Long-Range Tropospheric Transport of Pollution Aerosols into the Alaskan Arctic

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ABSTRACT

Noncrustal vanadium and manganese are used as chemical tracers for pollution-derived aerosols (collected over a period of four years in the near-surface air at Barrow, Alaska), in order to investigate tropospheric long-range transport of anthropogenic pollution from midlatitudes to the Alaskan Arctic. The analysis is based upon subjectively identifying characteristic transport pathway types using daily circumpolar weather maps. The transport occurs when the midlatitudinal and Arctic atmospheric circulations manifest quasi-persistent circulation patterns. Rapid transport of aerosols, on the order of 7–10 days, is dominated by quasi-stationary anticyclones and takes place along their peripheries where pressure gradients are relatively strong. The seasonal variation in concentration of the Arctic pollution-derived aerosol is related to the seasonal variation in the occurrence and position of midlatitude blocking anticyclones, of the Arctic anticyclone and of the Asiatic anticyclone. The positions of the major anticyclonic centers and their seasonal variation are responsible for the fact that different source regions contribute to the pollution-derived aerosol during different times of the year. Central Eurasian sources contribute predominantly during winter, Western Eurasian sources during spring, whereas North American and Far Eastern sources contribute little to the Arctic pollution aerosols collected in Alaska.

1. Introduction

Evidence indicates that the troposphere over Barrow, Alaska in late winter and spring is charged with anthropogenically-derived aerosols and gases (Rahn and McCaffrey, 1980; Daisey *et al.*, 1981; Weschler, 1981; Rosen *et al.*, 1981; Bodhaine *et al.*, 1981; Rasmussen and Khalil, 1982). On the basis of chemical signatures in submicron aerosols, it has been deduced that the trace constituents originate in midlatitude industrialized areas and are transported along pathways thousasnds of kilometers in length to Alaska. Aerosols showing anthropogenic characteristics are detected at other Arctic sites as well; for example, they have been detected at Mould Bay and Igloolik (Barrie *et al.*, 1981); Thule and Prins Christianssund (Heidam, 1981); Ny-Alesund (Heintzenberg, 1981; Larssen and Hanssen, 1979) and Bear Island (Larssen and Hanssen, 1979). The pollution-derived aerosol tracers all undergo similar seasonal variations; their presence constitutes an arctic-wide phenomenon.

In Section 2 we will discuss the chemical tracers used, in order to identify the presence of pollution-derived aerosols. We will also describe a scheme of meteorological/synoptic conditions found to be relevant to the possibility of tropospheric long-range transport. In Section 3 a number of characteristic transport pathway types will be presented and their main features identified. The seasonal variation of different transport pathway types is shown to be related to the seasonal variability of the aerosols (Section 4).

2. Data sets and method

Four years (September 1976–September 1980) of data consisting of elemental abundance of manganese and vanadium in the near-surface aerosol at Barrow, Alaska were investigated. The analysis was restricted to the months October–April because of the small amount of pollution-derived aerosols present during summer. The time series of chemical data were collected by K. Rahn and made available to us for this study; only 46 days of data were missing in the four-year set.

The aerosol samples were collected on cellulose filters at the Geophysical Monitoring for Climatic Change (GMCC) Observatory in Barrow. Samples were "sector controlled" to sample air from the "clean" sector, ranging from 5–125 deg azimith (Bodhaine *et al.*, 1981). Analysis for trace elements in the aerosols was performed by Neutron Activation Analysis at the nuclear reactor facility at the University of Rhode Island.

Vanadium and manganese were used as tracers in our study. Excess vanadium (XV) (excess over crustal material) is thought to arise primarily from the combustion of heavy residual oil (Zoller *et al.*, 1973). It is a valuable chemical tracer for midlatitude pollution-derived aerosols because the low viscosity fuels used at Arctic latitudes contain insignificant amounts of

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vanadium (Hofstader *et al.,* 1976). Excess manganese (XMn) derives from a number of pollution sources, an important one being coal combustion. The pollution components (XMn and XV) were derived from the measured total concentrations of Mn and V using Al as a crustal reference element. The procedure for deriving XMn and XV was discussed by Rahn (1976).

The use of the ratio XMn/XV ratio as a source-specific tracer for pollution-derived aerosols was suggested by Rahn (1981). The XMn/XV ratios for Eurasian source regions are higher than for sources in the northeastern United States. The variations in the XMn/XV ratio probably are related to the greater relative amount of fuel oil combusted in North America in comparison to Eurasia. Western European sources probably have somewhat lower XMn/XV ratios than central Eurasian sources.

The mean monthly concentrations of XV and XMn at Barrow are shown in Fig. 1 for the period September 1976 to September 1980. The concentrations are low in summer, but rise gradually during fall, reach a temporary plateau in January–February, and rise to a pronounced maximum in March. Concentrations rapidly decrease thereafter. The similarity of time variation of XMn and XV is supported by a high correlation coefficient ($r = 0.88$). During a year, concentrations of XMn and XV vary by average factors of 33 and 82. In contrast, the seasonal variation of pollution-derived aerosols over midlatitudes is about an order of magnitude smaller (Rahn and McCaffrey, 1980). The seasonality of XV and XMn at Barrow, therefore, cannot be understood by attributing it to the variation in intensity of a particular source. We also point out that there are no significant sources of vanadium and manganese within the geographic region of the Arctic. The seasonal variation of XV and XMn must be related to either variations in atmospheric transport pathways and/or to seasonal variations in microphysical processes which modify and remove aerosols from the atmosphere.

The XMn concentrations are generally larger than XV concentrations during fall and early winter. During February–April concentrations of XV are similar to those of XMn or even higher in March (Fig. 1). Consequently, the XMn/XV ratios are generally larger during winter than during spring. It follows that there must be a seasonal variation in transport pathway bringing aerosols from one source region in winter and from another source region in spring.

During transport over distances of thousands of kilometers, aerosols might spread by turbulent eddies over scales of distance comparable to large-scale synoptic features. In addition, polluted air masses from different source regions will eventually mix with each other. If the transport distances and times are large enough, one would expect to find a well-mixed and rather homogeneous aerosol at the end of the transport (Shaw, 1981). Barrie *et al.,* (1981) suggested the concept of a "bathtub" model in which the Arctic atmosphere is imagined to be approximated as a horizontally mixed reservoir into which air from midlatitudes is periodically injected. Due to the annual variation in scavenging processes in and around the Arctic, the flux of pollutants into the reservoir and their residence times while in it are lower in summer than in winter. Throughout the winter the reservoir becomes progressively dirtier as demonstrated by a steadily increasing "background".

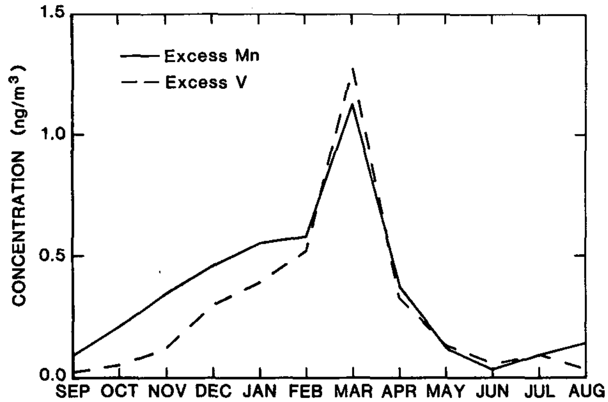

FIG. 1. Mean monthly concentration of excess vanadium and excess manganese (1976–80).

However, examination of data on the chemical composition for Barrow aerosols shows the following:

1) The Arctic pollution aerosol does not have uniform chemical characteristics as indicated by the change of the XMn/XV ratio from winter to spring and previously discussed. In addition, other ratios show seasonal changes as well, e.g., vanadium/carbon, sulfate/carbon (Rahn *et al.,* 1980), lead/carbon (Rosen *et al.,* 1982).

2) XMn concentrations during December and January sometimes are almost comparable to those during March with periods of lower concentrations in between (Fig. 2).

3) Individual samples show large fluctuations in concentration and ratio characteristics within different Arctic air masses which cannot be explained by the local synoptic conditions at Barrow, but have to be attributed to conditions during transport.

Thus, it appears that individual injections of pollutants from midlatitudes into the Arctic are able to retain, to at least a degree, individual "chemical" characteristics and the Arctic background pollution does not build up progressively as a well-mixed reservoir.

For these reasons we will investigate individual "episodes" of high XMn and V concentrations in some detail. One can anticipate that these episodes represent atmospheric conditions which allow for abnormally large acccumulation of pollutants over the source area, little scavenging along the pathways, rapid transport and well developed or persistent synoptic pressure systems.

The analysis involves identification and classification of synoptic conditions existing at the source regions and in the Arctic. The method used to analyze aerosol episodes is summarized as follows:

1) Samples at Barrow characterized by relatively high concentrations of XV and XMn were chosen from time series (Figs. 2 and 3) and are labeled. Some sampling times were quite long (up to 8 days) and meteorological conditions sometimes changed within a given sampling period. Time/height cross sections of potential temperature and mixing ratio were constructed to identify the periods when Arctic air reached the station (Raatz, 1982). We assume that only Arctic air masses carry pollutants into Barrow (Rahn and McCaffrey, 1980; Peterson *et al.*, 1980; Raatz, 1982).

2) Industrial source areas were identified which experienced anticyclonic influence for several days prior to the time of relatively high pollution concentration at Barrow, stagnation, and possibly accumulation of pollutants. In order to subject pollutants to long-range transport, we required that the period of stagnation be followed by a "surge" of air northward due to an approaching cyclone (to be further discussed in Section 3).

3) The transport pathways from the suspected source areas to Barrow were tentatively identified by inspecting daily surface, 850 mb and 500 mb circumpolar weather maps issued by the Deutscher Wetterdienst, Offenbach, FRG, and by the National Climatic Data Center, Asheville. The transport pathways were subjected to tests involving the calculation of travel time from the occurrence of the surge to the arrival of Arctic air at Barrow.

Depending on the complexity of the situation, the procedure was sometimes repeated, sometimes with changed order, but the overall objective was to obtain a consistency between meteorological "stagnation-surge" conditions at the source region, the location of a pathway and major synoptic pressure systems, travel times and meteorological conditions at Barrow. The method is iterative and continues until a self-consistent picture emerges.

Samples satisfying the previously mentioned set of conditions will be referred to as "pollution episodes" in contrast to the common usage of pollution episodes which describes only times of high concentrations of pollution at the receptor site.

3. Transport pathway types of pollution-derived aerosols

Sixty-one samples of relatively high concentrations of XV and XMn at Barrow were investigated and are identified in Figs. 2 and 3. Fifty of the 61 samples were successfully associated with "pollution episodes," as already defined. Seven samples were not associated with episodes of their own, but were continuation of the previous sample and its pollution episode. One sample (5 and 6 March, 1980) with high XV and XMn concentrations is suspected to have collected volcanic material following the eruption of Klyuchevskaya (56.06°N, 160.64°E) on the Kamchatka Peninsula (N. Lewis, personal communication, 1983). Only three samples could not be associated with a pollution episode. The number of documented pollution episodes is rather evenly distributed by year over the four winter seasons analyzed. During the winter season 1976/77 11 episodes were documented, 13 episodes in 1977/78, 12 episodes in 1978/79, and 14 episodes in 1979/80.

We were able to distinguish nine major types of transport pathways (Fig. 4). The classification scheme, based on three major source regions, includes North American sources (type I), western Eurasian sources (type II), and central Eurasian sources (type III). Subcategories a, b, etc., assigned depend upon the major synoptic pressure systems creating the path and the path's geographic location within the Arctic Basin. Ten percent of the episodes were identified as type I (North American sources), 42% as type II (western Eurasian sources) and 48% as type III (central Eurasian sources). It was difficult to identify transport pathway types leading to North American sources. Usually episodes of North American pollution-derived aerosol are not associated with high concentrations of XV or XMn and the presence of a transport pathway type I is frequently accompanied by the presence of a transport pathway type II. The presence of significant transport pathways at type I is questionable.

Transport pathways were strongly developed in the lower troposphere, but sometimes extended up to the 700 mb level. The major synoptic pressure systems creating these pathways were usually developed throughout the troposphere in the form of cold cyclones and warm anticyclones. The accumulation and surge of pollutants over the source region, however, can be accomplished by a shallow surface anticyclone. Fifty-six percent of the identified transport pathways were evident on the 5-day mean 700 mb maps (published in *Monthly Weather Review*). Eighteen percent of the transport pathways could not be identified on the 5-day mean 700 mb maps due to the averaging used to construct these maps. Thus, only 26% of the transport pathways remain unsupported. In addition, NOAA-ARL back-trajectories calculated for the lower troposphere (300–2000 m) and restricted to the Arctic supported the identified transport pathways in 58% of all cases.

Transport pathway types shown in Fig. 4 are characterized by strong meridional (northward) flow over the source region, and, depending on the location of the source region, by a meridional or zonal flow

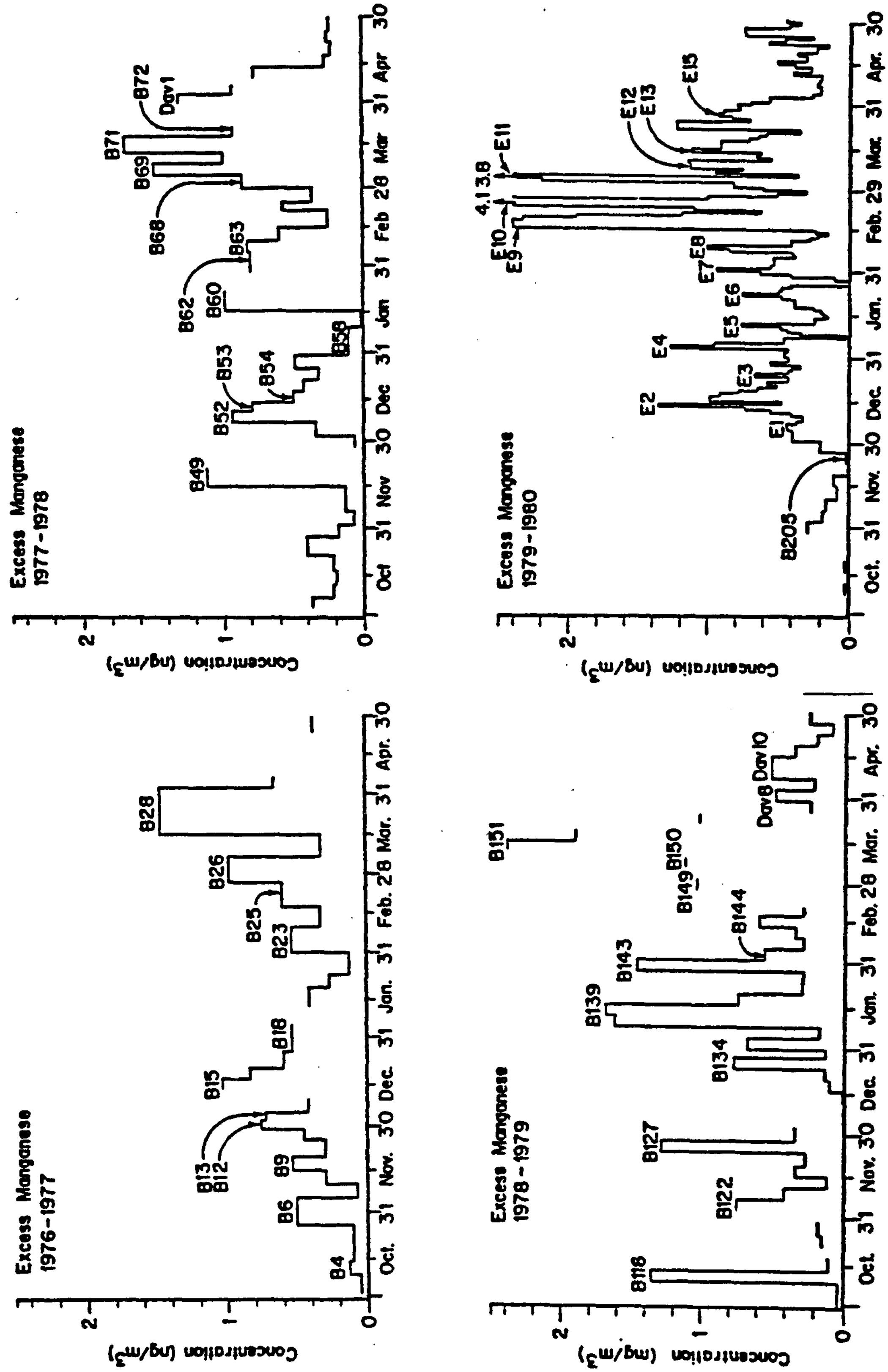

FIG. 2. Time series of concentrations of excess manganese for four winter seasons.

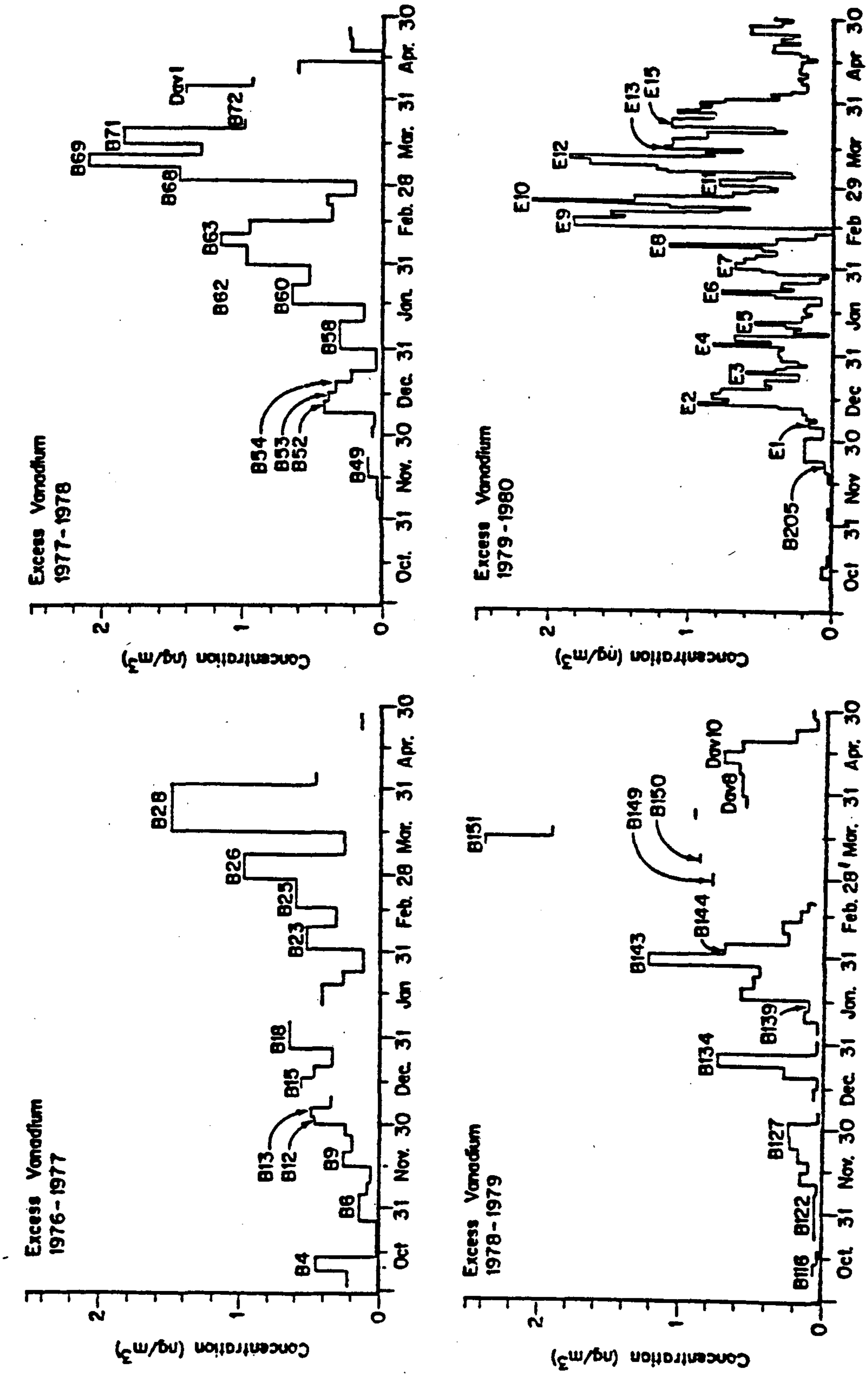

FIG. 3. As in Fig. 2, but of excess vanadium.

across the Arctic. Meridionality is necessary to accomplish an exchange of air masses between midlatitudes and the Arctic. Well-pronounced meridional situations over midlatitudes are formed when the westerlies are disturbed by a dynamic anticyclonic pressure system (blocking high). Blocking highs and their associated stagnant weather conditions seem to be important for providing a means for accumulation of pollutants over the source area. On the other hand, blocking highs are quasi-stationary pressure systems and therefore do not transport pollutants over extended distances. In the cases we studied, northward-flowing "surge" of air over the source regions was the precursor to the long-range transport of pollutants. The surge phenomenon develops when cyclonic systems approach the blocking high and build up strong pressure gradients between the two pressure systems (Fig. 5). The pollutants "escape" along the western side of the anticyclone into the Arctic, ahead of the cloud and rain bands of the cyclone which usually slows down or occludes due to the presence of the blocking high.

It is significant to note that 85% of the episodes investigated were characterized by anticyclonic conditions over the source region followed by a surge of pollutants northward. Surges and meridional exchange were most pronounced over Europe and less developed over the Soviet Union; cyclones and blocking anticyclones weaken as one goes eastward in Eurasia. Surges of central European pollution aerosols have been identified as being important in bringing pollution episodes to Scandinavia (O.E.C.D., 1979).

Transport pathways leading to the Arctic are associated with quasi-stationary anticyclones. Blocking anticyclones determine the synoptic conditions over the source area in the case of types Ia, IIa, IIb, IIc, IIIb and IIIc; cells of the Asiatic anticyclone are often an important part in the path like IIb, IIIa, IIIb, IIIc and IIId. In the vicinity of Barrow, the final leg of the transport pathway is determined by the Arctic anticyclone in cases Ia, IIa, IIb, IIc and IIIb, or by the eastward extension of Asiatic anticyclone over the Chukchi Peninsula (IIIc, IIId). However, according to Keegan (1958) the Arctic anticyclone over the Beaufort Sea is quite often an offspring of the Asiatic anticyclone.

The transport pathway types (Ib, IIIa) are due to transient pressure systems. In the case of Ib, a cyclone and anticyclone move as a set northwestward across Canada. In the case of IIIa, a cyclone travels from Scandinavia along the Soviet Arctic coast to Barrow, along the periphery of an extensive stationary Asiatic anticyclone. This cyclcone track has been discussed by Klein (1957).

Due to the fact that most pathway types were formed by quasi-stationary anticyclonic pressure systems, it was frequently possible to identify the major transport features on 5-day mean 700 mb maps as discussed previously. Transport pathways are associated with stable and persistent circulation patterns. Persistency in atmospheric circulation patterns seems to be characteristic of the Arctic.

Wilson (1958) studied the day-to-day persistency of the large-scale sea-level pressure patterns over the Arctic and found well-defined periods of quasi-persistent large-scale patterns. A total of 28 "persistent patterns" was determined by Wilson (1958), 12 of which indicated pathways from Europe and the Soviet Union to Barrow and 8 out of these 12 occurred during the period October–April. Namias (1958) has also commented on circulation patterns in the Arctic that possess unusual temporal stability, and he noted that particular types persistently recur in the same season.

To summarize, transport of pollution-derived aerosol takes place when the midlatitudinal and Arctic atmospheric circulations remain in a quasi-persistent mode. Thus, pollution-derived aerosols usually do not move as part of traveling cyclones or anticyclones, except for the transport pathway types Ib and IIIa. Sudden changes in the circulation pattern give rise to the episodic character of the Arctic pollution-derived aerosols. Transport of aerosols is most often accomplished by quasi-stationary anticyclones and, furthermore, takes place along peripheries of anticyclones where pressure gradients are strong. The zones of rapid transport therefore lie between a cyclone and an anticyclone, but the anticyclone appears to be the dominant pressure system guiding the transport.

Transport times of the pollutants were estimated on the basis of the occurrence of the surge at the beginning and the arrival of polluted Arctic air at Barrow at the end of the episode. Transport times were 7–10 days and differed insignificantly from one transport pathway type to another. Travel times during spring average one day less than during winter, because of the more intense atmospheric circulation around the time of vernal equinox.

4. On the seasonal variation of the transport pathway types

The occurrence of seasonal variation of the XMn/XV ratio suggests the occurrence of systematic trends in the different atmospheric circulation types or transport pathway types. The number of occurrences of specific transport pathways varies rather systematically (Table 1). Transport pathways relating to mainly central Eurasian source regions (Type III) dominate during October through January and transport pathways relating to mainly western Eurasian sources (Type II) predominate during February to March. Transport pathways leading to North American sources are not included in Table 1, because they are few in number and their presence is still doubtful.

For each month and each transport pathway type

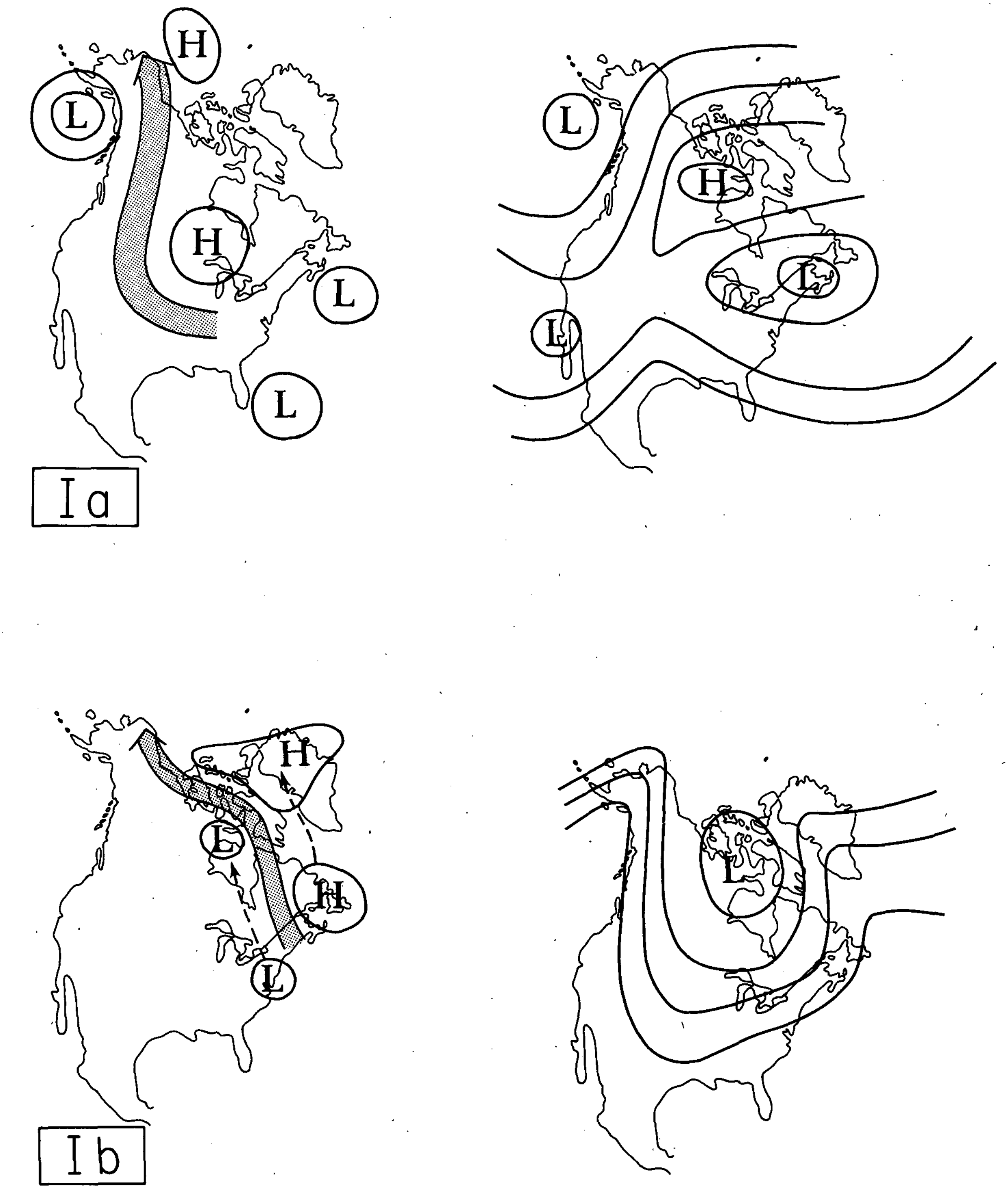

FIG. 4. Transport pathway types (surface and 500 mb).

identified, the mean XMn/XV ratio was calculated (Table 2). One finds consistent results that during winter source regions with relatively large ratios (XMn/XV > 1) contribute pollution aerosols, whereas during spring source regions with relatively lower XMn/XV ratios ($\sim <1$) become more important. Tables 1 and 2 suggest that central Eurasian sources are associated with aerosols characterized at Barrow

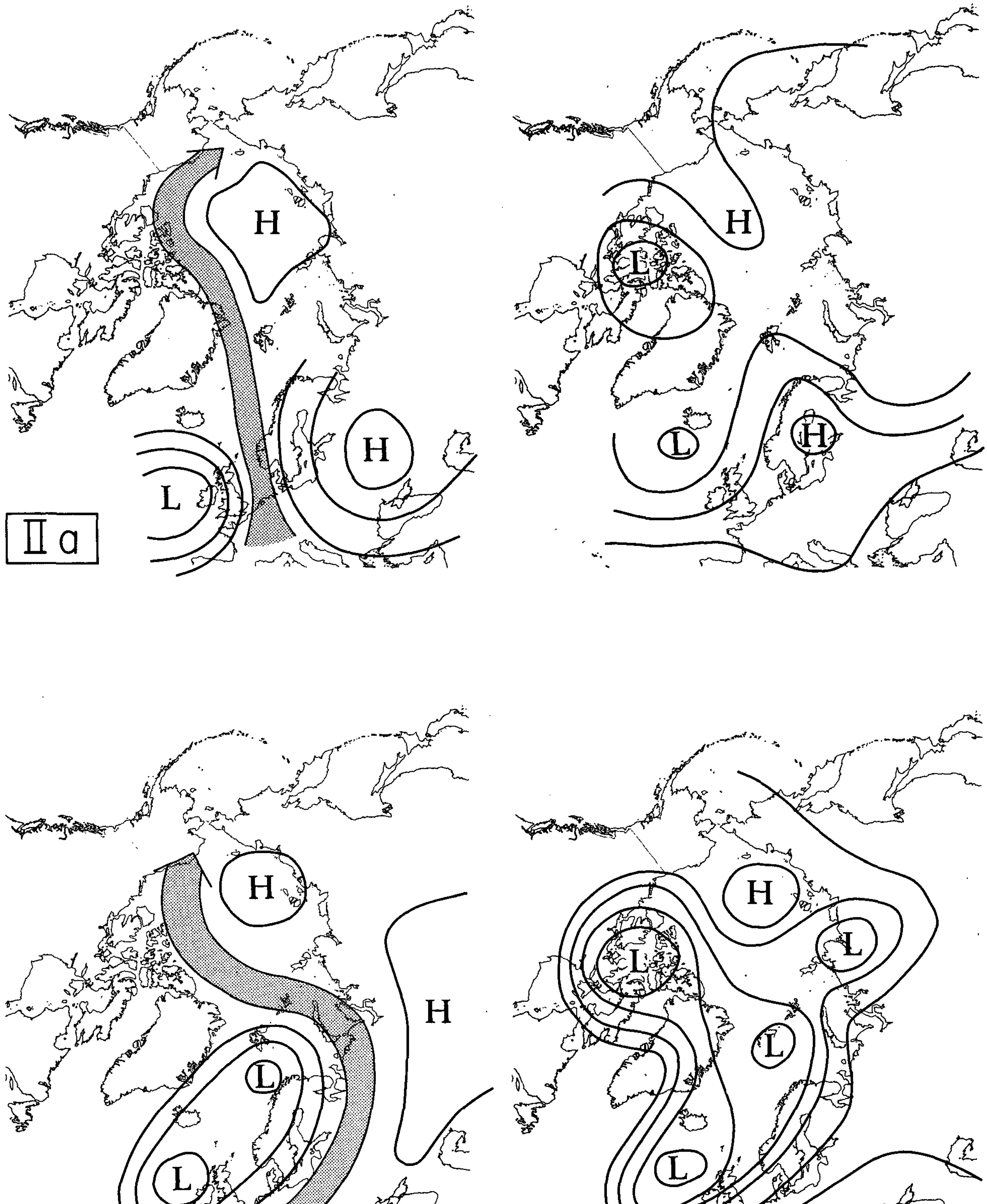

FIG. 4. (*Continued*)

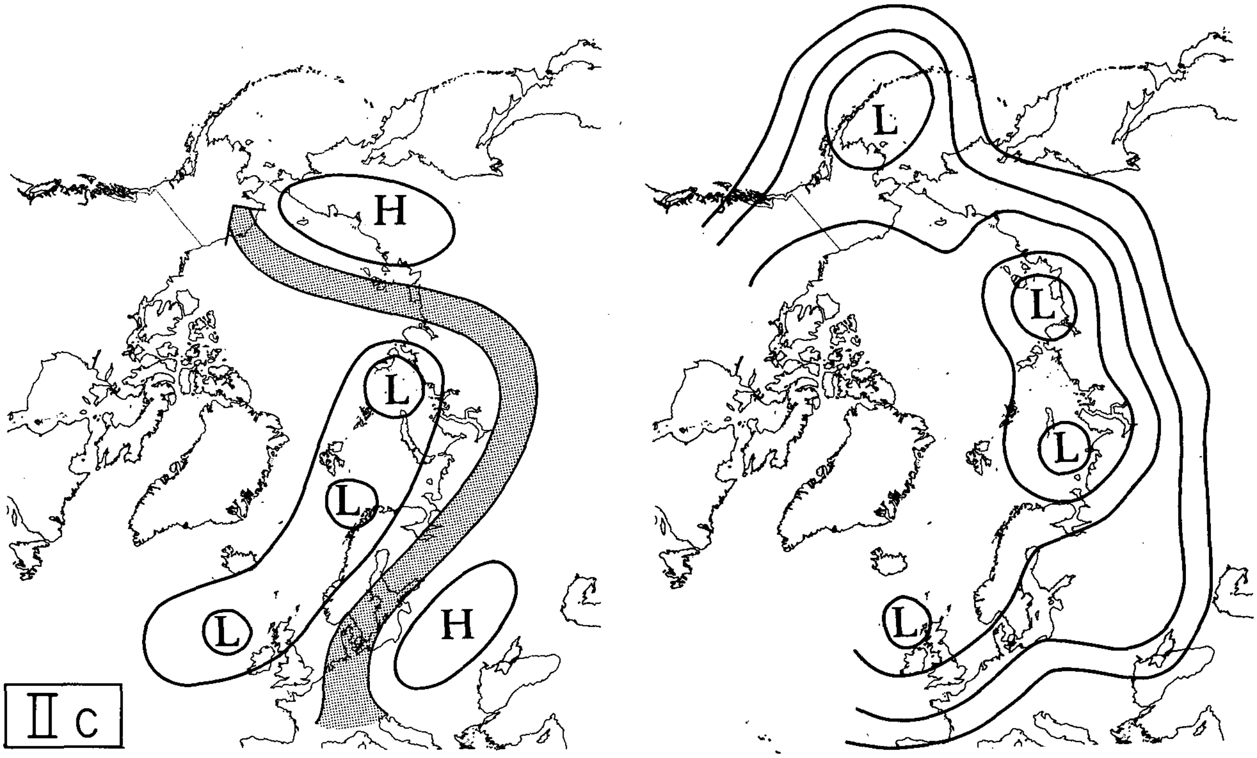

FIG. 4. (*Continued*)

by higher XMn/XV ratios than ratios associated with aerosols from western Eurasian sources [in agreement with Rahn's (1981) hypothesis]. Some inconsistencies arise, however, when a transport pathway type leading to a particular source region is characterized by two significantly different XMn/XV ratios; for example, IIa. The discrepancy is most likely due to our inability to identify a very exact geographical source region, especially over Europe where different industrial regions are located close together.

We now discuss the seasonal variation of the major synoptic systems creating transport pathways, e.g., the Asiatic anticyclone, the Arctic anticyclone, and blocking anticyclones over Eurasia. Transport pathway type IIId usually sets up during October/November; it is mainly determined by the presence of the Asiatic anticyclone and its eastward extension over the Chukchi Peninsula. As early as the first of October, the Asiatic anticyclone becomes discernible due to the intrusion of cold Arctic air over eastern Siberia (Lydolph, 1977). The eastward extension of the Asiatic anticyclone, which is at times as persistent and developed as the main cell of the Asiatic anticyclone, has its maximum of occurrence during November through January (Dmitriev, 1968). During the course of winter the Asiatic anticyclone expands and increases its influence further to the west. During this time the Arctic circulation is zonal and cyclonic in character (Namias, 1958) creating pathway type IIIa associated with a cyclone track along the Soviet Arctic coast (Klein, 1957). During spring, however, this track terminates over the Kara Sea due to the persistent presence of the Arctic anticyclone over the Beaufort Sea. Type IIIb is created when the westward extension of the Asiatic anticyclone reaches the Urals and the Arctic circulation changes into an anticyclonic circulation type which is most characteristic of April (Namias, 1958).

The extension of the Asiatic anticyclone over Europe occurs most frequently during spring (Lydolph, 1977; Reinel, 1960) and its eastern portion is partially or completely collapsed during February–March (Lydolph, 1977; Dmitriev, 1968). The westward extension of the Asiatic anticyclone often forms into blocking anticyclones (Reinel, 1960). All transport pathway types II are characterized by initial blocking over Europe and either a cyclonic (less frequent) or anticyclonic Arctic circulation. According to Treidl *et al.*, (1981), on an annual basis, the blocking frequency near 10°W dominates, whereas winter exhibits a commanding peak in the frequency of occurrence at 0–20°W and a weak secondary peak at 40–50°E. The main peak of frequency of occurrence of blocking is weakened in spring, while a strong peak appears at 20–50°E. This peak can be associated with the initial formation of transport pathway types II because it is

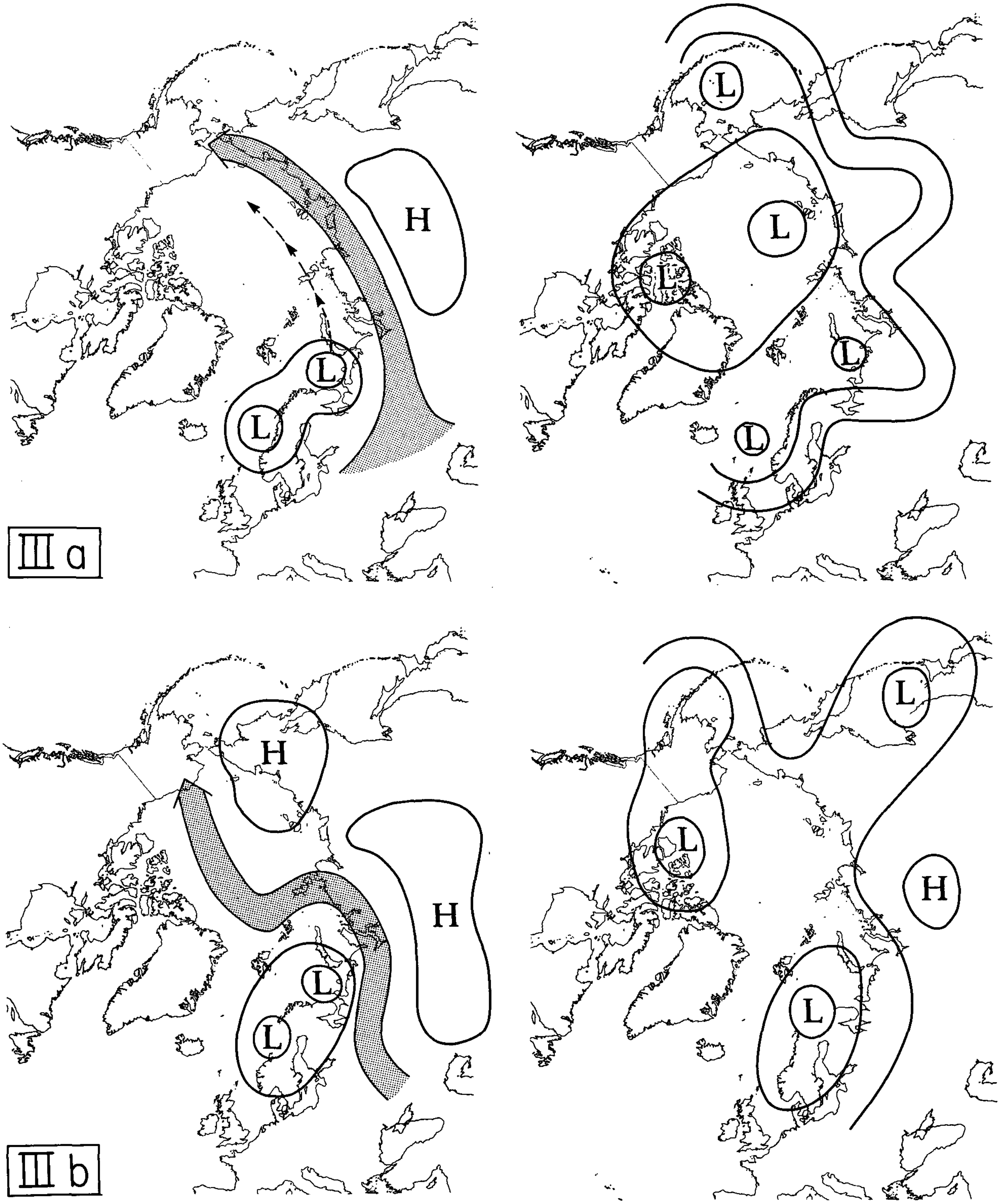

FIG. 4. (*Continued*)

located over and to the east of European source regions. The main peak in frequency of occurrence at 0–20°W is of no interest because it is located over the Atlantic.

Hess and Brezowsky (1969) presented a seasonal variation of the occurrence of Grosswetterlagen. Grosswetterlagen types characterized by meridional circulation over Europe have a maximum of occur-

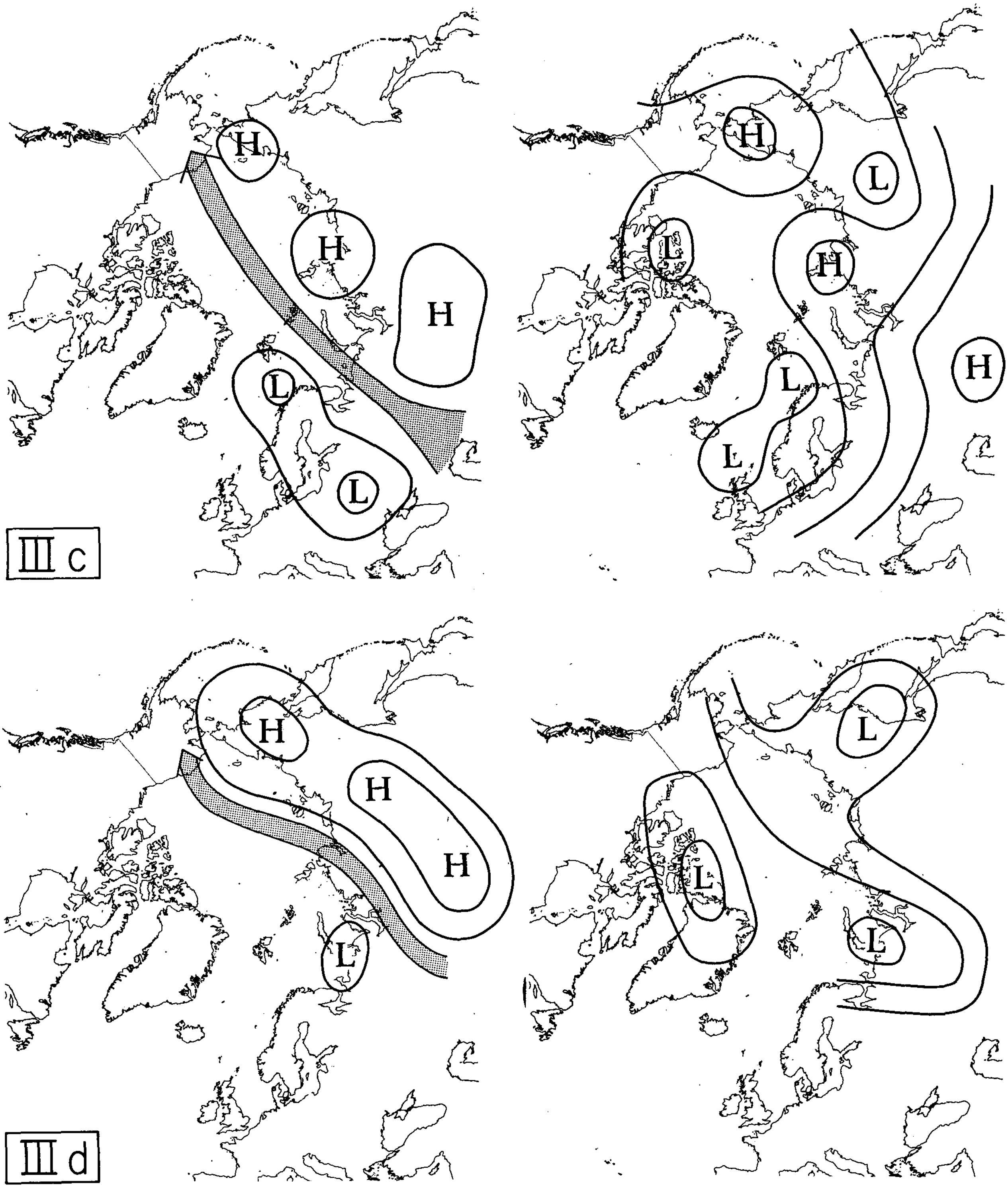

FIG. 4. (*Continued*)

rence during March–May and dominate the zonal and "mixed" circulation types.

The tabulation of anticyclonic pressure systems with closed isobars within the Pacific Hemisphere (90°W–90°E) of the Arctic north of 70°N (for the period October 1976–September 1979) indicated that the frequency of occurrence of the Arctic anticyclone over the Pacific sector of the Arctic undergoes a surprisingly weak seasonal variation and it seems more important to consider its mean monthly inten-

TABLE 1. Seasonal variation of frequency of occurrence of transport pathway types.

Type	Oct	Nov	Dec	Jan	Feb	Mar
IIId	2	2				
IIIa		5	3			
IIIb		1	2	3	2	
IIIc				2	2	
IIc			2	2	4	1
IIb			2	1	2	5
IIa	1					1
Total	3	8	9	8	10	7

sity which exhibits a strong seasonal variation with maximum values during January through March (Fig. 6). According to Barry and Perry (1973, p. 75), only during spring can one speak of a true "polar" anticyclone, which is then present over the Canadian Arctic.

5. Conclusions

The presence of the Arctic pollution-derived aerosols collected at Barrow, Alaska undergoes a seasonal variation with a spring maximum and a summer minimum. Embedded on this seasonal variation are smaller fluctuations due to distinct pollution episodes found to follow a series of events: 1) The source area in midlatitudes has experienced a period of stagnation due to the presence of an anticyclone allowing for the accumulation of pollutants; 2) the period of stagnation is followed by a surge of polluted air northward due to an approaching cyclone; 3) a distinct transport pathway occurs and is persistent enough to allow for transport across the Arctic. This scheme of meteorological/synoptic conditions developed itself by iteration in order to achieve a self-consistent picture on the occurrence of long-range transport. The episodic character of the pollution-derived aerosols is supported by the episodic nature of stagnation, by the sporadic occurrence of surges, and by the tendency of the Arctic circulation to change rapidly from one stable circulation mode to another. The nine types of transport pathways identified in this work are mainly determined by the presence of quasi-stationary anticyclones (Ib and IIIa being exceptions); cyclones have little importance for the long-range transport except for providing zones of pressure gradients in which rapid transport takes place along the periphery of the anticyclone.

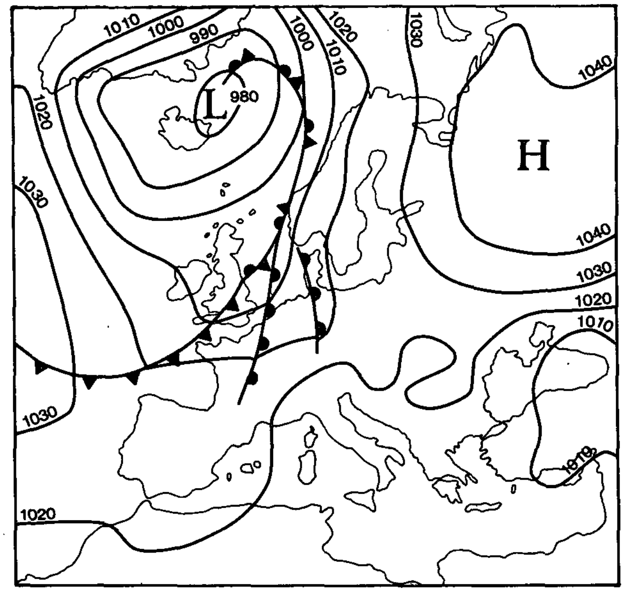

FIG. 5. Surface pressure distribution over Europe during a surge.

In winter we propose that effective long-range transport of aerosols into the Alaskan Arctic takes place under predominant anticyclonic influence. Conditions over the source area allow for accumulation of pollutants in a continental stable, cold and dry air mass. Transport takes place along the periphery of anticyclones where temperature inversions trap the pollutants and suppress dilution. Generally, the Arctic aerosols travel in cold, dry air. On the other hand, transport under cyclonic influence would most likely start within a marine, possibly unstable, warm and moist air mass resulting in strong mixing and scavenging of the aerosols. However, cyclones play an essential part in the formation of a surge event and in the formation of transport zones.

The seasonal variation of the pollution-derived aerosols at Barrow is comprehensible in terms of the seasonal variation of the presence/absence and position of the major anticyclones; i.e., the Asiatic anticyclone, the Arctic anticyclone and blocking anticyclones. We hypothesize that the summer minimum of pollution-derived aerosols in the Arctic is due, at

TABLE 2. Seasonal variation of mean XMn/XV ratios for each transport pathway type.

Type	Oct	Nov	Dec	Jan	Feb	Mar
IIId	12.2 ± 12.4	6.2 ± 5.6				
IIIa		5.3 ± 5.6	1.2 ± 0.3			
IIIb		1.6	1.7 ± 0.4	6.2 ± 8.4	1.3 ± 0	
IIIc				1.3 ± 0.1	1.2 ± 0.1	
IIc			1.5 ± 0.6	0.9 ± 0.1	1.1 ± 0.5	0.9
IIb			0.8 ± 0.1	0.8	0.7 ± 0.1	0.9 ± 0.04
IIa	2.9					0.8

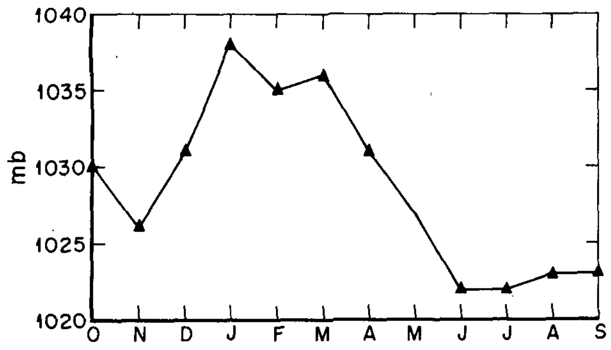

FIG. 6. Mean monthly intensity of the Arctic anticyclone when located over the Pacific Arctic.

least in part, to the absence of the Asiatic anticyclone, the lack of meridional exchange between midlatitudes and the Arctic, and the sluggish Arctic summer circulation. The occurrence of the widespread Arctic stratus cloud deck and increased precipitation over midlatitudes might be another reason for the absence of pollution aerosol during the summer. Furthermore, the lack of a corresponding Asiatic anticyclone over or east of source regions in North America and Japan, due to their lesser pronounced continentality, accounts for the negligible importance of these source regions to the Arctic pollution-derived aerosols.

The present analysis successfully used the XMn/XV ratio as a tracer for Central Eurasian and Western Eurasian source regions. As discussed and as shown in Table 2, there are still inconsistencies present in the data. It is anticipated that a system of several tracers (i.e., Rahn and Lowenthal, 1984) will lead to a better understanding of the source regions; however, the results of this meteorological/synoptic analysis are not expected to be altered significantly.

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