The distribution of ozone on pressure surfaces[1]

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ABSTRACT

The ozone distribution in the 300-, 250-, 200- and 150-mb surfaces was derived for the 3rd and 4th of May, 1963, based on earlier published maps showing the distribution of ozone mixing ratio in isentropic surfaces. Some remarks are also made on potential hazards of ozone to aviation, on the correlation between ozone mixing ratio and absolute potential vorticity and on the complicated "sandwiched" structure of the lower stratosphere in middle latitudes south of the polar front jet stream.

Introduction

In an earlier paper the authors studied the distribution of ozone in isentropic surfaces from the middle of the troposphere (320°K) up to and including the 510°K-surface at about the 50-mb surface (Berggren & Labitzke, 1966). Ozone soundings taken in North America on a daily basis during the period 29 April–10 May, 1963 were used and charts depicting the ozone distribution in six selected isentropic surfaces on the 3rd and the 4th of May, 1963, 12 GMT were made. The basic assumptions made were that the air particles conserved their ozone mixing ratio and their potential temperature (the reader is referred to the earlier paper, hereafter called Paper I, for a detailed discussion of the methods used).

The ozone maps thus arrived at, together with ozone mixing ratio time cross sections for each ozonesonde station, constitute an acceptable resolution in time and space. Thus, it would be possible to construct, with reasonable accuracy, maps showing the distribution of ozone mixing ratio on selected isobaric surfaces. The surfaces selected are 300, 250, 200, 150 mb as these pressure levels encompass all cruising levels for present-day commerical jet aircraft. These maps should make it possible to give an idea of what ozone mixing ratio values a jet aircraft, its passenger and crew can encounter during flight. At the same time, comparing jet stream analyses at the selected levels with the isolines for ozone mixing ratio, one could get a picture of the distribution of ozone around a jet stream.

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Materials and methods

Data used in this study were the ozone soundings and the radiosoundings from North America for the period 2 May, 00 GMT–5 May 1963, 00 GMT. The ozone soundings were put together in time cross sections for each station (see Fig. 1 of Paper I). For a number of selected isentropic surfaces (320, 330, 350, 375 and 400°K) analyses of the ozone mixing ratio were available from the earlier work (see Fig. 3 of Paper I). These surfaces cover the layer from the middle troposphere up to the 100–140 mb surface. Utilizing these maps the distribution of the ozone mixing ratio on the 300-, 250-, 200- and 150 mb surfaces was then arrived at in the following manner. For each radiosonde station the pressure at the selected isentropic surfaces was noted together with the corresponding ozone mixing ratio as read off from the previously mentioned maps. The proper ozone value for each pressure surface was then calculated by linear interpolation with respect to pressure. The intersections between the isentropic and isobaric surfaces were arrived at by

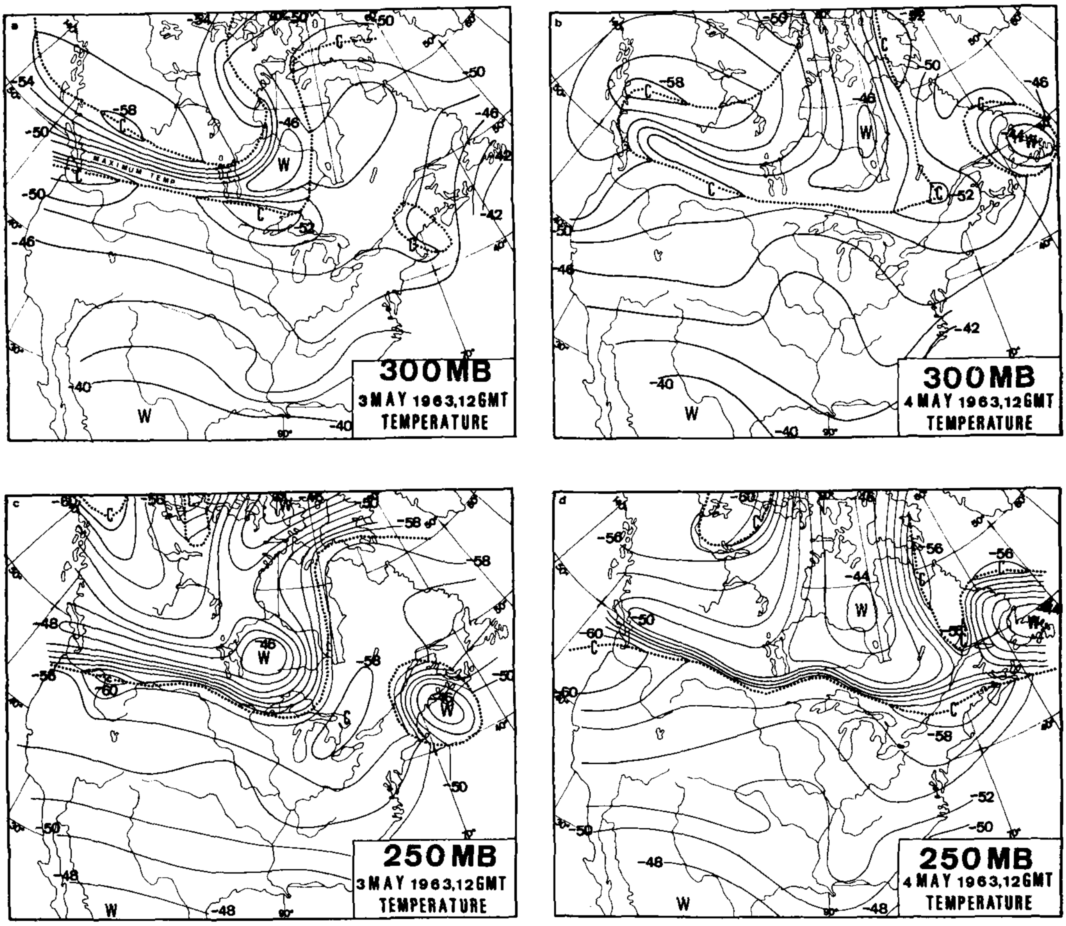

Fig. 1 a–d

Fig. 1. Detailed isotherm analyses (interval 2°C) for the 3rd and 4th of May, 1963, 12 GMT, and for the 300-, 250-, 200-, and 150-mb surfaces. Tropopause intersections are given as dotted lines.

analyzing the proper isotherms on the chosen isobaric surfaces. These intersections were transferred to the isobaric ozone maps together with the corresponding ozone values from the isentropic ozone maps. It was possible to get enough points on each isobaric map to ensure a reasonable analysis. (The errors are discussed in a separate section.)

Detailed isotherm analyses

To arrive at the best possible analysis of the intersection between the tropopause on the one hand and the isobaric and isentropic surfaces on the other, detailed analyses of the isotherm fields and wind fields were made for the isobaric levels in question. All maps for the period 3 May, 00 GMT–5 May, 00 GMT were analyzed for every 2°C and 20 knots, respectively, and in order to get a picture as three-dimensionally consistent as possible a large number of cross sections were analyzed. From these cross sections the isotherms and the isotachs were transferred to the isobaric maps, this being especially important north of the jet axis. In the case studied in this paper, it so happened that the jet axis was close to the U.S.A.–Canada border with its very marked discontinuity in station density. Without the cross sections it would have been impossible to achieve a consistent picture in time and space. It goes without saying that there was a feed-

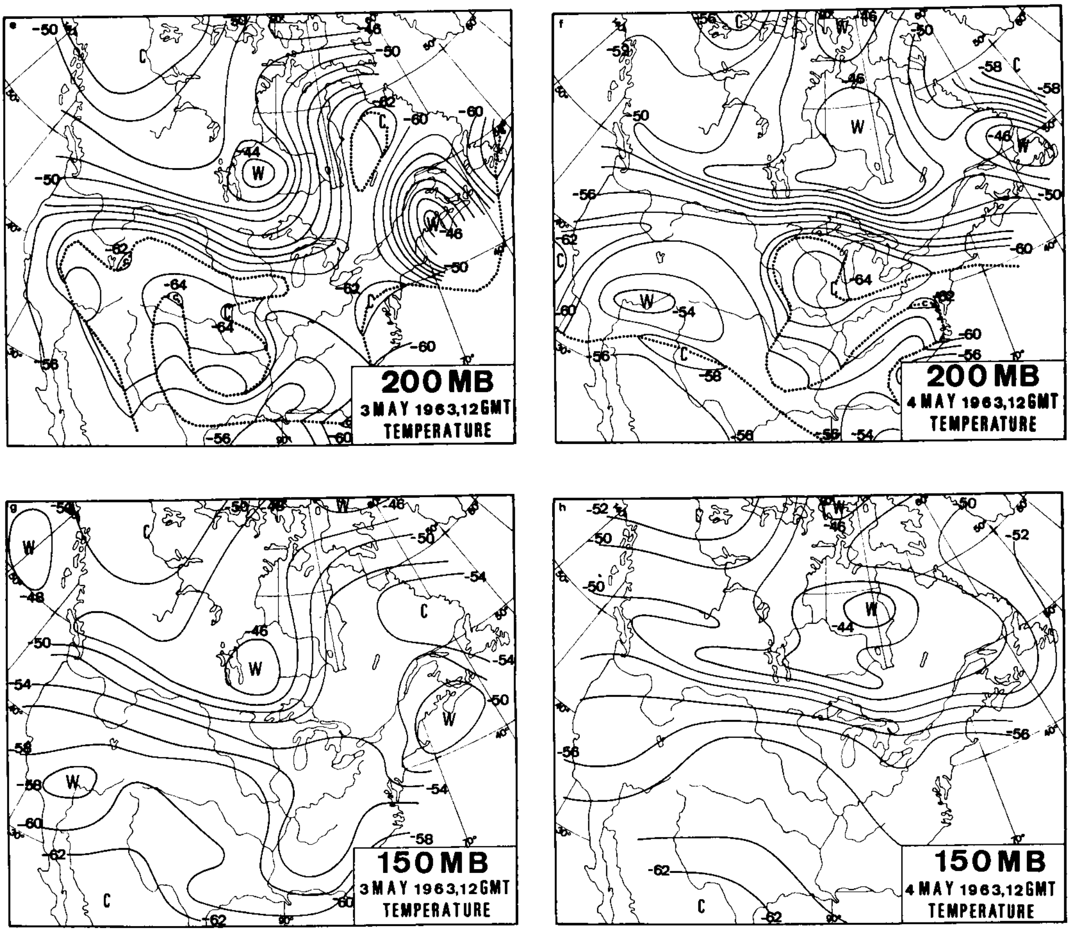

Fig. 1 e–h

back system operating during this analysis work, e.g. certain observational errors were detected in the isobaric analyses and taken care of in the cross section analyses.

The cross sections were analyzed using the concept of front reaching into the lower stratosphere (Berggren, 1952) with a vertical part at about the 250–300 mb level. This frontal model is admittedly subject to criticism, as are all other offered solutions to this difficult analysis problem. For the purpose of this paper, however, it is not critical which model we use, as most of them imply the same large-scale distribution of temperature, wind and ozone. When all cross-section and isobaric analyses, including the isobaric ozone analyses, were completed and all charts and maps were as mutually consistent as possible, the position of the tropopause intersection was entered on the isobaric ozone maps. In the case of the 300-mb maps, the southern border of the front at that level was chosen as the northern extension of the middle latitude tropopause found above and south of the polar front jet at about 200 mb. It should be emphasized that the intersections between the tropopause and the pressure surface in question were entered on the ozone isobaric maps after the analyses of the ozone mixing ratio were completed.

Fig. 1 gives the isotherm analyses and the tropopause intersections for the isobaric levels and the synoptic periods chosen. What should

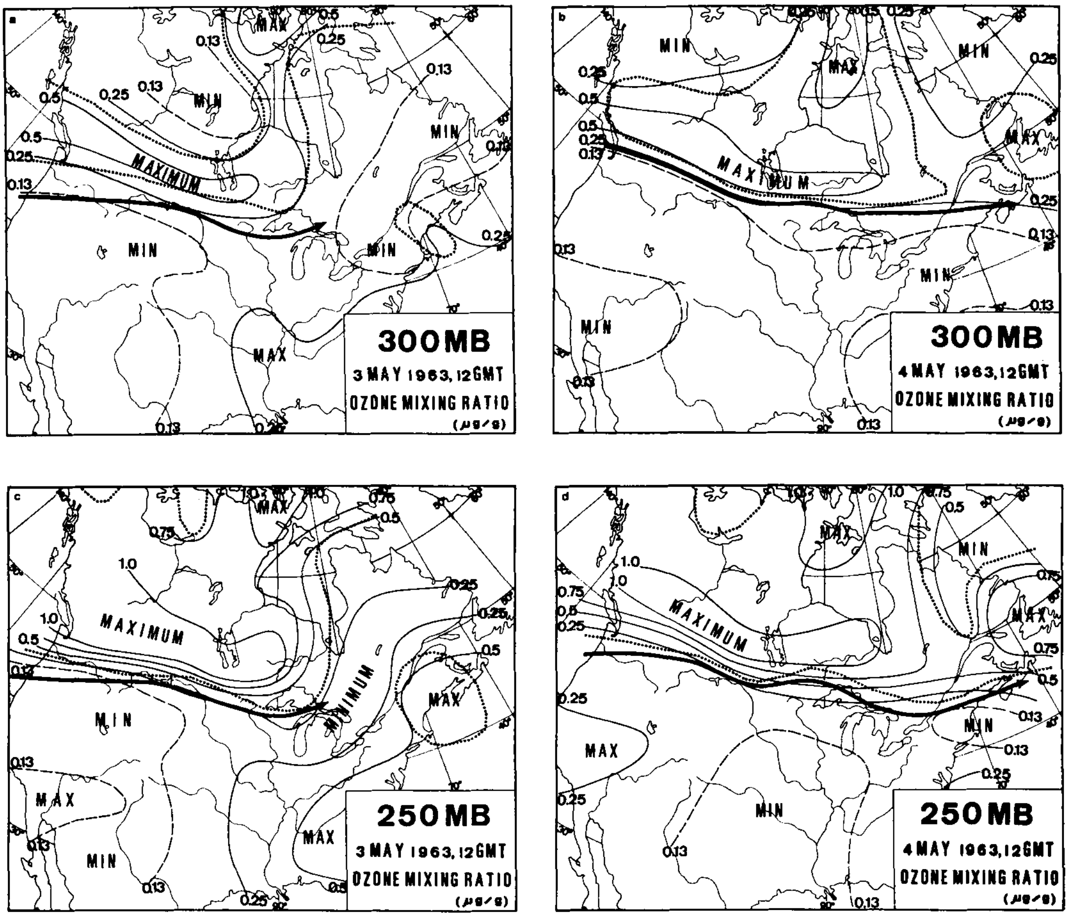

Fig. 2 a–d

Fig. 2. Distribution of ozone mixing ratio (in μg/g, interval 0.25 μg/g, intermediate lines dashed) for the 3rd and 4th of May, 1963, 12 GMT, and for the 300-, 250-, 200-, and 150-mb surfaces. Jet axes are given as heavy arrows.

be especially noted is that in southwestern Canada the warm area parallel to the tropopause intersection i.e. parallel to the polar front jet axis, indicated a marked sinking of this air during at least a period of its existence as part of this synoptic feature. It can also be noted that the jet streams have a tendency to split in two at higher levels (not indicated in Fig. 2).

Results

In Fig. 2 the 300-, 250-, 200- and 150-mb ozone mixing ratio maps are given for the 3rd and the 4th of May 1963, 12 GMT. On the 3rd a westerly jet had penetrated into the North American region just south of the U.S.A.–Canadian border and as far east as the Great Lakes area. On the 4th the jet extended clear into the westernmost Atlantic and stayed roughly at the same latitudes. On the northern side of the jet the tropopause dipped down below the 300-mb level (Figs. 2*a* and 2*b*) and close to the northern edge of the jet the ozone mixing ratio reached values of 0.50 μg/g or more. However, as can be seen from Fig. 2*b* it is only in a very narrow tongue parallel to the jet axis that the stratospheric air at 300 mb shows such high values. One has to go further north to once again reach values of 0.50 μg/g or higher. In these areas a value of 0.50 μg/g or more seems to be

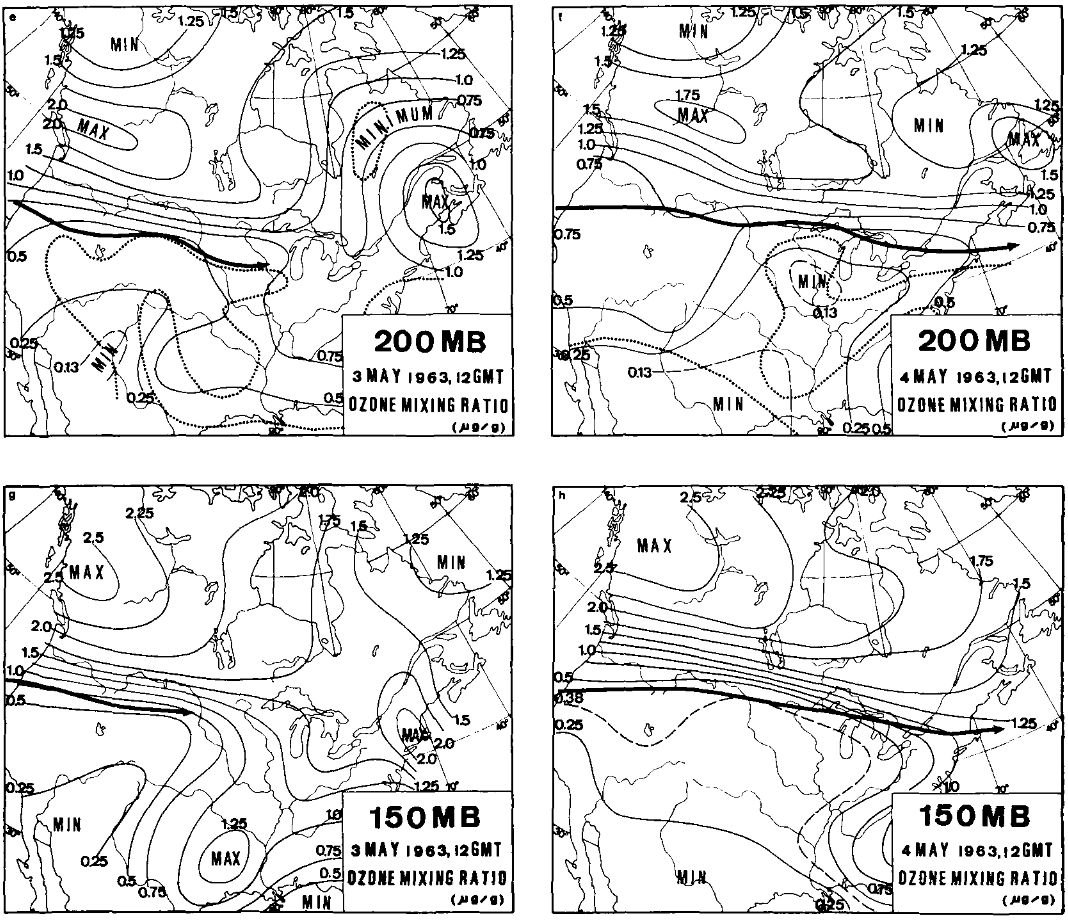

Fig. 2 e–h

normal for these altitudes. Comparing Figs. 1*a* and 1*b* with Figs. 2*a* and 2*b* it can be seen that the small tongue of higher ozone values just north of the jet axis coincides well with the warm area. In connection with the development of the jet the typical warm sector just north of it develops through stratospheric subsidence. This subsidence also brings down air with higher ozone mixing ratio. When the jet entered the North American continent it was already well developed and the calculated isentropic trajectories indicate that the air moved across the continent without significant height changes. Thus, the increase of ozone mixing ratio over, say, the southern tip of the Hudson Bay from Fig. 2*a* to Fig. 2*b* was due to quasi-horizontal advection of air which was brought down to this level much earlier in connection with the development of the jet.

The tropospheric values of the ozone mixing ratio at 300 mb are mainly less than 0.20 $\mu g/g$. The higher values in the easternmost parts of the continent are due to an earlier disturbance with a rather low tropopause moving towards the northeast along the coast. On the 4th (Fig. 2*b*) higher ozone values were over Newfoundland.

Studying the 250-mb maps (Figs. 2*c* and 2*d*) we notice that, in spite of the fact that the stratospheric part of the discussed area is much larger than at 300 mb, the maximum values are still observed in a narrow tongue parallel to the jet axis. The gradients along the northern edge of the jet stream are quite large. The numerical values of the ozone mixing ratio are naturally higher as all the isobaric surfaces studied in this paper are in a height range where the ozone generally increases with height. In the troposphere, however, there are still large areas with ozone mixing ratios as low as 0.13 μg/g or lower.

Coming now to the 200-mb surface (Figs. 2*e* and 2*f*) we notice that most of the area studied is in the stratosphere. The intersection between the 200 mb surface and the tropopause is rather complicated as this happens to be the level where the tropopause is quasi-horizontal over large areas. It is interesting to note that the largest gradients of the ozone mixing ratio are no longer found close to the tropopause intersection. Comparing the other maps and the situation of the jet stream axis we see that the gradients are coupled to the jet. The tropospheric values can still be as low as 0.13 μg/g or lower.

Finally, the 150-mb maps (Figs. 2*g* and 2*h*) show that the maximum gradients of ozone mixing ratio are still found in the same areas as at lower levels. Apart from the main maximum over southwestern Canada there are also pronounced maxima on the 3rd over northeastern and south-central U.S.A. On the 4th the former maximum can no longer be distinguished, whereas the latter one moved eastwards without much change. Rather low values are observed in western U.S.A. on the 3rd and over central U.S.A. on the 4th. These areas are situated where two tropopauses can be observed, the lower one at about 200 mb and the higher one at 100 mb or slightly higher. The layer between these two tropopauses very often has a complicated thermal structure and shows large vertical as well as horizontal variations of ozone. These were discussed in Paper I to some extent and have been reported upon by several authors (see, e.g., Breiland, 1964 and 1965; Sticksel, 1966). Differential advection often leads to secondary maxima in this layer. One example of this can be found when comparing Figs. 2*f* and 2*h*. At 200 mb the western parts of U.S.A. have values between 0.50 and 0.75 μg/g, while at 150 mb the same area has between 0.20 and 0.50 μg/g.

Ozone and aviation

There was a brief discussion in Paper I about the hazard of ozone to aviation. It was concluded that according to available information the critical value of ozone mixing ratio seems to be about 1.5 μg/g. Looking at Figs. 2*e* and 2*f* we notice that rather large areas have ozone values higher than the critical one. A transcontinental flight at the 200-mb level or slightly below it could be made for a prolonged period in ambient air, the ozone mixing ratio of which is above the critical. From Fig. 2 it is also clear that apart from higher latitudes and higher altitudes one should especially expect to find critical ozone values along the northern flanks of a middle latitude jet stream.

Discussion of errors

The reliability of the analyses given in Fig. 2 is hampered by a number of factors. As already mentioned, the isentropic ozone charts discussed in Paper I are based on a series of assumptions. The assumptions of the conservatism of potential temperature and the ozone mixing ratio do not introduce significant errors for the time period (24 hours) and the height range (9–14 kilometers), used.

The construction of the isentropic trajectories introduces an error in the position of the starting or the final point of a trajectory. Under the meteorological circumstances prevailing during the time period studied the error should in extreme cases be of the order of 200–300 km. It should be noted that most of the trajectories were computed with the aid of observed winds.

Another source of error introduced in constructing Fig. 2 is the interpolation between the isentropic values of ozone mixing ratio in order to arrive at the isobaric ones. Looking at the time cross sections with ozone mixing ratio it is, however, clear that in most cases the vertical distribution was such that the interpolation could be safely done. Furthermore, the vertical distance over which the interpolation was performed was small, as five different isentropic levels were used. For all isobaric levels it was possible to have at least one intersection between the surface in question and an isentropic surface. Together with the time cross sections for the ozonesonde stations it was possible

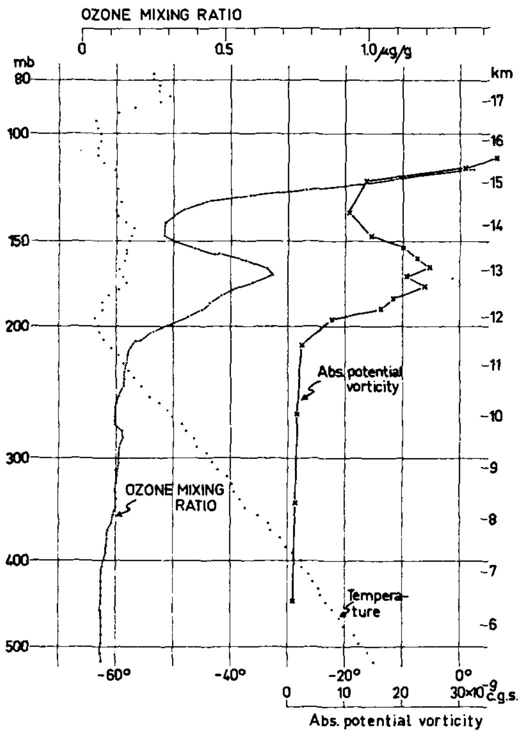

Fig. 3. Vertical distribution of temperature (dotted line) ozone mixing ratio (dash-dotted line), and absolute potential vorticity (crosses and solid lines) over Fort Collins, Colorado, on the 3rd of May, 1963, 12 GMT.

to get enough points on each isobaric map to arrive at a meaningful scalar analysis.

The instrument error of the ozonesonde is not of such magnitude (Hering & Dütsch, 1966) as to make the analyses in Fig. 2 doubtful. The inherent percentage errors are certainly smaller than the changes observed over 24 hours and the observed spatial variations on each of the maps. It is not believed that the instrument errors have any significant effect on the validity of the analyses in Fig. 2.

Ozone and absolute potential vorticity

In synoptic studies there is a need for conservative properties of air particles. For many purposes the potential temperature is very suitable and much of the work performed in connection with this paper and Paper I is based on the assumption of adiabatic motion. An even better parameter in this respect is, however, the absolute potential vorticity (P) defined as follows

$$P = -\frac{\partial \theta}{\partial p}(\zeta_\theta + f),$$

where θ is the potential temperature, p the pressure, ζ_θ the relative vorticity in an isentropic surface, and f the coriolis parameter.

As an example of the kind of values to expect Fig. 3 gives the distribution with height of absolute potential vorticity at the ozonesonde station at Fort Collins (40.6° N, 105.1° W) on the 3rd of May, 12 GMT. The method used for computing the values will be discussed below. The value of the absolute potential vorticity is characteristically one to two orders of magnitude larger in the lower stratosphere than in the troposphere. The stability factor $\partial\theta/\partial p$ usually attains a much higher value in the lowest layers of the stratosphere than in the uppermost troposphere. On the other hand it is clear from a study of the detailed vertical distribution of ozone that the ozone mixing ratio (1) increases, in most cases, very markedly at the troposphere and (2) varies with the vertical lapse rate of temperature in the lower stratosphere. Thus, ozone and absolute potential vorticity should show similar variations in the vertical. As a matter of fact it has been suggested (Danielsen, 1964) that they are highly correlated and that one could infer the ozone distribution from a known distribution of the absolute potential vorticity.

Fig. 3 gives the distribution of ozone mixing ratio together with absolute potential vorticity at Fort Collins. One notices that both curves show very low values in the tropopshere (below 200 mb) and a maximum at about 170 mb. A minimum in the ozone curve is observed at about 145 mb and in the curve for absolute potential vorticity curve at about 135 mb. Above the minima both parameters show a rapid increase with height. Fig. 3 also gives the temperature distribution with height, and we will return to this later. It should be pointed out here, however, that the temperature curve has not been smoothed and gives the half-minute values as tabulated in the original soundings. The ozone values are smoothed ones as pointed out in paper I, and the manner in which the absolute potential vorticity values have been computed also constitutes a smoothing

Table 1. *Correlation coefficients between ozone mixing ratio and absolute potential vorticity for selected isentropic surfaces and days, for 20 radiosonde stations within the area bounded by the latitudes 30 and 50° N and the longitudes 90 and 120° W*

The numbers within brackets indicate the number of pairs used in the computations.

	3 May, 1963 (12 GMT)	4 May, 1963 (00 GMT)	4 May, 1963 (12 GMT)	All data combined
320°K	0.54 (20)	0.68 (20)	0.51 (20)	0.58 (60)
330°K	0.87 (20)	0.86 (20)	0.75 (20)	0.78 (60)
350°K	0.47 (20)	0.41 (20)	0.34 (20)	0.39 (60)
375°K	0.64 (20)	0.61 (20)	0.46 (20)	0.64 (60)
400°K	0.63 (20)	0.63 (20)	0.60 (20)	0.69 (60)
All data combined	0.78 (100)	0.74 (100)	0.70 (100)	

operation. Thus, the very rapid change of the two parameters at the tropopause is somewhat blurred, as can be noticed in Fig. 3.

In order to study the relation between the distribution of ozone mixing ratio and the absolute potential vorticity a little further, the latter quantity was computed for a number of radiosonde stations for the 3rd (12 GMT) and the 4th (00 and 12 GMT) of May. The computations were made in the following manner.

For every 5°K potential temperature the pressure and the west and south components of the wind were known. For all available isentropic surfaces between 300°K and 400°K wind-component maps were analyzed and the pressure difference computed for a 10°K potential temperature difference, centered around the isentropic surface in question. The relative vorticity was computed using the distance of 2° latitude (222 km) as the unit distance. Among the available data absolute potential vorticity values for 20 stations were selected all situated in the area bounded by latitudes 30° N and 50° N and by longitudes 90° W and 120° W. As ozone values were available only for five selected isentropic surfaces in the temperature range given above, the computations of correlation coefficients had to be restricted to those surfaces.

Table I gives the correlation coefficients for the five selected isentropic surfaces and for three consecutive synoptic periods, 12 hours apart. Comparing the values one notices that maximum values are observed for the 330°K isentropic surface and minimum values for the 350°K surface. It should be kept in mind that some of the selected isentropic surfaces are entirely in the stratosphere and some are mainly in the troposphere over the area studied (see Paper I, Figs. 2 and 3). The 320°K surface enters the stratosphere in the northernmost part of the area, whereas the stratospheric part of the 330°K surface covers a slightly larger area. The 350°K surface is situated quite close to the secondary ozone maximum indicated in Fig. 3 and the 375°K close to the minimum (see Fig. 3). Finally the 400°K surface is close to the tropical tropopause extending as far north as to the latitude of the polar front jet stream. The reality of the differences between the correlation coefficients for the selected isentropic surfaces is difficult to evaluate, as the pairs of observations used are so strongly interrelated. Taking into account, however, that the ozone values used for the computations are interpolated from maps, which at best give only the large-scale features, and that the absolute potential vorticity was calculated over rather large distances in the horizontal as well as in the vertical, it can undoubtedly be said that the correlation coefficients in Table 1 are encouragingly high. A detailed study of this question should be made, using computed absolute potential vorticity values at the ozone stations for different periods of the year in order to study the feasibility of using regression equations, either on a daily, weekly or monthly basis.

The "sandwich" stratosphere

During the time period studied in connection with this paper a rather complicated thermal structure was observed in the lower stratosphere over central and western U.S.A., as indeed is quite often the case. The lowest tropopause was found at about 200 mb, extending from the polar front in the north down to southernmost U.S.A. This tropopause was very marked and a temperature inversion of up to 10°C or more was observed. Fig. 3 gives one example of this between 195 and 143 mb, although due to the very high resolution in the vertical the ascent curve in this layer is made up of several layers of varying stability. The radiosonde stations give a much more smoothed curve and the simultaneous sounding from Denver, only 120 km away, gave only one clear cut inversion of about 7°C immediately above the tropopause. Going back to Fig. 3 we also notice that from 143 mb and upwards the temperature is decreasing until at 109 mb nearly the same temperature is reached that was observed at the tropopause below. In this layer there are two layers with an adiabatic lapse rate with an almost isothermal layer in between. Again, the simultaneous Denver sounding gave only a constant decrease between the corresponding points.

Looking now at the curves for ozone mixing ratio and absolute potential vorticity in Fig. 3 we notice that both parameters have a secondary maximum in the inversion above the lower tropopause. The secondary minimum values are reached just above the top of the inversion, the ozone minimum apparently a little lower as a result of the smoothing procedure applied.

The layer between the two tropopauses, i.e. between 200 and 100 mb also showed some very marked changes with time of the ozone mixing ratio. Observations from the 1st and the 3rd of May at Fort Collins and Albuquerque (35.0° N, 106.6° W) may be taken as examples. At 125 mb the ozone mixing ratio decreased from 2 $\mu g/g$ to 0.23 $\mu g/g$ at Albuquerque and from 3 $\mu g/g$ to 0.7 $\mu g/g$ at Fort Collins; at the latter station an analysis of an ozone time cross section implies very clearly that less than 12 hours later the value was as low as 0.25 $\mu g/g$. These very marked changes were observed, while the lower tropopause changed very little and the large-scale features of the lower stratosphere were the same.

Looking at the large-scale synoptic features over the time period and area studied in this paper the day-to-day changes in temperature and wind were small. Nevertheless, the changes in ozone were very drastic. Unfortunately, no absolute potential vorticity values are available for the 1st and the 2nd of May. The rather small changes in temperature and wind would imply that only rather small changes would occur in the absolute potential vorticity during the time period in question. This would in turn imply that the correlation between ozone mixing ratio and absolute potential vorticity must have been another in the beginning of the period than at the end. The discussion of this interesting question must, however, be postponed until more information is available.

Combing the information of the vertical distribution and change with time of temperature, wind ozone mixing ratio, and absolute potential vorticity given above, one is led to the conclusion that the layer between 200 and 100 mb must be built up of air from very varying origin. It has been advocated (see e.g. Breiland, 1964) that this layer could be said to contain a lower part which would be of polar stratospheric origin and an upper part of tropical tropospheric origin. The values of ozone mixing ratio, absolute potential vorticity, vertical temperature gradient, and potential temperature in the upper part of the layer all speak in favour of an interpretation putting the origin of that air in the upper part of the tropical troposphere. However, when dealing with the lower part of the layer it becomes more difficult. The values of ozone mixing ratio and absolute potential vorticity undoubtedly correspond quite well to the values for the lowest part of the polar stratosphere within reasonable distance from the area under study. The main difficulty is to explain the potential temperature observed at the secondary ozone maximum of Fig. 3, i.e. about 350°–360°K. The corresponding values for the polar stratosphere where the ozone and the absolute potential vorticity values are about the same are in the 320°–330°K range. In order to resolve this difficulty one must assume one of two things. Either very strong non-adiabatic processes in the air moving southward must occur or the 'sandwiching' process took place much earlier than when the air entered the North-American continent. Although not enough evidence is as yet available, the present authors favour the latter explanation. Further studies will no doubt resolve the difficulty.

Conclusions

In spite of the fact that the analyses in Fig. 2 are based on a series of assumptions and that they are influenced by different sources of errors, it is believed that they give meaningful pictures of the synoptic, large-scale distribution of ozone mixing ratio on certain selected isobaric surfaces. The magnitudes of the gradients and the large-scale features which are well correlated with synoptic patterns, appear to justify the claim that analyses of the kind in Fig. 2 would provide a resonably good idea of the extent of exposure of a commercial jet aircraft to critical values of ozone concentrations. On the other hand, it is believed that before we are able to use the ozone measurements as meaningful complements to other meteorological observations in the study of the difficult analysis problems of what happens near the jet stream level, it is necessary to have, at least for a restricted period and space, a station density at least equivalent to the radiosonde station density in the United States and soundings at least every 3 hours. In addition it would be necessary to have aircraft measurements with continuous recording of the ozone content.

The correlation coefficients for ozone mixing ratio and absolute potential vorticity given in Table 1 show, according to the present authors' opinion, that it would be worth while to study in more detail the variation of that relationship in time and space. This should be done for the ozonesonde stations of the North American network as well as for the European network now being established.

The present study as well as others show that the lower stratosphere between the polar front jet stream and the subtropical jet stream often has a very complicated thermal structure. In future detailed studies of this interesting layer, observations of ozone mixing ratio will most likely play a very important role.

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РАСПРЕДЕЛЕНИЕ ОЗОНА НА ИЗОБАРИЧЕСКИХ ПОВЕРХНОСТЯХ

Определено распределение озона на поверхностях 300, 250, 200 i 150 миллибар для 3 и 4 мая 1963 г. на основе ранее опубликованных карт распределения отношения смеси озона на изэнтропических поверхностях. Сделаны также некоторые замечания о возможных помехах, вызываемых озоном, для авиации, о корреляции между отношением смеси озона и абсолютным потенциальным вихрем и о сложной слоистой структуре нижней стратосферы в средних широтах к югу от струйного течения полярного фронта.