SYNOPTIC CLIMATOLOGY OF THE CANADIAN HIGH ARCTIC

BY

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ABSTRACT. An objective classification of daily weather maps for the Canadian High Arctic was developed with a view to identifying those synoptic situations which greatly affect ablation season temperatures and annual precipitation totals. This classification was used to catalog synoptic types for the period January, 1946 to August, 1974. 22 basic types were recognized, accounting for ~96 % of days in the period. Most types have distinct seasonal maxima. Using data from Alert, Isachsen and Thule, monthly mean temperature characteristics of the types were obtained, enabling them to be ranked, warmest to coldest. Although "warm" and "cold" types were different for each station, the circulation characteristics of cold types, and of warm types, were similar. Stepwise multiple regression analysis was used to indicate the synoptic types which are closely related to inter-annual variations of mean monthly maximum temperatures. Generally, the maximum reduction of variance in the temperature record was achieved with a minimum number of synoptic types in the months April–August, suggesting greater "control" on temperature by a few types in spring and summer months. Ablation season climatic data were used to identify synoptic types which were "cool and wet", "warm and dry", "cool and dry" or "warm and wet". Cool, wet types have increased in frequency over the last 10–15 years whereas warm, dry types were slightly less frequent. Such changes are not sufficient to account for the deterioration in summer climate of the area in the 1960s; within-type changes are probably significant factors in this deterioration.

Stratification of precipitation data by synoptic type indicates a small number of types account for most of the annual precipitation at each station, though this is really a function of type frequency. Other, less frequent, types are more efficient precipitation-bearing situations, in terms of precipitation per day of type occurrence. In many of these situations, low pressure close to the station dominates the circulation; these may be North Atlantic depressions regenerated along the Siberian coastline. Even small changes in the frequency of these systems would have important consequences for High Arctic precipitation.

INTRODUCTION

Over the past ~30 years, synoptic meteorological observations have been made at a number of stations in the Canadian High Arctic and northern Greenland (Fig. 1). This network is sparse by midlatitude standards but relatively dense for such a high latitude region and provides a useful data set for studying climatic fluctuations and their relationships to the mass balance of snow and ice bodies in the region (cf. Bradley and England, 1978). Further insight into this question can be achieved by a synoptic climatological approach in which the data are stratified into sub-sets, defined by the particular circulation pattern over the region at the time the observations were made. In this way the weather events in one locality can be examined in terms of the prevailing atmospheric circulation (Barry and Perry, 1973). Hence those circulation types associated with, for example, extreme cold, heavy precipitation or strong ablation can be identified, and the type frequency over time may shed light on climatic fluctuations of the region (providing no "within-type" changes have taken place). Furthermore, circulation patterns associated with one type of weather at one locality may be associated with quite different conditions elsewhere and these inter-regional variations may also be of significance.

CLASSIFICATION PROCEDURE

In Arctic and sub-Arctic regions, a number of synoptic classification schemes have previously been developed. For Labrador-Ungava and the Baffin Island area selected months of the year have been classified (Barry, 1960, 1972) and the resulting catalogs of synoptic types have been examined in terms of those circulation patterns favoring either snow accumulation or ablation (Bradley, 1974; Barry *et al.* 1975). More recently, Alt has examined surface and 500 mb synoptic types for June–August in relation to glaciological conditions on the Devon Island ice cap

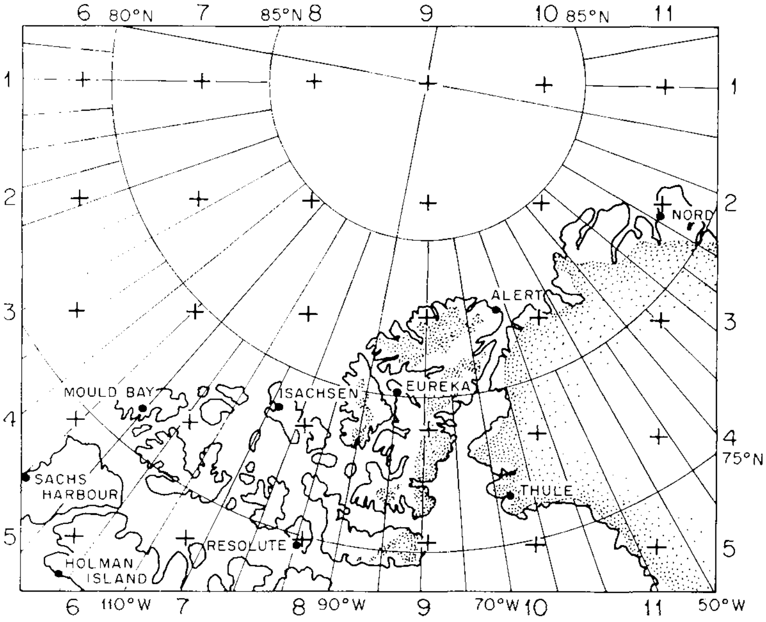

Fig. 1. Location of study area and grid network for synoptic classification scheme. Latitudinal zones 1 to 5 and meridional zones 6 to 11 are identified.

(Alt, 1978) following a similar study undertaken for the Meighen Island ice cap (Alt, 1975). In other work, Putnins (1966) developed a classification of synoptic types for the North Pacific/Chukotskiy/Alaska region, but this was not specifically applied to snow and ice conditions (Putnins, 1966; 1968). In all of these studies the initial classification of the synoptic types and the development of the synoptic catalog was subjective. In this study, the classification was as far as possible objective, based on the statistical properties of each circulation pattern. The methodology proposed by Kirchoffer (1973) was used and applied to a 30 point grid network of ~1200 GMT mean sea-level pressure data for the area shown in Fig. 1. Previous work using this approach has been reported by Moritz (1978) for Alaska, and Barry and Keen (1978) for the Baffin Island area.

Pressure data from the Northern Hemisphere Historical Weather Map Series (Jenne, 1975) were used. This series contains grid point data back to 1899; however observations from the High Arctic are virtually non-existent prior to the late 1940s, so in this study the period January 1, 1946 to August 31, 1974 was selected. For most of this period, both surface and upper air synoptic meteorological observations have been made at those stations shown on Fig. 1 and on drifting ice platforms in the Arctic Ocean and Beaufort Sea. Hence it is considered that the pressure data used were quite reliable. The classification procedure involves grouping similar circulation patterns on the basis of the sum of squares of the differences between data points on each map. The computed score, S, is thus:

$$S = \sum_{j=1}^{N} (Z_{aj} - Z_{bj})^2$$

where Z_{aj} = normalised grid values at point j on day a.
Z_{bj} = normalised grid values at point j on day b.
N = number of data points (30).

Normalised grid values are used to avoid two identical map patterns (but with different pressure values) being given a large score when the maps should in reality be considered as the same circulation type. This enables synoptic pressure maps from all times of the year to be considered in a single catalog (even though mean pressure may vary significantly from January through December). Seasonal differences are thus reflected in changes of type frequency. The normalisation procedure for each map is as follows:

$$Z_i = \frac{(x_i - \bar{x})}{s}$$

where Z_i = normalised value of the grid point
x_i = data value at grid point i
$\bar{x}$ = mean of all 30 points
s = standard deviation of the 30-point grid

In addition to computing the sum of squares of the differences for all points on the maps, subset values were computed for latitudinal zones 1 to 5 and meridional zones 6 to 11 shown on Fig. 1. These 11 "zone scores" (s_1 to s_{11}) were used in the procedure for assigning each map to a particular type as discussed below.

In order to reduce computational time to within reasonable limits, an initial classification was developed on a random sample of ~20 % of days from the entire period 1946–1974. This procedure provided a representative sample of 2128 days from all months of the year (an average of 5 to 7 days per month) and from all years of the period (from 14 to 24 % of days in each year). The data were normalised and the sum of squares of the differences scores (S and s_1 to s_{11}) were computed for all pairs of map patterns. A pair of maps were considered similar if:

(i) the overall score (S) was ≤ 30 (i.e.: $1.0 \times N$, the number of grid points) *and*

(ii) the latitudinal and meridional zone scores (s_1 to s_{11}) were $\leq 1.8N$ (where for latitudinal zones, $N = 5$, and for meridional zones $N = 6$).

The value of 1.8 was termined empirically and based on earlier work with the classification by Kirschoffer (1973) and Barry *et al.* (1977).[1]

This procedure was designed to ensure that not only were the types similar overall but that each sector of the map met stringent requirements of similarity.

At this stage, each map had been assigned 2,127 scores (overall and zonal) corresponding to the other days of the random sample. The map which had the largest number of scores below the designated thresholds ("key-day 1") was then removed along with all the qualifying similar types. The procedure was repeated for the second most 'typical' type ("key-day 2") and so on until all days were grouped into clusters of 5 days or more. In this way 22 major types were identified, accounting for 97.5 % of all days in the sample. The remaining days were considered to be unclassifiable by this procedure.

Because many days may have scores below the threshold for two or more types they could be misclassified if placed in the first type-group removed from the total data-set. Thus once the principal types were identified, the score comparison was repeated, this time assigning each map pattern to the key day type with which it had the *lowest* overall score (below the threshold value).

It was then assumed that these 22 types, derived from a random sample of days, were representative of the range of circulation patterns experienced in the entire 29 year period. Hence the remaining ~ 8,000 maps were normalised and compared with the 22 types, following the procedure outlined above.[2] 96.5 % of days were thus classified into the initial 22 synoptic types.[3]

The synoptic types

Table 1 shows the frequency and mean scores of the 22 synoptic types for the period January 1946–August 1974. It should be noted that the type number does not reflect its frequency ranking in the final catalog; frequencies changed from the random sample where the type numbers were assigned. Type 1 is most common, accounting for ~23 % of all days on an annual basis. However the occurrence of this type varies according to the season, with mid-winter frequencies generally three times the mid-summer level. The most common 10 types account for over 76 % of all days classified. Overall mean scores (S) range from 10.9 to 20.2 with scores generally inversely related to frequency, indicating greater internal diversity in the less frequent types (cf. type 1 and type 20). The synoptic types, represented by the "key days" for each type, are shown in Figs. 2 to 5. Key days are listed in Table 2 together with the predominant meridional component of airflow over most of

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[1] The determination of threshold values for the overall and zone scores is the only subjective aspect of this classification procedure. Altering the threshold changes the number and internal consistency of the types. It is equivalent to altering the correlation threshold in classification procedures such as those used by Lund (1963) and Hartranft *et al.* (1970).

[2] It can be readily appreciated that to perform on all ~10,000 days computations carried out on the sample would require enormous computer storage (and prohibitive costs); by using an initial random sample this problem was circumvented without, it is felt, materially affecting the synoptic catalog.

[3] Careful examination of the unclassified types suggests that in many cases non-classification was due to one or more erroneous data points in the data files.

Table 1. Summary of synoptic classification 'January 1, 1946 to August 31, 1974)

Type	Frequency %	Mean Score	Standard Deviation
1	23.4	10.9	4.8
2	9.3	13.4	5.3
3	7.1	12.3	5.0
4	12.0	13.1	5.4
5	3.9	14.1	4.3
6	5.0	13.9	4.6
7	4.4	14.9	4.9
8	2.3	15.9	5.6
9	2.3	16.5	5.2
10	1.2	17.5	5.3
11	2.6	15.7	5.3
12	3.1	16.1	4.2
13	3.5	13.6	4.7
14	1.0	20.2	4.0
15	4.1	13.8	4.5
16	4.0	12.9	4.6
17	1.1	17.4	5.2
18	1.5	16.8	4.8
19	1.1	17.3	5.1
20	0.8	18.9	4.5
21	1.7	15.4	4.6
22	1.2	17.4	4.9
Missing Data	0.5		
Unclassified	3.0		

the archipelago. The types are approximately equally divided between those with southerly and those with a northerly flow component, but in terms of overall frequency there is an overwhelming predominance of "northerly" types (outnumbering "southerly" types by more than 3 to 1).

The complete daily catalog is given in Bradley and England (1977); the seasonal frequency distribution of each type is summarized in Table 3. A comparison of Tables 2 and 3 indicates that, as one might expect, the types with a seasonal maxima in winter have predominantly northerly flow whereas summer types generally have southerly airflow.

Climatic characteristics of the synoptic types

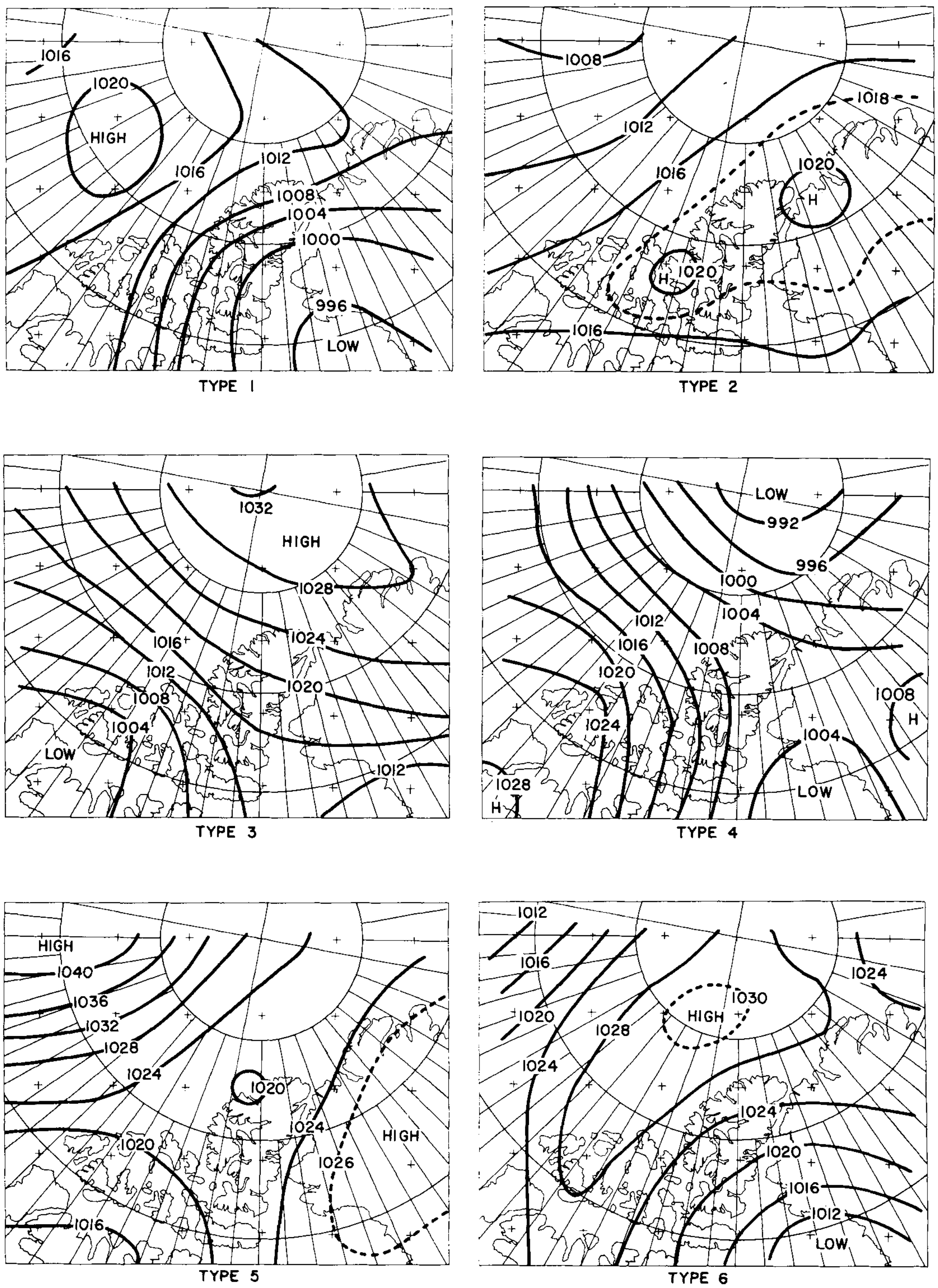
Monthly climatic data from each meteorological station in the High Arctic were stratified by synoptic type to determine the climatic characteristics of each circulation pattern. Some of the more interesting results are discussed here, with reference to climatic data from Alert, Thule and Isachsen (Fig. 1). Further discussion of climatic data from Eureka is given in Bradley and England (1977).

Temperature

For each month the types were ranked in order of increasing mean daily maximum temperature. At both Alert and Isachsen, the extremely warm or extremely cold types commonly maintain their relative ranking in all months.

At Alert, for example, types 8, 16, 11, 7 and 13 (Fig. 2 to 5) rank amongst the warmest types in all months. The warmest average maximum temperatures (Tmax) at Alert (10.7°C) are recorded during type 8 situations in July. These types are all characterized by low pressure to the west or southwest of Alert with relatively high pressure over Greenland. The resultant flow pattern leads to warmer air from the south being advected northward at all times of the year. By contrast, the four coldest types at Alert (types 1, 6, 15 and 21) are all characterized by low pressure to the south in Baffin Bay or high pressure to the west or northwest of Alert (Figs. 2 to 5). This leads to cold northerly or northwesterly airflow from the Arctic Ocean over the Alert area, hence the associated low temperatures. In winter months, mean temperatures at Alert may vary by up to 17°C during different synoptic situations; in summer, mean differences are <8°C.

At Isachsen, there is less consistency in the coldest and warmest types from month to month; in fact, type 9 is the warmest in June, July, and August whereas at other times of year it is generally one of the coldest types. In type 9 situations, a high pressure center over northwestern Ellesmere Island results in clear skies, adiabatic warming and high receipts of solar radiation. In addition, the relatively warm land mass of Ellesmere Island results in warm air advection over the Isachsen area. In winter months, this regional source of energy is absent and the lack of cloud cover and calm conditions lead to the development of strong inversions and intense cold; hence type 9 situations are relatively cold in winter, but warm in summer. Overall, the warmest synoptic situations at Isachsen are those with low pressure to the west or northwest and/or a high pressure cell to the east or northeast (types 13, 16, 2, 17, and 7) resulting in the advection of warm air from the south. The coldest synoptic types have either a low pressure center over, or to the east of, Isachsen (e.g. type 12) or a high pressure cell to the west bringing cold northerly air from the Beaufort Sea and

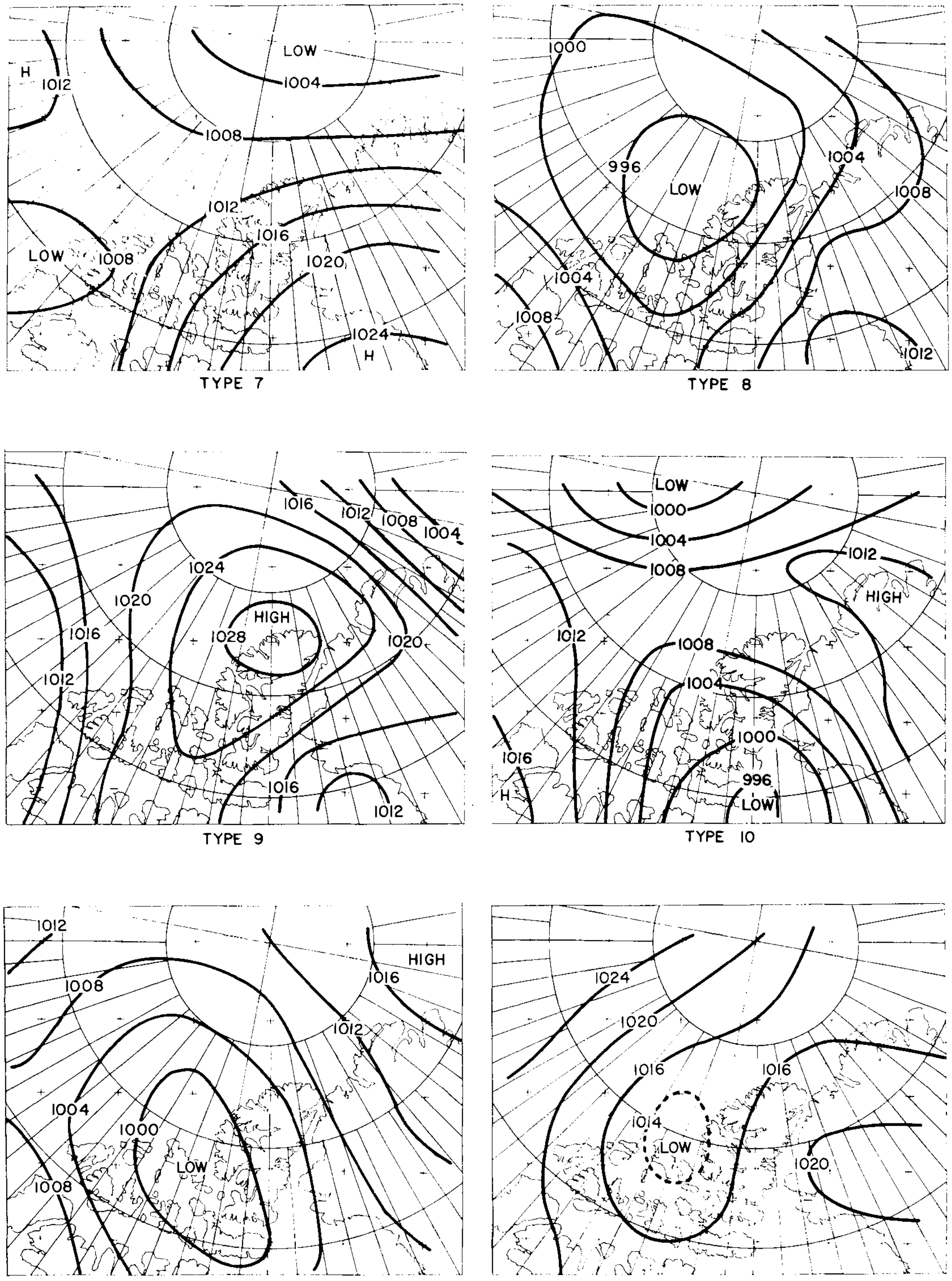


TYPE 1 TYPE 2

TYPE 3 TYPE 4

TYPE 5 TYPE 6

Fig. 2. Sea-level pressure distribution on key days for synoptic types 1 to 6.



TYPE 7

TYPE 8

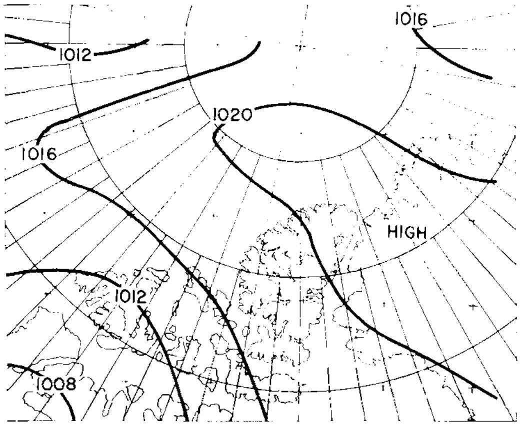
TYPE 9

TYPE 10

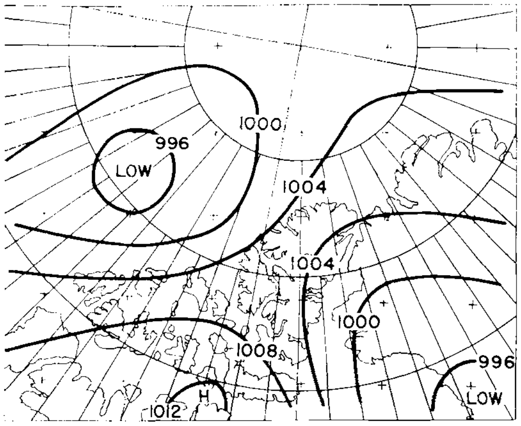
TYPE 11

TYPE 12

Fig. 3. Sea-level pressure distribution on key days for synoptic types 7 to 12.



TYPE 13



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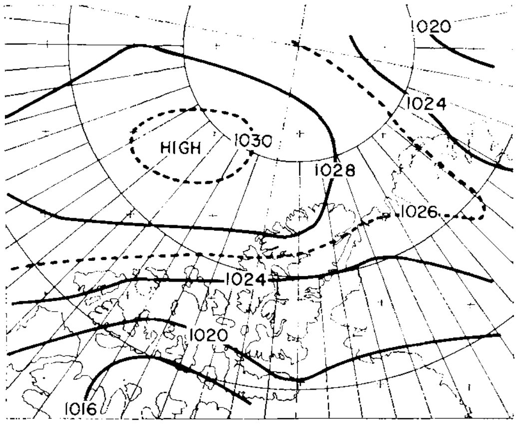

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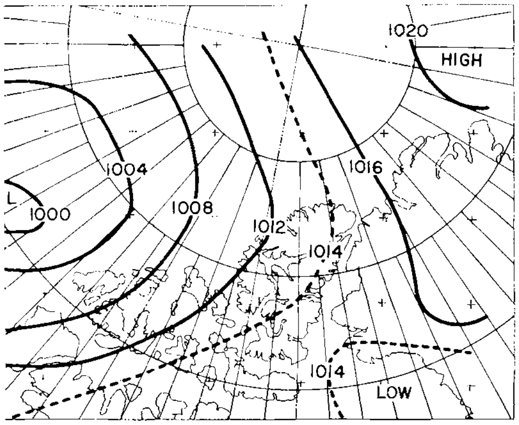
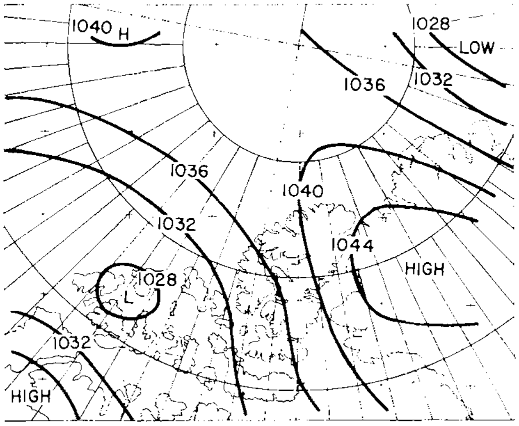
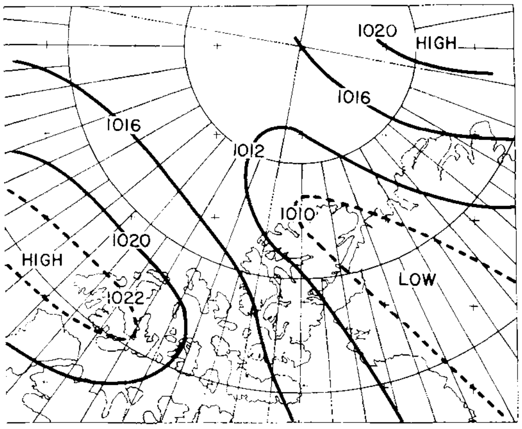


TYPE 16

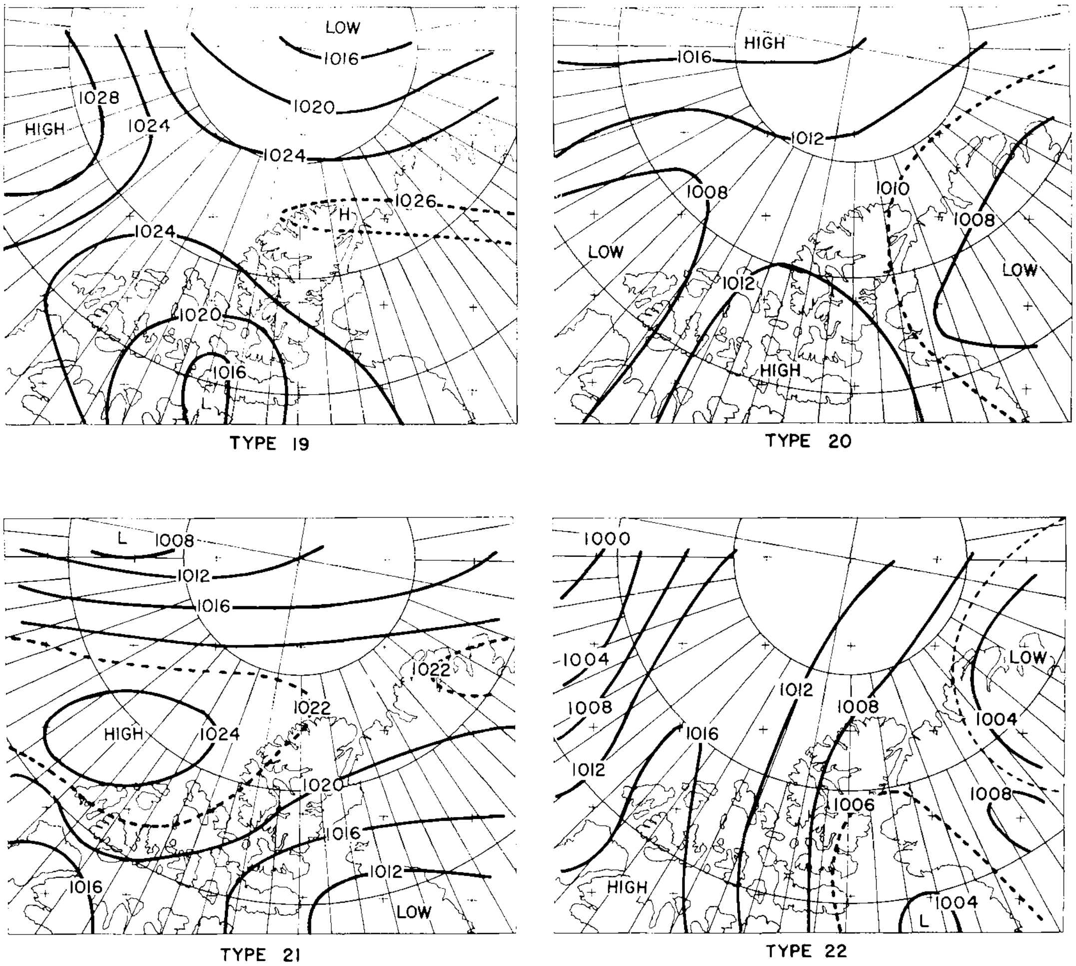


TYPE 17



TYPE 18

Fig. 4. Sea-level pressure distribution on key days for synoptic types 13 to 18.



TYPE 19

TYPE 20

TYPE 21

TYPE 22

Fig. 5. Sea-level pressure distribution on key days for synoptic types 19 to 22.

Arctic Ocean over the region (types 1, 4, 18, 21).[4]

At Thule, synoptic situations 10 and 11 lead to above average monthly mean temperatures throughout the year. This is also true (though less consistently) of types 3 and 15. Again, the pattern of low pressure west of the station resulting in warmer southerly or southeasterly airflow is characteristic. Cold synoptic situations include types 20, 22, 4, 12, 9 and 18. On these occasions, low pressure is generally located east or southeast of Thule with high pressure to the west.

It can be concluded that, at all three locations, the warmest and coldest types are not always the same but the general situations are clearly similar—northerly airflow from high pressure areas to the west of the station in cold types and southerly or southeasterly airflow toward low pressure centers to the west of the station in warm types.

Stepwise regression

In order to evaluate the relative importance of each type to the monthly fluctuations of temp-

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[4] It is of interest that the coldest temperature ever recorded in the Canadian Arctic Islands (−53.9°C [−65°F]) was registered at Isachsen during a type 1 situation.

Table 2. Key days for high arctic synoptic types

Type	Predominant Airflow[a]	Key Day	Type	Predominant Airflow[a]	Key Day
1	N	August 23, 1972	12	N(W)S(E)	May 20, 1974
2	?	April 25, 1963	13	S	June 25, 1954
3	N	November 7, 1964	14	S	August 11, 1953
4	N	March 25, 1973	15	N	June 9, 1957
5	N(W)S(E)	March 26, 1972	16	S	August 27, 1946
6	N	November 4, 1954	17	S	February 7, 1947
7	S	July 16, 1971	18	N	June 30, 1947
8	N(W)S(E)	July 19, 1960	19	N(W)S(E)	May 10, 1948
9	S(W)N(E)	October 11, 1953	20	S(W)N(E)	July 20, 1948
10	N	October 5, 1972	21	N	September 24, 1960
11	N(W)S(E)	July 3, 1950	22	N	September 6, 1961

[a] Where two directions are given, the predominant airflow is completely different in the western(W) and eastern(E) sectors of the region.

Table 3. Summary of type frequency by month

Type	Relative Seasonal Maxima	Type	Relative Seasonal Maxima
1	Mid-winter	12	Late Winter
2	Mid-summer	13	Spring & Fall
3	Spring & Late Summer/Fall	14	Late Summer/Fall
4	None	15	Spring & Fall
5	None	16	Late Summer/Early Winter
6	Fall/Early Winter	17	None
7	None	18	Summer
8	Mid-Summer	19	Spring
9	Winter	20	Early Winter
10	Spring/Summer	21	Spring & Fall
11	Late Summer	22	Summer

erature over time, a stepwise multiple regression analysis was undertaken with the mean maximum temperatures for each month (Tmax) as the dependent variable and the synoptic type frequencies in each month as the independent variables. For example, July maximum temperatures at Alert were analysed with the frequency of all 22 synoptic types in July. Synoptic type 1 was most highly correlated with Alert July Tmax, accounting for 53 % of the variance. As discussed earlier, type 1 is a characteristically cold type, hence the relationship is inverse with mean July temperatures higher in years with low type 1 frequency (Fig. 6). The next synoptic type entering the regression was type 3; (this is a warm type with average maximum temperatures 5°C higher at Alert than during type 1 situations). The addition of type 3 increases the total variance explained to ~63 %.[5] In this example, more than half of the variance of Tmax was explained by one variable (synoptic type 1 frequency) but this is exceptional as most months require at least two variables to explain >50 % of the variance (Table 4). Similar analyses of Isachsen monthly Tmax data indicate that Tmax

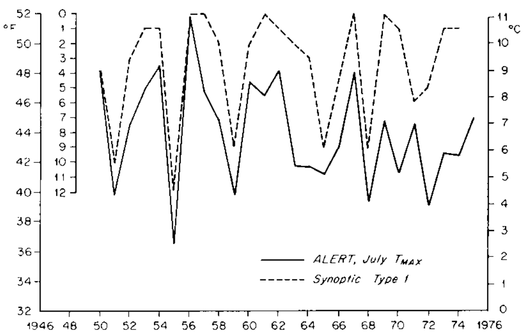

Fig. 6. Alert, July mean maximum temperatures and frequencies of synoptic type 1 in July (note: synoptic type 1 frequency scale is inverted).

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[5] $y=0.78x_1+0.84x_2+44.1$ where y=July Tmax (°C) and x_1 and x_2 are the monthly frequencies of synoptic types 1 and 3 respectively.

Table 4. Principal synoptic types accounting for variance of the monthly maximum temperature record

	Primary Type	%[1]	Correlation[2]	Secondary Type	%[1]	Correlation[2]	Σ%[3]
a) *ALERT*							
Jan.	16	21	+	6	14	–	35
Feb.	18	33	–	3	21	+	54
Mar.	21	25	+	11	20	+	45
Apr.	1	48	–	13	29	+	77
May	11	36	+	7	25	+	61
Jun.	22	20	–	8	15	+	35
Jly.	1	53	–	3	10	+	63
Aug.	1	23	–	17	14	+	37
Sep.	1	33	–	18	14	+	47
Oct.	1	22	–	19	15	+	37
Nov.	13	44	+	16	19	+	63
Dec.	12	22	–	7	16	+	38
b) *ISACHSEN*							
Jan.	4	23	+	15	14	+	36
Feb.	21	23	+	6	18	+	41
Mar.	9	30	+	13	13	+	43
Apr.	16	31	+	2	19	+	50
May	1	30	–	21	11	–	51
Jun.	15	13	+	9	12	+	25
Jly.	18	33	–	14	18	–	51
Aug.	15	36	+	3	19	+	55
Sep.	8	27	+	7	18	+	45
Oct.	13	33	+	22	13	–	46
Nov.	13	31	+	5	11	–	42
Dec.	7	23	+	20	13	+	36
c) *THULE*							
Jan.	6	13	+	18	10	–	23
Feb.	18	25	–	7	20	–	45
Mar.	11	29	+	20	21	+	50
Apr.	4	24	+	16	15	+	39
May	10	14	+	16	14	+	28
Jun.	3	27	+	15	17	+	44
Jly.	4	23	–	16	14	–	37
Aug.	4	27	–	11	17	–	44
Sep.	10	16	+	6	13	+	29
Oct.	4	36	–	7	25	+	51
Nov.	15	21	+	13	19	+	40
Dec.	5	24	+	4	19	–	43

[1] % Explanation of variance.

[2] Correlation with temperature record (+or–).

[3] Σ explanation of variance with 2 best independent variables.

in the months of April to August (excluding June) are dependent on a small number of synoptic types. Generally >45 % of explained variance in these months can be obtained with 2 independent variables. In other months (particularly December, January and June) temperature fluctuations are dependent on a larger number of types and at least 4 synoptic type variables would be needed to account for >45 % of the total variance.

Thule temperature data have generally lower correlations with synoptic type frequency (Table 4) particularly at the beginning and end of the ablation season (May and September). "Explanation" is generally highest in winter months (October to March). The reasons for these differences are not clear. It would seem likely that persistence of a particular synoptic pattern in certain months would greatly influence the temperature record. However, analysis of type persistence indicates that this explanation is inadequate in the case of Alert and Isachsen data, at least, because type durations are commonly longer in mid-winter than in mid-summer. No doubt many local factors play important roles which are sub-synoptic in scale and beyond the resolution of this large-scale classification scheme. For example, it is likely that frequent disturbance of the surface temperature inversion in winter months (on a local scale) would result in surface temperatures showing little correlation with the regional flow pattern. Katabatic winds, particularly in the Thule area, are also a likely source of local temperature "anomalies" (MacMillan, 1925). Similarly, local fog, associated with open water, is common (e.g. around Alert in early summer during anticyclonic situations) and temperatures are greatly reduced on a local scale. In view of all these factors, the correlations between monthly mean temperatures and large scale synoptic type frequency are surprisingly good.

In the ablation season the stepwise regression analysis indicates that a small number of synoptic patterns have particular importance; types 1 (at Alert) and 15 (at Isachsen and Thule) are similar synoptic situations with a high pressure center northwest of Ellesmere Island. Airflow is northerly over Alert, northeasterly over Isachsen and southeasterly over Thule. Type 1 is very cold at Alert in all months, whereas type 15 results in warm conditions at Isachsen (particularly in August when the Ellesmere Island land mass to the east is relatively warm) and at Thule in June. Other types of importance in summer months are types 18 and 4. Type 18 is very cold at Isachsen, with mean maximum temperatures averaging only 3.2°C in July; type 4 also results in relatively cold conditions at Thule (mean daily maximum temperatures in July and August only 5.5°C). The importance of these types to ablation season precipitation will be considered again in the following sections.

Precipitation

Daily precipitation totals at Isachsen and Alert have been stratified by synoptic type to identify those types important to annual accumulation. In this study, all "Traces" were assigned a value of 0.127 mm (0.005 inches) in order to take into account the large number of traces which occur, particularly in winter months (cf. Bradley and England, 1978).

Table 5 shows the main synoptic types and their frequency for the two stations. At Alert, types 1 and 4 are of overwhelming importance to annual precipitation, accounting for over 50 % of all precipitation recorded yet occurring on only 36 % of days. These types are also the most important at Isachsen but provide less precipitation, ~23 % of annual totals. Although at each locality a small number of types accounts for most of the annual precipitation, this partly reflects the frequency with which the types occur. Nevertheless, certain types are distinctly seasonal in occurrence and they may be important "precipitation-bearing" situations at certain times of year. For example, type 8 (low pressure center north of Isachsen, Fig. 3) reaches a maximum frequency of ~10 % in July. July is one of the wettest months at Isachsen with ~20 % of annual precipitation; type 8 situations account for 24 % of the July total yet they occur

Table 5. Synoptic types important to annual precipitation totals

	ALERT (July 1950 to Dec 1974)			*ISACHSEN* (May 1948 to Dec 1974)	
Type	% of Ann. Precip.	% Frequency	Type	% of Ann. Precip.	% Frequency
4	26.8	12.8	1	11.9	22.5
1	24.6	22.8	4	11.4	12.5
2	6.6	9.8	2	9.8	9.5
7	5.5	4.7	3	8.0	7.0
15	4.5	4.0	8	7.9	2.5
6	4.3	4.6	15	7.6	4.0
	—	—	7	6.7	4.7
	72.3	58.7	13	5.3	3.6
				—	—
				68.6	66.3

on only 3 days in the month on average. Type 8 synoptic types are thus very important to *summer* precipitation but over the year as a whole, other types result in more precipitation. Type 8 situations in July are among the coldest at this time of year (average daily maximum temperatures of 3.3°C, and a daily mean of only 1.4°C) so the frequency of this type is of particular significance to ablation in the area. Other very wet synoptic situations at Isachsen in summer months are types 2, 4, and 16.

Table 6. General climatic characteristics of synoptic types in summer months (June–August)

a) Isachsen		
	3 months	*2 months*
cool & wet	4, 8, 11	
cool & dry	1, 12, 18, 21, 22	20
warm & wet	2, 16	3, 5
warm & dry	9, 15, 17	6, 7, 10, 13, 19
b) Alert		
	3 months	*2 months*
cool & wet	1, 4	
cool & dry	5, 6, 18, 19, 21, 22	9, 14, 15, 20
warm & wet	2, 7	
warm & dry	11, 16	3, 8, 10, 12, 13, 17

Ablation season synoptic types

In order to assess the significance of each synoptic situation to summer ablation in the Isachsen and Alert areas, the contribution of each type to monthly precipitation totals (June–August) was plotted against the average temperature of the type, as illustrated in Fig. 7. In this way, 4 groups can be recognized which are (1) cool and wet, (2) cool and dry, (3) warm and wet and (4) warm and dry and the relative importance of each type during the ablation season can be assessed. Table 6 shows the types falling into these 4 categories during all 3, or 2 of the 3, summer months (June–August) at Isachsen and Alert.

At Isachsen, types 4, 8 and 11 are "cool and wet" throughout the summer. All three types are characterized by high pressure to the southwest of Isachsen resulting in westerly air flow over the region. Types 8 and 11 are dominated by a major low pressure area centered just to the east or southeast of Isachsen. In "warm and dry" types, Isachsen is either under the influence of an anticyclone or ridge (e.g. types 9, 15, 6) or low pressure to the south or southwest results in warm air advection from the southeast (types 17, 13, 7, 19). Average daily maximum temperature at Isachsen during "warm, dry" types is 2.8°C greater than during cool, wet types (June–August). "Warm, dry" types occur on 1.4 % of all days and result in only 1.2 % of annual precipitation whereas "cool, wet" types account for 13.2 % of annual precipitation and occur on only 5.7 % of days per year. An increase in the frequency of "cool, dry" types at the expense of "warm, dry" type frequency may thus result in significantly different summer conditions.

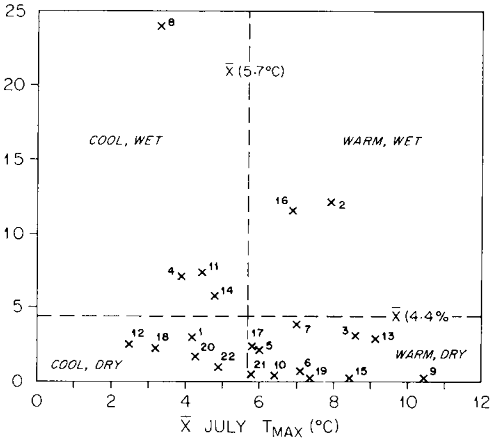

Fig. 7. Mean monthly maximum temperature conditions at Isachsen in July during synoptic type episodes and the contribution each type makes to the monthly precipitation total.

In view of the recent change in summer climate of the Canadian High Arctic (Bradley, 1973; Barry *et al.*, 1975; Bradley and England, 1978) it is of interest to examine synoptic type frequencies over time. Fig. 8 shows the summer (June–August) frequency of "cold, wet" and "

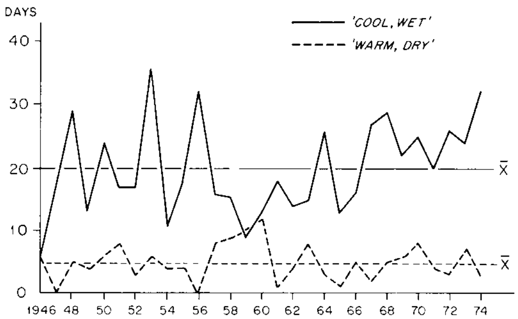

Fig. 8. Frequency of principal "cold, wet" types (4, 8, 11) and "warm, dry" types (6, 9, 13, 15, 17) at Isachsen in June–August of each year.

warm, dry" types at Isachsen. Although interannual variability is high, particularly in the earlier part of the record, "cool, wet" types have increased in frequency in recent years; "warm, dry" types have decreased in frequency slightly. "Cold, wet" types averaged ~24 days per summer after 1963 whereas the 1946–63 averaged was ~18 days. "Warm, dry" types are less frequent and averaged 5.4 days per summer from 1946–63 and ~4.3 days after 1963. Although these changes are interesting in that they are in the same direction as the change in summer climate of the area would indicate, they are not of sufficient magnitude to account for the marked changes observed (Bradley and England, 1978). It is thus possible that "within type" changes are important factors in the recent deterioration of summer climate in the region. Further work on this seems warranted.

A similar analysis was conducted on Alert summer climatic data and the results are summarized in Table 6b. Like Isachsen, type 4 situations are wet and cold (mean daily maximum temperature of 2.5°C). Type 4 situations occur on 13 % of summer (June–Aug) days but result in ~31 % of summer precipitation. In fact, during the three summer months, type 4 days account for 12 % of *annual* precipitation. Also important "cold, wet" types at Alert are type 1 situations in which airflow is northerly, from the Arctic Ocean. However, as these types occur on ~14 % of summer days and provide ~14.5 % of summer precipitation, their importance for precipitation totals is simply a function of their relatively high frequency.

"Warm, dry" conditions at Alert are associated with synoptic types 11 and 16. Type 16 was also warm at Isachsen but resulted in more precipitation at that station. Both patterns involve low pressure centers west of Alert but in the type 11 situations the center of the low is close to, but slightly east of, Isachsen. Thus at Alert, type 11 situations are warm and dry (average Tmax=6.8°C; and mean daily precipitation=0.05 mm) due to warm air advection from Baffin Bay, whereas at Isachsen they are cold and wet (average Tmax=2.7°C; mean daily precipitation=1 mm). A similar situation occurs with synoptic type 8 where a low pressure center between Alert and Isachsen places them in airflow from opposite directions, resulting in warm and generally dry conditions at Alert and cold, wet conditions at Isachsen.

The frequency of "cold wet" types (1 and 4) has increased since ~1957 with consistently higher frequencies since 1963. These types occurred an average of 24 days per summer, 1946–1963 and ~28 days per summer, 1964–1974. Warm, dry types (11 and 16) have decreased in frequency from 9.5 to 7.4 days per summer in the same periods.

Precipitation "efficiency" of synoptic types

Throughout the previous discussion of precipitation resulting from different synoptic types, the actual frequency of each type greatly affected its contribution to annual precipitation totals. In fact, a type may be "dry" by virtue of its low frequency but still result in relatively large amounts of precipitation per day of occurrence. In order to investigate the "efficiency" of a type in bringing precipitation to a region, the absolute frequency must be taken into account. By doing this, those types which may not (under the present climate) occur with great frequency, but which are very "efficient" at bringing precipitation to high latitudes, can be identified. It is then possible to hypothesize what conditions may result from a decrease in the frequency of "less efficient" types and an increase in the frequency of "more efficient" types.

To standardize the data for type frequency a "raininess" index is used where

$$R_{ij} = \frac{P_{ij}N_j}{N_{ij}P_j} \times 100\ \%$$

P_{ij} =precipitation from type i in period j;
N_{ij} =frequency of type i in period j;
N_j =total number of days in period j;
P_j =total precipitation in period j.

A type which occurs 10 % of the time and results in 10 % of precipitation would thus score an R value of 100. As type frequency increases and the resulting precipitation decreases, R→0.

An analysis of Isachsen monthly precipitation data (for July–September, when 56 % of annual precipitation occurs) indicates that types 7, 8, 11, 12, 14, 16, and 17 are extremely "efficient" precipitating-bearing synoptic situations (monthly R values of up to 390) even though under the present climate their infrequent occurrence may cause them to be thought of as "dry" types (see discussion above). All these types are dominated by a low pressure center in the vicinity of Isachsen, centered to the west, northwest or north of the station. In such situations warm,[6] relatively moist air drawn into the depression center from the south will affect temperatures as Isachsen.

Although individual depression trajectories have not yet been examined, earlier work suggests that in most of these synoptic situations, depressions have moved into the Isachsen area from the Arctic Ocean and northern Beaufort Sea. Namias (1958) and Reed and Kunkel (1960) note that many depressions entering the Beaufort Sea in summer originate along the Arctic front which closely parallels the Siberian and Alaskan coastlines where thermal contrasts are strongest at this time of year (Jackson, 1961). Similar observations were made by Klein (1957) and Wilson (1967). In relatively warm periods when depression tracks in the North Atlantic are displaced northward, regeneration of cyclones along the Siberian coast is likely to increase the frequency of these depressions crossing the Arctic Ocean and Beaufort Sea, with a concurrent increase in precipitation in the Isachsen region. Conversely, in cold periods when depression tracks are further south the frequency of these storm systems entering the Arctic Ocean Basin will be reduced and resultant precipitation amounts will be lower (in effect this is mirrored by the seasonal variation of these synoptic situations which nearly all reach maximum frequencies in summer months). Collectively these 7 cyclonic types occur on 19 % of days per summer (June–September) but result in 40 % of precipitation at Isachsen during these months; this is 23 % of *annual* precipitation. An increase in the frequency of these types by only 2 or 3 days per summer month (at the expense of "less efficient" types) would increase annual precipitation by at least 10 %. It is thus conceivable that generally warmer "North Atlantic" conditions would lead to increased cyclonic activity in the Beaufort Sea area with a concomitant increase in moist air being drawn into the region. Associated temperatures would depend on the particular types which predominate (see footnote 6) but it is certainly possible that associated temperatures could be quite low in spite of the advection of southerly air.

Summary

An objective classification of synoptic types has been developed for the Canadian High Arctic for the period 1946–1974. Most types have distinct seasonal maxima. Monthly mean temperature characteristics of the different synoptic types were determined for Alert, Isachsen and Thule and the types were ranked, warmest to coldest. In general, types retained their relative ranking in all months of the year. Stepwise multiple regression analysis of monthly synoptic type frequency and mean maximum temperatures at Alert, Thule, and Isachsen indicated those synoptic types which are closely related to inter-annual variations of temperature. Although the main types varied from station to station, generally maximum variance explanation with a minimum number of independent variables was achieved in the months April–August. Stratification of precipitation data by synoptic type indicated those types accounting for most of the annual precipitation at Alert and Isachsen. Generally, a small number of types account for the bulk of annual precipitation though this is really a function of type frequency. Ablation season temperatures and precipitation data for Alert and Isachsen were used to identify those types associated with "cool, wet" or "warm, dry" conditions. Generally, "cool, wet" types have increased in frequency over the last ~15 years while "warm, dry" types have been less frequent. This is true at both Alert and Isachsen even though the synoptic types are not the same in each case. However, these changes in type frequency are insufficient to account for the recent deterioration in summer climate of the High Arctic. It is likely that "within-type" changes are at least partly responsible for this deterioration.

"Precipitation efficiency" was investigated for the wettest months of the year. Certain synoptic types which are relatively infrequent under present climatic conditions are actually very efficient "precipitation-bearing" situations. At Isachsen, seven relatively infrequent cyclonic types account for 23 % of annual precipitation. It is suggested that many of the depressions which dominate circulation over the Isachsen area in these situations originate from the regeneration of North Atlantic depressions as they pass along the Siberian coastline. It is thus likely that in warmer periods, northward displacement of Atlantic depressions would increase the fre-

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[6] Types 7, 16 and 17 are relatively warm at Isachsen in June–August; types 8, 11, 12 and 14 are relatively cold (Table 6). However, at present these "warm" cyclonic types occur twice as often as the cold cyclonic types. In September, all types are relatively warm at Isachsen but Tmax is by that time <0°C.

quency of storms entering the Arctic Ocean Basin and hence result in heavier precipitation in the High Arctic. However, the associated temperatures at Isachsen are not necessarily warmer, even though increased advection of southerly air is involved.

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