VARIATIONS IN THE TOTAL AMOUNT OF OZONE OVER TROMSØ, AND THEIR CORRELATIONS WITH OTHER METOROLOGICAL ELEMENTS

BY

HARALD JOHANSEN

(Manuscript recived October 23rd, 1954).

1. Introduction.

The purpose of this paper is to try to throw further light on the connection which has been found to exist between the total amount of atmospheric ozone over Tromsø and other meteorological elements.

The paper is mainly a statistical analysis of the subject, worked out by means of simultaneous upper air and ozone observations at Tromsø during the period May 1941 — October 1944. The ozone observations have been worked out at Nordlysobservatoriet, Tromsø, and *E. Tønsberg*, Director of Nordlysobservatoriet, has kindly placed at my disposal all available ozone data from this period. For the method of observation and the reliability of the ozone measurements, reference is made to the papers by *Dobson* (1), and by *Tønsberg* and *Langlo* (*Olsen*) (19).

2. Correlations between the Total Amount of Ozone and the Height of the Tropopause.

In a previous paper (10) it has been shown that the variations in the total amount of ozone at Tromsø are related to the height of the tropopause and the temperature of the upper troposphere and lower stratosphere. The observations were grouped according to rise and fall regions of atmospheric pressure at ground level, and showed that the variations in the total amount of ozone were related to the height of the tropopause in the way that large amounts of ozone will accompany a lowering of the tropopause and a warming of the lower layers of the stratosphere. This result was in accordance with the results found by *Meetham* (13). In his well known work on the relations between ozone and other atmospheric characteristics, he showed that the ozone content measured at Oxford and Arosa was correlated with the height of the tropopause and with the potential temperature in the lower stratosphere in such a way that an increase in the total ozone of 0.01 cm was accompanied by a lowering of the tropopause by 1 km and a rise of the potential temperature at 18 km by 3° C. The relation which, according to the paper just mentioned, could be shown to exist between ozone and other meteorological elements at Tromsø, was based on only 31 simultaneous ozone and upper air observations

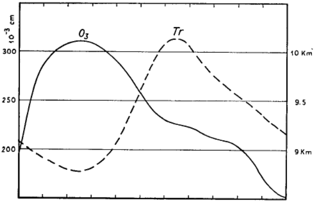

Fig. 1. The mean annual variation of ozone and tropopause height over Tromsø.

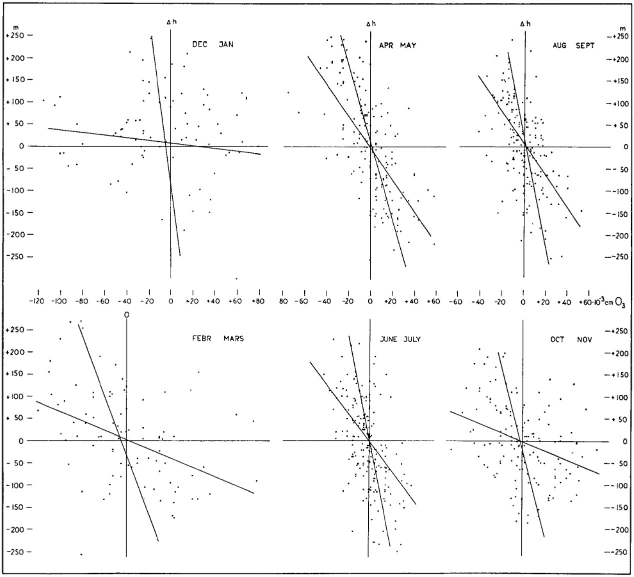

Fig. 2. Dot charts and regression lines of the deviations of daily values of total ozone (ΔO_3) and tropopause height(Δh).

during April 1938, whereas the present investigation deals with 941 observations of ozone and height of the tropopause during the period 1941—44.

Fig. 1 shows the mean annual variation in total amount of ozone at Tromsø for the period 1940—49, as given by *Langlo* (12) together with the mean annual variation of the tropopause for the period 1941 — 44 (11). From this figure it can be seen that maximum ozone content occurs during March—April, and that the annual curve of the height of the tropopause shows a minimum at about the same time of the year. Fig. 1 also shows a converse seasonal variation of the two elements during the period January-July.

The statistical treatment of the two elements assumes independence of the different values of the variables. Therefore, the correlation ratios have been computed by means of the deviations of daily values from the annual curves. The values thus obtained have been divided into 6 groups, each group containing the values for a period of 2 months. The values have been plotted on graph paper (Fig. 2), with the deviations of total ozone on the horizontal axis and the deviations of height of tropopause on the vertical axis.

Table 1. Correlation between Total Amount of Ozone and Heigth of Tropopause

Months	n	$r(0_3, h)$	F	Regression equations
1. Dec.—Jan.	86	—0.123	0.07	$\Delta h = -0\ 28\ \Delta 0_3$, $\Delta 0_3 = -0.05\ \Delta h$
2. Feb.—March	102	—0.434	0.05	$\Delta h = -1.06\ \Delta 0_3$, $\Delta 0_3 = -0.18\ \Delta h$
3. April—May	181	—0.642	0.03	$\Delta h = -3.57\ \Delta 0_3$, $\Delta 0_3 = -0.12\ \Delta h$
4. June—July	220	—0.524	0.03	$\Delta h = -3.19\ \Delta 0_3$, $\Delta 0_3 = -0.09\ \Delta h$
5. Aug. Sept.	190	—0.557.	0.03	$\Delta h = -3.60\ \Delta 0_3$, $\Delta 0_3 = -0\ 08\ \Delta h$
6. Oct.—Nov.	162	—0 317	0 05	$\Delta h = -1.01\ \Delta 0_3$. $\Delta 0_3 = -0.10\ \Delta h$

Table 1 gives the correlation coefficients $r(0_3,h)$ between ozone and height of the tropopause, the number of cases in each group (n), the probable errors ($F = 0.6745\ (1 - r^2)/\sqrt{n}$) and the regression equations.

When discussing the correlation coefficients given in Table 1, it is necessary to take into account the accuracy of the ozone observations. *Tønsberg* and *Langlo* (*Olsen*) (19) have shown that the maximum error in the ozone observations at Tromsø which should be taken into account at the different seasons, amounts to 0.060 cm during the darkest period of the year, decreasing to 0.005 cm during the period April—September. Therefore, great care should be shown when using the ozone measurements for the winter months.

The great difference, in numbers of observations, between winter and summer is partly due to lack of ozone observations during the darkest season, and partly due to the soundings reaching higher levels during summer than during winter.

Table 1 confirms the earlier results, that the total ozone and the height of the tropopause vary inversely. The correlation coefficient for December—January is found to be —0.123 and not even double its probable error. The small correlation does not offer any reason for assuming a connection to exist between 0_3 and h during midwinter. On the other hand, the fact that the correlation coefficient is negative, might indicate a tendency in the direction just mentioned. The other correlation coefficients in Table 1 do not indicate a very strong correlation, but they show that some connection doubtless exists between total ozone and the height of the tropopause. The highest correlation coefficients are found during the period April—September, with a maximum of —0.642 in April—May. For the group August—September the correlation coefficient is slightly higher than the coefficient for June—July, but the difference is not significant, as it is within the limits of the probable errors.

Correlating the ozone measurements at Oxford with the upper air observations from Kew and Sealand, and omitting the observations during the winter months, *Meetham* (13) found $r(0_3,h) = -0{,}56$. Averaging the correlation coefficients given in Table 1 and omitting the coefficients for the winter groups (1 and 6), we find $r(0_3, h) = -0{,}54$ at Tromsø.

3. Correlation between the Total Amount of Ozone and the Temperature in the Upper Troposphere and the Lower Stratosphere.

It is well known that the variations of the geopotential of the tropopause are accompanied by temperature variations in the upper troposphere and the lower stratospere in such a way that a warming of the lower layers of the stratosphere and a cooling of the upper layers of the troposphere accompany a lowering of the tropopause.

In order to investigate the connection between ozone and temperature variations, the variation in total amount of ozone has been correlated to the temperature variations at 6 and 12 km. The height of the tropopause above Tromsø is on the average 9,4 km, with a mean annual range of 1,5 km (11). The lowest position of the tropopause which was observed during the period considered was 6,4 km. The temperature variations at the level of 6 km can, therefore, safely be regarded as a good representation of the upper troposphere temperature variations.

For the representation of stratospheric temperature variations, the level of 12 km has been chosen. This level is situated well above the mean height of the tropopause, but it is not sufficiently high to give merely stratospheric temperature variations. Owing to the rapid decrease in numbers of observations with increasing height, the

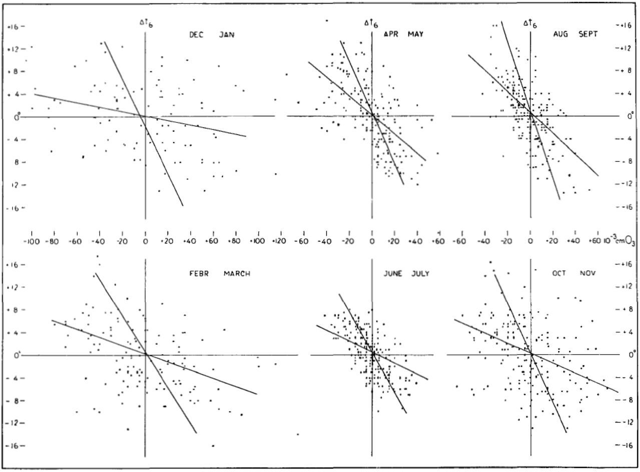

Fig 3 Dot charts and regression lines of the deviations of daily values of total ozone ($\Delta 0_3$) and temperature at 6 km (Δt_6).

level of 12 km was preferred and, consequently, the observations had to be rejected whenever the tropopause was above 12 km.

In order to eliminate the annual variations from the correlation coefficients, daily deviations from the smooth curves of annual variations have been used instead of day-to-day variations. The values have been divided into 6 groups, each group containing the values for a period of two months. Thus, the method, which have been used in determining the correlation between ozone and temperature, is consistent with the method used in the preceding chapter.

The dot charts given in Fig. 3 show the deviations of the total amount of ozone on the horizontal axis and the deviations of temperature at

Table 2. Correlation between Total Amount of Ozonè and Temperature at 6 gkm.

Months	n	$r(0_3, t_6)$	F	Regression equations
1. Dec.—January	122	—0.314	0.06	$\Delta t_6 = -0.04\, \Delta 0_3$, $\Delta 0_3 = -2.40\, \Delta t_6$
2. February—March	148	—0.481	0.05	$\Delta t_6 = -0.07\, \Delta 0_3$, $\Delta 0_3 = -3.21\, \Delta t_6$
3. April—May	206	—0.604	0.03	$\Delta t_6 = -0.17\, \Delta 0_3$, $\Delta 0_3 = -2.18\, \Delta t_6$
4. June—July	235	—0.601	0.03	$\Delta t_6 = -0.08\, \Delta 0_3$, $\Delta 0_3 = -2.83\, \Delta t_6$
5. August—September	223	—0.558	0.04	$\Delta t_6 = -0.18\, \Delta 0_2$, $\Delta 0_3 = -1.70\, \Delta t_6$
6. October—November	201	—0.448	0.04	$\Delta t_6 = -0.09\, \Delta 0_3$, $\Delta 0_3 = -2.26\, \Delta t_6$

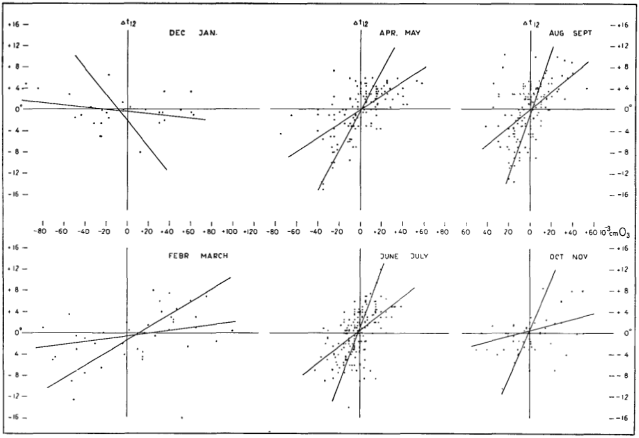

Fig. 4. Dot charts and regression lines of the deviations of daily values of total ozone ($\Delta 0_3$) and temperature at 12 km (Δt_{12}).

6 km on the vertical axis. The correlation coefficients with their probable errors and regression equations are given in Table 2.

For the determination of $r(0_3, t_6)$ 1135 sets of data were used. The corresponding number of sets of data for the determination of $r(0_3, h)$ was 941. Table 2 shows that the total ozone and the upper tropospheric temperature vary inversely. Comparing the coefficients given in Table 1 with the corresponding coefficients in Table 2, it can be seen that, even if the correlation coefficients are small, there seems to be a slightly closer connection between ozone and tropospheric temperature variations than between ozone and height of tropopause during the darkest season of the year. Otherwise the corresponding values are of the same order of magnitude, showing the highest correlation during the period April—September with a maximum $r(0_3, t_6) = -0.60$ in April—July. Omitting the coefficients during winter (group 1 and 6), and averaging the other coefficients, we get $r(0_3, t_6) = -0.56$. The corresponding value of the correlation of ozone with height of tropopause was $r(0_3, h) = -0.54$.

Owing to the rapid decrease in number of observations with increasing height, especially during winter, the sets of data for the determination of the correlation of ozone with stratospheric temperature variations $r(0_3, t_{12})$ were only 672, i.e., about 60 per cent of the numbers used for the determination of $r(0_3, t_6)$. The correlations beteen total amount of ozone and temperature at 12 km are illustrated by means of dot charts given in Fig. 4. The coefficients, the probable errors, and the regression equations are given in Table 3.

The correlation coefficient for December—January is found to be —0.29, and not even three times its probable error. The small correlation, which is based upon only 29 sets of observations, does not offer any reason for assuming a connection be-

Table 3 Correlation between Total Amount of Ozone and Temperature at 12 gkm.

Months	n	$r(0_3, t_{12})$	F	Regression equations
1. December—January	29	−−0.290	0.12	$\Delta t_{12} = -0.02\ \Delta 0_3 \quad \Delta 0_3 = -4.05\ \Delta t_{12}$
2. February—March	39	0.470	0.08	$\Delta t_{12} = 0.03\ \Delta 0_3, \quad \Delta 0_3 = 8.26\ \Delta t_{12}$
3. April—May	132	0.594	0.04	$\Delta t_{12} = 0.13\ \Delta 0_3, \quad \Delta 0_3 = 2.66\ \Delta t_{12}$
4. June—July	209	0.536	0 03	$\Delta t_{12} = 0.16\ \Delta 0_3, \quad \Delta 0_3 = 1.84\ \Delta t_{12}$
5. August—September	171	0 517	0 04	$\Delta t_{12} = 0.17\ \Delta 0_3, \quad \Delta 0_3 = 1.61\ \Delta t_{12}$
6. October—November	92	0 339	0.06	$\Delta t_{12} = 0.05\ \Delta 0_3, \quad \Delta 0_3 = 2\ 12\ \Delta t_{12}$

tween 0_3 and t_{12} during this season of the year. Besides, it should be remembered that the ozone measurements during the dark period (Dec.—Jan.) should be used carefully owing to the inaccuracy of the observations. In addition, it has been difficult to eliminate entirely the annual variations of the stratospheric temperatures, due to lack of observations during the same period. The other correlation coefficients in Table 3 show that some connection undoubtedly exists between total amounts of ozone and temperature in the lower layers of the stratosphere.

Table 3 confirms the results given in Tables 1 and 2, i.e. that the highest correlations occur during the period April—September with a maximum correlation coefficient $r(0_3, t_{12}) = 0.59$ in April—May. Averaging the coefficients in Table 3 and omitting the winter values (group 1 and 6), we get $r(0_3, t_{12}) = 0.53$. Comparing this value with the corresponding uncorrected value $r(0_3, t_{12}) = 0.56$. which is given in the work by *Meetham* (13), we find that the correlation coefficient between O_3 and t_{12} at Tromsø is almost equal to the coefficient at Oxford.

4. Correlations between the Total Amount of Ozone and Temperature, Potential Temperature and Pressure at Various Levels of the Atmosphere.

In the two preceding chapters it has been shown that the correlations of ozone with the height of the tropopause, as well as with the lower stratospheric and upper tropospheric temperatures, have an annual variation, showing moderate correlations during the period April—September with maximum correlation coefficients in April—May, whereas the correlations during midwinter roughly could be classified as hardly significant.

In this chapter correlations of ozone with temperature, potential temperature and pressure at different levels of the atmosphere are dealt with. Owing to the small number of upper air observations reaching heights of 15 km or more during winter, only upper air observations during the period April—September have been used. For the determination of the correlation coefficients, 412 simultaneous upper air and ozone observations are available. The method which has been used in determining the coefficients, is consistent with the method used in the preceding chapters. Thus, all deviations have been taken from smooth curves of annual variations.

Table 4 gives the correlation coefficients of total ozone with temperature and pressure at 3, 6, 9. 12 and 15 km, and with potential temperature at 6, 9, 12 and 15 km above the surface, together with the standard deviations, the probable errors (F) and the regression equations. The standard deviation of ozone is 17.22×10^{-3} cm and is not included in the Table. The coefficients within parenthesis are the corresponding values for Oxford as given by *Meetham* (13).

The variation of the correlation coefficients $r(0_3, t)$ with height shows that the maximum coefficient is found at the level of 6 km. The value $r(0_3, t_6) = -0{,}605$ is in good agreement with the values given in Table 2, which gives a mean correlation coefficient $r(0_3, t_6) = -0{,}588$ during the same period (April—September). The level of 9 km is situated just below the mean annual height of the tropopause (9.6 km) and belongs to the transitional zone between troposphere and stratosphere where the correlation between ozone and temperature changes from negative to positive values. Consequently, only small correlations are to be expected at this level of the atmosphere. The correlation coefficient $r(0_3, t_{12}) = +0.55$ is in excellent agreement with the values given in Table 3, where the mean correlation coefficient during the same period can be found to be $+0.549$.

Table 4. Correlation Coefficients of Total of Ozone with Temperature (t) and Pressure (p) at 3, 6, 9, 12 and 15 km, and with Potential Temperature (Θ) at 6, 9, 12 and 15 km above the Surface Number of Observations: 412

Correlated element	Standard deviations	Corr. coefficients		F	Regression equations
		Tromsø	Oxford		
t_3	4 338° C	—0.556		0.023	$\Delta t_3 = -0.140\ \Delta 0_3$, $\Delta 0_3 = -2.207\ \Delta t_3$
t_6	4 781° C	—0.605		0.021	$\Delta t_6 = -0.168\ \Delta 0_3$, $\Delta 0_3 = -2\ 180\ \Delta t_6$
t_9	3.659° C	—0.316		0.030	$\Delta t_9 = -0.067\ \Delta 0_3$, $\Delta 0_3 = -1.487\ \Delta t_9$
t_{12}	4.460° C	+0 552	(+0.56)	0.023	$\Delta t_{12} = 0.143\ \Delta 0_3$, $\Delta 0_3 = 2.132\ \Delta t_{12}$
t_{15}	2.817° C	+0.521	(+0.52)	0 023	$\Delta t_{15} = 0.085\ \Delta 0_3$, $\Delta 0_3 = 3.185\ \Delta t_{15}$
p_3	7 120 mb	—0.532		0.024	$\Delta p_3 = -0.220\ \Delta 0_3$, $\Delta 0_3 = -1\ 287\ \Delta p_3$
p_6	6.824 mb	—0.674		0.018	$\Delta p_6 = -0.267\ \Delta 0_3$, $\Delta 0_3 = -1.701\ \Delta p_6$
p_9	6.426 mb	—0 605	(—0.46)	0 021	$\Delta p_9 = -0.225\ \Delta 0_3$, $\Delta 0_3 = -1\ 621\ \Delta p_9$
p_{12}	3.504 mb	—0.561	(—0 43)	0.023	$\Delta p_{12} = -0.114\ \Delta 0_3$, $\Delta 0_3 = -2\ 758\ \Delta p_{12}$
p_{15}	2 472 mb	—0.387	(—0.36)	0.028	$\Delta p_{15} = -0.056\ \Delta 0_3$, $\Delta 0_3 = -2\ 697\ \Delta p_{15}$
Θ_6	5 225° C	—0 562		0 023	$\Delta\Theta_6 = -0.170\ \Delta 0_3$, $\Delta 0_3 = -1.852\ \Delta\Theta_6$
Θ_9	3.635° C	—0 080		0.033	$\Delta\Theta_9 = -0.017\ \Delta 0_3$, $\Delta 0_3 = -0.379\ \Delta\Theta_9$
Θ_{12}	6.552° C	+0.578	(+0 60)	0.022	$\Delta\Theta_{12} = 0.220\ \Delta 0_3$, $\Delta 0_3 = 1.520\ \Delta\Theta_{14}$
Θ_{15}	4.976° C	+0.560	(+0.63)	0.023	$\Delta\Theta_{15} = 0\ 389\ \Delta 0_3$, $\Delta 0_3 = 3.461\ \Delta\Theta_{15}$

The value at 15 km is slightly smaller than the value at 12 km, but the difference is within the limits of probable errors. The values at 12 and 15 km are found to be almost equal to the corresponding values at Oxford.

For the correlation of ozone with pressure, an inverse connection can be found at all layers from 3 to 15 km with the maximum value $r(0_3;\ p_6) = -0{,}674$ at 6 km, decreasing gradually upwards. Comparing the values at Tromsø and Oxford, the correlations at Tromsø are seen to be somewhat higher, especially at the 9 and 12 km levels.

The relationship between the tropospheric temperature and pressure variations and the ozone variations was early pointed out by *Dobson* and *Meetham* (4). From the surface pressure and the temperature at 4 km measured by aeroplanes near Cambridge, the pressure at 9 km was estimated. A comparison between the estimated pressure values and the ozone values above Oxford showed a close connection between them.

From the correlation coefficients of ozone with potential temperature it can be seen that the variations with height are almost similar to the variations of the correlation between ozone and temperature. It is, however, interesting to note that the correlation between ozone and potential temperature at 12 and 15 km is slightly higher than the correlation between ozone and temperature at the same levels

The variation with height indicates a decrease in the correlation with potential temperature at higher levels in the stratosphere. This result is not in accordance with the values at Oxford, which are found to be somewhat higher and increasing with height, indicating that the correlation between ozone and potential temperature at 18 km is very close ($r = +0.70$). In order to find a confirmation of the assumed decrease of the correlation with potential temperature in the stratosphere at Tromsø, the soundings reaching the level of 18 gkm have been examined. For the computation of the correlation coefficients only soundings during the summer months of June, July and August

Table 5. Correlation Coefficients of Total Ozone with Potential Temperature at 12, 14, 16 and 18 km.

Year	n	$r(0_3, \Theta_{12})$	F	$r(0_3, \Theta_{14})$	F	$r(0_3, \Theta_{16})$	F	$r(0_3, \Theta_{18})$	F
1941 .	29	0.582	0.083	0.482	0.096	0.343	0.111	0.223	0.119
1942	57	0.702	0 045	0 756	0.038	0.670	0.049	0 544	0.063
1943	42	0 366	0.090	0 380	0.089	0.354	0.091	0.337	0.092
1944 .	50	0.490	0 072	0.520	0.070	0.351	0.084		
Mean values·		0.535		0 535		0.430		0.368	

are available. The results are given in Table 5, which shows the correlation coefficients and their probable errors at the levels of 12, 14, 16, and 18 km for the summer months. The Table shows that the highest correlations between ozone and potential temperatures are found at levels of 12—14 km. Above these levels, a distinct decrease in the connection between the two elements is evident. The correlations, which have been computed for each year during the period 1941—44, show that the correlation between total amount of ozone and potential temperature at levels of 12 to 18 km may vary considerably from year to year.

5. On the Causes of Day-to-day Variations of the Total Amount of Ozone.

The statistical relationship between ozone and other meteorological elements, which have been given in the preceding chapters, cannot reveal anything about the causal relationship. Thus, it is impossible to determine which is cause and which effect. On the other hand, the variations in the correlation coefficients during the year and the variations with height, may give some valuable hints as to the causal relationship.

Most investigators have regarded the ozone variations as resulting from redistribution of ozone already present in the atmosphere. The numerous studies of the connection between the variations of total amount of ozone and other meteorological elements have pointed to the horizontal advection as an important cause of the day-to-day ozone variations, since it was assumed that polar air always had a high ozone content and tropocal air a low one. It was, however, early pointed out by *Dobson, Harrison* and *Lawrence* (2) that it was impossible to attribute the ozone variations solely to horizontal advection, and it was assumed that other factors than horizontal advection played an important rôle.

In an isopleth diagram given by *Gøtz* (7, 8), the latitudinal variation of ozone for each month shows that, in the northern hemisphere, the total amount of ozone has its maximum at about 60° N, except during the period February to May, when the ozone amount increases towards higher latitudes. Using all published series of observations, *Craig* (5) reached at the same conclusion. Recently it has been shown by *Langlo* (12) that the mean annual distribution of ozone with latitude is remarkably constant between 70° N and 45° N in Western Europe. For the latitudinal variation of ozone for each month, he points out that a very high ozone gradient normally exists between high and low latitudes in the period February to May, and that only small differences are found during the other seasons. Remarkably small differences between 70° N and Equator are found during the months of September and October. Comparing the mean meridional distribution of ozone with the maximum 24 hours change in ozone at 62° N, he was led to the assumption that the actual zonal distribution would be of greater importance for the day-to-day variations than would the meridional distribution.

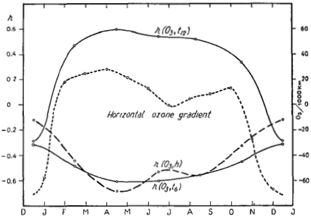

Fig. 5. Showing the annual variations of the correlation coefficients between total ozone and tropopause height (dashed lines) and between ozone and tropopause at 6 and 12 km (full lines). Dotted line shows the mean annual variation of the horizontal gradient between Dombås and Tromsø (units 10^{-3} cm 0_3/1000 km).

The correlation coefficients given in Tables 1, 2 and 3 are represented in Fig. 5, which shows the annual variations of the correlation coefficients between total ozone and height of tropopause and between ozone and temperature at 6 and 12 km, together with the mean annual variation of the horizontal ozone gradient between Dombås (62.1° N, 9.1° E) and Tromsø (69.7° N, 18.9° E). From the figure it can be seen that the highest positive ozone gradient occurs during the period February—May with a maximum horizontal ozone gradient in April. This corresponds well with the annual variation of the correlation coefficients, having their maximum values in April—May. On the other hand, only small values of the horizontal ozone gradient are found during the period June

—November, whereas the correlation coefficients show that, during the same period, some connection doubtless exists.

For the alternative explanation of the interdiurnal ozone variations, several investigators have pointed to the effects of large scale vertical motions. According to *Wulf* and *Deming* (21) the ozone content below the layer of maximum ozone content may be regarded as a semi-permanent gas. Thus, a uniform sinking of air from the layer of photochemical equilibrium would transport ozone from higher to lower levels in the atmosphere. At the same time photochemical processes in the upper layers would quickly restore the ozone deficiency, leading to an increase of total ozone amount. An ascending motion reaching the level of photochemical equlibrium would give the opposite effect.

Another point which also has to be taken into account is the effect on total ozone produced by horizontal convergence or divergence which accompanies large scale vertical motions. This effect has been calculated by *Nicolet* (15) and *Dütsch* (6) who showed that it could be an appreciable one. Similar results have recently been obtained by *Reed* (17, 18). By calculating the change in ozone content during vertical motions and accompanying horizontal convergence and divergence, he showed that this effect could account for nearly half of the observed ozone changes. When comparing the ozone measurements at New York University with the upper air charts, he found that all cases of large positive ozone deviations were associated with marked subsidence at the levels of 10, 13 and 16 km, the subsidence being largest at the lowest level, becoming progressively smaller at the higher levels. It is interesting to note that the correlation coefficient between ozone and potential temperature, given in Table 5, showed the highest values at the lower stratospheric levels, decreasing upwards.

The connection between the large scale vertical movements and ozone deviations which has been found to exist, shows that the dynamical processes must be of great importance, as *Haurwitz* (9) and *Palmén* (16) have already suggested. Also, the variations of the correlation coefficients, which are given in the preceding chapters, point to the ozone variations as being a result of mainly dynamical processes in the atmosphere. The variations in total ozone, which were found to exist, when grouping the observations according to fall and rise regions of atmospheric pressure at ground level (10), are also in agreement with the variations which ought to be expected if dynamical processes play an important part in the connection between ozone and weather.

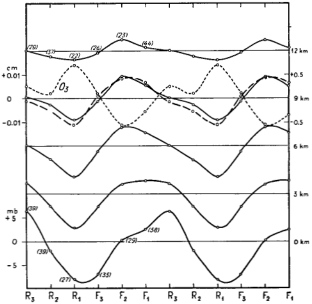

Fig. 6. Showing the anomalies of atmospheric pressure at the levels of 0, 3, 6, 9 and 12 km, together with the anomalies of the tropopause and the total amount of ozone. The groups F and R represent observations made in fall and rise regions of atmospheric pressure at ground level. Number in brackets gives number of observations in each group.

During a period of one year the observations have been grouped according to rise and fall regions at ground level, omitting the observations during December—January. Fig. 6 shows the anomalies of pressure at the levels of 0, 3, 6, 9 and 12 km, together with the anomalis of the tropopause and the total amount of ozone above Tromsø. The groups F represent observations made in fall regions and R in rise regions of atmospheric pressure, in the way that the groups F_2 and R_2 represent observations in the central part of the falling and rising regions, respectively. Fig. 6 may be regarded as representing the mean conditions of low and high pressure areas moving from west towards east. The Figure shows that the upper pressure system is displaced to the rear of the surface system, just as it must be expected in a system of west—east moving Lows and Highs.

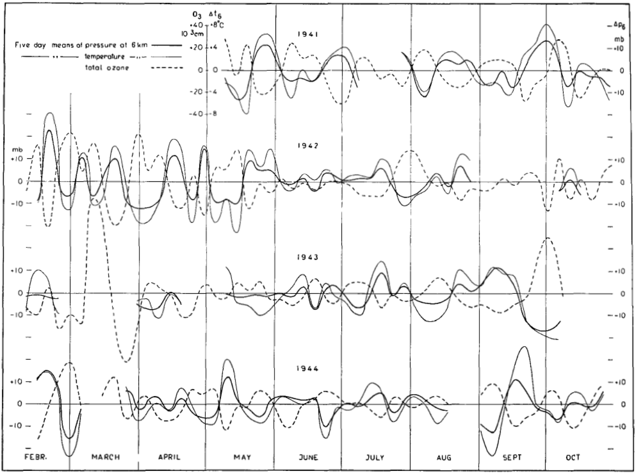

Fig 7. Showing the variations of the five-day means of total ozone together with the variations of the five-day means of atmospheric pressure and temperature at 6 km.

The relationship between the ozone deviations and the pressure waves shows that negative ozone deviations appear to the rear of the surface anticyclone and above the central part of the falling region. The positive ozone deviations appear to the rear of the surface cyclone above the areas of rising pressure. The irregular shape of the curve of ozone deviations during the falling period would probably disappear if the number of observations were increased. Fig. 6 reveals in a striking manner the close relationship which exists between ozone deviations and upper pressure waves, and between ozone and variations of the tropopause. It shows that the ozone varies exactly inversely to the pressure at the upper tropospheric and lower stratospheric levels and to the variations of the tropopause.

In the ordinary eastward-moving cyclone the pressure changes at ground level can be regarded as a result of two strong effects below and above the level of nondivergence, almost cancelling each other. If the upper air divergence is strong enough to overcompensate the convergence in the lower layers, there will be falling pressure at ground level and vice versa. The redistribution of air masses in the lower layers of the atmosphere will have no effect upon the distribution of total ozone, whereas convergence and divergence in the upper troposphere and in the lower stratosphere will cause ozone variations as calculated by *Nicolet* (15), *Dütsch* (6), and recently also by *Reed* (18). The resulting horizontal distribution of total ozone must, therefore, show high ozone values above the rising-pressure areas and low values above falling-pressure areas at ground level. In this way the horizontal ozone distribution will be more or less symmetrical with the upper pressure waves as shown in Fig. 6. The variations presented in

Fig. 6 are also in good agreement with the results in Table 4, showing the highest correlation coefficients between ozone and pressure at 6 and 9 km with a maximum correlation coefficient $r(0_3, p_6) = -0.67$. Fig. 6, thus, indicates that the best correlation between total amount of ozone and pressure is found in the upper tropospheric levels (between 6 and 9 km), i.e. the levels just below the tropopause. *Moser* (14), on examining drawings of the trajectories at 5, 11 and 16 km, finds the best correlation between the trajectories at the level of 11 km, and the ozone amount. He therefore assumed the main location of ozone variations to be in the stratosphere near the tropopause. His results do not exclude the possibility of even better correlations between trajectories and ozone at a level between 6 and 9 km, as indicated in this paper.

Fig. 7 illustrates another example of the close relationship between the total amount of ozone and the upper pressure waves. In this Figure the variation of the five-day means of ozone is given in relation to the five-day means of pressure and temperature at 6 km. It was the intention to compare the ozone variations with the pressure variations at a level of between 6 and 9 km, but owing to the scantiness of pressure observations at the higher tropospheric levels, the level of 6 km had to be used as the highest possible level where pentad values of pressure could be used. Also, the winter months of November, December and January were omitted, since it must be assumed that the ozone values during the darkest season are not reliable, as mentioned in chapter 2. The pentad values have been computed by means of the deviations of daily values from the annual curves, overlapping values having not been used.

Fig. 7 may be regarded as representing series of long upper pressure waves above Tromsø, moving from west towards east. It shows that the ozone content varies inversely to the upper cold throughs and warm ridges. Moreover, the largest ozone variations occur during spring and autumn in connection with the strongest pressure systems, as would be expected if dynamical processes in the atmosphere play an important part in causing ozone variations.

Fig. 7 also gives the impression that by using the five-day means, a closer relation results than by using the day-to-day variations.

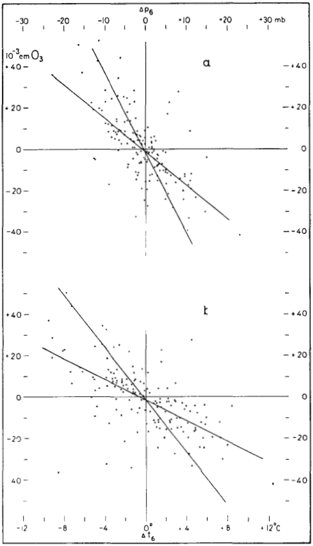

Fig. 8. Dot chart and regression lines of a) deviations of five-day means of ozone and pressure from the annual curves, and b) deviations of five-day means of ozone and temperature from the annual curves.

In order to decide if this actually is so or not, the correlation coefficients of ozone with pressure and temperature have been computed, using independent (not overlapping) five-day means of total ozone, pressure and temperature at 6 km. Fig. 8 a and b show dot charts and regression lines of the deviations of five-day means from the annual curves, and Table 6 gives the correlation coefficients, the standard deviations, the probable errors, and the regression equations. The standard deviation of ozone is 16.25×10^{-3} cm and is not included in the table.

The Table shows that the correlation of ozone

Table 6. Correlation Coefficients of Ozone with Pressure and Temperature at 6 km (five-day means). Number of Observations: 166.

Correlated element	Standard deviations	Correlation coefficients	Probable errors	Regression equations
p_6	6.439 mb	—0.659	0.031	$\Delta p_6 = -0.26\ \Delta 0_3,\quad \Delta 0_3 = -1.61\ \Delta p_6$
t_6	3.980° C	—0.630	0.032	$\Delta t_6 = -0\ 16\ \Delta 0_3,\quad \Delta 0_3 = -2.51\ \Delta t_6$

with pressure and temperature at 6 km, when pentad values are used, is almost equal to the correlation between ozone and the corresponding elements when day-to-day values are used. Table 5 gives $r(0_3, p_6) = -0.674$ and $r(0_3, t_6) = -0.605$, whereas the corresponding values from Table 6 are $r(0_3, p_6) = -0.649$ and $r(0_3, t_6) = -0.630$. Thus the differences between the values given in Table 5 and 6 are within the fiducial limits. Also, the standard deviations and the regression equations are almost identical in the two tables.

6. Ozone Variations in Relation to Fronts and Air Masses.

The relationship between ozone deviations and frontal systems have been studied by *Tønsberg* and *Langlo* (*Olsen*) (19), who showed that the low ozone values appeared in the warm sector and in the region covered by the warm front surface, the fall in ozone content often extending several hundred kilometres ahead of the surface warm front. In studying the ozone variations in connection with movements of individual cyclones, they were led to the assumption that some relation seemed to exist between the speed of ozone variations and the speed of the cyclone movements. Further, the marked rise in ozone content in connection with the passages of cold fronts, which was earlier stated by *Tønsberg* and *Chalonge* (20), could be verified. Similar results have also been obtained by *Dobson*, *Brewer* and *Cwilong* (3) who, in addition, found that certain occlusions did not produce any effect on the ozone value, presumably because they did not reach the stratosphere. In the case of old occluded systems the ozone maximum and the surface centre were found to coincide.

The soundings at Tromsø which were made almost every morning from May 1941 until November 1944 and, in addition, also every afternoon during the last 14 months of this period, give an excellent opportunity of studying the ozone variations in relation to fronts and air masses. Fig. 9 illustrates the method that has been used. The lower part of the figure shows isopleths of frontal boundaries and tropopauses (heavy lines) together with isopleths of temperature (thin lines). The upper part shows the variation of total ozone during the same period. In the middle part of the figure the isopleths of potential temperature are given together with the same frontal boundaries and tropopauses as in the lower part. Fig. 9 may be regarded as representing the conditions over Tromsø as the frontal systems pass from west to east.

Comparing the ozone variations with the isopleths of temperature a striking correspondence is found between the maxima and the minima of the ozone curve and the maxima and minima of the temperature at the tropopause. Thus, the ozone minima at A, D, F and I are found above the places where the lowest temperatures at the tropopause occur. Fig. 9 also indicates that the relationship between ozone variations and temperatures of the tropopause is closer than the relationship between ozone and the height of the tropopause. Low temperatures at the tropopause usually occur in connection with a high tropopause and vice versa, but this is not always the case, thus, the ozone minimum at A on May 7th occurs above the place where the temperature at the tropopause has a minimum, whereas the height of the tropopause is less than 8 km, and the tropospheric air mass clearly must be classified as a cold mass. A similar case can be found on May 13th when the ozone curve shows a secondary minimum between G and H, which corresponds well to the low temperature at the tropopause, whereas the tropospheric air masses are very cold and the height of the tropopause is unusually low. The study of the isopleth diagram in Fig. 9 and the study of similar diagrams, which are not reproduced here, confirm the reasons for assuming

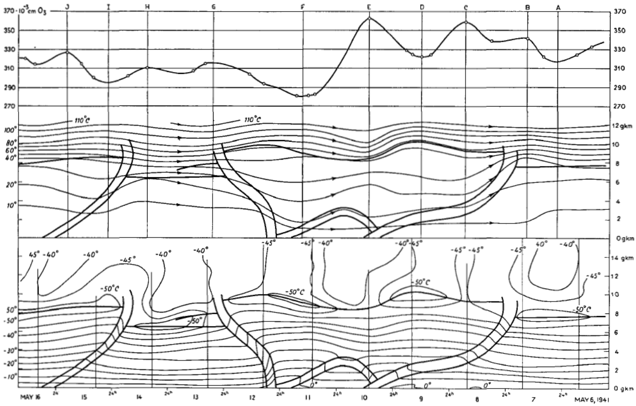

Fig. 9. Ozone values at Tromsø during the period from May 6th until May 16th 1941 (upper part) together with isopleths of frontal boundaries, tropopauses, potential temperature (intermediate part) and temperature (lower part).

that the ozone variations cannot be explained by the advection theory solely.

In the previous chapter the ozone variations which may result from the convergence and divergence effect in the upper troposphere and lower stratosphere have been pointed out. This effect can be studied by comparing the ozone variations in Fig. 9 with the isopleths of potential temperature which are drawn in the intermediate part of the same figure. The isentropes are drawn for every 10° C and show the ascending motion along the warm front surfaces and the descending motion along the cold front surfaces, together with the characteristic crowding of the isentropic sheets in the frontal surfaces. In the stratosphere the isentropes vary almost parallel with the tropopause. From the Figure it can be seen that the periods showing falling ozone are characterized by vertical shrinking of the isentropes and, therefore, by horizontal divergence causing depletion of masses at higher tropospheric and lower stratospheric levels. The periods of rising ozone correspond to the converse variations of the isentropes, i.e. vertical spreading and horizontal convergence. For instance, during the marked fall in ozone from E to F in the Figure, the tropopause rises and the temperature falls at the tropopause and in the stratosphere, whereas the temperature in the troposphere rises. During the same period the isentropes show ascending motion above the frontal surface and in the upper part of the troposphere, and descending motion in the stratosphere, resulting in horizontal divergence at the upper levels. Calculating the pressure difference between the 20° and 60° C isentrope, it was found that it had changed by about 100 mb, showing that a considerable depletion of air masses must have taken place. The fall in ozone from E to F was followed by a rise in ozone from F to G. During this period the isentropes show descending motion above the cold front surface and ascending motion in the stratosphere. In this case the rise in ozone is associated with vertical divergence and horizontal convergence in the upper troposphere and lower stratosphere.

The study of several cases of ozone variations in relation to fronts and isentropes has given similar results as outlined above, and confirms the assumptions about the upper convergence and divergence being instrumental in causing ozone variations.

7. Summary.

The variations in the total amount of ozone over Tromsø and associated changes in meteorological elements, such as upper air temperature, pressure and height of tropopause have been studied. The correlation coefficients between the total ozone and the elements just mentioned, showed an annual variation with only small coefficients during midwinter, and maximum correlation coefficients during April—May.

Correlation coefficients of total ozone with temperature and pressure at the levels of 3, 6, 9, 12 and 15 km showed that the highest coefficients could be found at 6 km.

Correlation coefficients between ozone and potential temperature in the stratosphere during summer showed that the highest correlation could be found at 12—14 km, decreasing upwards to the level of 18 km.

A comparison between the annual variations of the correlation coefficients and the annual variations of the horizontal ozone gradient between 60 and 70° N, showed that it was impossible to attribute the ozone variations solely to horizontal advection. By grouping the observations according to rise and fall regions of atmospheric pressure at ground level, it could be shown that the variations of total ozone were related to the fall and rise regions at ground level, to the height of the tropopause and to the upper pressure variations, pointing to dynamical processes being of great importance to the connection between ozone and weather.

The variation of the five-day means of ozone in relation to the five-day means of pressure and temperature at 6 km has been studied. It was found that the ozone content varied inversely to the upper cold troughs and warm ridges, and that the greatest ozone variations occurred during spring and autumn, as would be expected if dynamical processes in the atmosphere play an important rôle in causing ozone variations. The correlation coefficients of ozone with pressure and temperature at 6 km, when five-day means were used, were found to be almost equal to the correlation coefficients between ozone and the corresponding elements when day-to-day variations were used.

Comparing the ozone variations with the isopleths of fronts, tropopauses, temperature and potential temperature it could be shown that a close connection existed between ozone variations and upper convergence and divergence.

I should like to express my sincere thanks to *Mr. Finn Spinnangr*, Director of *Vervarslinga på Vestlandet*, Bergen, and to *Mr. Einar Tønsberg*, Director of *Nordlysobservatoriet*, Tromsø, for their inspiring interest in this work.

Thanks are also due to *Mr. Magnus Rasmussen* for his valuable help in preparing the material, and for drawing the figures.

Vervarslinga på Vestlandet,
Bergen, October 1954.

REFERENCES

1. *Dobson, G. M. B.:* A Photoelectric Spectrophotometer for Measuring the Amount of Atmospheric Ozone. Proc. Roy. Phys. Soc. 43, III, 1931.

2. — *D. N. Harrison,* and *J. Lawrence:* Measurements of the Amount of Ozone in the Earth's Atmosphere and its Relation to other Geophysical Conditions. Proc. Roy. Soc. London. A, Vol. 122, 1928.

3. — *A. W. Brewer, and B. M. Cwilong:* Meteorology of the Lower Stratosphere. Proc. Roy. Soc. London. A, Vol. 185, 1946.

4. — and *A. R. Meetham:* Atmospheric Ozone and Meteorology Quart. Journ. Vol. 60, 1934.

5. *Craig, R A.:* The Observations and Photochemistry of Atmospheric Ozone and their Meteorological Significance. Am. Met. Soc. Met. Monogr. Vol. 1, No. 2, 1950.

6. *Dütsch, H. U :* Photochemische Theorie des atmospharischen Ozons unter Berücksichtigung von Nichtgleichgewichtszuständen und Luftbewegungen. Dr. Diss. Univ. Zürich, 1946

7. *Götz, F. W. P :* Der Stand des Ozonproblems. Ber. dtsch. Wetterd. U.S.-Zone, Nr. 11, 1949.

8 — Ozone in the Atmosphere. Comp. of Met., 1951.

9 *Haurwitz, B :* Atmospheric Ozone as a Constituent of the Atmosphere. Bull. Am. Met. Soc. Vol. 19, 1938.

10. *Johansen, H.:* Eine aerologische Untersuchung mittels Radiosondierungen in Tromsø vährend der Zeit 31. März—30. April, 1939. Met. Ann. Bd. 1, Nr. 2, 1942.

11. — Mean Upper Air Data Obtained from Soundings at Tromsø during the Years 1941—44. Geof. Publ. Vol. XVII, No. 4, 1948.

12. *Langlo, K.:* On the Amount of Atmospheric Ozone and its Relation to Meteorological Conditions. Geof. Publ. Vol. XVIII, No. 6, 1952.

13. *Meetham, A. R.:* The Correlation of the Amount of Ozone with other Characteristics of the Atmosphere. Quart. Journ. Roy. Met. Soc. Vol. LXIII, No. 271, 1937.

14. *Moser, H.:* Ozon und Wetterlage. Ber. dtsch. Wetterd U.S.-Zone, Nr. 11, 1949.

15. *Nicolet, M.·* L'ozone et ses relations avec la situation atmosphérique. Inst. R. météor. Belg., Misc , Fasc 19, 1945.

16. *Palmén, E.:* Über die dreidimensionale Luftströmung in einer Zyclone und die Ozonverteilung. U. G. G. I. Proc Verb Ass. Météor. 1939.

17. *Reed, R. J.:* The Effect of Atmospheric Circulation on Ozone Distribution and Variations. Massachusetts Inst. of Tech., 1949.

18. — The Rôle of Vertical Motions in Ozone-Weather Relationship. Journ. of Met. Vol. 7, 1950.

19 *Tønsberg, E.* and *K. Langlo (Olsen):* Investigations on Atmospheric Ozone at Nordlysobservatoriet, Tromsø. Geof. Publ. Vol. XIII, No. 12, 1944

20. — and *D. Chalonge:* Ozone Measurements at the Auroral Observatory, Tromsø. Quart. Journ. Suppl. to Vol. 62, 1936.

21. *Wulf, O. R and L. S. Deming:* The Distribution of Atmospheric Ozone in Equilibrium with Solar Radiation and the Rate of Maintenance of the Distribution. Terr. Mag. Vol. 42, 1937.