Observation of Ice Crystal Formation in Lower Arctic Atmosphere

TAKESHI OHTAKE, KOLF JAYAWEERA AND KEN-ICHI SAKURAI[1]

Geophysical Institute, University of Alaska, Fairbanks 99701

(Manuscript received 12 April 1982, in final form 30 July 1982)

ABSTRACT

Clear sky ice crystals or diamond dust displays are observed in polar regions, both remote and populated, when the temperature falls to −20°C and where abundant sources of water vapor are present. In remote areas of the Arctic, these ice crystals are confined to the lowest 1000 m, leeward of open leads in the sea ice. The crystals always occur in air between ice and water saturation, and air dryer than ice saturation normally overlies the display. In populated regions, water vapor is supplied from man-made sources such as heating plants. Morphological studies of these ice crystals suggest that they are formed first by condensation into water droplets and then by freezing.

1. Introduction

In the polar and sub-polar areas, ice crystals are frequently observed precipitating from clear skies. However, despite extensive observations (Gow, 1965; Kuhn, 1970; Ohtake and Holmgren, 1974; Hogan, 1975; and Ohtake, 1976), a satisfactory formation mechanism for these ice crystals has never been described. The present study of ice crystal formation has been conducted in the Arctic since 1974 with ground-level observations, and was recently completed with the use of a research aircraft instrumented with meteorological equipment. This paper presents the results of these observations, from the ground and in the air.

2. Ground observations of ice crystals

Northern Alaska experiences ice crystal precipitation from clear skies during all but the summer months. Observations of the ice crystals and related meteorological parameters were conducted at the Naval Arctic Research Laboratory (NARL) at Barrow, Alaska.

a. Ice crystal concentration

The concentrations of ice crystals were measured continuously by using an ice crystal counter that employed an acoustic sensor combined with a pulse-height analyzer and a recorder (Ohtake and Holmgren, 1974). The sensor consists of a glass tube that tapers gradually from 2.5 cm diameter inlet to a 6 cm long, 1.5 mm capillary. This capillary is connected to a vacuum pump which draws in air containing ice crystals through the tube at 8.15 liters per minute. Ice crystals larger than 30 μm diameter give sharp clicking sounds which are detected by a microphone and counted. Particulate matter smaller than 20 μm, such as fog droplets and air pollution particulates, do not trigger the sensor. A 5 cm long rubber tube is connected to the inlet of the sensor to minimize false signals due to whistles caused by wind or blowing snow. Blowing snow occurs for wind speeds greater than 5.5 m s^{-1}. For wind speeds between 5.5 and 10 m s^{-1}, it is limited to the lowest 3 m of the atmosphere. This was determined by exposing slide glasses to blowing snow at several different elevations up to 5 m above ground. Since the sensor cannot distinguish between blowing snow particles and ice crystals, the sensor was used at a height of 3.2 m above ground. The sensor was pointed vertically. It was operated in conditions with wind speeds less than 10 m s^{-1}.

The maximum concentration of ice crystals recorded at Barrow by this equipment was 57 crystals per liter, on 29 March 1974, as shown in Fig. 1. The average concentration on that date was ~20 crystals per liter at a ground temperature of −22.3°C. Those crystals may have formed at a height of 400 m where the air was saturated with respect to water at a temperature of −18.5°C, according to radiosonde soundings. An interesting phenomenon in the study of ice crystal precipitation, found by the use of the acoustic sensor, was that the concentration of ice crystals fluctuated with periods varying from 12 to 90 min in the form of "ice crystal showers." During these fluctuations, the ice crystal concentrations varied by as much as a factor of six.

Ice crystal precipitation was normally observed between 0800 and 1900 LST. Furthermore, the ex-

[1] Present affiliation: Hokkaido University of Education, Asahikawa 070, Japan.

0022-4928/82/122898-07$05.75

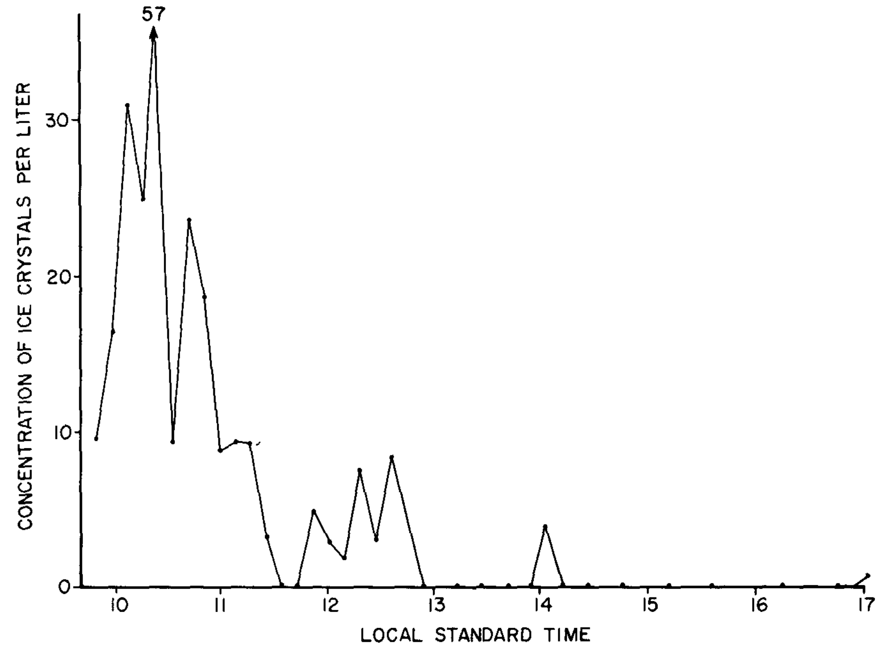

FIG. 1. Temporal variation of ice crystal concentration at the Barrow site on 29 March 1974.

istence of these displays was not limited to days with winds coming from the direction of open leads. This observation initially led us to cast doubt on the expectation that moisture from open leads in the pack ice is essential for the occurrence of ice crystal displays.

b. *Ice crystal shape and size*

A continuous snow crystal replicator was used to record the shape and size of the crystals. This replicator was a modified version of the type designed by Hindman and Rinker (1967). It can operate continuously for 40 h, and crystals were replicated on 35 mm clear leader film coated with 4% by weight of formvar dissolved in chloroform.

The shape of the ice crystals was compared with the temperature of the lower atmosphere. Plate-type crystals with sizes in the millimeter range were usually observed at ground temperatures higher than −22°C. At lower temperatures, columnar crystals occurred, with size ranges of 30–300 μm on the *c*-axis and 15–25 μm on the *a*-axis.

On some occasions the columnar crystals observed on the ground had humps on them as shown in Fig. 2. This type of crystal accounted for ~30% of the columnar crystals collected. It has the following characteristics:

1) In most cases, the hump-like column was observed on the basal plane of the parent columnar crystal so that its *c*-axis was parallel to that of the parent crystal.

2) In the few cases where the hump was appended to the prismatic plane, the *c*-axis of the hump was tilted with respect to that of the parent crystal.

3) There were linear patterns inside the parent columnar crystal which appeared to be strings of small air bubbles.

4) The average *c*- to *a*-axial ratio of the parent crystal was 0.9.

The first two characteristics were determined by utilizing the polarizing microscope technique described by Magono and Suzuki (1967). Also, etch pits, revealed by the formvar solution used for replication, are evidence that the observed crystal grew from two or more original crystals.

These crystals existed when the ground temperature was between −20 and −29°C and radiosonde data showed a saturated layer with respect to water near the 850 mb level. The temperature of the saturated layer was ~−25°C. The existence of these hump crystals and the physics of their formation are relevant to the origin of the clear sky ice crystals in the atmosphere.

3. Airborne observations

As described before, the majority of ice crystals precipitating from the atmosphere are observed at NARL in association with onshore winds, as expected. However, ice crystals smaller than 100 μm were usually present at NARL, even in association with slight offshore winds, when the humidity was

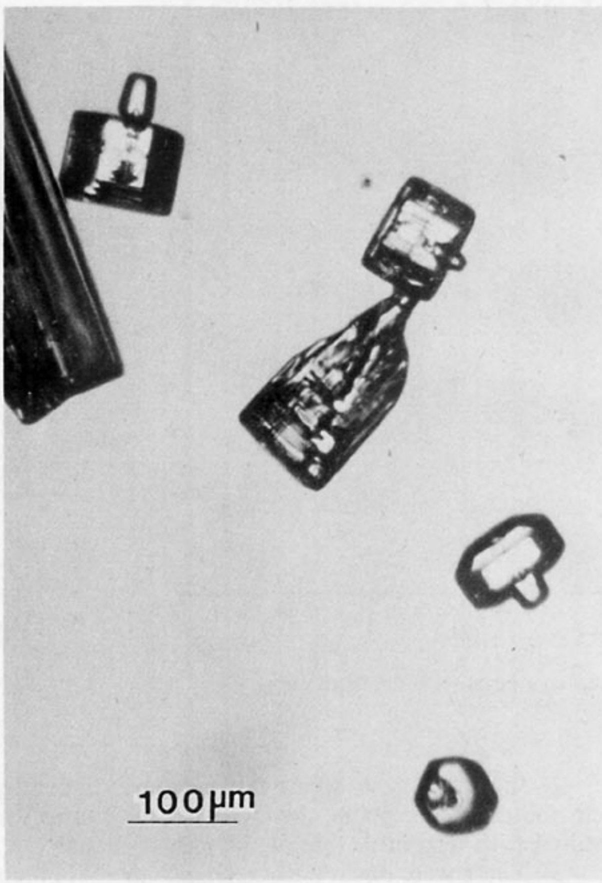

FIG. 2. Columnar ice crystals with humps or spicula, observed on 8 April 1977 at Barrow.

greater than ice saturation at temperatures lower than ∼−22°C. Since ground observations alone could not provide a satisfactory mechanism for formation of ice crystal displays, we conducted a measurement program during 31 March to 14 April 1977 with an instrumented aircraft in the vicinity of Barrow, Alaska. The aircraft was an Aerocommander (see Fig. 3) equipped with: 1) A static temperature probe; 2) A dew point hygrometer; 3) A manual formvar replicator with a decelerator; 4) A cloud condensation nucleus counter; 5) PMS cloud particle spectrometer OAP-1 with a range from 14–310 μm; and 6) navigation instrumentation. The meteorological, navigational and cloud particle data were recorded continuously with a real-time display for monitoring purposes. A continuous ice crystal replicator was operated on the ground at NARL and routine radiosonde observations, made by the National Weather Service at Barrow, were also utilized.

Airborne observations were made only on the days in which we observed some open leads on the Arctic Ocean by use of high resolution satellite imagery received at Gilmore Satellite Tracking Station near Fairbanks. When the winds were offshore, we did not observe any ice crystals at the runway, but large ice crystals were observed exclusively leeward of open leads. Size distributions of the ice crystals acquired on 14 April 1977 are shown in Fig. 4a as an example. It was confirmed that high concentrations of large ice crystals were associated with steam (also known as arctic sea-smoke) and fractostratus clouds. These clouds are created by rapid cooling of water vapor

FIG. 3. The instrumented aircraft used for sampling clear-sky ice crystals.

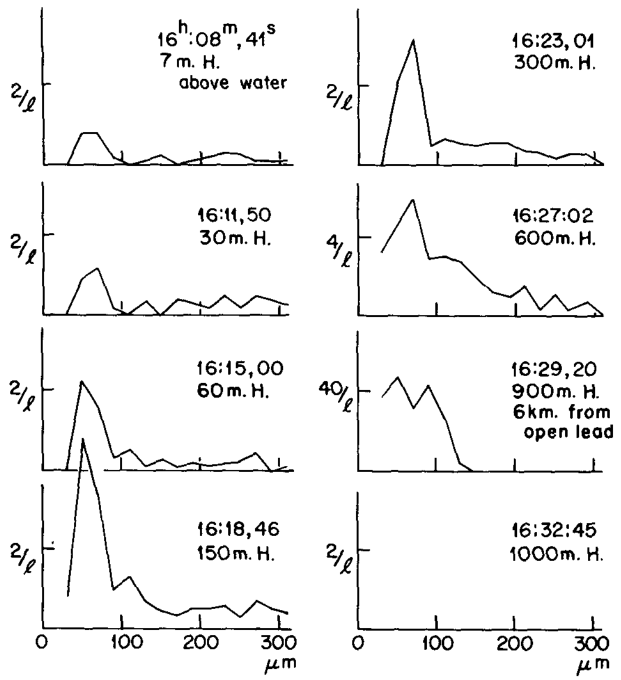

FIG. 4a. Ice crystal concentrations at various elevations downwind from open leads on 14 April 1977.

coming from water (at ∼−2°C) of open leads, when the air temperature is below −20°C and humidity is higher than ice saturation (see Fig. 4b). As shown in Fig. 4b, which gives typical temperature and humidity profiles indicated on the airborne observation records, the temperature profile between the surface and the base of the inversion is usually between dry adiabatic and moist adiabatic, with a strong inversion above. Along the temperature profile, the humidities are nearly at water saturation below the inversion, and the high humidity continues to an elevation of ∼100 m above the inversion base. This type of temperature and humidity profile is common, and occurs in summer in association with Arctic stratus clouds. The amount of water vapor evaporating from open leads at ∼−2°C water temperature increases considerably as the air temperature decreases below freezing. For example, when air at a temperature of −20°C with 70% relative humidity blows over the −2°C sea surface, the water vapor pressure over the water surface and the air differs by a factor of six, which is effectively nearly 500% supersaturation over water. Although such a high supersaturation may not be realized because of mixing with surrounding drier air, a large amount of evaporation of water vapor from open leads results in the formation of steam and then stratus clouds, as shown in Fig. 5. As the water droplets associated with the steam evaporate in the dry air in the leeward in the early stage, the water vapor maintains ice supersaturation conditions for long distances (several km).

Ice crystals were observed leeward of open leads from ∼7 to 900 m above the sea–ice surface. They were also confined to layers with humidity above ice saturation. The ice crystals in the temperature inversion layer at 900 m altitude and 3.7 km leeward from the open lead were smaller than 150 μm, and could be explained as ice crystals carried to higher elevation by slight turbulence and not completely evaporated. This could account for the high humidity at levels slightly higher than the inversion base. The occurrence of ice crystals on the lee side of open leads, and the lack of ice crystals above ice-saturated layers, show that moisture for the formation of ice crystals must be supplied from open leads and that they are not ice crystals which have survived a fall from invisible upper clouds. The steam and supercooled stratus clouds immediately downwind from the leads evaporated unevenly, leaving fractostratus further downwind and eventually only patches of humid air. Any ice crystals nucleated in the stratus will continue to grow as they are carried downwind even after the liquid phase has evaporated. This gives the impression that ice crystals are precipitating from apparently clear skies. It has been confirmed by other airborne experiments that, at times, the moisture supply for the crystal precipitations in clear-air comes from water vapor that had diffused from open leads. Patchy fractostratus clouds produced from open leads could explain the "ice crystal showers."

Airborne observations detected many frozen water droplets. Both airborne and ground observations of replicated ice crystals showed that some ice crystals had humps or spicula on their faces, as shown in Fig. 2. These ice crystals are similar to ice fog crystals observed at Fairbanks under the condition of rapid cooling of water droplets (Ohtake, 1970a). An example of a collection of frozen ice droplets in ice fog is shown in Ohtake (1970a, Fig. 3) and is reproduced in Fig. 6. Some of the frozen droplets have humps very similar to those observed in the present experiment, even when their diameter is near 10 μm. Ice fog is also formed by the rapid freezing of water droplets condensed under high supersaturated conditions;

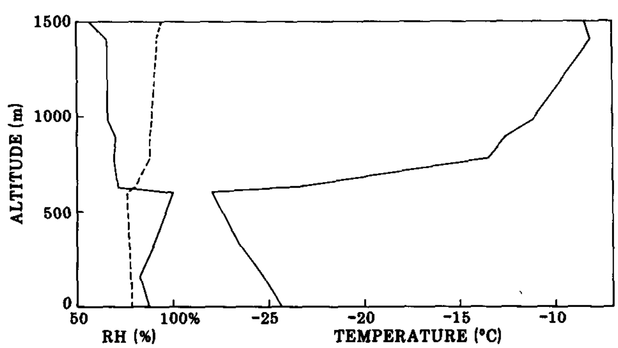

FIG. 4b. Air temperature and relative humidity (with respect to water) as measured by the aircraft instruments on 14 April 1977 (solid lines). The broken line shows the calculated relative humidity of the air if saturated with respect to ice at various altitudes.

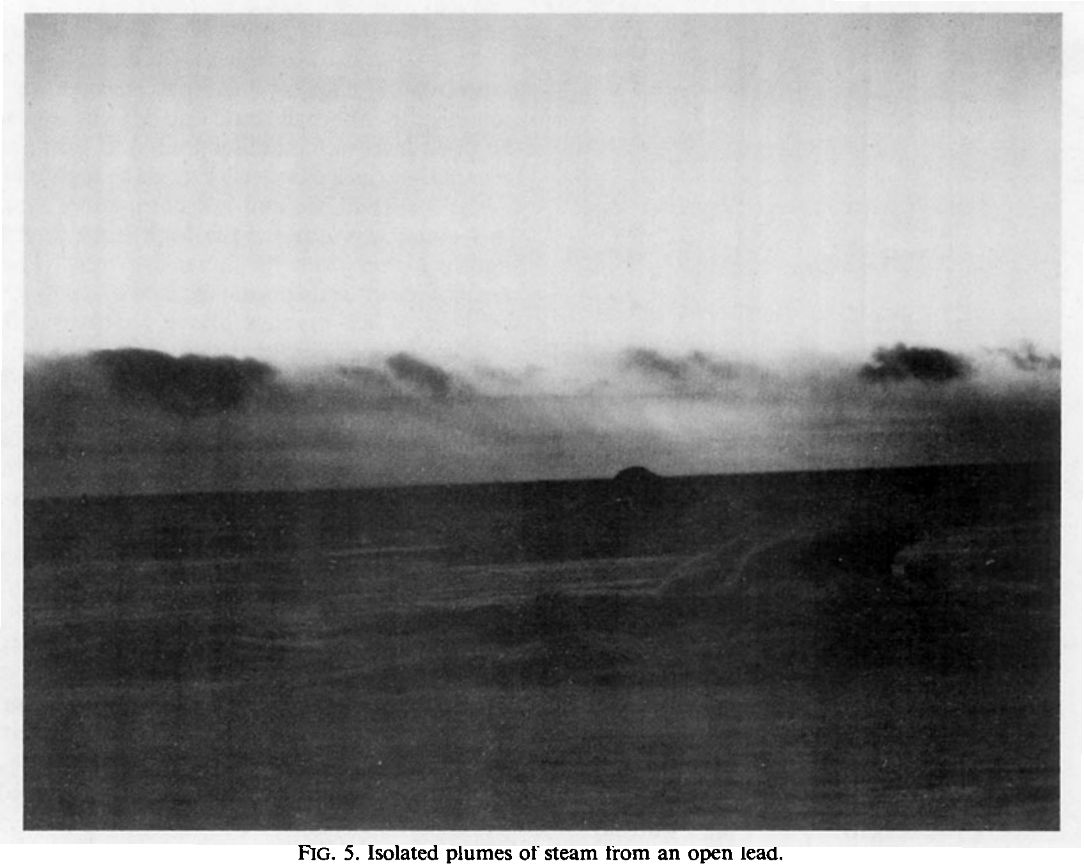

FIG. 5. Isolated plumes of steam from an open lead.

a mechanism very similar to that which occurs over open leads. Therefore, we postulate that spicula and humps observed in ice crystals are initiated by the rapid freezing of water droplets.

Existence of a hump can be taken to indicate that water droplets freeze from the outside, making a spherical ice shell. As the freezing process continues, pressurized water inside the freezing particle breaks the shell and ejects the unfrozen water to outside the frozen particle to form a spicule on the surface of the ice particle. In an ice-saturated atmosphere, the parent ice crystal grows to columnar or plate shape; meanwhile, the spicule also eventually grows to a hexagonal column attached to the larger parent crystal.

The aircraft observations also allowed us to select a series of crystals which we believe represent the different growth stages of these ice crystals. Such a sequence is illustrated in Fig. 7. In this figure, the different stages are shown only as an example to illustrate our proposed mechanism. The diameter of the frozen drop shown in Fig. 7a does not imply that a drop needs to be 40 μm diameter to form a spicule. This particular drop is exceptional; it is shown only to clearly illustrate the spicule during the freezing process. Such a large drop may have occurred from a combination of growth on a giant sea salt nucleus and under the high supersaturations that occur near an open lead. But spicules are observed at 10 μm diameter drops, when they freeze rapidly. (We did not exhibit a 10 μm drop in Fig. 7 because of the poor quality of the photographs for such small drops when taken from a high power optical microscope). The origin of columnar crystals with humps may be traced to frozen drops which are then grown in an ice-supersaturated environment. If the growth continues, then stepped columns similar to those observed at the South Pole (Ohtake, 1978, Fig. 4) may

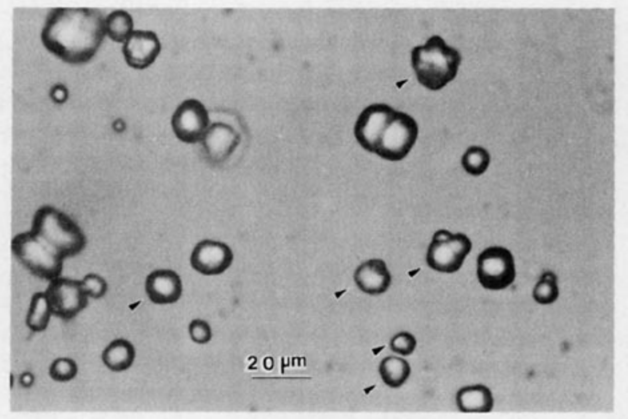

FIG. 6. Ice fog crystals sampled in Fairbanks. Crystals with humps are shown by arrows.

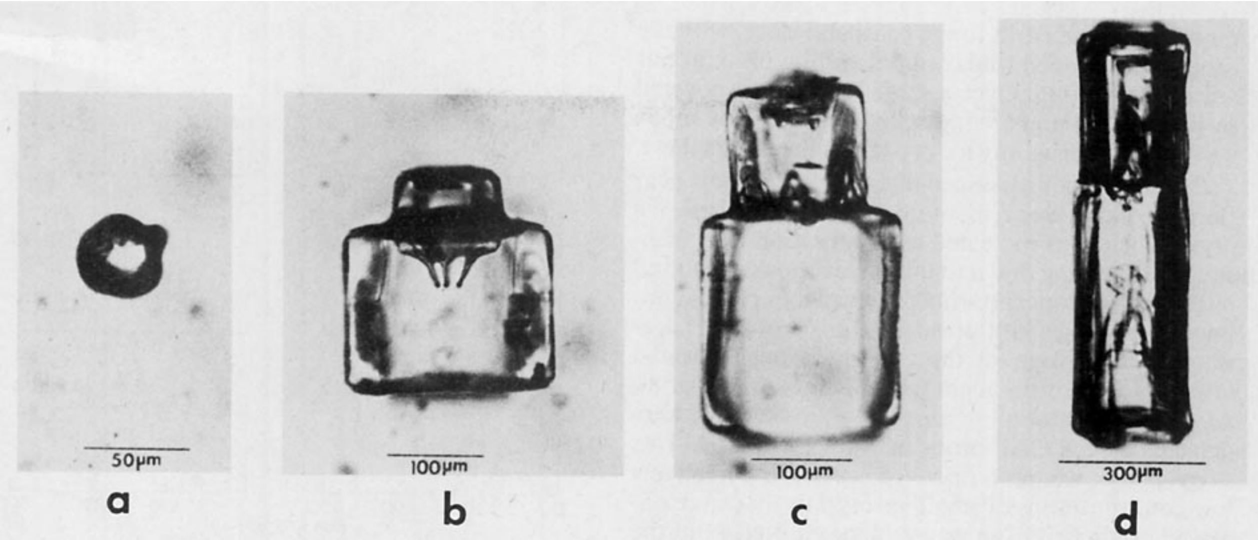

FIG. 7. A sequence showing the growth of ice crystals with humps from a frozen droplet.

result. These columnar crystals with humps are very similar to those produced in the laboratory by Magono *et al.* (1976). They were produced when atomized supercooled droplets froze at temperatures ranging from −20 to −25°C.

If wind direction remains onshore for a day or

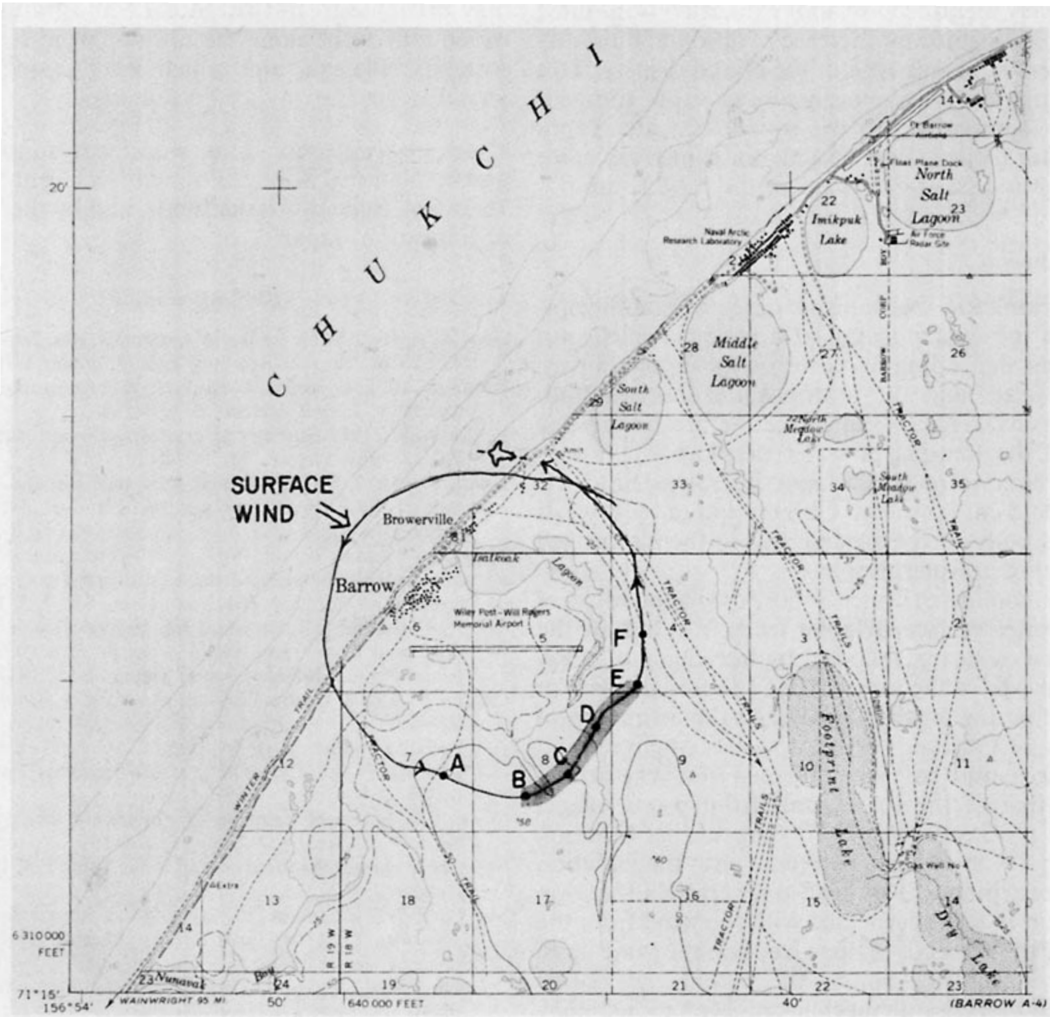

FIG. 8. An example of a flight track. Shaded part of the track indicates the location of the detected ice crystals.

more, open leads drift to the coast and close, with the result that no open leads remain within 300 km, nor are clouds visible. Over a large ocean area covered by pack ice, or land area completely covered by snow, we did not observe any ice crystals in the atmosphere.

During a reconnaissance flight for ice crystals near Barrow village, we accidentally found atmospheric ice crystals below us indicated by observation of a "subsun." After flying down to lower elevations, we found relatively low concentrations of small ice crystals confined to a wedge with a width of angle of ~35° leeward of the village, as the concentrations indicated at points B–E of the flight path (as shown in Fig. 8). At an elevation of 67 m along B–E, ice crystals were detected by the OAP probe as shown in Fig. 9. This suggests that when no open leads exist, the relatively low concentrations of small ice crystals that were observed originated from water vapor emitted from the Arctic villages. This type of ice crystal was mostly columnar, not larger than 200 μm in size, and was observed in the air between 30 and 200 m altitude for several kilometers, exclusively leeward of the villages. Hence the vapor source for these ice crystals is positively identified as vapor exhausted from these villages. No significant increase of absolute humidity was observed in this type of ice crystal display. This implies that the anthropogenic water vapor source is small in comparison to the source of water vapor from natural open leads. Exactly the same type of ice crystals was observed leeward of the NARL camp.

4. Conclusion

The formation mechanisms of ice crystal precipitation in the Arctic coastal area were classified into two kinds, depending upon the water vapor sources: 1) open leads and 2) anthropogenic sources. Both mechanisms of ice crystal formation are mainly the result of the freezing of water droplets which condense when warm water-vapor is emitted into the humid cold environment. Observation of ice crystals collected both on the ground and in the air verified the freezing of water droplets.

Rapid cooling of water vapor, available adjacent to the water surface of open leads, resulted in the formation of steam, followed by freezing and subsequent growth of the ice crystals. The initial stages of droplet freezing are very similar to the formation of ice fog (see Ohtake, 1970b). Crystals originating in the villages must have been formed in a very similar way to that of the ice crystals from power plants (Ohtake and Jayaweera, 1972). The diurnal variation of ice crystal abundance correlates with the variation of human activities. This kind of ice crystal formation was found to be uncorrelated with the wind from the ocean or the presence of open leads on the same days.

Ice crystals at the South Pole station may not be explained by the same mechanism, even though they may originate in fractostratus or altostratus clouds, which may form along the upslope wind toward the Antarctic Plateau, and which were frequently observed to accompany ice crystal displays.

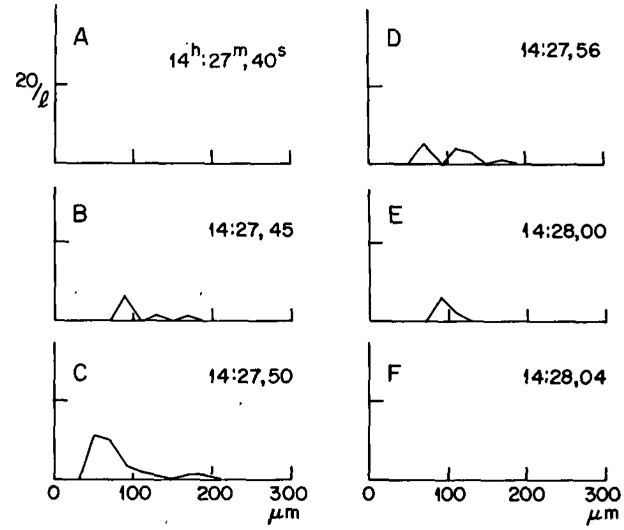

FIG. 9. The ice crystal concentrations observed at the locations A, B, C, D, E and F on the flight track shown in Fig. 8. Note that no crystals were observed at A and F.

Acknowledgments. This work was supported in part by National Science Foundation Grant No. DPP 76-21594, State of Alaska funds, and by the Ministry of Education, Japan.

REFERENCES

Gow, A. J., 1965: Snow studies in Antarctica. Res. Rep. 177, U.S. Army Cold Regions Res. Eng. Lab., Hanover, NH, 20 pp.

Hindman, III, E. E., and R. L. Rinker, 1967: Continuous snowfall replicator. *J. Appl. Meteor.*, **6**, 126–133.

Hogan, A. W., 1975: Summer ice crystal precipitation at the South Pole. *J. Appl. Meteor.*, **14**, 246–249.

Kuhn, M., 1970: Ice crystals and solar halo displays at Plateau station. 1968 ISAGE symposium, Hanover, NH, IUGG/IASH, 298–302.

Magono, C., and S. Suzuki: 1967, A study on crystal axes of snow crystals with complicated shapes utilizing a polarization microscope. *J. Fac. Sci., Hokkaido Univ.*, Ser. 7, **3**, 27–37.

——, S. Fujita and T. Taniguchi, 1976: Shapes of single ice crystals originated from frozen cloud droplets: *Proc. Int. Conf. on Cloud Physics,* Boulder, Amer. Meteor. Soc., 103–106.

Ohtake, T., 1970a: Unusual crystals in ice fog. *J. Atmos. Sci.*, **27**, 509–511.

——, 1970b: Studies on ice fog. Rep. UAG-R211, University of Alaska, 177 pp. [EPA, Office of Air Programs, Publ. APTD-0626].

——, 1976: Source of ice nuclei of atmospheric ice crystals at the South Pole. *Antarct. J. U.S.*, **11**, 148–149.

——, 1978: Atmospheric ice crystals at the South Pole in summer. *Antarct. J. U.S.*, **13**, 174–175.

——, and B. E. Holmgren, 1974: Ice crystals from a cloudless sky. *Preprints, Conf. on Cloud Physics,* Tucson, Amer. Meteor. Soc., 317–320.

——, and K. O. Jayaweera, 1972: Ice crystal display from power plants. *Weather,* **27**, 271–277.