Tellus (1983), *35B*, 255–265

SO_2 and $SO_4^=$ in the arctic: interpretation of observations at three Norwegian arctic-subarctic stations

By JOST HEINTZENBERG, *Department of Meteorology, University of Stockholm, Arrhenius Laboratory, S-106 91 Stockholm, Sweden* and STEINAR LARSSEN, *Norwegian Institute for Air Research, N 2001 Lillestrøm, Norway*

(Manuscript received December 30, 1982; in final form February 21, 1983)

ABSTRACT

Three years of SO_2 and $SO_4^=$ measurements (1978–81) at three Norwegian arctic-subarctic stations (70, 74, and 79° N) have been related to air mass trajectories. The average decrease in non-marine $SO_4^=$-concentrations with increasing latitude was found to agree well with the latitude distribution of direct- or short-path return-flow frequency of trajectories from the Eurasian source area. As expected from its reactive, short-lived character, average SO_2-concentrations decreased much more rapidly than the frequency of source trajectories when moving into the arctic.

The seasonal variations in sulphur concentrations and source trajectories were less well correlated, best at the southernmost station. From the study of all individual pollution episodes (defined by ≥ 2 times average sulphur concentrations) we deduced that an increasing fraction of high sulphur levels could be explained by long-path return flow, when moving deeper into the arctic. On Spitsbergen 50% of all pollution episodes occurred during return-flow that had entered the arctic between Novaja Zemlya and the Taymyr peninsula.

1. Introduction

The pack-ice covered arctic ocean is practically free from sources of gaseous and particulate trace substances in the atmosphere. However, studies in the Alaskan, Canadian and Eurasian arctic have revealed concentrations up to continental background levels for SO_2, $SO_4^=$, soot and trace metals in winter and spring (see Rahn, 1981). On the other hand, during the summer months July through September extremely low concentrations comparable to antarctic levels have been found in the arctic (Lannefors et al., 1983). Early on, the cause for the elevated winter concentrations of trace substances in the arctic was sought in long-range transport processes. The most highly suspected sources or arctic haze shifted from the deserts of eastern Asia (Rahn et al., 1977) via eastern North America (Rahn et al., 1977) to Eurasia (Rahn et al., 1982).

In the present study we correlated three years of SO_2 and $SO_4^=$ measurements at three arctic and subarctic stations in the European sector with air mass trajectories to gain further insight into the arctic haze problem. We have concentrated on the Eurasian source area and proceeded systematically from long-term average conditions via annual variations to a discussion of different types of air flow during individual episodes of elevated SO_2 and $SO_4^=$ concentrations at the measuring sites.

2. Data base

We have used data from a Norwegian measurement program which was set up to monitor components of the surface aerosols and their precursors in the arctic-subarctic region up to a latitude of approximately 80° N. Three stations are in operation: Jergul in Finnmark (70° N, 25° E), Bear Island (75° N, 19° E) and Ny-Ålesund, Spitsbergen (79° N, 12° E). A detailed description of the sites and the measurement programme can be found in Larssen and Hanssen (1980). Here we use the results for SO_2–S and non-marine sulphate $(SO_4^=\text{–S})_{NM}$, both in $\mu g\ m^{-3}$. The sulphate values

1) Contribution No. 478.

were corrected for sea salt contribution by means of the measured magnesium concentration in the aerosol. For large parts of the year SO_2 concentrations at the northernmost station Ny-Ålesund are below the detection limit of the used wet chemical method of analysis of KOH impregnated filters. Hence they are only taken up in the discussion of average results for the investigated time period October 1978 through September 1981 and in connection with pollution episodes.

The meteorological data consisted mainly of isobaric 850 mb 96 h back trajectories calculated by the Norwegian Meteorological Institute (NMI) from the three stations. They were available every 6 hours yielding a total number of about 4000 trajectories for our observational period. The same type of trajectories from a total of 35 stations of the co-operative programme for monitoring and evaluation of the long range transmission of air pollutants in Europe (EMEP) were used to construct the latitude distribution of trajectories from Europe discussed in section 3. NMI used a rectangular grid limited by the North Pole, 37° W 41° N, 13° E 24° N, 58° E 41° N. To simplify the classification algorithm used in the trajectory programmes, we crudely defined the Eurasian source area as <57° N and reaching from 4° W to 58° E. Any case with a trajectory from the so-defined source area to a measuring site was called a direct flow (DF) case.

The trajectory grid area does not include all possible pathways from this source area to the arctic stations, especially to Ny-Ålesund. In particular, the long path return-flow pathway leading from Europe via the western U.S.S.R. to the arctic through entry ports somewhere between Novaja Zemlya and the Taymyr peninsula and then back to the Spitsbergen region (Rahn, 1979) was not covered by the trajectory calculations. In principle there exists a second type of return flow to the European arctic that was not covered by the trajectory grid. It leads from western Europe towards central and northern Greenland before turning east. It is directed against the most frequent wind directions in this region and leads through a large marine area with effective wet-removal processes for air pollution. We did encounter it a few times during the observational period, though not often enough to bear statistical significance. Additional meteorological information was used to identify those return-flow paths, which reached east of the 60° E before entering the arctic: gained from local wind directions on Bear Island and air temperatures at all stations (wind directions of Jergul and Ny-Ålesund are orographically influenced and not representative for air mass transport), and from the circumpolar surface and 500 mb weather maps.

3. Discussion of average results

The three years of trajectory data for 35 northern European stations on latitudes between 57° N and 80° N were searched for trajectories leading from the above-defined Eurasian source area to these stations. The number of those trajectories found for each of these stations was related to the total number of trajectories available during the observational period. The results are plotted as a smoothed latitude distribution of source trajectories in Fig. 1.

The general trend of decreasing frequency of source trajectories with increasing distance from the source may seem trivial. However, the actual shape of the decrease is influenced by meteorology as well as by geometry and the finite length of the trajectories. This is illustrated by the site 58.2° N, 6.2° W Stornoway, Hebrides, marked in Fig. 1. According to geometry it should have a very high frequency of trajectories from the source region. However, it lies upwind of Europe and therefore receives polluted air masses only during 22% of the total time (about as often as Jergul).

The frequencies of direct-flow occasions or the relative number of sector trajectories (NST) at the

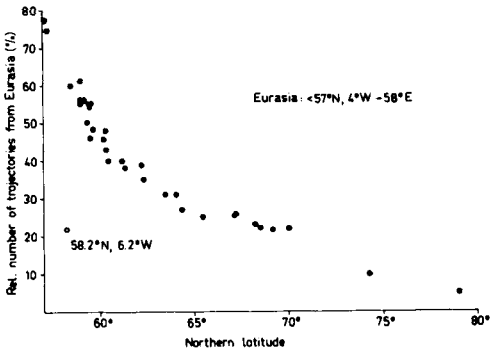

Fig. 1. Latitude distribution of trajectories from the Eurasian source sector to 33 European stations north of 57° N.

Table 1. *Frequencies of direct flow from the Eurasian source region DF (%) compared to 3-year averages of SO_2–S and $(SO_4^=–S)_{NM}$ at three arctic-subarctic stations*

Parameter	Jergul	Bear Island	Ny-Ålesund
DF (%)	23	10	5.2
SO_2–S ($\mu g\ m^{-3}$)	2.6	0.28	<0.1
$(SO_4^=–S)_{NM}$ ($\mu g\ m^{-3}$)	1.3	0.47	0.24

three arctic sites is compared to average air chemistry results in Table 1. Within a 10% margin, the $SO_4^=$ concentrations decrease with the same ratios with increasing latitude as do the direct flow frequencies. Hence on a long-term basis, the frequency of direct flow from Eurasia is consistent with the latitudinal trend in non-marine sulphate at our sites.

The SO_2 concentrations drop off much more rapidly than the $SO_4^=$ concentrations, almost a factor of 10 on the 600 km distance between Jergul and Bear Island and are below the detection limit after another 500 km of travel distance.

4. Seasonal variations

In the foregoing section we showed that direct-flow trajectories from Eurasia give a satisfactory picture of the long-term average concentration gradient of $SO_4^=$ from northern Scandinavia into the arctic. The picture of atmospheric transport becomes much more complicated when we start looking at the annual variations in the occurrence of source trajectories.

In Figs. 2a–c we separated the three-year data set of trajectories into 12 monthly collections. We recognize a latitudinal trend in the decrease of the total number of trajectories depicted in the graphs for Jergul, Bear Island and Ny-Ålesund, respectively. However, the strong maximum of source trajectories during the winter/spring season expected from previous air chemistry results (Larssen and Hanssen, 1980) is not obvious. Only March stands out as the month with the highest frequency of source trajectories at all three stations while April already exhibits close to absolute minimum frequencies of pollution trajectories at the two arctic stations. We also find strong relative trajectory maxima in May, June, August and October, and there is no clear seasonal trend. However, systematic month-to-month changes in transport path locations and consequently path-lengths can be seen at all stations.

A great circle line through the three sites (~30° E) roughly halves the Eurasian source area and may serve as a symmetry axis with respect to the transport pathways depicted in Fig. 2. In months like February, cyclonic and anticyclonic trajectories group almost symmetrically around this symmetry axis but reach out far west and east before arriving at the stations. In other months like August, most trajectories lie very close to the symmetry axis. Both westside and eastside short-path return flows are very frequent during October through December. We refer to Fig. 4 to clarify the distinction between short-path and long-path return flow to the European arctic. There the meteorological flow patterns for an extended long-path return-flow episode on Spitsbergen are presented.

Obviously, different rates of transformation and deposition to the surface along trajectories will be important in explaining concentrations of SO_2 and $SO_4^=$ in air masses arriving at the stations. We do not attempt to quantify these processes at this stage. Instead, we will proceed to investigate the seasonal trends of trajectory paths, noting that deposition processes will be different along different trajectory pathways. The intention is to illustrate the unique conditions governing long-range transport and lifetimes of pollutants in the arctic.

In Figs. 3a–c the annual variation of direct flow (DF) trajectories is presented as the number of DF-trajectories relative to the total number of trajectories possible during each month, i.e. 4 times the number of days per month. For each of the three stations these annual trends are compared to the monthly means of SO_2–S (except at Ny-Ålesund) and $(SO_4^=–S)_{NM}$. As could be guessed from Figs. 2a–c the annual trend in source trajectories becomes less regular with increasing latitude. Both SO_2 and $SO_4^=$ are best correlated with DF-frequencies at the station which lies closest to the sources area, i.e. Jergul. Here even the relative minimum in the DF frequency in April is reflected by the trend in SO_2 and possibly in the $SO_4^=$ results

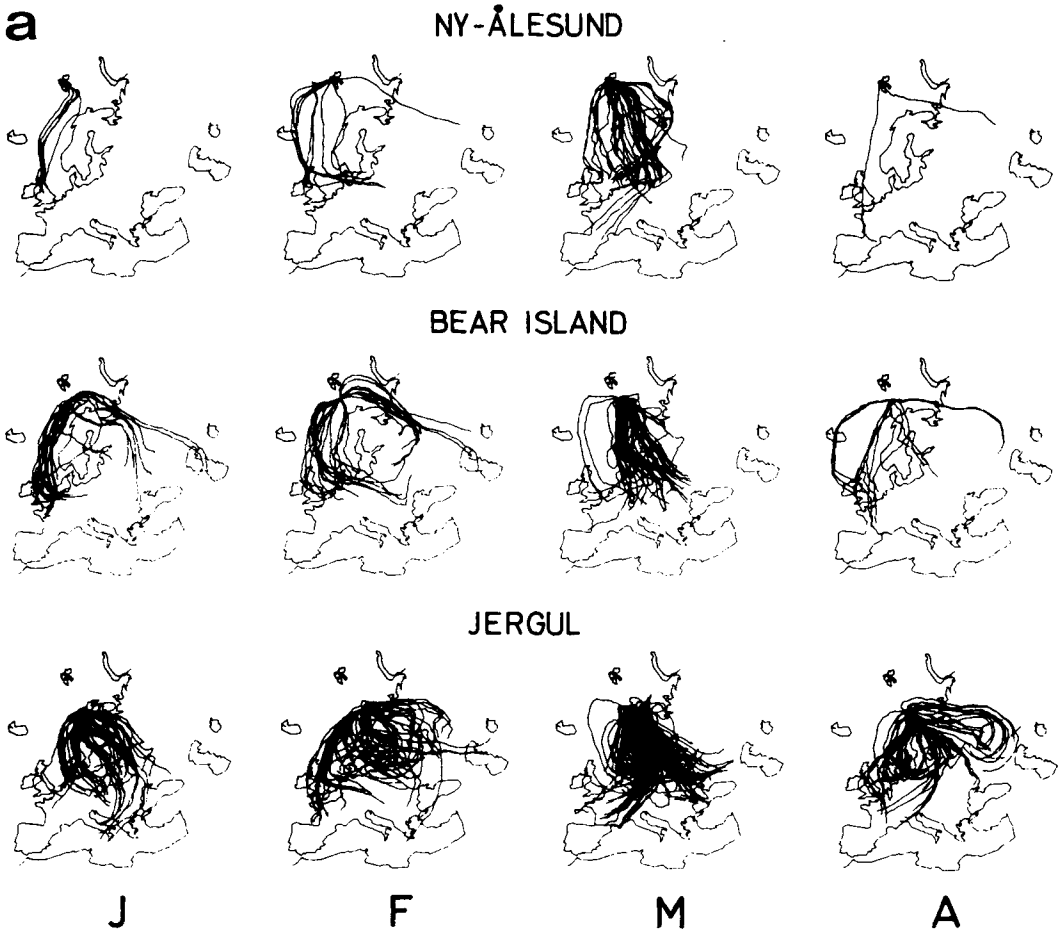

Fig. 2a. Trajectories from the Eurasian source region to Jergul (70° N, 25° E), Bear Island (75° N, 19° E) and Ny-Ålesund, Spitsbergen (79° W, 12° E) for the months January through April (1979–1981).

too. However, the October maximum in source trajectories does not lead to corresponding level increases in SO_2 or $SO_4^=$. The October picture in Fig. 2c reveals that most trajectories either come via the Norwegian Sea or even on spiralling paths over western Scandinavia to Jergul. This region experiences maximum precipitation in fall and early winter, which scavenges SO_2 along the trajectories.

SO_2 at Jergul has the largest annual variation with roughly a factor of ten. This is much more than within the source region where winter to summer concentration ratios are about 2. The winter to summer ratio in DF-trajectories at Jergul, on the other hand, is about five.

Already after 600 km further travel towards the north, very little SO_2 variations are left. None of the three peaks in DF-trajectories in March, May and August are reflected in the SO_2 results. The $SO_4^=$-concentrations are also poorly correlated with the source trajectories. The $SO_4^=$ winter maximum is much broader than the trajectory maximum and the small summer peak is hardly significant. The winter to summer ratio in $SO_4^=$ is about 2.5, roughly five times the winter to summer ratio of SO_2.

The distribution of the total amount of sulphur between the gas phase and the particulate phase changes with the aging of the polluted air mass. At Jergul during winter and spring most of the sulphur arrives as SO_2 while most of the sulphur that reaches Bear Island is found as $SO_4^=$. One might be tempted to calculate SO_2 conversion rates and $SO_4^=$ residence times by assuming a direct transport

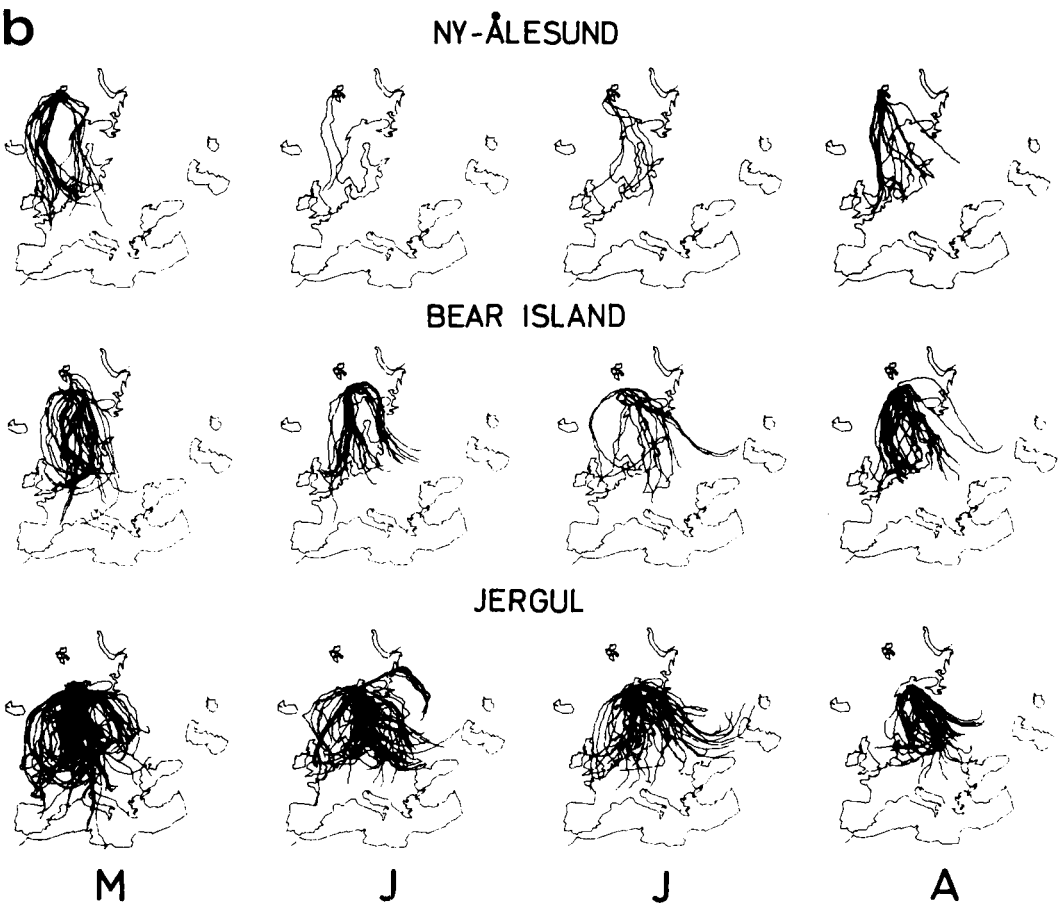

Fig. 2b. Same as Fig. 2a but for the months May through August (1979–1981).

from Jergul to Bear Island. However, the deep trajectory minimum in April which is not reflected in the chemical results, indicates the possibility of other than DF-trajectories as sources of sulphur at Bear Island.

A look at the annual trends of DF-trajectories and $(SO_4^=\text{–S})_{NM}$ at Ny-Ålesund confirms the suspicion of other than direct-flow trajectories contributing to arctic haze particles. Only the absolute trajectory and $SO_4^=$ maxima coincide in March. April, however, has nearly equally high $SO_4^=$-concentrations while almost no DF-trajectories reach the sampling site. Moreover, March and April $SO_4^=$ levels at Ny-Ålesund are the same as on Bear Island, 500 km *closer* to the source area on direct pathways. On the other hand, the winter to summer concentration ratio increases to a factor of ten at Ny-Ålesund. It cannot be explained completely by a lack of DF-trajectories in summer. During the cleanest months August through October the direct-flow frequencies are at average winter values. As an explanation for the extremely low summer $SO_4^=\text{–}S_{NM}$ levels (between 50 and 100 ng m^{-3}) we propose a very persistent summer feature of the arctic: low stratus or fog as very efficient scavengers for trace substances. Their effectiveness is illustrated by the fact that the total amount of water in the atmospheric boundary layer rains out and becomes resuspended 10–20 times per 24 hours (Holmgren and Enger, 1981). Steffensen (1982) gives the highest frequency of fog as 17 to 22% for Bear Island in July and August, while Huschke (1969) reports the months May through August as having the highest frequencies of low clouds taking the European arctic sector as a whole.

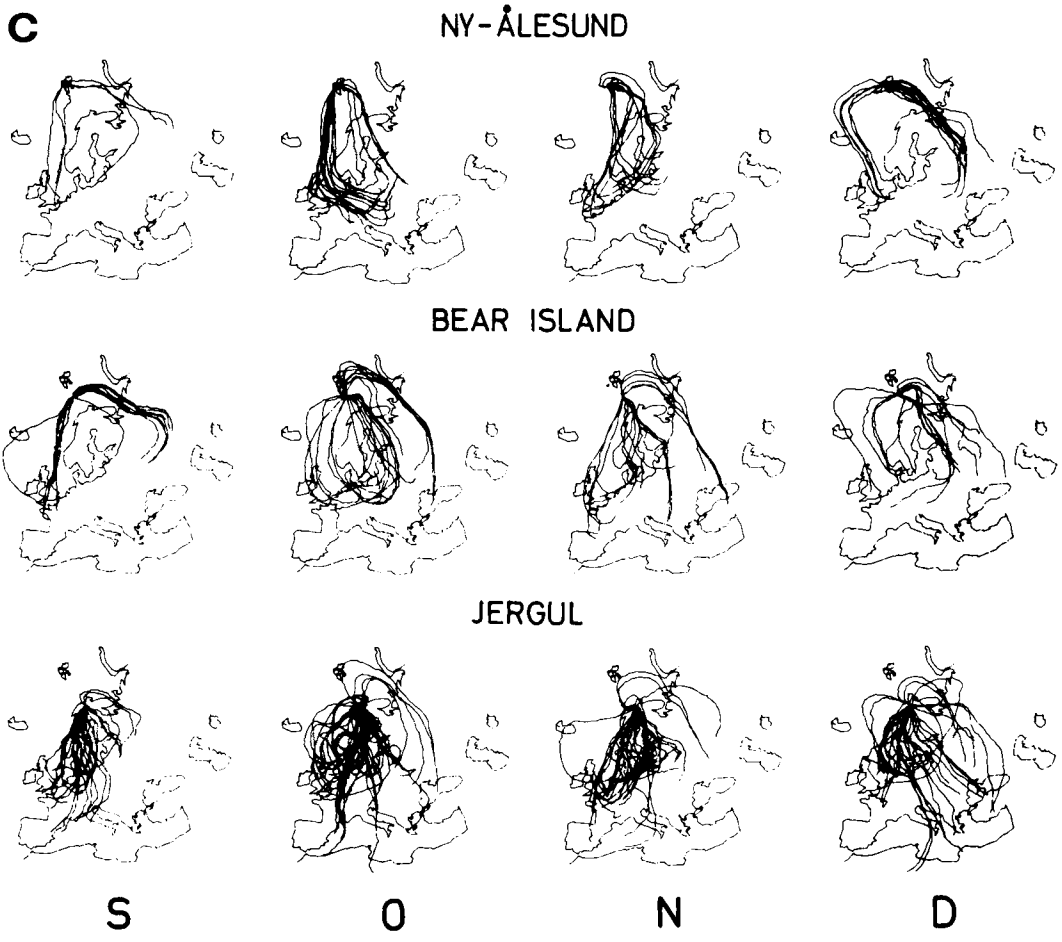

Fig. 2c. Same as Fig. 2a but for the months September (1979–1981), October through December (1978–1980).

If this explanation is valid we have another factor (besides non-direct-flow trajectories from sulphur sources) influencing the annual variation of our chemical results in the arctic. Hence we satisfy ourselves with the decreasing correlation between DF-trajectories and sulphur concentrations with increasing northern latitude and try to extract more information from the study of individual pollution episides.

5. Air flow during individual pollution episodes

In the foregoing section we saw that the direct-flow trajectories became decreasingly satisfactory in explaining the annual variations in SO_2 and $SO_4^=$ concentrations when moving deeper into the arctic. In part this is certainly due to the fact that we are moving towards the NW corner of the trajectory grid, the increasing length of trajectories to Eurasia plus the scarcity of meteorological observations in the arctic. However, there are systematic discrepancies between the annual variations of trajectories and those of the pollutants at all 3 stations, encouraging a more detailed study of occasions with high SO_2 or $SO_4^=$ concentrations.

We define a pollution episode as a time period during which the concentration levels were at least two times the three-year averages given in Table 1. These concentration limits are somewhat arbitrarily chosen. However, they are close to those used in a earlier transport study of previous Bear Island SO_2-data (Rahn et al., 1980) which facilitates the comparison of the results.

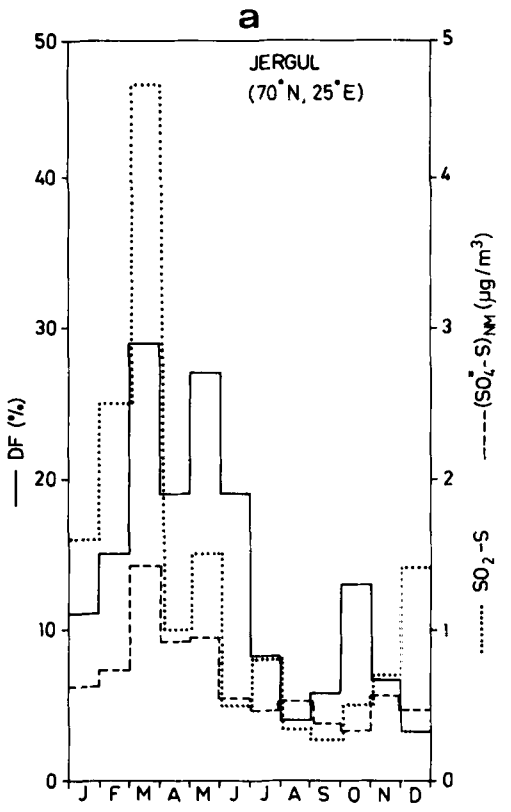

Fig. 3a. Annual variation of SO_2–S (·····), $SO_4^=$–S (– – – –), and the relative number of Eurasian source trajectories (——) to Jergul, Norway (70° N, 25° E), based on the period October 1978 through September 1981.

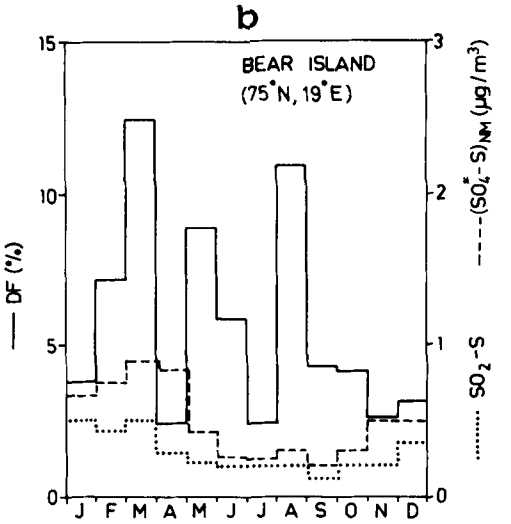

Fig. 3b. Same as Fig. 3a, but to Bear Island (75° N, 19° E).

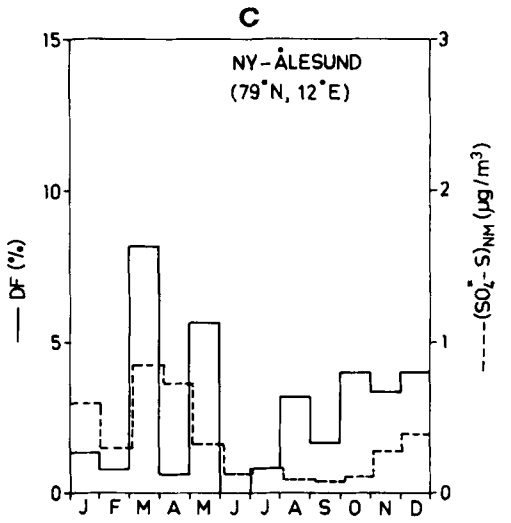

Fig. 3c. Same as Fig. 3a, but to Ny-Ålesund, Spitsbergen (79° N, 12° E). No data on SO_2–S available.

During the 3-year period, a total of about 50 pollution episodes occurred for both SO_2 and $SO_4^=$ at Jergul and Bear Island. Most of the $SO_4^=$-episodes coincided. However, a few cases occurred with elevated SO_2-levels up to ±5 days out of phase compared to the $SO_4^=$-episodes. The extent of these episodes ranged between one and 24 days. Ny-Ålesund experienced only 28 pollution episodes.

With the help of the direct flow trajectories and meteorological data mentioned in section 2 we tried to break down the air flow during each pollution episode into three classes: (1) direct flow (DF), including short-path return-flow if our trajectories indeed lead back to the Eurasian source region, (2) long-path return-flow (RF) if local wind, air temperature and weather maps indicated air flow via Rahn's suggested return-flow path, and (3) unidentified flow occasions (UFO) in cases where none of two transport classes would fit. The results are collected as percentage contributions of the different flow types in Table 2. SO_2 at Ny-Ålesund was not considered in the statistics because of the scarcity of data. UFO's ranged between 4 and 11%. They include the few cases with return-flow from the NW and some cases with local or mesoscale (Jergul) pollution episodes. About 90%

Table 2. *Percentage contributions of direct flow, return-flow or unidentified flow occasions (UFO) to the identification of pollution episodes at three arctic-subarctic stations*

	Direct flow (%)		Return-flow (%)		UFO (%)	
Site	SO_2–S	$(SO_4^=$–S$)_{NM}$	SO_2–S	$(SO_4^=$–S$)_{NM}$	SO_2–S	$(SO_4^=$–S$)_{NM}$
Jergul	78	84	13	8	9	8
Bear Island	56	60	40	32	4	8
Ny-Ålesund	—	46	—	43	—	11

of all pollution episodes at each station could be identified as either DF or RF.

There was a systematic shift in the distribution of the two transport types when moving from northern Scandinavia into the arctic. It remains visible even after allotting half the UFO percentages to each of the flow types as approximate error bars. At Jergul about 80% of the pollution episodes could be explained by direct flow while return-flow can explain 10% of both SO_2 and $SO_4^=$-episodes. Five degrees further north the ratio DF/RF decreases to 60/40. Finally at 79° N both transport types had the same frequency of occurrence. We see no significant difference between frequencies of $SO_4^=$ and SO_2-episodes. This implies that SO_2-residence times during return-flow conditions must be longer than the 1–2 days given by Rodhe (1978) as an average for Europe. Rahn et al. (1980) estimate 5–10 days for winter episodes with low dry and wet deposition, low temperatures and lacking solar radiation. Based on all available episode data the results in Table 2 give an explanation for the decreasing correlation between DF-trajectory occurrence and sulphur concentrations when moving north by allowing increasing weight on return-flow transport. However, for the monthly averages shown in Figs. 3b and c this argument does not work. We hoped to be able to fill in the gaps in DF-trajectories by return-flow episodes to explain the persistence of high $SO_4^=$-concentrations in April, but we could not find a systematic increase in RF-episodes during that month. An alternative explanation would be a residence time of sulphate particles in the Arctic of about one month or longer. Taking the mass median particle radius in arctic haze of 0.15 μm (Heintzenberg et al., 1981) and the results of Jaenicke (1978) on size-dependent dry removal residence times of aerosols yields about 25 days in arctic haze. Thus we have two pieces of evidence for a long sulphate residence time in the winter arctic.

To illustrate the meteorological conditions leading to the return-flow episodes and to demonstrate the unique transport situations leading to the pollution of the European arctic we discuss in detail an SO_2 episode during December 1980 at Ny-Ålesund. Surface weather maps from the onset of high SO_2-concentrations until after the peak SO_2-levels are collected in Fig. 4. A series of disturbances passed over northern europe and Russia. Highly polluted air from central Europe and the industrialized areas of the U.S.S.R. (as far as the Ural region around Sverdlovsk) were incorporated into the disturbances along their way. Then a cold high pressure ridge over Siberia forced these polluted air masses northwards towards the Pole, where a high over Greenland directed them back towards the south west.

The first front reached Spitsbergen the 10th of December. SO_2–S levels rose from below the pollution threshold to 0.6 $\mu g\ m^{-3}$ on the 8th, to 3 $\mu g\ m^{-3}$ on the 12th and remained about 0.6 $\mu g\ m^{-3}$ until the 25th of December. If we take Sverdlovsk as the last station in the Eurasian "loading area" for SO_2 we calculate a transport path of 5500 km from there to Ny-Ålesund according to the surface flow pattern in Fig. 4. The displacement of the fronts yields an average travel speed of 8 m s^{-1} leading to a travel time of 8 days. On this very long-range transport, three processes can decrease the SO_2-concentrations: dilution, conversion and removal by wet and dry deposition. Rahn and McCaffrey (1979) determined empirically a dilution factor of 0.88 per day for transport at 8 m s^{-1} through the Arctic region. Photochemical conversion of SO_2 must have been extremely low because most of the transport occurred in the polar

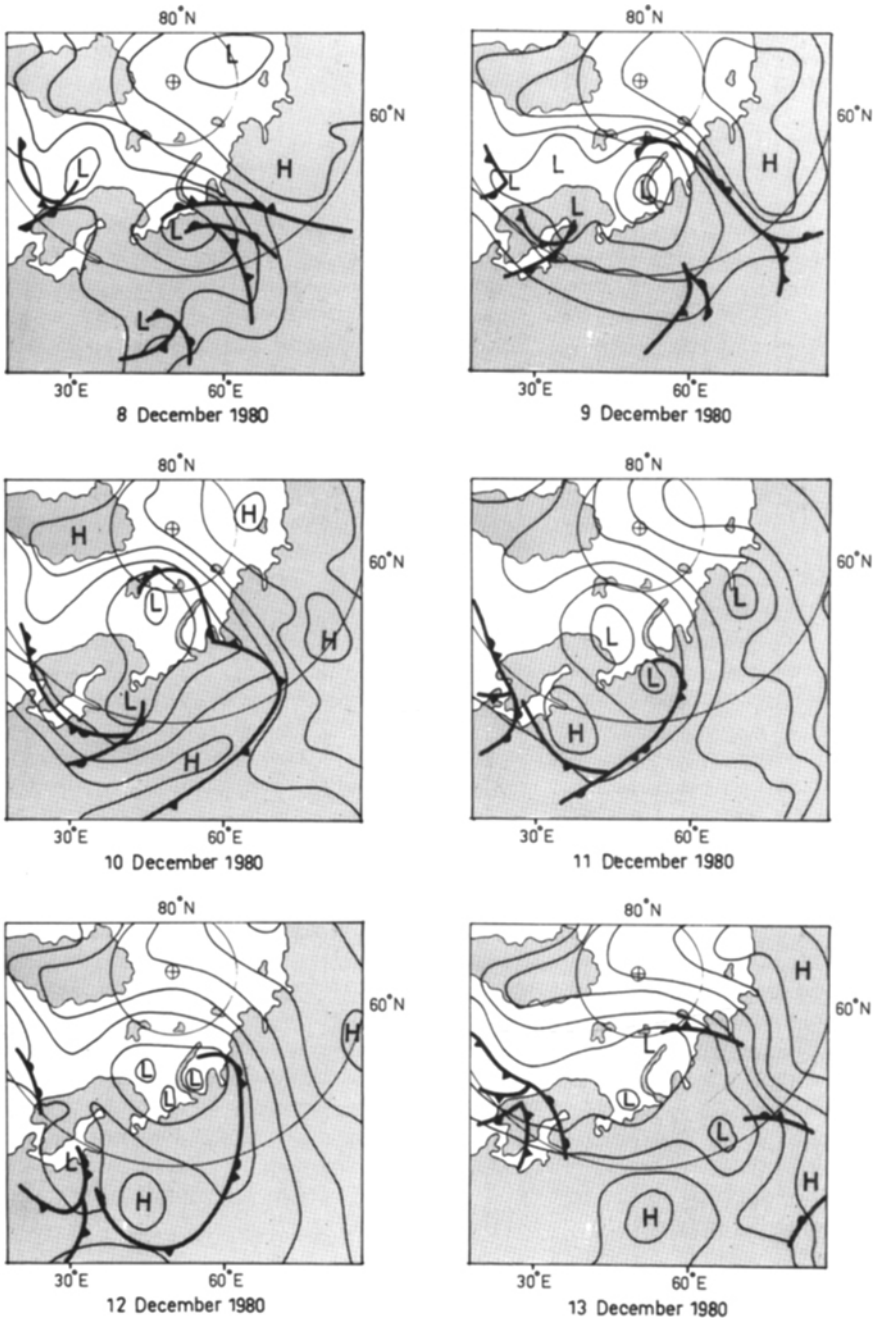

Fig. 4. Surface weather maps related to a period with extremely high SO_2-levels on Spitsbergen. The interval between the isobars is 10 mb.

night region. Even at the southernmost point of Sverdlovsk the maximum sun elevation was 10° with 6 h daylight. According to Granat and Johansson (1983) dry SO_2 deposition to non-melting snow and ice covered surfaces is negligible. Thus, taking only into account the dilution

factor yields a SO_2–S concentration of about 8 μg m^{-3} at Sverdlovsk. Judging from annual SO_2-emission data for the Sverdlovsk region (Dovland and Saltbones, 1979) and winter SO_2-concentrations over Europe (Rodhe and Granat, 1983), SO_2 concentrations in December at Sverdlovsk should be about 10 μg SO_2–S per m^{-3}. With this starting level of SO_2 there is no need to assume any transformation or deposition on the way from Sverdlovsk to Spitsbergen to arrive with the measured SO_2 values at Ny-Ålesund. The relatively low $SO_4^=$ values of 0.4 to 0.8 μg $(SO_4^=\text{–S})_{NM}$ per m^3 during that period at Ny-Ålesund support our hypothesis of fresh Eurasian air reaching Spitsbergen on a 5500 km long return-flow path.

6. Summary and conclusions

Three years of SO_2 and $SO_4^=$ measurements (1978–81) at three Norwegian arctic-subarctic stations (70, 74, and 79° N) have been related to air mass trajectories. The average decrease in non-marine $SO_4^=$-concentrations with increasing latitude was found to be in good agreement with the latitude distribution of direct- or short-path return-flow frequency of trajectories from the Eurasian source area. As expected from its reactive, short-lived character average, SO_2-concentrations dropped off much more rapidly than the frequency of source trajectories when moving into the arctic.

Annual variations of sulphur concentrations and frequencies of source trajectories agreed less well, best at the southernmost station. A deep gap in April and strong maxima in May and August in source trajectory frequencies on Bear Island and at Ny-Ålesund were not reflected in SO_2 or $SO_4^=$-concentrations. The air-mass origin of all individual pollution episodes during the three-year period was studied to clarify the discrepancies between trajectory frequencies and sulphur concentrations. When moving deeper into the arctic, an increasing fraction of these episodes could be explained by long-path return-flow transport that entered the arctic between Novaja Zemlya and the Taymyr peninsula. On Spitsbergen 50% of all pollution episodes occurred during return-flow conditions. With an example of a return-flow SO_2-transport from the Sverdlovsk region to Spitsbergen we have demonstrated how highly polluted air can travel large distances in the cold dark arctic without significant chemical ageing.

We were not able to fill in the April trajectory drop on Bear Island and on Spitsbergen by long-path return-flow episodes and conclude that the persistently high $SO_4^=$ concentrations in April are due to residence times of sulphate particles of up to 30 days in the late winter arctic. The low concentrations of sulphur pollutants during the August trajectory maximum we explain by the very effective wet scrubbing efficiency of the persistent low stratus and fog banks in the arctic during this part of the year.

The study has demonstrated the value of a permanent station for the monitoring of air pollutants on Spitsbergen. Besides monitoring the background air quality in the climatically sensitive arctic region itself, the unique meteorological flow situations in winter allow a survey of pollution effluents from central Europe, Russia and even the industrialized region east of the Ural. For that purpose even reactive pollutants such as SO_2 should be monitored because they acquire tracer qualities inside the winter arctic.

7. Acknowledgements

We gratefully acknowledge the essential contribution to the meteorological data base made by the trajectories supplied by the Norwegian Meteorological Institute through the extensive help of J. Saltbones. Our work was supported in part by the National Swedish Environment Protection Board, Dnr 500-788-80-Ff.

REFERENCES

Dovland, H. and Saltbones, J. 1979. Emissions of sulphur dioxide in Europe. EMEP/CCC-Report 2/79, Norwegian Institute for Air Research. (Available through the second author.)

Heintzenberg, J., Hansson, H.-C. and Lannefors, H. 1981. The chemical composition of arctic haze at Ny-Ålesund, Spitsbergen. *Tellus 33*, 162–171.

Holmgren, B. and Enger, L. 1981. Stratus and the atmospheric boundary layer over the Arctic Ocean. Paper presented at the 8th meeting of the European Geophysical Society, Uppsala, August 24–29, 1981.

Huschke, R. E. 1969. Arctic cloud statistics from "calibrated" surface weather observations. Rand Corporation, RM-6173-PR.

Jaenicke, R. 1978. Über die Dynamik atmosphärischer Aitkenteilchen. *Ber. Bunsenges. Phys. Chem. 82*, 1198–1202.

Lannefors, H., Heintzenberg, J. and Hansson, H.-C. 1983. A comprehensive study of physical and chemical parameters of the Arctic summer aerosol. *Tellus 35B*, 40–54.

Larssen, S. and Hanssen, J. E. 1980. Annual variation and origin of aerosol components in the Norwegian Arctic-Subarctic region. Proceedings of the WMO Technical Conference on Regional and Global Observation of Atmospheric Pollution Relative to Climate, Boulder, CO, 20–24, August 1979. WMO-No. 549, Geneva.

Rahn, K. A., Borys, R. D. and Shaw, G. E. 1977. The Asian sources of Arctic haze bands. *Nature 268*, 713–714.

Rahn, K. A., Borys, R. D. and Shaw, G. E. 1977. Particulate air pollution in the Arctic: large scale occurrence and meteorological controls. Proceedings of the 9th International Conference on Atmospheric Aerosols, Condensation and Ice Nuclei, Galway, Ireland, 21–27.

Rahn, K. A. 1979. The Eurasian source of arctic aerosol. Report 34/79, Norwegian Institute for Air Research. (Available through the second author.)

Rahn, K. A. and McCaffrey, R. J. 1979. On the origin and transport of the winter arctic aerosol. *Ann. New York Acad. Sci. 338*, 486–503.

Rahn, K. A., Joranger, E., Semb, A. and Conway, T. 1980. High winter concentrations of SO_2 in the Norwegian arctic and transport from Eurasia. *Nature 287*, 824–826.

Rahn, K. A. (guest editor), 1981. Arctic air chemistry. *Atmos. Environ. 15*, 1345–1516.

Rahn, K. A., Brosset, C., Ottar, B. and Patterson, E. M. 1982. Black and white episodes, chemical evolution of Eurasian air masses, and long-range transport of carbon to the arctic. In: *Particulate Carbon: Atmospheric Life Cycle*, eds G. T. Wolff, R. L. Klimisch, Plenum Publ. Corp. 327–342.

Rodhe, H. 1978. Budgets and turn-over times for atmospheric sulphur compounds, *Atmos. Environ. 12*, 671–680.

Rodhe, H. and Granat, L. 1983. Summer and winter budgets for suffer over Europe; an indication of large seasonal variations of residence time. *Idöjaras 87*, 1–6.

Steffensen, E. 1982. The climate at Norwegian arctic stations. Klima 5, 1–44, published by the Norwegian Meteorological Institute.