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MASTER

A RAND NOTE

ANOMALOUS SNOWFALL CAUSED BY NATURAL-DRAFT COOLING TOWERS

L. Randall Koenig

May 1980

RAND/N-1479-DOE

Prepared For The U.S. Department of Energy

Rand
SANTA MONICA, CA. 90406

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PREFACE

The release of waste heat and moisture to the atmosphere through evaporative cooling towers can have meteorological effects exceeding the mere creation of a visible plume. Rand research sponsored by the U.S. Department of Energy (Contract No. AC03-76EV01191) seeks to identify those effects and to study them quantitatively. Anomalous snowfall from cooling-tower plumes was identified as one of the effects, and the meteorological conditions leading to such snowfall have been determined empirically (see R-2465-DOE, cited below).

This Note studies further the empirical evidence and uses a numerical model of cloud microphysics both to verify theoretically the empirical criteria and to learn more about the development of such anomalous snow. It is addressed to analysts seeking a means of predicting anomalous weather caused by the rejection of large quantities of waste heat directly to the atmosphere and to planners involved in site selection for large power-generating facilities.

Related Rand publications include:

- Koenig, L. Randall, *Anomalous Cloudiness and Precipitation Caused by Industrial Heat Rejection*, R-2465-DOE, September 1979.
- Murray, Francis W., and L. Randall Koenig, *Simulation of Convective Cloudiness, Rainfall, and Associated Phenomena Caused by Industrial Heat Released Directly to the Atmosphere*, R-2456-DOE, June 1979.
- Murray, Francis W., *The Climatic Probability of Snowfall Induced by Cooling-Tower Plumes*, N-1443-DOE, January 1980.

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SUMMARY

Scattered reports of significant amounts of snow anomalously produced by cooling-tower plumes suggest that this process may be of importance. This conclusion is supported by study of high-resolution satellite images. Tabulation of a number of aerial observations of plumes at subfreezing temperatures indicates that a plume is likely to produce measurable snow if its temperature is colder than -13°C and the saturation deficit of the ambient air is less than 0.5 g m^{-3}. These factors are important because they affect the rates of nucleation and growth of ice particles. The rate of mixing between plume and ambient air is also important because it affects the rate of evaporation within the plume, which in turn determines the length of time available for snow particles to grow large enough to fall out.

These empirically derived criteria were tested using a numerical model of cloud microphysics that simulates the most important processes of transfer of water substance between vapor, liquid, and ice, including nucleation and development of particle-size spectra. Dynamic processes were specified, not modeled. Among the many quantities computed is the flux density of snow at the base of the plume. From this, together with average fallspeed and horizontal wind speed, one can compute the amount and pattern of snowfall at the ground.

Sixteen runs were made using different temperatures, relative humidities, and mixing rates. Some had relative humidities greater than 100 percent to simulate merging of the plume with a natural cloud. Comparison of the computational results with observations of actual plumes shows that the model has skill in predicting plume behavior. In particular, the model strongly supports the criterion of -13°C for plume snowfall. The model, however, predicts the maximum snowfall depth to occur nearer the source than is observed. This probably results from the slowness of the model in developing a broad spectrum of particle sizes.

Mixing of the plume with the environment may increase snowfall if the ambient air is supersaturated with respect to ice or may decrease

snowfall if it is subsaturated. With a sufficiently moist atmosphere, total snowfall may exceed the flux of moisture from the cooling tower. The distance of closest deposition of snow depends on rate of plume rise, mixing, and horizontal wind.

The model could best be improved by including interactive dynamics. An objective method to regulate efficiently the introduction of new ice-particle categories would also be desirable.

ACKNOWLEDGMENT

The assistance of Francis W. Murray in preparing this report is greatly appreciated.

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CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Trivial snowfall has occasionally been attributed to industrial effluents (for example, Agee, 1971, and Parungo et al., 1978a). Claims have also been made that snow depths to 13 cm were deposited due to effects of plumes from large evaporative cooling towers (Otts, 1976). Lesser amounts but unquestionably caused by the glaciation of cooling-tower plumes were documented during aerial reconnaissance of plume behavior (Kramer et al., 1976, and undated reports of Smith-Singer Meteorologists to the American Electric Power Service Corporation). If plumes can produce snowfall to the extent claimed by Otts, it seems clear that they have the potential to cause more serious hazards than generally believed.

The purpose of the work reported here was to assess the potential for snowfall from cooling-tower plumes. Observations and theory are used to establish the conditions necessary for plume glaciation and snowfall. In a second paper, Murray (1980) analyzes climatological information to assess the frequencies at which snowfall might be expected at selected sites in the United States.

II. INFORMATION DERIVED FROM OBSERVATIONS

NATURE OF THE OBSERVATIONS

Sources

Occurrences of snow falling from natural-draft cooling-tower plumes have been documented by Otts (1976) and by Kramer and his associates at Smith-Singer Meteorologists. The latter carried out aerial surveys of cooling towers located in West Virginia, Ohio, and Kentucky from December 1974 through March 1975 and December 1975 through March 1976. During 42 observations (made on 35 days), the plume was at subfreezing temperatures. Snowfall occurred in eight cases. These observations are available in two undated reports from the American Electric Power Service Corporation. Kramer et al. (1976) provide supplementary material on these observations, including information on measured snowfall depths.

Direct observations indicate that the areal extent of snowfall from cooling towers greatly exceeds the resolution of several satellite systems and therefore should be detected in their imagery.

Figure 1, obtained on 12 January 1973 by the LANDSAT system, includes portions of eastern Ohio, western Pennsylvania, and northern West Virginia. Attention is directed to the narrow streaks of snow that cover portions of the ground. At five locations (A through E) industrial plumes are identifiable. The first is located near Stratton, Ohio (presumed from the W. H. Sammis plant); the second at Brilliant, Ohio (the Cardinal plant); the third at Captina, West Virginia (the Kramer plant); the fourth at Beverly, Ohio (the Muskingum plant); and the fifth near Morgantown, West Virginia (the Fort Martin plant at Maidsville). Except for the Muskingum and Fort Martin plants, these are believed to use once-through cooling, and in these cases the plumes are assumed to be caused by stack emissions.

The major snow streaks were laid down at some earlier time, for they lie at an angle of about 45° (clockwise) from the plumes. Downwind of the Brilliant plume there is a snow streak that lies at an angle of about 45° from the main streaks. This snowfall may have been

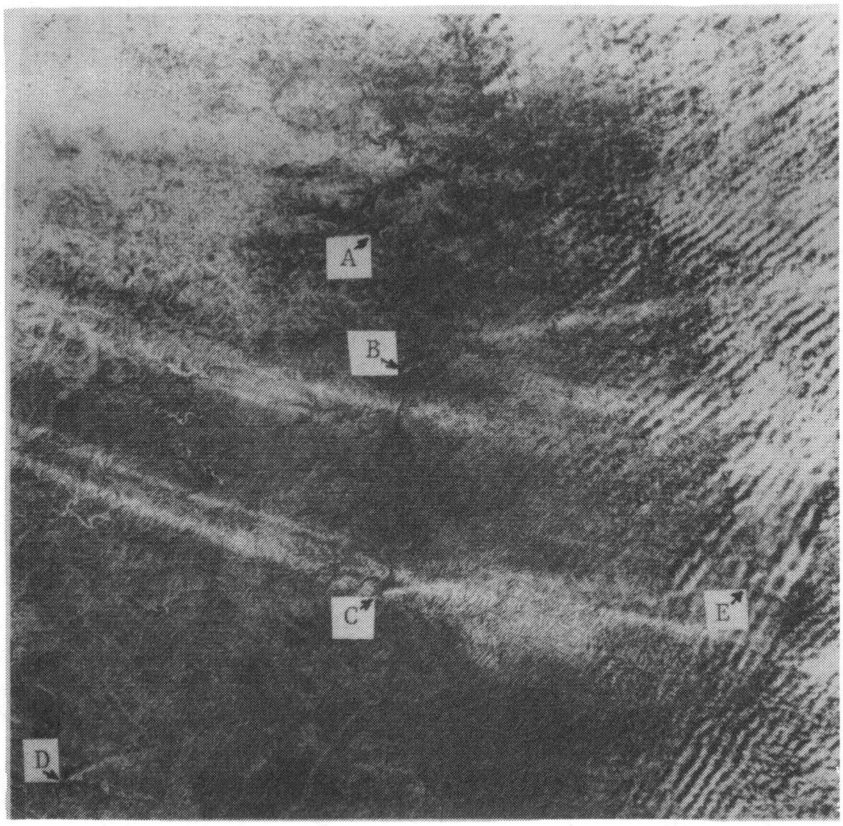

Fig. 1 — LANDSAT image 1173-15362-5 obtained on 12 January 1973 showing parts of Ohio, Pennsylvania, and West Virginia

"A" points out a plume at Stratton, Ohio
"B" points out a plume at Brilliant, Ohio
"C" points out a plume at Captina, West Virginia
"D" points out a plume at Beverly, Ohio
"E" points out a plume near Morgantown, West Virginia

caused by the plume just before the image was obtained. Also, there is a large oval-shaped area of snowfall east (downwind) of the Captina plume. This suggests plume-associated snowfall during a period in which the plume wandered over a 45° sector.

The Captina plume appears to flow toward Morgantown. The strato-cumulus clouds downwind of Captina and Morgantown have a fuzzy appearance not shared by clouds lying crosswind on either side of Morgantown.

A fuzzy appearance of clouds often indicates that the cloud contains mostly ice particles, whereas sharp outlines indicate water drops. If this is true in this case, one may conclude that as the plume merges with natural clouds, it induces ice formation (and snowfall). Since the Captina plant uses once-through cooling rather than cooling towers, there is evidence of a microphysical effect caused by stack emissions; however, this does not necessarily indicate that the emissions themselves contain ice-forming materials. The evidence is mixed (c.f. Parungo et al., 1978a, 1978b; Schnell et al., 1976). Perhaps the stack emissions only cause turbulence that mixes nuclei into the cloud. Figure 2 was obtained on 6 January 1976, two days after the observations by Otts of snowfall from the Amos plume (indicated by A on the image). The snow pattern to the east of the plant is similar to that mapped by Otts (see Fig. 3). However, to the west snow has also fallen, and one might question whether the plant was responsible for the streak. The Smith-Singer data include 5 and 6 January 1976. On neither day was snowfall detected. On 5 January 1976, the air was calm, and the plume spread out in all directions for a distance of three miles from the plant; snowfall may have occurred under similar circumstances when observations were not being taken (the temperature was sufficiently cold). This could account for the snowfall in the near vicinity of the plant and, in particular, to the west of the plant. The 6 January 1976 observations, obtained at about the time this image was taken, indicated a very short plume and ground temperature of -12°C. Ground temperatures remained below 0°C between 4 and 6 January 1976 (see Koenig, 1979, for more information).

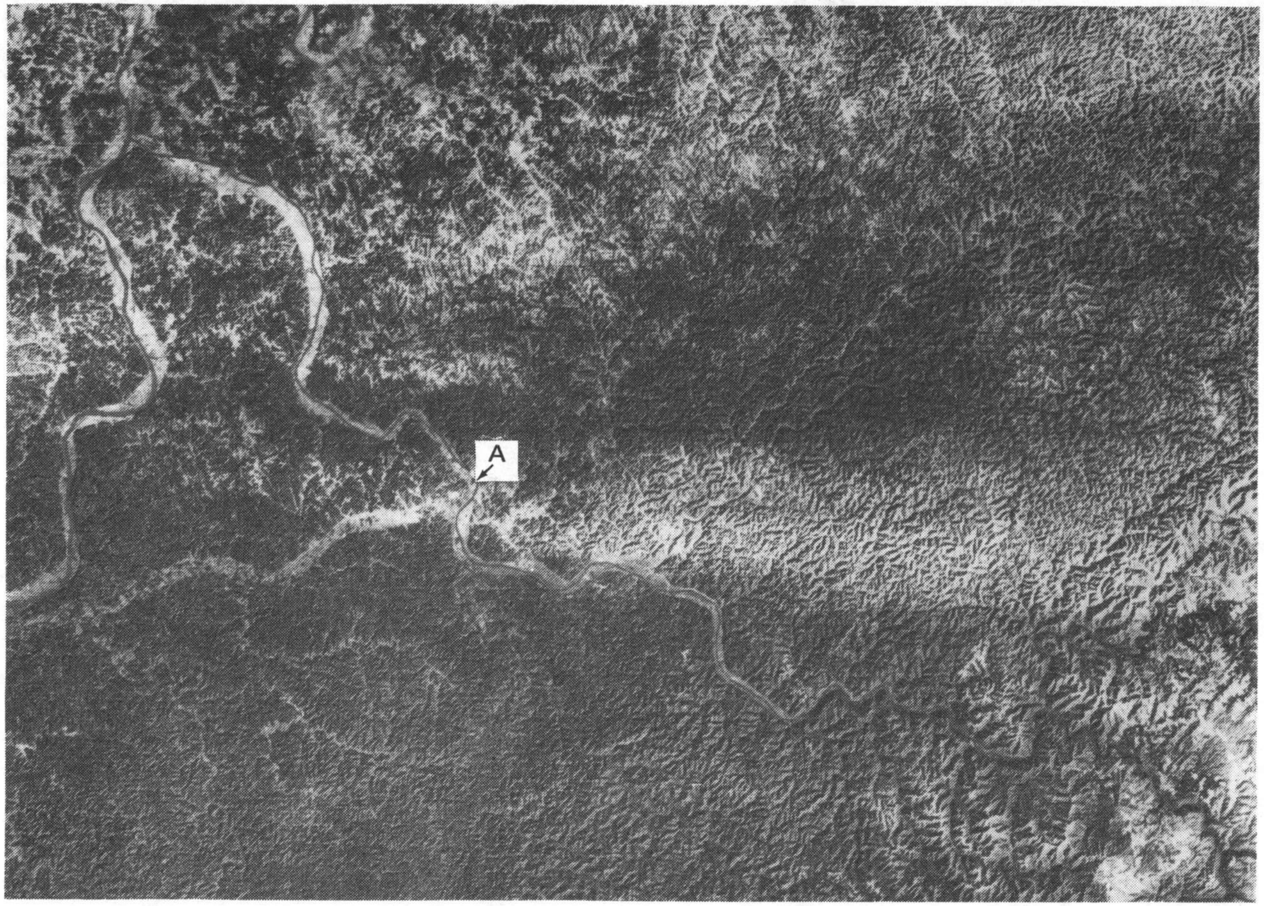

Fig. 2 — LANDSAT image 2349-15225 obtained on 6 January 1976 showing an area including Ohio and West Virginia. The John E. Amos power plant is indicated by "A".

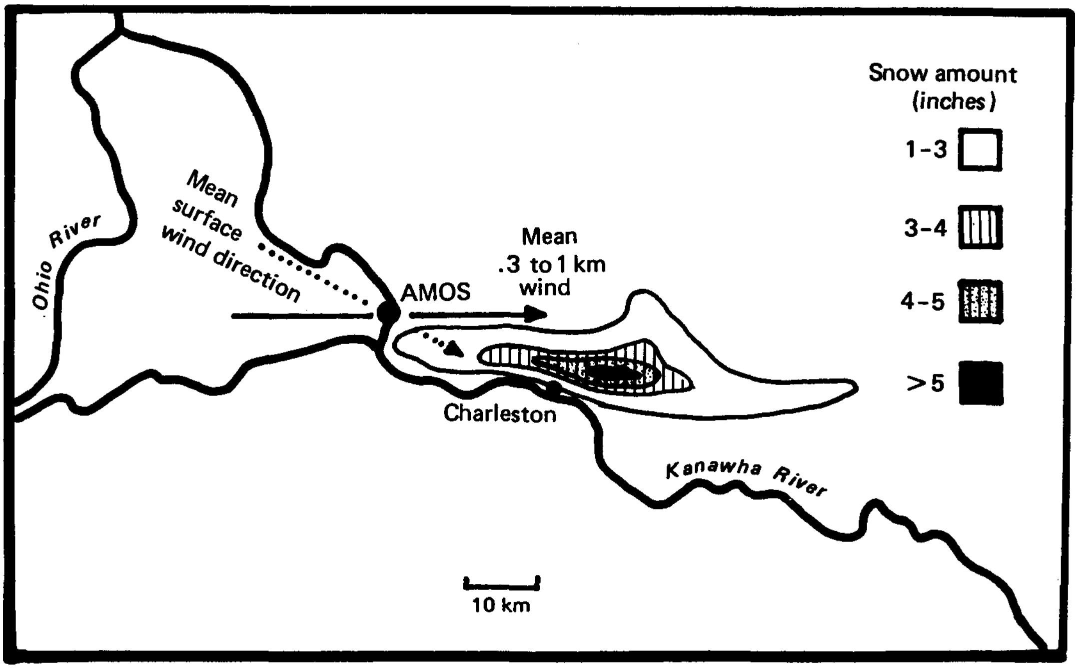

Fig. 3 — Map of snowfall deposited downwind of the Amos plant on 4 January 1976 (after Otts, 1976)

PRECIPITATION CHARACTERISTICS

Snow Location

The Smith-Singer Meteorologists data indicate snow falling from the base of the plume about 5 km from the tower, reaching the ground at a distance starting about 8 to 13 km and falling for distances sometimes exceeding 70 km. Otts' data for 4 January 1976 (Fig. 3) indicate snow within 3 km of the plant with the maximum distance being 58 km. The location of the closest in deposition of snow probably is a function of temperature, plume height, and low-level windspeed, but the data are too sparse to separate those using field data alone.

Time-averaged spread angles of the snow mapped by Otts and Kramer et al. were around 25°, but the major snow accumulations occurred within spread angles one-half this value. Otts found that the maximum snowfall accumulation occurred 29 km from the source, while Kramer and his associates found accumulations increasing out to the maximum range from the tower at which data were obtained (38 km).

Snow Quantity Compared with Tower Water Output

The snowfall accumulation on 4 January 1976 (Fig. 3) occurred over a five-hour period. A conservative estimate of 2×10^7 m^3 of snow can be made.

Otts (personal communication, 1977) described the snow as very light and fluffy. On the assumption that the density of the snow lay between 100 (a typical value) and 10 (a very low value) kg m^{-3}, the estimated snowfall rate is between 1×10^5 and 1×10^4 kg s^{-1}-- two or one orders of magnitude greater than the evaporation rate of water in the cooling towers. *This indicates that greater snow mass can accumulate than the water vapor mass leaving the tower exit in the same period of time.*

Since natural clouds were in the vicinity, the snow mass probably included moisture within portions of the nonprecipitating cloud that mixed with the glaciating plume. The maximum snowfall occurred at the axis of the plume. Evidently the condensate from the existing cloud was drawn in toward the center of the plume. The crystals did not spread outward into the natural clouds. This dynamical structure can be observed in other situations where local glaciation creates a hole in a thin, supercooled cloud deck (for example, Johnson and Holle, 1969).

CRITERIA FOR SNOWFALL

Using the data of Smith-Singer Meteorologists and Otts, Koenig (1979) plotted a chart (Fig. 4) of plume-glaciating characteristics against plume temperature and ambient air saturation deficit and found that the joint requirement of temperatures below -13°C and ambient saturation deficits less than 0.5 g m^{-3} with respect to liquid provided an empirical basis for separating circumstances in which self-precipitation of snow from plumes should and should not be expected.

From theory it can be argued that the amount depends upon the concentration of ice particles and also their rate of growth compared to the rate of evaporation of the plume. Recalling the dependence of the concentration of active ice-forming nuclei on temperature and the

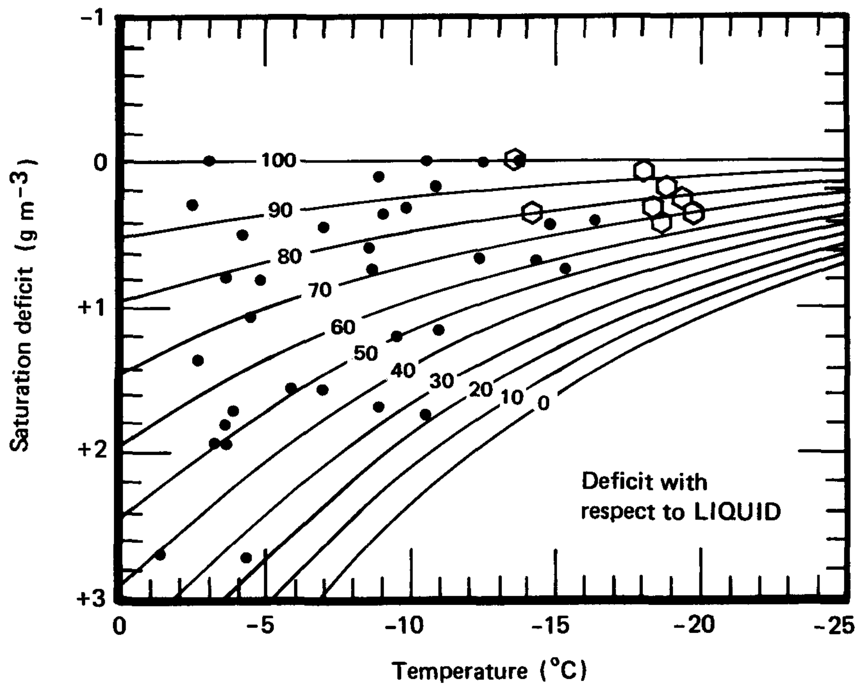

Fig. 4 — Observed behavior of natural-draft cooling tower plumes as a function of temperature and saturation deficit. Black dots indicate absence of snowfall; open hexagons indicate snow fell from plume. The percentage relative humidity is shown by upward sloping lines.

peak growth rate of ice crystals in the vicinity of -15°C, the temperature criterion for plume glaciation is not surprising.

The saturation deficit exerts major control on the rate of evaporation of the plume. Conditions might arise to cause snow to first fall at a distance well removed from the cooling tower. This might occur with an exceptionally long-lasting plume having temperatures warmer than -13°C. Because of the meandering of the plume, one would expect snow accumulations to be small and, except by aerial observation, to be difficult to associate with cooling-tower emissions.

As can be seen from Fig. 4, the criteria are not perfect predictors. Other lesser influences are believed to be factors that also control the evaporation rate of the plume, for example, those that regulate the rate of mixing of the plume with its surroundings. The stability of the atmosphere influences mixing, and evidence suggests that either great stability or great instability inhibits plume glaciation. Great stability may produce a long-lasting but shallow plume from which ice particles may fall before achieving sufficient size or fallspeed to survive the fall to the ground. Great instability leads to turbulent conditions, and plumes rapidly mix with the environment. This usually promotes evaporation. Even if the plume is long-lasting, its water content may fall so low that ice-particle growth becomes too slow.

Strong winds should promote turbulence and plume dissipation and inhibit plume glaciation; however, in the ranges encountered during the Smith-Singer observations, wind apparently exercised little control on snowfall occurrence.

The numerical simulations discussed in the next section provide additional evidence on factors regulating snowfall from cooling-tower plumes.

III. NUMERICAL SIMULATION

REQUIREMENTS

Numerical simulation provides a means to anticipate the behavior of the plume in the absence of observation--provided that the model satisfactorily emulates the processes shaping the characteristics of the plume. Whether it does so may be checked by running the model using temperature and wind values equal to those observed in actual cases.

As stated earlier (and discussed more fully in Koenig, 1979), observations and theory indicate that plume glaciation causing snowfall depends on the concentrations and growth of the ice particles present, which in turn depend on:

1. Temperature.
2. Ambient air saturation deficit.
3. Mixing between the plume and ambient air.

Given an air parcel saturated with liquid water, the concentration of ice particles and their growth rates are functions of temperature (Factor 1). Factors 2 and 3 control the vapor and condensed water content of a plume parcel as it drifts downwind. The rate of conversion of liquid to ice also serves as a feedback mechanism, for it influences plume water content.

Accordingly, a model to simulate plume glaciation must account for two major processes:

1. Mixing the plume and ambient air.
2. Microphysical processes involved in the growth and evaporation of liquid and ice particles.

Several models to account for the mixing between the plume and ambient air have been constructed for the purpose of developing a means to predict the length of a plume for "shadowing" studies (see, for example, Hanna and Pell, 1975). These models typically ignore microphysical processes and define a plume as being present if the air is saturated with respect to water. To study plume glaciation, microphysical processes describing the evolution with time of the transfer of water substance between vapor, liquid, and ice must be addressed.

DESCRIPTION OF MODEL

The model predicts the characteristics of a plume element, or puff, as it emerges from the cooling tower, rises, and travels downwind. In all the cases reported here, the moisture source flux is 1000 kg sec^{-1}. It is emitted to the atmosphere as saturated air having a temperature of 25°C. These conditions are appropriate for wet towers at a plant delivering about 2500 MW of electricity (Kadel, 1970).

Dynamic Considerations

The dynamic properties of the plume are specified. The rate of rise is a function of altitude. Initial values, one at the tower and one incrementally below the summit, are assigned, and linear interpolation is used to calculate intermediate values. The plume emerged from the tower at 4 m s^{-1} in all the runs to be discussed.

Mixing with the environment is specified as inversely proportional to time. Ordinarily parameters are chosen so that the width of the plume is about 1.5 km at 12 km distance, but they were varied to test the influence of mixing on snowfall production. Since mixing is a function of time and not distance, at a given distance (everything else being equal), the lower the wind velocity, the more the mixing of plume and environmental air. Dilutions of the plume as functions of time for various mixing specifications are shown in Fig. 5.

In the runs discussed here, the plume depth was limited to 500 meters. The results of brief runs using shallower plume depths showed that the flux of snow varies directly with plume thickness, and the extent of glaciation (the ratio of ice to liquid water in a plume volume) varies inversely with plume thickness. These results would be expected because the mass of an ice particle falling from the plume is inversely proportional to its lifetime within the plume, and the total number of ice particles varies with plume volume.

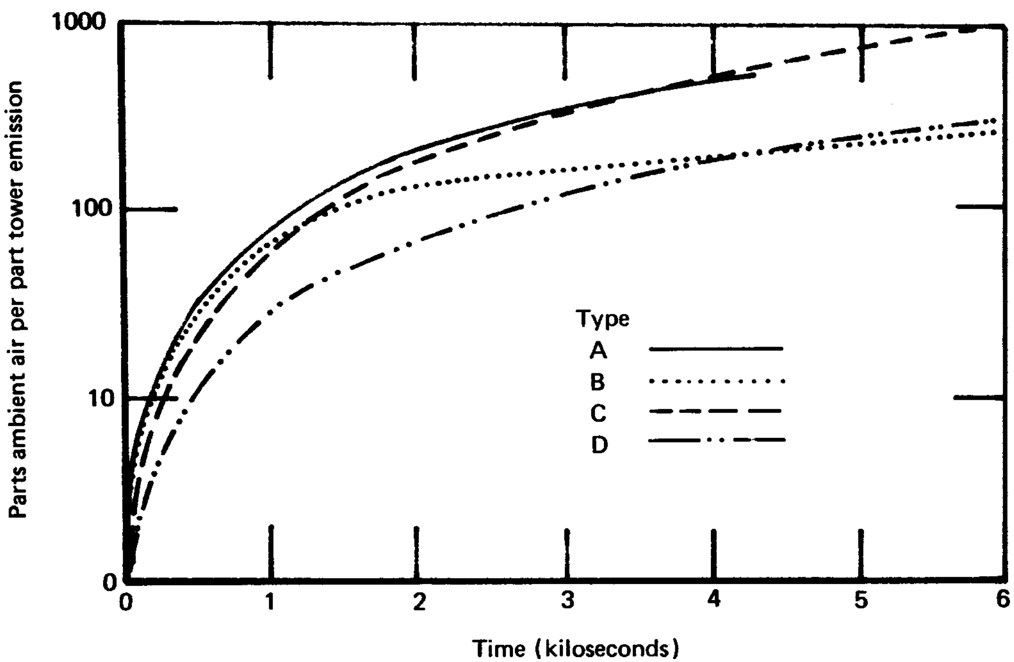

Fig. 5 — Plume dilution as a function of time for various mixing specifications

Microphysical Considerations

The rates of transfer of water substance between vapor, liquid, and ice are treated in detail. The model contains liquid-vapor phase microphysics based on Koenig (1971a) and ice-phase microphysics based on Koenig (1971b and 1972). Updating included incorporation of data on riming thresholds, collision efficiencies, and fall velocities (e.g., Heymsfield, 1972; Locatelli and Hobbs, 1974; Pitter and Pruppacher, 1974; and Schlamp et al., 1975). The microphysical portion of the model was not "tuned" for this particular application.

A population of aerosols is assumed to be present in the air passing through the cooling tower. These aerosols are potential condensation nuclei; the number and sizes activated depend on the maximum plume supersaturation and the aerosol size distribution. In these experiments a total of 5×10^9 particles per m^3 was assumed. For simplicity, they were considered to be salt particles and were divided into 35 size categories ranging in dry size from 0.01 to 4.25 μm in radius. The number and sizes activated depended on the maximum plume supersaturation. At no time did all the aerosols serve as cloud condensation nuclei (i.e., grow beyond their critical radii).

Supersaturation (or subsaturation) is found by an iterative process that balances the rates of growth of aerosols, droplets, and ice particles with the rate at which water vapor becomes available for condensation due to decreasing temperature or other causes.

The warm-rising plume element cools by adiabatic expansion and (more importantly) by entraining cooler ambient air. The entrainment of stack effluents can be simulated by prescribing that aerosols in the air going through the tower differ from those in the entrained air, but this was not done in the runs discussed here.

Mixing also dilutes the plume and, if the environment is subsaturated, tends to evaporate the plume. An environment supersaturated with respect to ice renews the plume. The aerosols in the entraining air adjust to the plume relative humidity at the time of entrainment, and the old and new drop spectra are merged in such a way that the chemical composition and mass of drops are preserved. In this combined spectrum, condensation is the dominant process, and the chemical composition and sizes of the drops are followed in order to account for drop curvature and molality in computing values of condensation rate. The mathematics of the merger does not precisely conserve drop concentration, however.

After drops in a certain category have grown sufficiently large that curvature and molality no longer play a significant role in the rate of condensation, they are transferred to a second category that uses a fixed-drop-size interval. This spectrum is divided uniformly on a logarithmic scale into forty class intervals. An accounting for chemical composition is retained, but it is not as precise as in the condensation-dominated spectrum, for as the computation proceeds, drops of varying chemical composition but of approximately the same size are merged in a single class interval. This spectrum is designed to account for coalescence growth of plume drops.

After the plume cools below 0°C, ice particles are introduced according to the specified relationship between temperature and ice-nucleus concentration, provided that the air is supersaturated with respect to ice. In these runs, 10 m^{-3} active nuclei at -4°C and an increase of one order of magnitude per 4°C decrease in temperature were specified. Periodically, additional ice particles are introduced to account for nuclei in the entraining air and changes in temperature. Thus, with time, a spectrum of ice particles having various ages and characteristics develops. Computation of ice-particle growth requires a large proportion of the computer resources. For economy, one wishes to minimize the categories of ice, but this desire must recognize the need for sufficiently frequent introductions of ice to make the computation smooth. No automatic means was found to time additions of ice, and, as will be seen in the results, the desired balance between economy and gradual transition was not always found. Fallen snow particles are taken into account in tracking ice-particle concentration. Thus, with time, the concentration of ice particles decreases if temperatures remain more or less constant--even with entrainment.

Ice particles grow by vapor diffusion and riming. To agree with observations, the habit of ice (plates, columns, dendrites, etc.) and the ratios of lengths along the crystallographic axes depend on temperature and vapor supersaturation. This dependency and the degree of riming also affect fallspeeds.

For each class of ice particle, the amount of snow leaving the plume depends on its total mass in a plume element and the ratio of its fallspeed to the depth of the plume. Snow is deposited on the ground at a location given by the plume height times the average horizontal windspeed divided by the fallspeed of the ice particles added to the distance at which the snow leaves the plume.

The pattern of snowfall is of most interest. The primary computed values providing this are the flux density (mass per unit area per unit time) and total flux (mass per unit time) of snow at the ground as a function of distance from the source. They were computed in 100-meter intervals from the cooling tower and then aggregated into larger intervals. Values of the bulk density and shapes of snow particles are used in computing the growth of ice particles and can be used to convert mass flux to rate of increase in the depth of the snow. Alternatively, one can assume some arbitrary ratio for snowfall depth to water equivalent depth. A plume element is considered uniform in composition at a given time; hence the snow falling out of the plume is considered uniform in the crosswind direction. No mixing is assumed under the plume; hence snow falls on the ground having a crosswind extent equal to the width of the plume at its point of emergence. If, at some later time, snow falls from the same plume element and becomes deposited in the same interval, its horizontal extent will be greater than the first deposit, and crosswind snow depth will decrease stepwise with distance from the plume axis. Figure 6 depicts the scheme producing the snow pattern. Time steps of two seconds or less (when mixing occurred) were used in the calculations. Irregularities were produced more by the step-wise introduction of ice particles than by the precipitation scheme.

In the figures showing results of computations, snow flux at the ground is the sum of fluxes received under the center line of the plume--one cannot sum these fluxes multiplied by plume width to determine the total snow flux. Values for the total snowfall flux are available, however, to compare with the moisture flux at the tower.

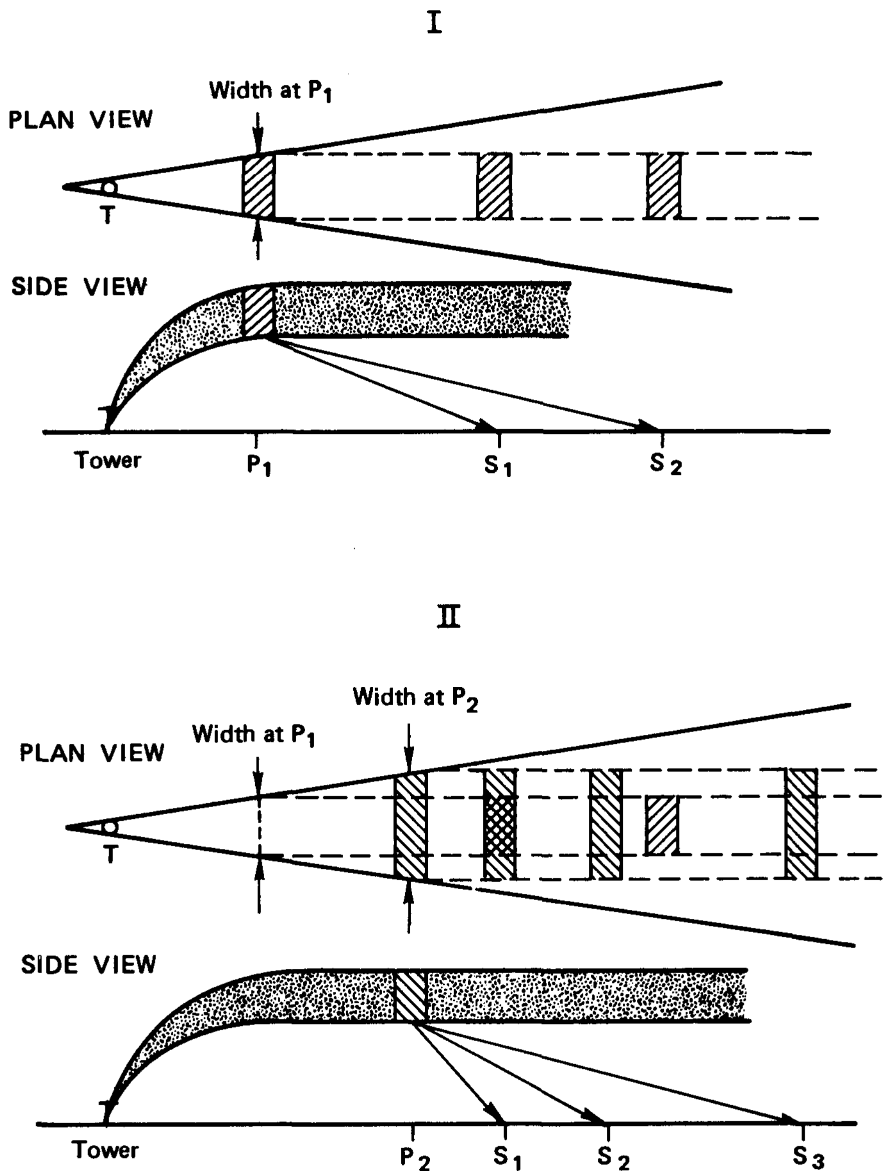

Fig. 6—Explanation of snowfall accumulation scheme

Plan and side views of plume at two times are shown: I—earlier; II—later. Cooling tower located at T, plume element at P_1 and P_2. At time (I), two categories of snow emerge from plume, one deposited at S_1, the other at S_2, as shown in the plan view. The width of the deposit is the width of the plume at the point that the snow emerges from the plume. At time (II), a third category of snow also emerges from the plume. The illustration shows a possible effect of the growth of ice particles in the plume. Since the snow particles have grown, they fall faster and, in spite of the plume being further downwind, may actually fall closer to the tower than particles leaving the plume at an early time.

Extensive information on the properties of the plume is required during the calculations and is available whenever desired. This includes the water vapor saturation, the size distribution of liquid and ice particles in the plume, their rates of growth or decay, the chemical content of the drops, the form of the ice particles (columns, dendrites, etc.), their bulk density and aspect ratio, their degree of riming, their fallspeeds, their contribution to snow-flux density, and the location where they fall to the ground.

APPLICATION

Sixteen runs will be discussed. Their initial conditions are summarized in Table 1. The purpose of these runs was twofold: first, to check the ability of the model to simulate nature, and second, to explore the influence of various factors on snowfall characteristics. Confidence in our ability to meet the latter goal depends on the fidelity of the model, but the model need not be "perfect" in order to extract valuable information.

Relative humidities greater than 100 percent with respect to liquid water were assumed in some cases. This provided a simple means to specify the merging of the plume with a liquid water cloud, for condensation then occurs immediately. In those instances, the water content of the natural cloud at the plume summit is the negative of the saturation deficit given in Table 1.

DISCUSSION OF RESULTS

The results of the experiments are summarized in Tables 2 and 3. The discussion that follows first draws attention to variations in the runs having identical plume summit temperatures and then proceeds to draw generalizations concerning the effects of various factors on snowfall.

Temperature -12°C

Cases 1 and 2 used plume summit temperatures of -12°C. They differed in mixing rates, winds, and relative humidity (80 percent and 100 percent—the latter is equivalent to a merger with a 0.2 g m^{-3} liquid cloud).

Table 1

INPUT CONDITIONS[a]

Case	Temperature (°C)	Relative Humidity (%)	Saturation Deficit ($g\ m^{-3}$) Liquid	Saturation Deficit ($g\ m^{-3}$) Ice	Mixing Category[b]	Plume Rise ($m\ s^{-1}$) Tower	Plume Rise ($m\ s^{-1}$) Summit	Ambient Horizontal Wind ($m\ s^{-1}$) Ground	Ambient Horizontal Wind ($m\ s^{-1}$) Plume Summit
1	-12	80	0.41	0.18	A	4	3	4.5	8.5
2	-12	110	-0.20	-0.43	D	4	4	5	15
3	-13	80	0.38	0.15	A	4	3	4.5	8.5
4	-13	95	0.09	-0.13	A	4	3	4.5	8.5
5	-13	80	0.38	0.15	D	4	1	5	15
6	-14	70	0.52	0.30	D	4	1	5	15
7	-14	110	-0.17	-0.39	D	4	1	5	15
8	-14	110	-0.17	-0.39	C	4	1	5	15
9	-15	80	0.32	0.10	A	4	3	4.5	8.5
10	-16	80	0.30	0.08	D	4	4	5	15
11	-16	100	0	-0.22	B	4	4	5	15
12	-16	100	0	-0.22	D	4	4	5	15
13	-16	110	-0.15	-0.36	D	4	4	5	15
14	-17	80	0.27	0.06	A	4	1	4.5	8.5
15	-17	80	0.27	0.06	A[c]	4	0.5	5	10
16	-17	80	0.27	0.06	B[c]	4	0.5	5	10

[a]All experiments used a moisture source strength of 1000 kg s^{-1}.

[b]See Fig. 5.

[c]Refer to text.

Table 2

SNOWFALL CHARACTERISTICS

Case	Temperature (°C) and Relative Humidity (%)	Snow Flux (kg s^{-1})	First Appearance at Plume Level (km)	First Deposit on Ground (km)	Maximum Flux Density Location (km)	Maximum Flux Density Value (g m^{-2} hr^{-1})	Maximum Snow Depth[a] (mm hr^{-1})
1	-12 (80)	1.4	2.8	69	76	0.3	.003
2	-12 (110)	88.	3.0	75	93	24.0	.24
3	-13 (80)	44.	2.8	28	34	3.9	.039
4	-13 (95)	340.	2.8	21	24	31.0	.31
5	-13 (80)	24.	6.9	50	61	7.0	.070
6	-14 (70)	120.	6.9	26	28	120.0	1.2
7	-14 (110)	1400.	6.9	27	34	460.0	4.6
8	-14 (110)	3300.	6.9	21	25	750.0	7.5
9	-15 (80)	710.	2.8	6	8	1100.0	11.
10	-16 (80)	450.	4.5	15	16	1400.0	14.
11	-16 (100)	1900.	4.5	10	11	2800.0	28.
12	-16 (100)	1100.	7.5	17	18	2200.0	22.
13	-16 (110)	1800.	3.0	17	18	2100.0	21.
14	-17 (80)	360.	4.3	20	20	47.0	.47
15	-17 (80)	390	6.8	22	22	49.0	.49
16[b]	-17 (80)	500	4.8	11	11	89.0	8.9

[a]Assuming snow bulk density is 100 kg m^{-3} and steady-state conditions.

[b]See text.

Table 3

PLUME CHARACTERISTICS AT CONCLUSION OF RUN

Case	Temperature (°C) and Relative Humidity (%)	Duration of Run (sec)	Puff Location (km)	Vapor Saturation (%)		Water Content ($g\ m^{-3}$)		Ice Particle Concentration (m^{-3})
				Liquid	Ice	Liquid	Ice	
1	-12 (80)	2000	16	-9.0	+2.3	.011	.0013	870
2	-12 (110)	4000	95	-0.60	+11.0	.19	.0055	270
3	-13 (80)	4000	33	-15.0	-3.8	.0078	.00064	410
4	-13 (95)	4000	33	-0.88	+13.0	.088	.0123	500
5	-13 (80)	6000	87	-14.0	-3.0	.0078	.00063	520
6	-14 (70)	4200	61	-21.0	-10.0	.0050	.00012	670
7	-14 (110)	6000	87	-0.88	+13.0	.088	.012	160
8	-14 (110)	6000	87	-0.94	+13.0	.087	.011	110
9	-15 (80)	1600	13	-14.1	-0.8	.006	.015	N.A.
10	-16 (80)	2500	36	-13.0	+1.1	.0062	.012	4100
11	-16 (100)	5750	85	-9.1	+5.7	.0081	.010	620
12	-16 (100)	4000	57	-9.7	+4.7	.0059	.031	1300
13	-16 (110)	6000	89	-7.0	+7.8	.0075	.014	430
14	-17 (80)	3100	27	-16.0	-0.63	.0069	.019	8500
15	-17 (80)	3100	30	-15.0	-0.09	.0069	.022	10300
16	-17 (80)	3100	30	-15.0	-0.32	.0069	.021	9900

[a] Complete evaporation of liquid droplets does not occur because their condensation nuclei cause their equilibrium vapor pressures to be lower than that of pure water.

More snow accumulates in Case 2, but even here less than 0.3 g m^{-2} hr^{-1} falls at one location, and no snow falls closer than 75 km from the source. Snow accumulation within 100 km of the tower accounts for only 9 percent of the source strength. Snow flux and accumulation are about two orders of magnitude smaller in Case 1.

The fact that snow is deposited at about the same distance in both cases, in spite of much stronger winds at plume level in Case 2, is attributable to the more rapid growth of ice particles, their greater proportional rime growth, and consequently their greater fall-speeds in Case 2 compared with Case 1. This circumstance is caused by the continual renewal of liquid condensate as the plume mixes with cloudy air.

Temperature -13°C

Two cases, 3 and 5, were run at -13°C and 80 percent relative humidity. Thus conditions were near the boundary of criteria expressed in Section II specifying circumstances leading to snowfall of possible concern. More snow fell in Case 3, the run with greater mixing. This is believed to be a computational artifact. The horizontal windspeed in Case 5 is considerably greater than that in Case 3, and snow is deposited farther downwind. It continues beyond the 100 km arbitrary cutoff distance, and therefore there is an indication that the truncation of the flux calculation is more significant in Case 5 than in Case 3. The greater maximum flux density in Case 5 supports this view. Figures 7 and 8 illustrate the relationship between the flux density of snow at plume level at the ground for Cases 3 and 5, respectively.

In Case 4 the ambient relative humidity was 95 percent. This is supersaturated with respect to ice. One-third of the source flux returns to earth as snow, and the maximum snow-flux density corresponds to about 3 mm of snow if steady-state conditions are maintained for 10 hours. This run was somewhat short (4000 sec). The puff being followed moved only 33 km from the source, and the plume remained supersaturated with respect to ice. Since ice supersaturation was maintained by the entrainment of rather moist air, ice would have

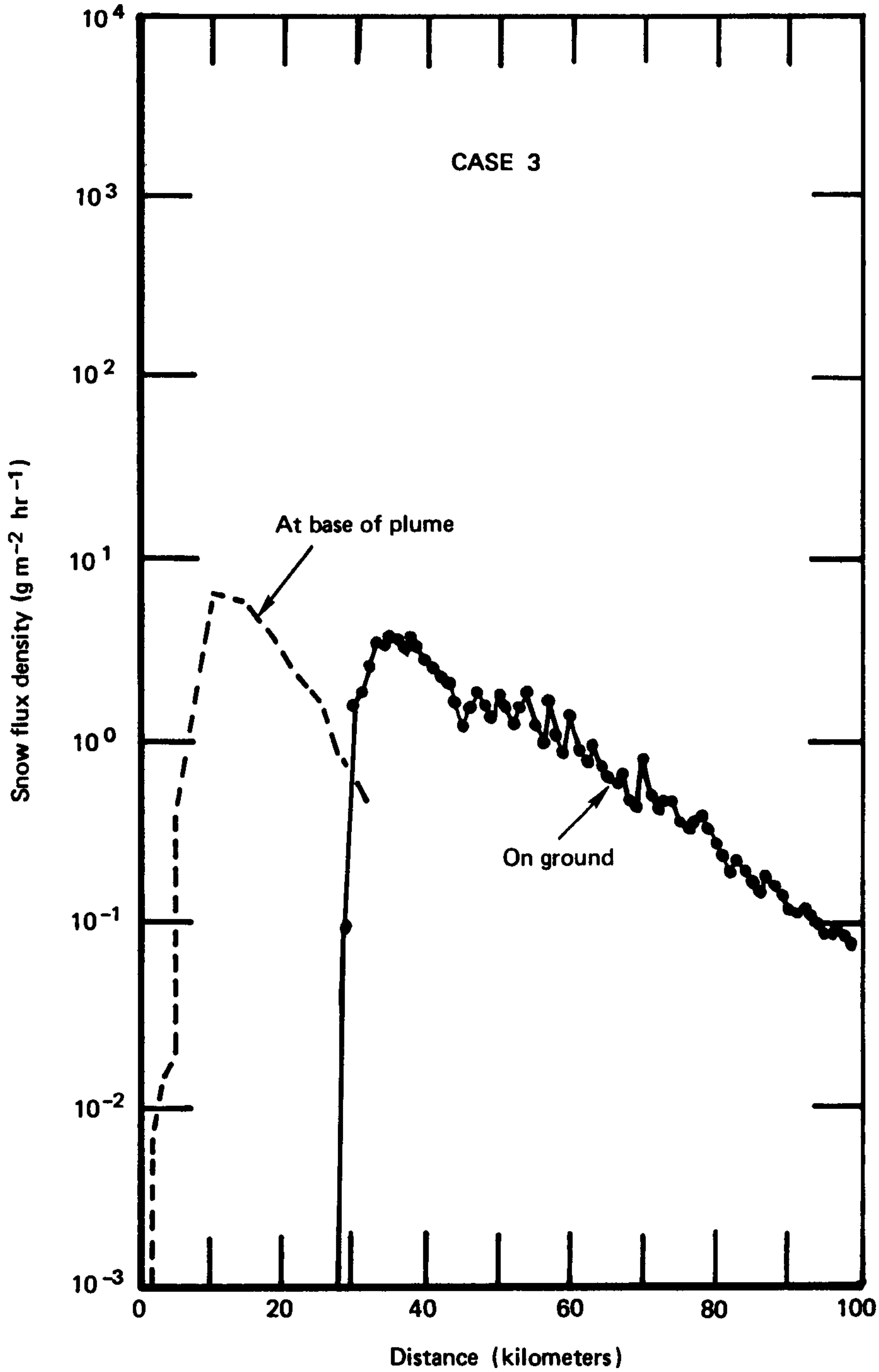

Fig. 7 — Snow-flux density at the base of the plume and on the ground for Case 3 (13 °C). Averages over 1 km radial distance on the plume center line are shown

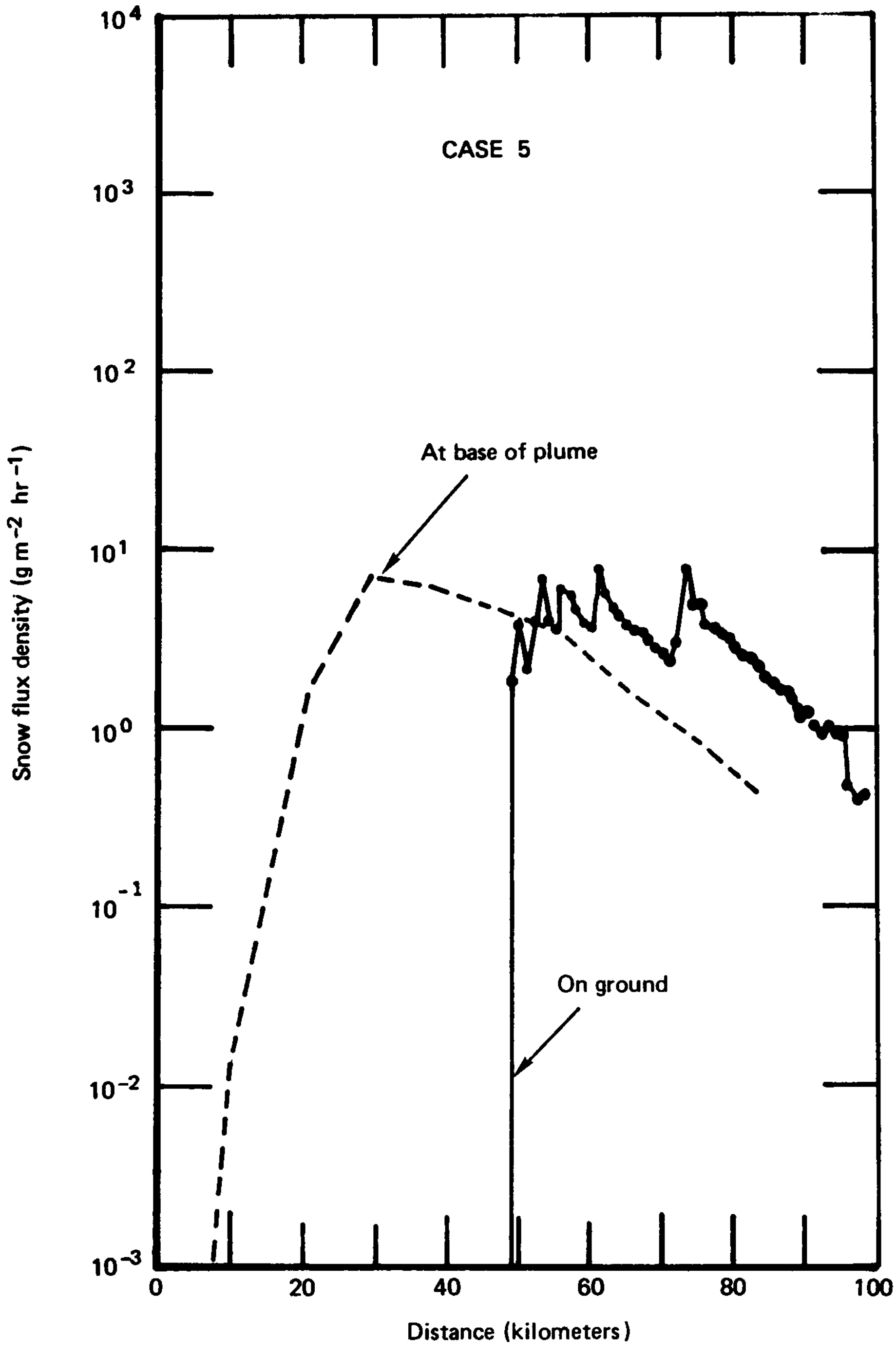

Fig. 8 — Snow-flux density at the base of the plume and on the ground for case 5 (-13 °C). Averages over 1 km radial distance on the plume center line are shown

continued to grow and fall out had this calculation been continued. Therefore, the reported snow flux is considered low, but the maximum flux density is probably correct.

There is a wide difference in the location of the first deposition of snow in these three runs. Cases 3 and 4 have similar wind structure. The earlier snow deposition in Case 4 is attributed to the greater growth rate of the ice particles due to the entrainment of supersaturated (with respect to ice) air in contrast to subsaturated air in Case 3. The earlier snow deposit in Case 3 than in Case 5 is attributed mainly to the stronger horizontal wind speed in the latter case.

Temperature -14°C

Experiments conducted using -14°C plume summit temperatures differed in relative humidity and mixing. Winds were kept constant.

Cases 7 and 8 used relative humidities of 110 percent (corresponding to merger with clouds containing 0.17 g m^{-3} liquid water). The rate of mixing in Case 7 was less than that in Case 8 and the expected result occurred: the snow flux in Case 7 (140 percent of the source strength) was less than that of Case 8 (330 percent of the source strength). Snow flux is accumulated only within 100 km of the source of moisture. Since cloud merger takes place, there is an opportunity for snow to continue indefinitely. As shown in Figs. 9 and 10, both the flux and flux density of snow in Cases 7 and 8 become constant beyond 50 km. This is caused by the replenishment of plume moisture and ice nuclei during entrainment. The effect of greater mixing of supersaturated air (i.e., merger with a cloud) is shown by comparison of the quasi-steady-state snow flux of Case 7 with that of Case 8. The snow flux in Case 8 is greater than that in Case 7 due to the greater spreading of the plume, but the flux densities are similar beyond about 60 km due to the constant plume depth. The program assumes that ice nuclei are introduced with the cloudy air that merges with the plume. If this is not the case (one may argue that they have previously precipitated, leaving a nucleus-free cloud), the snow would ultimately cease.

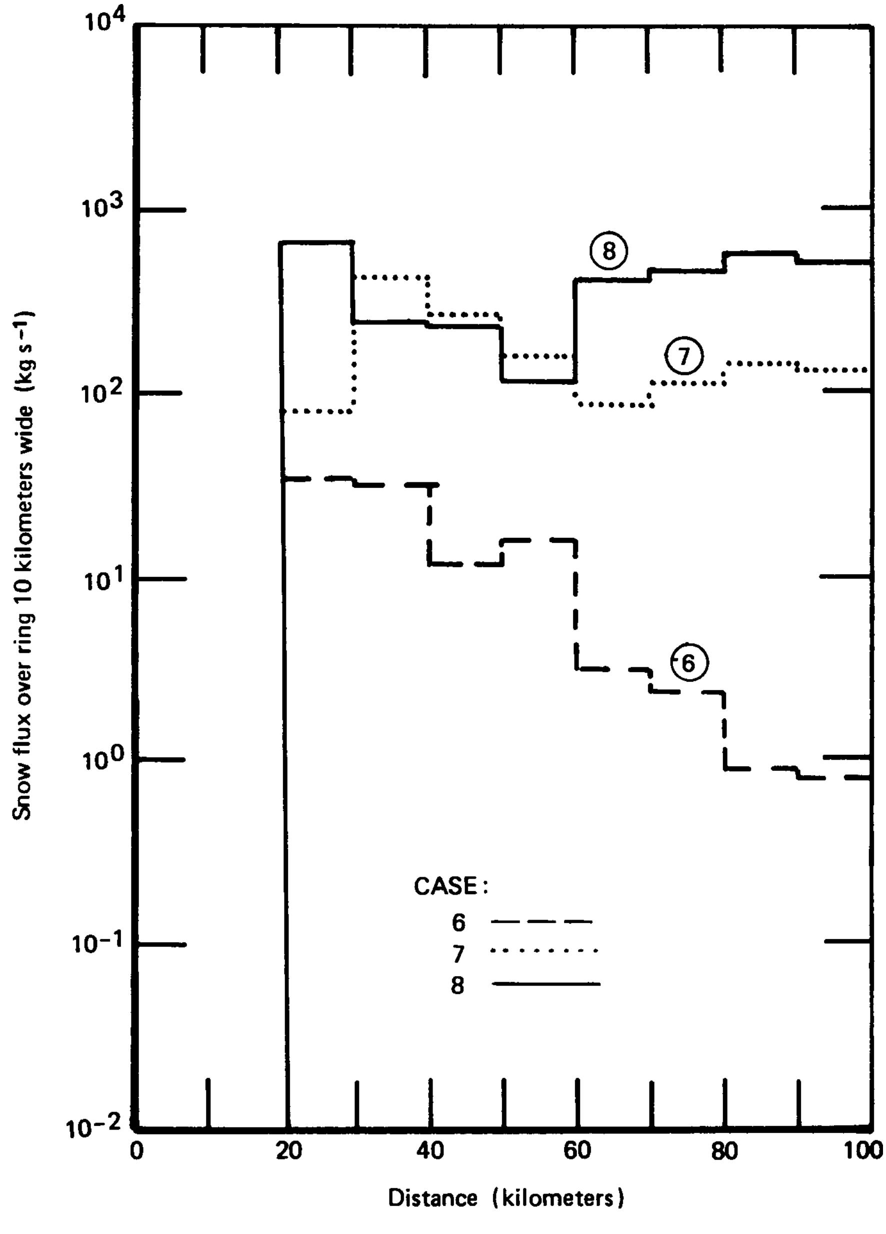

Fig. 9 — Snow flux at the ground averaged over 10 km radial distance increments along the plume centerline for Cases 6, 7, and 8 (-14°C)

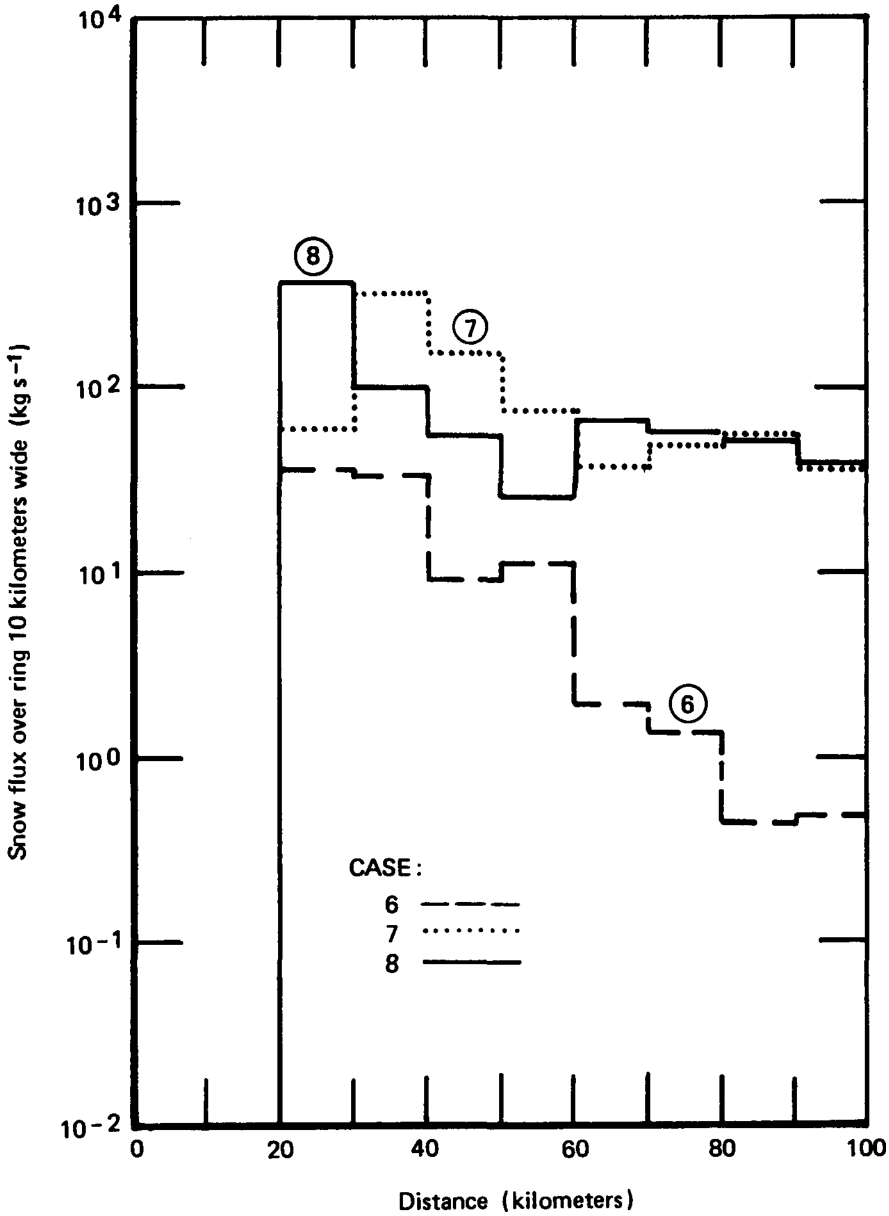

Fig. 10 — Snow-flux density at the ground averaged over 10 km radial distance increments along the plume centerline for cases 6, 7, and 8 (-14 °C)

In comparison with Case 8, snow begins accumulating farther from the source in Case 7, and the maximum snow depth also occurs at a greater distance. This apparently is caused by the slower mixing of ambient air into the plume and consequently slower decreases in plume temperature. This circumstance retards both the introduction of ice particles and their growth in Case 7 as compared with Case 8.

Case 6 was run at 70 percent relative humidity. Snow flux was 12 percent of the source strength, and peak snow-flux density reached 120 g m^{-2} hr^{-1} (compared with 460 and 750 g m^{-2} hr^{-1} for Cases 7 and 8, respectively). In Case 6, peak flux density occurs at the location where snow first falls to the ground. It rapidly decreases thereafter due to the erosion of the plume caused by mixing with the relatively dry environment. The conditions of this run are near the boundary of the criteria for objectionable snowfall set forth in Section II.

Temperature -15°C

Ice crystal growth rates by diffusion are at a peak at -15°C, and this is reflected in the relatively large snow flux (71 percent of the source flux) in the case using this temperature, in spite of the fact that the plume entrains subsaturated ambient air. Both the rapid growth and fallout of the ice particles and the erosion of the plume due to mixing cause the peak flux to occur very close to the location of the first appearance of snow at the ground. Snow flux drastically falls off with distance once the peak is reached.

Temperature -16°C

Four experiments used -16°C as the ambient temperature at the plume summit. They differed in relative humidity and mixing rates, but not in wind velocities. Figure 11 shows snow-flux densities at the ground as a function of distance from the source for three of these cases, and Fig. 12 shows the flux density at both ground level and plume base for the fourth case.

From Table 3 it can be seen that the plume was supersaturated with respect to ice at the conclusion of Case 10. This indicates

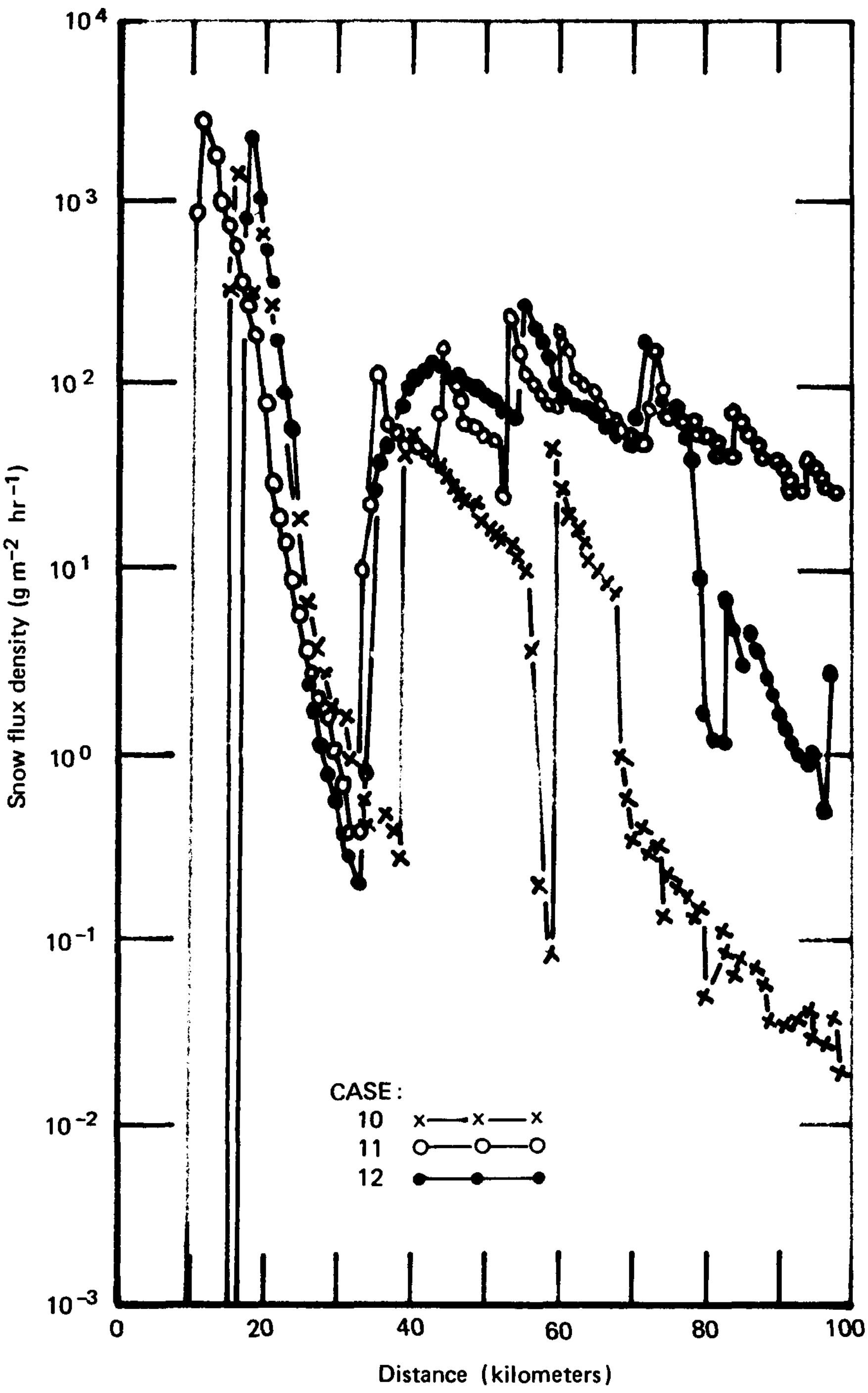

Fig. 11 — Snow-flux density at the ground averaged over 1 km radial distance increments along the plume centerline for Cases 10, 11, and 12 (-16 °C)

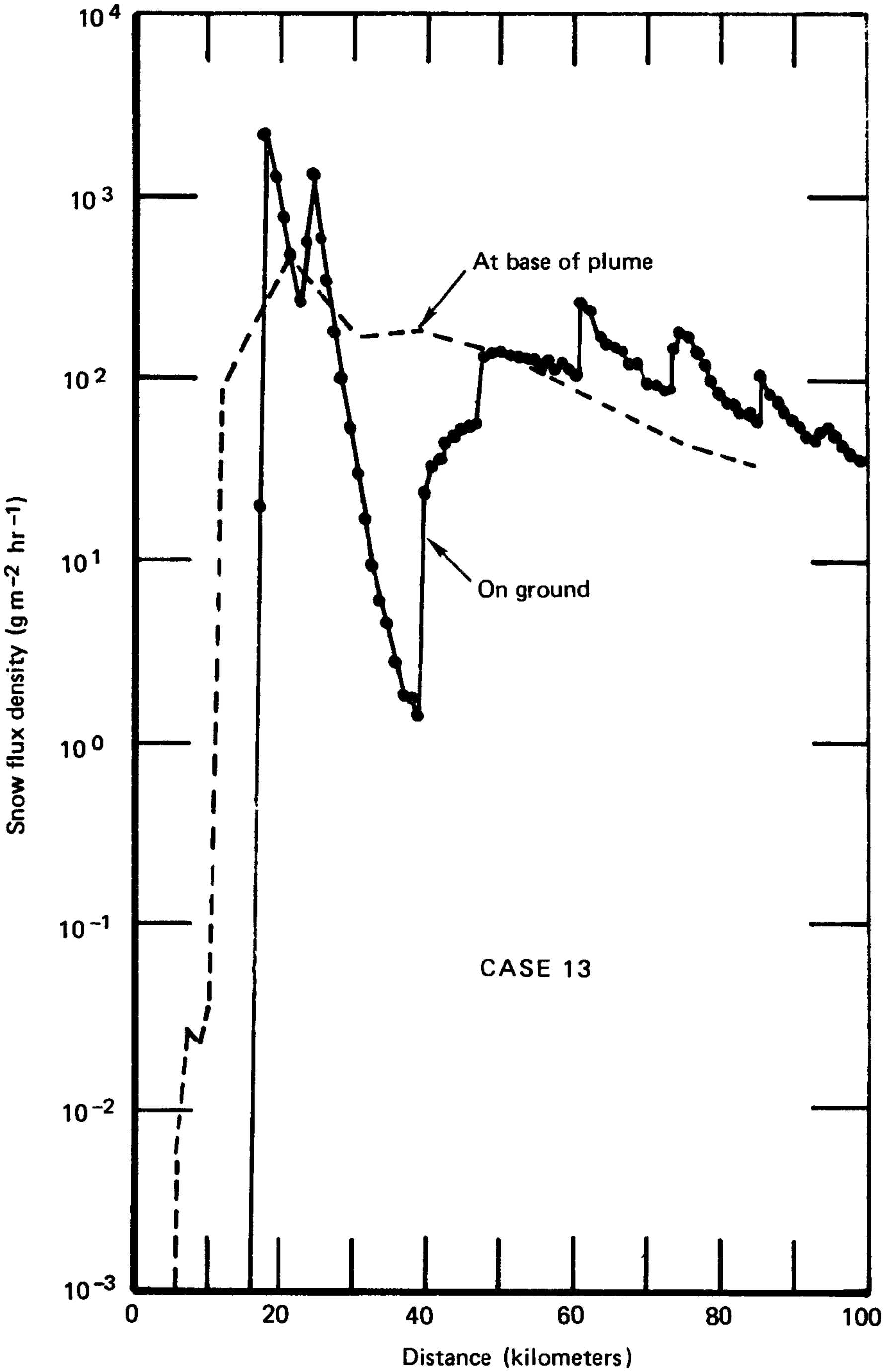

Fig. 12 — Snow-flux density at the ground averaged over 1 km radial distance increments along the plume centerline and flux density at the base of the plume for Case 13 (-16 °C)

the run was short of what would be desired, but experience shows little additional snow would have fallen, for the plume ice content is low, and inspection of the output data shows both ice-content and ice-growth rates were rapidly decreasing with time.

Cases 10, 12, and 13 are identical except for ambient air relative humidity and the sequence of introduction of ice crystals. As expected, there is a direct relationship between relative humidity and snow flux (the timing of the introduction of ice particles influences to an obvious extent the snow-flux density as a function of location but plays only a minor role in regulating total snow flux).

Cases 11 and 12 provide means to evaluate mixing rate differences in an ice-supersaturated environment. The result verifies expectations: greater snow flux and accumulation occurred in Case 11 which used the greater mixing rate. Case 12 was terminated rather too early, but comparison of snow flux at a given time shows the same relationship (at 3100 seconds, for example, Case 11 had 1500 kg s^{-1} and Case 12 had 900 kg s^{-1}). Note that in Case 11 about three-quarters of the total accumulation during the 5750-sec run fell during the first 3100 sec.

Table 2 indicates greater snow flux in Case 11 (1900 kg s^{-1}) with ambient relative humidities of 100 percent compared to Case 13 (1800 kg s^{-1}) with 110 percent relative humidities (corresponding to merger with a cloud having a liquid water content of 0.13 g m^{-3}). Both cases were carried out for essentially equal time periods. The cause of the unexpected differences lies in the fact that Case 11 had a greater mixing than Case 13. The available moisture in the greater volume of entrained air in Case 11 exceeded that in Case 13 in spite of the latter's greater available moisture on a unit volume bases.

Comparison of Case 11 with Case 10, 12, or 13 also shows that snow falls closer to the source in the case with greater mixing. The greater mixing of Case 11 than of the others leads to more rapid cooling, and this in turn leads to earlier and more rapid ice-particle growth. However, in spite of less total snowfall, the flux density (snowfall depth) along the plume center line often is greater in Case 13 than in Case 11 (see Figs. 11 and 12). The explanation probably lies in the greater area at a given range over which the snow falls (for example, after drifting downwind for 3100 sec, at which time both puffs are 45 km from the source, the Case 11 puff is 0.9 km wide, whereas the Case 13 puff is 0.6 km wide). Figures 11 and 12 reveal the general tendency of the model to predict the greatest snowfall to occur almost coincidental with the first deposition of snow on the ground. This reflects the high liquid water content (around 1 to 2 g m^{-3}) of the plume as it reaches its maximum height, the rapid growth of ice particles this liquid provides, and the similar lifetime of all ice particles. The last factor causes the ice particles to have a rather narrow size distribution, and consequently little sorting occurs as they fall out. Later the lifetimes of the ice particles are much more varied, for the particles have undergone different growth histories and their characteristics vary widely. Consequently, their fallspeeds are dissimilar, and as they fall they become sorted by the horizontal wind. This causes dispersion of the snow and tends to reduce accumulations. The greater area over which the material is deposited also acts to lessen accumulations. Acting counter to these effects causing snow accumulations to decrease with distance is the increase in snow flux at the plume level that generally continues well after the plume first begins snowing (see Figs. 8 and 12).

Snow falls closer to the source in Case 10 than in Case 12 (in spite of lesser water vapor in the entrained air and consequently the expectation that ice growth would be somewhat slower in Case 10 than in Case 12). The close-in deposition of ice in Case 10 is caused by rapid growth of one category of ice (no category grows quite so rapidly as in Case 12--the growth is more uniform). This again shows the sensitivity of the model to the limited categories of ice particles. In nature, nonuniformity of the environment of the growing ice particles would stochastically create a broad spectrum of particle sizes and more uniform deposition.

Temperature -17°C

Three runs, made early in the development of the model, using plume level temperature of -17°C, are included in Tables 1, 2, and 3.

All used relative humidities of 80 percent. Each used different mixing criteria. In Case 14, Type A (Fig. 5) mixing was used; in Case 15, mixing was somewhat greater than Type A; and in Case 16, it was less than Type B but greater than Type A. Comparing Cases 15 and 16 (which used identical wind specifications) shows the expected: the greater the mixing in a subsaturated environment, the lower the snow flux. Comparison of Case 14 with 16 also supports this expectation; however, it is not supported by the comparison of Cases 14 and 15. That comparison perhaps shows influences of the greater plume rate of rise in Case 14 but somewhat lower rate of mixing. The net result is that Case 14 has marginally lower snowfall than Case 15, but this may be an artifact. These runs use markedly different time intervals for the introduction of new ice categories, and the similarity in results makes it unwise to speculate on causes of differences.

Evaluation

Comparison of these numerical results with observations of plume behavior that are documented by Kramer and his associates at Smith-Singer Meteorologists and by Otts shows that the model enjoys skill in predicting plume behavior. The sharp contrast in behavior between -12°C and -14°C is particularly noteworthy. The location of first appearance of snow at plume level and the first deposition of snow seem satisfactory, but these are regulated mainly by the assumed vertical rise of the plume and horizontal wind speeds and are not particularly valuable indicators of the fidelity of the model. No measurements exist with which to compare the computed properties of the plume.

The main discrepancy between the model and observations is the location of the maximum depth of snow (assuming for the moment that the ratio of snow depth to flux density is a constant, and therefore measured snow depth can be related to snow flux; but see the following section on the ice-particle characteristics). In nature, the maximum depth of snow appears considerably farther downwind of the first deposition of snow than the predicted maximum snow-flux density. The problem probably lies in deficiencies in the treatment of mixing between the plume and its environment and the failure of the model to develop an ice spectrum with a wide variety of fallspeeds that is necessary if the horizontal wind is to effectively sort and disperse the snow as it falls. With time this kind of spectrum develops in the model but not in the early stage.

Few measurements of the snow flux and flux density are available. The model seems to be adequate in this regard, erring perhaps on the low side. Only one source flux (and flux density) was used in this work; it (1000 kg s^{-1} of water vapor) was somewhat less than that of the Amos plant where Kramer and his associates made most of their observations. The source and snow fluxes should be directly correlated, and therefore the flux of snow would be greater if the larger source strength were used.

As revealed in Figs. 7 through 12, the flux of snow at the ground is not smoothly distributed. This is due to the limited number of categories of ice particles used in the calculations. Wind sorts the particles as they fall, tending to disperse the snow, but from a given location in the plume all particles in each separate category fall in the same location, and there are wide gaps in the instantaneous deposits of snow (see Fig. 6). The flux of snow along the entire length of the plume smooths the deposition, but the tendency for a sawtooth pattern remains (see Fig. 11). This pattern is caused by the generally diminishing contribution of individual ice-particle categories as their number concentration decreases as they grow and fall out in their downwind journey.

As shown in Figs. 7 and 12, the snow flux at the plume as a function of location is smoother than that at the ground. At plume level wind sorting has not yet occurred, so the flux largely reflects the rate of growth of ice, which is relatively smooth. (Data on this parameter are assessable infrequently in the printouts of the experiment, and therefore the lines on Figs. 7 and 11 depicting these values may not be as smooth as they would have been if more points were available for plotting.)

The model is considered to have sufficient fidelity to be valuable for evaluating the role of various factors on snow flux and (with greater uncertainty) flux density.

IV. DISCUSSION OF THE ROLE OF VARIOUS FACTORS IN SNOW ACCUMULATION

TEMPERATURE

The number concentration of ice particles nucleated and their growth rates are highly temperature-sensitive. Accordingly, the expected result is that the temperature at the summit of the plume is a major factor in determining the degree of plume glaciation and the location and amount of snowfall. This is confirmed by the data shown in Table 2.

The ambient temperature at the summit of the plume largely controls the plume temperature during the growth of the ice particles. Early in the lifetime of a plume parcel, the tower exit temperature (in these experiments held constant at 25°C), mixing rates, and plume vertical rise rates importantly influence plume temperatures and consequently the early concentration and growth rates of the ice particles.

ATMOSPHERIC MOISTURE CONTENT

The lifetime of a plume puff (the length of the plume itself) varies inversely with the saturation deficit of the ambient air mixing into the plume. Therefore, it is not surprising that data in Table 2 indicate that, for a given temperature, snow flux varies inversely with the relative humidity of the ambient air (compare Cases 3 and 4, 4 and 5, 6 and 7, 6 and 8, and 12 and 13).

Cases 11 and 13 seem to be exceptions, but in both of these cases the air is supersaturated with respect to ice, and the greater dilution of the plume in Case 11 than in Case 13 results in more water vapor becoming available for ice growth and more snow being deposited in spite of Case 12 having the higher relative humidity.

Plume moisture content, through control of ice-particle growth rates, also regulates the location of deposition of the snow. This is most evident in the distance from the source to the first deposit of snow (contrast Cases 3 and 4).

MIXING

The rate of mixing with the environment affects the amount of snowfall.

If the ambient air is supersaturated with respect to ice, then the greater the mixing, the greater the snow flux (contrast Cases 7 and 8, and Cases 11 and 12).

If the ambient air is subsaturated with respect to ice, then the greater the mixing, the faster the plume evaporates and the less snow that falls (contrast Cases 3 and 5).

HORIZONTAL WIND SPEED

Trajectories of snow particles are regulated by their fallspeeds and the horizontal wind speeds. For a given fallspeed, the stronger the horizontal wind the farther from the source one expects to see snow first falling from the plume, the farther downwind it is deposited, and the greater the area over which it falls. Dispersion caused by the sorting in accordance with fallspeed by the horizontal wind also increases with wind speed.

Consequently, snow-flux density (accumulation) is inversely correlated with horizontal wind speed, but snow flux should be independent of horizontal wind speed.

PLUME RISE

A value of 4 m s^{-1} was used in all runs for the exit velocity of the plume from the cooling tower. The value of plume rise near the summit varied from 0.5 to 4 m s^{-1} (after reaching the summit the vertical velocity becomes zero in all cases). Linear interpolation provides intermediate values. Accordingly, the time required for the plume to reach equilibrium height (1200 meters in all cases) depends on the plume rise value near the summit. Since mixing is time-dependent, the degree of mixing at any height depends on the plume rise rate. This, in turn, affects the rate of decrease of plume temperature and, due to the temperature dependence of the activity of ice-forming nuclei, the concentration of ice particles during the early lifetime of the plume.

The plume rise rate also affects the location where ice particles first fall from the plume: the faster the plume rises and becomes stabilized the earlier the ice particles fall out and the closer to the source one might expect to see snow falling from the plume.

INFLUENCE OF AMBIENT WATER CONTENT ON ICE-PARTICLE CHARACTERISTICS

The snow particles that fall close to the source generally show growth attributable to riming to be greater than that due to diffusion (5 to 1 being a representative ratio). Later the snow continues to have rime growth exceeding that due to vapor diffusion if either: (1) the plume merges with a cloud and droplets continually become available for rime growth (Case 7, for example), or (2) the air mixed into the plume is so dry that vapor densities fall close to or below ice saturation and little or no growth by diffusion takes place (Case 6, for example). If the ambient vapor density lies between the two extremes, growth by diffusion may increase in vigor relative to rime growth. Drops for riming become depleted, but vapor for diffusion becomes replenished (Case 11, for example).

Since snow deposited as heavy rimed particles will have greater bulk density than snow deposited as essentially pristine crystals, one should expect variations in the depth of snow that are dependent on the type of snow particle deposited as well as the snow flux. Accounting for this effect would result in snow depths being less than anticipated (using a constant ratio of flux to depth) close to the tower, and greater well away from the tower, in the common circumstances.

V. CONCLUSIONS

The amount of snow falling from cooling-tower plumes depends on the outcome of the competition between the evaporation of the plume and the total growth of ice particles. The depth of snow depends on these factors plus the dispersion of the snow.

The growth of ice depends on the concentration of ice particles and their growth rates. Both of these factors are strong functions of temperature. The evaporation of the plume depends on the ability of the ambient air to receive water vapor (that is, the saturation deficit of the ambient air) and the rate of mixing between the plume and its surroundings. In ice-supersaturated environments, the snow flux is not limited by evaporation but may be limited due to the fallout of snow particles and the inability of any mechanism to replenish them.

Observations, theory, and numerical experiments all point to criteria of temperatures below -13°C and ambient water vapor deficits less than 0.5 g m^{-3} in order for measurable snow to fall within about 50 km of a 1000 kg s^{-1} water vapor source. The above statement assumes winds of the order 10 m s^{-1} at the plume.

Numerical modeling shows skill in reproducing observations, and therefore confidence can be placed on the ability of simulations to reveal the interconnections between snowfall and various characteristics of the plume and the atmosphere.

Among these interconnections is mixing between the plume and its environment. Mixing may increase or decrease snowfall depending upon whether the environment is supersaturated or subsaturated with respect to ice. Simulations strongly suggest that the closest deposition of snow is a function of the vertical rise rate of plume elements and their degree of mixing with the environment as they rise. The primary factor connecting these properties is the rate of cooling of the plume. The colder the plume the greater the concentration of ice particles and the greater the amount of snow created.

The focus of attention on improving the model should be placed on dynamics. Using available theory, one can compute the rate of rise of a plume element, its height of rise, and its entrainment of ambient air, given the vertical structure of the atmosphere. It would be useful to use this capability rather than the arbitrary specifications of plume dynamics that were used in this work.

The microphysical components of the simulation that establish the rates of growth and evaporation of plume hydrometeors are judged satisfactory. The weakest point in the microphysical aspects of the model is the lack of an objective method to regulate efficiently the timing of the introduction of new ice-particle categories in response to the cooling of the plume and the mixing of additional nuclei into the plume. For economy of computation, one seeks to minimize the number of ice-particle categories, but for accuracy in results one wishes an infinite number of categories. The satisfying balance is difficult to find.

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