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VARIABILITY OF TOTAL AND SOLID PRECIPITATION IN THE CANADIAN ARCTIC FROM 1950 TO 1995

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ABSTRACT

Trends in solid and total precipitation, as well as in the ratio of solid to total precipitation (hereinafter S/T ratio), in the Canadian Arctic in recent decades have been investigated. In addition, the influence of air temperature and circulation factors (atmospheric and oceanic) on the above-mentioned precipitation characteristics have been examined. Recently updated and adjusted data by the Canadian Climate Centre from 16 stations located in the Canadian Arctic and two stations from the sub-Arctic were used for the investigation. The southern boundary of the study area was taken after *Atlas Arktiki* (Tresjinkov, A. 1985. Glavnoye Upravlenye Geodeziy i Kartografiy: Moscow; 204 pp). The majority of the data cover the period from 1950 to 1995.

A statistically significant increase in all kinds of areally averaged seasonal and annual precipitation for the Canadian Arctic over the period 1950–95 has been found. On the other hand, the S/T ratio did not change significantly, except for summer values, and its behaviour was also in accord with small variations noted in air temperature.

An increase in air temperature in the Canadian Arctic most often led to a rise in all kinds of annual precipitation sums, but only when the warmest and coldest years were chosen based on individual stations. The pattern of the relationship is significantly more complicated, and can even be opposite to that presented above, when the sets of the warmest and coldest years are chosen based on the areally averaged annual temperature for the Canadian Arctic. Significantly more stable results of changes were found for the S/T ratio, which in warmer periods was usually lower. However, more detailed and reliable investigations of temperature–precipitation relationships conducted for individual stations showed that though the S/T ratio in warmer periods may well be lower, this only applies to the southern (warmer) part of the Canadian Arctic (<70 °N).

During periods with high positive values of the North Atlantic Oscillation Index (NAOI), a decrease in precipitation is observed in the south-eastern part of the Canadian Arctic, i.e. in the area where strong cooling was also observed. During El Niño events most of the Canadian Arctic had both greater precipitation and a higher S/T ratio than during La Niña events.

The most unequivocal results of precipitation and S/T ratio changes were found for changes in the Arctic Ocean circulation regimes. In almost the whole study area, a lower precipitation and S/T ratio were noted during the anticyclonic circulation regime in the Arctic Ocean. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: solid and total precipitation; solid to total precipitation ratio; air temperature–precipitation relationships; time series analysis; Canadian Arctic

1. INTRODUCTION

Knowledge about precipitation and its tendencies in the Arctic is just as important as knowledge of air temperature. This information is needed, first of all, to estimate correctly the mass balance of the Arctic glaciers and the Greenland Ice Sheet. In turn, the behaviour of all kinds of glaciers is very important for the future evolution of the Arctic, as well as the global climate system. Firstly, both land ice and sea ice significantly change the albedo of the Earth; secondly, land ice itself also influences, to a great extent, global sea level changes. More accurate predictions of the cryosphere's behaviour may be made when both

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temperature and precipitation tendencies are taken into account (Przybylak, 1996). However, as this paper will demonstrate, it is a rather difficult task. There are, at least, two reasons for this: (i) the relations between different components of the cryosphere and the climatic variables are not simple and universal (e.g. see Foster *et al.* (1996)); and (ii) the relations between air temperature and precipitation in the Arctic are also not simple and universal (e.g. see Karl *et al.* (1993), Przybylak (1995, 1996) and Curtis *et al.* (1998)). Investigations conducted by the above-mentioned authors concerning the last problem have shown that a commonly accepted assumption, e.g. also made by most climatic modellers, that an increase of air temperature leads to an increase of precipitation in the Arctic is very often not true.

In the context of global warming, it is very important to stratify the atmospheric precipitation into solid and liquid and see their tendencies in recent years. It is even more important to establish the influence of air temperature, especially in the winter half-year, on the ratios of both solid and liquid to total precipitation. At present, our knowledge is rather limited and also too generalised. In recent years only three papers have appeared (Karl *et al.*, 1993; Mekis and Hogg, 1999; Zhang *et al.*, 2000) and these have mainly investigated the problem of tendencies observed in solid to total precipitation ratio (hereinafter S/T ratio) in recent decades. Karl *et al.* (1993) did not find any significant change in the S/T ratio in North America in the latitudinal zone 55–70 °N over the period 1950–90. In turn, Zhang *et al.* (2000), using updated and adjusted station data, found significant positive trends in the annual S/T ratio in the northern part of Canada, including the Canadian Arctic, over the period 1950–98. On the other hand, for three of the seasons that they analysed (excluding summer), small mainly insignificant rises in the ratio occurred. To date, however, no detailed investigation of this issue using only data from the Arctic has been conducted. To my knowledge, in-depth analysis of the relationships existing between air temperature, atmospheric and oceanic circulation on the one hand, and the S/T ratio on the other hand, have also not been undertaken for the Arctic. However, snowfall–temperature relationships were recently reported by Davis *et al.* (1999), but for the whole of Canada. It is hoped that the results of the research presented here will improve to some extent our knowledge of this area.

The main aims of this paper are (i) to establish the trends in solid and total precipitation, as well as in S/T ratio in the Canadian Arctic in recent decades, and (ii) to investigate the influence of air temperature and circulation factors (atmospheric and oceanic) on the above-mentioned precipitation characteristics.

The study area includes the Canadian Arctic, where its southern boundary is taken after *Atlas Arktiki* (Tresjinkov, 1985) (Figure 1).

2. DATA AND METHODS

The research problem undertaken in the present paper can only be investigated for the areas of the Canadian Arctic and Alaska, for which the appropriate data exist, i.e. precipitation sums are stratified into solid and liquid. For the rest of the Arctic, such data do not exist or are not available. Reliable results can only be obtained when good quality data are used for the investigation. For most parts of the Arctic, such data are generally not available because the majority of them represent raw data not corrected for large measuring errors. The undercatches of the precipitation connected with different kinds of measuring error can reach about 40% (Legates and Willmott, 1990; Groisman and Easterling, 1994). Until now, only Bryazgin (1976), using his own method, has undertaken attempts to make adjustments of the precipitation series for the whole Arctic (see maps published in Gorshkov (1980) or *Atlas Arktiki* (Tresjinkov, 1985)). More recently, however, for Canada (including the Canadian Arctic) such work on daily data (Bryazgin did this for monthly totals) has been carried out by Mekis and Hogg (1999) at the Canadian Climate Centre. This work also included solid and liquid precipitation treated separately. In addition, they also homogenized the data, e.g. removing systematic biases resulting from changes in the measurement program.

For the purposes of the present paper this new database was used. From the Canadian Arctic, 16 stations were extracted for the investigation. In addition, data from two sub-Arctic stations were also used (Figure 1). The majority of the data cover the period from 1950 to 1995. Such a period starting from 1950, though not usually used in climatological work, was chosen because almost exactly the same period (only 3 years longer) was used by Zhang *et al.* (2000) in analysing precipitation trends for the whole of Canada.

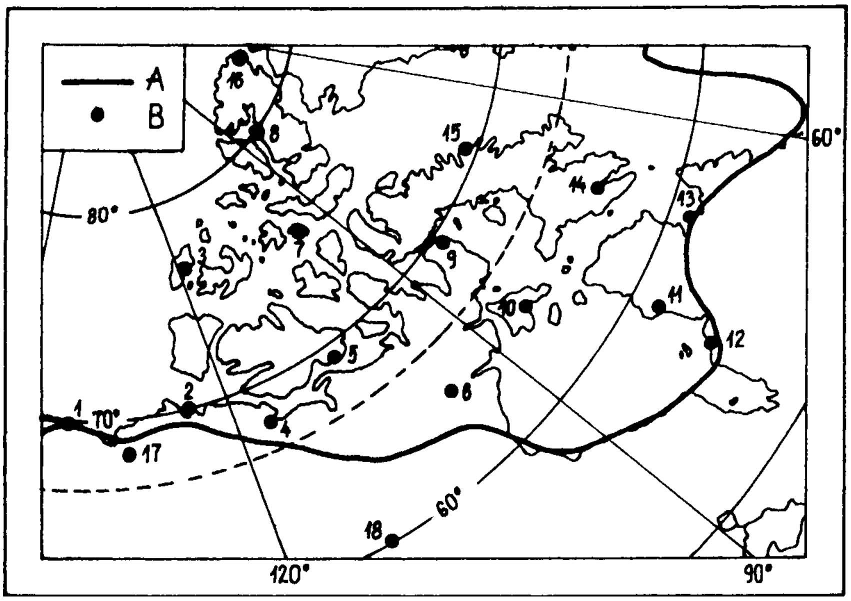

Figure 1. Study area and location of meteorological stations used. Key: A, the border of the Arctic after *Atlas Arktiki* (Tresjinkov, 1985); B, location of meteorological stations used: (1) Komakuk ($H = 14$ m); (2) Cape Parry ($H = 17$ m); (3) Mould Bay ($H = 15$ *m*); (4) Coppermine ($H = 24$ m); (5) Cambridge Bay ($H = 27$ m); (6) Baker Lake (13 m); (7) Resolute A ($H = 67$ m); (8) Eureka ($H = 10$ m); (9) Hall Beach (8 m); (10) Coral Harbour A ($H = 64$ m); (11) Inukjuak ($H = 3$ m); (12) Kuujjuarapik ($H = 21$ m); (13) Kuujjuaq ($H = 37$ m); (14) Iqaluit A ($H = 34$ m); (15) Clyde A ($H = 25$ m); (16) Alert ($H = 63$ m); (17) Inuvik ($H = 59$ m); (18) Fort Smith A ($H = 203$ m)

The mean monthly air temperatures and monthly sums of solid, liquid and total precipitation have been obtained from the Canadian Climate Centre. These data were used to compute both seasonal values (DJF: winter; MAM: spring, etc.) and annual values. Then the areally averaged temperature and precipitation series for the period 1950–95 were calculated for each season and for the year. For this purpose, simple arithmetic means of the stations' data within the region were used. All data have been converted to the form of anomalies using 1950–95 as the reference period. The seasonal and annual regional series of air temperature anomalies for the period 1950–95 were the basis for choosing:

(i) the sets of the ten individual warmest and ten individual coldest seasons and years;
(ii) the warmest and coldest 10-year blocks of seasons and years.

The relationships between air temperature and precipitation were investigated by computing for each analysing station the difference of total precipitation, solid precipitation and the S/T ratio between sets of warmest and coldest seasons and years. More precisely, the mean seasonal and annual values computed for the cold years were subtracted from the appropriate values computed for the warm years. The results are presented in the form of maps, where isolines of equal differences have been drawn using the simple method of geometric interpolation. To date, such a methodology has mostly been used for the construction of scenarios of temperature and precipitation changes in a warmer world (e.g. see Palutikof *et al.* (1984), Palutikof (1986) and Przybylak (1995, 1996)).

However, for a better investigation of the influence of air temperature on precipitation and its different kinds, it is better to go down to the level of individual stations. This means that precipitation differences are only calculated for the station, which simultaneously was the basis for choosing the warmest and coldest seasons and years. Such an approach eliminates situations in which, on average, the warmest and coldest seasons and years in the Canadian Arctic can have quite different thermal conditions in different areas. Such cases may frustrate attempts to obtain real relationships.

A similar method was used to investigate the relationships between circulation factors and precipitation in the Canadian Arctic. The precipitation and the S/T ratio differences were calculated here between the sets of years with high and low values of the best known indices (the North Atlantic Oscillation Index (NAOI) and the Southern Oscillation) characterizing atmospheric circulation in the North Atlantic and tropical Pacific respectively, or, in the case of oceanic circulation, between years with opposite Arctic Ocean circulation regimes (anticyclonic minus cyclonic; e.g. see Proshutinsky and Johnson (1997)). More details are given in Section 5 describing the research results.

3. LONG-TERM MEAN PRECIPITATION AND ITS CHANGES

3.1. Total and solid precipitation

Corrected values of mean seasonal and annual precipitation totals, stratified into solid and liquid precipitation, were obtained from the Canadian Climate Centre and are presented in Table I. Annual precipitation sums are greatest in the warmest part of the study area, i.e. in its south-eastern part. These high

Table I. Atmospheric precipitation amounts (millimetres) in the Canadian Arctic (1–16) and sub-Arctic (17–18), 1951–90

No.	Station	Parameter[a]	DJF	MAM	JJA	SON	Year
1	Komakuk	1	20.0	16.2	87.3	59.1	193.8
		2	19.9	15.1	10.4	46.9	100.0
		3	0.1	1.1	76.9	12.2	93.8
2	Cape Parry[b]	1	43.6	50.6	77.1	92.4	259.4
		2	43.2	47.5	9.1	73.6	171.8
		3	0.4	3.1	68.0	18.8	87.6
3	Mould Bay	1	21.3	27.5	60.2	50.0	156.1
		2	21.3	27.0	24.0	46.5	114.7
		3	0.0	0.5	36.2	3.5	41.4
4	Coppermine	1	48.0	54.8	98.7	93.7	294.6
		2	47.2	49.0	4.5	61.9	160.4
		3	0.8	5.8	94.2	31.8	134.2
5	Cambridge Bay	1	28.8	39.5	77.8	66.2	212.1
		2	28.7	36.8	8.2	50.0	123.5
		3	0.1	2.7	69.6	16.2	88.6
6	Baker Lake	1	40.6	57.8	117.9	119.1	337.5
		2	40.5	49.8	6.5	72.2	168.8
		3	0.1	8.0	111.4	46.9	168.7
7	Resolute A	1	23.8	34.7	89.4	67.0	215.6
		2	23.8	34.2	30.2	60.3	149.3
		3	0.0	0.5	59.2	6.7	66.3
8	Eureka	1	15.2	13.7	39.7	32.9	99.8
		2	15.2	13.6	9.2	31.9	68.6
		3	0.0	0.1	30.5	1.0	31.2
9	Hall Beach[b]	1	44.0	64.3	109.7	100.7	317.9
		2	44.0	62.5	14.7	81.8	201.1
		3	0.0	1.8	95.0	18.9	116.8
10	Coral Harbour A	1	48.0	68.2	133.5	121.3	372.2
		2	47.8	64.3	14.3	83.6	210.4
		3	0.2	3.9	119.2	37.7	161.8

Table I. (*Continued*)

No.	Station	Parameter[a]	DJF	MAM	JJA	SON	Year
11	Inukjuak	1	66.7	74.1	175.4	194.4	508.6
		2	66.0	56.9	7.0	96.7	230.2
		3	0.7	17.2	168.4	97.7	278.4
12	Kuujjuarapik	1	135.7	119.5	252.0	272.0	776.2
		2	133.1	83.1	9.0	116.4	344.2
		3	2.6	36.4	243.0	155.6	432.0
13	Kuujjuaq	1	149.1	116.8	189.8	193.5	658.4
		2	147.2	94.3	7.4	109.2	364.2
		3	1.9	22.5	182.4	84.3	294.2
14	Iqaluit A	1	94.5	107.3	181.2	158.8	544.3
		2	93.8	103.1	14.9	110.3	324.7
		3	0.7	4.2	166.3	48.5	219.6
15	Clyde A	1	40.4	54.5	85.3	126.4	309.2
		2	40.3	54.0	34.6	116.3	249.3
		3	0.1	0.5	50.7	10.1	59.9
16	Alert	1	31.3	35.6	72.1	68.9	208.9
		2	31.2	35.6	49.6	68.3	185.0
		3	0.1	0.0	22.5	0.6	23.9
17	Inuvik[b]	1	67.4	61.7	112.3	101.5	342.1
		2	66.9	53.2	7.7	79.8	206.9
		3	0.5	8.5	104.6	21.7	135.2
18	Fort Smith A	1	76.3	69.7	157.4	114.5	418.4
		2	74.9	36.7	0.4	55.4	167.5
		3	1.4	33.0	157.0	59.1	250.9

[a] 1: total precipitation; 2: solid precipitation; 3: liquid precipitation.
[b] 1961–90.

atmospheric precipitation sums are connected here to very intense cyclonic activity. Annual totals oscillate between 500 and 800 mm (Kuujjuarapik: 776.2 mm; Kuujjuaq: 658.4 mm; Iqaluit: 544.3 mm). On the other hand, the lowest amounts of precipitation occur in the northern part of the Canadian Arctic, where the lowest temperatures are also noted (see *Atlas Arktiki* (Tresjinkov, 1985) and Przybylak (1996, 1997)). In these areas the annual sums usually do not reach more than 200 mm (Eureka: 99.8 mm; Mould Bay: 156.1 mm; Alert: 208.1 mm). The corrected annual precipitation sums (after the influence of measurement errors have been deleted) presented in Table I are higher than uncorrected values (Przybylak, 1996) by 26 to 58% depending on the station analysed (Table II).

In the Canadian Arctic the highest precipitation occurs either in summer, in the regions where climate is more continental (ten stations), or in autumn, especially in the areas with vigorous cyclonic activity (six stations) — Table I. Similarly, the lowest seasonal precipitation sums are also noted in only two seasons, i.e. in winter (11 stations) or in spring (five stations).

Solid precipitation occurs in all seasons, but its clear dominance is observed in autumn. Only in two stations, located near the southern boundary of the Arctic (Kuujjuarapik, Kuujjuaq), are the highest solid seasonal precipitation sums noted in winter (Table I). The secondary maximum in snowfall is observed in spring in most of the analysing stations. Liquid precipitation, according to expectations, clearly dominates in the summer season. Quite large rainfall sums also occur in autumn. On the other hand, in spring, and especially in winter, this kind of precipitation is a rather rare phenomenon (Table I).

In the study period 1950–95, the lowest total and solid precipitation sums, both seasonal and annual, clearly occurred in the 1950s (Figures 2 and 3), whereas the highest sums mainly occurred during the last

Table II. Comparison of measured and corrected annual precipitation totals in selected stations of the Canadian Arctic, 1951–90

Station	Precipitation (mm)		Corrected to measured precipitation ratio in (%)
	Measured[a]	Corrected[b]	
Coppermine	219.6	294.6	134
Resolute A	136.8	215.6	158
Eureka	67.3	99.8	148
Coral Harbour A	278.0	372.2	134
Iqaluit A	431.8	544.3	126
Clyde A	215.4	309.2	144
Alert	152.5	208.9	137

[a] After Przybylak (1996).
[b] Data used in present paper.

two decades. As a result, the calculated linear trends are positive for all cases, and all of them (with the sole exception of the summer total precipitation sums) are statistically significant. It is worth adding here that, in the period analysed, no significant changes in air temperature were observed (Figure 4). Moreover, in the 1950s positive temperature anomalies prevailed, except during winter. After 1980, a cooling in the Canadian Arctic was observed, mainly in autumn and winter, but this did not reduce the amounts of precipitation. Moreover, positive anomalies occurred, and were especially high in autumn (up to 30 mm). Also, in summer the relationships between temperature and precipitation sums are not consistent throughout the period analysed (cf. Figures 2 and 4).

These rough comparisons suggest that the observed increase in precipitation in recent decades in the Canadian Arctic was not connected with temperature changes. It is possible that one of the most probable reasons for this situation is the change in atmospheric circulation. Curtis *et al.* (1998) came to the same conclusion in their explanation of a decrease in precipitation in recent decades in the Alaskan Arctic stations. One should also add here, that Curtis *et al.* (1998) are wrong in their claim that a decrease in precipitation occurred over the whole western Arctic. They based this conclusion on the analysis of the snow depth on 30 April. They were aware of the weaknesses of such an approach, writing '... snow depth is a parameter which is not expected to be in total agreement with the measured precipitation'. Analyses of the direct observational precipitation data of both the raw series (Przybylak, 1996) and the corrected series (Zhang *et al.*, 2000; *vide infra*) evidently show a significant increase in precipitation throughout the whole Canadian Arctic, and also almost throughout the whole of Canada. This means that snow depth on 30 April is rather a bad proxy for the reconstruction of winter and spring amounts of precipitation in the Canadian Arctic. Przybylak (1996), in analysing precipitation trends for the whole Arctic over the period 1951–90, found that between Alaska and the Canadian Arctic a change in trends from negative to positive occurred.

3.2. *The S/T ratio*

Knowledge about the relationships between the S/T ratio and air temperature in the Arctic is very important for the prediction of precipitation changes. In addition, it also allows the identification of local, regional and even global climate changes based on the S/T ratio changes. However, as has been mentioned in Section 1, the state of our knowledge about the above-mentioned relationships is far from satisfactory, especially for the Arctic. It is suggested that a shortening of the period with freezing temperatures suitable for snowfall will lead to a decrease in the S/T ratio. On the other hand, expected increases in air temperature in the Arctic, mainly in seasons with below-freezing temperatures, should cause an increase in solid precipitation, and, as a result, the S/T ratio should also increase. Such a view assumes that warmer conditions have made more moisture available to precipitation events, which have still been in the form of snow. Some climate models

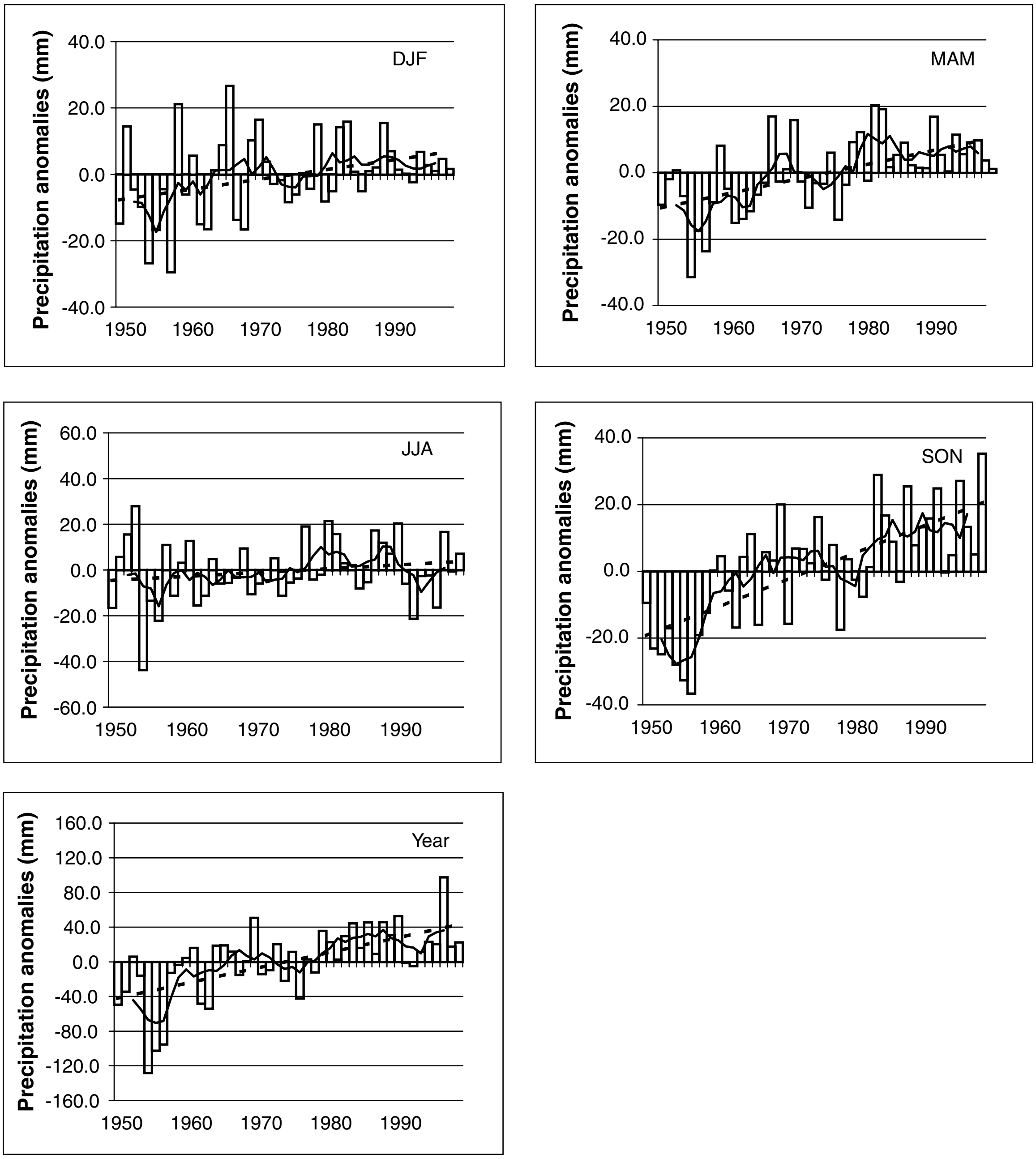

Figure 2. Year-to-year courses of mean seasonal and annual anomalies of total atmospheric precipitation and their trends in the Canadian Arctic over the period 1950–95. Key: bars = year-to-year courses; solid lines = running 5 year mean; dashed lines = linear trends. Please note also that the scale is different for summer than for the other seasons

confirm this opinion, showing that snow accumulation in the Arctic region should increase as a result of global warming (Ye and Mather, 1997).

The areally averaged S/T ratio for the period 1950–95 was equal to 57.3% and oscillated between 45.2% (1953) and 66% (1972) — Figure 5. Clearly, the lowest S/T ratio occurred in the 1950s. Then the ratio rose, and since the beginning of the 1970s a stabilization of its values at a level of about 59% has been observed. In line with expectations, the highest S/T ratio was noted in winter (98.7%) and

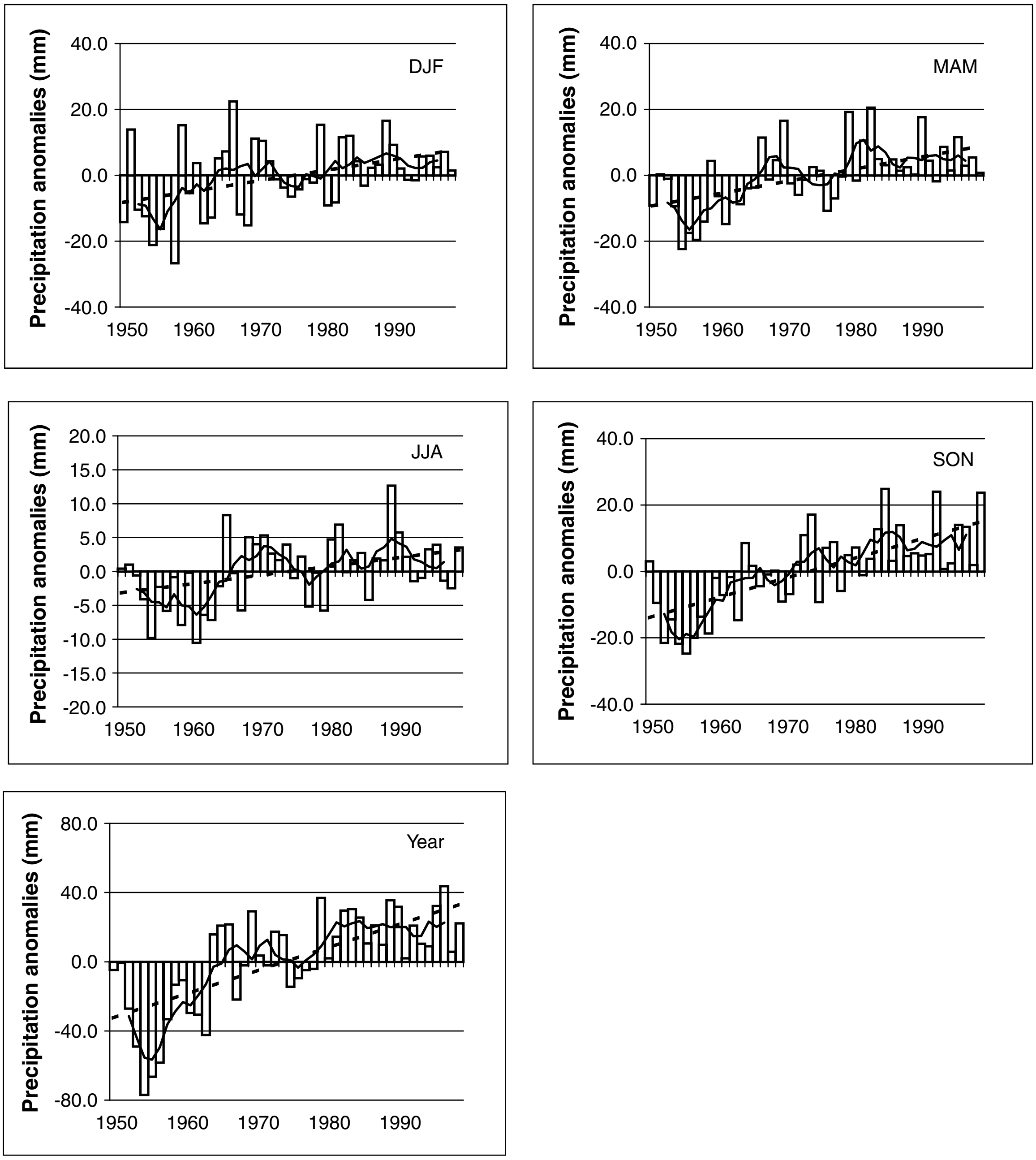

Figure 3. Year-to-year courses of mean seasonal and annual anomalies of solid atmospheric precipitation and their trends in the Canadian Arctic over the period 1950–95. Key: bars = year-to-year courses; solid lines = running 5 year mean; dashed lines = linear trends. Please note also that the scale is different for summer than for the other seasons

the lowest in summer (12.5%). In the transitional seasons, clearly a greater mean S/T ratio was noted in spring (86.3%) than in autumn (67.7%). In the study period, positive trends in the S/T ratio have been observed in winter, and particularly in summer (Figure 5). In the latter season the changes were statistically significant at the 0.05 level. However, as has been mentioned earlier, this rise occurred mainly prior to 1970. The annual S/T ratio interannual variations corresponded quite well with the course of the summer ratio. However, in this case, the linear trend calculated for the whole period is not statistically

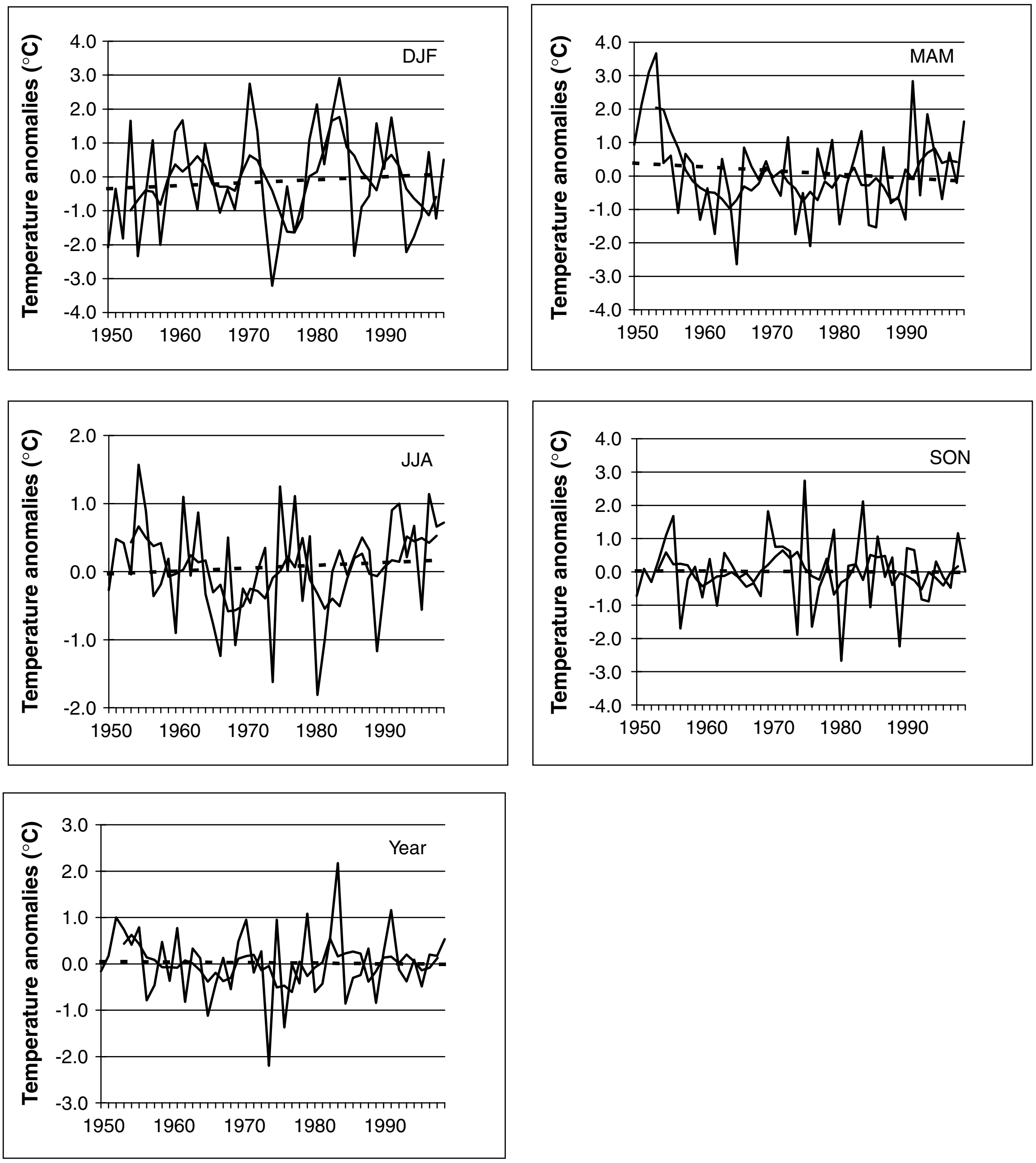

Figure 4. Year-to-year courses of mean seasonal and annual anomalies of air temperature and their trends in the Canadian Arctic over the period 1950–95. Key: solid lines = year-to-year courses; heavy solid lines = running 5 year mean; dashed lines = linear trends. Please note also that the scale is different for summer than for the other seasons

significant. Also, both seasonal and annual linear trends of the S/T ratio for the period 1976–95 are small and statistically insignificant. The S/T ratio in spring and autumn does not show any significant trends during the whole study period (Figure 5). The results presented agree well with the results reported by Karl *et al.* (1993) for the latitudinal band 55–70 °N in North America and by Zhang *et al.* (2000) for northern Canada.

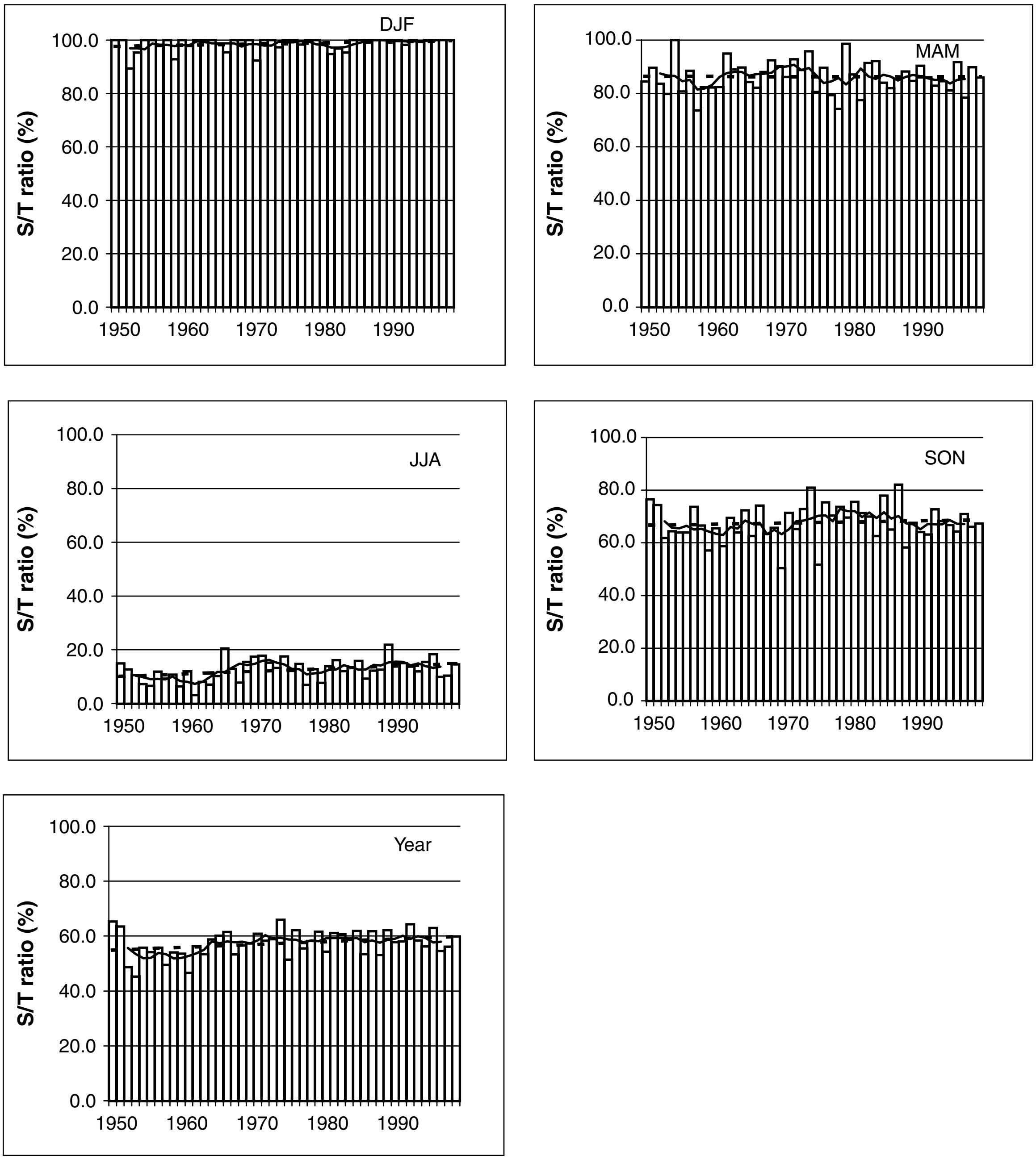

Figure 5. Year-to-year courses of mean seasonal and annual S/T ratios and their trends in the Canadian Arctic over the period 1950–95. Key: bars = year-to-year courses; solid lines = running 5 year mean; dashed lines = linear trends

4. THE INFLUENCE OF AIR TEMPERATURE ON TOTAL AND SOLID PRECIPITATION AND ON THE S/T RATIO

4.1. Total precipitation

Changes in annual total precipitation from cold to warm years and periods in the Canadian Arctic are shown in Figure 6. The results obtained depend significantly on the method used for deciding on the choice of warm and cold years. When individual years were taken into account, the rise of total precipitation occurred throughout most of the Canadian Arctic (Figure 6(a)). Such a tendency was also observed in most of the study area in all seasons, except in summer when a decrease in precipitation prevailed (Figure 7). In turn, quite the opposite results were identified for annual total precipitation when differences were calculated between the warmest and coldest decades (Figure 6(b)). More precise and reliable results were obtained when seasonal total precipitation differences were calculated for 10-year periods chosen according to seasonal mean air

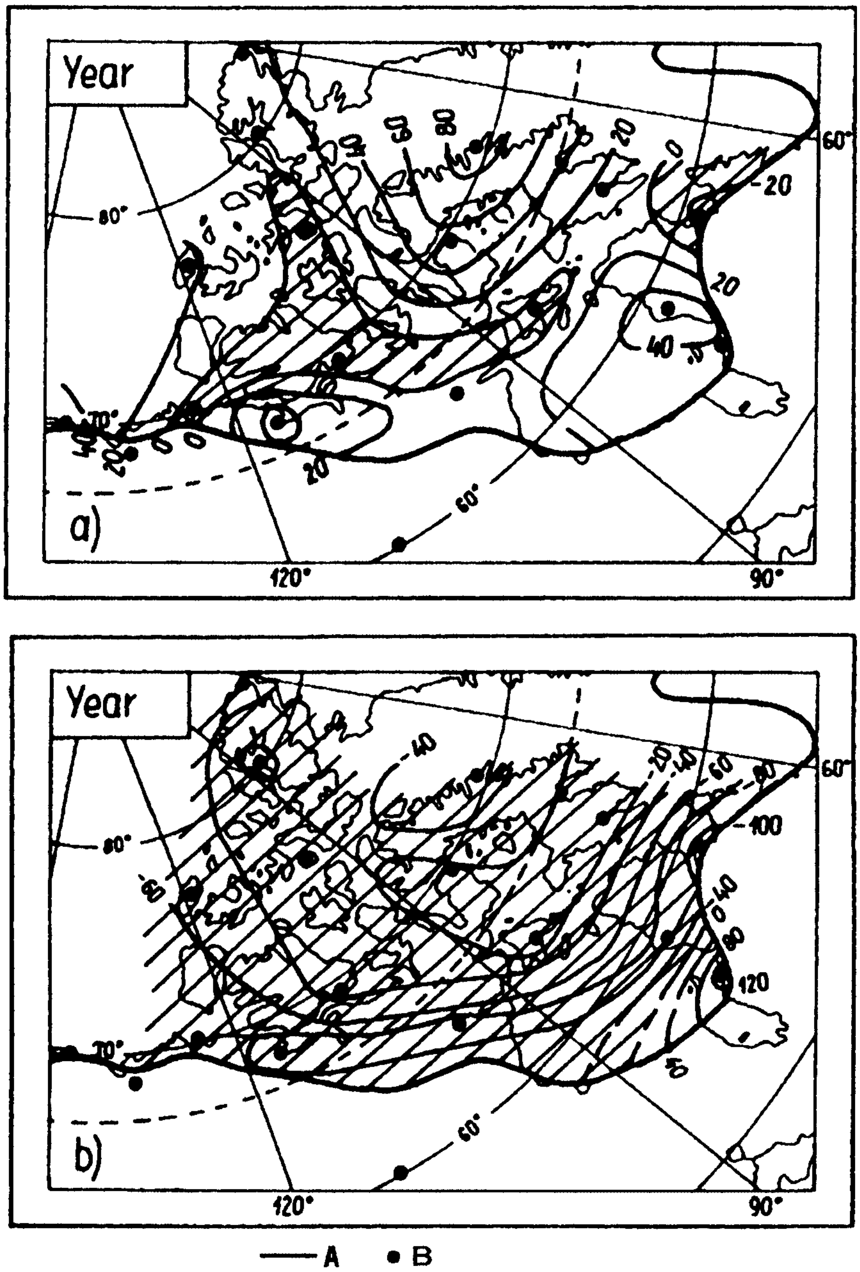

Figure 6. Mean annual total precipitation differences (millimetres) in the Canadian Arctic between the ten individual warmest and coldest years (a) as well as between the ten consecutive warmest and coldest years (b) in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

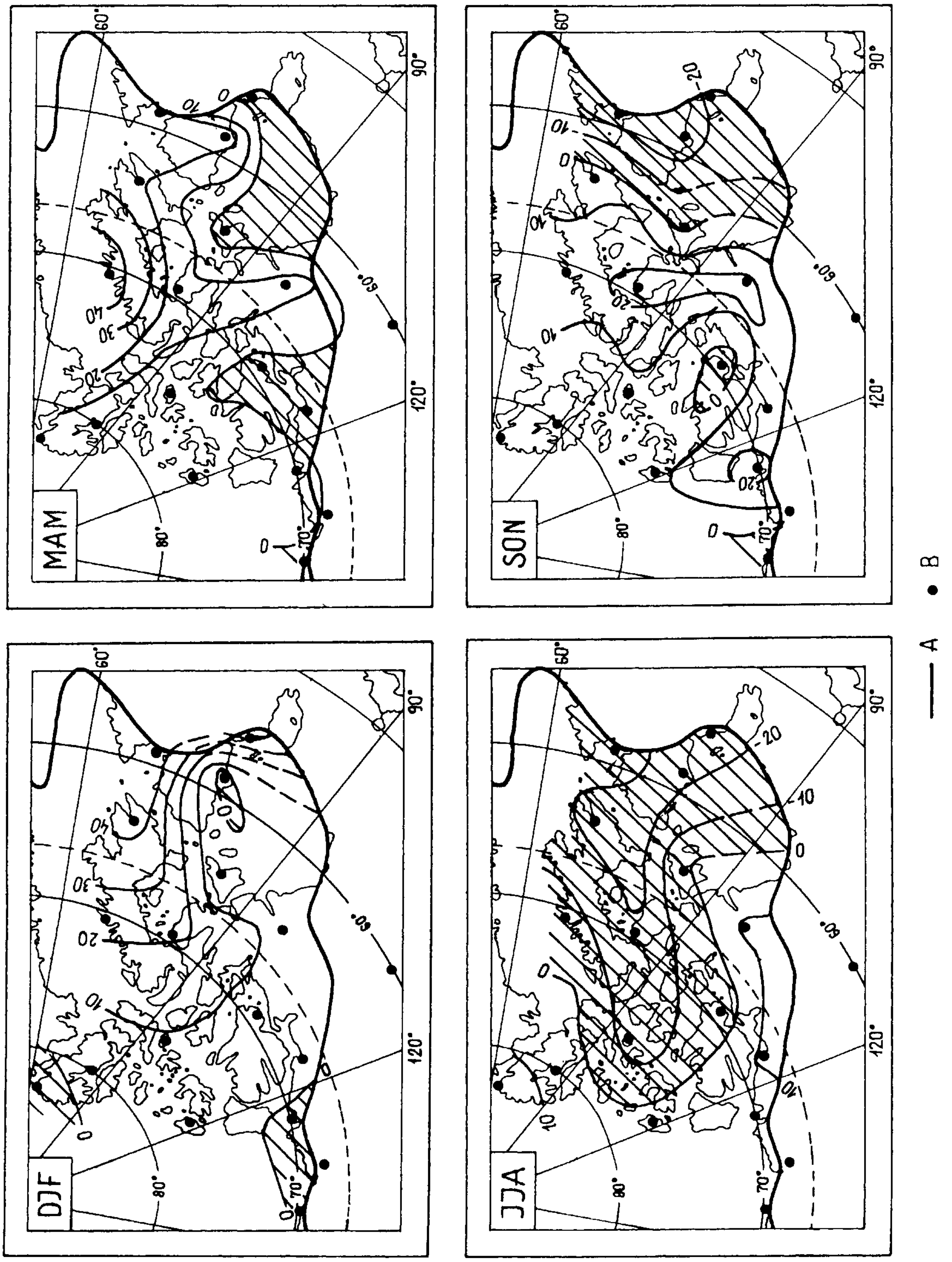

Figure 7. Mean seasonal total precipitation differences (millimetres) in the Canadian Arctic between the ten individual warmest and coldest seasons in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

temperatures (not shown). In this case, in all seasons a rise in the total precipitation between cold and warm periods was noted in most of the Canadian Arctic, and this was particularly common in autumn. In the other seasons, any decreases are located mainly in the western part of the study region. It should be noted that such a discrepancy in temperature–precipitation relationships between annual and seasonal values did not occur when the ten individual warmest and the ten individual coldest years and seasons were chosen. This option, from the two that have been discussed, seems to give more reliable results and will, therefore, be used more generally in the further analysis.

In conclusion, based on the sets of scenarios that have been presented, one can say that in a warmer Canadian Arctic the total precipitation should generally be greater. However, in some parts of the Canadian Arctic, and in some seasons, decreases may be observed, probably due to changes in atmospheric circulation from cold to warm years (not investigated here).

4.2. *Solid precipitation*

A significantly greater agreement between the two methods used exists for solid precipitation (cf. Figure 8(a) and (b)). In warmer decades the annual solid precipitation sums were usually lower than in colder decades (Figure 8(b)). In the case of the sets of ten individual years, the opposite behaviour occurred in the eastern part of the Canadian Arctic (Figure 8(a)). By analysing the seasonal solid precipitation differences, good agreement of results over the whole area of the Canadian Arctic can be seen in winter and in summer; on the other hand, there is lesser agreement in spring and especially in autumn (Figure 9). Warmer winters are characterized by positive anomalies of solid precipitation, reaching 40 mm in the south-eastern part. As has been mentioned in Section 3.2, the reason for this behaviour could be the greater moisture content available to precipitation events, which, due to still low temperatures, are in the form of snow. An opposite relationship is noted in summer, as might be expected. A decrease in snowfall was noted almost everywhere, except in a small fragment in the north-eastern part (Figure 9). The greatest decrease (30 mm) occurred in the central part of Baffin Island. On average, warmer springs, similar to winters, are characterized mainly by positive anomalies of solid precipitation, and these are especially high in Baffin Island (30–40 mm). In turn, relationships between temperature and solid precipitation in autumn are more similar to those observed in summer. Generally, in autumn, below 70 °N a decrease in solid precipitation was observed, and this was particularly marked (50–60 mm) near the southern border of the Canadian Arctic (Figure 9). This pattern could be explained by the fact that the autumn month which receives the most precipitation in the Canadian Arctic is September. Temperatures above freezing point in this month occur only just below *ca* 70 °N and, therefore, the decreasing trend is only limited to this part of the Canadian Arctic.

4.3. *The S/T ratio*

Significantly, the best agreement of the results between the two methods used was for the annual S/T ratio (Figure 10). As can be seen, warming led, in most of the Canadian Arctic, to a decrease in this ratio. Such a tendency is also common in all seasons analysed (Figure 11). The greatest decreases are observed in autumn and (most particularly) in summer, with decreases for the latter season reaching up to 20–30% in the eastern coastal part of Baffin Island. Quite similar results were obtained when these differences were calculated between the ten consecutive warmest and ten consecutive coldest seasons (not shown). The greatest discrepancies were noted only in autumn, when an increase in this ratio occurred in large parts of the western and southern Canadian Arctic. The spatial distribution of the S/T ratio differences is generally in good agreement with the spatial distribution of the solid precipitation differences, but only for annual values (cf. Figure 8(a) and (b) with Figure 10) as well as for summer and autumn values (cf. Figure 9 and Figure 11).

The careful reader will have noted that each of the methods used has greater or lesser weaknesses, resulting mostly from the application of the areally averaged temperature series from the Canadian Arctic to delimit warm and cold years and seasons. As has been mentioned earlier, to obtain more accurate and reliable data it is necessary to go down to the level of individual stations. In practical terms, this means that the precipitation and the S/T ratio differences are calculated for a given station between warm and cold years and seasons

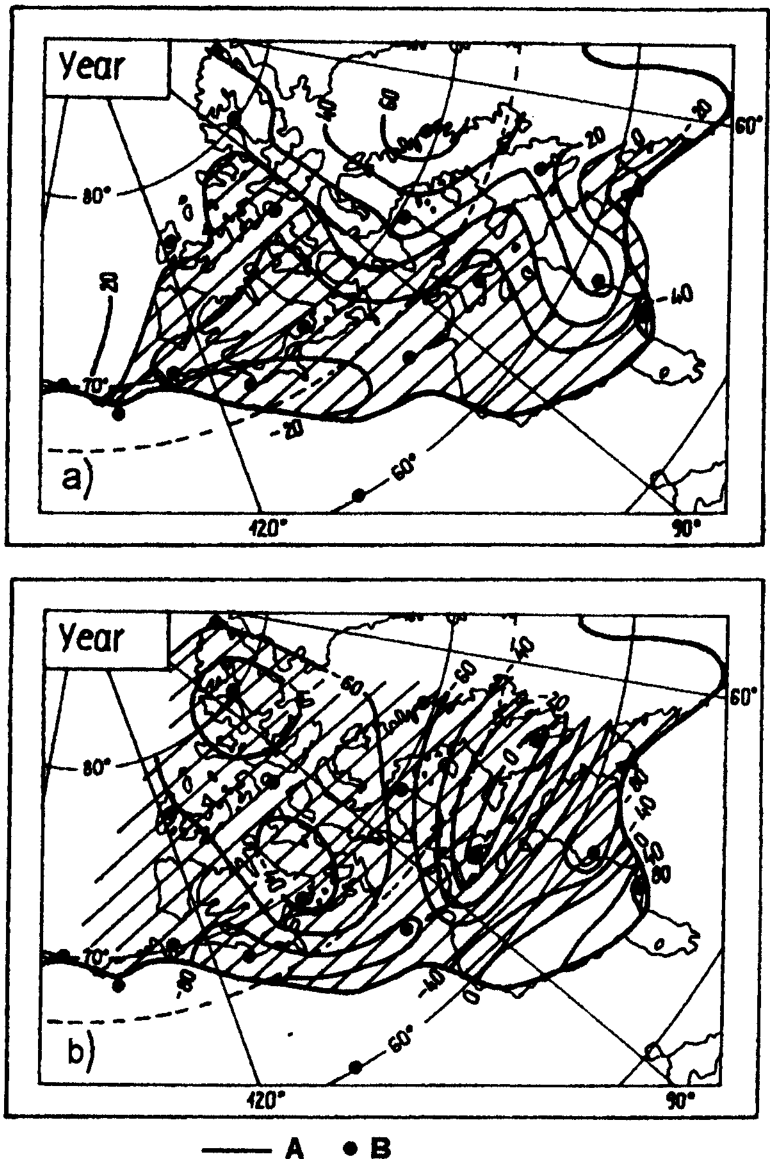

Figure 8. Mean annual solid precipitation differences (millimetres) in the Canadian Arctic between the ten individual warmest and coldest years (a) as well as between the ten consecutive warmest and coldest years (b) in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

directly selected on the basis of the temperature series from that station. This method, however, requires more work. Therefore, such a procedure was only conducted for five stations (Alert, Resolute A, Clyde A, Coppermine and Coral Harbour A), which, however, represent all parts of the Canadian Arctic. In addition, these stations have been chosen because they have the most reliable and longest series of data and have also been used most often by other authors. As can be seen in Table III, at almost all stations (except Alert station, which represents the coldest fragment of the study area) there was an increase in all kinds of precipitation in warmer years. In Alert, even warmer winters and springs give lower amounts of solid precipitation. According to expectations, warmer summers are characterized everywhere by below-normal solid precipitation. In some stations (Resolute A and Coral Harbour A) even rainfall is lower in this season. In the south-western part of the Canadian Arctic (Coppermine), negative anomalies of solid precipitation are also noted in the transitional

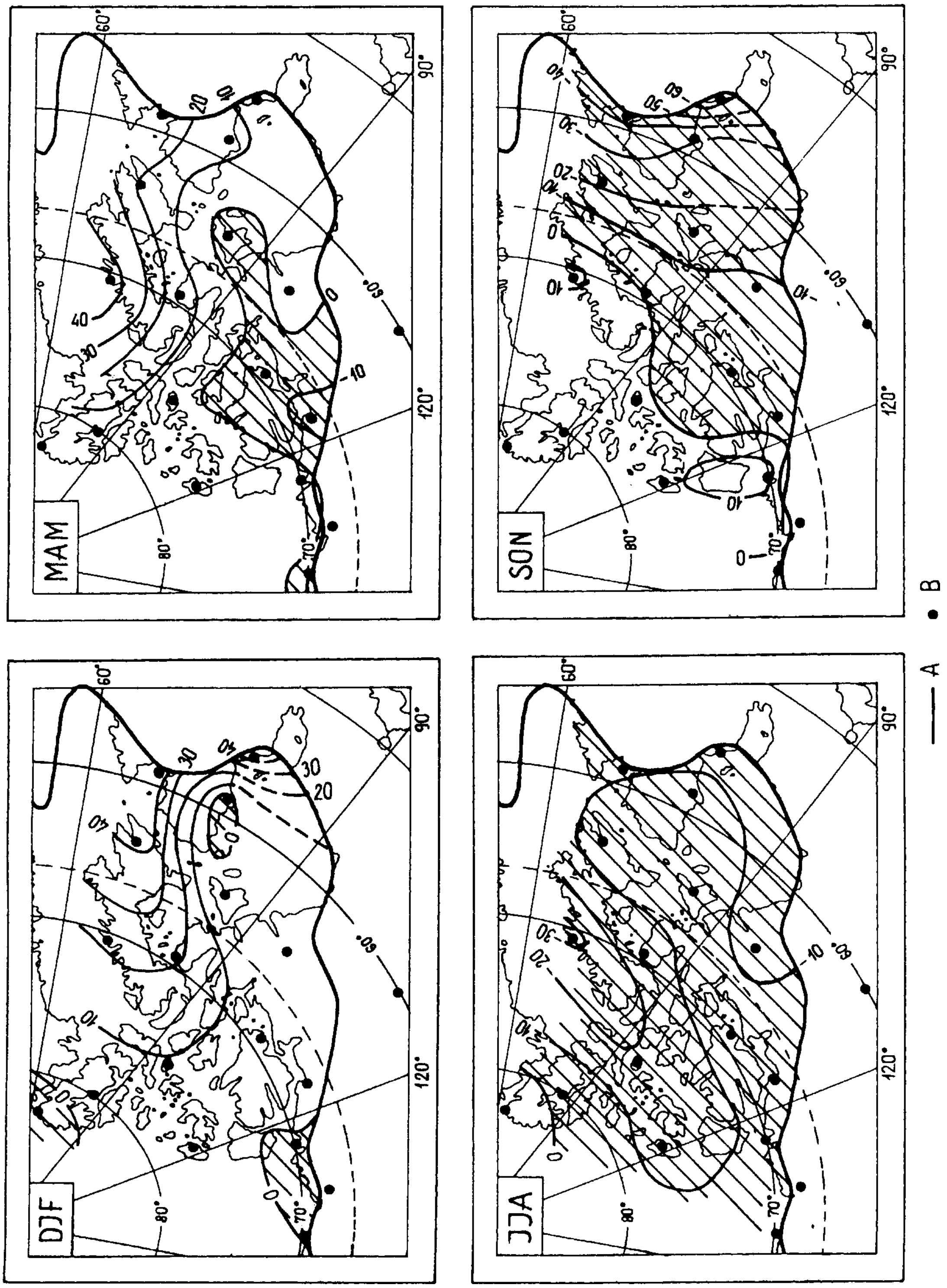

Figure 9. Mean seasonal solid precipitation differences (millimetres) in the Canadian Arctic between the ten individual warmest and coldest seasons in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

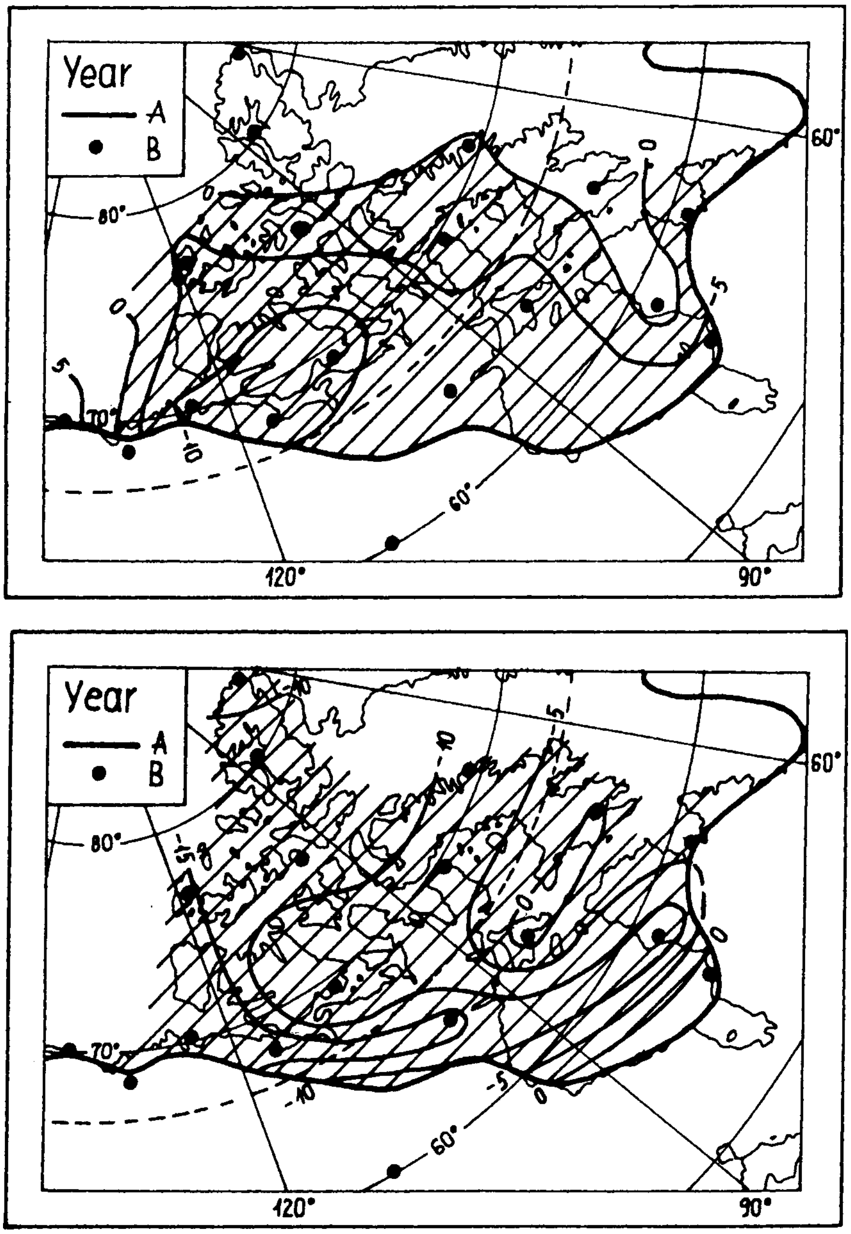

Figure 10. Mean annual S/T ratio differences in the Canadian Arctic (percent) between the ten individual warmest and coldest years (upper map) as well as between the ten consecutive warmest and coldest years (lower map) in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

seasons (Table III). Generally, Davis *et al.* (1999) obtained results similar to those presented above in their analysis of data for the whole of Canada. They found that the snowfall–temperature relationship is positive in high latitudes and is negative in southern Canada. Furthermore, they reported that the transition zone, north of which warmer months receive more snowfall than colder months, migrates southward from autumn to winter and northward from winter to spring.

The annual S/T ratio changes calculated for these five stations showed that the spatial distribution of this ratio is different to that presented in Figure 10. They reveal the existence of opposite annual S/T ratio changes in the coldest, northern ($\gtrsim$70 °N) and warmest, southern parts of the Canadian Arctic. In the warmest years

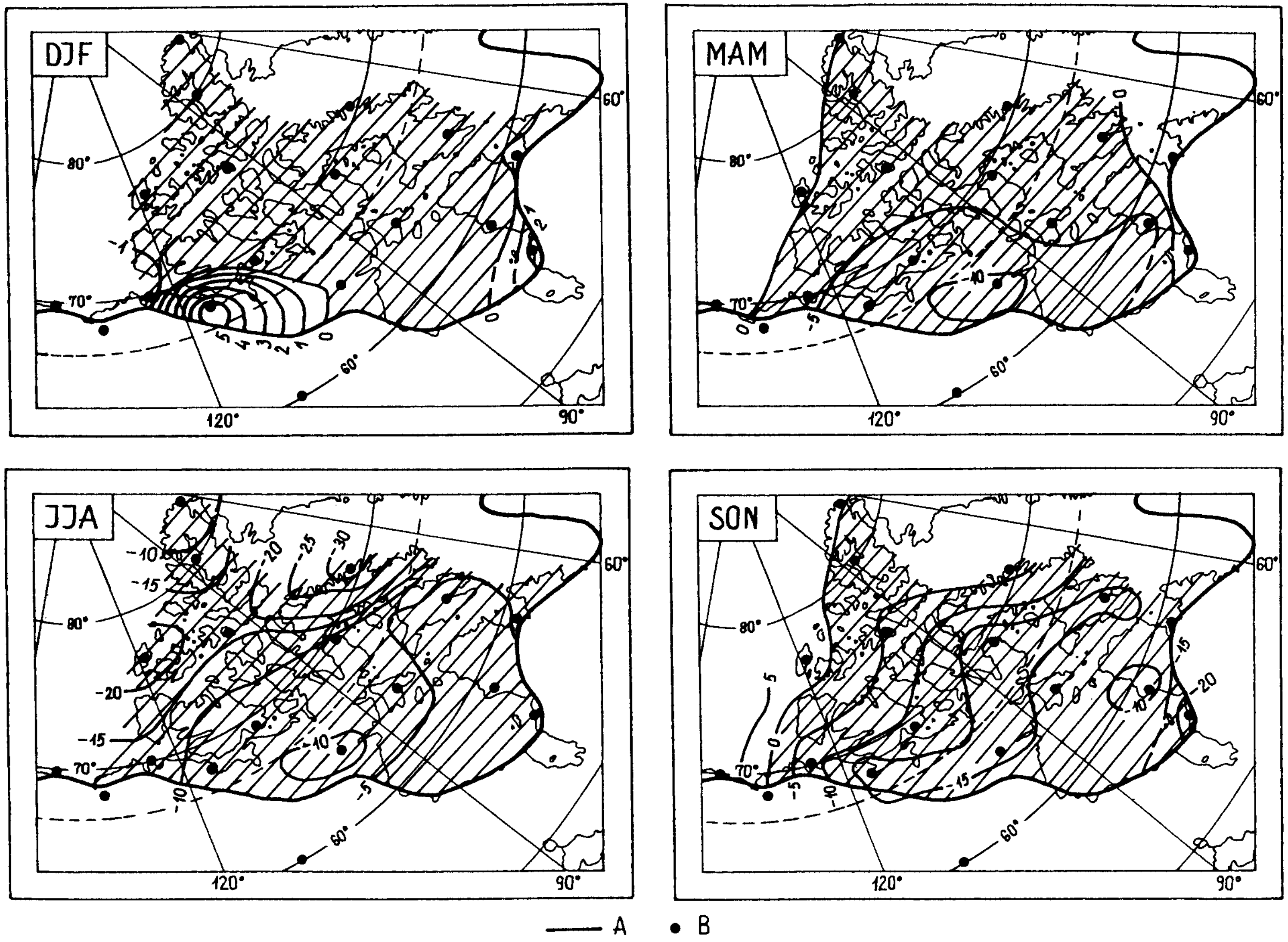

Figure 11. Mean seasonal S/T ratio differences in the Canadian Arctic (percent) between the ten individual warmest and coldest years in the Canadian Arctic. Negative differences are hatched. Other key as in Figure 1

Table III. Mean differences in precipitation (millimetres) in the Canadian Arctic between the ten warmest and ten coldest seasons and years selected separately for each station

Station	Parameter[a]	DJF	MAM	JJA	SON	Year
Alert	1	−1.0	−0.3	−9.8	11.4	−17.3
	2	−1.1	−0.4	−20.3	−11.5	−11.9
	3	0.1	0.1	10.5	−0.1	−5.4
Resolute A	1	11.0	1.5	−33.1	29.1	26.0
	2	10.9	1.2	−30.3	24.9	21.0
	3	0.1	0.3	−2.8	4.2	5.0
Clyde A	1	28.1	17.6	−28.1	23.3	17.4
	2	27.8	16.7	−42.1	17.8	15.2
	3	0.3	0.9	14.0	5.5	2.2
Coppermine	1	16.3	−10.5	−5.3	4.2	27.1
	2	16.2	−13.6	−7.2	−21.5	10.9
	3	0.1	3.1	1.9	25.7	16.2
Coral Harbour A	1	24.4	8.3	−14.7	17.2	45.2
	2	23.9	10.2	−14.0	−14.4	0.4
	3	0.5	1.9	−0.7	31.6	44.8

[a] 1: total precipitation; 2: solid precipitation; 3: liquid precipitation.

an increase of this ratio in the north and a decrease in the south was observed. In the Canadian Arctic, near 70 °N, the mean annual air temperatures oscillate between −12 and −14 °C (Przybylak, 1996). Thus, based on the findings presented here, it may be assumed that in all other areas that fulfil this thermal criterion (< −12 to −14 °C) both in the Arctic and outside the Arctic, an increase in the annual S/T ratio should also be observed during warmer periods.

This threshold in temperature separating the two opposite responses of the S/T ratio to changes in temperature is probably somehow connected with the moisture content of the air for temperatures below 0 °C and with the duration of the period with freezing temperatures. It is well known that the moisture content may be positively correlated with temperature. Thus, a change in annual air temperature from ‘very cold’ to ‘cold’ (in the range of temperatures lower than −12 to −14 °C) should result in an increase in solid precipitation (the moisture content probably being a more important factor than the shortening of the period with freezing temperatures). On the other hand, for annual temperatures higher than −12 to −14 °C, the rise in temperature leads to the shortening of the period with freezing temperatures having a greater influence on the occurrence of solid precipitation than that connected with changes in moisture content. As a result, a decrease in total precipitation is observed. Confirmation of this hypothesis requires further detailed investigation.

It has been easier to provide a clearer picture of the seasonal S/T ratio differences calculated between the warmest and the coldest seasons than for the annual S/T ratio differences. In all seasons negative differences occurred everywhere, except the Alert station (in autumn) and the Coral Harbour A station (in spring); thus, this entirely confirms the results presented in Figure 11. The differences between the annual and seasonal S/T ratio pattern changes in the northern Canadian Arctic might be related to the fact that, quite often, high annual air temperature is a result of one or two exceptionally warm seasons, whereas other seasons might even have below normal temperatures. Such years, when taken for analysis, can obscure the obtaining of real relationships. Thus, the relationship between air temperature and the S/T ratio will be established more reliably when seasonal data are used.

Based on the sets of scenarios that have been presented, one can conclude that, in a warmer Canadian Arctic, a decrease in the S/T ratio will probably occur. The total precipitation will increase, and thus either liquid precipitation will increase more than solid precipitation or liquid precipitation will increase while solid precipitation decreases. However, the value of the decrease in solid precipitation must be lower than the value of the increase in liquid precipitation. It seems that the reason for the decrease in the S/T ratio is the fact that the role played by the shortening of the period with freezing temperatures suitable for snowfall is greater than the role of rising moisture availability.

5. THE INFLUENCE OF CIRCULATION FACTORS ON TOTAL AND SOLID PRECIPITATION AND ON THE S/T RATIO

5.1. NAOI

It is a well known fact that in the Arctic, including the Canadian Arctic, the amount of precipitation depends not only on air temperature, but is also influenced by circulation factors, particularly the atmospheric circulation. The influence of atmospheric circulation changes in the North Atlantic on precipitation in the Canadian Arctic has been investigated using the NAOI. Because the influence of the NAOI on climate is greatest in winter, only for this season has its relationship with precipitation in the Canadian Arctic been examined.

The influence of atmospheric circulation changes in the North Atlantic on precipitation in the Canadian Arctic is presented in Figure 12. Because, in winter, solid precipitation almost always dominates, only the results for total precipitation are shown. It may easily be noted that during the highest values of the NAOI (strong zonal circulation over the North Atlantic and Europe) significant drops in precipitation (up to 50–70 mm) occur in the south-eastern part of the Canadian Arctic. On the other hand, positive anomalies in the rest of the study area are observed. This pattern is in agreement with the noted air temperature changes resulting from the same NAOI changes (see figure 12 in Przybylak (2000)), i.e. decreases in precipitation are connected with decreases in air temperature and *vice versa*.

5.2. El-Niño–Southern Oscillation (ENSO) phenomenon

Przybylak (2000) showed that air temperature in the Canadian Arctic also depends on circulation changes in the tropical part of the Pacific Ocean connected with the ENSO phenomenon. Relationships between precipitation and atmospheric circulation changes in that region were estimated by calculating solid and total

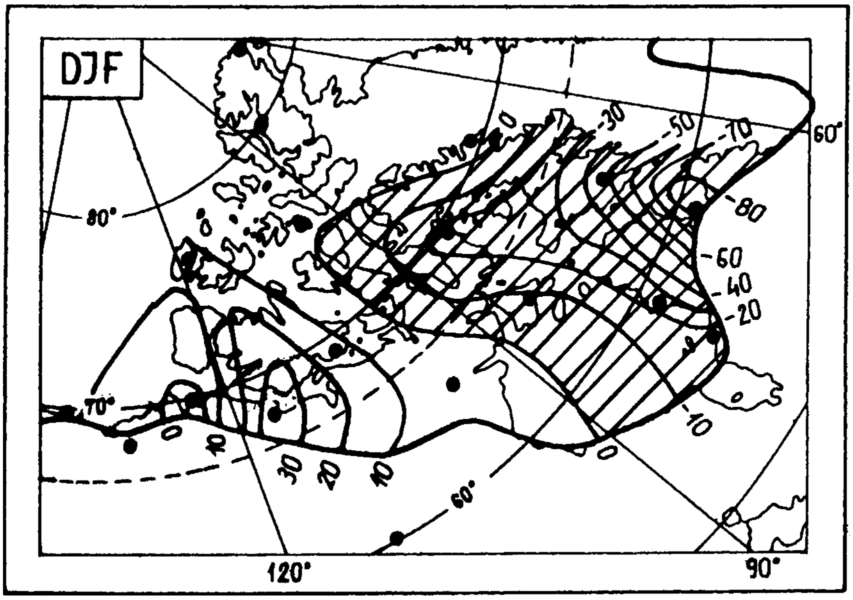

Figure 12. Total winter precipitation differences (millimetres) between the most extreme 7 year run of NAO+ winters and NAO− winters. The NAO+ and NAO− winters were taken after Dickson *et al.* (1997). Negative differences are hatched. Other key as in Figure 1

precipitation differences between the ten years with the strongest El Niño event and the ten years with the strongest La Niña event (the years have been chosen based on the sea surface temperature in the Niño 3.4 region). For this analysis the following years were chosen (after Przybylak, 2000): 1957, 1965, 1969, 1972, 1982, 1987, 1991, 1992, 1993 and 1994 (El Niño); 1950, 1955, 1956, 1964, 1971, 1974, 1975, 1985, 1988 and 1989 (La Niña).

The pattern of precipitation anomalies in winter connected with the influence of the El Niño phenomenon (not shown) is almost opposite to that presented for the NAOI in Figure 12. A decrease in precipitation occurred mainly in the north-western part of the Canadian Arctic. Also, during other seasons, apart from summer, positive anomalies prevailed during the El Niño phenomenon. In summer, positive anomalies were noted only in the south-eastern and the south-western parts of the study area. Annual total precipitation sums are generally higher during the El Niño events, except in the northern and central part of the Canadian Arctic (Figure 13(a)). Both seasonal (not shown) and annual (Figure 13(b)) patterns of solid precipitation changes due to the El Niño events are roughly similar to those presented above for the total precipitation. The largest disagreement is noted mostly in summer, when, in the case of the solid precipitation, positive anomalies prevail in most of the study area. As can be seen in Figure 13, the area with negative anomalies of solid precipitation is reduced in comparison with total precipitation. The annual S/T ratio in the years with El Niño events is, in most of the Canadian Arctic, higher than during the La Niña events (Figure 14, upper map). Similar situations, though with different spatial patterns, occur in all seasons except for winter, when during the El Niño events only about half the area has a higher S/T ratio than during the La Niña events.

Przybylak (2000) found that the influence of ENSO on Arctic temperature is significantly lower than that associated with circulation changes in the North Atlantic (NAOI). In the case of the Canadian Arctic, the temperature changes are two or three times smaller (cf. his figures 12 and 14), but both show negative anomalies during years with the El Niño phenomenon and with high values of the NAOI. For the NAOI changes, owing to the significant temperature signal, the relationship between this variable and precipitation is in keeping with expectations (see Section 5.1). On the other hand, as a result of a weak El Niño minus La Niña temperature signal, the relationship between temperature and precipitation behaviour is the opposite to that expected. What is interesting and difficult to explain is the fact that the rise of precipitation (Figure 13) is very clear in the Canadian Arctic. The decreases cover only a small area and are low.

5.3. Arctic Ocean oscillation

Proshutinsky and Johnson (1997) have discovered a certain oscillating behaviour in the Arctic Ocean over a period of 10–15 years, which they call the Arctic Ocean oscillation. They found two major regimes describing the modelled wind-driven ice and water motion. One regime is characterized by anticyclonic circulation and the second by cyclonic ice and water motion. The regimes alternate every 5–7 years. In more recent papers (Polyakov *et al.*, 1999; Proshutinsky *et al.*, 1999) they found an opposite influence of each of the regimes described on different components of the Arctic climate system, including the atmosphere. Both model simulation and observational data showed that during the anticyclonic circulation regime both temperature and precipitation are lower in the Arctic. In the light of these results, it is very interesting to examine the influence of these circulation changes on solid and total precipitation, as well as on the S/T ratio, in the Canadian Arctic. The relationships were investigated by calculating the precipitation and the S/T ratio differences between blocks of separate time periods amounting to a total of 18 years with Arctic Ocean anticyclonic regimes (1958–62 + 1972–79 + 1984–88) and cyclonic regimes (1967–71 + 1980–83 + 1989–93).

The clearest picture of solid and total precipitation, as well as S/T ratio, changes has been obtained by analysing the influence of these two opposite circulation regimes in the Arctic Ocean (see Figures 14–16). As can be seen from these figures, negative differences prevailed during the anticyclonic circulation regime almost throughout the whole study area, except during summer for the area mainly below 70 °N. Patterns of seasonal solid precipitation changes are roughly similar to those presented in Figure 16 for the total precipitation. The greatest discrepancy concerns the magnitude of the values of the differences in summer, which are many times lower in the case of solid precipitation. When we look at the seasonal differences of

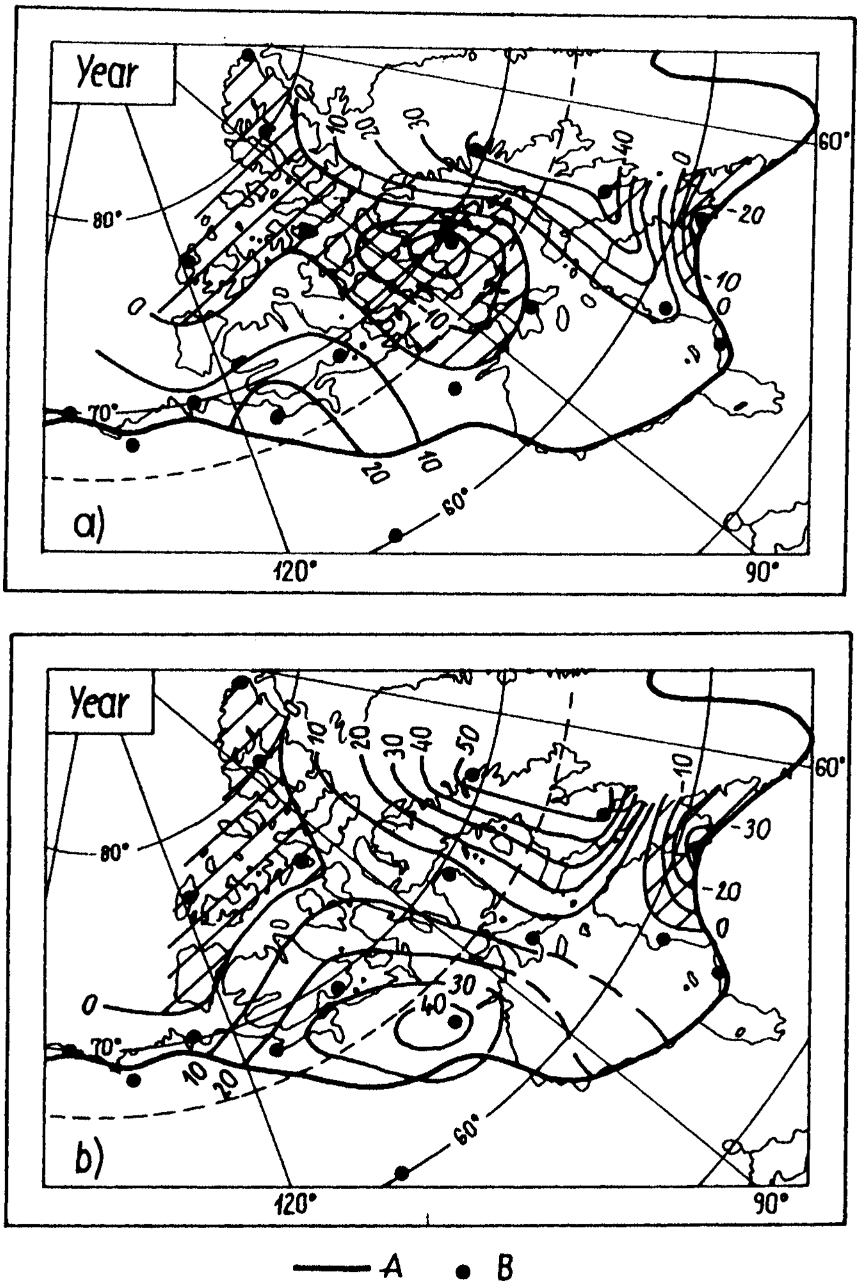

Figure 13. Mean annual total (a) and solid (b) precipitation differences (millimetres) in the Canadian Arctic between the ten years with the strongest El Niño events and the ten 10 years with the strongest La Niña events. Negative differences are hatched. Other key as in Figure 1

the S/T ratio between two analysed circulation regimes (not shown), the picture is not as clear as it is for annual differences (Figure 14, lower map); however, in all seasons there is still a clear dominance of negative differences.

This very unequivocal picture of changes in solid precipitation, total precipitation, and in the S/T ratio, in the two opposite circulation regimes analysed in the Arctic Ocean, is influenced by changes in environmental parameters noted for the two circulation regimes mentioned (see figure 5 in Proshutinsky *et al.* (1999)). Within

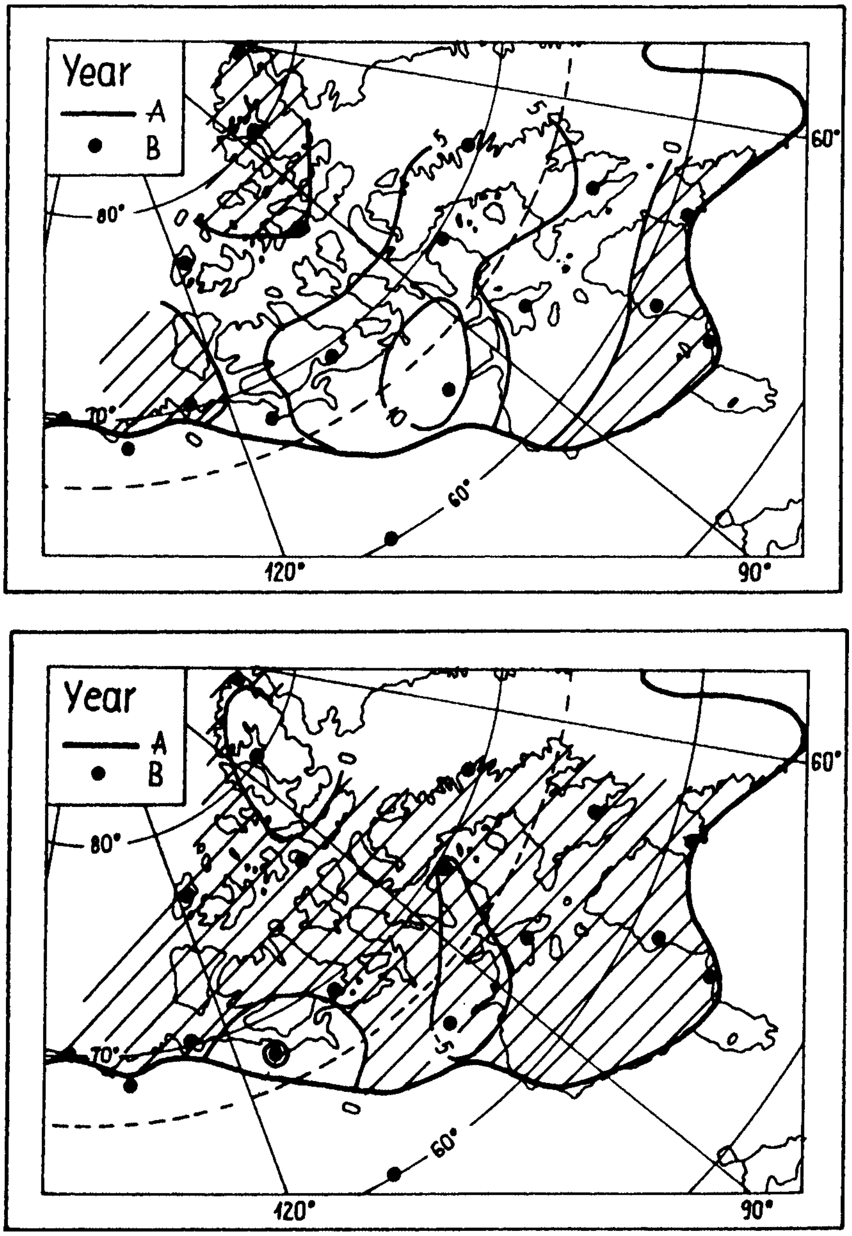

Figure 14. Mean annual S/T ratio differences in the Canadian Arctic (per cent) between the ten years with the strongest El Niño events and the ten years with the strongest La Niña events (upper map) and between blocks of 18 years with the Arctic Ocean anticyclonic and cyclonic regimes (lower map). Negative differences are hatched. Other key as in Figure 1

these parameters is the surface air temperature, which in all seasons (except summer) shows a significantly lower temperature (up to 3–5 °C) during the anticyclonic regime than during the cyclonic regime. This strong temperature signal also implies appropriate and stable precipitation behaviour. On the other hand, in summer, when there is practically no temperature change between the two composites analysed, the picture is mixed and is significantly different to the other seasons (see Figure 16). This means that, in summer, variables other than temperature influence the precipitation amounts in the southern Canadian Arctic. It seems likely that some changes probably occurred here in atmospheric circulation, which thus brought more moisture to that region during the anticyclonic circulation regime in the Arctic Ocean.

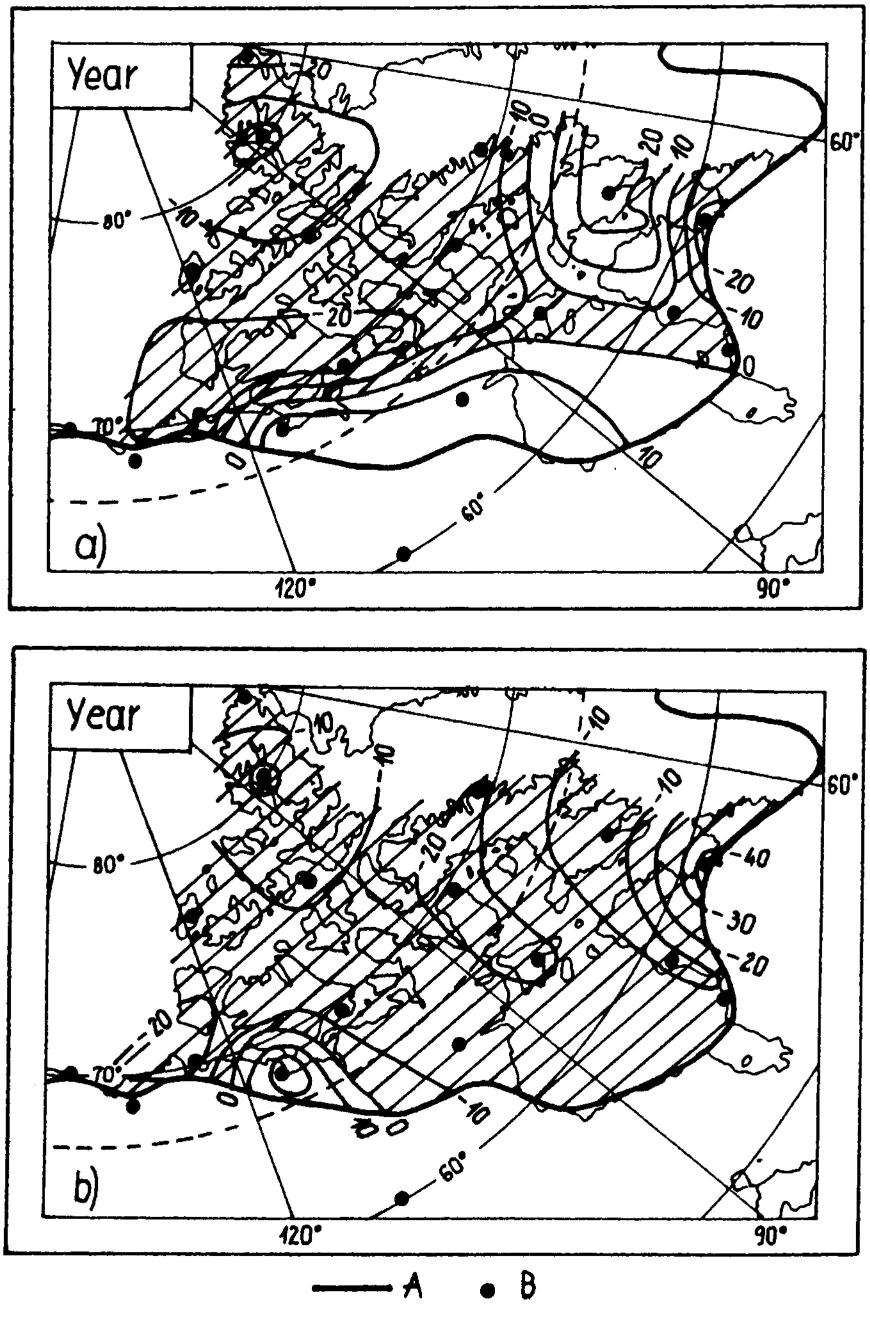

Figure 15. Mean annual total (a) and solid (b) precipitation differences (millimetres) in the Canadian Arctic between blocks of 18 years with the Arctic Ocean anticyclonic and cyclonic regimes. Negative differences are hatched. Other key as in Figure 1

The behaviour of the S/T ratio is also in keeping with expectations. In the part of the year with temperatures below freezing point, a change from ‘cold’ (cyclonic regime) to ‘very cold’ (anticyclonic regime) temperatures implies a decrease in solid precipitation, and thus also a decrease in the S/T ratio. This tendency also occurs in summer, and this fact is difficult to interpret. Such a possibility could only be explained by appropriate changes in atmospheric circulation, which, in spite of the drop in temperature, still provide more liquid than solid precipitation.

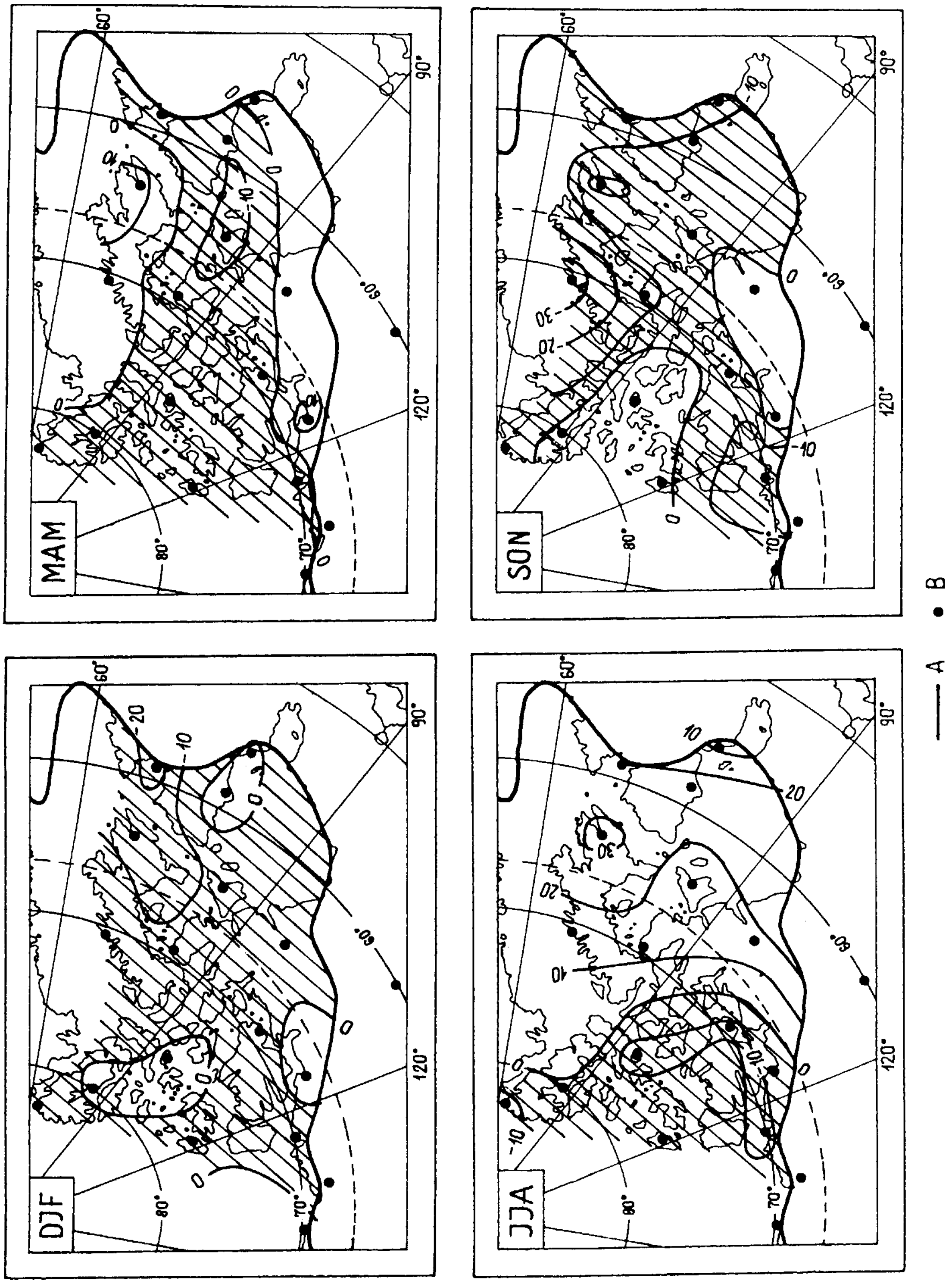

Figure 16. Mean seasonal total precipitation differences (millimetres) in the Canadian Arctic between blocks of 18 years with the Arctic Ocean anticyclonic and cyclonic regimes. Negative differences are hatched. Other key as in Figure 1

For the purposes of prediction, the existence of clear relationships between the circulation regimes in the Arctic Ocean and precipitation are very valuable. Since the circulation regime has an oscillating character with shifts between cyclonic and anticyclonic flow every 5–7 years, it is possible to estimate the probable future behaviour of precipitation for this time span. According to Proshutinsky *et al.* (1999), the cyclonic circulation regime ended in 1997. Thus, we can conclude that until about 2002–2004, when the anticyclonic circulation regime should still be present, atmospheric precipitation should be lower in comparison with the previous period 1989–1997.

6. CONCLUSIONS

The main results of the investigation are as follows.

The corrected annual precipitation sums (after the influence of measured errors are deleted) are higher than uncorrected values by 26 to 58%, depending on the station analysed.

A statistically significant increase in all kinds of areally averaged seasonal and annual precipitation for the Canadian Arctic occurred during the period 1950–95 (Figures 2 and 3). On the other hand, the S/T ratio did not change significantly, except for summer values (Figure 5), and its behaviour was also in accord with small variations noted in air temperature (Figure 4).

An increase in air temperature in the Canadian Arctic most often led to the rise of seasonal (except summer) and annual precipitation sums, but only when the warmest and coldest years were chosen based on the individual stations. The pattern of the relationship is significantly more complicated, and can even be opposite to that presented above, when the sets of the warmest and coldest years are chosen based on the areally averaged annual temperature for the Canadian Arctic (see Figures 6–9). Significantly more stable results of changes occurred for the S/T ratio, which in warmer periods was usually lower (Figures 10 and 11). More detailed and reliable investigations of temperature–precipitation relationships conducted for the individual stations confirmed the results obtained for seasons, but simultaneously showed that the lower annual S/T ratio is limited only to the southern (warmer) part of the Canadian Arctic (<70 °N).

During the periods with high positive values of the NAOI, a decrease in precipitation was observed in the south-eastern part of the Canadian Arctic (Figure 12), i.e. in the area where a strong cooling was also observed (see figure 12 in Przybylak (2000)).

During El Niño events most of the Canadian Arctic had both greater precipitation and a higher S/T ratio than during La Niña events (Figures 13 and 14).

The most unequivocal results of precipitation and S/T ratio changes were connected with changes of the Arctic Ocean circulation regimes. In almost the whole study area, a lower precipitation and S/T ratio were noted during the anticyclonic circulation regime in the Arctic Ocean (Figures 14–16).

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