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ON THE POSSIBILITY OF WEATHER MODIFICATION BY AIRCRAFT CONTRAILS

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ABSTRACT

The possible effect of contrails in modifying the weather is reconsidered in the light of information obtained from ground-level contrails in Alaska. It appears likely that inadvertent cloud seeding by jet aircraft may be of the same order of magnitude as that attained in commercial cloud seeding operations. Further investigation is needed; but in the meantime, the possibility of contrail contamination should be kept in mind when evaluating the results of seeding operations.

1. INTRODUCTION

Aircraft contrails first attracted public attention during World War II; but as air traffic has built up to its present level, they have come to be accepted as part of the environment. Even during World War II, it was difficult to watch the cloud cover laid down by a large bomber formation without wondering what it might be doing to the weather; at present, there is widespread belief among the general public and some feeling among scientists (Fletcher 1969, Reinking 1968, Livingston 1969, and Schaefer 1969) that contrails are increasing cloudiness, if nothing more, in some regions. The writer himself has seen instances in which a single contrail seemed to grow until it became an overcast covering the whole sky. If the contrail were indeed responsible, which is by no means certain, this would constitute definite proof that contrails are capable of a significant effect on local weather, and even possibly on global climate, if such occurrences are widespread and frequent. It seems worthwhile, in view of all this, to consider quantitatively whether or not there is reason to believe contrails are capable of exerting a significant influence on weather.

2. OBSERVATIONS ON THE COMPOSITION OF THE CONTRAIL

Any quantitative discussion should start with the contrail itself. A medium-sized jet airliner—the Boeing 727 to be specific—burns over 3100 kg of fuel per hour while cruising, producing over 1.2 times as much water (more than a kilogram per second). It is this water that forms the contrail, and a discussion of the basic processes by which it does so was given by Appleman (1953). His discussion also gave a fairly accurate description of the conditions under which a contrail will be formed, but did not discuss the nature of the contrail particles further than to specify that they are ice crystals. Some attempts have been made to sample the contrail particles in flight, but there is always skepticism as to how well the particles collected under such circumstances represent those in the contrail. During the winters of interior Alaska, however, conditions are frequently such that a contrail is left while the aircraft is taxiing and taking off or landing so that it is easily accessible for study. (On the ground, the contrail is called ice fog, and it can become a serious problem in flight operations.) This discussion is based on observations made under the direction of Ohtake (1967; see also Huffman 1968) during the course of investigations of ice fog from this and other sources. As a result of these observations, enough is known about the way the contrail is formed to make it safe to state that the contrail formed at cruising altitude is very unlikely to differ greatly from that formed on the ground.

Ephemeral contrails are of no particular interest here, although a great deal can be learned about conditions in the atmosphere by observing their formation and disappearance; the discussion will therefore be limited to those formed while the aircraft is cruising in atmosphere at least approximately saturated with respect to ice and at a temperature of approximately $-40°C$ or lower. When the jet exhaust enters such an atmosphere, it is very rapidly cooled by expansion and turbulent mixing, and the water vapor condenses in the form of very small droplets. Although the cooling is so rapid that levels of supersaturation at which homogeneous nucleation could take place should be reached, electron microscope photographs of the crystals show no evidence that it ever happens. The droplets all appear to form on nuclei, which are abundantly provided by the exhaust products, even if not otherwise present. The liquid droplet phase is very short-lived—of the order of a second—since the ambient atmosphere is below the spontaneous freezing threshold. The droplets freeze, and the result is a cloud composed mainly of the small, roughly spherical crystals called "droxtals" by the Stanford group who first reported them (Thuman and Robinson 1954). The time before the cloud is completely frozen is much too short to allow mass exchange to take place between liquid droplets or between liquid drops and ice crystals, but there may be some crystal growth while the environment is between water and ice saturation. The end result seems to be dependent mainly upon ambient temperature and little upon details of the way the exhaust enters the atmosphere, the ice fog produced by an automobile exhaust being practically identical to that from a jet engine. One therefore feels quite confident in using the results of the ground observations to discuss the contrail formed at cruise altitude.

Nearly 80 percent of the crystals collected near the airport runway had a diameter near 4 μ. All collection methods are open to the suspicion of weighting in favor of larger particles; furthermore, very small particles would not have been detected at all. Many of the crystals collected showed evidence of having ruptured and emitted a spurt of water as they froze from the outside in (Bally-Dorsey effect, Blanchard 1951); this may have produced crystals too small to be detected, though there is no evidence of this effect. At any rate, assuming spherical shape and 2 μ radius gives an average reciprocal mass of approximately 3×10^{10} droxtals gm^{-1}, which is believed to be a very conservative lower limit.

3. CONTRAIL CRYSTALS AS FREEZING NUCLEI

A cruising Boeing 727 then produces 3×10^{13} crystals sec^{-1} if all of the water vapor produced by the fuel combustion goes into crystal formation, as probably happens under the stated conditions, or 10^{13} if only a third of it does. (The writer feels that the actual crystal production rate is probably at least 10^{14} and possibly 10^{15} sec^{-1}. This seems to be confirmed by the area and optical depth of the contrail.) Except for hail suppression operations, large-scale weather modification attempts currently in progress employ ground-based generators to introduce freezing nuclei into the atmosphere. Under these conditions, silver iodide, the nucleating material most generally used, is considered to deliver 10^{13} freezing nuclei gm^{-1} of silver iodide on the average. Under optimum conditions, it may deliver as many as 10^{15} nuclei gm^{-1}; under adverse conditions, it may deliver none at all, since silver-iodide nuclei deteriorate rapidly in effectiveness after entering the atmosphere. It can be seen, then, that a medium-sized jet forming a persistent contrail is introducing nuclei in numbers equivalent to ground-based generators burning more than a gram per second of silver iodide. Since silver iodide is introduced with the object of forming ice crystals from supercooled water droplets, it seems obvious that the contrail ice crystals can produce any effect of which the silver-iodide nuclei are capable, and in addition can do things of which silver iodide is not likely to be capable, such as extracting water from air supersaturated over ice but under water saturation. (Silver iodide apparently can be effective in the absence of water droplets by acting first as a condensation and later as a freezing nucleus, but there seems to be some doubt about how efficient it is in this.) It is then evident that, whenever and wherever persistent contrails are being produced, the airlines are conducting a seeding operation in which each passing aircraft deposits nuclei in numbers at least comparable to a ground-based seeding attempt. The coverage is global in extent, and while random in the sense that airline flights are not scheduled with weather modification in mind, it is not really random with respect to meteorological conditions. Airline operations are affected by the weather, and such things as pressure pattern navigation for instance could well introduce a significant bias. The formation of a persistent contrail is itself a function of ambient conditions that would seem to lead to the crystals being deposited preferentially in situations favorable to modifications of the weather being produced.

4. MODIFICATION BY PROCESSES OTHER THAN SEEDING

The contrail crystals are so small that they fall very slowly in still air, even at jet cruising altitudes, and in the presence of even slight updrafts will not fall at all. Under some conditions, it seems likely that they can accumulate sufficiently to cause some high cloudiness along a busy airway even if they remain essentially unchanged in size and numbers after they are first introduced. This, however, seems to be marginal, and it is unlikely that simple accumulation, even if accompanied by modest growth, is causing much effect at present. There is, however, good reason to believe that some mechanism exists that results in crystal multiplication.

Careful observation of contrails shows that, in general, their behavior is consistent with the higher rates of crystal production given in the discussion above; but in many instances, the contrails attained dimensions that are very difficult to explain by simple growth of the existing crystals unless the numbers given here are very gross underestimates. The crystals in the contrails that exhibited this behavior were obviously growing very rapidly, since well-defined fall streaks developed from them in less than half an hour; so they were evidently in air highly supersaturated with respect to ice. (Natural air can become very much more highly supersaturated with respect to ice than it ever does with respect to water because of the very low content of nuclei capable of removing water vapor from the air once it is below water saturation.) It is also obvious that, if the contrail crystals really did produce the complete sky coverage in the instances mentioned in the introduction, some rapid and efficient process of crystal production must have been triggered. (It is quite evident that systematic and quantitative observation of contrails can lead to a considerable increase in our knowledge of the meteorology of the 200- to 300-mb region and of cloud physics in general, in addition to the value of such observations in connection with the subject of this paper.)

5. GENERAL DISCUSSION AND INFERENCES

It has been shown above that there is good reason to believe that aircraft contrails may be capable of considerable weather modification by producing cirrus clouds at altitudes close to those at which the aircraft is cruising. It is obvious that the contrail crystals may influence cumulus development by getting into clouds that extend to and beyond normal jet cruising levels. A little reflection will show that there is also good reason to believe that contrail crystal seeding may be producing all the effects of which deliberate seeding with freezing nuclei is capable. Crystals falling from cirrus clouds through what appears to have been at least moderately dry air have been observed to survive for astonishing distances (Braham and Spyers-Duran 1967). The contrail crystals must grow considerably before they fall, but they are frequently seen to develop respectable fall velocities within a few minutes after they are formed. Whether or not they are capable of surviving a long fall through dry air, it is likely that they are often deposited in air that is saturated with respect to ice all the way from the altitude of formation to the cloud bases. Under such conditions, they will of course at least survive to the melting level, and it is likely that they will grow and possibly multiply. Under such conditions, they can enter clouds anywhere above the freezing level and possibly for some distance below. (It is difficult to see how they could be injected into a cloud in a manner that would exactly duplicate the conditions of a seeding flight through it or a silver-iodide shell exploded inside, but not so difficult to see how the contrail crystals might produce essentially the same results.) It is not intended here to undertake an exhaustive discussion of the possible effects of cloud seeding by contrail crystals, but one or two possibilities seem worth mentioning.

The orographic cloud situation in which a wet airmass is being driven upward over a mountain range is considered to be one of the more favorable for increasing precipitation by ground-based silver-iodide seeding. This situation, however, leads to an airmass that is rising and cooling over a region that extends for a considerable distance upwind and to altitudes well beyond those at which jet airliners normally cruise. It is likely, therefore, that the air will be at or near saturation, at least over ice, from the cloud base up, and that a persistent contrail will be formed that can and will seed the clouds. When one considers the number of airline flights over an area such as that west of Denver, Colo., one immediately wonders what the airlines may be doing to the statistics used in evaluating the results of commercial seeding. (It should be noted that the writer is *not* contending that either or both operations actually *do* increase precipitation, he is merely pointing out that both should be considered.)

The plains region of the United States is traversed by heavy air traffic; in the summer, it is also heavily populated by towering cumulus so that a jet aircraft is often flying among them. The flight path rarely goes through the clouds because of the turbulence and the likelihood of encountering hail, but the whole region is likely to be saturated with respect to ice. The air is also likely to contain considerable numbers of natural ice crystals, so it is not immediately obvious that the introduction of the contrail crystals can have any effect. However, while riding an aircraft through this region, one sees numerous contrails left by other flights, so it is evident that the natural ice crystal concentrations are much exceeded along the flight path and that this condition persists for some time. Schaefer (1969) mentions this in discussing inadvertent weather modifications. He implies the seeding capabilities but does not discuss them specifically. The probability that a developing thunderhead will entrain such a high ice crystal concentration is thus increased; and a little calculation shows that, if the Russians and the French are right, it could lead to suppression of destructive hail.

There seems little doubt that contrail crystal seeding sometimes disperses clouds in the same manner as seeding with Dry Ice[1] does. Over the years, many instances of cloud dispersal by aircraft have been reported in *Weather*, and many very good photographs have been published. In most instances, not enough data are available to form a firm opinion of how the dispersal was accomplished, but the resemblance of the photographs and the descriptions of the occurrences to those of the results of seeding supercooled water clouds with Dry Ice is so striking that it seems safe to conclude that most, if not all, of the reports are examples of the seeding of clouds by contrail ice crystals. The possible consequences of this are considerable; in fact, it seems probable that one of the projects for modifying the global climate discussed by Fletcher (1965), namely modification of the cloud cover over the North Polar Basin by cloud seeding, is already underway, although the scale is still more modest than he envisioned.

6. CONCLUSIONS

The conclusions reached as a result of the above discussion are that nearly all results that can be produced by seeding with ice crystals are in fact being produced as a result of routine airline operations; that the effectiveness of ice crystals as nuclei over such a wide range of meterological conditions and the scale on which they are being deposited make it likely that they are affecting precipitation to a much greater extent than are present deliberate seeding operations (although the deliberate operations may still show more net results because of the selection of situations suitable for seeding).

It cannot be concluded that any *net* effects *are* necessarily being produced on even local climates, although it seems certain that the seeding is taking place, because the possible results of any kind of seeding are not well understood at present and because the very massiveness and frequency of the seeding makes it likely that such a profusion of effects in contradictory directions is being produced that the net result may be small. The actual magnitude and direction of the effect on the weather can only be established by analysis of the records. The purpose of this paper is to show that there is sound basis for the

[1] Mention of commercial products does not constitute an endorsement.

403-235 O—70——4

suspicion that contrails *may* be influencing the weather and that it is important to find out if they *are*.

In conclusion, it should be stated that if contrails are affecting the weather it is not necessarily for the worse, although if there is any considerable change it is sure to make someone unhappy. The Russians might well be pleased with an ice-free Arctic Ocean; but if it leads to a major glaciation in central Canada, it is unlikely that the Canadians and Americans would regard it as favorable.

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CORRESPONDENCE

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Effect of Range on Apparent Height and Frequency of High-Altitude Radar Precipitation Echoes

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As coauthors of the captioned *Monthly Weather Review* article (Vol. 97, No. 6, June 1969, pp. 429–431), we welcome this opportunity to restate some of our findings so that possible misinterpretation by interested readers may be avoided.

Our conclusion concerning echo altitude and frequency of occurrence due to range effects should state that the net or resulting errors due to range are insignificant rather than the errors are insignificant. The individual errors can be substantial, as mentioned in our paper, and as pointed out in a private communication from Dr. D. Atlas, Director of the Laboratory for Atmospheric Probing at the University of Chicago. We agree, for example, that there is a balancing effect between the increasing width of the beam with range that tends to increase the altitude of reported tops and the beam-width averaging or filling effect that decreases the average reflectivity of the top region with range. Also, height errors obviously depend on reflectivity and its height profile, so that, as Dr. Atlas emphasizes, serious overestimates of precipitation echo tops may occur when the edges or side lobes of the beam detect sufficient reflectivity from below. That such false echoes may occasionally enter the records despite operational procedures and professional manpower as used in the WSR–57 network underscores the fact that reflectivity is a vital factor in radar climatology of storm tops.