Tellus (1996), 48B, 372–386
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TELLUS
ISSN 0280–6509

Characteristics of the concentration and composition of aerosols during Foehn in West Greenland

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(Manuscript received 20 July 1994; in final form 18 September 1995)

ABSTRACT

Measurements of the number of aerosol particles in 5 size ranges (0.3–0.5, 0.5–1, 1–2, 2–5, and >5 μm in diameter) were carried out continuously at Godhavn (69°15'N, 53°34'W), West Greenland from the middle of December 1989 to the end of January 1990. The concentrations of particles larger than 0.3 μm were less than 10 cm^{-3} near the surface. This concentration is 1/2 to 1/5 of that measured at Inuvik, Arctic Canada and at Alta, Northern Norway at a similar latitude. The fluctuation of the number concentrations was very small when Greenland was covered by high pressure, and a weak downslope wind was blowing from the island ice cap. Sudden change to strong northeasterly wind was accompanied by an abrupt increase of air temperature. Concurrent with these changes, the number concentration of smaller particles decreased, and particles larger than 2 μm in diameter increased. These variations are considered to be caused by a strong Foehn, accompanying a well-developed low pressure cell passing northeast along the southern coast of Greenland. After the Foehn had ceased, weak southerly winds were accompanied by greater number of particles of 1–2 μm. Many sea salt particles were brought from the sea south of the station which was not completely covered by sea ice, even in the midwinter seasons. The number concentration and composition of aerosols were closely related to the wind system at Godhavn, West Greenland.

1. Introduction

Many global environment problems are related with the dynamic properties of aerosol particles. It is necessary to know the time variations of both concentration and the elemental composition of aerosol particles in the Arctic, to examine the influence of particles originating at midlatitude on the Arctic atmosphere. Although there are several long-term records of Arctic aerosol composition and concentration, there have been few investigations of the dynamics of aerosol variation, necessary to model the influence of midlatitude on the Arctic.

Megaw and Flyger (1973), Flyger et al. (1976) and Radke et al. (1976) first investigated the variation of aerosol with respect to location and altitude over Greenland, Alaska and the Arctic. Flyger et al. (1976) stationed an observer first in a fjord near the coast and on the ice sheet, and found that midlatitude pollution, measured above 700 hPa, was not observed by concurrent surface measurements. Two much larger airborne campaigns, AGASP-I (Schnell, 1984) and AGASP-II combined multiple airborne sampling with ground based observations. Reviews of surface aerosol chemistry at Arctic stations are provided by many workers (Rahn and Heidam, 1981; Rahn, 1981b; Davidson et al., 1981; Ottar, 1989; Sheridan, 1989; Heintzenberg et al., 1991). According to Barrie et al. (1981), Rahn et al. (1977, 1980) and Rahn (1981a), the Arctic regions are polluted by aerosol

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particles which are transported from the midlatitudes of Eurasia, North America and the northern portions of the former U.S.S.R.. Miller (1981) calculated the 5-day back trajectories of air arriving at Barrow, Alaska, and concluded that pollutants could be transported for 2,000 km or more from southern regions in the winter seasons. At times, the pollutants were transported across the North Pole (Heidam, 1981; Miller, 1981). Rosen et al. (1981) reported a sudden increase of graphitic carbon at Barrow attributed to anthropogenic activities. These pollutants are considered to be the cause of some decrease of visibility, and they carry a possibility of the climatic change on a global scale. Hoff et al. (1983) conducted two field experiments at Igloolik, Northwest Territories, Canada at 1981 and 1982 to study the composition and mass size spectrum of Arctic haze aerosol.

Many observations of aerosol particles continue, notably those of NOAA-CMDL at Barrow, Alaska. Surface observations within the Arctic regions have continued (Shaw, 1983, 1985; Iversen and Joranger, 1985; Pacyna and Ottar, 1985; Heidam, 1985; Heintzenberg and Covert, 1987; Barrie and Hoff, 1985; Rahn, 1985; Bodhaine, 1989), beyond the international sampling network of Rahn (1981b), including some by a Swedish icebreaker (Lannefors et al., 1983). The majority of these observations were based on analyses of bulk samples of aerosol particles or gases which were sampled for several days. Most of these collections were at level coastal sites.

A long, continuous record of surface aerosol and gas concentrations is available from Barrow, Alaska by NOAA, GMCC, and a shorter record has been obtained at Alert N.W.T. Canada. Flyger and Heidam (1978) compared summer aerosol concentration with local meteorological conditions at Kap Harald Maltke, Greenland during summer, and Kikuchi et al. (1978) compared aerosol concentration with meteorological conditions at Inuvik N.W.T. Canada in winter. They applied time cross section sounding analysis to aerosol observed at Inuvik, and Hogan et al. (1984) coordinated SEM-EDX analysis of collected particles to sounding cross section at Barrow in Alaska, Dye III in Greenland and Igloolik in N.W.T. Canada. Heidam (1984) collected aerosol samples through a year at five locations in Greenland, and analyzed by PIXE to determine the elemental composition of the Arctic aerosol.

Comparison of nearby meteorological soundings with short duration aerosol collection or measurement was shown by Leaitch et al. (1984) to provide an objective analysis of transport of lower latitude aerosol to the Arctic surface. The experiments described in this paper extend the comparison of surface observations with meteorological observations, as the Foehn at the observation site permit study of lower tropospheric aerosol to the surface in strong subsidence.

In this paper, the results of continuous measurement of aerosol particles in 5 size ranges and analysis of elemental composition of aerosol with meteorological conditions, specifically, with respect to Foehn event.

2. Location and measurements

The measurements were carried out at Godhavn (69°15′N, 53°34′W), West Greenland. The town is located on the south coast of Disko Island as shown in Fig. 1. The population of the town is approximately 900. The measurement instruments were set up in a storeroom of the Arctic Station operated by the University of Copenhagen, Denmark as shown in Fig. 2. Behind the Arctic Station, a lava plateau extended northward. As seen in Fig. 2, only a small amount of snow accumulated around the coastal area even in midwinter seasons, although the inland high plateau of Greenland was covered with a thick ice sheet. The sea surface was frozen near the coast, but it was not frozen offshore. The measurements were carried out continuously from 20 December 1989 to 22 January 1990.

3. Measurement instruments

The measurements of the concentration of aerosol were obtained with a particle counter (Type KC-1B) made by Rion Co. Ltd. This counter can measure the diameters of aerosol particles by detecting the peak heights of the optical scattering which result from crossing the light beam over the particles. It can display the number concentrations of aerosol particles in 5 size ranges at the same time: 0.3–0.5, 0.5–1, 1–2, 2–5, and $>5\,\mu$m in

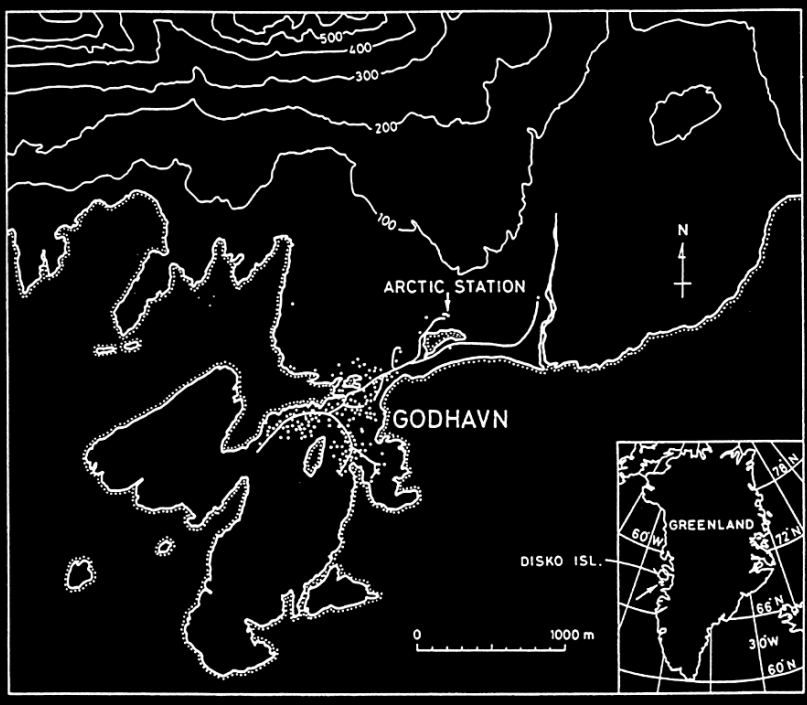

Fig. 1. Location of the observation site at Godhavn, Greenland.

Fig. 2. The Arctic Station of the University of Copenhagen, Denmark and lava plateau behind it.

diameter. The individual number concentrations within an air sample are printed out by a digital printer and stored by a data logger. The sampling volume was adjusted 10 l min^{-1}. The size spectra of aerosol particles could be obtained at 20-min intervals. Outdoor air was drawn into the equipment through a 2-m teflon tube. The particle counter was set up in a cool room in order to

avoid large temperature differences between the sample air and the equipment.

Simultaneously, particles were collected on filter paper using an aerosol sampler shown in Fig. 3, which was developed by Taniguchi and Kikuchi (1989a). A millipore filter paper 90 mm in diameter is mounted on a small turntable. An inlet pipe and a suction pipe intersect the filter as shown in Fig. 4. The diameter of both pipes in the same size of 11 mm. These pipes are pressed tightly on the surface of the filter paper by coil springs. The sample air enters through the inlet pipe, and the aerosol particles are collected on the upper surface of the filter paper. Air is sampled for one hour, and the suction pump is stopped. The inlet pipe is lifted by a solenoid, and both pipes are released from the filter. The turntable supporting the filter paper is rotated 25° to the next position by a synchronous motor. The pipes grasp the next position of the filter paper, and the suction pump resumes sampling.

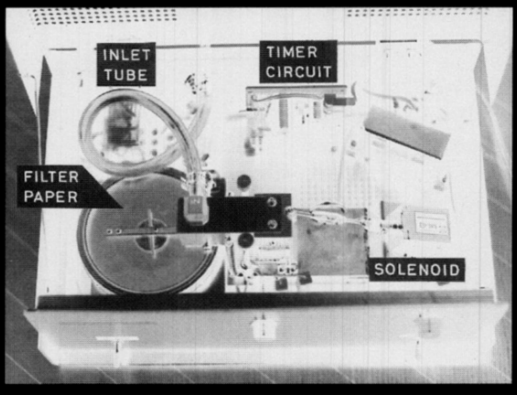

Fig. 3. A plan view of the aerosol sampler.

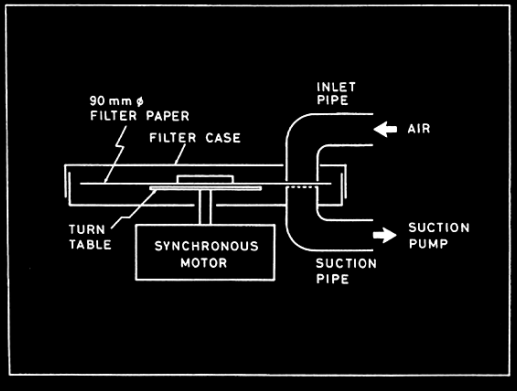

Fig. 4. A rough illustration of the mechanism of the aerosol sampler.

12 patches of hourly samples of the airborne aerosol particles are obtained on each filter paper. The filters are replaced twice a day. In the present study, the sampling volume of the air containing the aerosol particles was approximately 120 l for each hourly sampling.

This apparatus has these advantages: a tight sealing case such as used in the impactor method used by Bigg (1980) and Leaitch et al. (1984) is not required. As a result, it is easy to operate even in the Arctic regions in the midwinter seasons. Although during the observation period the sampling was carried out continuously, 24 h a day, no difficulties were encountered. Furthermore, it can be used at a variable flow rate, thus it is possible to adjust the flow rate to appropriate values depending on the degrees of pollution. At all flow rates, it does not need calibration for the change of collection efficiency for small particles. After the measurements were completed, filter papers on which the aerosol particles were collected were sealed to keep from absorbing moisture and were brought back to the laboratory. Then a number of sampled portions on the filter papers were cut out and they were mounted on stages for a scanning electron microscope (HITACHI, S-430). The size and the features of aerosol particles were studied, and their photographs were taken. The chemical elements included in individual aerosol particles were analyzed by an energy dispersive X-ray microanalyzer (HORIBA, EMAX-1800S) which can detect chemical elements heavier than sodium.

4. Results and discussion

4.1. Time variations of the concentration of aerosol particles in five size ranges

The number concentration of aerosol particles in the 5 size ranges were measured continuously from December 1989 to January 1990. Chronologies of the data are shown in Fig. 5; the ordinate indicates the logarithm of the number concentration of aerosol particles/cm^3 of the air, and the abscissa indicates the UTC. The local mean time at Godhavn is 3 h behind the UTC. The precipitation and the wind data depicted by

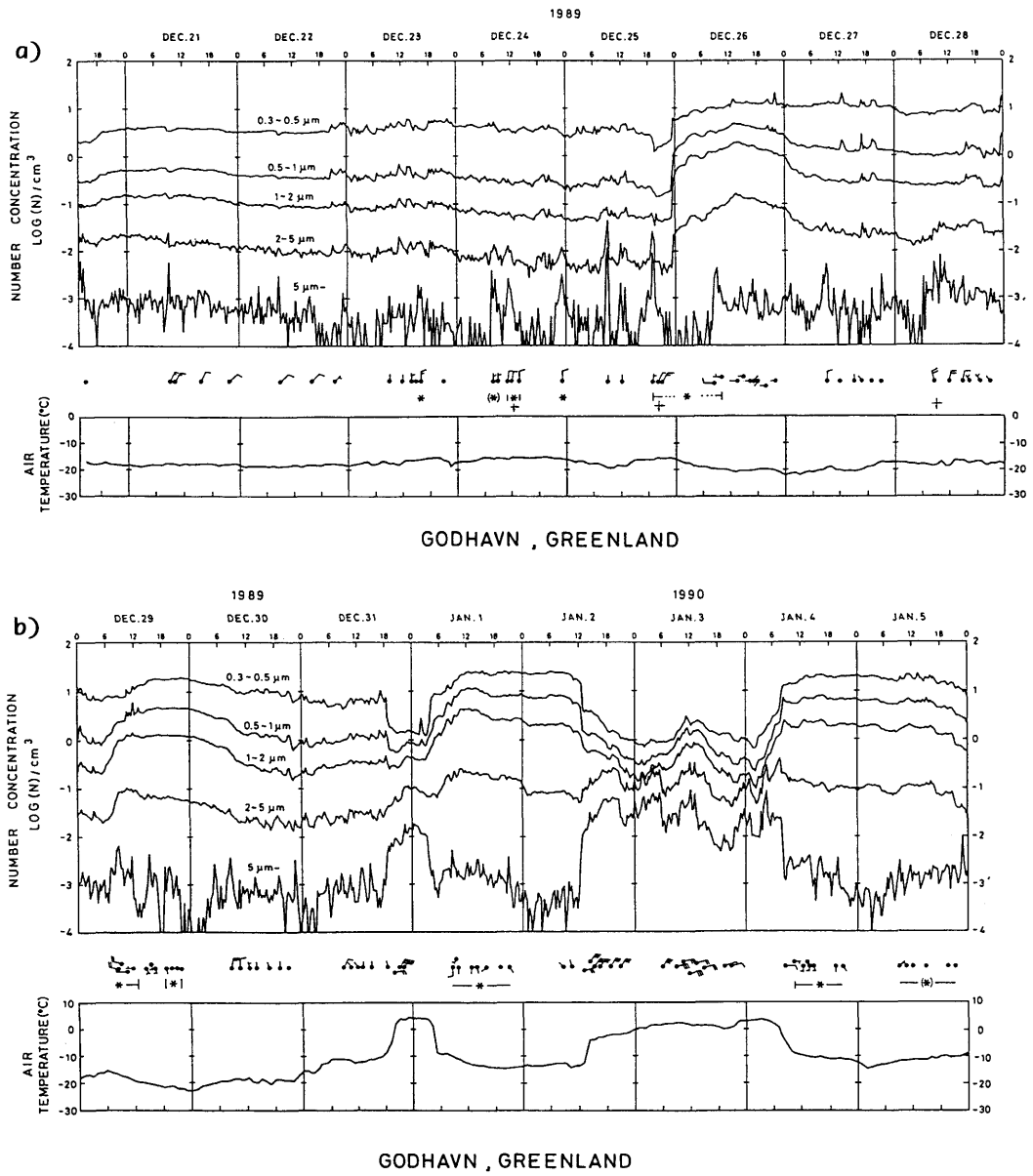

Fig. 5. Time variations of the number concentrations of aerosol particles in 5 size ranges at Godhavn, Greenland.

symbols were obtained by visual observation during daylight. In most cases the snowfall rates were very weak.

The number concentration of aerosol particles of 0.3–0.5 μm in diameter was 1 to less than 200 cm^{-3} and most frequently less than 10 cm^{-3} in average. This concentration was one half to one fifth of that measured at Inuvik, Northwest Territories, Arctic Canada (Taniguchi et al., 1987; Taniguchi and Kikuchi, 1989a) and Alta, Northern Norway (Taniguchi and Kikuchi, 1989b). Shaw (1983) measured the aerosol particle size distribu-

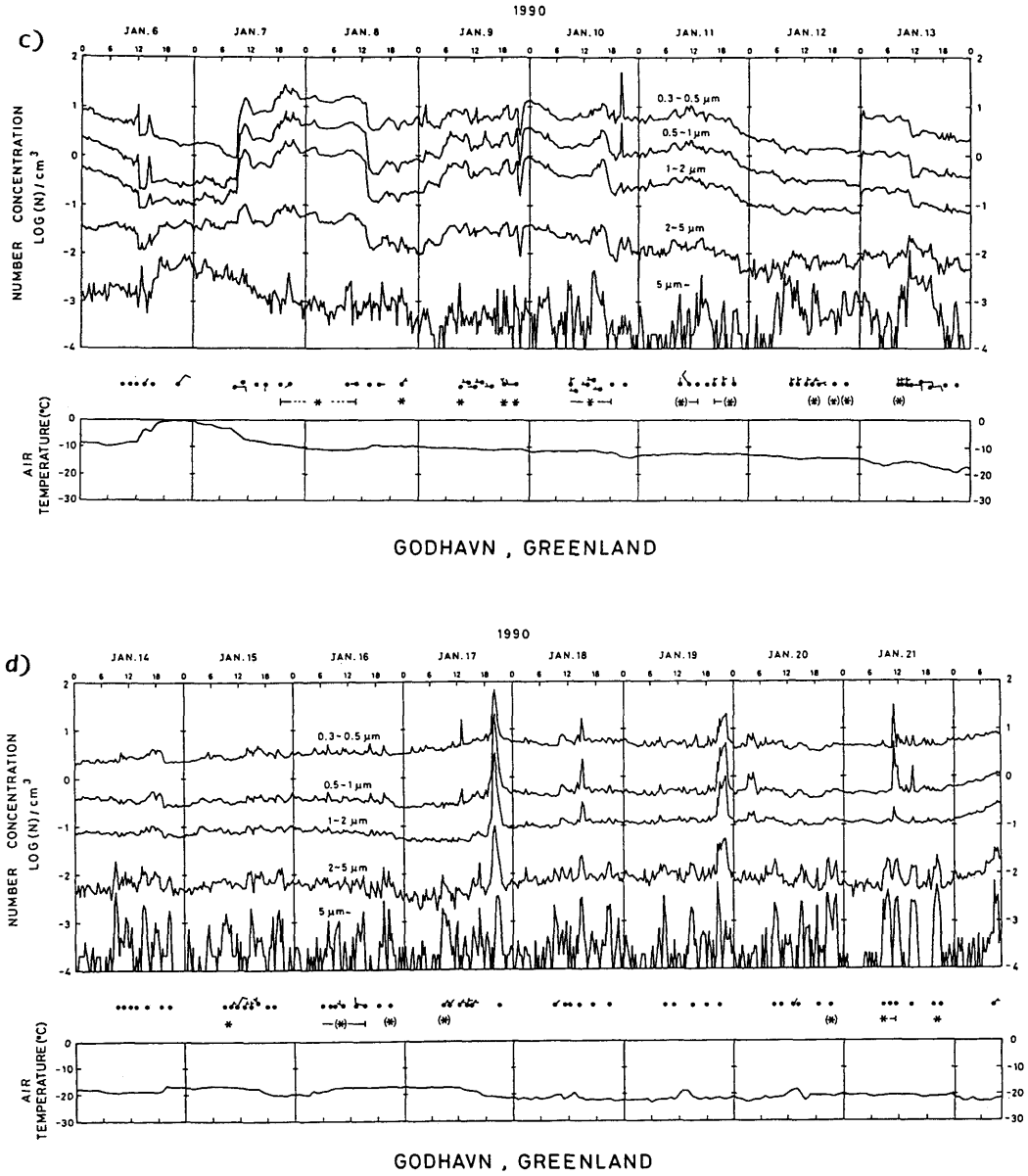

Fig. 5. (cont'd).

tion spectrum of Aitken nuclei in Alaskan air mass system classifying Arctic haze and non-haze episodes at the interior Alaska. He obtained the number concentrations ranging from 300 to 2000 cm^{-3} with maximum near 1×10^{-6} cm radius to the particles entering the central Alaska from the Pacific marine environment and from 150 to 700 cm^{-3} with bimodal distribution for the air mass entering from the Eurasian Arctic. Hogan et al. (1984) measured the aerosol concentration and size parameters of the Aitken nuclei at several sites in the western hemisphere Arctic; namely

Barrow in Alaska, Igloolik in Northwest Territories, Canada and DYE III in Greenland. They reported the number concentration of 10 to 10^4 cm^{-3} depending upon the weather conditions and a systematic diurnal variation during the summer at Barrow. At Igloolik, the concentrations of 0 to several thousands in both August 1981 and February 1982 were recorded. Further, at Dye III (location height $\simeq$700 hPa) in Greenland in summer 1982, several to several thousands of the Aitken nuclei were reported. Surface and airborne observations made by Flyger et al. (1976) showed that the katabatic flow from the ice cap carried 100 to 200 cm^{-3} of total Aitken nuclei, while air near the summit of the Greenland ice cap carried tens to hundreds cm^{-3}. Later work by Flyger and Heidam (1978) in Northern Greenland showed a great time variation in Aitken nuclei concentration and reported of hundreds cm^{-3} in most frequently. Bodhaine (1989) analyzed the continuous record of condensation nucleus (CN) and aerosol scattering coefficient (σ_{sp}) measurements using the data from 1976 to 1986. As a result, CN showed a semiannual cycle having a maximum of several hundred cm^{-3} coinciding with the maximum in σ_{sp} in early spring, and a secondary maximum in August. Minima in CN of about 100 cm^{-3} occurred in summer and late fall. It is difficult to compare directly because of the differences of size ranges of particles, observation periods, specifically their intermittent measurements and so on.

During our observation period, fluctuations in the number concentrations were very small, especially on 21 and 22 December 1989. On those days, the mainland of Greenland was covered by high pressure as shown in Fig. 6, and a weak downslope wind was blowing from the inland ice sheet. At the observation site marked by a double circles, a weak northeasterly wind prevailed.

On the evening of 31 December 1989, a strong northeasterly wind came up suddenly, accompanied by an abrupt increase of air temperature from -12 to $+5$°C as shown in the lower panel of Fig. 5. With these changes, the number concentration of aerosol particles in the smaller size ranges suddenly decreased by about one order of magnitude, and in contrast, particles larger than 2 μm in diameter increased at the same time. Similar variations were observed on 2 to 4 January and 6 to 7 January 1990. These variations of air temperature and wind are associated with strong Foehn, well known in Greenland (Berthelsen et al., 1989).

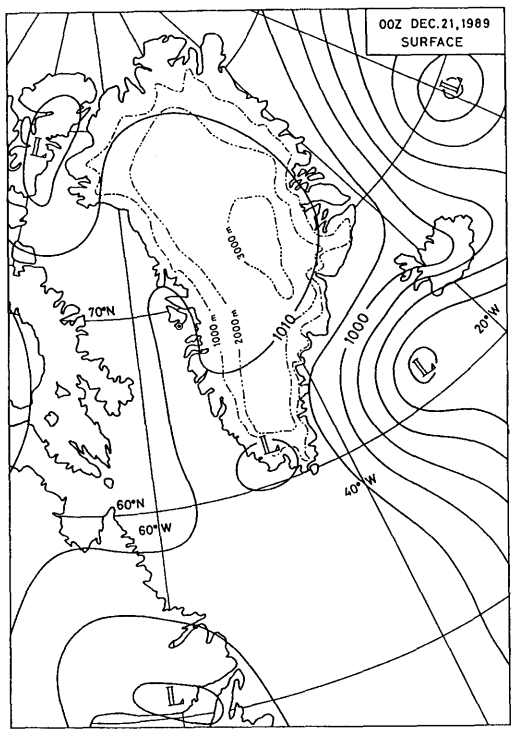

Fig. 6. The typical pressure pattern when the time variations of the number concentrations of aerosol particles were little.

Fig. 7 represents an example of the pressure pattern during Foehn of 3 January 1990. A well-developed low pressure cell was travelling northeast along the southern coast of Greenland. The wind was circulating around this low pressure, from the east coast to the west coast of Greenland, and overriding the inland high plateau covered by ice sheet. This might bring increased temperature and stronger winds to the west coast.

As the result of the Foehn, it was considered that smaller particles were blown away and replaced by the strong northeasterly winds which came from the high plateau of Greenland. As well-known, the inland and high altitude air is very clean (Flyger et al., 1976), and in addition, in some cases the upper clean air was dragged to the ground surface. In contrast, the increase of the number concentrations for larger particles might have been caused by the fact that the strong wind

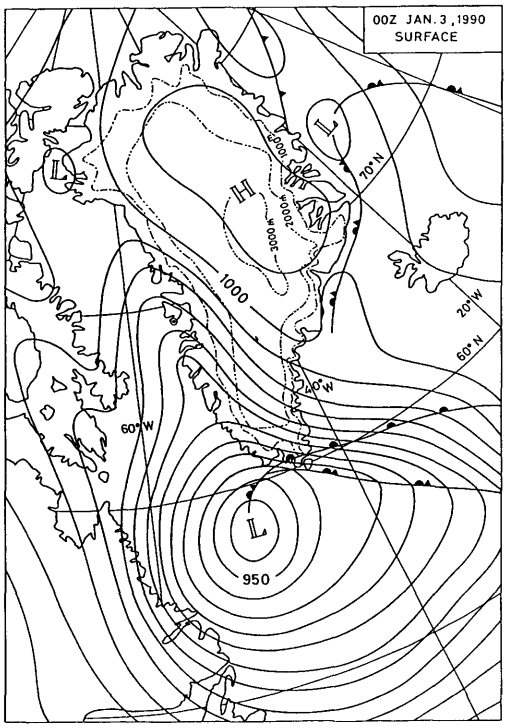

Fig. 7. The typical pressure pattern when the Foehn happened.

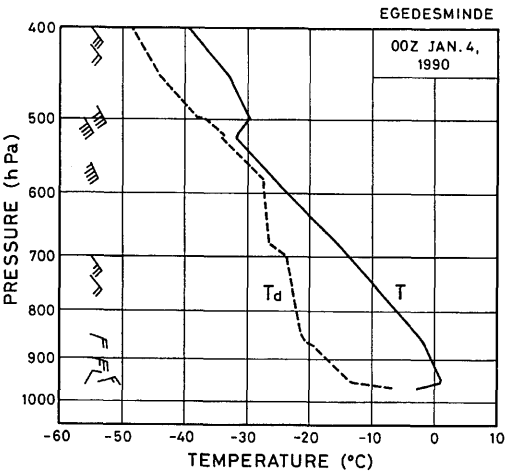

Fig. 8. Sounding curves at Egedesminde, Greenland when the Foehn happened.

had blown up the soil particles into the air from the ground surface or bare rocks nearby. Fig. 8 represents an example of sounding curves on the Foehn, which was obtained at Egedesminde Meteorological Observatory, 70 km to the south of our observation site. Warm, dry air had filled in the lower troposphere, and relatively strong northeasterly winds were commonly seen near the surface.

After the Foehn had ceased, a weak low pressure cell remained in the northwest of Greenland in most cases as shown in Fig. 9. In these situations, weak southerly winds were blowing around the observation site accompanied by high number concentrations of aerosol particles, especially for particles of $1 \sim 2\,\mu$m in diameter (see Fig. 5: 1–2 January, and 4–5 January 1990). Sea salt particles were brought to the observation site from the sea to the south by these southerly winds. In such conditions, most particles were composed of sea salt elements as will be described in Subsection 4.3.

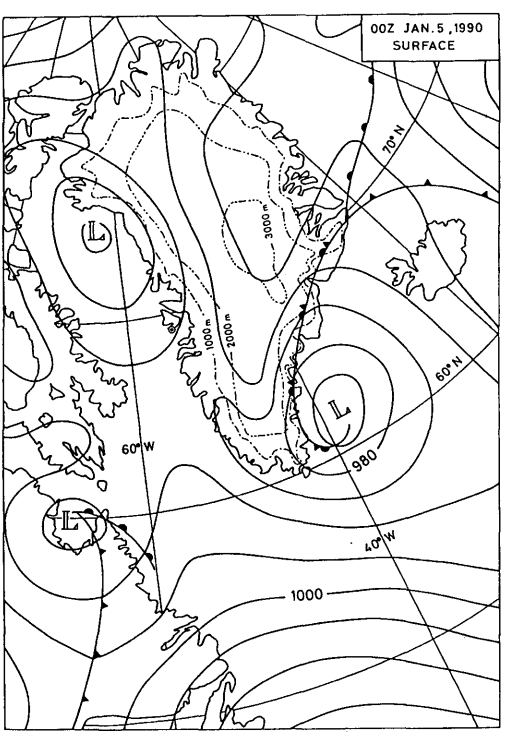

Fig. 9. The typical pressure pattern after the Foehn ceased.

4.2. *Relative volume concentration of aerosol particles in each size range*

The presentation of aerosol data has been thus far confined to number of particles in 5 size ranges. It is necessary to consider the integrated particle volume, and the relative change in size among the particle population, to interprete aerosol change with respect to meteorological variation. Whitby (1978) showed that the number concentration in each size range can be converted to particle volume concentration for each size range with acceptable accuracy. From this, the relative volume concentration can be obtained, and the proportions of the volume concentration of each size range to the total volume concentration of aerosol particles in all size ranges can be obtained. This allows expression of the time variations of the size distributions of aerosol particles.

Fig. 10 represents one of the examples showing these variations. The upper panel of this figure is the time variation of the number concentrations of aerosol particles as similar to Fig. 5. The middle panel is the variation of total volume concentration of all size ranges, and the lower panel is the relative volume concentrations in each size range in relation to the total volume concentration of all size ranges in percentage. These fluctuations are now accentuated, relative to the concentration chronology in Fig. 5.

When strong, dry, local winds associated with aerosolizing, soil particles were dominant, during the Foehn of 31 December to 1 January and 2–4 January in Fig. 10, the relative volume concentration for particles larger than 2 μm in diameter occupied the main portion of the total volume. When moister, warmer winds associated with marine air occurred, sea salt particles were dominant (1–2 January and 4–5 January 1990), and the relative volume concentration for particles of 1 to 2 μm in diameter comprised a majority of the particle volume.

Fig. 11 shows the relative volume concentration measured at Alta (69°56′N, 23°16′E), Northern Norway (Taniguchi and Kikuchi, 1989b).

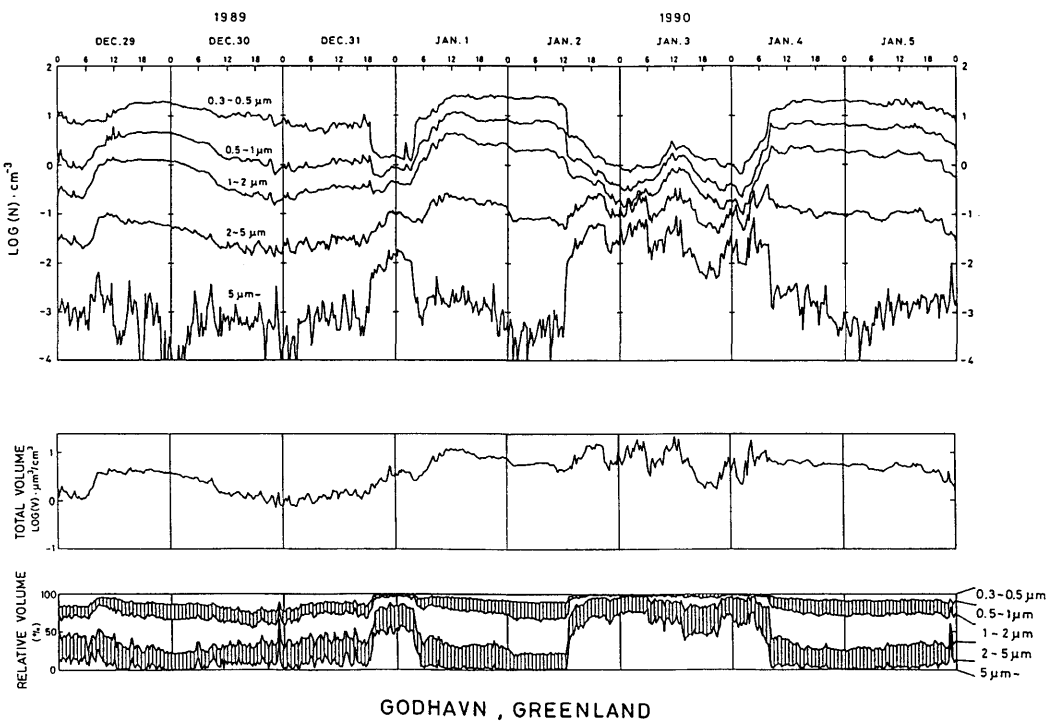

Fig. 10. Time variation of the number concentrations (upper), the total volume concentrations (middle) and the relative volume concentrations (lower) when no local pollution was observed at Godhavn, Greenland.

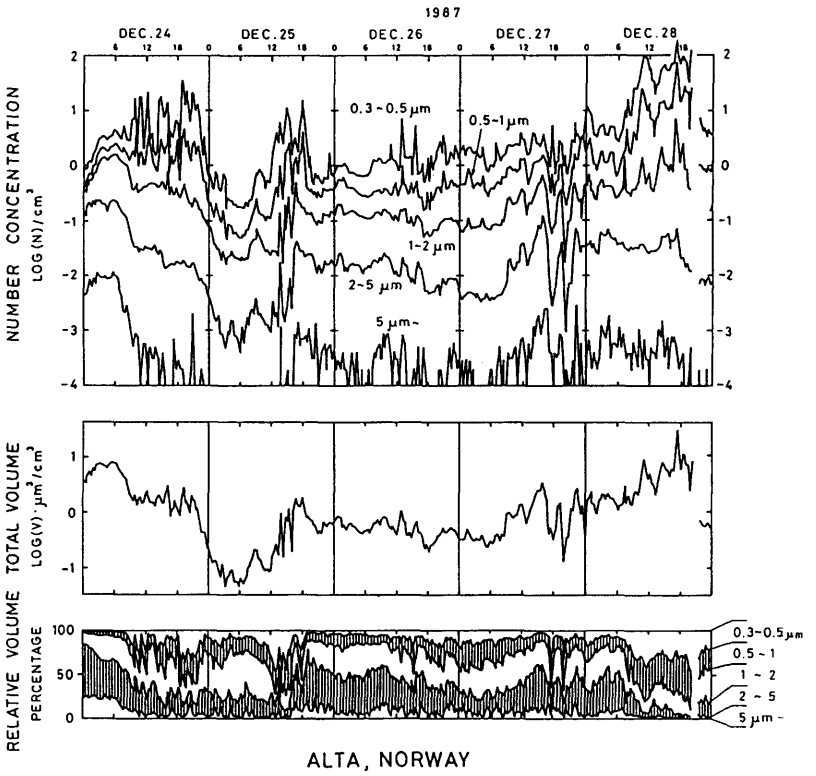

Fig. 11. Same as in Fig. 10 but for polluted conditions were observed at Alta, Northern Norway. Local pollutions are seen on 24 to 25 and 27 December 1987.

Relatively high frequency fluctuations occurred on 24–25 December 1987. Such fluctuations represent a great size distribution change in a short period due to mixing of sources of local pollution near the observation site. A different type of variation at Alta, Northern Norway is seen in Fig. 12. In the period from 2–5 January 1988, the number concentrations indicated high values with considerable fluctuations, while fluctuations in the variation of the relative volume concentrations were scarce. Size distribution did not change, but concentrations did. The advected air was not affected by local sources, but by variation in exchange to local surface. A polluted air parcel was brought into the observation site from long distance areas.

As shown above, using the expression of the relative volume concentration it is possible to clarify the difference of the origin of the advected air parcels which arrived at the observation site.

4.3. *Frequencies of the chemical components of aerosol particles*

Aerosol particles collected on filter paper using the aerosol sampler which was developed by Taniguchi and Kikuchi (1989a) were analyzed by a scanning electron microscope (SEM) and an energy dispersive X-ray microanalyzer (EMAX) system. Two examples analyzed by SEM-EMAX system are represented in Fig. 13. The horizontal bars as shown at lower right corners of the SEM photographs define the scale of these photographs. The particles analyzed by these system are larger than 0.3 μm in diameter comparable with the particles measured instrumentally. The figure on the left, a particle with rugged feature shows sharp peaks for elements of soil origin, namely Al and Si. The figure on the right contains elements of maritime origin, namely Na and Cl.

The chemical elements included in individual

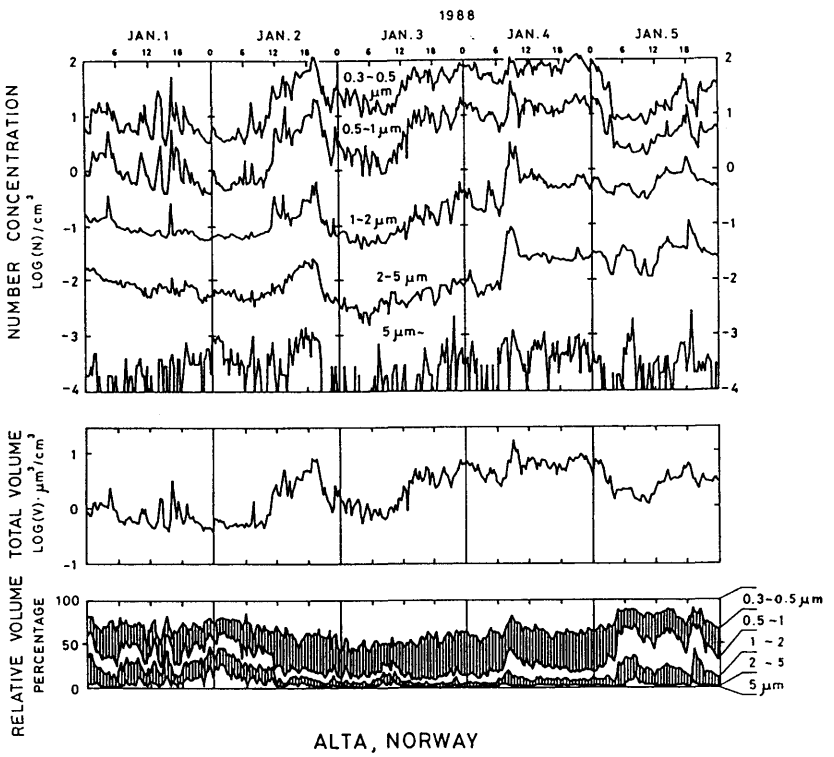

Fig. 12. Same as in Fig. 11 but for widespread pollutions from long distant areas were observed at Alta, Northern Norway.

particles were determined for a large number of collected particles. The frequencies of detection for each element within all collected particles are shown on the lower panel in Fig. 14. In this figure, results from the analyses for samples collected at other observation sites in the Arctic regions carried out by the authors in previous years (Inuvik, Northwest Territories, Arctic Canada and Alta, Northern Norway) are also shown on the upper and middle panels. The indication of frequency distribution is the same as Parungo et al. (1979). The distributions obtained at three observation sites are similar. According to the measurements of the composition and mass size spectrum of Arctic haze aerosols made by Hoff et al. (1982), anthropogenic components were predominant on submicrometer aerosols and marine components were on supermicrometer. However, we were not able to compare our data with them.

It is well-known that, on an global scale, the primary origin of the natural aerosol particles act as the center nucleus of snow crystals is of soil origin and the secondary is of marine origin at high latitude areas (Kumai and Francis, 1962). However, elements of marine origin were frequently detected comparably with elements of soil origin. This may result from the fact that the location of Godhavn is near the coast with unfrozen sea even in the midwinter in the Davis Strait of the Labrador Sea.

Most elements heavier than Ti in Fig. 14 are considered to be attributed to anthropogenic sources, for example, metal refining and smelting factories (Pacyna, 1984; Ottar et al., 1984). These elements are scarcely detected at Godhavn, although they are frequently detected at Inuvik, Arctic Canada and less frequently at Alta, Northern Norway.

4.4. *Component ratios of typical elements by means of triangular diagrams*

The histograms in the previous section provide the frequency of presence or absence for each

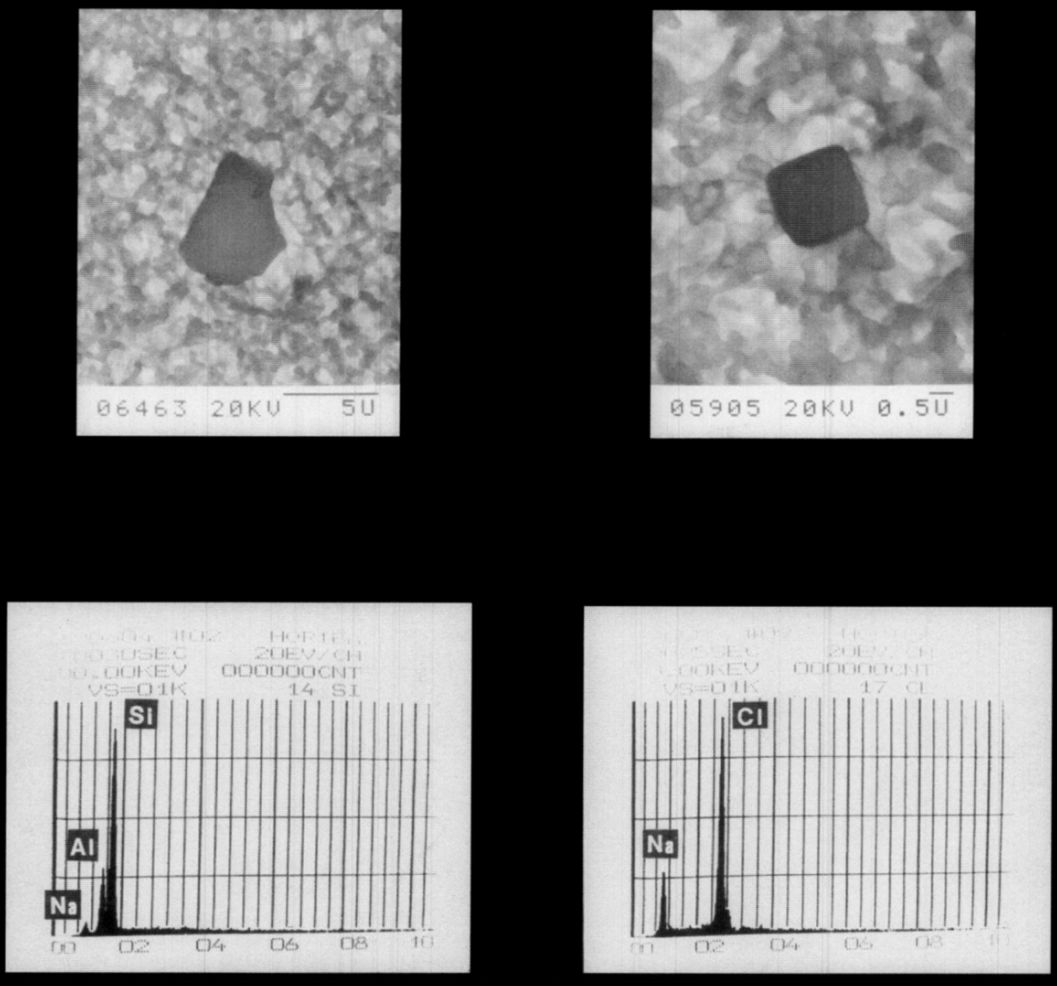

Fig. 13. SEM-EMAX analysis of a particle of soil origin (left) and a particle of marine origin (right).

element within the analyzed particles. The elemental composition and the origin of aerosol particles in each sampling period at the observation site, are expressed by triangular diagrams in Fig. 15. The representative elements of soil, marine and anthropogenic origin, Si, Na and S are presented as a triangular diagram with peak heights corresponding to the component ratios of these elements. This procedure is similar to Murakami and Kikuchi (1982).

Fig. 15 represents an example for the cases when the main land of Greenland was covered by a high pressure, and a weak downslope wind was blowing from the inland ice cap where the altitude is up to 3000m ASL (22, 28 December 1989). At the observation site, a weak northerly wind prevailed in this period. Another case when the strong easterly wind was blowing from the inland under strong Foehn (3 January 1990) is shown in the lower right diagram of the same figure. In this figure, it is apparently recognized that the almost all particles were of soil origin.

In contrast to this, the particles of marine origin were predominant in the cases when weak southerly wind was blowing after the Foehn as shown in Fig. 16. These particles were composed of Na, Mg and Cl, then they are considered to be made from dehydrated sea spray on the sea surface. At

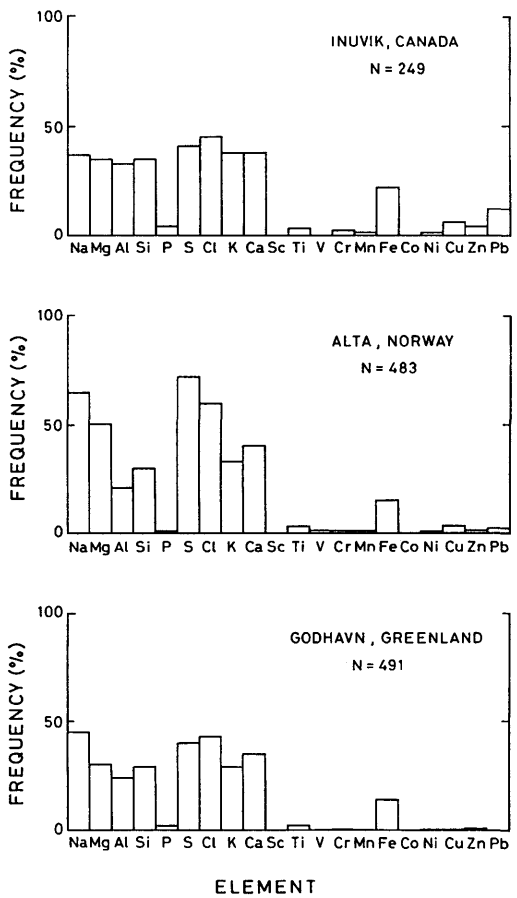

Fig. 14. Frequency distributions of detection for each element within all of analyzed particles collected at Inuvik, Arctic Canada (upper), Alta, Northern Norway (middle) and Godhavn, West Greenland (lower).

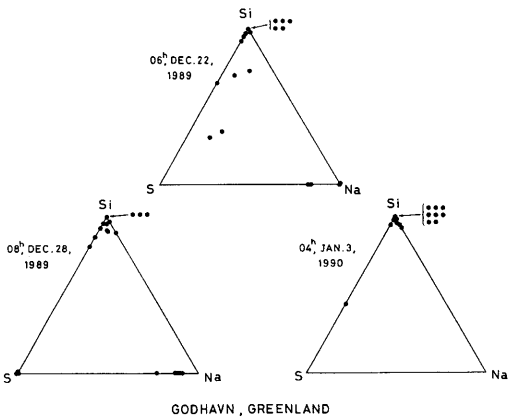

Fig. 15. Triangular diagrams for the cases of weak downslope wind (upper and lower left figures) and of Foehn (lower right).

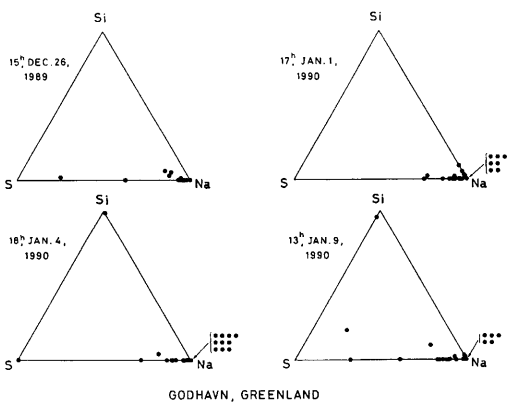

Fig. 16. Same as Fig. 15, but for the cases of southerly winds after the Foehn.

the beginning of the strong wind caused by the Foehn, the particles of soil and marine origin, and a few anthropogenic sources coexisted as shown in Fig. 17.

As a whole in the present study, the particles of anthropogenic origin were seldom found at Godhavn as human activities are limited there. According to Heidam (1984), the high Arctic troposphere in winter constituted a well mixed aerosol reservoir. And in the following study, Heidam (1985) investigated that non-crustal elements were found in Greenland and attributed them to be of marine origin, combustion process and ferro-metal processing sources.

5. Concluding remarks

The number concentrations of aerosol particles were measured at Godhavn, West Greenland in midwinter for about one month continuously.

The background value of aerosol particles was less than $10\,cm^{-3}$ of the air for particles of 0.3–0.5 μm in diameter. This value was smaller by about one half to one fifth of the magnitude compared with the values measured at Inuvik, Arctic Canada. Drastic variations of number concentrations were recorded accompanying the Foehn. With these variations, the number of aerosol particles for smaller size ranges decreased suddenly by about one order of magnitude, and

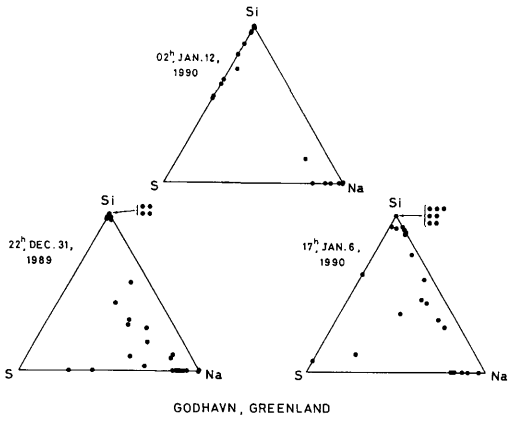

Fig. 17. Same as Fig. 15, but for the cases when the strong wind began to blow accompanying the Foehn.

on contrary, particles larger than 2 μm increased at the same time. It was considered therefore that in such Foehn that smaller particles were blown away and replaced by the strong northeasterly winds which came from the high plateau of Greenland. In contrast, the increase of the number for larger particles might be caused by fact that the strong wind had blown up the soil particles into the air from the ground surface or bare rocks nearby.

Further, the values of the volume concentrations of aerosol particles were obtained from the values of the number in each size range. Using these values, the local pollution was possible to distinguish from the widespread pollution.

Chemical components of individual aerosol particles collected at Godhavn were analyzed by means of the SEM-EMAX system. As a result, the elements of marine origin were frequently detected comparably with elements of soil origin. The origins of aerosol particles were inferred from the triangular diagrams using representative three chemical elements of Si, Na and S. The results were closely related to the wind systems at the west coast of Greenland.

6. Acknowledgments

We would like to express our thanks to Dr. Ole Bennike, Scientific Leader and Mr. Leif Skytte, Manager of the Arctic Station of the University of Copenhagen, Godhavn, Greenland. They gave us permission to use their station and facilities for our research project. Further, we express our thanks to Mr. Jorgen Taagholt, The Commission for Scientific Research in Greenland, Danish Polar Center in Denmark for his comments about our project and the Danish Meteorological Institute for the supply of weather data and weather charts. Mr. Peter Lind, Copenhagen Office of Greenland Travel Co. gave us a special arrangement for air cargo to Greenland. We express our appreciation to Dr. Austin W. Hogan, CRREL who gave us useful comments and checked our manuscript.

This research project was supported by the Grant-in-Aid for Scientific Research (Overseas Scientific Survey; Project No. 01041002) of the Ministry of Education, Science and Culture of Japan.

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