OBSERVATIONS OF EFFECTS ON CLOUDS AND RAINFALL CAUSED BY EFFLUENTS FROM PAPER MILLS*

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1. INTRODUCTION

Hobbs et al. (1970) have reported that, on many occasions, the effluents from paper mills have been observed to have an appreciable influence on the visible structure of clouds forming downwind. They described one occasion when rain was observed to fall from clouds forming in the plume of the paper mill at Port Townsend, Washington, but not in any other clouds in the vicinity. Their measurements of cloud condensation nuclei (CCN) in and out of the plumes of paper mills demonstrate that paper mills are sources of CCN. As a result of these observations and measurements, they postulated that paper mills emit giant CCN (<1 μm in diameter). Furthermore, they reasoned that the large cloud droplets which form on the giant CCN would increase the collection of smaller droplets and might thereby increase rainfall.

Aerosol particle measurements made in and out of the plume of the paper mill at Port Townsend, Washington, by Eagan et al, (1974), confirmed that this mill is a source of giant aerosol particles (>1 μm in diameter). Furthermore, these authors found that small, non-raining, warm, cumulus clouds located in the plume of the mill contained higher concentrations of droplets ⩾30 μm in diameter than otherwise similar clouds located in nearby air unaffected by the plume. They concluded that these large droplets formed on giant particles emitted from the mill which served as CCN.

The concentrations of giant particles, in and out of the plume of the Port Townsend paper mill, which deliquesce and serve as CCN, were determined by Hindman et al. (1975) from observations of aerosol particles ⩾ 5 μm in diameter collected on optical microscope slides. It was found that the concentrations were greater by a factor of six in the plume than out of the plume. These measurements confirm the conclusion reached by Eagan et al. that the paper mill is a source of giant CCN.

Hindman (1975) sampled small, non-raining, warm cumulus located in and out of the plume of the Port Townsend paper mill. He found that the clouds contained similar total droplet concentrations, but that the clouds located in the plume contained higher concentrations of droplets ⩾30 μm in diameter. The size distributions of CCN were measured beneath these clouds and droplet size distributions were calculated from these measurements using the numerical model of warm cumulus clouds developed by Silverman and Glass (1973). The measured and calculated droplet size distributions

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were in good agreement. It was concluded from these results that the paper mill plume is not a source of small CCN (∿ 0.08 μm diameter which would increase the total concentrations of droplets in clouds. However, it was concluded that the plume is a source of large (0.2 to 1 μm diameter) and giant CCN which cause the measured high concentrations of large droplets in clouds located downwind.

The effects on rainfall caused by the large and giant CCN from the plume of the Port Townsend paper mill were calculated using the numerical model of warm cumulus clouds developed by Silverman and Glass and the numerical model of warm stratus clouds developed by Tag et al. (1970). The concentrations of large and giant CCN measured in the plume were calculated to have no significant effects on the amounts of rainfall from maritime, warm cumulus. The calculations indicated an increase in rainfall from maritime, warm stratus of 6%. This increase was due to droplet rainout alone and not to collection of the smaller stratus droplets by the larger droplets produced by the large and giant CCN from the mill. The results of the calculations with the numerical models indicate that the large and giant CCN alone may not be responsible for the anomalous showers observed by Hobbs et al. (1970).

In this paper observations of anomalous showers from clouds in the plumes of paper mills are described, and the effects of heat and moisture plus the CCN from the mills on the formation of the showers are discussed.

2. OBSERVATIONS

Hobbs et al. (1970) reported that, on many occasions, the effluents from paper mills have an appreciable influence on the visible structure of clouds forming downwind. For example, on April 30, 1969, clouds a few hundred meters in depth, forming in the plume of the paper mill at Port Townsend, Washington, were observed to produce rain over the Puget Sound at a distance of 2 to 3 km downwind of the mill. Clouds in the vicinity of the mill, but not affected by its plume, were observed to not produce rain.

On September 4, 1974, a uniform deck of stratocumulus clouds was producing rain at a distance of 5 km downwind of the paper mill located at Everett, Washington. Figure 1 is a photograph of the mill and the shower. The unique odor of the paper mill was detected in the rain shower. At the time of the photograph, showers were occurring at Seattle-Tacoma Airport 33 km south (upwind) of Everett and in rural country 25 km north (downwind) of Everett.

On August 20, 1974, a deck of stratocumulus clouds was producing a "shower" (consisting primarily of giant aerosol particles and a few raindrops) at a distance of 3 to 4 km downwind of the paper mill located at Port Townsend, Washington. Figure 2 is a photograph of the mill and the "shower". Shortly after the photograph was taken, rainshowers were observed over Sequim Bay (14 km downwind of the mill) and the smoke from the mill was observed to be drifting past Sequim Bay to Port Angeles (47 km to the west of the Port Townsend mill). No rainfall was observed from the scattered cumulus located upwind of the mill.

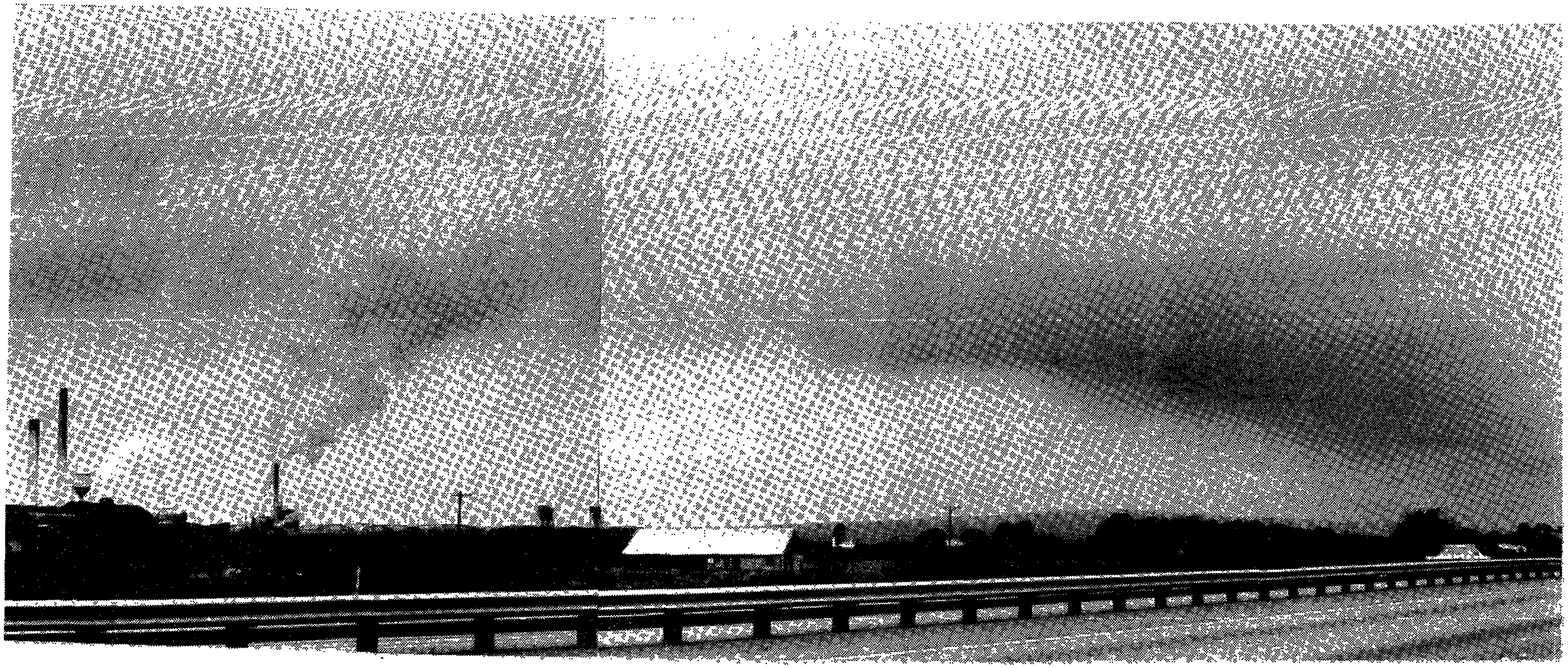

FIG. 1

The plume from the paper mill at Everett, Washington, lofting into a stratus deck. The rain shower, at the right of the photograph, is 5 km from the stack. The unique odor of the paper mill was present in the rain shower. The photograph was taken at 1300 PDT, September 4, 1974. The 1300 PDT observation at nearby Paine Field was as follows: E3⦶9⊕7 61/56/2705/003. Showers were occurring at Seattle-Tacome Field 33 km south of Everett and in rural country 25 km north of Everett at 1300 PDT on September 4, 1974. Showers occurred in Seattle at about 0600 PDT on September 4, 1974.

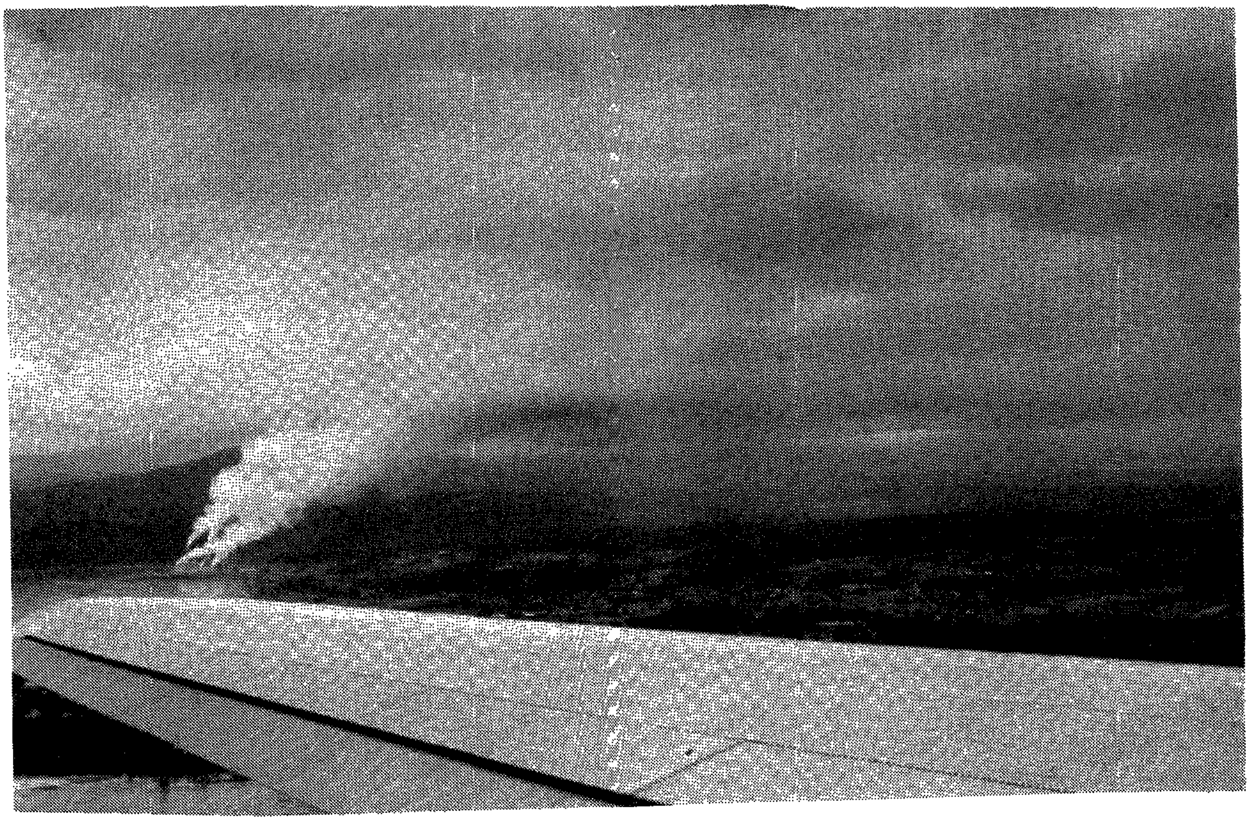

FIG. 2

The plume from the paper mill at Port Townsend, Washington, lofting into a stratus deck. The "shower", slightly to the right of center of the photograph (3 to 4 km from the mill), consisted mainly of giant aerosol particles and a few raindrops. The photograph was taken at 1137 PDT on August 20, 1974. Rain showers were observed over Sequim Bay (14 km downwind of the mill) at 1150 PDT and the smoke from the mill was observed to be drifting pass Sequim Bay to Port Angeles (47 km to the west of Port Townsend mill) at 1150 PDT. Rainshowers occurred over the Puget Sound at Tatoosh Island at 0300 PDT on August 20, 1974.

3. DISCUSSION

The observation of Hobbs et al. on April 30, 1969, and those presented in Figs. 1 and 2, indicate that during meteorological conditions favorable for the production of rain the plumes from paper mills cause rain showers to occur 3 to 5 km downwind of the mills. Therefore, it appears that the effluent from the paper mills may act in the place of natural perturbations to initiate the formation of rain.

The effluents from paper mills consist of heat, water vapor, particles and gases (SO_2, CO, etc.). Calculations by Hindman (1975) indicate that the particles alone may not be responsible for the anomalous rainfall. It was also shown that the gasses probably do not influence rainfall significantly. The rapid formation of precipitation within a short distance downwind of the mills indicates that the heat, water vapor and particles emitted by the mills invigorate the convective and precipitation processes in clouds downwind of the mills. This may occur as follows: (i) the heat from the mills produces positively buoyant air parcels which cause clouds to rise to higher levels than they would otherwise[1]. The parcels contain not only additional heat but additional moisture and CCN from the mill. (ii) The additional moisture, plus the increased rise of the parcels, causes more liquid water to be produced than in parcels without heat and moisture from the mills. (iii) This liquid water condenses upon the large and giant CCN from the mill. (iv) The resulting cloud droplet size distribution within the rising parcels is conducive to the rapid formation of raindrops due to the reservoir of small cloud droplets which are ripe for collection by the significant number of large droplets forming on the large and giant CCN emitted by the mill. The reservoir of small droplets is not dissimilar from the reservoir in nearby ambient clouds because the mill is not a significant source of small CCN which form small cloud droplets. (v) The clouds invigorated by the effluents from the mill rise higher than surrounding clouds, and mix with the dry air above the cloudy layer. The mixing causes the cloud droplets to evaporate (leaving the larger raindrops). (vi) The evaporating droplets cool the cloudy parcels and causes them to become negatively buoyant. The negatively buoyant parcels containing the raindrops then descend through the cloudy layer and cause rain on the ground a short distance downwind of paper mills.

Effects caused by heat and moisture from a paper mill on clouds and rainfall were estimated from meteorological sounding data collected on August 3, 1975, a day in which warm cumulus were raining in the vicinity of Port Townsend paper mill. The data are presented in Fig. 3. The layer from the surface to 920 mb (cloud base) has a temperature lapse rate which is less than dry-adiabatic, a situation not conducive to convective cloud development. For vertical motions to occur, the surface temperature must increase by about 1.5C. This increase would cause the temperature lapse rate to become less than dry-adiabatic, a situation conducive to vertical motions.

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[1] It is common to observe mounds on the top of otherwise smooth cloud decks which are caused by heat released by industrial sources (see Scorer, 1972).

The temperature of a rising-air parcel, initially 1.5C warmer than its surroundings at the surface, is depicted by the diamond points in Fig. 3. The parcel cools at the dry-adiabatic lapse rate from the surface to 920 mb. At 920 mb the parcel has cooled sufficiently to become saturated; therefore, this would be the level of cloud base. Above 920 mb the parcel cools at the moist-adiabatic lapse rate (assuming for simplicity no dilution of the parcel by the environmental air). The parcel is warmer than the environment and continues to rise until it cools to the environment temperature. Vertical motions cease at this point (about 790 mb) and the top of the cloud is established at this level. Cloud A in Fig. 3 represents the cloud depth achieved by the rising parcel.

The amount of water condensed in the rising parcel was calculated by subtracting the mixing ratio at the cloud-top level from the mixing ratio at the cloud-base level. The condensed water amounts to 3.0 g m^{-3}. The liquid water content generated by a rising but entraining parcel was calculated to be 1.8 gm^{-3} using the Silverman and Glass (1973) numerical cloud model. The results of the model calculations indicated that this amount of condensed water is sufficient to form rain (a result in agreement with the observed rainfall on August 3, 1975).

Now, consider a saturated plume from a paper mill which has risen to cloud base. It is assumed that the parcel is saturated and 2C warmer than the environment at cloud base. The triangle points in Fig. 3 show the decrease in temperature of this parcel with increasing height (decreasing pressure). The parcel, rising undiluted, reaches an equilibrium level at about 670 mb compared to 790 mb for the undiluted parcel which did not contain additional heat and moisture from the mill. Cloud B in Fig. 3 represents the cloud depth achieved by the rising parcel which contained the additional heat and moisture. The condensed water amounted to 6.0 g m^{-3}, and 100% increase from the water condensed in the parcel unaffected by the heat and moisture from the mill. This 100% increase in liquid water is expected to cause an increase in precipitation. The increase in precipitation will be less than 100% but probably greater than 20%. Additional calculations with the Silverman and Glass model should be carried out to estimate the effect of additional heat and moisture on precipitation from warm cumulus clouds.

This analysis indicates that the dynamical processes in warm cumulus clouds may be invigorated by heat and moisture released from a paper mill. This invigoration, plus the acceleration of the precipitation formation processes by the large and giant CCN from the mill, provides a potential explanation for the observed effects on clouds and rainfall caused by the effluents from paper mills. The explanation seems plausible in view of experiments in which the dynamical and microphysical processes in cold cumulus clouds have been invigorated by injections of artificial ice nuclei (Simpson and Dennis (1974) summarize this work). The artificial ice nuclei accelerate the freezing of supercooled water. The accelerated freezing provides additional heat which causes the clouds to grow taller than their unseeded neighbors. The taller clouds condense more water. The increased water content, plus the increased numbers of ice nuclei, lead to an increase in rainfall.

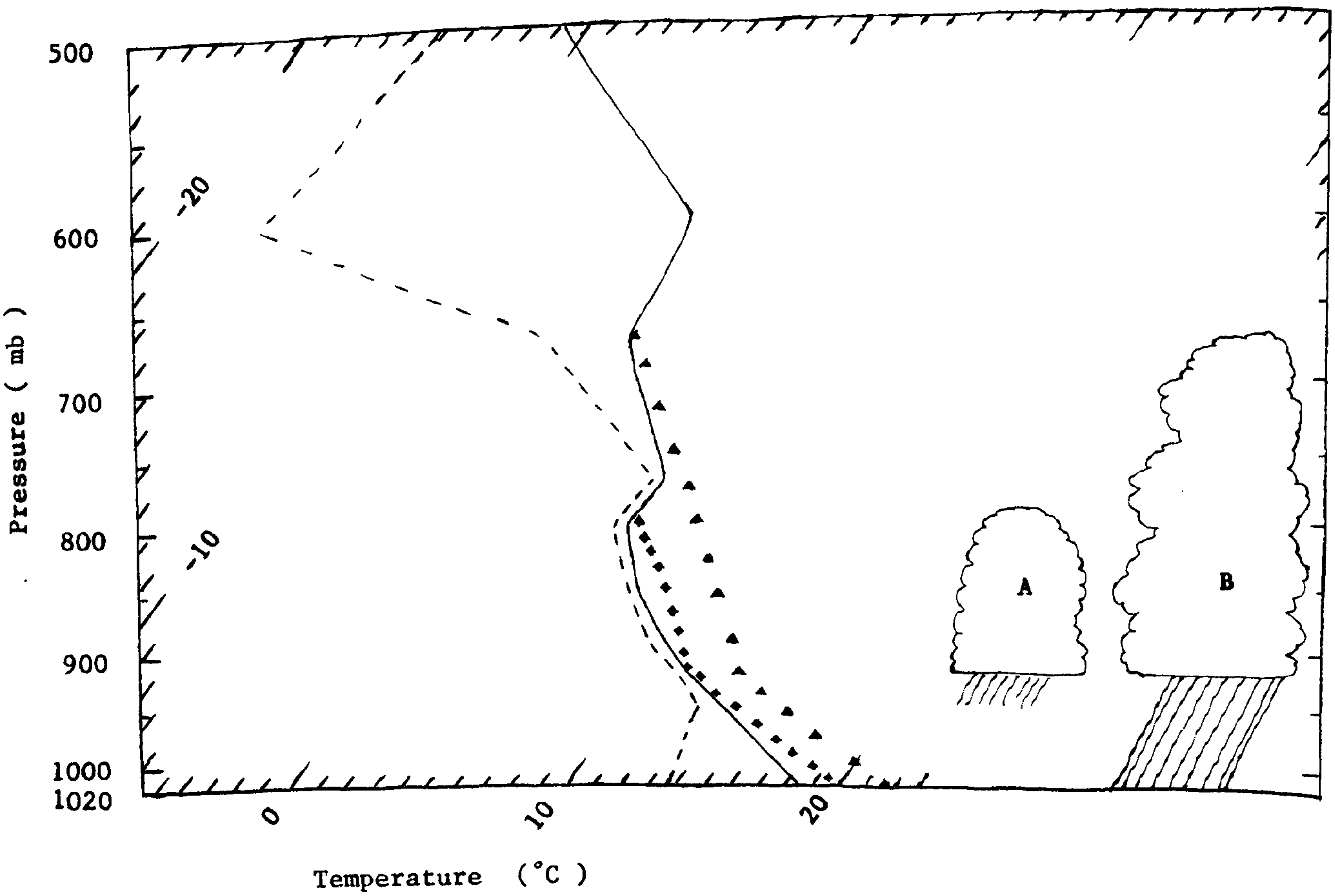

FIG. 3

Meteorological sounding constructed from the 1700 PDT Quillayute, Washington, sounding (surface to 850 mb) and the 0500 PDT Quillayute sounding (850 to 500 mb), for August 3, 1975. The sounding approximates the conditions expected at 1300 PDT when rainshowers occurred near Quillayute. The solid line is the environment temperature, the dashed line is the environment dewpoint, the line of diamonds represents the temperature of a rising parcel initially 1.5C warmer than its surroundings and not affected by the paper mill plume, and the line of triangles represents the temperature of a rising parcel affected by the plume. Cloud A represents the depth of the cloud formed by the parcel not affected by the mill. Cloud B represents the depth of the cloud assuming the rising parcel is warmed by 2C at cloud base by the heat from a paper mill.

4. CONCLUSIONS

Observations are presented which demonstrate that the effluents from paper mills cause rainshowers to occur a short distance downwind of the mills. These showers have been observed to occur both with and without nearby rainshowers unaffected by the effluents. Calculations have shown that, alone, the large and giant CCN emitted by the mills cannot account for the showers. It appears, however, that heat and moisture from the mills in combination with the additional CCN can explain the observed rainshowers. These showers may produce more rainfall than nearby showers unaffected by the effluents. However, further research will be necessary in order to correlate the showers caused by the effluents with the anomalous increases in rainfall in the vicinity of paper mills reported by Hobbs *et al*. (1970).

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