple properties of this range can be used to greatly truncate the otherwise impossibly large requirements of the computer resolution. With the aid of the Kolmogorov spectrum function, certain statistical relationships can be established for the local interactions between the explicit (resolvable) scale motions and those of the subgrid length scales (which are not known in detail). This is represented by an eddy viscosity K suggested by Smagorinsky, et al.¹²:

$$K = (c\Delta)^2 \left| \left[\partial \bar{u}_i / \partial x_i + \partial \bar{u}_j / \partial x_j \right]^2 \right|^{1/2} \quad (4)$$

in 3-D model. This expression for K is valid only if first- or second-order space differencing is used; higher order schemes require a different eddy viscosity.⁸

¹²J. Smagorinsky, et al., Mon. Weather Rev., 93, 1965, 727.

Lilly¹³ has shown that Eq. (4) is consistent with the existence of a 3-D inertial subrange on scales comparable to or less than Δ , and derived

$$c \simeq 0.23 \alpha^{-3/4} \simeq 0.2 \quad (5)$$

where $\alpha \simeq 1.5$ is the universal constant for the IS. The turbulent energy E , obtained by integrating the Kolmogorov spectrum, is

$$E \simeq 1.5 \alpha \epsilon^{2/3} (\Delta/\pi)^{2/3} \quad (6)$$

Deardorff¹⁴ found that $c \simeq 0.21$ is appropriate when the driving mechanism for turbulence energy is thermal convection, but $c \simeq 0.13$ when it is large-scale velocity shear.

The Navier-Stokes and continuity equations for an incompressible flow are written as

$$\partial u_i / \partial t + u_k \partial u_i / \partial x_k = -\partial / \partial x_i (p/\rho) + \nu \partial^2 u_i / \partial x_k^2 \quad (7)$$

$$\partial u_i / \partial x_i = 0 \quad (8)$$

Define a smoothed variable (filtered to remove the fluctuations of sub-grid scale), obtained by Reynolds averaging over the grid volume, as

$$\bar{u}_i(\underline{x}, t) = 1/\Delta^3 \iiint u_i(\underline{x}_i, t) d\underline{x}_i \quad (9)$$

where $i = 1, 2$, and 3 , and the integration is over the limits of $\underline{x}_i \pm \Delta \underline{x}_i/2$. Now Eqs. (7) and (8) become

$$\begin{aligned} \partial \bar{u}_i / \partial t + \bar{u}_k \partial \bar{u}_i / \partial x_k - \partial \tau_{ik} / \partial x_k &= -\partial / \partial x_i (p/\rho + 2E/3) \\ &+ \nu \partial^2 \bar{u}_i / \partial x_k^2 \end{aligned} \quad (10)$$

$$\partial \bar{u}_i / \partial x_i = 0 \quad (11)$$

where τ_{ik} is a subgrid scale (SGS) Reynolds stress given by

$$\tau_{ik} = -\left(\overline{u_i u_k} - \bar{u}_i \bar{u}_k - 2E\delta_{ik}/3 \right) \quad (12)$$

¹³D. K. Lilly, IBM Sci. Computing Symp., IBM Form 320-1951, 1967, 195.

¹⁴J. W. Deardorff, J. Atmos. Sci., 29, 1972, 91.

and E is the small scale kinetic energy written as

$$2E = \left(\overline{u_k u_k} - \overline{u_k} \overline{u_k} \right). \quad (13)$$

Note that τ_{ik} is defined such that normal stresses vanish ($\tau_{ii} = 0$) in isotropic turbulence. The first-order subgrid turbulence closure is now accomplished by assuming that τ_{ik} are proportional to the strain rates of the large-scale flow:

$$\tau_{ik} = k \left(\partial \overline{u_i} / \partial x_k + \partial \overline{u_k} / \partial x_i \right) = K D_{ik} \quad (14)$$

where D_{ik} is the mean flow deformation tensor and K is the eddy viscosity given by Eq. (4).

This approach was used by Deardorff¹⁴ in the 3-D numerical study of neutral and unstable planetary boundary layers using a grid of $40 \times 40 \times 20$ points to treat a region of $5 \text{ km} \times 5 \text{ km} \times 0.45 u_* / f$ or z_i .

Second-order SGS turbulence closure: The stably stratified layer above an unstable turbulent atmospheric boundary layer tends to drive the vertical fluxes of heat and momentum from relatively large scales to subgrid scales. The SGS eddy viscosity closure does not permit an accurate treatment of the motions and heat flux near the top of the convective layer. Individual anisotropic subgrid turbulence intensities and temperature (and other scalar) variances are not calculable by the eddy-coefficient method. These effects can be treated adequately by writing the transport equations for the SGS turbulent fluxes (from which the eddy viscosity closure can be derived as a lowest-order approximation).

The evolution and form of the subgrid transport equations is similar to that of transport equations for ensemble-averaged (over all eddy scales) variables given by Lumley¹⁰ and Donaldson,¹⁵ among others, except that the variables here are averaged over the subgrid space. These equations introduce further unknowns (resulting from the nonlinearity of the problem and the information lost by averaging) in the

¹⁵C. Donaldson, Workshop on Micrometeorology, AMS, Boston, 1973, 313.

form of (1) triple correlation terms, (2) pressure-velocity (or scalar) gradient terms, and (3) dissipation terms. As in dynamical models, these terms must be approximated in terms of other known or calculable quantities in a dimensionally-consistent, physically-plausible manner to affect closure; several adjustable constants typically appear that must be chosen by comparison with experimental data (or by intuitive reasoning). The length, velocity, and time scales used in the closure models are Δ , $E^{1/2}$ and $\Delta/E^{1/2}$, respectively.

In all second-order models, as Lumley¹⁰ notes, there is an article of faith involved: if a crude assumption for second moments predicts first moments adequately, perhaps a crude assumption for third moments will predict second moments adequately. In the subgrid turbulence models, however, the closure approximations directly affect only the subgrid-scale portion of the fluxes. Except for stable stratification, this portion typically turns out to be only 15-20% of the total flux.¹⁶ This advantage is gained here at the expense of time-consuming numerical calculations capable of resolving the energy containing eddies and the beginnings of an inertial subrange.

For a neutral PBL, the model contains ten equations for ten variables ($\bar{u}_i$, $\bar{p}$, $\overline{u'_i u'_j}$); for thermally stratified PBL, there are five additional equations for $\bar{\theta}$, $\overline{\theta'^2}$, and $\overline{u'_i \theta'}$; if moisture is included, six more equations for $\bar{q}$, $\overline{q'^2}$, $\overline{u'_i q'}$, and $\overline{q' \theta'}$; Deardorff used this 21-equation subgrid transport model for the Wangara study of convective PBL structure.¹⁷ The buoyancy and stratification terms in the equations affect the subgrid fluxes in a realistic manner, which preserves the sharpness of the inversion base above a deepening convective layer while allowing internal gravity waves to exist above the inversion base. The anisotropy of the subgrid normal stresses, caused by the buoyancy terms, is also reproduced by the model.

Critique of the approach: A great deal of success has been achieved in direct simulation of turbulence in 3-D flows with the SGS modeling.

¹⁶J. W. Deardorff, *Ibid.*, 271.

¹⁷J. W. Deardorff, Bound. Lay. Meteorol., 7, 1974, 81

This approach has very much to commend it in that there is no Re-limitation on the simulations, since the effect of subgrid turbulence is taken into account. According to Orszag,⁸ the subgrid approach must be ultimately involved in the solution of all turbulence problems, since one is interested in details of the large scales and not just their statistical properties. Such a simulation gives a far more faithful representation, in far more detail, than traditional eddy diffusivity approaches. There are, however, certain drawbacks.

Selection of subgrid scale: The accuracy of the subgrid closures requires that the separation of the flow into subgrid scale and large scale components does not have a significant effect on the evolution of large scales. The success of this method depends not only on having a sufficiently high Re to have an inertial subrange (so that energy containing and dissipative scales are, to a first approximation, dynamically related only by the value of the spectral energy flux) but also on being able to use a grid scale small enough to lie in the inertial subrange. This may not always be feasible due to the large number of grid points required to make even a crude model of the modeled 3-D region, and the resulting computational expenses. We must then use a grid scale lying in the energy containing range of the spectrum and compute only the statistical properties of the turbulence. The so-called SGS motions then contain virtually all the turbulence and dynamical modeling becomes much more important. Since the entire influence of turbulence is then being computed through the moments, it is no longer correct to think of turbulence quantities as being subgrid scale; for example, the scale of the turbulence is not then related to the grid scale but must be obtained from dynamical considerations.¹⁰

The current methods for inclusion of the subgrid effect have a number of disadvantages including the use of ad hoc turbulence transport models for the subgrid components and the neglect of any stochastic effect of fluctuations in subgrid flow variables on the generation of fluctuations in large scales.

Statistical averages: There is also difficulty in obtaining adequate statistics to compute accurate statistical averages of quantities. This is due to the fact that the arithmetical mean of N independent values of a random variable with average A and standard deviation D fluctuates about A with amplitude of order $D/\sqrt{N}$. Consequently, increasing the sample size by a factor 100 only reduces errors by a factor 10. Large samples are necessary for high accuracy; Lumley¹⁰ estimates of the order of 200 runs are required to obtain 10% accuracy in second-order quantities with the subgrid turbulence models. This increases the computer costs enormously.

In homogeneous turbulence, large samples are readily available since 3-D spatial averages may be used. In isotropic turbulence, averages may be obtained as arithmetical means over bands in wave number (k) space. In 2-D shear flows, where averages are functions of x and z , the spatial averages may be obtained as averages over the y -direction; if the flow is (statistically) homogeneous in x , then the longitudinal direction may also be used for averaging. Similarly, in a statistically axisymmetric shear flow, the azimuthal (θ) direction and sometimes the longitudinal (x) direction may be used for spatial averages. However, realistic shear flows have at least one direction of inhomogeneity, and this means a significant degradation of accuracy of spatial statistics (compared with statistically homogeneous flows).

In a general 3-D turbulent flow, the situation with regard to statistics is very serious. If there is no direction of spatial homogeneity (for example, a fully 3-D region of an urban environment), then averages may be computed in only two ways. First, time averages may be used if the flow is statistically stationary, and by the ergodic hypothesis, these may also be interpreted as ensemble averages. However, it is not sufficient to use the flow values at N successive time steps to get N independent measurements because the flow is strongly correlated from one time step to the next. In order to get N independent samplings of an energy-containing scale of motion, for example, it is necessary to calculate through order NT , where $T = \ell/\bar{u}$ is the large eddy circulation time. This increases the number of computer operations by a factor N .

Second, averages of an arbitrary (statistically inhomogeneous, non-stationary) flow can always be computed as an ensemble average in which the average is taken over N distinct flows with the same statistics. Each calculation is a realization in an ensemble, and the number of independent runs (N) should be sufficiently large to obtain stable statistics. This increases the computing times by a factor N over that necessary to compute a single flow. A single run of subgrid model is so expensive as to preclude the possibility of doing statistics on an ensemble of them.

To date the 3-D subgrid turbulence models have been used primarily for horizontally-homogeneous flows; in such flows, the number of runs necessary to obtain stable statistics can be substantially reduced by spatial averaging in the homogeneous (x and y) directions, as follows:

$$\langle \bar{q} \rangle = 1/(L_x L_y) \int_0^{L_x} dx \int_0^{L_y} \bar{q}(x, y, z, t) dy \quad (15)$$

where the angular bracket indicates a linear horizontal averaging operator, $\bar{q}$ is any variable, and L_x and L_y are the longitudinal and lateral limits of a horizontal plane in the modeled 3-D region. Note that a horizontally averaged variable $\langle \bar{q} \rangle$ is a function of z and t only. Any quantity deviating from the horizontal average of its own level is represented by the double prime symbol:

$$\bar{q}'' = \bar{q} - \langle \bar{q} \rangle. \quad (16)$$

For a steady-state structure, $\bar{q}''$ isopleths (in x - y plane) represent the eddy patterns of $\bar{q}$ at a given height. We also note that the horizontally averaged continuity Eq. (11) implies

$$\partial \langle \bar{w} \rangle / \partial z = 0. \quad (17)$$

It should be emphasized that in Deardorff's numerical studies,¹⁶ the PBL was treated as the region of continuous turbulence induced by surface wind shear and heating and extending up to a quiescent non-interacting free atmosphere; the turbulence and mean structure were considered statistically steady (i.e., as if the PBL height and its turbulence statistics were frozen in time).

In the energy park study, where a turbulent buoyant plume interacts with the PBL structure, the assumption of statistical stationarity might still be valid; however, the flow is not statistically homogeneous in x and y directions if the plume is considered as a finite perturbation, and it is questionable whether a horizontally averaged variable $\langle q \rangle$ can be defined.

Boundary conditions: There are a variety of difficulties relating to the imposition of B.C. on the flow.

1. Lateral B.C. For problems with horizontal homogeneity, cyclic (periodic) B.C. at the vertical sides of the 3-D region are used, as follows:

$$\begin{aligned}\bar{q}(0, y, z, t) &= \bar{q}(L_x, y, z, t) \\ \bar{q}(x, 0, z, t) &= \bar{q}(x, L_y, z, t)\end{aligned}\tag{18}$$

This is possible since there is no physical solid boundary present in either downstream or lateral direction. Such B.C. can be imposed on the pressure fluctuations, even though a large-scale horizontal mean pressure gradient may exist. The assumption of periodicity corresponds to the procedure (in wave number space) of assigning a wave length of $m\Delta x$ in x-direction and $n\Delta y$ in y-direction for wave number one, where m and n are the respective grid intervals. Periodicity of all variables in x and y directions permits a harmonic analysis for the functions (or the functionals) of these variables in these two directions.¹⁸

One can expand the variables into a double complex Fourier series and apply an algorithm for Fast Fourier Transform (FFT) suggested by Cooley and Tukey,¹⁹ which cuts down the computing times substantially. The pressure field is preferably calculated by the FFT method as an exact solution for the finite-difference Poisson equation at each grid point.

For the energy park problem, it may not be possible to use periodic B.C. since there is no horizontal homogeneity. The pressure field has

¹⁸C. J. Kau and R. L. Peskin, Tech. Rep. 101, GFDP, Rutgers University, New Brunswick, New Jersey, 1972, 115 pp.

¹⁹J. W. Cooley and J. W. Tukey, Math. Comput., 19, 1965, 297.

to be calculated by a less accurate iterative method of successive over-relaxation approximation, which is time-consuming computationally.

2. Upper B.C. The vertical gradients of all the variables (except $\bar{w}$ and $\bar{p}$) are set equal to zero at $z = L_z$ (or $\Delta z/2$ below this height for some quantities because of the staggered grid); $\bar{w} = 0$, and the B.C. for $\bar{p}$ are calculated directly from Eq. (10) for $i = 3$. The upper boundary should be placed sufficiently high so that practically all the boundary layer turbulence would occur below it. The inversion base at $z = H$ should be penetrable by convective elements for a realistic simulation. Therefore, one should choose $L_z > H$ to allow for the effects of entrainment of overlying air into the PBL. A solid upper boundary at $z = H$ might be adequate for the energy park study.

3. Lower B.C. A height just above the roughness elements is considered $z = 0$. At this height (or at $z = \Delta z/2$ for some quantities), the vertical gradients of all turbulent fluxes (except $\overline{u'w'}$ and $\overline{v'w'}$) are set equal to zero. $\bar{w}$ and $\bar{p}$ are specified as above; $\bar{u}$ and $\bar{v}$ are calculated at $\Delta z/2$ using surface layer similarity relationships. The surface shear stresses are related to these winds using a horizontally averaged value for the surface drag coefficient. The surface is assumed to be horizontally homogeneous in roughness and temperature. The latter is calculated from a surface energy balance equation, a major input of which is the solar zenith angle. The surface moisture $\bar{q}$ is calculated from a specified initial soil moisture, taking into account the very slow decrease in soil moisture content during the day.¹⁷

For the energy park problem, if a Galilean transformation of the 3-D grid is not possible, then the momentum, heat, and moisture injection of the plume should be properly parameterized and specified as B.C. at the lower boundary or at an appropriate spatial location in the 3-D grid region.

Galilean transformation: In an explicit finite difference forward time-marching computational scheme, there are two criteria that restrict the maximum time step Δt in order to assure the stability and convergence of the numerical solution:

$$\Delta t \leq \min(\Delta x_i / \bar{u}_i), \quad i = 1, 2, 3 \quad (19)$$

is the Courant-Friedrichs-Lewy condition to avoid a linear advective instability. The other is a diffusive criterion,

$$\Delta t \leq 1/4 \left[(\Delta z)_{\min}^2 / K \right]. \quad (20)$$

Deardorff¹⁶ found that criterion Eq. (19) is more restrictive than Eq. (20). To somewhat alleviate this condition, he allowed the coordinate system to translate downstream with the approximate speed of the mean flow of the PBL. This Galilean transformation is equivalent to a fluid moving through a stationary grid. The translation speed (which turns out to be about 80% of the maximum mean flow velocity) should be taken into account when formulating the lower B.C. on fluxes and the Coriolis terms. Even with this translation, only from 1/4 to 1/2 of Δt from Eq. (19) seemed necessary to obtain convergence of the numerical solution. The dynamics are too crudely treated if a large fraction of the grid interval is covered in one time step. An implicit method of time differencing which could remove this criterion on Δt is not desirable in the detailed treatment of turbulence.

There are problems with grid translation in a flow with no horizontal homogeneity, such as in the energy park problem. A fully developed, statistically steady, bent-over plume may be considered a finite perturbation in the flow, and its interaction with the PBL introduces spatial inhomogeneities in the 3-D grid region. It may not be possible to simulate this by translating the grid over a fully developed vertical (or bent-over) plume, even if the latter is calculated approximately and specified a priori. The alternative is to translate the grid along with the plume fixed to it, and it is questionable if this would yield a realistic simulation. If the Galilean transformation in some form cannot be used, then Δt would become much smaller and the computing times much larger. This question requires careful consideration.

Time differencing schemes: Two time differencing schemes are suggested:

1. Leap-frog method. Consider $\partial u / \partial t = Q$. (21)

This is written as

$$\left[u^{(n+1)} - u^{(n-1)} \right] / 2\Delta t = Q^{(n)} \quad (22)$$

To avoid linear diffusive instability, the subgrid stress terms in the forcing function Q should be written at time level $(n-1)$. The leap-frog method has neutral numerical stability, i.e., it neither amplifies nor damps spuriously. However, values on even time steps are very weakly tied to values at odd time steps; a significant $2\Delta t$ oscillation can develop, leading to catastrophic instability. To avoid this, it is advisable to perform an averaging of values at odd and even time steps once each 30-50 time steps. This occasional time averaging scarcely damps the variances of the dependent variables if the coordinate system moves downstream with a speed nearly equal to that of the mean flow and the eddies.

2. Adams-Bashford method. The finite-differencing analog of Eq.(21) is written as

$$\left[u^{(n+1)} - u^{(n)} \right] / \Delta t = 1.5Q^{(n)} - 0.5Q^{(n-1)} \quad (23)$$

This is preferable over the leap-frog method for the subgrid transport equations since the A-B method is free from the large $2\Delta t$ oscillation (of the leap-frog method) due to the occasional "enforcement of realizability." The latter is the requirement that subgrid velocity and temperature variances be positive definite and that local correlation coefficients for the subgrid turbulent fluxes never exceed unity in magnitude.

Nonlinear advection terms: Consider the flux form for a nonlinear advection term:

$$\bar{u}_j \left(\partial \bar{u}_i / \partial x_j \right) = \partial / \partial x_j \left(\bar{u}_i \bar{u}_j \right) \quad (24)$$

It is preferable to write the flux form to conserve exactly the spatially integrated kinetic energy with respect to these terms, since this avoids a nonlinear numerical instability and conserves the mean property itself. The finite difference form of this energy-conserving

scheme is written by the Arakawa method²⁰ to second-order accuracy. As an example, consider $\partial/\partial z(\bar{u}\bar{w})$; at constant values of $(j\Delta y, n\Delta t)$, we can write this as

$$\left. \partial/\partial z(\bar{u}\bar{w}) \right|_{j,n} = \left[\left(\bar{u}_{i,k} + \bar{u}_{i,k+1} \right) \left(\bar{w}_{i,k+1} + \bar{w}_{i-1,k+1} \right) - \left(\bar{u}_{i,k-1} + \bar{u}_{i,k} \right) \left(\bar{w}_{i,k} + \bar{w}_{i-1,k} \right) \right] / 4\Delta z \quad (25)$$

Though the subgrid transport equations can remove cascaded energy or scalar variance from the calculated 3-D fields of $\bar{u}_1$ and θ , the rate of removal may be insufficient if truncation errors of the advective type are too large. Adverse effects of truncation error are more serious than uncertainties in subgrid closure assumptions. The small scale features of the flow lose their predictability within roughly one "turnover" time of the dominant eddies in the flow, due to truncation errors using a second-order energy-conserving finite difference scheme.¹⁶ This error could be alleviated by treatment of a horizontal region smaller than 8 km square, but it would be more profitable to switch to a fourth-order difference scheme for the advection terms. This scheme neither preserves energy nor enstrophy, but theoretically it reduces discretization errors substantially (errors up to fourth order in grid interval are not present).

Complexity and computing time: There are four factors to be considered in the evaluation of a turbulence model:

- (1) general applicability
- (2) accuracy
- (3) simplicity
- (4) computing time.

The first implies that the model should be capable of predicting as many flows as possible with a unique set of values for the universal constants; these constants, governing each physically distinct effect, should be determined in a situation in which that effect is not influenced by others. Any gain in the first two of these four factors would necessarily

²⁰D. G. Fox and J. W. Deardorff, Paper No. 72-HT-61, AICHE-ASME Heat Trans. Conf., Denver, Colorado, 1972.

be at the expense of the other two, and this is the trade-off in the subgrid turbulence modeling.

The direct simulation of turbulence with subgrid scale modeling is very complex and expensive. Deardorff's Wangara convective study (with 21 equations) required 1 minute of CDC-7600 computer time for each $\Delta t = 6$ sec; the treatment of a diurnal cycle required 350 hrs of computer operation time, another 200 hours for preliminary runs and model development, and countless manhours for analysis of results from such a study, which compares with analysis of data from a large field program. The computer time and memory space requirements increase by a factor 2.5 over the eddy viscosity approach.

In the energy park study, there are two additional variables, namely, the cloud liquid water content (LWC) $\bar{s}$ and the precipitation LWC $\bar{r}$; this may require 15 additional equations ($\bar{s}$, $\overline{s'^2}$, $\overline{u'_1 s'}$, $\overline{\theta' s'}$, $\overline{q' s'}$, $\bar{r}$, $\overline{r'^2}$, $\overline{u'_1 r'}$, $\overline{\theta' r'}$, $\overline{q' r'}$, $\overline{r' s'}$), i.e., a total of 36 equations in the subgrid transport equation model. Besides the incredible complexity of integrating this coupled system, the computer operation time to simulate a diurnal cycle would be about 600 hrs (not including preliminary runs and model development). The programming, operation, and data analysis require a very large number of manhours. The development of such a program requires at least two years, three persons (two research scientists, part time; 1 computer programmer with some turbulence knowledge, full time), excellent computer facilities (with at least one hour operation time made available each day), data storage, display and plotting facilities.

The complexity and computing time requirements should be adequately appreciated, and the SGS approach should be selected only if there is a serious long-term commitment to the development of this model. Large savings in computer operation time may be obtained by suitable parameterization of the problem and integrating the equations to a steady state for only three representative stability (unstable, neutral, stable) conditions, instead of simulating the entire diurnal cycle. Though the inclusion of LWC in the model may be desirable, this may not affect the

plume dynamics significantly.²¹ If these second-order effects are ignored, it is necessary to carry only 21 equations in the model, with substantial savings in computer time.

Step-by-step approach: In pursuing a complicated numerical program, it is advisable to treat first a simplified version of the problem; when this has been checked against available observations, the complicating factors may be added. For example, Déardorff's 3-D numerical model of channel shear flow was later extended using the same code but with the addition of Coriolis forces, lateral pressure gradient, and revised upper B.C. to simulate the neutral PBL; this program was later extended for the unstably stratified PBL.

The same step-by-step approach should be followed in the development of a model for the possible concentration of vorticity in the energy park problem. First, we have to demonstrate that Deardorff's 3-D model can simulate a turbulent nonbuoyant or buoyant plume discharged into a (1) quiescent neutral atmosphere, (2) laminar neutral (or stratified) flow, and (3) turbulent neutral atmosphere. Then, we can model the release of a turbulent buoyant moist plume from a large source into a turbulent stratified atmosphere. We would like to know whether it is the atmospheric vorticity or the plume wake vorticity that is important and to study the interaction between these two, resulting in a possible concentration of vorticity that could lead to catastrophic consequences. In such a study, the resolution of the model should be adequate to scale these effects.

²¹G. A. Briggs, Lectures on Air Poll. & Env. Imp. Anal., AMS, Boston, 1975, 59.

2.2 Laboratory Experiments

2.2.1 Laboratory Plume Studies

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Laboratory Plume Studies

Research on the experimental study of buoyant plumes was initiated at the Heat Transfer-Fluid Dynamics Section of the Reactor Division (now Engineering Technology). The experiments will be conducted in an elevated and confined "box." At the center of its base, hot air will be injected through a variety of orifice configurations. Tobacco smoke will be used for visual observations and hot-wire anemometry will be employed for the study of the plumes' temperature and velocity fields. The goals of this study are aimed toward a better understanding of the processes of plume mergence, entrainment, and vorticity enhancement.

2.3 Field Experiments

2.3.1 Cooling Tower Plume Field Studies

2.3.1.1 Plume Characterization

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Introduction

This report deals with the characterization of cooling tower plumes. The field data from the plume characterization study can be utilized to test and improve models of drift and plume behavior, to provide guidance for future experimental needs and design, and to improve the siting criteria for multi-unit sites.

The second section of this report describes the field studies at and the results from the Rancho Seco, Trojan, and Centralia Power Plants.

Characterization of Cooling Tower Plumes

Description of field tests. In-plume measurements with an instrumented Cessna 411 aircraft were made at the Rancho Seco Nuclear Generating Station (913 MWe) near Sacramento, California; the Trojan Nuclear Plant (1130 MWe) on the Columbia River 50 miles north of Portland, Oregon; and the coal-fired Centralia Steam Plant (1400 MWe) 50 miles north of the Trojan Plant. Additional surface-based operations conducted at Rancho Seco included pibal tracking to determine the wind velocity profile, time-exposure photographs of the plume for external plume definition and measurements of sulfate deposition due to the drift of entrained circulating water.

Heat rejection at Rancho Seco is from two 425-ft natural-draft towers whose exit diameters are 195 ft; at Trojan, from a single 500-ft natural-draft tower with exit diameter of 250 ft; and at Centralia, from four mechanical-draft towers. Results of the analyses are summarized below for three days' operation at Rancho Seco (February 17, 18, and 20 in 1975) and one day (May 13, 1976) at Trojan and Centralia.

During the course of these flights, measurements of temperature, humidity, turbulence, Aitken nuclei and cloud droplet spectra were taken. The temperature sensor is a linear-response thermistor bead accurate to 0.5°C. Humidity is measured with a carbon-strip humistor accurate to about 10% relative humidity and with a Cambridge hygrometer accurate to 0.5°C dewpoint. Turbulence is measured with a Meteorology Research, Inc., Universal Indicated Turbulence System, and the Aitken nuclei concentration is determined with a G. E. particle counter. Turbulence measurements were not taken at Rancho Seco. These variables are recorded 2.4 times/sec on a Metrodata magnetic tape recorder.

Cloud droplet spectra are measured with a laser probe (ASSP-100) and data system (PDS-100) from Particle Measuring Systems and recorded four times/sec on a Kennedy incremental, magnetic tape recorder. This system with 0.25 sec averaging time is the most responsive aircraft instrumentation and the best, therefore, for defining the visible plume boundaries. Droplet numbers are accumulated in 15 equal-width intervals within each of four pre-selected ranges: 0.5-7.5, 1.0-15.0, 2.0-30.0, and 3.0-45.0 μm . Liquid water contents (LWC) are determined through integration of the droplet spectra.

Comparison of the temperature and droplet data has shown that the response of the temperature sensor is quite rapid. Recoveries of the turbulence and relative humidity sensors are both slower and quite similar. The turbulence sensor is known by its specifications to average over approximately 3 sec and a similar average can be assumed for the humidity sensor. Therefore, dewpoint derived from the temperature and relative humidity sensors would be expected to be somewhat low because of the longer-averaged humidity measurement.

The dewpoint sensor, however, demonstrated a lag of 2 sec for a given plume intercept. Furthermore, the dewpoint temperature of the plume derived from the temperature and relative humidity sensors was 14.4°C for the given intercept, whereas the maximum indication of the dewpoint sensor was only 12.0°C. Consequently, the dewpoint sensor is not considered reliable as utilized for in-plume measurement. For near-constant conditions in the ambient air, the dewpoint temperatures — measured and calculated — are in good agreement.

Rancho Seco field tests. Conditions during the three days at Rancho Seco, which had sufficiently long visible plumes for sampling, are shown in Fig. 2.3.1. Inversions are evident in the profiles of February 17 and 18. The visible plume penetrated the inversion on the 18th, but not on the 17th. Fair-weather cumulus clouds were scattered near 600 m msl on February 20, the day of least saturation deficit. Wind speeds were 2, 4, and 9 m/sec on the 17th, 18th, and 20th, respectively. Another important difference was that the power level on the 18th was 635 MWe, whereas it was 850 and 820 on the 17th and 20th. Consequently, heat rejection and vapor flux were each about 20% lower on the 18th.

Fig. 2.3.1. The vertical profiles of temperature and saturation deficit of the ambient atmospheres during the Rancho Seco tests.

It was noted previously that the visible plume penetrated the inversion on the 18th. Figure 2.3.2 shows that the droplet distributions are shifted to smaller diameters above the inversion base, near 800 m msl. This is shown particularly well by the normalized set of curves on the right and might be attributed to evaporation in the somewhat drier air above the inversion base. Although Fig. 2.3.2 shows an increase in LWC with height, other results suggest the relationship is coincidental since differences as large are observed at one level. Off-axis plume penetrations can account for the LWC variability.

With the assumption that there is no organized change in droplet size spectra over limited heights, plume penetrations over a range of heights were combined to yield the Fig. 2.3.3 spectra composites. The ordinate is the number of droplets in each size interval divided by the number in the interval centered at $6.5 \mu\text{m}$. The two lower curves are those observed below and above the inversion on February 18. Presumably, they are lower than those on the 17th and 20th because of the reduced moisture flux when the plant operated at reduced power.

Before examining several plume traverses in detail, Fig. 2.3.4 is presented to show the variability of ambient Aitken nuclei concentration both with time and height. The peak of the distribution on the 18th corresponds with a low wind speed layer immediately below the inversion base. Its characteristics are important in the interpretation of Aitken nuclei concentrations appearing during the plume traverses.

Figures 2.3.5, 2.3.6, and 2.3.7 are plume traverses at 458, 610, and 1068 m msl, respectively. The two traverses in opposite directions at each height show general agreement for each of the three variables, although there are differences in detail. Excesses in temperature and humidity within the plume decrease with height as would be expected for a plume undergoing dilution by ambient air. At 1068 m the plume temperature is lower than that of the ambient air, having cooled approximately dry adiabatically in a nearly isothermal environment. The derived plume mixing ratios show excesses above ambient of 2.0, 1.5, and 0.25 gm/kgm at 458, 610, and 1068 m msl, respectively. Droplet evaporation beneath the plume is suggested by the increased humidity in Fig. 2.3.5 and the increased humidity and decreased temperature in Fig. 2.3.6 downwind of the penetrations.

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Fig. 2.3.2. Liquid water distributions in the Rancho Seco plume at various altitudes for 2/18/75 A.M.

ORNL-DWG 76-19326

Fig. 2.3.3. The droplet spectra for the Rancho Seco plume at various reactor power levels, at various altitudes, and for various dates.

Fig. 2.3.4. Vertical profiles of Aitken nuclei and temperature for the various test runs at Rancho Seco.

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Fig. 2.3.5. Profiles of temperature, relative humidity, and nuclei concentration at Rancho Seco for an altitude of 458 m (msl) on 2/18/75 A.M.

ORNL-DWG 76-19329

Fig. 2.3.6. Profiles of temperature, relative humidity, and nuclei concentration for Rancho Seco for an altitude of 610 m (msl) on 2/18/75 A.M.

Fig. 2.3.7. Profiles of temperature, relative humidity, and nuclei concentration at Rancho Seco for an altitude of 1068 m (msl) on 2/18/75 A.M.

Figure 2.3.5 clearly shows a temperature drop immediately after leaving the plume for both flight directions. This is obviously an instrumental problem arising from a wet-bulb — or more properly, a "swamp cooler" — effect. The temperature sensor housing at the temperature of the ambient air acquires a film of water in the plume where the humidity relative to that temperature was at 90% saturation, according to the measurements. Upon reentering the ambient air at 60% relative humidity, temperature of the air cooled by evaporation of the water film is measured by the sensor.

The relationship of Aitken nuclei in the plume and ambient air at the three traverse heights differs substantially. At the lowest height the plume is undiscernible because concentrations in the plume and its environment are equal. The upwind, ambient air concentration is about four times larger at 610 m, while the in-plume concentration retains its previous value. Thus, the air beneath the plume, downwind of the penetration, shows the effect of dilution by the plume. Above the inversion, the upwind concentration is increased due to entrainment of high concentration ambient air from below. Beneath the plume at this height, a slight enrichment in Aitken nuclei is evident. It is apparent that cooling towers are effective in the vertical transport of pollutants.

Figures 2.3.5, 2.3.6, and 2.3.7 also appear to show a tower-generated circulation. This is evidenced best by the downwind peaks in Aitken nuclei at the two lower traverse heights. Particularly at 458 m, the peaks located 1 km downwind of the plume must be due to a downdraft of ambient air containing the higher concentration above. To a lesser degree, the downdraft is reflected in the accompanying temperature increase. The well-defined temperature increase downwind of the plume in one traverse at 1068 m also can be attributed to downdraft.

Growth of the plume due to entrainment of ambient air can be estimated from these airborne measurements. Figure 2.3.8 demonstrates how mixing ratio data were used for such an estimate. The ratios of excess mixing ratio values at the tower exit to maximum excess mixing ratio values at various sampling heights, designated the dilutions, are plotted against the normalized heights, thereby determining the relationship

Fig. 2.3.8. A plot of a normalized dilution vs a normalized height for the Rancho Seco tests.

$$D = 1 + 1.56 H^{1.32} \quad (1)$$

where

$$H = \frac{z - z_o}{2R_o} \frac{U_o}{W_o} \quad (2)$$

$$D = \frac{(MR)_{Eo} - (MR)_o}{(MR)_{EZ} - (MR)_z} \quad (3)$$

and $z - z_o$ is the height above tower exit

R_o is the tower exit radius

U_o is the wind speed at exit height

W_o is the efflux velocity.

Subscripts Eo and EZ identify the plume mixing ratios at the exit and at other heights, respectively, whereas the single subscripted mixing ratios refer to ambient conditions.

For comparison of Eq. (1) with other results, the entrainment parameter α was calculated using Wigley's relationship,¹

$$\frac{VK^2}{W_o R_o^2} = [1 + (\alpha z/R_o)(U/W_o)^{1/2}]^2 \quad (4)$$

and assuming that $D = VK^2/W_o R_o^2$ and $U_o = U$. In this manner the value of α was calculated to be 0.32. Most quoted values are in the range 0.3-0.5.^{2,3}

Time-exposure plume photography presents another means for estimating plume dilution. Figure 2.3.9 shows a measurement grid overlying a 5-min time-exposure of the Rancho Seco plume. Details of the plume photo measurements technique are given elsewhere.⁴ The resultant measurements were plotted as shown by the heavy lines of Fig. 2.3.10 and those, in turn,

¹T. M. L. Wigley, J. Appl. Meteor., 14, 1975, pp. 78-86.

²S. R. Hanna, J. Appl. Meteor., 11, 1972, pp. 793-799.

³T. M. L. Wigley and P. R. Slawson, Atmos. Environ., 9, 1975, pp. 437-445.

⁴J. M. Thorp, PNL Annual Report for 1975 to the USERDA, BNWL-2000 PT 3, 1976, pp. 272-280.

PHOTO 5207-76

Fig. 2.3.9. A camera site and the photo interpretation grid used to analyze the Rancho Secc plumes.

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Fig. 2.3.10. Schematic of the technique used to obtain plume dilution from ground-based photography.

approximated by the broken lines to represent the plume as an isosceles triangle whose base is normal to the plume axis at the furthestmost distance of plume definition. Dilution is taken to be the square of the ratio of plume diameter to the cooling tower diameter. The value of α , so calculated, is 0.38.

Trojan and Centralia field tests. The Trojan and Centralia cooling tower plumes were penetrated on May 13, during a 3-hr period in the morning. Figure 2.3.11 indicates that conditions were quite similar at the two sites below approximately 500 m msl, which was the inversion base at Trojan. The inversion base at Centralia was approximately 100 m higher when sampling was performed there.

Figure 2.3.12 indicates the ability of Range 3 on the cloud droplet spectrometer to represent the cooling tower plume droplet size spectra. Although it less faithfully measures smaller droplets than Range 4 and larger drops than Ranges 1 and 2, it does satisfactorily represent the spectra. Consequently, the spectra can be determined with fewer traverses by operating the spectrometer on Range 3 alone.

Figures 2.3.13 and 2.3.14 compare Trojan and Centralia droplet spectra at several heights. Differences with height and between the natural draft and mechanical draft towers are seen to be slight during this day of operation. At this point in the analysis, it appears that the droplet spectra characteristics of peak and width do not vary greatly between the three sites.

Table 2.3.1 summarizes the temperature, humidity, and turbulence data from the Trojan and Centralia sites. The elevations shown are with respect to mean sea level. Exit height at Trojan is at 168 m msl, while it is 92 m msl at Centralia.

The last three columns concern the determination of relative humidity from the Cambridge dewpoint hygrometer and the temperature sensor for comparison with the relative humidity measured by the carbon-strip humistor. In the plume, saturation mixing ratio is calculated using the peak temperature, and mixing ratio is calculated from the peak dewpoint temperature although, as discussed earlier, it lags by a couple of seconds. Measurements for the ambient air were taken simultaneously for the two instruments 20 sec before the plume centerline as indicated by the temperature sensor.

Fig. 2.3.11. Ambient temperature soundings at the Centralia and Trojan Power Plants on 5/13/76.

Fig. 2.3.12. Droplet distributions in the Centralia plumes on 5/13/76 at an altitude of 800 ft (msl).

Fig. 2.3.13. Droplet distributions in the Centralia plumes on 5/13/76 at various altitudes.

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Fig. 2.3.14. Droplet distributions in the Trojan plume on 5/13/76 at various altitudes.

Table 2.3.1. Field data from the Trojan and Centralia sites

Centralia 5-13-76							
<u>Ambient</u>	T	Td	RH	TURB	MR	SMR	RH
1600 ft	10.0	6.4	81	56	6.4	8.2	78
800 ft	11.6	8.5	82	174	7.2	8.8	82
<u>Plume</u>							
1600 ft	10.8	9.9	93	520	8.0	8.6	93
800 ft	14.4	12.0	100	523	9.0	10.6	85
Trojan 5-13-76							
<u>Ambient</u>							
1800 ft	10.8	8.0	82	132	7.2	8.7	83
1600 ft	10.2	7.6	82	125	7.0	8.2	85
1400 ft	10.6	7.2	81	122	6.7	8.4	80
1000 ft	11.4	8.5	82	284	7.3	8.8	83
<u>Plume</u>							
1800 ft	10.5	10.3	86	331	8.4	8.6	98
1600 ft	10.2	10.2	95	297	8.2	8.2	100
1400 ft	12.0	11.6	~100	543	9.0	9.3	97
1000 ft	14.6	12.5	~100	732	9.3	10.8	86

Both in the ambient air and in the plume, and especially the latter, the dewpoint derived relative humidity is observed to be quite erratic.

Plume turbulence is observed to be a good indicator of the plume. At the higher sampling levels where differences in humidity and temperature between the plume and its environment are small, there remains a large difference in the levels of turbulence.

The future. The analysis is continuing with the expectation that the Rancho Seco data will be fully tabulated by October 1976. An effort will be made in the same time period to ascertain instrument response times and, if possible, to make them more responsive.

2.3.1.2 Environmental Impact

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Introduction

In September 1974, a comprehensive series of detailed airborne meteorological, aerosol and air chemistry measurements in cooling tower and merged cooling tower-stack plumes were begun by scientists in the Department of Meteorology at Penn State University. Because of its proximity (at least by air) to the university and the outstanding cooperation of the plant's management, who had earlier also aided the LAPPES (Large Power Plant Efficiency Study) program, the Keystone Power Plant near Indiana, Pennsylvania, was chosen for study. To date the 35 research flights completed have produced unique measurements of the following types:

1. Penetrations of the visible plumes from as close as ≈ 35 m from the tower mouth to in excess of 24 km downwind including recording of turbulent temperature and velocity fluctuations to a spatial resolution of less than 2.5 m.
2. Samples of drift water (using an isokinetic impactor for droplets $>50 \mu$ which was developed specifically for this project) in the visible plumes from as close as ≈ 35 m from the tower mouth to distances of ≈ 500 m downwind.
3. Measurements of cloud condensation nuclei and aerosol in five size ranges from 0.5 to $\approx 8 \mu$ up and downwind, and within the stack and merged plumes from the plant.
4. Hydrometer samples in the "convecting" and dissipating portions of visible plumes.
5. Preliminary measurements of pH in the cooling tower, stack and merged plumes and pH as a function of aerosol size.
6. With the recent, March 1976, addition (with ERDA funds) of an SO_2 analyzer to the aircraft instrument package, a series of SO_2 , SO_x and sulfate measurements in the stack and merged plumes has also been started.

In addition to the airborne studies, the ERDA "plumes" project also includes indirect sounding of turbulent temperature and velocity fluctuations on a continuous basis using a sophisticated Doppler sodar system. To our knowledge the PSU Doppler sodar, development costs for which were shared by EPA and ERDA, is the most sophisticated university-developed sounder in the world and one of only four or five Doppler units in existence.

In order to aid in the design of field experiments and to provide data analysis guidance, the project also includes a numerical modeling effort. The focus of this effort to date has been to mesh an "adequate" plume model with an atmospheric background model in order to simulate interaction between the plume and its immediate environment.

Airborne Measurements

Turbulent temperature and velocity fluctuations. More than 100 plume penetrations at distances from the tower ranging from ≈ 35 m to more than 24 km have been completed. From the turbulence measurements the temperature and velocity distributions across each plume are first computed. Measured distributions suggest that with few exceptions convection and entrainment are rapidly occurring on all scales up to at least half the plume diameter.

From as many penetrations as possible the dependence of mean plume atmosphere temperature difference ΔT as a function of range along the plume is compiled. Figure 2.3.15 shows one such plot. The mean temperature difference is of limited utility as a predictor of plume behavior. This is simple because the mean temperature difference at the tower mouth is much more spatially and temporally variable than has normally been assumed. Particularly for estimates of turbulent energy fluxes, much better measurements than now exist of temperature and velocity fluctuations at a tower mouth are required. At the Keystone plant our closest airborne penetrations have been made at approximately one mouth diameter from the mouth. Even at this close range sufficient mixing with the environment has occurred so that it has not been possible to obtain a good sample of the unmodified plume characteristics.

The ΔT versus range plots do suggest that "overshoot" is a persistent feature and that plume trajectories might be well approximated by "critically damped" solutions to an ordinary second order differential equation.

For each penetration frequency distributions of the instantaneous plume-mean atmospheric temperature differences are also computed. Individual frequency distributions and the distributions mapped as a function of range along the plume (Fig. 2.3.16)) show:

Fig. 2.3.15. Composite diagram of measured mean plume-atmosphere temperature differences as a function of range along the plumes derived from penetrations on flights AEC 2, 3, 4, 6, and 8.

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Fig. 2.3.16. Example of a "3-d" map of instantaneous plume-mean atmospheric temperature distributions positioned as a function of range along the plume axis. Width of widest distribution is $\approx 10^{\circ}\text{C}$. Flight AEC-3, January 24, 1975.

1. The relative insensitivity and large variation of the mean plume atmosphere temperature difference.

2. That the variance, or even better that the skewness and kurtosis of the distribution are sensitive measures of convection and entrainment (or the lack thereof).

3. That dissipation of the plume once convection has ceased will occur in accordance with local "passive contaminant" diffusion processes.

In order to ascertain the statistical stability of individual temperature distribution functions we have repeatedly penetrated the plume at essentially the same location. Figure 2.3.17 shows the results of such a series. Six to eight penetrations are sufficient to produce good estimates of the heat flux (discussed in the following section). The composite distribution is well approximated by a "top hat" function.

Comparison of measured plume vertical sensible heat fluxes with cooling tower outputs. The vertical heat flux is one of the primary inputs to any model used to predict plume characteristics. In general, plume rise models assume that this heat flux is constant with height, at least in the early stages of plume rise. Since this heat flux can be extracted from our turbulent temperature and velocity measurements it is possible, in principle, for us to test this constant-flux hypothesis. Heat flux results also provide a check on the aircraft turbulence measurements by enabling a comparison with the cooling tower sensible heat output. Temporal changes in the plume can make interpretation difficult and thus several penetrations through the plume at a given height so as to obtain reasonable spatial sampling are required.

The actual sensible heat flux emanating from a cooling tower is considerably more difficult to obtain because circulating water flow and make-up water are not monitored. With the assistance of personnel at the Keystone plant we have devised a method for obtaining heat and water vapor flux estimates from the cooling towers.

Results to date demonstrate that the aircraft instrumentation is capable of measuring vertical sensible heat fluxes that compare favorably with estimates from the cooling towers.

Airborne drift water measurements. Drift water measurements have been made on eight flights during the past year. In the portion of the

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Fig. 2.3.17. Example of a "3-d" map of instantaneous plume-mean atmospheric temperature distributions for repeated penetrations through the plume at the same range over a 40-min period. Width of distributions is $\approx 14^{\circ}\text{C}$. Flight ERDA 2-6, March 2, 1976.

plume containing drift water the plume dimensions are such that typically only two to five seconds of data are acquired during a single penetration. In order to obtain a sufficiently large sample, about eight penetrations at the same location are required to generate one size distribution function.

Figure 2.3.18 summarizes four drift water samples obtained on different flights. The large median and mode diameters surprised us for they greatly exceeded present drift eliminator standards. At the earliest opportunity we made a visual inspection of the eliminators in the Keystone towers - all were intact. While new towers may have somewhat more efficient eliminators, we believe that environmentally influenced highly irregular air flow rates may be contributing to the ejection of the large drops. We see no way in which the observed drops may be produced outside the tower by, for example, known coalescence mechanisms.

The drift water measurements obtained to date are now being used in the Hosler et al. ballistic trajectory model to estimate surface deposition rates.

Aerosol and air chemistry studies. About a third of the airborne measurements have been conducted specifically to study the consequences on the aerosol population of the merging of the stack and cooling tower plumes. In order to obtain background information about the characteristics of the aerosol population of both plumes we have measured in them both the concentration of condensation nuclei (Aitken) and the size distribution of large particles. The measurements of condensation nuclei ($d \geq 0.0025 \mu\text{m}$) have been made with a RICH 100 Condensation Nucleus Counter and those of large particles ($d \geq 0.5 \mu\text{m}$) with a Royco 225 sizing optical particle counter which has been modified in-house for aircraft use.

Cooling tower plume studies. Aerosol measurements to date have established that

1. Inside the plume the number concentration of aerosol particles is larger.
2. An inverse correlation exists between the increase in large particles and condensation nuclei.

Fig. 2.3.18. Summary of airborne drift water samples obtained on flights AEC 8 and 9, ERDA 2-2 and 2-3.

Stack plume studies. Atmospheric particulate and SO₂ concentration upwind and downwind of the Keystone Power Plant were monitored and readings of sulfur dioxide were taken with a Thermo Electron SO₂ monitor. Results indicate that the power plant acts as both a direct and indirect source of aerosol particles within the size range of 0.0025 to 0.5 μ m. Continuous increases in particle concentration downwind of the stacks suggest that the production of new particles by atmospheric chemical reactions, possibly involving the oxidation of SO₂, is possible. Particle generating reactions can overwhelm the dilution effects of atmospheric diffusion at least to distances up to 11 miles downwind of the plant.

Figure 2.3.19 is an example of a plot of simultaneous measurements of SO₂ and particle concentration recorded during flight ERDA 2-17. The non-correspondence of the peaks was a general feature for this entire flight. Some displacement of the peak is expected due to the different time response of the two instruments. However, the differences observed do not correspond to our best estimates of the differences in response time suggesting that the relationship between SO₂ concentration and particle concentration is of a more complex nature.

Indirect Measurements of Turbulent Temperature and Velocity Fluctuations with Doppler Sodar

During the past nine months the highly sophisticated Doppler sodar system which has been developed at Penn State for cooling tower plume and planetary boundary measurements (Sodar Research is partially supported by EPA Grant R800397) has been undergoing extensive field testing and evaluation. This work has resulted in both hardware and software modifications which have significantly improved system performance.

For comparative purposes the specifications of the sodar with respect to the only commercially available acoustic radar are listed below.

	<u>Commercial System</u>	<u>PSU Sodar</u>
Frequency	1600 Hz	1000 Hz
Pulse repetition frequency	9 or 18 sec	Selectable, optimized for variable bistatic geometry
Pulse duration	50, 100, 200 msec	Selectable, optimized for range gating and width of transmitted spectrum

Fig. 2.3.19. Example time series of SO₂ concentration and condensation (Aitken) nuclei showing reduced condensation nuclei concentration in region of maximum SO₂ concentration.

	<u>Commercial System</u>	<u>PSU Sodar</u>
Transmitted (Electric) Power	100 watts	120 watts
Antenna(s)	1.33 m	1.52 m
Antenna positioning	Stationary	Steerable azimuth and elevation
Receiver bandwidth	20, 40, 80 Hz	10, 30, 100 Hz and variable digital
Gain compensation	1/r analog	1/r analog and variable digital for bistatic geometry
Recording:		
Visual	Facsimile recorded	Storage scope and automatic camera for vertical time section
Digital		On line Nove 2/10 computer for quantitative Doppler and amplitude data
Range:	Normal 350-500 m Maximum <1 km	Normal $\approx$ 1 km Maximum $\approx$ 1.7 km

In order to estimate the magnitude of plume-scattered acoustic signals received with the monostatic and bistatic systems computer programs have been written which include all relevant system parameters and can predict received signal strength for arbitrary vertical profiles of acoustic extinction (relative humidity and temperature dependent) and angle dependent scattering across section (turbulent temperature and velocity fluctuation dependent).

C_T^2 and C_V^2 values have been estimated for aircraft penetrations made during five flights. The values obtained $\approx$ 1.5 km downwind ranged from 10^{-4} to 10^{-1} with values within the plume in general 2 to 10 times the values outside the plume. The difference was particularly large for passes through the lower portions of the plume where values using a 10 point average of as high as 5×10^{-2} were observed. In general, within the plume, values ranged from 5×10^{-4} to 1×10^{-2} . These values are in general agreement with Neff.¹

¹ W. D. Neff, Quantitative Evaluation of Acoustic Echoes from the Planetary Boundary Layer, U. S. Dept. of Commerce, NOAA Environmental Research Laboratories Technical Report, Boulder, Co, 34 pp (1975).

The sodar field program is scheduled for late summer - early fall 1976.

Numerical Modeling of Plume-Atmosphere Interactions

All currently available plume models consider only the effects of atmospheric conditions on plume behavior and plume properties, but, with the possible exception of Calabrese et al.² no feedback from plume to atmosphere is considered. Calabrese et al. allow for dispersed plume quantities to be added to the ambient properties but do not discuss their effects on the ambient properties. In the long run if one is to determine the impact of the cooling tower plumes on the environment feedback processes must be investigated with an interactive plume-atmosphere model.

The goal for the current year was to develop a meshed system of a suitable vapor plume model and a small scale atmospheric dynamic model to study the mutual plume-environment interactions. For our purposes, one component of the meshed system, the atmospheric model, was already available. Suitable plume models considered appropriate for adaptation were those of Weil³ and Wigley and Slawson.⁴ We composited a model based on both Weil and Wigley and Slawson in which we retained both latent and condensation heating within the plume, and the effects of atmospheric latent heat. However, we did exclude the effects of atmospheric liquid water.

Prior to incorporation into the atmospheric model, the composite model was tested for its sensitivity to varying atmospheric conditions, and to compare its performance to the parent and other models. Model results have also been compared with available observations. Tests were conducted with the model in its Lagrangian puff form instead of converting it to a grid point version because of the greater computational efficiency.

²R. V. Calabrese, J. Halitsky, and K. Woodward, Prediction of temperature and moisture distribution in cooling tower plumes, Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, September 9-13, AMS Preprint Volume, 400-407 (1974).

³J. C. Weil, The Rise of Moist, Buoyant Plumes, J. Appl. Meteor., 13, 434-443 (1974).

⁴T. M. L. Wigley and P. R. Slawson, The Effect of Atmospheric Conditions on the Length of Visible Cooling Tower Plumes, Atmos. Environ., 9, 437-443 (1975).

Sensitivity tests were conducted to examine the effects of entrainment parameters, atmospheric stability, and relative humidity on plume size and shape, and other characteristics. A major departure in these tests from previous studies was the attempt to control the shape of the plume as a function of stability by relaxing the assumption of circular symmetry along the entire length of the plume. For example, under neutral conditions, circular symmetry is maintained for the entire plume length but for isothermal and more stable environmental lapse rates, circular symmetry is maintained only to the top of the first maximum rise. Then the plume is assumed to be elliptical and grows only in the horizontal cross-plume direction, i.e., the vertical dimension remains constant beyond the point of first maximum rise. Under neutral conditions the entrainment velocity is parameterized as a constant fraction of the plume vertical velocity (As a consequence of our turbulent temperature and velocity measurements we are now attempting to improve on our parameterization of the velocity term.) during the initial phase when plume turbulence is the dominant entrainment mechanism, then in terms of the eddy dissipation when the latter becomes dominant. Under stable conditions plume turbulence is assumed dominant up to the first maximum rise, then a stability dependent, exponentially decaying entrainment velocity is adopted. The sensitivity of model plume length to varying relative humidity conditions under different stabilities provided a useful basis for evaluating model performance by a comparison of results with other studies.

Figure 2.3.20 shows that for the chosen values of wind speed and environment temperature, visible plume length is almost independent of humidity and stability changes up to a critical value of relative humidity (~84% in this case when plume length dramatically increases in an almost discontinuous manner). The magnitude of the increase is inversely proportional to the stability. Figure 2.3.21 shows the effect of varying stack radii and initial entrainment factors. The ratio of stack radius to entrainment factor is a combined measure of the rate of output of vapor and the change in buoyancy. A large ratio corresponds to large output or small buoyancy decay rate or both. Curve 3 in Fig. 2.3.21 is the same as curve 3 in Fig. 2.2.20, and is included as a reference. The ratios are the same for curves 3 and 4 in Fig. 2.3.20

Fig. 2.3.20. Visible plume length as a function of relative humidity and stability. DTDZ in units of degrees C/m.

derived from different combinations of stack radii and entrainment factors. The agreement between the two curves is generally good with only slight deviations at very high relative humidities and plume lengths in excess of the critical length separating short from long plumes. Curves 1 and 2 of Fig. 2.3.21 represent increased stack outputs and/or decreased buoyancy decay rates, and show that under these conditions the critical humidity separating short from long plumes decreases although the critical length of the short plumes is essentially unchanged. Figure 2.3.22 shows the effect of changing the environmental temperature keeping the stability, wind speed, and ratio of stack radius to entrainment factor fixed. The curve for $\Delta T = 20^\circ$ corresponds to curves 3 of Figs. 2.3.20 and 2.3.21. The critical relative humidity increases in a warm environment and decreases in a cold environment, with a more drastic change from short to long plume in warm air than in cold air. The critical length of the short plume increases almost linearly with decreasing humidity from the warm to cold environment.

The results imply that cooling tower plumes exist predominantly as short or long plumes with few of intermediate length, and these are more likely to exist in cold, less moist environments.

Specific Recommendations for Continuing and New Research

<u>Topic</u>	<u>Priority</u>	<u>Level of Effort</u>	<u>Required Time to Completion</u>
Measurement and analysis of plume relative humidities and tower latent heat flux	1	Ph.D. dissertation	2-3 yr
Verification of aerosol production and SO_x transformation model(s)	1	Ph.D. dissertation	1-2 yr
Sodar measurement range dependent plume entrainment coefficient	1	Post-doctoral	1-2 yr
Further development of numerical model	1	M.S. - Ph.D.	1 1/2-3 yr
Improvements to cooling tower monitor instrumentation	2	M.S.	1-2 yr
Modification of solar and IR radiative transfer near plumes	2	M.S.	2 yr

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Fig. 2.3.21. Visible plume length as a function of relative humidity, stack radius (mm) and entrainment parameter.

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Fig. 2.3.22. Visible plume length as a function of relative humidity and the mean plume-atmosphere temperature difference.

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Fig. 2.3.23. A map of the Dresden, Illinois, cooling pond complex of the Commonwealth Edison Company, showing the locations of the lift pump (S) through which heated water enters the first sub-pond and of the fixed tower (T) used for eddy-correlation measurements during 1974 and 1975.

<u>Topic</u>	<u>Priority</u>	<u>Level of Effort</u>	<u>Required Time to Completion</u>
Preliminary study of pathogen measurement and transport	3	M.S.	1-2 yr
Development of state-of-the- art airborne system for ERDA or AENEC plume programs	?	Post-doctoral & technical programming	2 yr
Modification of local Precip- itation, W _x and Climatology	?	Ph.D. and Post- Doctoral	5+ yr
Heavy Metal Transport and Chemistry	?	Ph.D.	2-3 yr

2.3.2 Cooling Pond Surface Heat Exchange
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Introduction

The use of both natural and man-made ponds to dissipate the waste heat accompanying industrial power generation is quite common, although the newest facilities in the United States usually make use of other types of cooling systems, often involving cooling towers. This trend away from the use of cooling ponds is partially a result of recently imposed regulations concerning the environmental impact of waste heat disposal systems on nearby natural water bodies. However, the choice that results in the minimum effect on the total local environment or in the least economic impact in the surrounding area is not always obvious if atmospheric effects are considered.

In the context of large energy centers, cooling ponds offer advantages that cannot be dismissed lightly. A cooling pond represents a more diffuse source of heat and water vapor than does a cooling tower, and thus is less likely to trigger meso-scale atmospheric phenomena such as cloud formation, precipitation, and vorticity enhancement. Moreover, large cooling ponds offer a site of temporary heat storage which might be of some benefit when atmospheric conditions do not allow efficient operation of some of the alternative cooling systems. In any case, the primary factor concerning the use of cooling ponds in large energy centers is the vertical flux of latent and sensible heat to the atmosphere, since it is these fluxes which (1) determine the operational efficiency of the heat dissipation system, (2) control the pond water temperature to which biological systems are exposed, and (3) trigger conditional instability and its related meso- and synoptic-scale effects in some (largely unknown) circumstances, and (4) govern the formation of steam fog.

Work at Argonne National Laboratory has concentrated on the parameterization of the processes of heat transfer between hot water surfaces and the air, with the main aim of developing accurate procedures for the prediction and assessment of the rates of heat and moisture injection into the air from industrial cooling ponds.

Methods which attempt to determine the effect of cooling ponds upon the atmospheric environment often deny one of the most striking and

characteristic features of such ponds, namely that the relatively large water surface is usually at a considerable temperature excess above the air. At times, surface temperatures can be more than 20°C greater than the air. This phenomenon produces strong buoyant motions in the air as it passes over a cooling pond, and coupling between the air and the water surface is correspondingly more efficient than in the case of natural, unheated water bodies. The rates of sensible and latent heat transfer are very high, often more than an order of magnitude greater than those found in natural circumstances.

The generation of steam fog over the surface of a cooling pond is a well-known feature that has been the subject of a number of studies. Many such investigations have recognized the importance of the surface fluxes, but almost none have utilized parameterizations of these fluxes which are compatible with modern micrometeorological theory. The same criticism can be made of most studies of cooling pond performance. Thus, the major aim of the ANL program investigating cooling pond behavior, in its early years, has been to apply current micrometeorological techniques to the special case of an industrial cooling pond, in order to develop and verify accurate formulations for the surface fluxes of heat and water vapor. Modeling of the thermal performance of cooling ponds has been undertaken, and measurements of the plume from a cooling pond are planned.

All of the studies performed to date by the ANL research team have taken place at the Dresden, Illinois, cooling lake of the Commonwealth Edison Company. This lake, illustrated in Fig. 2.3.23, is divided into five ponds of which the first has received the most attention. Surface temperatures in pond No. 1 often exceed 40°C in summer.

The "Standard" Experimental Determinations of Fluxes

A number of micrometeorological techniques have been employed in studies at Dresden. The emphasis has been given to the direct measurement of the fluxes of momentum and sensible and latent heats. A range of rapid-response sensors capable of providing linear analog signals

were developed and are listed in Table 2.3.2. These sensors were employed in conjunction with eddy-correlation equipment, for which purposes a fixed tower was centrally located in pond No. 1. The eddy-correlation method of flux measurement is well known as a technique that is both accurate and direct. It suffices to describe the method in the case of evaporation; the vertical turbulent flux of water vapor is evaluated as the time averaged product of the vertical velocity component and the concentration of water vapor in air. The method produces accurate values provided the sensors and the experimental arrangement meet critical, but well documented, specifications.

Other than the obvious requirement for rapidly responding sensors, the most critical consideration in eddy-correlation applications concerns the role of the upwind (uniform) fetch. The method gives determinations of the local flux at a point in space, but caution must be exercised to ensure that this flux is the same as that at the underlying surface. For this reason, all measurements that are intended to relate to the water surface should be made within the constant flux boundary layer; this layer is generated slowly as air passes across a new surface and is typically of depth about 0.2-1.0% of the fetch. Therefore, it is completely inappropriate to obtain measurements above the bank of a cooling lake (for example) in order to estimate fluxes from the water surface.

Significant Accomplishments of the Dresden Field Program

During the first field season (summer and autumn, 1973), the rate of growth of the internal boundary layer over pond No. 1 was investigated, and errors likely to result from the inappropriate location of instruments were evaluated. Preliminary tests were made (in surface temperatures of up to 42°C) of parameterizations based on recent micrometeorological experience over the sea and large inland lakes. Also, tests were made of optical line-of-sight methods for determining spatially averaged surface fluxes of sensible and latent heats.

Not surprisingly, analysis of the data obtained during 1973 pointed to the requirement for direct determinations of the surface fluxes.

Table 2.3.2 Fast-response sensors developed for use in eddy-correlation evaluations of surface fluxes at Dresden

Sensor description	Frequency response	Height of operation	Field use periods
Yaw-sphere anemometer	0.4 Hz	1 m	1975
Fine-wire thermometer	8 Hz	1 m	1975
Hot-wire anemometers	10 kHz	50 cm	1975/6
Lyman-alpha hygrometer, modified,	40 Hz	50 cm	1976
and coupled fine-wire thermometer	2 kHz	50 cm	1976

Consequently, a major effort was made to deploy eddy-correlation equipment during the following year. The measurements of sensible heat flux and surface stress that were obtained (eddy fluxes of moisture were not measured in this first year of covariance studies) verified the general form of the relationships derived as a result of air-sea interaction studies, and in fact were of sufficient quality to permit a "tuning" of the surface roughness parameterization; the surface roughness at Dresden was found to be about half that of open ocean at the same wind speed. The verified "Low-Level Bulk Aerodynamic" (LLBA) formulations have been used in subsequent studies of, for example, the role of surface thermal skins overlying cooling ponds, the feasibility of optical line-of-sight assessment techniques, and the relevance of different engineering approaches for characterizing the heat dissipation rates from cooling ponds.

During 1975 further measurements of the eddy fluxes of sensible heat and momentum, together with covariance measurements of the evaporation rate, were made. This new body of eddy flux data has been used to confirm the findings of the previous year, particularly in regard to the previously unproven formulae concerning the latent heat flux.

Numerical models of cooling ponds have been developed and are presently being tested. These models are intended to keep track of the surface temperature and surface fluxes, as functions of space, time, plant output, meteorological conditions, etc. These models are intended to serve the dual purpose of (1) describing the performance characteristics in a manner suitable for use in adjusting plant operations and (2) providing accurate determinations of the moisture and heat inputs to the atmosphere, for use in effects evaluations.

Table 2.3.3 presents a list of publications and reports which have resulted from the field program at Dresden.

Outline of Future Research

The formulations of surface fluxes that have been developed at Dresden have now been verified using direct measurements, and the program

is approaching the stage of considering the observation, description, and parameterization of atmospheric effects. First, however, it is necessary to test the results of the Dresden field program at a variety of locations. In particular, the capability to predict the surface temperature of and heat fluxes from proposed cooling pond installations should be tested.

It is proposed, further, to conduct a series of feasibility studies of different methods for identifying and monitoring the plume downwind of existing cooling ponds. The experiments, which are intended to employ both in situ and remote-proving methods, will link the existing parameterization procedures which describe the thermal performance characteristics of heated water surfaces with numerical simulations of plume dispersion downwind of the pond complex.

Table 2.3.3 Reports and publications derived from the Dresden cooling pond field program

1. ANL Reports

- Hicks, B. B., M. L. Wesely, and R. L. Hart, Field Studies at the Dresden Cooling Pond; An Introduction, Argonne National Laboratory, Radiological and Environmental Research Division Annual Report, ANL-8060, Part IV, January-December 1973, 1-7 (1974).
- Hicks, B. B., Low-Level Bulk Aerodynamic Measurements Over a Cooling Pond, ibid., 8-25 (1974).
- Wesely, M. L., Line-Average Thermal Exchanges Measured Above a Cooling Pond Using an Optical Technique, ibid., 26-41 (1974).
- Hicks, B. B., On the Stability Dependency of Atmospheric Dispersive Properties Near the Surface, ibid., 55-67 (1974).
- Hicks, B. B., The Dependence of Bulk Transfer Coefficients Upon Prevailing Meteorological Conditions, ibid., 42-54 (1974).
- Hicks, B. B., Cooling-Pond Studies at Dresden: An Introduction, Argonne National Laboratory, Radiological and Environmental Research Division Annual Report, ANL-75-3, Part IV, January-December 1974, 1-3 (1975).
- Hicks, B. B., M. L. Wesely, and C. M. Sheih, Eddy-Correlation Measurements Over a Cooling Pond with Limited Fetch, ibid., 4-18 (1975).
- Hicks, B. B. and M. L. Wesely, Some Errors that Can Result from the Use of Industrial Techniques for Assessing the Thermal Performance of Cooling Ponds, ibid., 19-28 (1975).
- Wesely, M. L. and Z. I. Derzko, Atmospheric Turbulence Parameters from Visual Resolution, ibid., 29-32 (1975).
- Wesely, M. L., Line Averages of Thermal Exchanges Above a Cooling Pond Using Observations of Masking by Mirages, ibid., 33-41 (1975).
- Hicks, B. B., On the Limiting Surface Temperature of Cooling Ponds, ibid., 42-53 (1975).
- Sheih, C. M. and R. C. Lipschutz, Hot-Wire Anemometry Equipment for Short-Fetch Covariance Applications, ibid., 151-159 (1975).
- Hicks, B. B., M. L. Wesely, and C. M. Sheih, Eddy-Flux Measurements at the Dresden Cooling Pond, Argonne National Laboratory, Radiological and Environmental Research Division Annual Report, ANL-75-60, Part IV, January-December 1975, in press.

Table 2.3.3 Reports and publications derived from the Dresden cooling pond field program (Continued)

Wesely, M. L., B. B. Hicks, and G. D. Hess, A Preliminary Study of the Relationship between Surface Temperatures at the Dresden Cooling Pond, ibid.

Hicks, B. B. and M. L. Wesely, An Examination of Some Bulk Formulae Used for Assessing the Performance of Industrial Cooling Ponds, ibid.

Hicks, B. B., M. L. Wesely, and J. Wilczek, Preliminary Tests of a Model of Cooling-Pond Thermal Performance, ibid.

2. External Publications

Hicks, B. B., On the Limiting Surface Temperature of Exposed Water Bodies, J. Geophys. Res., 80, 5077-5081 (1975).

Hicks, B. B., A Procedure for the Formulation of Bulk Transfer Coefficients Over Water, Boundary-Layer Meteorol., 8, 515-524 (1975).

Wesely, M. L., and Z. I. Derzko, Atmospheric Turbulence Parameters from Visual Resolution, Appl. Optics, 14, 847-853 (1975).

Wesely, M. L., A Comparison of Two Optical Methods for Measuring Line Averages of Thermal Exchanges Above Warm Water Surfaces, J. Appl. Meteorol., in press.

WORKSHOP I SUMMARY

PLUME MODELING--FIELD DATA INTERACTIONS

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July 1976

ATMOSPHERIC EFFECTS OF NUCLEAR ENERGY CENTERS PROGRAM

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
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U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

WORKSHOP I SUMMARY
PLUME MODELING — FIELD DATA INTERACTIONS

prepared by
Steven R. Hanna

One of the functions of the Steering Committee for the Energy Research and Development Administration program entitled "Atmospheric Effects of Nuclear Energy Centers (AENEC)" is sponsorship of workshops on topics that fall within the responsibilities of the program. The first of these workshops, on "Plume Modeling — Field Data Interactions," was held in Oak Ridge on June 16-18, 1976. Of the 31 scientists who attended the workshop, ten were from ERDA national laboratories, seven were from universities, six were from consultant groups, and eight were from other government agencies. Most of the community of persons who model and measure cooling tower plumes were in attendance. Because this group had never before met together, there was much lively discussion and many minor disagreements. Fortunately, after discussing these problems for two and a half days, the group was able to reach a consensus on most subjects.

There were four scheduled presentations: two on modeling by S. Hanna (ATDL) and R. Drake (PNL) and two on observation programs by M. Wolf (PNL) and D. Thomson (PSU). In addition, most of the attendees gave short informal presentations on their current programs. These presentations can be summarized as follows:

I. Modeling

1. S. Hanna (ATDL) is applying a one-dimensional (1D) plume and cloud growth model to observations from the Amos and Rancho Seco power plants and a St. Louis refinery. He finds that cloud development can be roughly predicted but is sensitive to atmospheric temperature and humidity profiles.

2. R. Drake (PNL) is running a 2D slab model of deep convection using typical nuclear energy center (NEC) latent energy inputs. When a large natural storm already exists, the NEC causes only a 10% increase in such quantities as rainfall and vertical velocity.

3. L. Winiarski (EPA) discussed his basic studies of the entrainment process.

4. J. Lee (PSU) has a model for plume development which gives the result that a critical relative humidity exists for determining plume length at any given temperature and cooling tower output.

5. W. Cotton (CSU) discussed 3D simulations of convection, showing that, even for a 2km cubic domain, the computer limits resolution to 100m. A one-hour simulation takes ten hours of CDC 7600 time. He feels that mesoscale systems, such as sea breezes and orographic convergence, strongly determine the position of convective storms.

6. H. Fuch (Motor-Columbus) outlined his plume model, which adjusts the entrainment coefficient to account for aerodynamic effects near the towers.

7. T. Overcamp (Clemson University) has a drift deposition model which shows that a simple trajectory model gives nearly the same results for salt deposition as the Gaussian diffusion model.

8. F. Murray (Rand) feels that axisymmetric models, which are best for studying single clouds, will not be useful for NEC's, where there may be multiple clouds. The individual sources cannot be resolved in a large 2D or 3D model.

9. H. Orville (S. Dakota Sch. Mines and Tech.) discussed his 2D slab model, which has 10^4 grid points and can accurately simulate ice processes. He suggests that, in a sensitivity study, the equations should be thoroughly analyzed first.

II. Field Measurements

1. M. Wolf (PNL) has flown through cooling tower plumes at Rancho Seco, California, and Centralia and Trojan, Washington,

measuring vertical wind speeds, temperature and water vapor excesses, and cloud droplet sizes. He finds that a visible plume can occur with a mean relative humidity in the plume of only 60 or 70%. He determined the entrainment coefficient to be 0.32 (PSU found 0.4).

2. D. Thomson, J. Norman, J. Pena, and R. Pena (PSU) fly in the Keystone, Pennsylvania, cooling tower plumes, measuring turbulent fluctuations of winds, temperatures, and moisture, and cloud droplet and aerosol parameters. The plume is found to be quite turbulent and puffy. Fast response (fraction of a second) instruments are required.

Aitken nuclei are observed to form in the plume as it blows downwind. There are several very large (3mm) drift or blow-through drops striking the ground within 200m of the towers.

3. M. Kramer (Smith-Singer Met., Inc.,) discussed his three-year program of aircraft observations of plumes in West Virginia. Last winter a 1-in. snow was observed beneath the cooling tower plume at the John E. Amos plant at distances from 5 to 13km downwind of the tower. No in-plume measurements are made.

4. G. Schrecker (Environmental Systems Corporation) is measuring drift concentrations around the Chalk Point, Maryland, cooling tower.

5. P. Harrison (Meteorology Research, Inc.,) described his aircraft observations last December of the Chalk Point plume. Instrument responses and flight plans have been revised so that the plume can be better detected during this month's observation program.

6. D. Wilson (Lockheed-Huntsville) discussed remote flow measurements that could be made with a laser doppler velocimeter.

7. W. Dunn (ANL) showed slides of a new sensitive dew point instrument that he will use to measure the water content in cooling tower plumes.

As a result of information given in the above presentations, discussion during the presentations, and further discussion on the evening of June 17 and the morning of June 18, the following recommendations can be made:

1. Sensitivity tests should be run with models in order to determine the necessary accuracy of input variables.

2. A single 2D or 3D model which has the domain of a cumulus cloud but can resolve turbulent eddies in plumes is not possible with present computers. A small-scale model can be used for the plumes until they reach a length of 200m or more from the source. The values predicted by the small-scale model can then be used as input to the model with a larger domain.

3. Plume merging can be studied only with a 2D or 3D model.

4. An information center should be created in the AENEC program which keeps track of all cooling tower experiments and lets all investigators know what experiments are underway. This center does not necessarily have to store all raw data.

5. The increased entrainment rate due to aerodynamic effects at the tower mouth should be studied further.

6. Instruments used in aircraft studies of plumes should have response times as fast as possible. There are a few sets of data which are virtually useless because the instrument response time (especially for humidity instruments) was too slow.

7. A few measurements of liquid water content at the cooling tower mouth are needed to determine if it is large enough (greater than 1g/kg) to have a significant cooling effect on the plume when it evaporates.

8. Remote measurements (laser, radar, acoustic) of turbulent velocities in plumes and clouds should be made, since time-mean velocity fields through the plume can be observed from a single ground-based location.

9. Surveys of potential NEC sites should include the locations or paths of preferred mesoscale convection fields.

10. Modelers and experimenters were agreed that the following accuracies are currently practical in tower and plume observation programs:

	Item	Accuracy
Tower parameters	Initial flux	10%
	Temperature	1°C
	Relative humidity	5%
	Vertical speed	1m/s
	Liquid water content	1g/kg
Plume parameters	Temperature difference	0.2°C
	Vertical speed	0.5m/s
	Liquid water content	0.1g/kg
	Drift water	10 ⁻⁴ g/kg
	Relative humidity	2%
	Plume width	5m
	Visible plume length	10% or 50m

There was no indication by modelers of any need for improvement in these accuracies.

11. For model testing, time-mean data are best; i.e., several aircraft flights should be made through the same portion of the plume during a period of 30 minutes. A single pass of the aircraft is so fast that the observations are essentially instantaneous.

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