# The vertical distribution of ozone over Arosa on 16 April 1962 and the synoptic situation

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ABSTRACT

A very marked change in ozone content in upper troposphere and lower stratosphere, observed during international intercomparisons of ozone sondes at Arosa in April 1962, is studied in relation to the synoptic situation. Some values are given for the observed ozone variations with time and space. The potential value of ozone data in synoptic research is discussed.

## The vertical distribution of ozone over Arosa on 16 April 1962 and the synoptic situation

In April 1962 international intercomparisons of different types of ozone sondes were performed at Arosa, Switzerland. During the test period striking changes of ozone occurred in the upper troposphere and the lower stratosphere. Before going into a discussion of these changes, a short description of the general synoptic situation is necessary. In Fig. 1*a*–1*c* are given 500 mb charts for the 15th, 16th, and 17th of April, respectively. On the 15th of April, cold air of polar origin covered Switzerland, southern France, and northern Italy (Fig. 1*a*). Another cold pool was situated over western Turkey and surrounding areas. On the south side of these cold pools a westerly air current prevailed over the Mediterranean and northern Africa. At 0000 GMT on the 16th (Fig. 1*b*) the cold pool was still holding its position over southern France and adjacent areas and its trough axis ran from the areas just west of Portugal to southern France and further on to northernmost Italy. During the 16th the warm southwesterly current was breaking through over southern Europe and at 0000 GMT on the 17th the warm air had reached Central Europe (Fig. 1*c*). The eastern part of the cold pool and its trough line swung to the north, while the trough line in the southern part moved in over the western parts of the Iberean peninsula. Thus, the cold air that covered Switzerland, southern France, and northern Italy was replaced by warm air (at 500 mb) during the 16th. This paper will try to relate the observed large changes in ozone during that day with the synoptic features of the circulation changes.

The observed variation of ozone over Arosa during the period 10–19 April 1962 is given in Fig. 2. In the lower part of the figure values are given for the total amount of ozone (expressed in m atm-cm), and the average ozone partial pressure (in $\mu$mb) in layer 1 (800–250 mb) and in layer 2 (250–125 mb). These values were arrived at by Umkehr measurements. An Umkehr measurement is taken from the time of astronomical sunrise and until a sun height of 30° and from a sun height of 30° to astronomical sunset. In April at Arosa it takes about three hours to make a complete Umkehr observation and it is centered around 06 GMT and 1630 GMT, respectively.

Umkehr observations were taken from the afternoon of the 10th to the morning of the 13th. Then there was a break in the observation series due to bad weather. The observations were resumed in the morning of the 16th and continued for the rest of the period indicated in Fig. 2. During the time period covered by the figure intercomparisons were made on the 13th, 14th, 16th, and 19th. Isolated flight of ozone sondes were made at other times. Of interest here are the flights made on the three first days indicated above. Unfortunately, no Umkehr observations were taken on the 14th, as already mentioned, but the ozone soundings made on the

[1] The work on which this paper is based was completed while the author visited the National Center for Atmospheric Research, Boulder, Colorado.

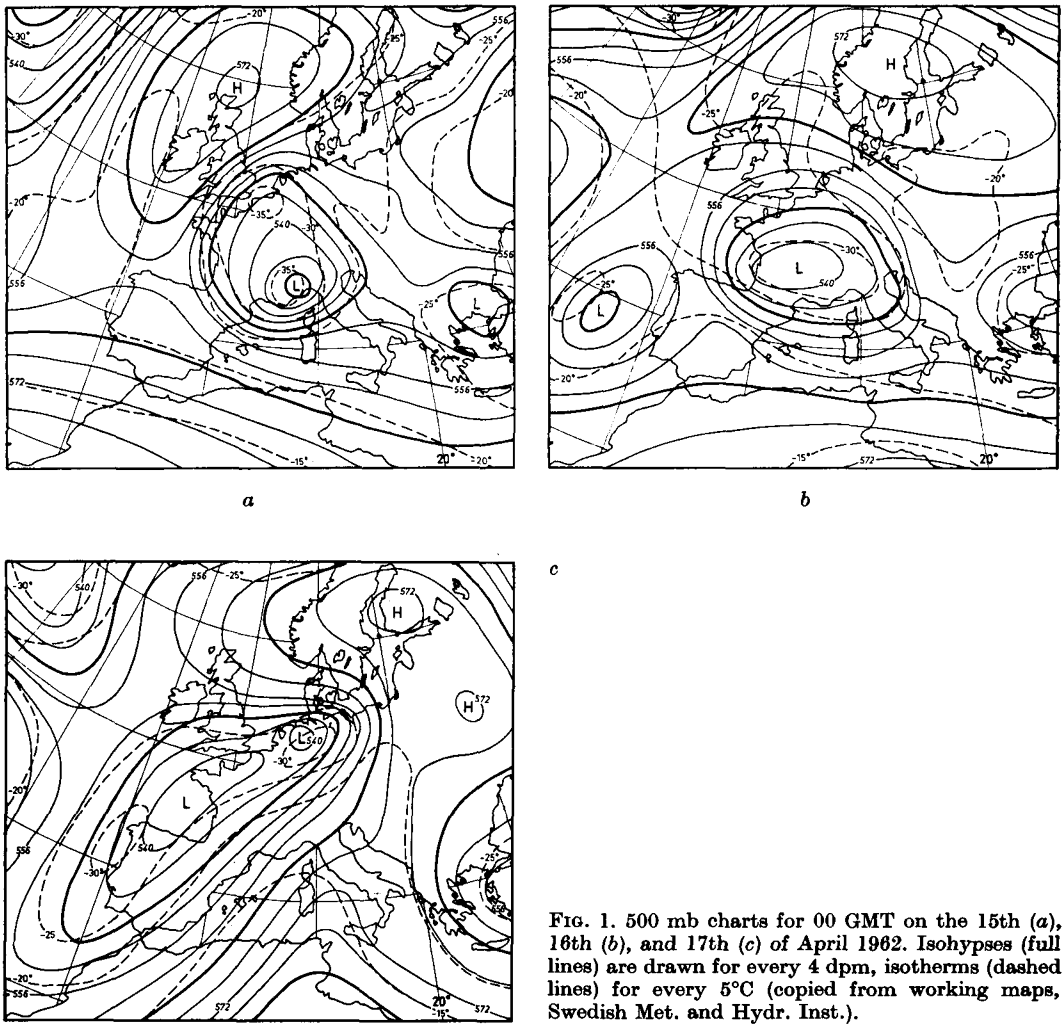


FIG. 1. 500 mb charts for 00 GMT on the 15th (*a*), 16th (*b*), and 17th (*c*) of April 1962. Isohypses (full lines) are drawn for every 4 dpm, isotherms (dashed lines) for every 5°C (copied from working maps, Swedish Met. and Hydr. Inst.).

13th and the 14th make it possible to arrive at a reasonable value for the total ozone amount on the 14th. Using the ozone soundings made on the two days it is possible to get an integrated value of ozone between 800 and 4 mb. Extrapolations to 1000 mb and 1 mb, respectively, make it possible to arrive at the following values for the integrated ozone amount: 329 m-atm-cm (13th) and 419 m-atm-cm (14th), respectively. The first value is too low and it seems to be about 35 m-atm-cm off as compared with the values given by the Umkehr observations. The indicated increase, however, between the 13th and the 14th should, however, be acceptable and we thus arrive at reasonable values of about 450 m-atm-cm for the 14th. When the observations were resumed on the 16th the observed value of total ozone was 453 m-atm-cm. During the day, however, a sharp drop in the amount of ozone occurred. The decrease continued until the 18th. As far as the vertical distribution of ozone is concerned the Umkehr measurements gave the values for layer 1 and 2 as indicated in Fig. 2. All three curves are parallel except on the 18th. The increase in layers 1 and 2 started already on the 17th while the total amount continued to drop until the 18th.

The 500 mb and 300 mb temperatures and winds are given in the upper part of Fig. 2. As could be expected, a negative correlation was

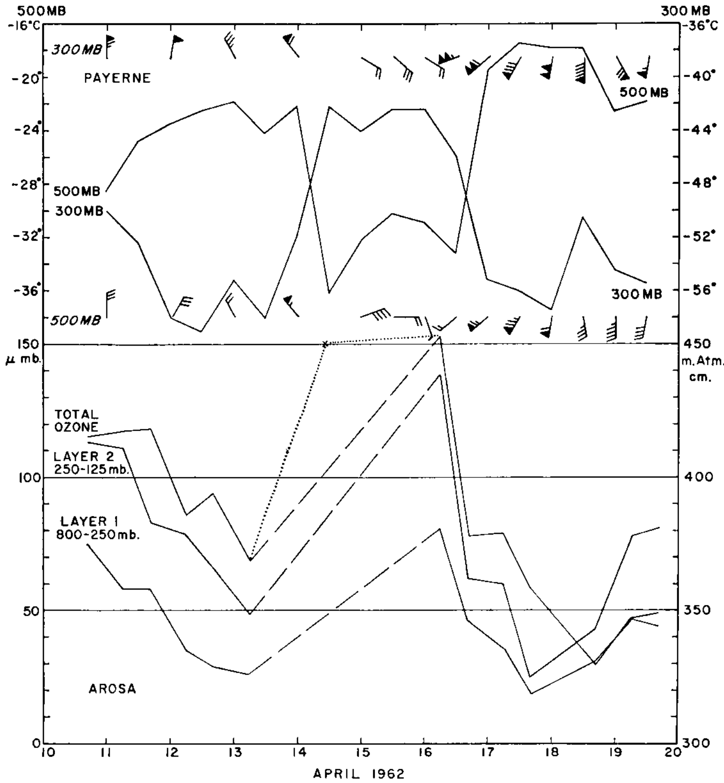


FIG. 2. Daily variations (at Arosa) of ozone (total in m Atm cm, layers 1 and 2 in $\mu$mb), 500 and 300 mb temperatures and winds (at Payerne) during the period 10–19 April 1962. The cross indicates an estimated total value (see text) and the dotted line a probable distribution of total ozone between the 13th and 16th.

observed between the 500 mb and 300 mb temperature changes. High values of ozone amounts are connected with low 500 mb temperatures. The dominating wind direction from the 10th to the 14th (winds are given for every 24 hours at 0000 GMT) is between north and northwest, indicating that Payerne during this period was west or southwest of a trough or a low. On the 14th the wind shifted sharply to east and southeast and Payerne was now north of the low (Fig. 1*a*). As can be seen from Fig. 2, a radical change occurred in the synoptic pattern over Switzerland during the 16th. The indicated temperature and wind variations give a good example of a case where a cold regime in low and middle troposphere is quickly changed over to a regime with strong advection of warm air from a southerly direction. The ozone changes observed during this period were quite large and due to the intercomparisons, vertical ozone soundings are available for the 16th with only 4½ hours time difference. Before going into the details of these soundings, however, let us first look at the change of total ozone during the 16th. Fig. 3 gives the variation of the total amount of ozone as measured using wave length pair *C*. The decrease during the day from 462 m-atm-cm at 0829 GMT to 364 m-atm-cm at 1612 GMT or 21 per cent is unusually large. As can be seen from Fig. 3, however, the decrease during the day was rather uniform and the observations can tell us nothing about at what levels the main events were taking place. In order to study the detailed variations in the vertical distribution of ozone it is necessary to make use of ozone soundings. On the 16th intercomparisons were made at 1003 GMT and 1438 GMT, respectively. The two ozone sondes being compared were the Regener chemoluminescent sonde and the Brewer electrochemical

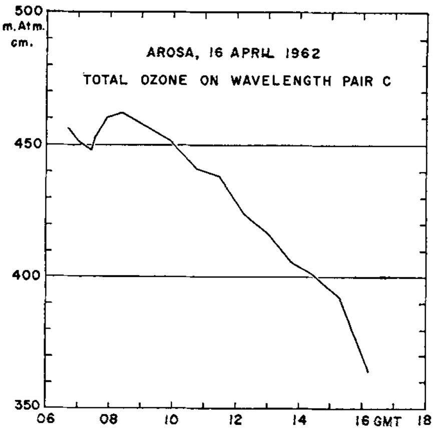


FIG. 3. Change of total ozone during the 16th of April 1962, at Arosa as measured using the $C$ wave length pair.

sonde. Thus, because of the intercomparisons we now have excess not only to two soundings only $4\frac{1}{2}$ hours apart, but also to two simultaneous soundings at each occasion. This will enable us to study, with some confidence, vertical as well as time variations of ozone around noon of the 16th. In Fig. 4 are given the two Brewer soundings together with the morning and afternoon Umkehr measurements. As can be seen from the soundings the main changes occurred below the 200 mb level. The indicated changes in Fig. 4 are supported by the simultaneous Regener soundings. There is, however, a discrepancy above the 50 mb level which will not be discussed in this paper as the object here is to relate observed changes of ozone below 250–200 mb with the synoptic pattern. The Umkehr observations given in Fig. 4 indicate the great changes in ozone but due to the smearing effects of the evaluation technique, it is not possible to tell where the main events were taking place (DÜTSCH, 1963).

In order to establish the synoptic features as accurately as possible, a large number of charts and diagrams were constructed. For all stations indicated in Fig. 5 ascent curves were drawn and for most of them time cross sections were constructed. Some space cross sections were also constructed and those which will be discussed in this paper are indicated in Fig. 5. Cross section I is the section which comes closest to Arosa and which at the same time is as clear cut as possible. It would have been possible

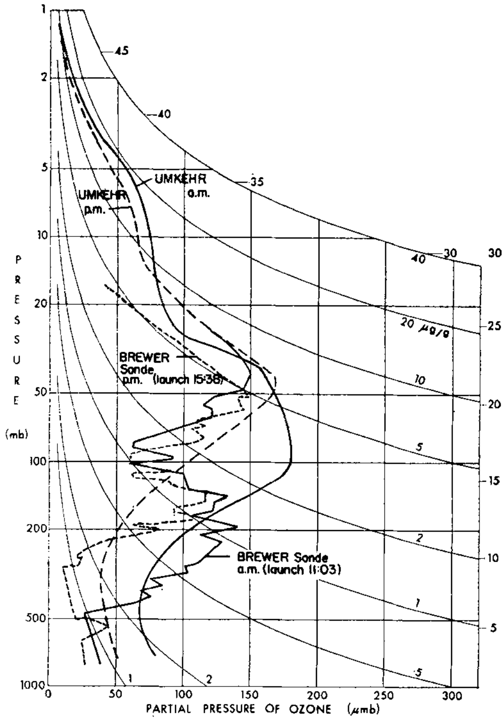


FIG. 4. Vertical distribution of ozone at Arosa on 16th April 1962 at 1003 and 1438 GMT, respectively. The morning and afternoon Umkehr-curves are also given (from DÜTSCH, 1963).

to show a cross section going south-north from station 07761 on Corsica to station 10035 in northern Germany. This section, however, crosses the northern part of the front too near the area where the front at 500 mb recurves. The

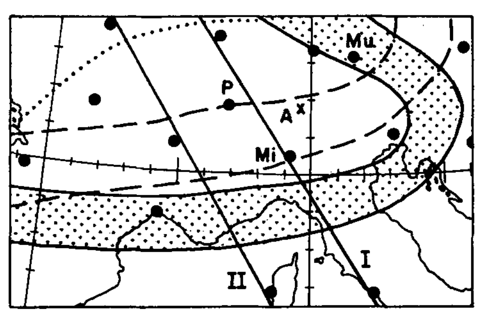


FIG. 5. The positions of the 500 mb front at 0000 GMT (boundaries given by solid lines) and 1200 GMT (dashed lines) on the 16th of April 1962 and at 0000 GMT on the 17th (southern boundary given by the dotted line). Filled circles indicate radiosonde stations used.

best picture of the frontal structure was arrived at using cross sections I and II and other sections to the west of Arosa. It was also easier to interpret these sections with regard to the events taking place over Arosa. The general direction from which air was advected in over Arosa was from the southwest.

As no temperature soundings from Arosa for the time of the intercomparison were available to the author, other radiosonde stations had to be used in order to establish the distribution of temperature over Arosa at the time of the rapid change in the vertical distribution of ozone. Two different methods were used in order to arrive at the most likely distribution of temperature over Arosa: (1) a time cross section for Arosa was constructed by interpolation between time cross sections from neighboring stations and (2) space cross sections through Arosa at the time of the two ozone soundings (1003 and 1438 GMT, respectively) were constructed using space cross sections at 1200 GMT and charts giving isochrones for the passage of the front at different levels. In order to indicate the complexity of the problem, three successive positions of the 500 mb front have been given in Fig. 5. From this figure it is clear that during the time period studied Arosa and the Swiss radiosonde station Payerne (06610) was in the cold air in the beginning of the period. The front passed these stations in a regular fashion which would make it possible to make meaningful interpolations. The same is true for the Italian radiosonde station at Milan (16080). Both Payerne and Milan would thus serve as good basic stations for the interpolations. In order to arrive at the best interpolation possible it was also considered necessary to include a station to the north of Arosa. The nearest stations are Stuttgart (10739) and Munich (10866) in southern Germany. Munich was chosen because six-hourly winds were available from that station. The distances between the three stations and Arosa are of the order of 200 km. As can be seen from Fig. 5, Munich will show a more complicated sequence of events than the other two stations. At the beginning of the period, the Munich sounding passed through the 500 mb front and the front thus passed Munich twice during the period. This will come out clearly in the later discussion.

## Interpolation using time cross sections

For most of the stations indicated in Fig. 5, time cross sections were drawn using the twelve-hourly observations (as already stated, six-hourly wind observations were used for Munich). Three of these sections are reproduced in Fig. 6. In the case of the Payerne and the Milan cross sections the analysis was relatively simple as these stations were in the cold air up to at least 500 mb in the early part of the period and mostly in the warm air after that. Munich was, however, in the beginning of the period partly in warm air. This air mass moved north and at 1200 GMT on the 16th polar air was to be found at all levels over Munich. The typical low tropopause and the warm stratosphere is easily recognized. Then the front (at 500 mb) moved in over the station again.

The cross sections contain fronts, tropopauses, isotherms, and observed winds. As can be seen from the plotted winds, the wind distribution over Payerne and Milan is somewhat surprising. In both cases the vertical wind shear through the front at 1200 GMT on the 16th is rather strong and in good qualitative agreement with the thermal wind equation. The first wind maximum over Milan occurred already at 500 mb where a speed of 91 knots was reported. The next and main maximum occurred at 350 mb (132 knots). Also Payerne reported a double maximum of 105 knots at 339 and 300 mb, respectively. The same double maximum structure was observed at several other stations in the area and it can also be noticed over Munich at 0000 GMT on the 17th.

After the analysis of the three cross sections given in Fig. 6 had been completed, fronts and tropopauses from all three sections were entered on the same sheet of paper and on the same time scale. The average position of the two sides of the front was then computed for the 700, 600, 500, 400, 350, 300 and 250 mb levels using the inverted values of the distances between the three stations and Arosa as weighting functions. The average pressure at the tropopause was computed using the same weighting functions and for distances corresponding to 6, 12 and 18 hours before and after the time of passage of the warm side of the front at 500 mb at each station. In some cases only two stations could be used for this computation as Munich was influenced by the front twice. Finally average

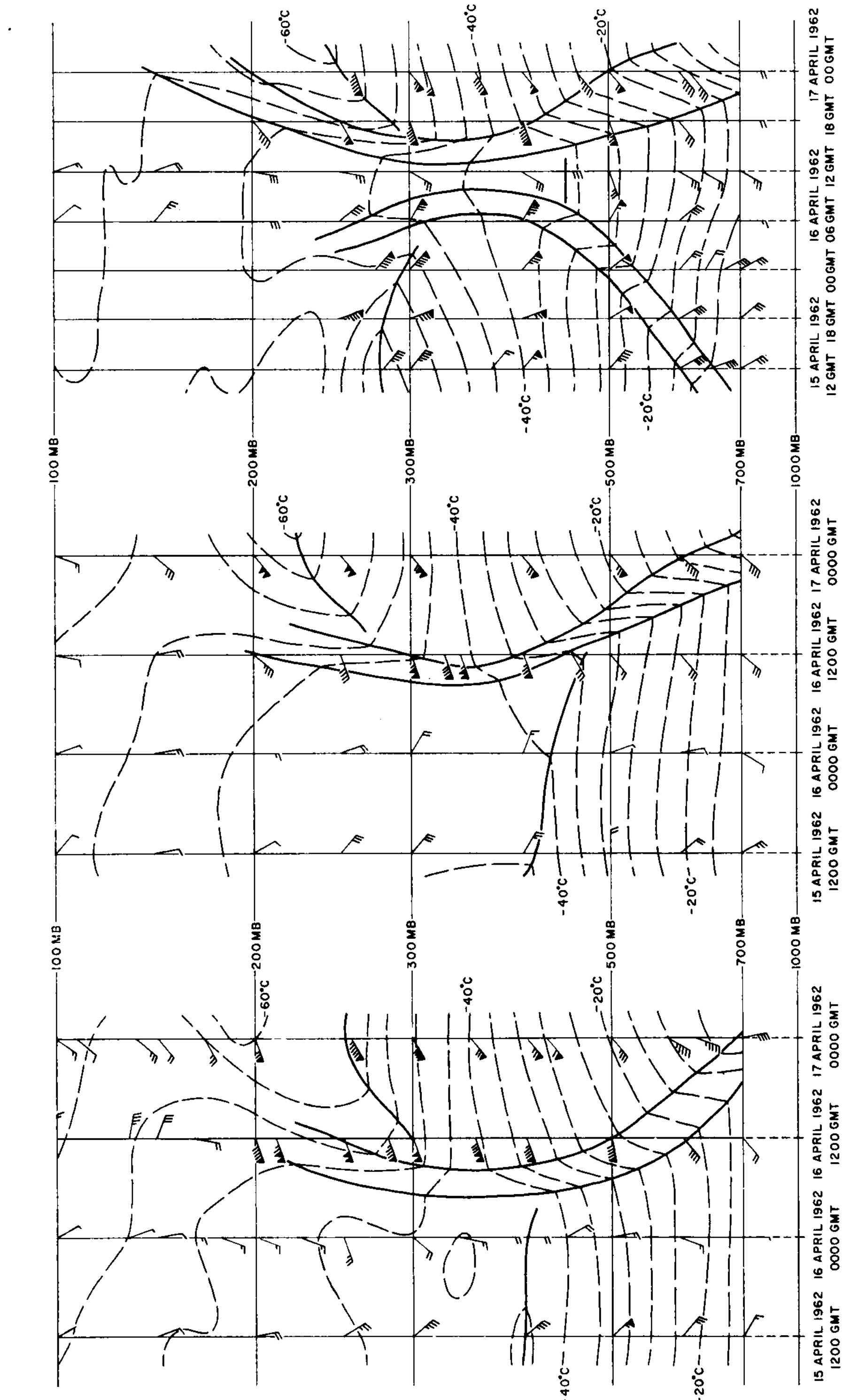


FIG. 6. Time cross sections for Milan (16080), Payerne (06610), and Munich (10866) for 15–17 April 1962. **Heavy** solid lines are frontal boundaries and tropopauses; dashed lines isotherms for every 5°C; winds are given in knots (triangle 50 knots, full barb 10 knots, half barb 5 knots; north-south direction vertical).

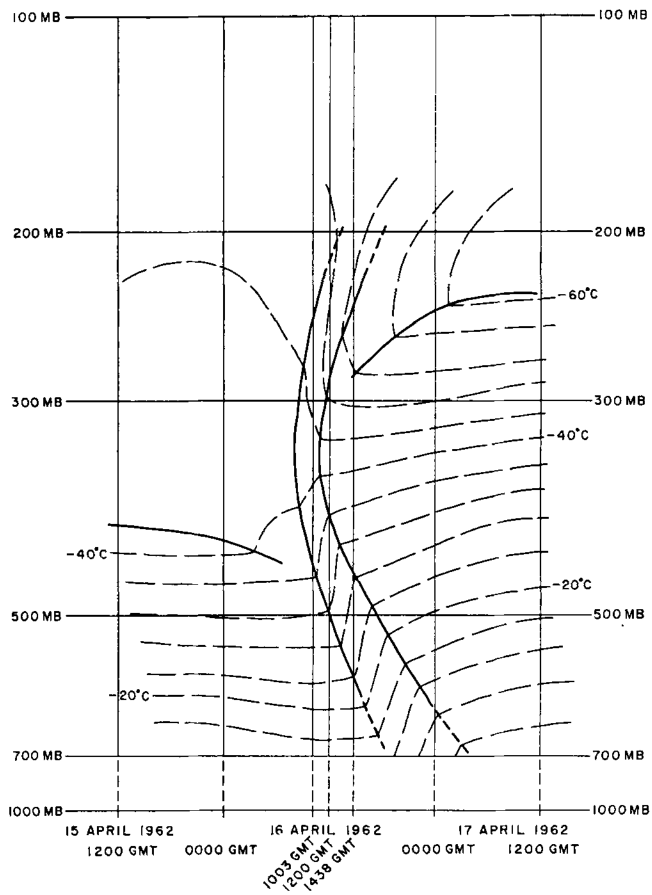


FIG. 7. Computed time cross section for Arosa, 15–17 April 1962. The times of the ozone soundings (1003 and 1438 GMT) are indicated.

temperatures were computed for each of the pressure levels indicated above and using the same weighting functions. The temperatures were read off at equal distances from the frontal boundaries in the three time cross sections used. The result of these computations is given in Fig. 7, which represents a computed time cross section for Arosa. It is now possible to get an idea of the vertical distribution of temperature over Arosa at the time of the intercomparisons, i.e. at 1003 and 1438 GMT. In Fig. 7 the time of the ozone soundings is indicated by vertical lines. According to the figure the 1003 GMT sounding started in cold air and reached the lower part of the front at 450 mb. From there on and up to 240 mb the balloon was within the frontal layer. At the level where the front was vertical the sounding passed quite near the edge of the advancing air mass.

At the time of the next sounding, i.e. 1438 GMT, the new air mass had advanced further and the balloon entered the front already at 580 mb. Near the 450 mb level the balloon entered the warm air and at 285 mb the middle tropopause was reached. At 240 mb the sounding again entered the front and stayed within the frontal layer to the top of the layer investigated here.

The discussion of the vertical ozone distribution will be postponed to a later paragraph.

## Interpolation using space cross sections

Using the stations indicated in Fig. 5 and also some outside of this area a number of space cross sections were drawn. The two main ones were taken along the lines I and II indicated in Fig. 5. Section I is the principal one and the

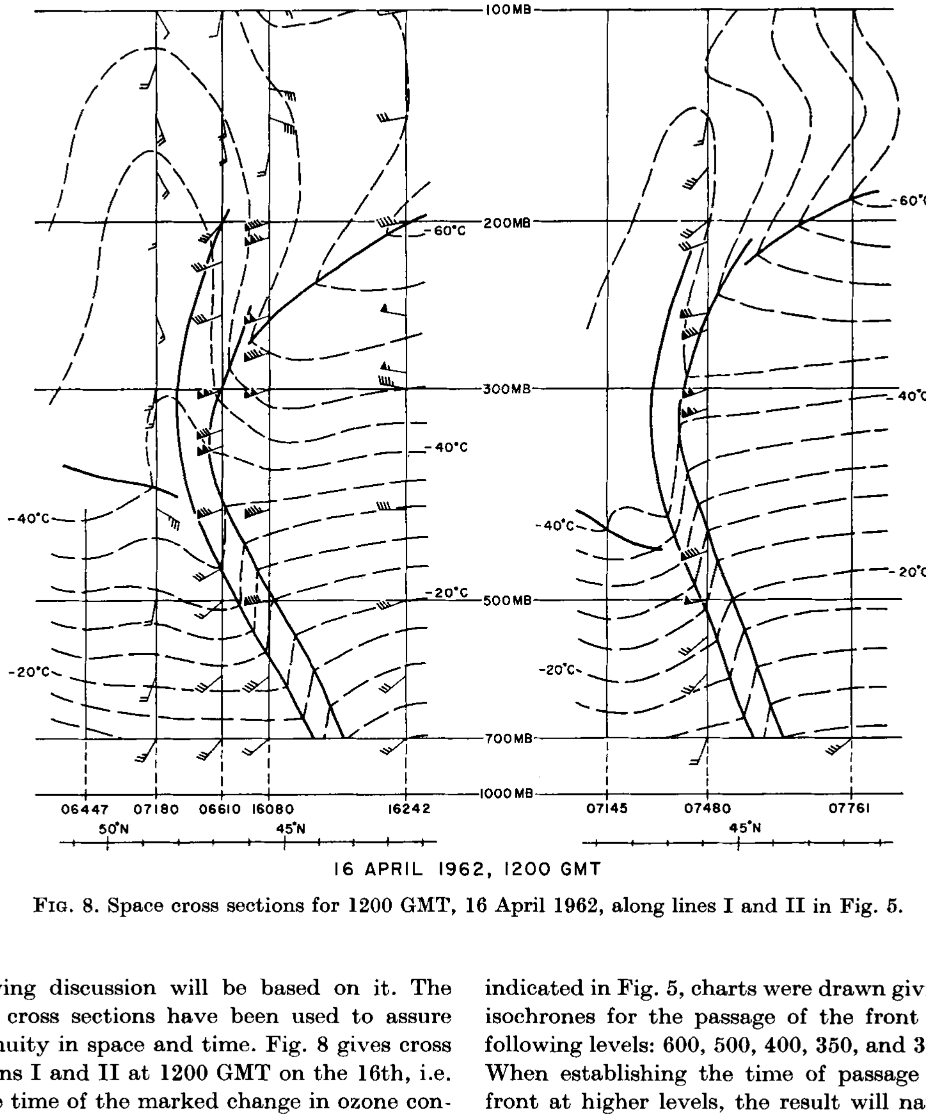


FIG. 8. Space cross sections for 1200 GMT, 16 April 1962, along lines I and II in Fig. 5.

following discussion will be based on it. The other cross sections have been used to assure continuity in space and time. Fig. 8 gives cross sections I and II at 1200 GMT on the 16th, i.e. at the time of the marked change in ozone concentration below 200 mb.

Using the wind direction of the advancing air in the upper troposphere as the direction of projection, the position of Arosa on cross section I was established. If the direction of the isotherms at, say, 500 mb had been used instead of the wind direction, the position of Arosa on cross section I would have been moved slightly towards Payerne. It would, however, not have passed the position of Payerne on the cross section.

With the aid of all the cross sections drawn during the course of this study and also using all the plotted ascent curves for the stations indicated in Fig. 5, charts were drawn giving the isochrones for the passage of the front at the following levels: 600, 500, 400, 350, and 300 mb. When establishing the time of passage of the front at higher levels, the result will naturally depend upon the type of analysis model used. The estimated time of passage of the edge of the advancing air mass below 250 mb would not, however, differ much if another model would have been applied instead of the one used in this paper. For this reason the time passage of the front as given here is believed to give the time of passage of the forward edge of the advancing air mass reasonably accurate. We will return later on to a discussion of the accuracy of the estimates.

Combining cross section I with the charts giving the time of passage of the front at different levels, it was possible to construct two

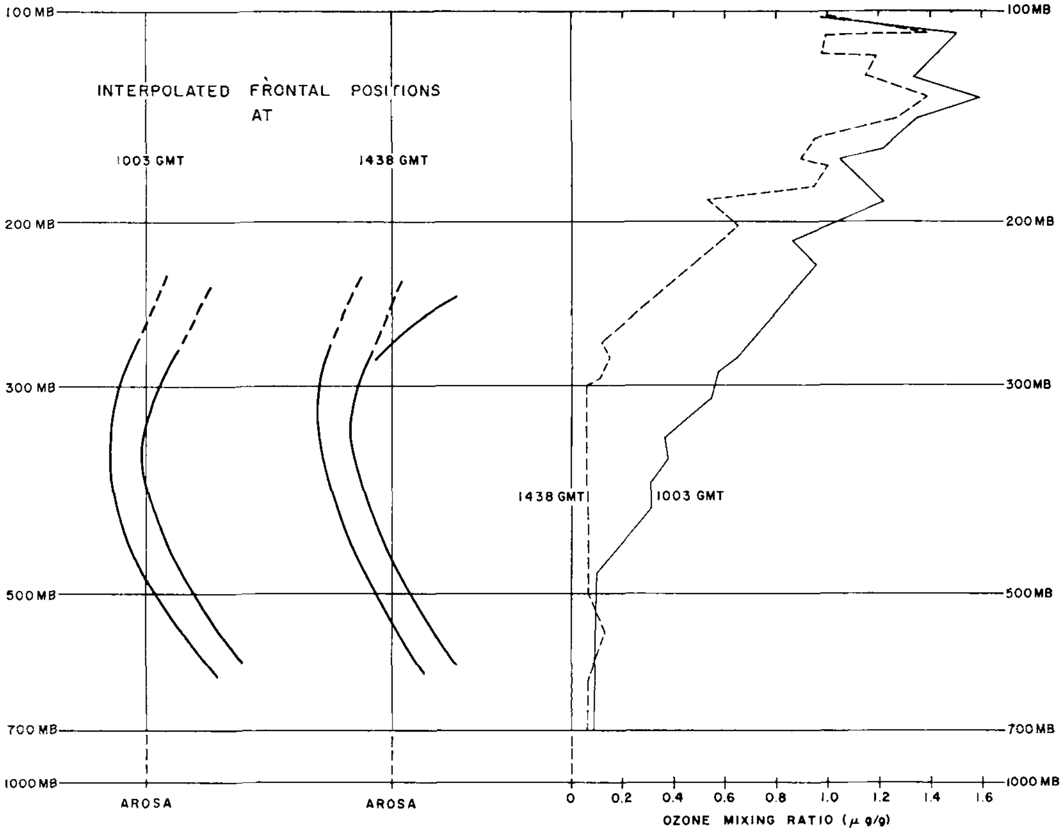


FIG. 9. Estimated space cross sections for 1003 GMT (left) and 1438 GMT (middle), 16 April 1962, along line I in Fig. 5. The positions of the ozone soundings are given by vertical lines. To the right the vertical distribution of ozone mixing ratio is given in $\mu$g/g.

space cross sections at the time of the intercomparisons, i.e. 1003 and 1438 GMT, respectively. These interpolated cross sections are given in Fig. 9. The necessity for using estimates of the speed of the front at different levels is clear from the fact that the slope changed during the time interval studied. The front moved at a higher speed at higher levels, giving rise not only to a change of the slope of the front but also to a change of the level at which the front became vertical.

Comparing Fig. 9 and Fig. 7 we notice that the position of the hypothetical Arosa soundings are slightly different in the two figures. In Fig. 7 the 1003 GMT sounding reached the front at 450 mb and stayed within the front up to 240 mb. In Fig. 9 the front is reached at 480 mb. The vertical line representing the sounding again crosses the frontal boundary at 385 mb to remain in the advancing air mass up to 335 mb. Between 335 and 260 mb the sounding is within the upper part of the front. This difference in position relative to the vertical part of the front corresponds to a difference of one hour in the time of passage of the front.

In the case of the hypothetical 1438 GMT sounding in Fig. 7, i.e. the result of interpolation using time cross sections, the sounding was in the front between 580 mb and 450 mb. At 285 mb the middle tropopause was reached and the upper part of the front at 240 mb. In Fig. 9 the constructed sounding passes through the front between 540 and 460 mb, the tropopause at 270 mb and again into the front at 245 mb. The largest differences in the two estimates are connected with the position of the front in lower levels. The average front in Fig. 7 is influenced considerably by the frontal structure over Munich. The very deep frontal layer given by Fig. 6 for Munich is representative only for the northern portions of the front. It seems therefore likely that the vertical extent of the front as given by Fig. 9 is more representative for the southern portions of the front, and thus also for the conditions prevailing over Arosa between 10 and 15 GMT on the 16th. The difference in Fig. 7 and Fig. 9 of the distance from the vertical portion of the front to the vertical line in question corresponds to one hour, i.e. the same difference as already observed for the 1003 GMT sounding.

Before going into a discussion of the ozone distribution as given by the ozone soundings at 1003 and 1438 GMT, respectively, we should discuss the accuracy of the estimates on which Fig. 7 and 9 are based. Over and above the usual errors in radio soundings which are well-known and will not be discussed here, the time and space cross sections are influenced by time errors. Firstly, when constructing the cross sections it has been assumed that the soundings took place at 00 and 12 GMT, respectively. Secondly, when analyzing the isochrones for different pressure levels, the accuracy of the analysis is not greater than about one hour. Thirdly, when constructing Fig. 7, it was assumed that the front moved with a constant speed over the area in question. This was not quite the case and for this reason the interpolation using time cross sections has an added inaccuracy. Finally, all soundings have been represented by straight vertical lines which implies instantaneous observations at all levels. The balloon rises, however, with a speed of about 300–400 m $min^{-1}$ and reaches the 200 mb level 30–40 minutes after the release of the balloon. The same slight inaccuracy is, however, present in all cases and the residual error is considered to be rather small and negligible.

From what has been said so far one can draw a conclusion regarding the time difference between the two estimates in Fig. 7 and Fig. 9. As stated above this difference amounts to one hour, i.e. the same order of magnitude as given for the errors. The differences which can be observed when studying Fig. 7 and 9 might therefore not be real. On the other hand it is reasonable to assume that an interpolation using space cross sections is slightly better than an interpolation using time cross sections under the conditions prevailing in the case studied in this paper. Thus, the most probable solutions of the problem to construct two hypothetical soundings for 1003 and 1438 GMT, respectively, are the ones given in Fig. 9. It should also be noted that the position of Arosa was projected into the cross section using wind data in the upper troposphere. However, in the lower troposphere the wind direction and the direction of the isotachs were slightly different. This means in effect that the vertical line representing Arosa in Fig. 9 should slant slightly towards the left.

## The vertical distribution of ozone in connection with the synoptic pattern

The right part of Fig. 9 gives the vertical distribution of ozone mixing ratio as observed by the Brewer sonde during the intercomparisons at 1003 and 1438 GMT on the 16th. At the same time a Regener sonde was flown and the two sets of observations support each other quite well. Unfortunately, the values between 650 and 500 mb were missing from the Regener sounding at 1438 GMT. As was already stated in connection with Fig. 4, a striking change of ozone was observed between 1003 and 1438 GMT below 200 mb. We will now try to connect these changes with the hypothetical cross sections in Figs. 7 and 9. Starting with the 1003 GMT ozone sounding we notice a sharp change in the vertical gradient of ozone mixing ratio at 475 mb. This corresponds well to the value given in Fig. 9 for the lower boundary of the front at that time over Arosa (480 mb). It is also reasonably well in accordance with the corresponding value from Fig. 7 (450 mb). Thus, *the rapid increase in ozone seems to start at the* lower boundary of the front. Before going any further we should say a few words again about the analysis model used in this paper. Looking at the different cross sections given in this paper it is obvious that it may at times be difficult to distinguish between the lower boundary of the front and the southernmost part of the polar tropopause. When applying the analysis model in which one does not distinguish between the lower boundary of the front and the polar tropopause, this difficulty is resolved. This solution may, however, represent an over-simplification of the problem. So far, no unanimous agreement has been reached on this subject.

The strong vertical gradient of ozone continued up to 222 mb. Above that level rapid vertical variations were observed. Looking at the ozone sounding as a whole it is possible to divide the sounding in three parts: first, a tropospheric part with nearly constant ozone mixing ratio. Above that a layer with a strong increase of ozone. The top of this layer is found at 222 mb. Above that there are strong vertical variations of ozone. The same division into three different parts could also be made in the case of the Regener sounding at 1003 GMT. The corresponding values are 480 mb (in the Brewer sounding 475) and 250 or 200 mb (222 mb). Looking closely at the soundings one will notice that the layer with strong increase has some irregularities in the 300–400 mb layer. These irregularities in the vertical distribution of ozone occurred at levels where, according to Fig. 7 and 9, the front was vertical. It is interesting to note that this region on the cyclonic side of the jet stream core is also one of the preferred regions for clear air turbulence.

In connection with the advance of a new air mass over Arosa with the corresponding lowering of the lower front and increase in the height of the tropopause and the upper front, a marked decrease of the ozone mixing ratio occurred (Fig. 9). As a consequence of the earlier discussion it would be tempting to combine the secondary maximum between 620 and 500 mb with the warm front over Arosa. According to Fig. 9, however, the front is found between 540 and 460 mb. The corresponding values from Fig. 7 are 580 and 450 mb, respectively. Thus, it seems as if the increase in ozone concentration started well below the lower frontal boundary and as if the maximum was reached just at this boundary. There are, however, other evidences speaking in favor of the assumption that the maximum actually occurred in the frontal layer. Other authors have reported on cases where the maximum occurred in the front (Briggs & Roach, 1963). The newly developed synoptic ozone sonde network in USA has already provided some very typical cases indicating this type of distribution (Hering, 1964). Using the provisional data so far available, a tentative study has been undertaken of cases where a front was indicated around the 500 mb level. Eleven cases were studied and in all cases the increase of ozone started below the lower boundary of the front. The average value of the pressure difference was 22 mb. The data also suggested that the pressure difference increased with the vertical depth of the front. In the case of the 16th of April 1962 the ozone increase started at 620 mb (Fig. 9). Using the difference indicated above, this would place the lower boundary of the front at about 595 mb. From Fig. 7 it can be seen that the lower boundary was placed at 580 mb. However, in the case of the northern extension of the front, its vertical dimension was larger than in the southern parts. Keeping the lower boundary fixed and using a more representative value for the vertical extent of the front would place the upper boundary at 480–500 mb. From Fig. 9 we arrived at the values 540 mb and 460 mb for the boundaries of the front. Taking all the values into account it seems likely that the observed maximum at 550 mb in Fig. 9 occurred within the front. The effect of varying the projection direction mentioned earlier also suggests this interpretation. Looking at the upper part of the 1438 GMT sounding we find that there is a hump in the zone curve slightly above the 300 mb level. In Fig. 7 and 9 we find that the hypothetical sounding at 1438 GMT passes through the tropopause at 270 mb (Fig. 9) and 285 mb (Fig. 7), respectively. The upper part of the front is reached at 245 and 240 mb, respectively. Thus, in both cases the conclusion is that the balloon should have been in a stratospheric layer, 25–45 mb deep, before entering the front once more. The first increase in the ozone curve starts at 300 mb and the second one at 270. This would indicate that the ozone concentration has a secondary maximum in the shallow stratospheric layer first reached by the balloon provided that the position of the tropopause is off by 15–30 mb. With the same provision the main increase is observed in connection with the upper portion of the front. The Regener sounding, however, did not show the corresponding hump at these pressures as it showed only a marked increase from 285 mb.

## Vertical and horizontal gradients and rate of change with time of ozone mixing ratio

From the ozone soundings made at 1003 and 1438 GMT it is possible to estimate gradients and rate of change with time of the ozone mixing ratio. For all levels below the 250 mb surface the maximum horizontal (more correctly isobaric) difference was observed at 270 mb. Using the observed speed of the front at this level we arrive at a value of 0.32 $\mu g/g$ per 100 km for the maximum horizontal gradient of ozone mixing ratio. The corresponding value for the maximum rate of change with time was 0.13 $\mu g/g$ per hour.

From Fig. 7 and Fig. 9 it is clear that the above given values for the horizontal gradient and the rate of change with time are representative for an area which is partly within the upper part of the front and partly in the lowest layers of the stratosphere. For the 350 mb level, i.e. near the level at which the front was vertical, the corresponding values were 0.15 $\mu g/g$ per 100 km and 0.06 $\mu g/g$ per hour respectively. The later values would apply to an area between the jet stream core and the vertical front and more specifically to the 200 km nearest to the front.

The above-mentioned values are in close agreement with the corresponding values computed from the simultaneous Regener soundings.

The two ozone soundings at 1003 and 1438 GMT, respectively, give an indication of the ozone distribution partly in the forward edge of the advancing air mass and partly in the front. It is not possible with the material at hand to draw any conclusions about horizontal gradients of ozone mixing ratio within the front at about 300 mb and in the stratosphere above the polar tropopause. For the time being it is only possible to give estimates of horizontal gradients representative for the edge of the advancing air and for parts of the front. As more and more ozone soundings are becoming available, it will eventually be possible to give a more complete picture of the distribution of ozone around the jet stream core.

The vertical gradient of ozone mixing ratio has been computed for the lower and upper part of the front at 1003 GMT, i.e. between 475 and 405 mb and between 280 and 222 mb. The gradients were 0.19 and 0.20 $\mu g/g$ per km, respectively. The Regener soundings gave exactly the same value for the lower layer and 0.25 $\mu g/g$ per km for the upper layer. For the 1438 GMT sounding the vertical gradient in the upper part of the front, i.e. between 270 and 202 mb, was 0.28 $\mu g/g$ per km. The corresponding value for the Regener sounding was 0.20 $\mu g/g$ per km.

## Some speculations about the use of ozone data in synoptic research

As has been pointed out earlier in this paper several different models have been used in the meteorological literature in connexion with studies of the structure of the atmosphere near the jet stream. The meteorological parameters used have been temperature, wind, potential temperature and absolute potential vorticity. However, the dimensions of the phenomena studied and the distances between observing stations make it very difficult to arrive at clear-cut relations, hence all the different opinions about the best model to use in connexion with studies of fronts and jet streams. Looking at Fig. 9 we notice that the two ozone soundings give a reasonable and rather detailed picture of the ozone distribution in this region. However, at an earlier time, corresponding to the left part of the cross section we have no information and this is a region which is a most interesting one. It would have been very interesting to have had soundings at, say, 0800, 0600 and 0400 GMT. No such soundings are available, unfortunately; there was, however, one sounding made on the 14th, i.e. two days before the period studied so far in this paper. This ozone sounding happened to be made at the time of arrival of the cold air mass over Switzerland as already mentioned in connexion with Figs. 1 and 2. The synoptic situation during this day has been studied in a manner similar to the one described above, but in less details. According to this study the sounding on the 14th passed through the vertical portion of the front; this time, however, in the part of the front nearest to polar air mass. The two situations are rather similar with regard to temperature and wind distribution and for the sake of argument all three soundings have been entered schematically in Fig. 10 in relation to the same front. The sounding for the 14th passed through the vertical portion of the front as already stated and as indicated in Fig. 10. The inclination of the front between 500 and 300 mb was, however, steeper on the 14th than on the 16th which makes the position of the lower part of the vertical line misleading. This fact has no great bearing, however, on the following discussion. If we now assume that all three soundings were actually made through the same front, the implied time difference and horizontal dis-

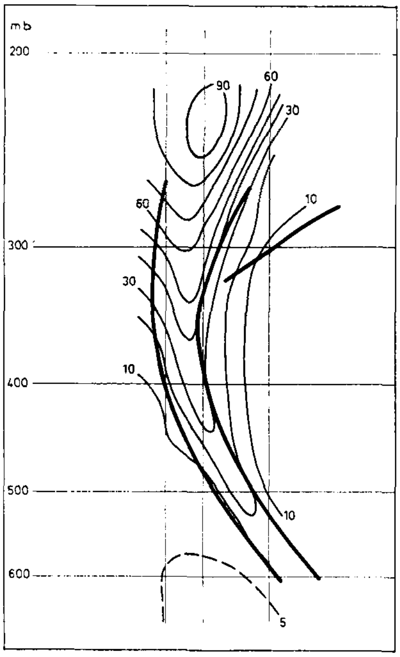


FIG. 10. Schematic picture of the distribution of ozone mixing ratio (in $10^{-2}\,\mu g/g$) around a high-reaching front. The analysis is based on ozone soundings made at Arosa in April 1962.

tance between the three soundings would be of the order of 2–4 hours and 100–200 km, respectively. An analysis of the ozone mixing ratio gives the distribution indicated in Fig. 10. The most striking feature is the maximum at each level within the front, suggesting a downward transport of stratospheric air. It is interesting to note that the distribution arrived at using these very heterogeneous data gives the same general features reported on by BRIGGS & ROACH (1963) and others. In their article these authors give an average distribution of ozone mixing ratio which has a maximum about 200–250 km from the jet axis in the first kilometer layer above the jet level. These findings which are based on aircraft observations correspond to the maximum observed between 350 and 300 mb in Fig. 10. The general position of the maximum between 400 and 300 mb in Fig. 10 is also in good agreement with the ideas put forward by REED (1955) and by REED & DANIELSEN (1959). However, above 300 mb Fig. 10 indicates an almost vertical zone of maximum ozone mixing ratio, whereas in the other articles there is an indication of a slope to the left with height. It is not the purpose of this paper to argue about the most probable solution of the problems touched upon above in light of the character of observations on which Fig. 10 is based. As the observations are taken at different fronts and their true relationship cannot be ascertained and as the absolute accuracy of the measurements is not discussed here, Fig. 10 must be taken as what it is meant to be: an unconventional way of pointing out the importance of a dense network in time and space of ozone sonde stations. Having access to vertical soundings situated as indicated in Fig. 10 together with two or three more in the polar air mass with, say, two-hourly intervals, one would be in a position to make really meaningful synoptic studies of the conditions around the jet axis.

It would also be very interesting to study, among other things, the events occurring as a marked jet stream maximum passes over a station if, say, two-hourly ozone soundings were carried out together with wind, temperature, and humidity measurements at the same intervals and at the same locations. In this connection one must not of course forget the potentialities of aircraft observations. These types of observation series will make it possible to attack the problem of how to analyze the wind and temperature fields around the jet stream in a most rational manner. It might then be possible to arrive at generally accepted analysis models for the front and tropopause analysis in the layer between 500 and 150 mb in the neighborhood of a jet stream.

## Conclusions

The investigation reported in this paper has the character of a pilot study. The material used was deficient in several respects: there were no temperature, humidity and wind readings available along with the ozone data; the intercomparisons were not made at the location of a radiosonde station and for these two reasons it has been necessary to interpolate both in time and space in order to arrive at a reasonable picture which could represent the atmospheric conditions at the time of the ozone observations. The European radiosonde network is rather difficult to work with in a detailed synoptic study because of the non-homogeneity of the network. The study has been undertaken and reported on in spite of these deficiencies because the type of material used is fairly new and very promising. Speaking strictly from a synoptician's point of view the main interest in the ozone observations is not primarily connected with studies aiming at revealing the distribution of ozone but rather to study the synoptic events using ozone as a tracer, thus being able to introduce a new and independent variable. Both types of studies have, however, to be carried out and there will be something to be gained from both sides. The feed-back system that is built into a group of studies of the kind discussed here is quite powerful and the future possibilities which can be envisaged are exciting.

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