Midwinter Ozone Variations and Stratospheric Flow over Canada, 1958—1959

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Abstract

The total ozone variations at Edmonton and Moosonee during December, 1958 and January, 1959 are examined in relation to daily synoptic analysis up to the 25-mb level. The stratospheric perturbations of the polar-night westerlies appear to dominate the ozone record when that régime is over the station. Otherwise, the usual Normand tropospheric perturbation effect is indicated. Correspondence is analyzed using adiabatic vertical motions computed at the 200, 100 and 25-mb levels, in addition to the 200-mb geopotential height and the 100—25-mb thickness.

1. Introduction

The work of Sir CHARLES NORMAND (1953) and others has shown that daily ozone variations are related to the perturbed circulation of the upper troposphere. Negative correlations have been obtained between total ozone and 300-mb geopotentials, implying that ozone is more abundant over troughs than over ridges. Since these correlations were mostly established in northern Europe, one can safely assume that these troughs and ridges are parts of the travelling wave-trains of the circumpolar westerly vortex. It is known, furthermore, that the 300-mb waves extend without significant change of phase to 100 mb or above, i.e., into the lower stratosphere. Above the tropopause, the westerlies descend into troughs and climb on to ridges. Theoretical demonstrations by REED (1950), GODSON (1959), and others have shown that subsidence in the stratosphere must contribute to increases in total ozone, as long as ozone mixing ratio increases with height; similarly uplift decreases the total ozone. The Normand effect—high ozone in troughs, low in ridges—is hence qualitatively consistent with theory.

Quantitatively, however, the picture is less satisfactory, since the amplitude of the ozone variations considerably exceeds expectation. Moreover there are periods, especially in winter, when the Normand effect seems to vanish; even at their best, the computed correlations rarely explain more than 25 to 35 per cent of the ozone variance. No doubt advection complicates the effects of vertical motion, but it can hardly account for the width of the disparity. Hence it is obvious that other causes of ozone variation exist.

The present writers suggest that much of the remaining variance of total ozone is due to vertical motion in the newly-discovered baroclinic waves of the polar-night westerly vortex (HARE, 1960; GODSON and LEE, 1958). This vortex affects the layers from 150 mb to above 25 mb. It develops in high latitudes in the darkness of midwinter—hence the term *polar-night vortex* introduced by KOCHANSKI (1955)—and sometimes extends below the U.S.-Canadian border for a few weeks before collapsing in the spectacular sudden-warmings well-known from the work of SCHERHAG (1952), CRAIG and HERING (1959), TEWELES (1958) and others. Since vertical motion of the order of 2 to 3 cm sec^{-1} over long trajectories occurs within the wave-perturbations of this vortex, it seems reasonable to expect that ozone variations should occur in response to it.

To subject this idea to a preliminary test, the time-series of total ozone at Edmonton, Alberta, and Moosonee, Ontario, were examined alongside synoptic charts and cross-sections for the stratosphere over North America. Because of the large amount of work involved, the study was restricted to the months of December, 1958 and January, 1959. Both ozone stations were far enough north to be affected by the polar-night vortex, but had enough daylight even in midwinter for continuous ozone determination. The results are suggestive, but far from conclusive. They do, however, show that the middle stratospheric temperature field and total ozone are closely related.

2. The data employed

The daily ozone values used in this study were obtained by Dobson spectrophotometers maintained by the Canadian Meteorological Service during the I.G.Y. period at Edmonton and Moosonee. Values are in cm of O_3 at S.T.P. and it is estimated that the standard error of the measured 24-hour change in total ozone is about 0.010 cm. All temperature values were derived from radiosonde ascents for 0000 hrs G.C.T., with interpolated values from synoptic charts where necessary.

The synoptic charts and cross-section were drawn at the Central Analysis Office, Canadian Meteorological Service, by the Arctic Meteorology Research Group, McGill University, as part of a routine analytical project. The area of analysis at 200 mb was circumpolar, north of 35° N. The 100-mb maps were analyzed over North America, the Atlantic and Europe, also north of 35° N. At 25 mb daily analysis was carried out over North America, every fifth day's map being extended to a circumpolar area by suitable extrapolation techniques.

The values of vertical motion (in cm sec^{-1}) were computed from charts at the 200, 100 and 25-mb levels by the adiabatic trajectory method. The values plotted are those for the 24-hour trajectory centered on 0000 hrs G.C.T. for the specified date. In view of the errors in the original contour analysis, and the length of trajectory involved, these values can be taken only as crude estimates of the order of magnitude and sign of the vertical motion.

3. Results

Fig. 1 presents time cross-sections for December, 1958, at Edmonton and Moosonee. Fig. 2 gives similar diagrams for January, 1959 at the same stations. The upper section in each diagram gives total ozone (cm at S.T.P.) and the thickness of the 25 to 100-mb layer in geopotential meters. The central section gives vertical motion in cm sec^{-1}, subsidence being considered negative; the negative periods

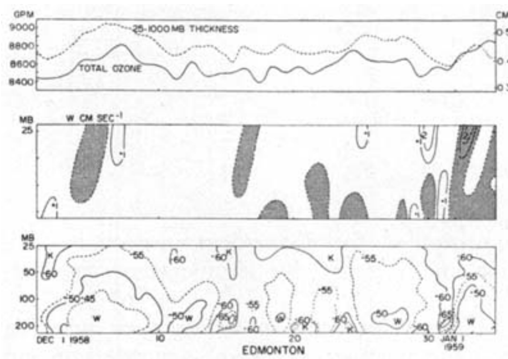

Fig. 1 a.

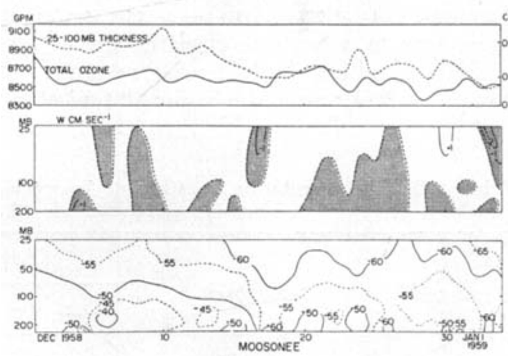

Fig. 1 b.

Fig. 1. Time sections of— observed 25—100 mb thickness and total ozone; 24-hour average adiabatic vertical motion (w), subsidence areas stippled; observed temperature (°C), warm areas (W), and cold areas (K).

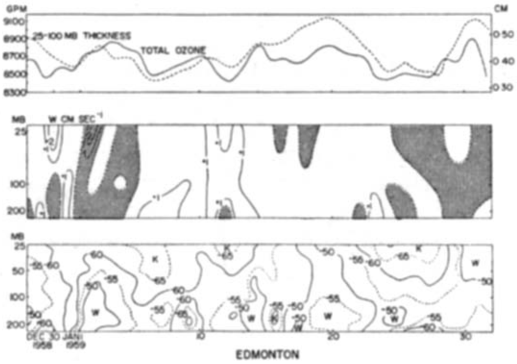

Fig. 2a.

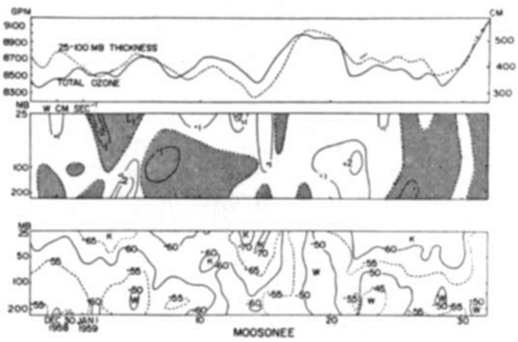

Fig. 2. Similar to Fig. 1.

are stippled for convenient inspection. The bottom sections give temperatures in deg. Celsius.

The vertical motion values vary between 24-hour averages of above $+2$ cm sec^{-1} and below -2 cm sec^{-1}. Over trajectories of this duration, an average of ± 2 cm sec^{-1} is equivalent to a vertical displacement of 1.7 km. Hence uplift and subsidence at rates of 1—2 km in 24 hours must be assumed typical of the stronger stratospheric disturbances over these stations. It is obvious from the diagrams that the vertical motion systems fall mainly into two suites—those centered at or above 25 mb (arising from perturbations in the polar-night vortex) and those centered at or below 200 mb. The latter are, of course, associated with the familiar travelling waves in the tropospheric westerlies. The 100-mb level has a minimum of vertical motion. Only during two short periods at Moosonee do systems appear centered at 100 mb. It is noteworthy that the time-average of vertical motion at Edmonton is clearly positive at all levels.

The temperature fields show a similar division. At 200 mb there is a very high variability due to the lower suite of vertical motion systems, as well as longer-period spells of warmth (e.g., December 1—13 at Edmonton). All these thermal systems diminish rapidly with height, few of them being visually identifiable above 50 mb. The upper part of each section shows the much longer-period fluctuations typical of middle stratospheric waves (HARE, 1960).

The 25 to 100-mb thickness curves naturally reflect the vertically integrated thermal field of the middle stratosphere, and hence show predominantly long-period variations. At both stations the largest fluctuations occur in early December and again in January. It is obvious at a glance that the total ozone curve is closely related to these thermal curves, more especially at Moosonee. The closeness of correlation is reduced by variable phase-lags in the major oscillations, but it is quite clear that each warm phase is ozone-rich, each colder period ozone-poor. Table I gives linear correlation coefficients between total ozone and (a) 25 to 100-mb thickness and (b) 200-mb geopotential height for both stations in both months. As an additional indicator of the processes at

Table 1. Linear correlation coefficients between total ozone (O_3), 25 to 100-mb thickness (ΔZ), and 200-mb geopotentials (Z_{200}), Edmonton & Moosonee

Line	Variates	Edmonton		Moosonee	
		Dec.	Jan.	Dec.	Jan.
(a)	O_3, ΔZ	+0.73	+0.65	+0.25[2]	+0.65
(b)	O_3 Z_{200}	—0.55	—0.23[2]	—0.53	—0.46
(c)	Z_{200}, ΔZ	—0.55	+0.28[1]	+0.16[2]	—0.64

[1] Significant at 5 % level. Remainder significant at 1 % level.
[2] Not significant at 5 % level.

work, line (c) give the correlation between 25 to 100-mb thickness and 200-mb geopotential height.

Table 1 shows that total ozone and the temperature of the 25 to 100-mb layer marched together except in December over Moosonee, when the correlation fell to an insignificant value, while retaining its positive sign. Reductions of variance for the other months ranged from 42 to 53 per cent. It has already been suggested that part of the unexplained variance arose from unsystematic phase lags, and that the resemblance between the two curves was closer than these reductions may suggest. The O_3 versus Z_{200} correlations, which correspond closely to those of Normand, were all negative, and were smaller. It is of interest that the cross-correlation of Z_{200} versus ΔZ gave very erratic results. At Edmonton in January, however, significant correlation between O_3 and ΔZ existed in the absence of both the Normand effect and a significant correlation between Z_{200} and ΔZ.

4. Interpretation

An attempt will now be made to interpret these results in the light of the stratospheric circulation during these months. A summary of that circulation has been given elsewhere by HARE (1960). It was there shown that the principal developments were as follows:—

(i) *From December 1—11, 1958*, a warm stratospheric ridge lay over Alaska and arctic Canada, with a closed anticyclone at 25 mb. This ridge drifted slowly southeastward. Fig. 1 shows the deep warm layer at Edmonton associated with this system. Moosonee lay throughout the period along the southern margin of the ridge, experiencing a slight warming on December 10.

(ii) *On December 11—15*, a drastic cooling of the middle stratosphere occurred over the arctic coast, as the polar-night vortex moved across the pole towards North America. The leading baroclinic trough reached western Alaska on December 11, reaching Edmonton on December 15 and Moosonee on December 18. *Thereafter for the remainder of the midwinter* the polar-night vortex dominated all Canada. The polar-night jet lay on the average across northern Alaska, dipping southward to about 65° N in the quasi-permanent east Canadian trough. Fig. 3 presents circumpolar 500-mb and 25-mb charts for December 29, 1958, showing the two circumpolar vortices, that of the troposphere having maximum winds

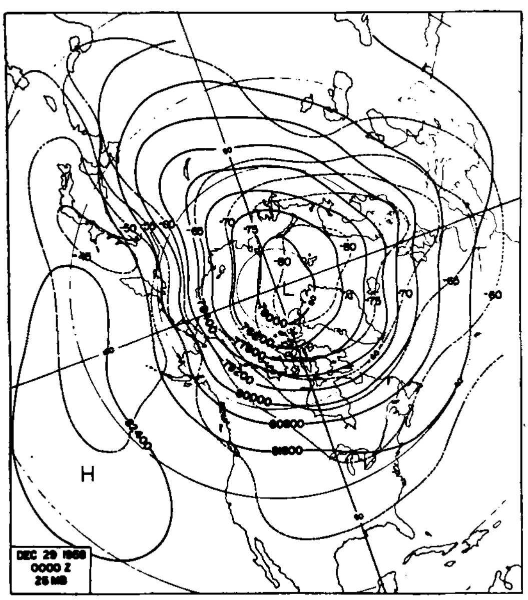

Fig. 3 a.

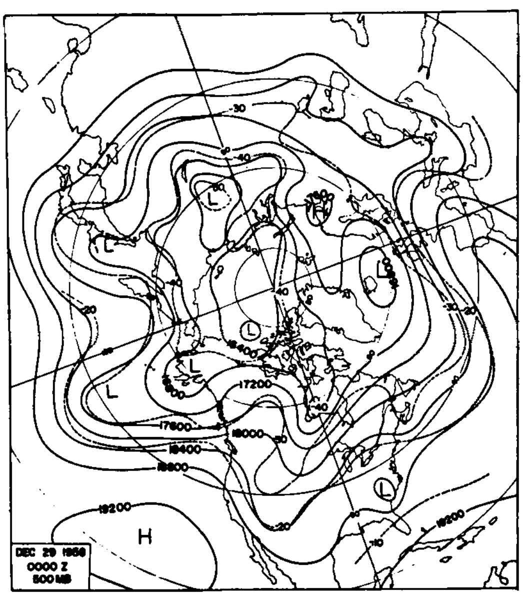

Fig. 3 b.

Fig. 3. Constant pressure charts. Solid lines—contours (gp ft) Dashed lines—isotherms (° C)

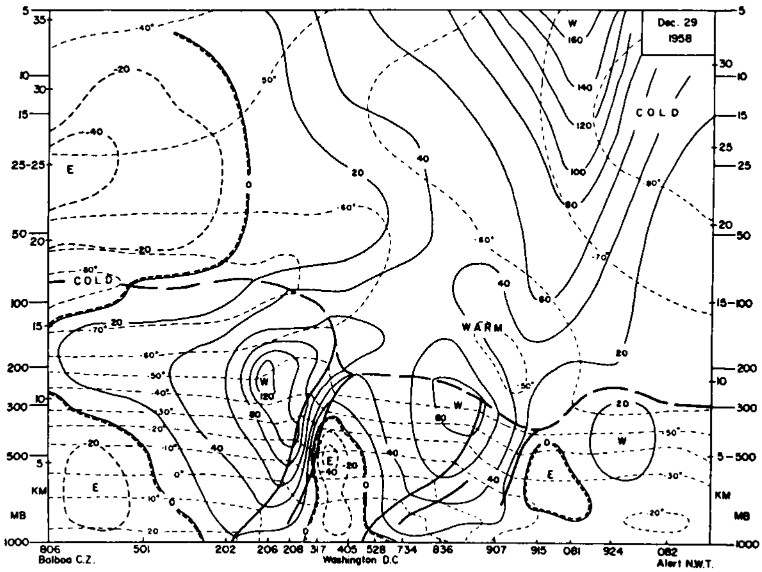

Fig. 4. 80° W cross-section for December 29th, 1958. Thick lines—fronts, tropopause. Thin dashed lines—isotherms (° C). Medium solid and dashed lines—zonal isotachs (kts)

in latitudes 35°—50° N. The essential separateness of the two vortices, stressed previously by HARE (1960), shows up in the cross-section along 80° W for December 29 (Fig. 4).

(iii) *From December 15 until January 30*, a series of baroclinic waves in the polar-night westerlies moved east across Canada, with a consistent phase velocity of about 11° longitude per day. For the sake of easy identification, these waves have been arbitrarily numbered. Table 2 gives their dates of passage at Edmonton and Moosonee. As Figs. 1—2 show, these waves were clearly marked in the thickness and temperature records, but no simple association with vertical motion was shown. The scale of these features is indicated by Fig. 5, which shows troughs IV and V.

The Edmonton ozone curve will now be examined in the light of this history. The warm, anticyclonic phase of December 1—10

Table 2. Baroclinic waves in middle stratosphere December 15—January 30, 1958—59

Perturbation	Date past Edmonton	Date past Moosonee
Trough I	December 15	December 18
Ridge I (insignificant)	—	—
Trough II	December 22	December 25 (weak)
Ridge II	December 27	December 30 (weak)
Trough III	December 30	January 2
Ridge III	January 2	January 5
Trough IV	January 6	January 9 (weak)
Ridge IV (insignificant)	—	January 11 (weak)
Trough V	January 12	January 15
Ridge V	January 18	January 19[1]
Trough VI	January 24	January 23[1]
Ridge VI (insignificant)	—	—
Trough VII	January 27	January 30
Ridge VII	January 30	January 31[2]

[1] Waves moving from NNW, with marked tilt.
[2] Sudden warming effect, with collapse of trough VII east of Hudson's Bay.

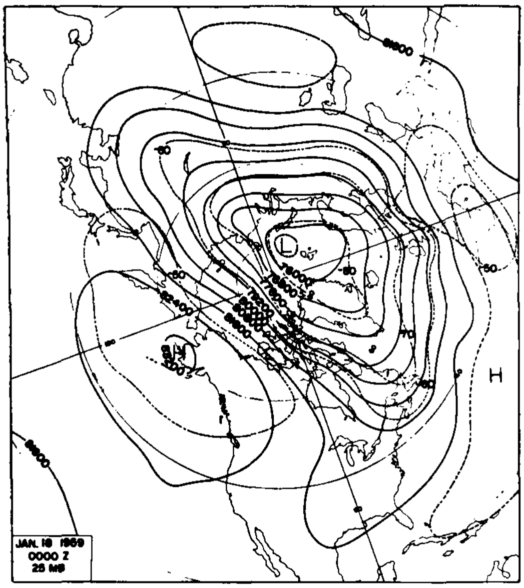

Fig. 5. Similar to Fig. 3.

had high ozone, with the ΔZ and O_3 curves behaving alike. Troughs I and II were of small amplitude, and had no discernible effect on ozone. Hence December 11—22 was a period when ozone variations were of small amplitude, and were probably governed by the motion of tropospheric waves; the effects of these waves on the 200-mb temperature field is well shown in Fig. 1. Ridge II, well-developed over western Canada, produced a warm stratosphere and high ozone, the ozone rise preceding the thickness rise by two days. No subsidence could be detected except at 200 mb on December 24, feeble uplift being typical of the period. Trough III amplified vigorously near Edmonton, with 24-hour ascent of 2 cm sec^{-1} at 25 mb. The uplift was, however, offset by subsidence at 200 mb; ozone amounts rose slightly.

In January, Edmonton's record is unmistakably dominated by the middle stratospheric waves. At these levels troughs are cold, ridges warm; hence the ridges show up in Fig. 2 as maxima of ΔZ, and troughs as minima. It is quite obvious that the O_3 curve behaves in a closely similar fashion, though, as the +0.65 correlation coefficient shows, there are phase-lags and marked differences in relative amplitude. The Normand effect is largely suppressed, even though the lower stratospheric temperature field shows that tropospheric waves were active for much of the month.

At Moosonee, it will be recalled (Table I) that December produced only a small correlation between O_3 and ΔZ. As Fig. 1 shows, until December 17 (when the polar-night westerlies invaded the area) ozone hardly varied. Thereafter the O_3 and ΔZ curves are similar, but with marked phase-lags. A significant, though small, negative correlation between O_3 and Z_{200} shows that the Normand effect was at work, in spite of the fact that the tropospheric westerlies lay well to the south for much of the month. In January, however, the middle stratospheric systems increased in amplitude, and as at Edmonton, dominated the ozone variation. The parallelism of the O_3 and ΔZ curves is very striking. Ridges III and IV produced small ozone peaks, but the much more profound ridging of January 23—24 produced a 50 per cent increase in ozone in 48 hours. Even more striking was the ozone increase—almost a doubling—between January 29 and February 1, associated with the sudden warming that followed the collapse over eastern Canada of trough VII. It is noteworthy that ΔZ and Z_{200} were significantly correlated in January, with a negative sign. This may account for the persistence of a small negative correlation between O_3 and Z_{200}, in spite of the displacement of the tropospheric westerlies far south of Moosonee.

If one compares the Edmonton and Moosonee January records, it is apparent that the ozone "waves" stayed roughly in phase with the thermal waves, and that these in turn remained in phase with those of the motion field (as, of course, hydrostatic considerations require). Throughout the month the stream velocity of the polar-night circulation was much stronger than the phase-velocity of the waves. Hence the wind blew through the isotherms of the thermal field, which was advected by the phase velocity of the baroclinic waves. It follows that in the middle stratospheric waves, the wind also blew through the ozone maxima and minima, since these remained in phase with the thermal systems.

Little has been said about the computed values of vertical motion. Since they were computed by an approximate method from very long trajectories, it is perhaps too much to expect that they will show any very close correlation with ozone variation; moreover, it is at present quite impossible to estimate the stream-advection of ozone, which obviously obscures the vertical motion effect. It is of some interest, however, to take the computed values and assess the order of magnitude of the ozone changes they might be expected to produce. Daily observations of the vertical ozone profile were unavailable, but a representative profile for winter at Edmonton was supplied by Dr. W. L. Godson, Meteorological Branch, Canadian Department of Transport. The original profile (derived from Umkehr determinations) was expressed in cm of O_3 at S.T.P. per 6 km layer. These values were converted into units of microns (10^{-4} cm) of O_3 per millibar layer—i.e., mixing ratio. These values were then plotted as a linear function of pressure to give an equal-area transformation of ozone change for given vertical displacements of the curve. The slope of the ozone mixing ratio curve was found to be as follows:—

Pressure Surface	Slope of O_3 Profile (μ mb^{-2})
25 mb	0.7
50 mb	0.25
100 mb	0.1
200 mb	0.04

For convenience, the Umkehr values were also integrated over pressure and time. This gave an increase of *0.008 cm* for each of two stratospheric layers, *20 mb to 100 mb* and *100 mb to 250 mb* for a unit vertical motion of *1 cm sec*$^{-1}$ over a *twelve-hour* period. The computed vertical motions at Edmonton gave an average daily change of 0.005 cm in the upper layer and 0.006 cm in the lower layer. The largest change computed for either layer was about 0.03 cm in 24 hours as compared to the largest total ozone change of 0.09 cm. The correspondence between the computed ozone changes for both layers and daily total ozone changes, over the two-month period, was not impressive, confirming the expected complexity of the vertical and horizontal advective processes.

5. Conclusions

The writers suggest that these results support (though they do not finally prove) the importance of baroclinic waves of the polar-night vortex in daily ozone variation in the midwinter months in high latitudes. In summary:—

(i) when the polar-night westerlies were present over Edmonton and Moosonee, and their baroclinic waves were of high amplitude (as in January), the variation in total ozone followed fairly closely the motion of these waves, ozone maxima and minima seeming to move with their phase-velocity, as did thermal maxima and minima;

(ii) the correlation between ozone and middle stratospheric temperature was high at such times; at Edmonton, moreover, it was also high in the anticyclonic phase of early December. In general, this correlation exceeded the well-known Normand correlation;

(iii) no obvious correlation with local vertical motion could be established.

If conclusion (i) is valid, it is clear that ozone and temperature variation along trajectories must be governed by similar conservation equations; if vertical motion and divergence are considered to be the appropriate mechanism, these must be so adjusted along the trajectories as to permit the isolines of ozone concentration to remain in phase with the ridges and troughs in the contour pattern.

These tentative findings cannot be extended to other latitudes or seasons. At all other times of year the middle stratosphere has undisturbed flow, with little vertical motion in middle and high latitudes. At such times the Normand effect must dominate the ozone record. Even in winter, moreover, the polar-night waves have a high amplitude only in sub-arctic latitudes, and there is some evidence that amplitudes over Eurasia are less, and the wave-structure more complex, than over Canada.

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