A Contribution to the Climatology of the Arctic Stratosphere

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(Manuscript received 7 June 1961, in revised form 17 August 1961)

ABSTRACT

A previous study by the author of January temperatures in the mid-stratosphere at several arctic stations near 80W has been extended to include stations in other sectors of the Arctic and the additional months of December and February. Distinctly bimodal temperature frequency distributions are evidently confined to the general area of the Canadian Archipelago and northern Greenland, and are characteristic of this region throughout the winter. Mean 25-mb charts and mean cross-sections are used to illustrate two quite dissimilar thermal and circulation regimes that tend to dominate the arctic stratosphere for long periods during the polar night.

1. Introduction

Early attempts to investigate the polar stratosphere were hampered by the extremely small number of soundings penetrating the levels above 200 mb. Scherhag's hemispheric mean January charts for the 225, 96 and 41-mb levels (Scherhag, 1948) constitute one of the earliest attempts to portray the wintertime circulation pattern in the arctic stratosphere. Various irregular series of daily or mean monthly charts for North America or the Northern Hemisphere and for isobaric surfaces ranging from 300 mb to 25 mb appeared several years later (Air Weather Service, 1953, 1954; U. S. Weather Bureau, 1955). Some mean 200-, 100- and 50-mb charts for the period 1949–53 have been published by Wege (1957) also. The number of observations available for the levels above 200 mb has increased substantially in recent years, and with the close of the IGY period the first installments of two important series have appeared: a three month period of daily hemispheric charts at the 50-, 25- and 10-mb levels (Behr *et al.*, 1960) and a year of three times monthly 10-mb charts over North America and Greenland (U. S. Weather Bureau, 1959).

The phenomenon of explosive warming first reported by Scherhag (1952, 1958) and since studied by many others (Teweles, 1958; Teweles and Finger, 1958; Hering and Salmela, 1958; Craig and Hering, 1959) helped to renew interest in the arctic stratosphere. Austin and Krawitz (1956) studied the large changes in the 50-mb temperature and flow fields in an attempt to relate them to tropospheric changes. A recent investigation by Wexler and Moreland (1958) resulted in a better description of the persistent cold (−70 to −80C) cyclones and warm (−40 to −55C) anticyclones that appear to be characteristic of the circulation at the 50-mb level. Godson and Lee (1958) confirmed the existence of these stagnant circulation systems and further illustrated their thermal structure by means of time cross-sections of temperature extending to levels between 30 and 15 mb. Palmer (1958) concluded that explosive warmings in the lower stratosphere follow a breakdown of the stratospheric polar vortex at high levels near the pole, and he presents evidence suggesting a connection between this breakdown and solar activity, this latter hypothesis being given further support recently by Scherhag (1960). Hare (1960) has produced the most extensive study of the arctic stratosphere to date. He emphasizes two aspects of the winter circulation: (1) the Alaskan warm ridge; and (2) the eastern Canada cold trough; both of these features were found to be strongest above the 50-mb level. McClain (1960) has presented up-to-date means, standard deviations and frequency distributions of January temperature for the 200-, 100- and 50-mb levels at four arctic stations near 80W. The frequency distributions are markedly bimodal, a characteristic that is more pronounced at the higher levels and latitudes.

Both case studies and climatological studies suggest that two quite distinct regimes dominate the thermal field of the wintertime arctic stratosphere. The present investigation extends McClain's climatological study to cover the months of December and February and additional stations in other areas of the Arctic. In addition the thermal and circulation patterns of a warm-regime and of a cold-regime month are contrasted with the aid of hemispheric mean 25-mb charts and mean cross sections along the 80th meridian west.

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[1] The research reported in this document has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF 19(604)-7230.

2. Observations

A preliminary survey of available arctic temperature data for the 200-mb level and higher and for the period 1950–1959 is summarized in Table 1. From this table it is seen that although the observational samples from the North American stations and Tromso are large, that from Nord is small, and those from the Soviet Union are very small. There are several additional sounding stations in the Russian sector of the Arctic, but their observational records are even poorer than those shown in Table 1. Because of the paucity of data in some parts of the Arctic, the statistical analyses were not extended above the 100-mb level; furthermore, in the cases of Nord, Mys Cheliuskin and Mys Schmidt the observations for all three winter months were combined in order to construct reasonably representative frequency distributions, means and standard deviations. For the North American stations and for Tromso, ample data were available to compute the various statistics for the months of December, January and February separately.

TABLE 1. Summary of the number of available temperature observations at arctic stations, 1950–59.

Station	Dec		Jan		Feb		Winter	
Level (mb)	200	100	200	100	200	100	200	100
Barrow	269	216	265	226	193	169	727	611
Resolute	213	182	275	202	181	179	669	563
Alert	233	199	253	191	181	154	667	544
Tromso	203	167	214	177	191	125	608	469
Nord	118	96	116	77	103	90	337	263
Mys Cheliuskin	70	35	56	27	69	29	195	91
Mys Schmidt	53	34	54	29	52	34	159	97

The problem of selective termination of ascents, i.e., greater frequency of premature balloon failures when temperatures are low and/or winds are high, has been discussed in the author's previously cited paper and elsewhere (Hare, 1960). To increase the sample sizes at the Russian stations, the regression technique used by McClain (1960) was employed. The correlations between the 200-mb and 100-mb temperatures were not as high as had been found for the January temperatures in this earlier study (e.g., ≥ 0.90 for Alert, Resolute, Eureka and Coral Harbor); but, because of the meagerness of the observational data, it was decided to make use of the regression equations to obtain temperature estimates at the 100-mb level. Table 2 gives the linear correlation coefficients and the regression equations, as well as the probable errors (PE), the residual errors (RE), and the number of observational pairs (N). The regression estimates were used to compute adjusted 100-mb means and frequencies for the wintertime temperatures at Nord, Cheliuskin and Schmidt; these are shown in Fig. 1. In the case of the statistics computed for the individual months, it was necessary to make such an adjustment only for the February 100-mb temperatures at Tromso.

TABLE 2. Regression statistics for several arctic stations (Dec, Jan, Feb, 1950–59)

Station	*r*	*PE*	Regression equations (°C)	*RE* (°C)	*N*
Mys Cheliuskin	0.68	0.04	$T_{100}=-29.4+0.57T_{200}$	6.0	82
Mys Schmidt	0.85	0.02	$T_{100}=-\ 4.8+0.86T_{200}$	3.0	91
Nord	0.72	0.02	$T_{100}=+\ 1.1+1.07T_{200}$	6.3	261
Tromoso*	0.72	0.03	$T_{100}=-\ 7.7+0.89T_{200}$	5.0	112

* (Feb. only)

3. Frequency distributions

In Fig. 1 are frequency distributions of wintertime (December, January and February combined) 200-mb and 100-mb temperatures for a number of widely separated stations in the Arctic. Means and standard deviations of temperature are found in this figure also. It is seen from this figure that the double mode structure in the 100-mb temperature frequencies found by McClain (1960) for a number of stations near 80W (e.g., Alert, Resolute, Eureka and Coral Harbor) is apparently confined to the Canadian Arctic Archipelago and northern Greenland, for although it appears in the frequencies for Resolute and Nord, it is not in evidence at Tromso, Cheliuskin, Schmidt or Barrow. It may also be noted from Fig. 1 that the single 100-mb modes at Tromso and Mys Cheliuskin (about −68C) correspond closely to the *low*-temperature modes at Resolute and Nord (at about −65C and −71C, resp.), while the single modes at Mys Schmidt and Barrow (at about −53C) correspond to the *high*-temperature modes at Resolute and Nord (at about −50C and −55C, resp.). Furthermore, the 100-mb temperature distributions for Tromso and Mys Cheliuskin are skewed toward higher temperatures, while that for Barrow is skewed toward lower temperatures. Except for Barrow and Resolute, the temperature frequencies at the 200-mb level exhibit little or no skewness. Table 3 contains values of the coefficients of skewness (γ_1) and kurtosis (γ_2), together with their respective standard errors (Brooks and Carruthers, 1953), for the distributions shown in Fig. 1. The values in Table 3 in parentheses have magnitudes at least twice that of their respective standard errors and therefore represent skewness or kurtosis that is probably real. The widely-separated dominant modes for Resolute result in the frequency distribution being platykurtic (negative kurtosis) in the extreme, especially at the 100-mb level. Although the 100-mb temperature frequencies for Tromso show no evidence of a secondary mode, they also exhibit rather large negative kurtosis. The frequencies for Nord, however, indicate no significant kurtosis, apparently because the low-temperature mode is so much more prominent than the high-temperature one.

Consistent with the foregoing are the standard deviations found in Fig. 1, which make manifest the large

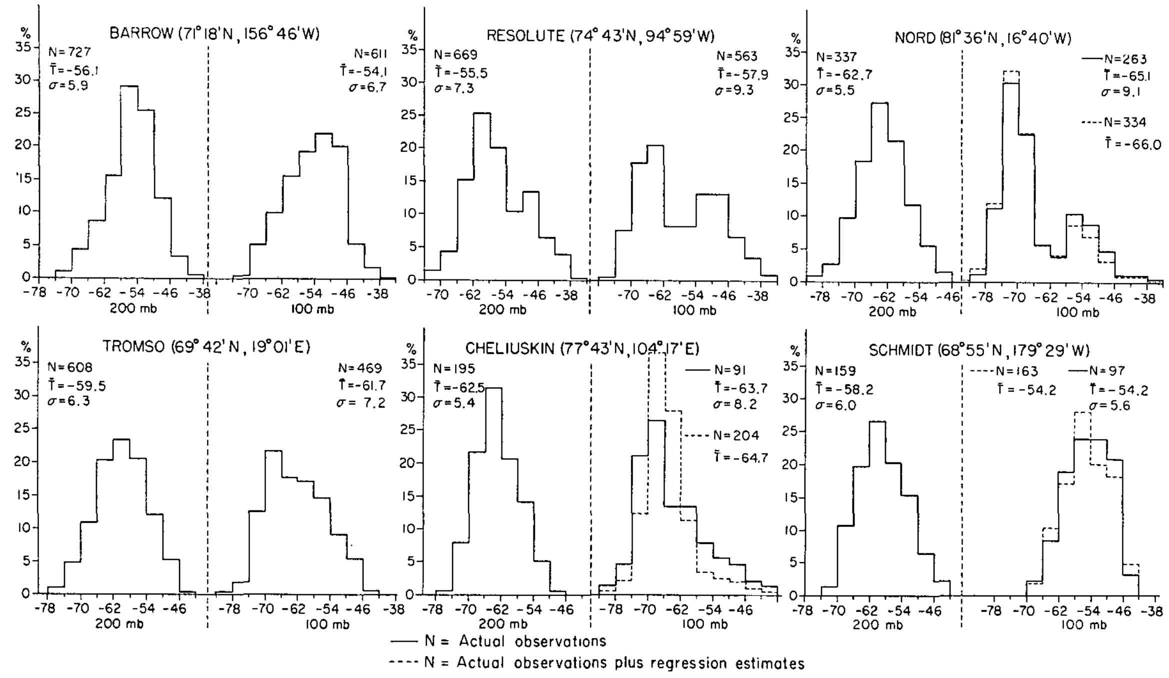


FIG. 1. Frequency distributions of winter season 200-mb and 100-mb temperatures at six arctic stations.

TABLE 3. Skewness (γ_1) and kurtosis (γ_2) of wintertime stratospheric temperature frequencies at arctic stations (Dec, Jan, Feb, 1950–59).

	200 mb					100 mb				
	γ_1	SE	γ_2	SE	N	γ_1	SE	γ_2	SE	N
Barrow	(−0.36)	0.09	0.15	0.18	727	(−0.22)	0.10	(−0.52)	0.20	611
Resolute	(0.40)	0.10	(−0.46)	0.19	669	(0.32)	0.10	(−1.02)	0.21	563
Nord	0.02	0.13	−0.14	0.27	337	(1.01)	0.13	0.25	0.27	339
Tromso	−0.09	0.10	(−0.54)	0.20	608	(0.29)	0.11	(−0.74)	0.23	469
Cheliuskin	0.29	0.18	−0.38	0.35	195	(1.00)	0.17	(1.40)	0.34	203
Schmidt	0.20	0.19	−0.54	0.39	159	−0.18	0.19	−0.72	0.38	165

TABLE 4. Auto-correlation in wintertime 100-mb temperatures at Resolute (1956–57, 1957–58, 1958–59).

Lag (days)	r_a
1	0.98
5	0.78
10	0.53
15	0.31
20	0.15
25	−0.03

dispersions typical of arctic stratosphere temperatures in general. Note particularly those at stations such as Resolute and Nord ($\sigma \geq 9$C), whose distributions are bimodal, compared with those characteristic of middle and low-latitude stations ($\sigma \leq 5$C) (see Goldie *et al.*, 1957), whose distributions tend to be unimodal and rather peaked (see the temperature frequencies published by Tolefson, 1957).

Because of the high auto-correlations in the 100-mb temperature series at such stations as Resolute (Table 4), it is desirable to suppress the persistence in the data before testing the reality of the bimodality in the frequencies. Following the procedure outlined by Brooks and Carruthers (1953), the persistence factor, s, was computed for the Resolute wintertime temperature series and was found to equal 10.5 days. Since the persistence factor is roughly the average length of time over which a single observation may be regarded as representative, each month of the 10-year Resolute series was divided into thirds and a new sample of 95 ten-day means was constructed. The upper portion of Fig. 2 gives the resulting frequencies and also those of a normal distribution having the same mean and standard deviation. The corresponding chi-square value is 16.63 (5 degrees of freedom), which is significant at the 1 per cent level and makes it highly unlikely that the sample was drawn by chance from a normal distribution. As a further experiment the bimodal distribution for Resolute appearing in Fig. 1 was split at $T = -58$C and fitted with the sum of two normal distributions. The excellence of the fit is seen in the lower portion of Fig. 2 and by the associated chi-square value of 9.32 (6 degrees of freedom), which is less than the value corresponding to a probability of 0.10, thus making it unlikely that the observed distribution differs significantly from the hypothesized compound normal distribution.

Based on the climatological evidence presented here, relatively low-temperature conditions appear to predominate in the wintertime arctic stratosphere in the Scandinavian and western Russian sector, while relatively high-temperature conditions predominate in the eastern Russian and Alaskan sector. The remaining sector, covering eastern Canada and northern Greenland, is evidently shared by both types of regime, although the colder one is the more frequent of the two. Fortunately, there is at least one station from each of the three sectors for which there are reasonably ample observations during each of the three winter months. Fig. 3 gives the means and frequencies of 200-mb and 100-mb temperatures for Tromso (cold-sector), Barrow (warm-sector) and Resolute (mixed-regime sector). As was the case with the winter period as a whole, any tendency toward a bimodal structure or skewness in the distributions is much more pronounced at the 100-mb than it is at the 200-mb level. The frequencies for Resolute are distributed in a bimodal fashion in each of the three winter months, although the relative importance of the two modes changes over the course of the season. Although generally unimodal, the distributions at Barrow and Tromso tend toward a second mode in January, and this is reflected in correspondingly high negative values of kurtosis. This secondary mode is a high-temperature one at Tromso (at about -48C), but it falls within the transitional range at Barrow (at about -60C). There appears to be no systematic shift in the modes from month to month at any of the three stations, but the mean temperatures exhibit a general increase from December through February. It thus appears that the principal characteristics of the temperature distributions that were found for the winter as a whole (Fig. 1 and Table 3) are representative also of the months individually, although higher temperatures tend to become somewhat more frequent during the latter part of the winter, particularly in the mixed-regime sector.

The 100-mb frequency distributions for Resolute and the other mixed-regime stations suggest that both cold and warm periods tend to be very persistent once established, while the transition periods are relatively short. To better illustrate this aspect of the thermal patterns, three-day running means of 100-mb temperature at Resolute were determined for the winter months for seven consecutive years; these are presented graphically in Fig. 4. The boundary temperatures of the transitional range correspond to those bounding the antimodal class range of the frequency distributions for Resolute for the winter months (see either Fig. 1 or Fig. 3). Note that most of the cold or warm periods run three to six weeks or longer, while the transition periods are of the order of one week in duration. Note also that the transition from warm to cold, or vice versa, is not confined to any particular part of the season. The great stability of these thermal regimes is further demonstrated by Fig. 5, which contains frequency distributions of the interdiurnal temperature change at the 200-mb and 100-mb levels. In spite of the 15C separation of the 100-mb modal temperatures at Resolute, three-fourths of all the interdiurnal changes are two degrees or less (see

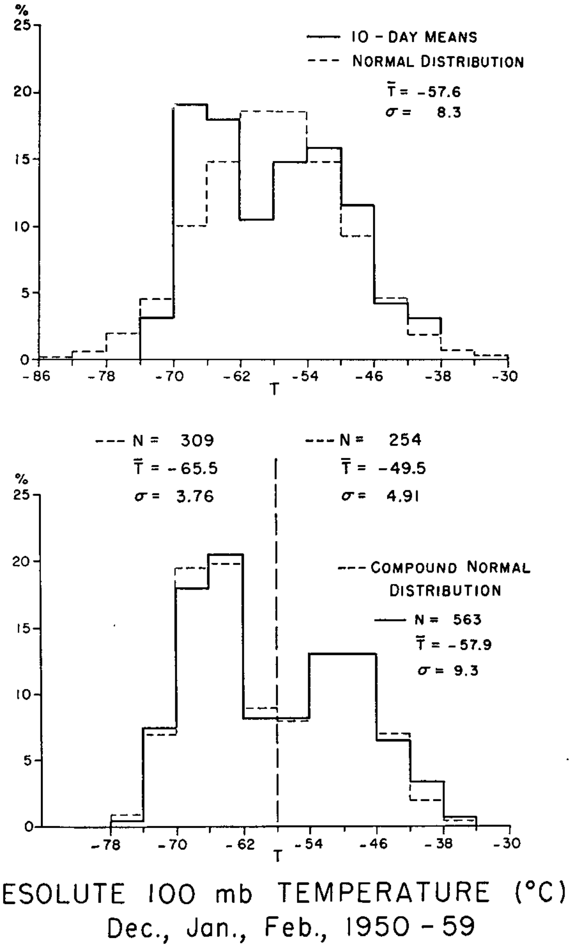


FIG. 2. Comparison of Resolute 100-mb temperature frequencies with normal and compound normal distributions.

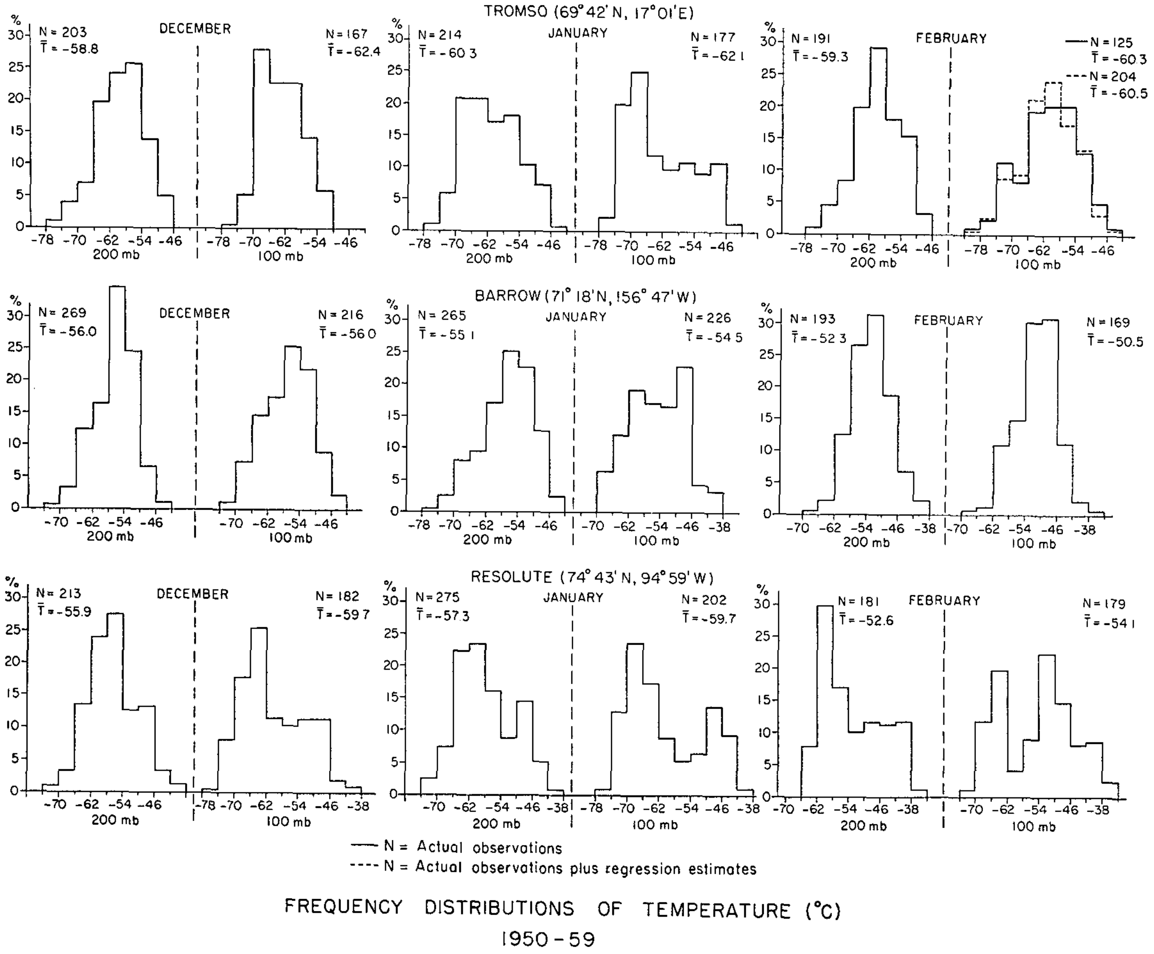


Fig. 3. Frequency distributions of Dec., Jan. and Feb. 200-mb and 100-mb temperatures at three arctic stations.

Table 5). In fact, it may be seen from both Fig. 5 and Table 5 that the percentage of very small interdiurnal changes is apparently greatest at the mixed-regime stations and is greater at 100 mb than at 200 mb.

Table 5. Percentage of interdiurnal temperature changes $\leqslant 2$C, regardless of sign (Dec, Jan, Feb, 1950–59).

Station	200 mb	100 mb
Tromso	44.5	60.9
Barrow	55.2	68.7
Resolute	67.8	74.8

4. Circulation patterns associated with cold and warm periods in the stratosphere over eastern North America

One can take advantage of the great persistence of the warm and cold periods by constructing cross sections and isobaric charts that are means over periods as long as a month. This procedure helps offset the lesser density and accuracy of observations at these very high levels. It is seen from Fig. 4 that there were many periods in the winters of 1952–1959 when temperature conditions at Resolute were such that warm and cold months could be contrasted in the same winter or for the same calendar month in different years. Availability of daily observations, as well as published mean data or charts for particular months, determines the ease and accuracy with which such comparisons can be made. To insure the maximum number of observations for the levels at and above 100-mb, winter seasons that are as recent as possible should be used. In constructing Fig. 6, the mean data and charts in the National Summaries and the World Climatic Data published by the U. S. Weather Bureau have been used whenever possible, although it was necessary to supplement these, especially for the levels at and above 200 mb in the Canadian Arctic. The mean charts in Figs. 7 and 8 were derived from the daily 25-mb charts published by Behr *et al.* (1960).

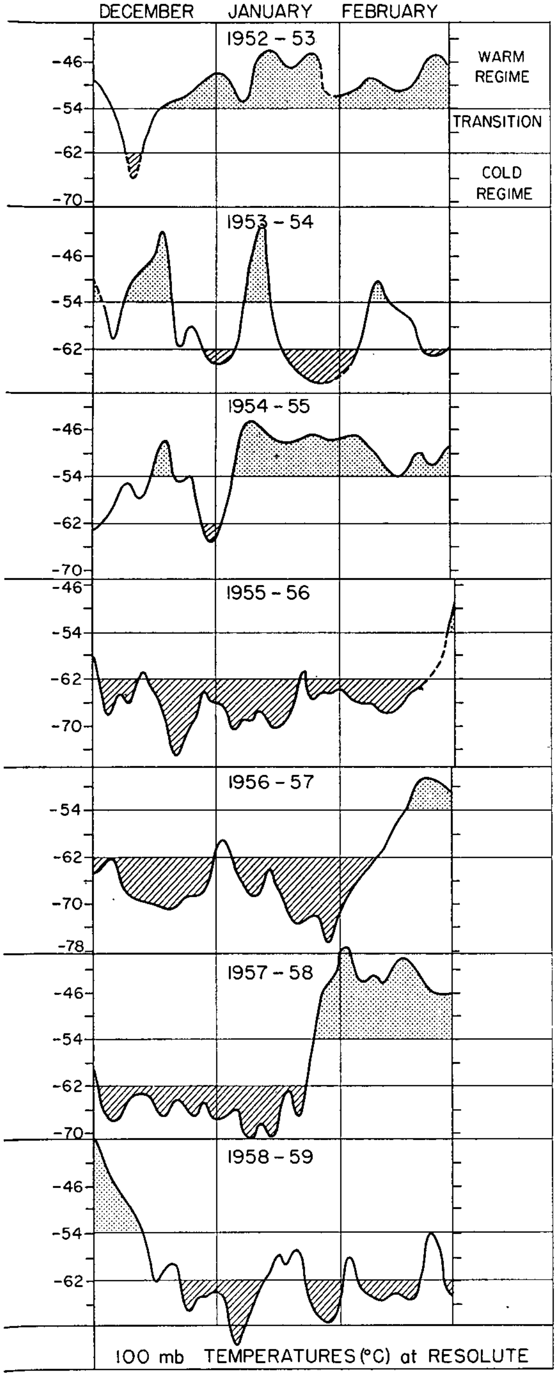


FIG. 4. Time-temperature graphs of winter season 100-mb temperatures at Resolute.

It is seen from Fig. 4 that February 1958 was a warm month throughout at Resolute, whereas February 1959 was predominantly a cold month. Because of the many previous studies employing vertical cross sections along 80W, and because of the proximity of Resolute and other mixed-regime stations (e.g., Alert, Nord, Eureka and Coral Harbor) to this meridian, the cross sections presented in Fig. 6 were constructed at this particular longitude. Comparison of these cross sections reveals that there were only minor differences in mean temperature everywhere in the troposphere and stratosphere except poleward of about 50N; here, in the polar stratosphere, the February 1958 mean temperatures were as much as 26C higher than the ones in February 1959. In February 1958 temperatures increased poleward from the tropics deep into the Arctic everywhere above about the 300-mb level; whereas in February 1959 the meridional gradient reversed sign near 55N, temperatures decreasing poleward from there. Mean cross sections along 80W constructed for the warm month of January 1955 and the cold month of January 1959 (not reproduced) exhibit features nearly identical to those of February and January 1958, respectively. It is evident from these cross sections that the arctic stratosphere was, in this meridional plane, highly baroclinic in the mean during February 1959, but was nearly barotropic in the previous February. Reasoning on the basis of the thermal wind equation, one could infer the existence of a so-called *polar-night* jet stream from the mean isotherms for February 1959, but not from the isotherms for February 1958.

It is interesting to note that in the arctic stratosphere the cross section for the cold winter month, February 1959, bears a striking resemblance to Kochanski's (1955) cross section of *mean* temperature along 80W in January. In contrast, the cross section for the warm winter month, February 1958, closely resembles Kochanski's mean April or July cross section in the arctic stratosphere portion. The winter season 100-mb temperature distribution at Resolute (Fig. 1) can be used to obtain the relative frequency of warm ($T>-54$C) and cold ($T<-61$C) regimes there: warm days prevailed about 37 per cent of the time, cold days about 47 per cent, and transitional days occupied the remainder (16 per cent) of the time. One is led to the conclusion, therefore, that Kochanski's January cross section is not representative of *mean* wintertime conditions in the arctic stratosphere.

In Figs. 7 and 8 are presented mean 25-mb charts for the months of January and February 1958. In January the arctic stratosphere was largely dominated by a vast cold-core cyclone centered near northeast Greenland and by a lesser warm-core anticyclone centered just south of the Aleutian Islands. The mean charts for February present a totally different picture from that of January, for not only have the circulation centers shifted their location, but also both of them are much weaker. The cyclone center is now situated in Finland, while the anticyclone center is now in northwest Canada. The low center has filled by 1000 gpm, and whereas the lowest and highest temperatures associated with the 25-mb cyclone and anticyclone, resp., were −74C and −41C in January, in February they were

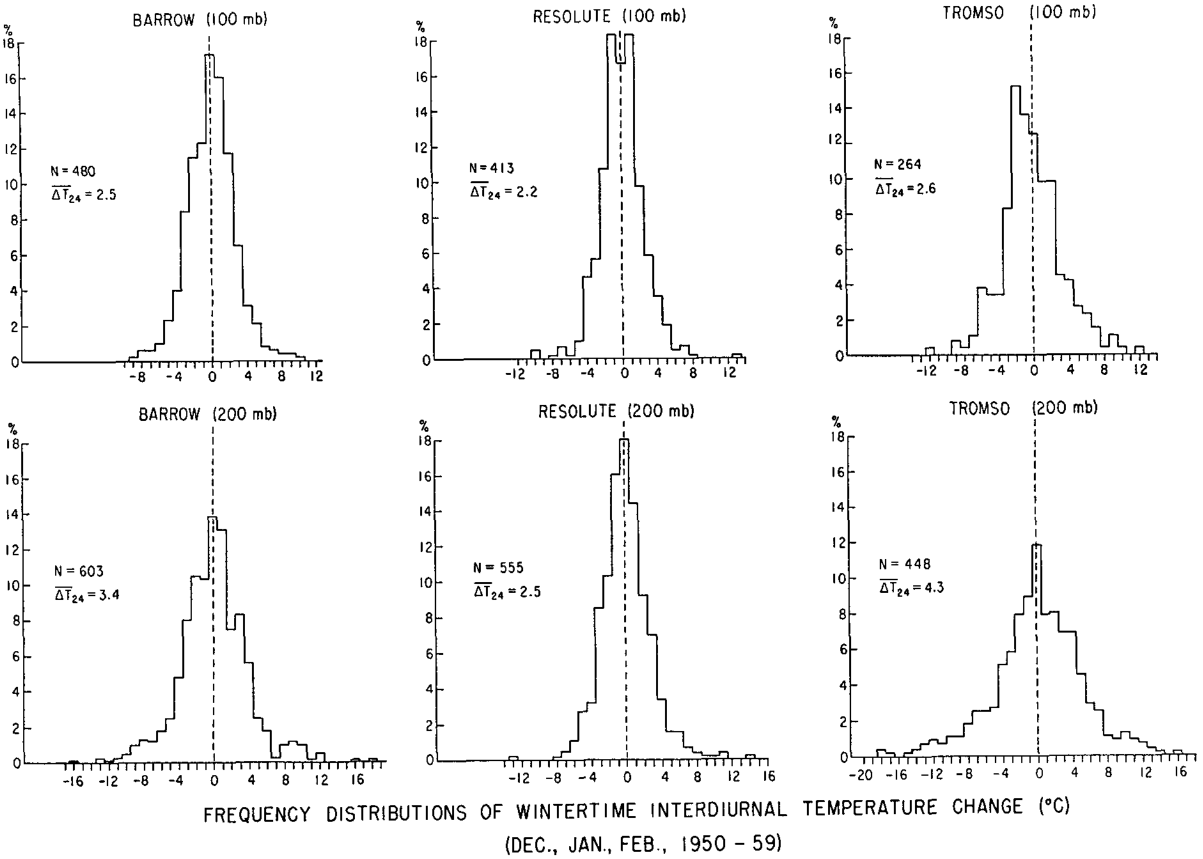


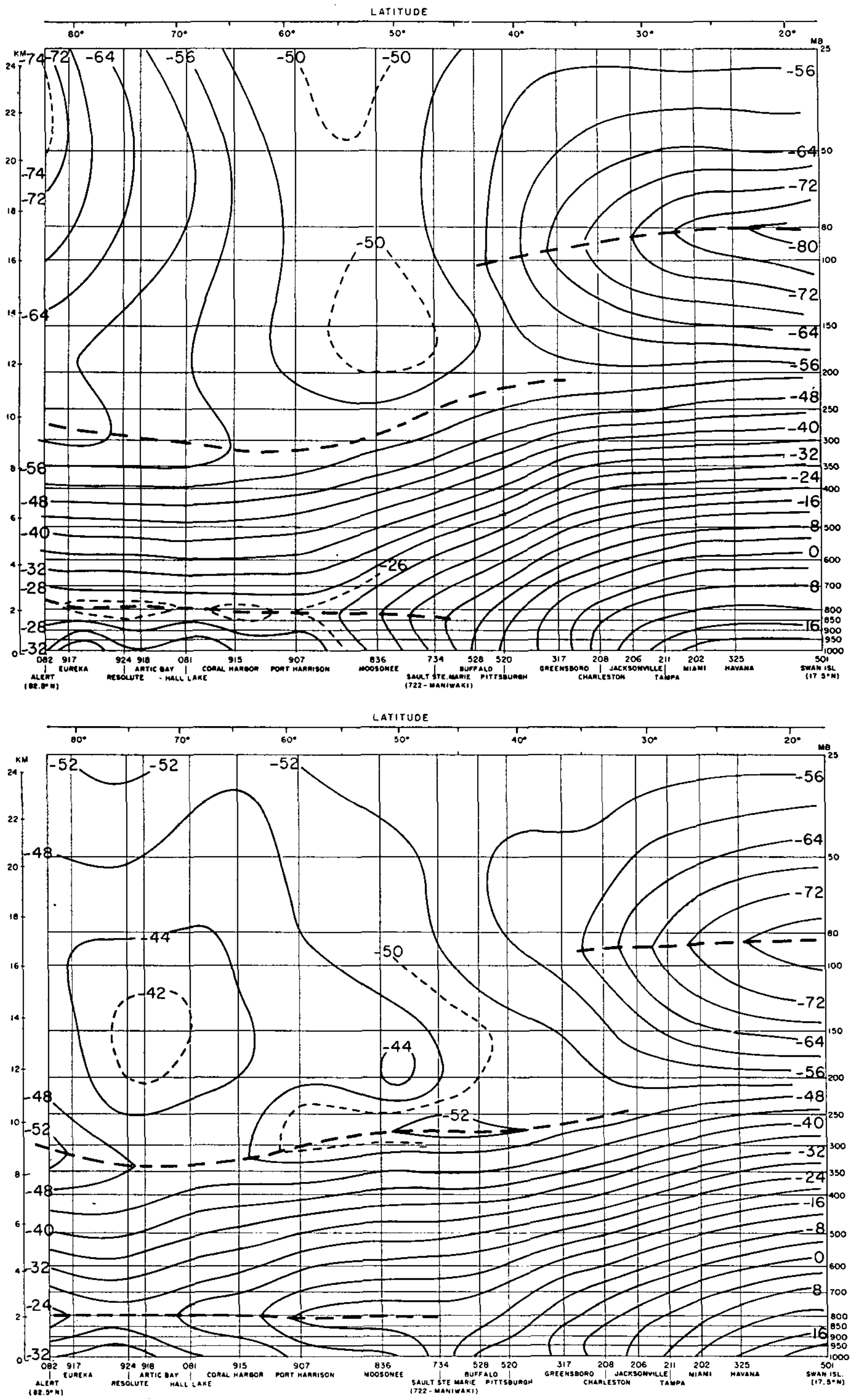
Fig. 5. Frequency distributions of wintertime 200-mb and 100-mb interdiurnal temperature changes at three arctic stations.

−58C and −51C, respectively. The overall height difference between the high and low centers at 25 mb diminished from 2100 gpm in January to 900 gpm in February. The magnitude and extent of the warming which took place between January and February 1958 at the 25-mb level is further illustrated in Table 8. An average temperature increase of 11.7C took place over the entire polar cap north of the 65th parallel, while even the belt from 35N to 65N experienced an average increase of 3.1C. In short, the entire stratosphere from 200 mb to 25 mb (and probably higher) and poleward of about the 40th parallel was highly baroclinic in the mean during January 1958, particularly over North America, where a well-developed polar-night jet was present. February, on the other hand, was characterized by a considerably less baroclinic state, particularly over North America, where mostly light easterly winds prevailed.

Table 8. Area-averaged mean temperatures (°C) for January and February at the 25-mb level.

Month	Area	$\bar{T}$
Jan. 1958	65–90N lat., 0–360 long.	−62.7
Feb. 1958	65–90N lat., 0–360 long.	−51.0
Jan. 1958	35–65N lat., 0–360 long.	−54.8
Feb. 1958	35–65N lat., 0–360 long.	−51.7

Mean January and February 1958 charts over North America for most of the standard isobaric levels from sea level to 100 mb appear in the National Summaries published by the U. S. Weather Bureau. It may be seen from an examination of these mean charts that the differences in circulation pattern and baroclinity that are illustrated in Figs. 7 and 8 for the 25-mb level are found at the 100-mb and 200-mb levels also, although the contrast between the two months becomes increasingly smaller downward, and significant differences are no longer apparent from simple inspection at the 300-, 500-, or 700-mb levels. The foregoing is consistent with certain features of the time cross sections of temperature presented by Godson and Lee (1958); namely, the "temperature waves" of long periods (20–30 days) that they illustrated were confined essentially to the 100-mb level and above. The layer below 200 mb was characterized by temperature oscillations of considerably smaller amplitude and period. An aerological study of the January-February 1958 situation by Zubyan (1959) led him also to conclude that the mid-stratospheric temperature



VERTICAL CROSS SECTION THROUGH ATMOSPHERE ALONG 80° WEST LONGITUDE

FIG. 6. Upper: vertical cross-section of mean temperature along 80W in February 1959; Lower: vertical cross-section of mean temperature along 80W in February 1958.

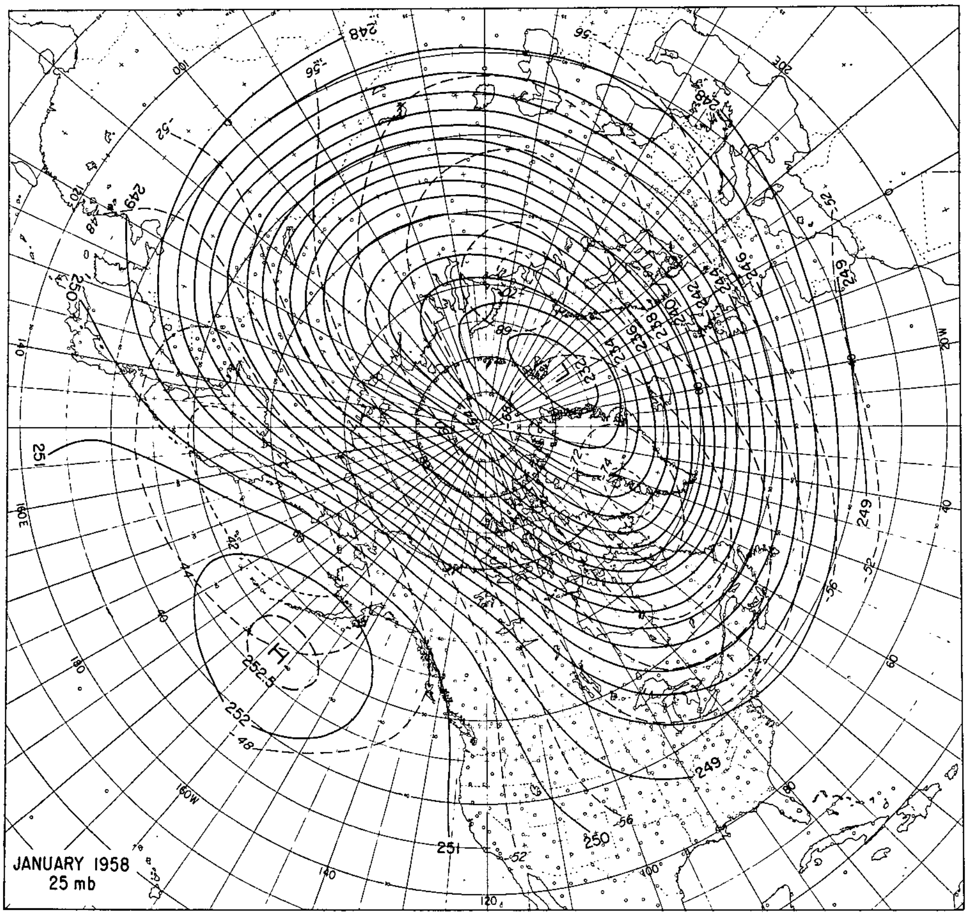


FIG. 7. Mean 25-mb chart for January 1958.

field and its variations bore no relation to those of the lower stratosphere and upper troposphere. Hare (1960) stresses that all evidence indicates that the baroclinic waves centered above the 50-mb level are normally independent of those found below the 200-mb level.

5. Concluding remarks

This article has attempted to illustrate and further document statistically some interesting aspects of the circulation and thermal characteristics of the arctic stratosphere in winter that have come to light in recent years. Although the frequency distributions and other statistics that are presented for the stations of Cheliuskin, Schmidt and Nord are quite tentative because of the small number of available observations, it seems reasonable to expect that the inclusion of additional data from future soundings will result chiefly in an increased frequency of low temperatures relative to high ones. This effect, which is indicated in Fig. 1 by the changes in the 100-mb frequency distributions that resulted from inclusion of the regression estimates, should come about as soon as improved balloon capability diminishes the temperature dependence of the bursting altitude, an improvement that took place about 1957 at the stations operated by the United States and Canada. With the foregoing in mind, it is probably safe to conclude from Fig. 1 that the remarkable bimodality that appears in the wintertime 100-mb temperature frequencies at arctic stations in eastern North America and Greenland is not characteristic of any other portion of the north polar region, although both Tromso and Barrow do have rather highly-skewed and platykurtic distributions.

The two distinct and widely-separated modes that appear in frequency distributions of temperature at the 100-mb level, which is well above the tropopause level at all times, at such stations as Resolute must very certainly represent the alternation during the winter of two quite dissimilar circulation and thermal regimes in the arctic stratosphere. Time-temperature graphs and analyses of interdiurnal temperature change and of autocorrelation have been used to bring out the extraordinary persistency of these regimes, as well as the irregularity in the dates of onset of these synoptic situations, some of which correspond to the so-called "explosive warmings."

Although only a few series of historical charts have been constructed for these levels in the arctic, and most of these are for very recent winters, these together with the climatological data presented or referred to here do enable one to draw a few inferences about the conditions that likely existed in the recent past. The mean cross sections and 25-mb charts presented here illustrate the general types of circulation and thermal patterns that could account for the observed frequency distributions of temperature, provided they were sufficiently persistent in nature. The main features of one of these distinct regimes are a large, intense, cold (minimum temperatures about −75C) cyclone centered somewhere near Greenland, and a smaller, less intense, warm (maximum temperatures about −40C) anticyclone somewhere just south of the Aleutians. The mid-stratosphere during these periods is highly baroclinic, particularly in the American Arctic, and a strong polar-night jetstream is present. The mean isotherms have considerably greater amplitude than the contours, which suggests persistent ascent of air moving southeastward into the trough over eastern Canada, as well as descent of air moving out of the trough. This is substantiated by examination of the daily 25-mb charts; e.g., strong and persistent warm advection is indicated over north central Canada during most of this period, but the local temperature changes are small and non-systematic.

The main features of the other circulation and thermal regime are a moderately warm (about −50C) and relatively weak anticyclone in the Canadian Arctic, and a cool (about −60C) and relatively weak cyclone near northern Scandanavia. The mid-stratosphere is typified by very low baroclinity and weak *easterly* winds prevail over North America. In the example presented here the rapid breakdown of the high-baroclinity regime and transition to the low-baroclinity one was accompanied by a very substantial warming of the entire arctic at high levels, indicating that something more was involved than the simple advective hypothesis advanced by Zubyan (1959). The manner in which the breakdown proceeds is apparently quite variable, for the sequence of events in the case studied by Craig and Hering (1958)

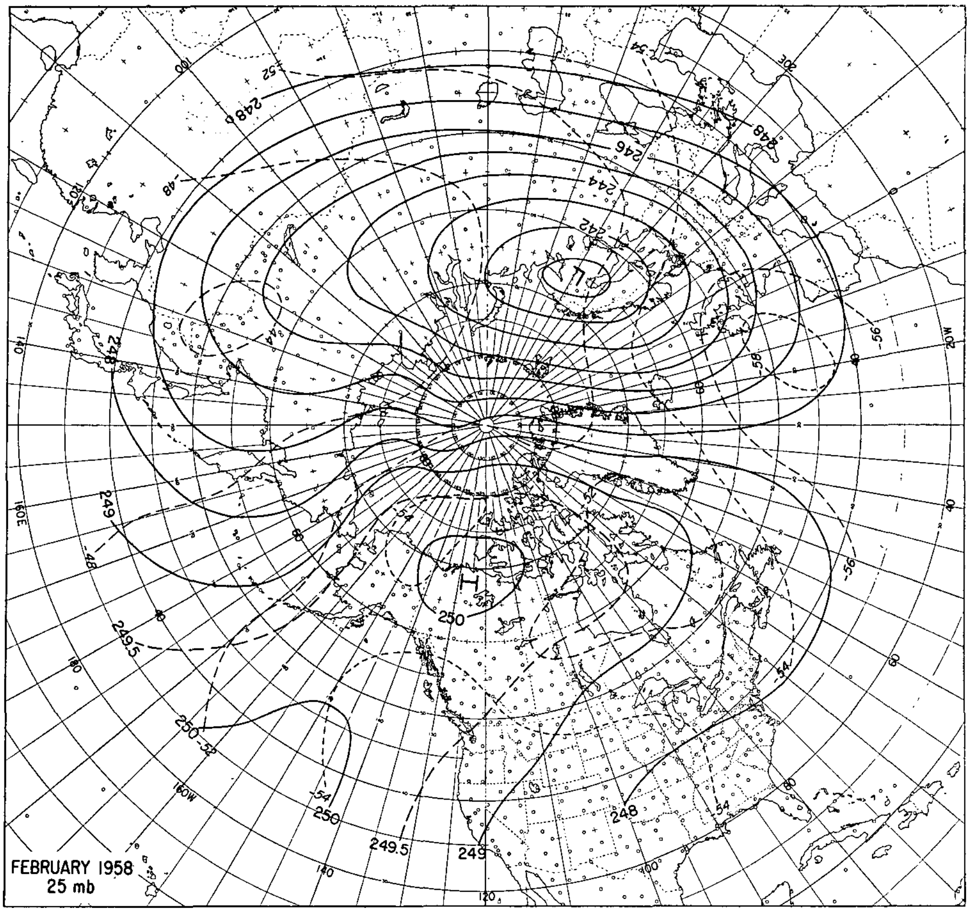


Fig. 8. Mean 25-mb chart for February 1958.

and also by Teweles and Finger (1958) was rather different from that in the case studied here and in the one investigated by Hare (1960). However, the widespread warming and the overall decrease in baroclinity was in evidence in all the cases. It could be mentioned in this connection that Godson and Lee (1958) concluded from their investigations of rapid warmings in the Canadian Arctic that their causes can vary from level to level, stage to stage, and year to year. Warm advection appeared to predominate at times, subsidence at others, and a combination of these processes at yet others.

Only increasingly accurate and more complete observations of the conventional meteorological type, together with special rocket and satellite data, can eventually lead us to a satisfactory description and explanation of the existence and evolution of these interesting thermal and circulation regimes in the arctic stratosphere.

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