THE ARCTIC STRATOSPHERIC JET STREAM DURING THE WINTER OF 1955–1956

By Roy Lee and Warren L. Godson

Meteorological Service of Canada

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ABSTRACT

The existence of an Arctic stratospheric jet stream in winter, hitherto largely inferred from mean geostrophic wind sections, is considered on the basis of actual winds for the Canadian Arctic area during the winter of 1955–1956. Temperatures at the 100-millibar level at a number of stations over the Canadian Arctic were examined to throw light on the intensely baroclinic zone below the jet stream.

Meridional movements and intensity changes of the jet stream during this winter, as inferred from a statistical study of the 100-mb temperature field, are in accord with the conventional view that the jet stream is maintained by differential radiational heating and cooling of the ozone layer across the boundary of polar night.

1. Introduction

In recent years, considerable study has been devoted to jet streams — those narrow-core high-speed currents of air that are usually found in the layer from 30,000 to 40,000 ft above sea level. With the accumulation of data farther into the stratosphere by improved balloon techniques, there has arisen an increasing amount of evidence which points to the presence of a jet stream above 20 km in the vicinity of 75°N during the winter months. The earliest evidence from which one can infer an increase in zonal wind with height around this level in the Arctic stratosphere appeared in the form of mean meridional cross-sections of the temperature field. For example, over two decades ago, Palmén (1934) showed the existence of a warm pool in the stratosphere at around 50°N in winter, to the north of which lay a zone of maximum meridional temperature gradient extending to 70°N. This strongly baroclinic zone appeared to extend in the vertical to at least 24 km above mean sea level. A later study by Palmén (1948), of a similar temperature field along 80°W, included geostrophic wind computations based on the temperature distribution which demonstrated increasing westerly winds in the stratosphere around 60°N. Other studies have shown similar increases in geostrophic zonal wind in the stratosphere at high latitudes, notably those of Hess (1948), U. S. Air Weather Service (1953), Mintz (1954), Kochanski (1955), Heastie (1955), and McIntyre (1955). Studies by Loewe and Radok (1950) and Hutchings (1950) indicated a corresponding phenomenon in the southern hemisphere. In this article, specific reference will be made to Kochanski’s mean cross-section for 80°W, although these remarks apply equally well to the papers of the other authors.

Kochanski’s mean cross-section shows a distinct jet stream above the 20-km level between 70 and 80°N, which is replaced in July by a core of easterly winds. The corresponding April and October mean cross-sections also indicate light winds with easterly components at these levels and latitudes, although very light mean westerlies persist near the pole during these months. According to Kochanski, this polar night maximum is only a tentative one, derived from hydrostatic considerations rather than from actual wind observations. He further states that, while the analyses of mean soundings and maps point to the existence of this maximum, wind reports above 16 km in the vicinity of this feature are almost entirely lacking. We are thus confronted with the question of whether the stratospheric jet stream at high latitudes can be shown to exist as a synoptic entity, by individual cross-sections.

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FIG. 1. Upper-air stations in Canadian Arctic.
It is clear from Kochanski's mean cross-sections that the westerly jet is a feature of the stratospheric circulation only during the winter period. The associated thermal structure requires a rapid decrease of temperature northward at high levels across the boundary of polar darkness. Consideration of the latitude and height of the mean jet stream has led many earlier authors to the hypothesis that the logical mechanism for this thermal field and associated jet stream lies in the ozone layer, which absorbs solar ultraviolet radiation and re-radiates in several infrared bands. There are two natural consequences which follow from the hypothesis and which can be tested by reference to actual temperature observations at a sufficiently high level. Since the boundary of polar darkness develops initially near the pole, advances southward until the winter solstice, and is followed by a northward retreat in the late winter, its passage across any station should be detectable by changes in the temperature field at a level within the strongly baroclinic zone below the jet stream. Moreover, the initial development of the baroclinic zone should be accompanied by a differential rate of temperature fall across the boundary of polar darkness.

2. Data and methods of study

The basic data used in this study were the observed winds and temperatures at altitudes greater than 40,000 ft at all stations in the Arctic and sub-Arctic, between 60 and 140°W, during the period from 16 October 1955 to 30 April 1956. Fig. 1 shows the locations of upper-air stations in the Canadian Arctic. The following stations will be referred to explicitly in this article: Alert (082), Eureka (917), Isachsen (074), Mould Bay (072), Sachs Harbour (051), Norman Wells (043), Aklavik (968), Whitehorse (964), Resolute (924), Coral Harbour (915) and Thule (202). The international station numbers are listed in parentheses.

For the 1955–1956 winter, the 100-mb level (near 16 km) was the highest, offering a nearly continuous set of temperature data for the entire Canadian Arctic area. It was found that the lapse rates between 150 and 100 mb changed very little over relatively long periods of time. Furthermore, the standard deviations of the 100-mb temperatures over 20-day periods were low, of the order of 1 to 2°C, except at certain critical periods which will be elaborated upon later. Thus, extrapolation in the vertical and interpolation in space and time provided a legitimate basis for completing

![Figure 2: 10-day running-mean 100-mb temperatures.](image-url)
the series of 100-mb temperatures for nine of the eleven possible Arctic and sub-Arctic rawinsonde stations. The number of estimated temperatures at the 100-mb level in each time series varied from station to station. For example, at Resolute, 100-mb temperature observations at both 0300 and 1500 GCT were missing on 37 days out of the 197-day period, whereas 150-mb observations were missing at both times on only seven days. Again, at Norman Wells, there were five days in this period during which no data were available at 100 mb, while on only two days were there no data at the 150-mb level. To filter out short-period fluctuations and to minimize the effects of estimated values, 10-day running means were formed. Fig. 2 shows the 10-day running-mean temperatures at 100 mb for a selected number of stations from mid-October until early April. The stations range from 65°N (Norman Wells) to 83°N (Alert). An interpretation of these curves follows in section 3.

The meridional movement of the mean position of the jet stream can be demonstrated by a statistical analysis of the basic temperature data for the 100-mb level. By analogy to the jet streams in the middle latitudes, we can postulate the existence of migratory waves of variable amplitude which are propagated along the jet stream and which will produce meridional movements of the axis over short periods of time. The presence of the jet stream over a station will be manifested by a large daily variability in temperature at high levels, as a result of horizontal and vertical air motions in the vicinity of the jet-stream axis. Information on this variability will thus be complementary to the information obtained from the curves of running-mean temperatures. A convenient statistical measure of the magnitude of the variability is the variance, or square of the standard deviation. When the variance is evaluated relative to the running-mean temperatures, the effects of long-period trends are removed from consideration. Twenty days was selected as a suitable period for computing average temperatures and for evaluating running variances. At Alert, for example, a 20-day running-mean temperature curve virtually eliminated the long-period fluctuations in the 10-day mean curve. The presence of the mean

![Figure 3. Running variance of 20-day running-mean 100-mb temperatures.](image-url)
position of the jet stream will then be accompanied by large variances, whereas a station far from the mean position of the axis will experience small variances. The results of this analysis are presented in section 4.

Finally, the problem of investigating the existence of the Arctic stratospheric jet stream as a synoptic entity is attacked by direct analysis of measured winds and temperatures on vertical cross-sections. To facilitate the selection of cross sections with sufficient wind data to permit direct analysis, a complete time cross-section of wind and temperature above 40,000 ft was made for each rawinsonde station during the winter of 1955–1956. Dates for which data were available for the construction of suitable cross-sections were then found by comparing these time cross-sections. Numerous vertical cross-sections of the Arctic stratospheric jet stream were constructed in this study, mainly in November and early December 1955, and in late February and in March 1956. Three selected jet-stream cross-sections are presented in fig. 5, 6 and 7, and will be discussed in section 5.

3. Temperature field at 100 mb

In October 1955 (see fig. 2), running-mean 100-mb temperatures in the Canadian Arctic area all lay within a range of 2°C. The mean temperatures fell uniformly at an average rate of about 1/2°C/day at all stations as the duration of daylight decreased. After the onset of polar darkness at the 20-km level at Alert on 28 October, an increasing N-S temperature gradient developed between Alert and the more southerly sta-

![Graph showing temperature changes over time](image)

**Fig. 4.** Observed and estimated 100-mb temperatures at Norman Wells and Alert between 15 February 1956 and 5 April 1956.
tions, probably due to differential cooling along the fringe of polar night. Simultaneously, quasi-periodic mean-temperature fluctuations appeared at all stations. As the N-S temperature gradient increased, the amplitudes of the mean-temperature fluctuations also increased. One possible interpretation of these fluctuations is that they are produced by the movements of stable waves of increasing amplitude in the baroclinic zone below the stratospheric jet stream, analogous to those found in the troposphere below the jet streams of middle latitudes. Other factors, such as vertical motion, etc., will also be important in producing these changes. The maximum N-S temperature gradient was achieved in late February, and was followed by an unstable wave behavior in which cold air plunged southward at most stations. With reference to fig. 2, one can see the intense cooling which occurred at all stations except Alert after 27 February 1956. This cooling was quite different from that observed earlier, presumably with the relatively stable waves. On this occasion, the 10-day running-mean temperatures at all stations, except Alert, cooled to about −67°C. Indeed, individual observations at Norman Wells (65°N) even reached a minimum of −70°C at 0300 GCT 10 March. At this time, the N-S temperature gradient collapsed in this region.

During the last three weeks in March, temperatures at 100 mb throughout the Canadian Arctic and sub-Arctic increased from −70°C to around −45°C. Thereafter, a quasi-uniform temperature field of about −45°C was established at 100 mb in this area. Furthermore, all signs of strong westerly winds as well as of temperature fluctuations disappeared at these levels by early April.

It will be noted that at Alert, the most northerly station, the period from the winter solstice to the end of January is characterized by a notable absence of the periodic temperature fluctuations which were promi-

![Image](image_url)

**Fig. 5.** Vertical cross-section oriented approximately NE-SW for 1500 GCT 20 November 1955. Tropopause is indicated by thick solid line, isotherms (°C) by broken lines, and isotachs of observed northwesterly winds in stratosphere by thin solid lines (kn).
ment between 15 November and 20 December. For the most part, these fluctuations continue with increasing amplitude at the more southerly stations. Furthermore, after the third week in January, they again reappear at Alert and increase in amplitude until 21 March, whereas the same fluctuations exhibit a tendency to decrease at lower latitudes, e.g., Isachsen, Resolute and Mould Bay, just prior to the steady warming trend during the latter part of March.

A reasonable synoptic interpretation of these mean 100-mb temperature curves in fig. 2 can be formulated in terms of the N-S temperature field in the baroclinic zone below the jet stream. Along this baroclinic zone, it is possible to postulate the existence of waves which are propagated along the jet stream. The horizontal movement of these waves across any station together with the associated vertical motions will produce day-to-day, as well as long-term, changes in the temperature field. To the north and south of the strongly baroclinic zone, there will be very little temperature change produced by the moving disturbances. Thus, since the mean temperature at Alert remains almost constant near −72°C for a period of 35 days, between 21 December 1955 and 25 January 1956, it can be said that the mean position of the baroclinic zone is well to the south of Alert at this time. Furthermore, the reappearance of periodic temperature fluctuations at Alert after 25 January, while the mean temperatures remain around −72°C, can be interpreted to indicate the approach of the northward edge of the baroclinic zone below the jet stream. Moreover, the observed N-S shift of the maximum amplitude of these fluctuations in December, followed by a S-N shift in the late winter, would be fully consistent with the postulated movement of the jet stream itself.

On the basis of these temperature curves and the series of cross-sections, it can be tentatively stated that the jet stream associated with the strong stratospheric temperature gradient forms in the far north in November and then moves slowly southward during December, increasing in intensity. Its mean position lies to the south of Resolute in mid-winter, as indicated by the very low values of the 10-day running-mean temperatures at Resolute during January. General con-

![Fig. 6. Vertical cross-section oriented approximately NE-SW for 1500 GCT 26 February 1956. Tropopause is indicated by thick solid line, isotherms (C) by broken lines, and isotachs of observed northwesterly winds in stratosphere by thin solid lines (km).](image-url)
firmation of this feature for earlier winters can be found in the map of the 60-mb mean wind flow in January presented by Bannon and Jones (1955). According to this study, a mean maximum wind speed occurs in January along a line joining Sachs Harbour and Coral Harbour. This line intersects the meridian through Resolute over 400 mi south of the station. During February and March, the jet stream shifts northward with a maximum intensity occurring near the end of February. It decreases in intensity rapidly in March, as the differential radiative-cooling-and-heating mechanism is reversed.

4. 20-day running mean variances of 100-mb temperatures

The running variances of the daily 100-mb temperatures for overlapping 20-day periods for Alert (83°N), Isachsen (79°N), Resolute (74.5°N) and Norman Wells (65°N) are shown in fig. 3. Consider first the variance curve for Alert. There are two distinct maxima of variance on this curve, centered around 10 December 1955 and 23 March 1956, respectively. During the remainder of the period from 4 November 1955 to 6 May 1956, the variance had values between two and four. Thus, the standard deviation of the 100-mb temperatures over 20-day periods during most of the winter was of the order of 2°C, providing justification for the original space-extrapolation and time-interpolation techniques to fill in missing observations at the 100-mb level.

The earlier maximum in the 20-day running variances at Alert can be attributed to the passage of the mean position of the jet stream southward across Alert. The relatively small value of the maximum at this time would be consistent with the smaller N-S temperature gradient and, hence, the weaker jet stream, in November and December.

The broad minimum of the variance between 26

![Vertical cross-section oriented approximately NE-SW for 0300 GCT 26 March 1956. Tropopause and frontal surfaces are indicated by thick solid and broken lines, respectively; isotherms (C) are indicated by broken lines, and isotachs of northwesterly flow in stratosphere by thin solid lines (km).](image-url)
December 1955 and 28 February 1956 is a natural consequence of the fact that Alert is in a nearly barotropic zone, well to the north of the mean jet stream during this period. The occurrence of the second maximum about 23 March can be attributed to the presence of the jet stream over Alert when it is moving northward.

In the case of Isachsen and Resolute, the curves of the running variances are similar to that for Alert in the early part of December, with the notable exception that the peaks are reached at successively later times as one progresses southward. This observation is in accord with the postulated southward movement of the jet stream in the fall. Moreover, the maximum value of the variance for Resolute is greater than at Isachsen, which, in turn, is greater than at Alert. This observation supports the increasing N-S temperature gradient indicated by the 10-day running-mean temperature curves. A disturbance along an intense jet stream will produce larger variances than will a similar disturbance along a weak jet stream. Finally, the periods when the variances are a minimum at Isachsen and Resolute are much shorter than at Alert. For example, the variances at Alert are less than five for a period of 74 days, whereas at Resolute they are generally less than six for a period of only 44 days.

A significant feature of the variance curves at Isachsen and Resolute after 4 February is the occurrence of two distinct maxima separated by a well-defined minimum around 7 March, the approximate date on which 10-day running-mean temperatures reached a minimum at most of the Arctic stations, in particular those around 65°N. We may attribute the final maximum in variance at Isachsen and Resolute to the return of the mean jet stream to higher latitudes. With reference to the middle maximum, we know qualitatively that a major change occurred in the quasi-zonal flow after 27 February, when we observed the southward plunge of cold air at most of the stations, followed by strong warming in which radiation undoubtedly played a large role, with Alert lagging behind in this latter respect. During this period, the mean position of the jet stream could still be south of Resolute; but its meridional excursions could influence temperatures at Resolute.

The technique of computing variances is, in itself, not capable of resolving the maxima according to each physical process. However, a likely explanation of the double maximum following 4 February is that the mean jet-stream position had already reached Resolute on its northward migration, but was carried southward temporarily by the pronounced southward burst of cold air at these levels in the Canadian Arctic. Thus, it is believed that the second maximum in the variance at Isachsen and Resolute can be attributed to the southward plunge of cold air at all stations in the Canadian Arctic as described in section 1. This is primarily a dynamic phenomenon and was presumably associated with a N-S temperature gradient which exceeded some critical value. It is at first thought surprising that these maxima are not more pronounced, as might have been anticipated from the 10-day mean temperature curves in fig. 2. It is evident, however, that the pronounced warming and cooling were smooth changes, rather typical of a marked change in the circulation pattern. That two separate maxima in the variance are not observed at Alert after 4 February would then arise from the fact that the instability did not greatly disturb the temperature field at 83°N, although the gradual increase in the variance at Alert suggests that this effect may have occurred in early March to a limited extent.

The variance curve for Norman Wells in fig. 3 differs from the others during November, in that the variances are much greater initially. The reason for this departure became apparent when the tropopause pressures at Norman Wells during October and early November were examined. In this period, the tropopause frequently occurred at a pressure as low as 220 mb, indicating that maritime tropical air was found frequently at high levels over Norman Wells. The day-to-day fluctuations in tropopause pressure occurred between 300 and 220 mb. On this basis, we can conclude that the polar-front jet stream was located in the vicinity of Norman Wells during that period, and the large variances during early November at this station were largely controlled by the polar-front jet stream, which influences the 100-mb temperature field to some degree. It is pertinent to note that November was a month during which a persistent block occurred over the Bering Sea, tending to steer cold air southeastward across the Canadian prairies and the northwestern United States. During the rest of the winter, the tropopause was near the 300-mb level, and the variances were accordingly smaller.

The first significant maximum in the variance curve for Norman Wells coincides with the winter solstice. Presumably the Arctic stratospheric jet stream reached its southernmost mean position around that time, at least in the western Arctic. Moreover, the broad maximum at Norman Wells, relative to those at Isachsen and Resolute, suggests that the maximum is due to a combined arrival and departure phase of the jet stream. Following this maximum, the variances at Norman Wells reached values comparable with Alert, of the order of two, for a brief period in late January. At this time, the mean position of the jet stream must be to the north of Norman Wells. Evidence in support of this belief can be found from fig. 2, which shows the 10-day mean 100-mb temperatures to be around −55°C at this time.

The second large peak in the curve for Norman
Wells occurs at the end of February and early in March. Since this maximum occurred nearly simultaneously with the second maxima at Isachsen and Resolute, it is believed that it was physically due to the breakdown of the zonal flow around that time, which was manifested by the extremely great mean cooling observed at Norman Wells between 27 February and 10 March. On the other hand, the single maximum at Alert agrees in time with the corresponding major maxima at Isachsen and Resolute.

The observed and estimated 100-mb temperatures at Resolute and Norman Wells between 15 February and 5 April are shown in fig. 4, to demonstrate the extremely rapid rate of cooling produced by the southward burst of cold air at high levels. On 15 February, the difference in 100-mb temperature between the two stations was 12°C, which remained relatively constant until 4 March. Between 0300 GCT 4 March and 0300 GCT 7 March, the 100-mb temperature at Norman Wells fell 16°C. The corresponding cooling at Resolute was only 5°C. From 7 March to 12 March, the difference in temperature between the two stations was negligibly small. A minimum temperature of −70°C was reached on 10 March, following which the temperature difference of 12°C between the two stations was re-established by 12 March. However, a gradual decrease of this difference occurred until 1500 GCT 28 March, when the 100-mb temperature gradient reversed following the reversal in the latitudinal input of solar radiation at the vernal equinox.

5. Synoptic cross-sections of the Arctic stratospheric jet stream

Three vertical cross-sections of the Arctic stratospheric jet stream are presented in figs. 5, 6 and 7. Measured winds were used exclusively in the wind analyses.

Fig. 5 shows a cross-section of the jet stream at 1500 GCT 20 November 1955. Stations selected for the cross-section are Eureka (917), Isachsen (074), Mould Bay (072), Sachs Harbour (081) and Norman Wells (043). The orientation of the cross-section is NE-SW, so that the northwesterly winds at and above the 100-mb level are nearly at right angles to the plane of the cross-section. It will be recalled that, during November, the jet stream is in its initial stages of development and is therefore relatively weak. Nevertheless, the observations do define a wind-speed maximum clearly in this cross-section. The general tilt of the axis toward the south was a characteristic feature of all cross-sections constructed. The 50-mb temperature field is of particular interest. One can observe the greatest concentration of isotherms between Sachs Harbour (051) and Isachsen (074); farther south, the 50-mb temperature gradient is quite small.

A vertical cross-section through the jet stream at 1500 GCT 26 February 1956 is shown in fig. 6. It was around this time that the jet stream was most intense. The orientation of this cross-section is also NE-SW, and the strong northwesterly winds in the stratosphere are again nearly at right angles to the plane of the cross-section. The highest reported wind on this cross-section is 160 kn around the 80,000-ft level at Eureka (917). The strong horizontal temperature gradient below the jet stream is clearly evident; the temperature increases from −70 to −50°C in a distance of 800 mi. South of Resolute (924), the stratosphere is nearly isothermal both in the vertical and horizontal. Owing to the orientation and irregularity of the cross-section, there is some doubt as to the reality of the double maximum.

A vertical cross-section for 0300 GCT 26 March 1956 is presented in fig. 7. The maximum wind occurs at or above the 25-mb level over Isachsen (074), with a speed of around 120 kn. It is also noted that a maximum wind was reported in the Alert sounding at 35 mb, indicating that the actual height of the jet axis is very nearly at that level on this occasion. The horizontal temperature gradient at 100 mb is 10°C over a distance of 860 mi, certainly much less than in the 26 February cross-section in fig. 6, where the maximum horizontal temperature gradient was estimated to be 20°C in 800 miles. This decrease in horizontal temperature gradient is in accord with the mean temperature curves shown in fig. 2. The highest reported wind on this cross-section was slightly greater than 100 kn at the 25-mb level, considerably less than the 160-kn wind in the previous section. At 50 mb, the maximum temperature fall occurs between Mould Bay (072) and Thule (202), just below the jet stream. South of Mould Bay, the 50-mb temperatures vary only between −44 and −49°C. We note that stratospheric temperatures at Alert are warmer by 10°C than in the February section.

The tropopause occurs around the 300-mb level in all three cross-sections, except in fig. 7 where there is observed an intrusion of a slightly warmer tropospheric air mass above which the tropopause is found at 250 mb.

6. Conclusions

In conclusion, it may be stated that the existence of the high-latitude winter stratospheric jet stream has now been demonstrated on a synoptic basis for the North American sector. Its mean altitude and its latitudinal variation through the winter, as shown by a statistical study of the 100-mb temperature field, make it probable that differential solar heating of the ozone layer is the primary physical process initiating the jet stream in the fall and intensifying it in the winter. This intensification during the 1955–1956 winter might have led to a form of baroclinic insta-
bility at the end of February. The question of whether this is a normal behavior or not must await further investigation. The development of a pronounced meridional flow pattern at this time rendered the differential heating-and-cooling mechanism inoperative, and the jet stream tended to weaken. At about this time, the differential thermal heat source itself became weak and eventually reversed its direction; consequently, the jet stream disappeared early in the spring.

The data available from the 1955–1956 winter are not, however, adequate to present a clear picture of the wind and temperature structure above the 100-mb level. The 25-mb, or 25-km, level is near the middle of the ozone layer and probably above the median level. It is here that the primary effects of differential solar heating should be sought. Effects at lower heights, such as the 100-mb level, will be secondary, and will arise, at least in part, as a result of infrared radiative flux divergence. During the forthcoming International Geophysical Year, it is intended in Canada to obtain observations at the 25-mb level on a daily basis throughout the year. Moreover, ozone observations will be undertaken at Alert and Resolute. It is hoped that it will then be possible to achieve a far greater understanding of the production, behavior and decay of the high-latitude high-altitude westerly jet stream.

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