INVESTIGATIONS ON ATMOSPHERIC OZONE AT NORDLYSOBSERVATORIET, TROMSØ

BY

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I. Observations and Results.

Introduction.

The results of *Dr. Dobsons* extensive ozone measurements during the years 1925 to 1927 (13, 14, 15, 16) made it very desirable to extend the measurements to the highest possible latitudes. Even in the summer season of 1929 observations were made at Spitzbergen (20) by *Dr. Götz.* Then five years later in 1934 *Dr. Dobson* and *Dr. Meetham* made observations at Nordlysobservatoriet in order to determine the vertical distribution of atmospheric ozone over Tromsø (26). And on this occasion Dr. Dobson most kindly offered us one of his "old" instruments for observation at Tromsø. The spectrograph arrived in the summer of 1935, ready for use at once.

The following winter we made the first moonlight observations for ozone determinations (30) by means of a large kvartz spectrograph constructed by *Dr. L. Vegard* (31). Just the same winter season starlight observations were undertaken at Abisko in North Sweden by Barbier, Chalonge and Vassy (3), who before returning home paid a visit to Nordlysobservatoriet, and very kindly left behind a star spectrograph (5) for observations the next winter season. Thus in the summer of 1935 we disposed of instruments for ozone measurements by sunlight, starlight and moonlight.

To be well informed about ozone observations and working methods one of us (Tønsberg) made a journey to Dr. Dobson in Oxford, Dr. Chalonge in Paris and Dr. Götz in Arosa, and is deeply grateful for all kind advice and information.

Later on (1936) a star spectrograph of the Chalonge pattern (5) was built at Nordlysobservatoriet, and in the autumn of 1939 we got a Dr. Dobson spectrophotometer (11).

The instruments mentioned above have earlier been described in detail in connection with discussions of methods and results, why we should not give detailed descriptions here, but present methods and results in brief.

The paper is divided into three sections, containing in succession, Observations and Results, undertaken and dealt with by Tønsberg, Vertical Distribution, worked out in close collaboration, and Ozone Variations during Passage of Cyclones, developed by Langlo Olsen.

For mechanical work and observations Mr. M. Jacobsen should be especially remembered, as well as Mr. R. Larsen who has made a number of observations.

For grants covering expenses to observations and calculation work thanks are due to Statens Videnskabelige Forskningsfond and Nansenfondet.

Short Description of the Optical Method for Determination of the Amount of Atmospheric Ozone.

The method has been developed by Chr. Fabry & H. Buisson (17), but has undoubtedly gained for practical purposes by the modifications introduced by G. M. B. Dobson (13). The principle base of the method lies in the highly increasing absorption power by ozone of the ultraviolet radiation at the limit of the solar spectrum, say 3300 A to 3000 A.

Let us temporarily assume the earth to be flat, then a monocromatic radiation of intensity I_0, when entering the earth's atmosphere in a direction of zenith distance Z, and intensity I_h at the height h, will be reduced to an intensity $I_h \cdot 10^{-a \cdot \sec Z \cdot dh}$ by passing through a layer of thickness dh. Here a is called the absorption coefficient of the air of the layer dh, and will depend upon the density and composition of the air and consequently change with height. Summing up the absorption through the whole atmosphere the intensity at the surface of the earth will be expressed by:

$$I = I_0 \cdot 10^{-\sec Z \int_0^\infty a\, dh} \text{ or}$$

$$\log I = \log I_0 - \sec Z \int_0^\infty a\, dh = \log I_0 - k \cdot \sec Z$$

where $k = \int_0^\infty a\, dh$ expresses the total loss of intensity suffered by a radiation by passing vertically through the entire atmosphere.

Observations have stated that k is due both to scattering and absorption of the radiation. Suitable to our purpose we write

$$k = \delta + \beta + a x.$$

Where δ is the scattering coefficient of the atmosphere due to particles which are large compared with the wavelength of light, and which have shown to be approximately independent of the wavelength.

β is the scattering coefficient of the atmosphere due to air molecules and particles which are small compared with the wavelength of light, and which according to Rayleigh's formula (18) scatter light inversely as the fourth power of the wavelength.

a being the absorption coefficient for 1 cm. of pure ozone at normal temperature and pressure, then x will be the thickness in cm. of the ozone layer, or the amount of ozone in the atmosphere at normal conditions.

From the intensity equation

$$\log I = \log I_0 - k \cdot \sec Z$$

follows that $\log I$ is a linear function of $\sec Z$ when I_0 and k are considered to remain constant for every chosen wavelength during a series of intensity measurements at various altitudes of the sun. Assuming the intensity I at the earth's surface to be measured in arbitrary units, and $\log I$ plotted against $\sec Z$ in a diagram (fig. 4, page 7), then the points should lie on a straight line, the angle coefficient of which is equal to k.

But the intensity equation involves another possibility too, which leads to a fundamental constant for the daily routine ozone measurements. Hence we shall have $\log I = \log I_0$ not only for $k = 0$, according to our assumptions, but also for the impossible value $\sec Z = 0$. All the same by extrapolating the straight $\log I/\sec Z$ curve (fig. 4) to $\sec Z = 0$ we are able to read off the value of $\log I_0$ in arbitrary units for any chosen wavelength.

For a pair of wavelengths λ and λ' the intensity equations are respectively:

$$\log I = \log I_0 - (a x + \beta + \delta) \sec Z$$
$$\log I' = \log I'_0 - (a' x + \beta' + \delta) \sec Z$$

$$x = \frac{\log I_0/I'_0 - \log I/I' - (\beta - \beta') \sec Z}{(a - a') \sec Z}$$

By means of this equation we can calculate the ozone value x from one single photograph by measuring the intensities I and I', if we assume $\log I_0/I'_0$ to be a constant measured beforehand, and the values of $(\beta - \beta')$ and $(a - a')$ are known.

As to $\sec Z$, its value should have to be corrected for two reasons, the curvature of the earth, and the fact that the atmospheric ozone forms a region with its centre of gravity about 25 km. above the earth's surface.

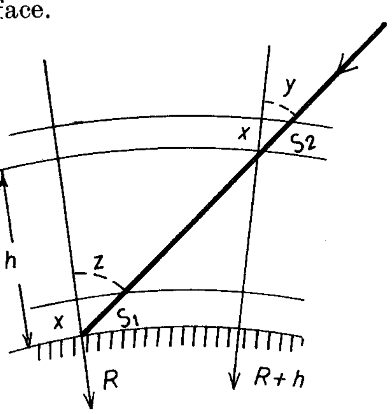

Fig. 1. The path-length s of a lightbeam at the ground and at a heigth h.

Regarding fig. 1 we have approximately for the path-lengths:

$$s_1 = x \cdot \sec z \text{ and } s_2 = x \cdot \sec y$$

where y is the zenith distance seen from a height of 25 km. The connection between y and z is given by $\sin y = \frac{R}{R + h} \sin z$.

The approximate proportionality between s_1 & $\sec z$ and s_2 & $\sec y$ however, will diminish with increasing z. Meanwhile Bemporade has calculated the path-length accurately, taking into account both the curvature of the earth and the refraction. Thus the relative path-length of light through the whole atmosphere will be given by Bemporade's corrected values of sec z, by Dobson denoted by m, and the relative path-length of light through the ozone region — with its centre of gravity 25 km. above — will be given by the corrected values of sec y, by Dobson denoted by μ. With these new designations the ozone equation is written:

$$x = \frac{\log I_0/I'_0 - \log I/I' - (\beta - \beta')\, m}{(\alpha - \alpha')\, \mu.}$$

A further examination of the various terms of the equation will follow.

Sunlight Observations.

The instruments used were an "old" Dr. Dobson spectrograph from 1935 to 1939, and a "new" Dobson — the spectrophotometer — later on.

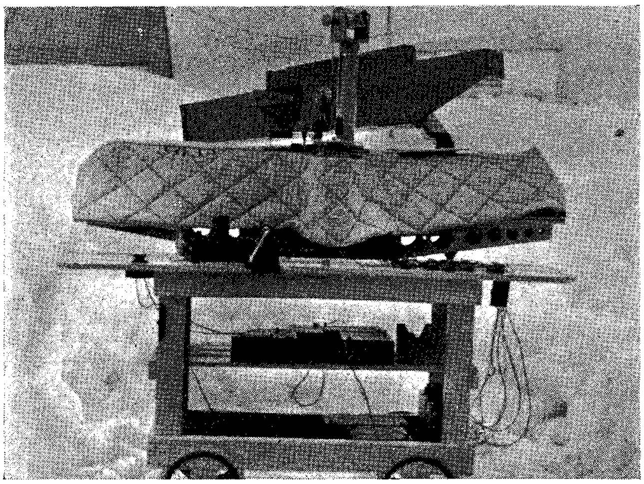

Fig. 2. Dr. Dobson's "new" and "old" ozone instruments.

The "old" Dobson spectrograph was constructed especially for ozone measurements from photographs of the sun in the wavelength region 3300 A to 2900 A. A detailed description of the apparatus in construction and use is given by Dr. Dobson (13). The instrument is an excellent one, giving photographs free from fogging and of high sharpness. The dispersion corresponds to about 14 A units per mm. in the actual region. An enlargement of a photograph is seen on fig. 3. It is evident that the light has passed through an optical wedge before falling on the plate.

For relative intensity measurements (determination of log I/I') of the selected wavelengths we have used a visual photometer of the P. P. Koch pattern (23) with two photo-electric cells, the second one serving as a grid leak cell. The measuring accuracy of the photometer has proved satisfactory.

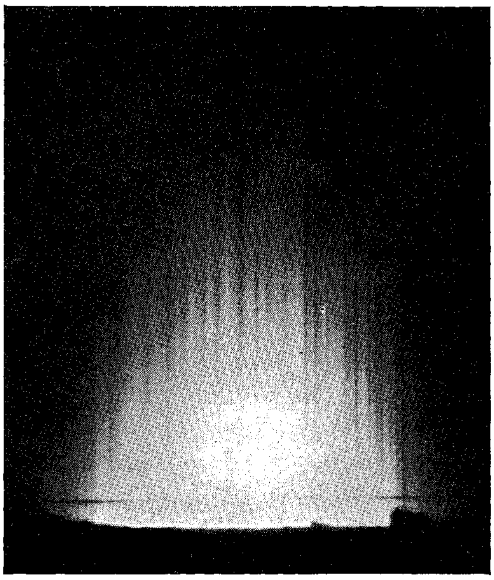

Fig. 3. Enlargement of an "old" Dobson photograph.

Just before sending the spectrograph from Oxford Dr. Dobson took 12 trial photographs, and simultaneously measured the amount of ozone by means of his spectrophotometer. Besides the 12 photographs we got a list of selected wavelengths with all necessary constants and coefficients. Thus a definite test of our intensity measurements was possible. This test proved satisfactory, giving ozone values not differing more than 0.006 cm. as a maximum from the true ones (determined by the spectrophotometer), the mean difference being 0.002 cm.

Consequently we should have reason to believe that the ozone values of Tromsø were directly comparable with those of Oxford, so far as the spectrograph had remained unchanged. This requirement, however, was not quite fulfilled, as it was found desirable already in August 1935 to try an adjustment of the spectrograph to obtain the highest possible sharpness of the spectral lines. But it is not likely that this slight alteration has affected the ozone values by any considerable amount, so far as some measurements simultaneously undertaken between this instrument and the spectrophotometer showed no appreciable differences in the ozone values. A subject to be dealt with later on.

Some remarks on the different terms of the ozone equation (page 5) seem to be desirable. In addition to the wavelengths employed by Dobson, and supported with the necessary constants and coefficients, we have selected two more, 3086 A and 3125 A, to be able to extend the measurements some days in the spring and autumn. For the new pairs of lines 3086 A & 3264 A and 3125 A & 3232 A we have limited ourselves calculating the constants log I_0/I'_0, understanding the ozone values to be known. For that purpose we selected 20 spectra from 1935 and 28 spectra from 1936. The resulting constants are given in the summary just behind. The differences from the mean values of constants were rather slight, extending to an error in the ozone values of 0.006 cm. for the wavelengths 3086 & 3264 A and of 0.010 cm. for the wavelengths 3125 & 3232 A as a maximum.

For the selected wavelengths the constants and coefficients tabled below have been used. The scattering coefficients β were calculated by means of Rayleigh's formula (18 page 193). The absorption coefficients α were those determined by Ny Tsi-Ze and Choong Shin-Piaw (28).

Wavelength λ in A	3264	3232	3125	3086	3062	3052	3022
Optical wedge constant...........	0.174	0.185	0.203	0.204	0.204	0.204	0.196
Absorption coeffic. α	0.13	0.22	1.00	1.84	2.40	2.58	3.63
Scattering coeffic. β	0.29	0.30	0.34	0.36	0.37	0.37	0.39

Pairs of wavelengths	3052 3232	3062 3264	3022 3264	3086 3264	3125 3232
Log I_0/I'_0	1.371	1.606	1.661	1.605	0.965
$(\alpha - \alpha')$	2.36	2.27	3.50	1.71	0.78
$(\beta - \beta')$	0.07	0.08	0.10	0.07	0.04

Among these 5 pairs of wavelengths we have for far the greater number of spectra limited ourselves dealing with the first and second. For measurements made earlier than 20/3 in the spring and later than 10/10 in the autumn the wavelengths 3086 & 3264 A and 3125 & 3232 A had to be trusted on solely. Consequently ozone values within these two periods of time will have a considerably reduced accuracy. As to accuracy and sources of error in general we should refer to the papers of Dr. Dobson (13, 14, 15, 16). A single remark to differences in ozone values by different pairs of wavelengths within the same spectrum seem to be desirable. Such differences were in general less than 0.005 cm. for the wavelengths 3052 & 3232 A and 3062 & 3264 A, and less than 0,010 cm. for the wavelengths 3086 & 3264 A and 3125 & 3232 A.

Considering all sources of error and regarding the whole picture of values, the limit of uncertainty should be put to about ± 0.020 cm.

In 1939 and 1940 some simultaneous measurements between the "old" spectrograph and the spectrophotometer were made for comparison of the resulting values. The outcome is given below. Unit 0.001 cm.

1939	"New" Dobson	"Old" Dobson	Correction	
			+	—
24/8	206	208		2
25/8	190	189	1	
26/8	204	200	4	
27/8	201	198	3	
28/8	193	194		1
2/9	183	183		0
7/9	184	185		1
1940				
28/3	297	295	2	
22/5	273	274		1
23/5	272	266	6	
24/5	270	267	3	
25/5	264	254	10	
27/5	260	258	2	
13/6	258	263		5
14/6	246	238	8	
6/8	236	228	8	
9/8	235	234	1	

The measurements indicate small but slightly increasing differences, and *the possibility of a small lifting of say 0.005 cm. of the ozone values by the spectrophotometer should not be excluded.*

Spectrophotometric Measurements.

A detailed description of the spectrophotometer in construction, management and evaluation of the readings is given by Dr. Dobson in his "*Instructions for Use of Dr. Dobson's Spectrophotometer*" (12). Although we cannot pay too much tribute to the ozone spectrograph, the spectrophotometer has evidently predominant advantages. With this instrument values of the amount of atmospheric ozone can be obtained easily and rapidly by observations on direct sunlight as well as on the zenith sky, clear or cloudy. Fortunately the sensitivity of the instrument is sufficiently high to make observations possible even throughout the darkest winter season at Tromsø. In this connection we should remark that our instrument — marked no. 14 — according to Dr. Dobson showed a higher sensitivity than any other of the instruments dealt with. Further we should mention that the instrument during the three years it has served us, has worked very satisfactorily and never failed to be in order. Some gaps in the observational series have other reasons. That the instrument is kept in a central heated and very dry room should be preferable. Better advised from experience we always take the instrument inside between succesive observations even when these are made with short time intervals.

Observations by Direct Sunlight.

These observations are the fundamental ones, and should be taken to the lowest possible height of the sun, which for our instrument is about 16° — corresponding to a zenith distance of 74° —, a lower sun evidently gives too small ozone values. A single observation merely consists of a dial reading which determines the ratio of the intensities of the wavelengths 3110 A and 3300 A. Remembering the ozone equation (page 5), this ratio has been written log I/I'. To be able to determine just the same ratio of intensities — log I_0/I'_0 — at the outside of the atmosphere we take series of observations at different altitudes of the sun. To secure a reliable value of log I_0/I'_0 such observational series should not be taken unless on days with steady meteorological conditions. Although log I_0/I'_0 for our instrument had been determined by Dr. Dobson at Oxford, we have made a number of observations at Tromsø to check the Oxford value. On fig. 4 two of our very smooth series are shown, taken when ozone has remained constant. Our average value of log I_0/I'_0 coincides exactly with the Oxford value which was 2.943, while our 22 individual values are scattered between 2.928 and 2.955.

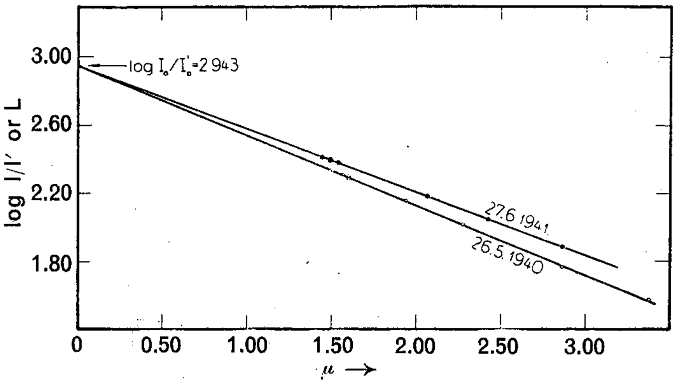

Fig. 4. Series of observations to determine the fundamental constant log I_0/I'_0.

Let log I_0/I'_0 and log I/I' be written respectively L_0 and L, and the values of the coefficients of the wavelengths 3110 A and 3300 A put into the equation, then we have:

$$x = (L_0 - L)/(\alpha - \alpha')\,\mu - (\beta - \beta')\;m/(\alpha - \alpha')\,\mu$$

$$x = \frac{2.943 - L}{1.17\,\mu} - 0.085$$

where the ratio m/μ has been put equal to a constant, although it changes from 1.003 by the highest position of the sun to 1.03 by the lowest available for measurements. The above given formula, very simple indeed, should be preferred at Tromsø to the original more complicated formula also proposed by Dr. Dobson (11). Here an additional measurement of the relative intensities of the wavelengths 3300 A and 4450 A was introduced in order to determine and count for the scattering of the light of the atmosphere due to air molecules and particles which are small compared to the wavelengths, the scattering being put inversely proportional to the fourth power of the wavelength. Observations on days when the sky was hazy should however show obviously wrong results, when the scattering due to those small particles was accounted for according to the inverse fourth power assumption. Dealing with this scattering as neutral — which just has been made in the simple ozone formula above — we get more reliable results, especially on days when the sky is hazy.

As to the accuracy of direct sunlight values of ozone we have above verged on the chief sources of error, being the possible variations in the difference of the scattering coefficients depending on the atmospheric conditions, and the variations in L_0 and L depending both on the instrument and the sun, or more exactly on the constancy of these. We should have to take into consideration both systematic and nonsystematic errors, carefully discussed by Dr. Dobson and collaborators (11, 12, 22), and summed up to a probable amount of 0.005

to 0.010 cm. of ozone in the daily routine observations, provided the necessary check observations being made from time to time. According to our experience we should agree to the amount of error given above in the direct sunlight values of ozone.

Observations on the Clear Zenith Sky.

These observations are based on the direct sunlight measurements, which should be made alternately with those on the zenith sky, the latter being equally simple and consisting merely of a dial reading for the determination of the ratio of intensities (*L*) of the "short" wavelengths 3110 A and 3300 A, and recording of the time which gives the sun's zenith distance or μ. Generally an additional observation of the ratio of the intensities (*L'*) of the "long" wavelengths 3300 A and 4450 A is made, the reason why will be given where the observations on the *cloudy* zenith sky are dealt with.

It has been found by Dr. Dobson that there is a definite relation between the amount of ozone (determined by direct sunlight observations) and the intensity readings *L* obtained from the clear zenith sky observations for any given value of μ. Every point in a diagram between *L* and μ has a particular ozone value. Fig. 5 gives a picture of this diagram or chart, the construction of which is based upon alternate observations of direct sunlight (0_3) and on clear zenith sky (*L* and μ). To prevent unreliable results such observations should not be made unless meteorological conditions and ozone remain steady or constant. This is extremely important when μ is greater than 3.50, the lower limit of direct sunlight observations.

Dr. Dobson had provided each instrument with a chart like that of fig. 5, but our check observations at once showed that we should have to change it considerably — mainly because of a different vertical distribution of ozone at Oxford and at Tromsø — and above all, extend it to extreme ozone values, and prolong the curves to far greater μ or lower sun. In the table below we have given the results of some check observations taken during 1941 and 1942 after the ozone-curves had been drawn according to the outcome of a number of earlier series of observations.

⊙ 0_3 means direct sun values. Sb. 0_3 means blue zenith sky values. $\Delta\ 0_3$ means correction of Sb. — values. Unit 0.001 cm.

The table below shows a good agreement between the sun and zenith sky measurements, and according to our experience the zenith sky values are equal in quality to the sun values, and probably more reliable on days when the sky is hazy. Nevertheless the chart on fig. 5 has two pronounced

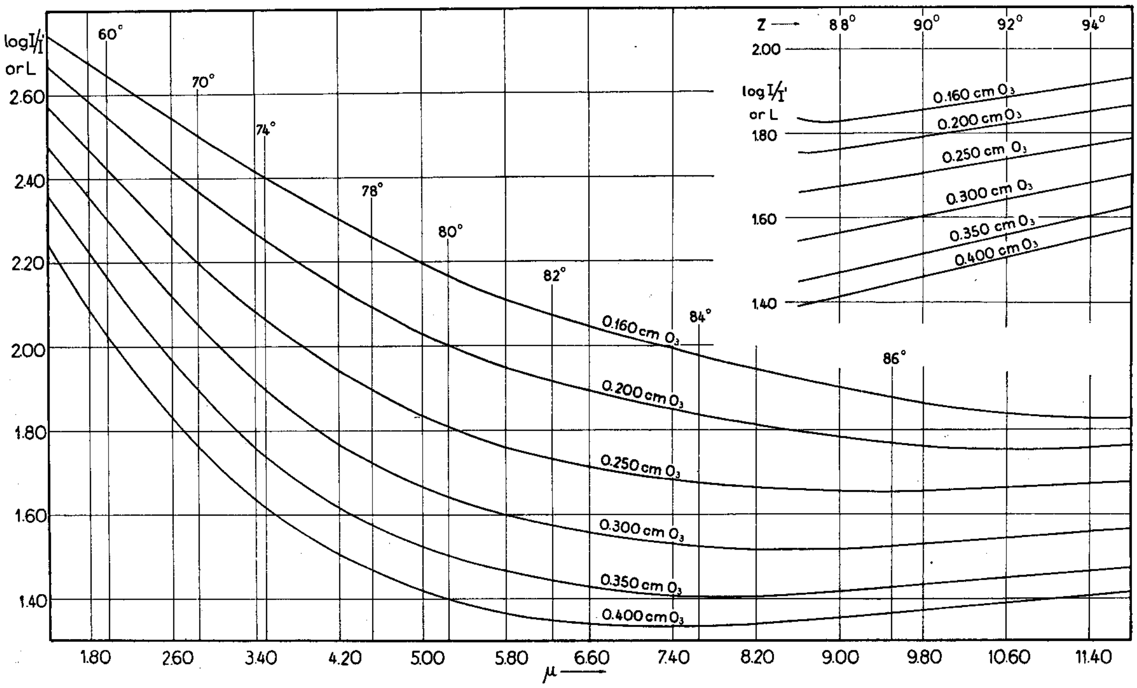

Fig. 5. Chart for the evaluation of ozone by zenith sky observations.

μ	$\odot\ O_3$	Sb. O_3	$\Delta\ O_3$		μ	$\odot\ O_3$	Sb. O_3	$\Delta\ O_3$	
			+	—				+	—
2.08	375	372	3		1.89	250	254		4
2.67	368	376		8	1.90	243	242	1	
2.65	342	344		2	1.89	243	242	1	
1.84	341	339	2		1.44	238	241		3
2.31	340	342		2	1.84	244	245		1
2.28	338	335	3		2.07	230	226	4	
2.21	333	334		1	2.43	231	232		1
2.29	334	332	2		2.87	230	228	2	
2.23	323	325		2	1.51	220	219	1	
2.17	324	322	2		1.85	220	219	1	
1.69	315	314	1		1.74	220	218	2	
1.67	315	318		3	1.55	220	217	3	
1.48	307	307	0		1.48	217	212	5	
1.77	306	306	0		1.77	214	217		3
1.91	304	302	2		2.17	210	208	2	
2.13	298	299		1	1.79	206	206	0	
1.70	298	300		2	1.76	207	203	4	
1.74	286	289		3	1.83	206	206	0	
1.54	286	283	3		1.97	203	206		3
1.56	284	285		1	3.08	199	201		2
1.51	273	273	0		2.28	193	192	1	
1.92	267	268		1	2.58	184	184	0	
2.16	267	266	1		2.50	180	178	2	
3.17	260	262		2					
1.54	260	259	1						

infirmities. 1. The extrapolation of the curves to ozone values higher than 0.380 cm. and lower than 0.170 cm., these values being the extremities of direct sunlight values. The said extrapolation has no definite base, only a probable one. 2. The prolongation of the curves beyond μ greater than 3.50, being based merely upon the assumption of the ozone amount remaining constant during the series of observation, an assumption which easily may fail even under the most stable weather conditions. Passing by $\mu = 3.50$ to the right on fig. 5 the mean ozone curves become more and more uncertain, mainly because of an increasing inaccuracy in the dial readings of the instrument with decreasing sun and intensity of light. Even when the sky is cloudy, however, the sensitivity of the instrument is sufficient to obtain dial readings down to a position of the sun of 3° under the horizon. During the darkest season, however, it is difficult to fix a certain reading and one should have to determine an upper and lower limit of readings, using the mean value for the evaluation of ozone.

Further we should have to underline the fact that the ozone curves of fig. 5 are based on observations made from March to October, while we are using them throughout the year. This will only be correct if the vertical distribution of ozone remains relatively unchanged during all seasons. It has just been found that the dial readings corresponding to very low sun mainly depend on the ozone content in a height of 35 km. or more, and not so much on the ozone content at lower levels.

Let us draw attention to the fact that dial readings of the "long" wavelengths 3300 A and 4450 A on the clear zenith sky for the very same value of μ may differ considerably, even so much that a "cloud correction" may come into consideration; alike the one for observations on a real cloudy sky, to be dealt with soon.

Before leaving the clear zenith sky observations we should — according to our experience — give some estimation of the accuracy of these observations attainable at different values of μ or different seasons of the year. The sensitivity of the instrument or the unsteadiness of the galvanometer needle should be carefully watched, and should not exceed the impulses caused by the observational actions. Assuming the observations to be taken approximately at noon the uncertainty of the dial settings may be put equal to 1°, corresponding to an error of 0.005 cm. in all ozone values in the time interval from 20/2 to 20/10, when the maximum value of μ reaches about 5. In the period 20/10 to 15/11 (and respectively 25/1 to 20/2) when μ is changing from 5 to 12 the uncertainty of dial settings increases from 1° to 3°, and correspondingly the error in ozone will increase from 0.005 cm. to maximum 0.015 cm. for values lower than 0.300 cm., to maximum 0.020 cm. for values at 0.350 cm. and to maximum 0.030 cm. for values at 0.400 cm. In the period after 15/11 (respectively before 25/1) the uncertainty of dial settings is rapidly increasing passing about 5° on 22/11 (and 21/1) at the beginning (and end) of the season of obscuration at Tromsø, and reaching some-what 10° at winter solstice. For a greater uncertainty of dial settings no observations have been evaluated. An inaccuracy of the dial readings of 5° corresponds to a maximum error in ozone of 0.035 cm. for values lower than 0.340 cm. and to 0.055 cm. for values at 0.400 cm. For an

Period	1/1–14/1	15/1–31/1	1/2–20/2	21/2–31/3	1/4–30/9	1/10–24/10	25/10–14/11	15/11–30/11	1/12–31/12
Possible observational error in 0_3 in cm....	0.060	0.040	0.025	0.015	0.005	0.010	0.020	0.040	0.070

inaccuracy of 10° in the readings we have respectively errors of ozone of 0.070 cm. and 0.110 cm. Considering the ozone values that generally come out at the different seasons of the year, we may give the following outlined table to illustate the inaccuracy of measurements on the *clear* zenith sky.

We should further remember a possible systematic error of the direct sunlight values of about 0.010 cm., and look forward to a "cloud correction" error of say 0.010 cm.

Observations on the Cloudy Zenith Sky.

These observations are made in a similar way as those on the clear zenith sky, by alternate dial readings of the relative intensities L ($\log I/I'$) and L' ($\log I''/I'$) of the two pairs of wavelengths. The quality of the observations will differ considerably, being good when the clouds remain steady, and poor when they are changing rapidly. It is important that the two observations are made on similar types of cloud.

For the reduction of cloudy sky intensities L_c to blue (clear) sky intensities L_b Dr. Dobson has introduced an empirically based method. It has been found that the values of L'_b ("long" wavelengths) for a given sec z or "m" are approximately the same for every clear day, and that they are but slightly affected by the amount of ozone present. The average connections at Tromsø between L'_b, "*m*" and 0_3 — based on a considerable number of observations — are given on fig. 6. In fact two such charts — both relating to clear zenith sky — the one somewhat displaced to the other — are used alternately whether we have sunshine on the observational spot or not. A reading of the "long" wavelengths on cloudy zenith sky — L'_c — should ever be reduced by $\Delta L' = L'_c - L'_b$, L'_b being obtained from the chart on fig. 6, when "m" is known and the actual ozone value approximately judged by means of L_c ("short" wavelengths) from the chart on fig. 5. The magnitude of $\Delta L'$ changes considerably and depends on the height and thickness of the clouds. By making observations on days when the zenith sky is alternately changing between clear and cloudy is has been found a definite relation between $\Delta L' = L'_b - L'_c$ and $\Delta L = L_b - L_c$ ("short" wavelengths) depending on the position of the sun or μ. This relation for low clouds is illustrated on fig. 7. Dr. Dobson, however, has found it necessary to distinguish between high, middle and low clouds, and for that reason we deal with three different charts of the type on fig. 7. At Tromsø we have had to make observations to extend these charts beyond $\mu = 5$, a task however not yet fulfilled quite satisfactorily.

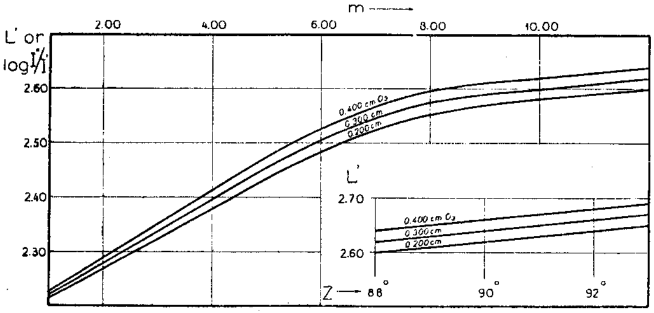

Fig. 6. Chart of average standard readings L'_b of the "long" wavelengths on the clear zenith sky.

Thus to evaluate an observation on the cloudy zenith sky we proceed as follows: From the chart on fig. 6 we obtain L'_b, and by means of $\Delta L'$ from

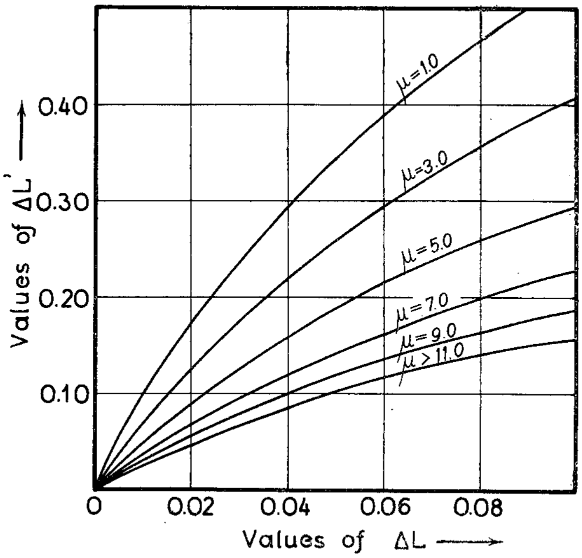

Fig. 7. Chart of "cloud correction" ΔL for *low* clouds.

the chart on fig. 7 we get ΔL, which added to L_c gives L_b, which again from the chart on fig. 5 gives the ozone value.

We cannot of course expect the same accuracy from measurements on the cloudy zenith sky as from those on the clear, and particularly for very low sun the "cloud correction" is not quite satisfactorily determined. But this does not matter so much after all, the "cloud correction" for very low sun always being relatively small.

As to the error introduced by the inaccuracy of the "cloud correction" we should estimate it generally to be less than 0.010 cm. in the ozone value, unless for rapidly drifting and changing clouds; and no marked annual variation is present.

Observations on days when the sky is evidently or actually hazy, although clear, have been dealt with as "cloud" observations. The "cloud" correction in the ozone value will generally amount to no more than 0.005 cm. This procedure means that we believe it to be right to fix a certain standard reading for every value of "*m*" (fig. 6 page 10), which should be reached on the blue sky, and if not lifted to it.

Starlight Observations.

It has found to be possible to use both starlight and moonlight for ozone measurements provided the suitable apparatuses were at hand. A very good star spectrograph was constructed by Chalonge & Vassy (5). A picture of the instrument is seen on fig. 8.

Measurements undertaken by the French at Abisko in North Sweden during the winter season of 1934/35 brought the first ozone values from the polar night (3). To obtain more similar values the spectrograph was kindly put to our disposal for the winter season of 1935/36. We got several star spectra, which were sent Dr. Chalonge for evaluation. By far the majority, however, were unfortunately too weak or fogged by aurorae to give reliable ozone values. The few values obtained will be found in the ozone table marked by St.

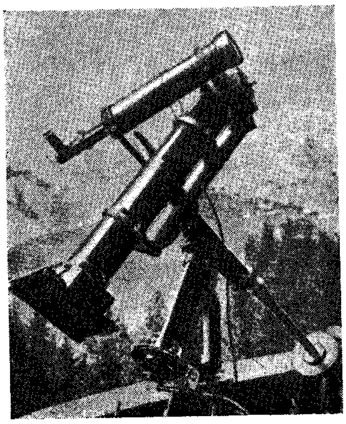

Fig. 8. The French star spectrograph.

As to the method of evaluation of the star spectra it is simply the same as for direct sunlight spectra. For details we refer to papers of Barbier, Chalonge and Vassy (3, 4).

Some important features in the construction of the spectrograph should however be emphasized here. By placing the camera lens aslope in the direction of the parallel light beams from the prism, the spectral light *points* of the star will be drawn out to *lines* of some height on the photographic plate, and thus enable us to obtain reliable photometric measurements. It is evident that the height and intensity of the spectral lines will depend upon the angle of slope of the lens, which may be regulated. In the actual wavelength region the spectrograph has a dispersion which corresponds to about 17 A per mm.

The telescope is an indispensable part of the spectrograph, one may say that its filament is the slit of the spectrograph. And during an exposure the spectrograph must be moved in such a way that the star is kept closely on a selected point of the filament.

Every plate must be provided with an intensity scale, which is obtained by means of an artificial star, being a hydrogen tube (6) giving a continuous spectrum of nearly constant intensity in the actual region of wavelengths. The graduation of the intensity scale is obtained by means of diaphragms of different apertures. Thus it is important that the plane where the diaphragms alternate is *uniformly* illuminated.

Let us mention that a similar star spectrograph of that of Chalonge and Vassy has been built at Nordlysobservatoriet. We have, however, not yet succeeded in obtaining sufficiently reliable fundamental constants to present the results of observation here. The main difficulty by the series of observation is the fogging of the spectra caused by auroral displays which suddenly occur.

Moonlight Observations.

Our first attempts on ozone determinations by means of the moonlight were carried out during the winter season of 1934/35 (30). The spectrograph used (31), seen on fig. 9, has a dispersion which corresponds to about 14 A per mm. in the actual region of wavelengths. Through a lens a picture

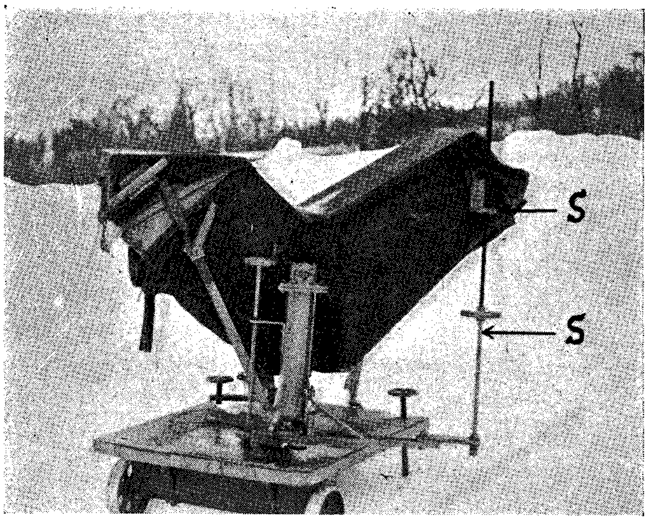

Fig. 9. The spectrograph used for moonlight observations.

of the moon was thrown on the slit, and during the exposure kept there by means of the auxiliary bar or screw marked SS on fig. 9. The height of the moon was measured by a theodolith, and refers to the middle of the exposure.

For determination of the ozone values we made use of *the method of the shortest wavelength* λ_0, developed by Dr. Götz (18, 20), while based on earlier observations by A. Cornu (9, 10). This method is not an independent one, as we need at least one otherwise determined ozone value — a reference value — in connection with a successful series of spectra taken at different heights of the moon. But the method is very simple indeed, it requires no intensity measurement, one simply has to read off the shortest wavelength λ_0 visible on the plate.

The observations of Cornu mentioned above led to the discovery of a connection between the shortest visible wavelength λ_0 in the sun's spectrum and the height h of the sun. If for an observational series λ_0 were plotted against log sin h, the points fell approximately on a straight line, a "Cornu" line (fig. 10). The "line", however, showed parallel displacements from one day to another and above all from season to season, moving against ever shorter wavelengths from summer to autumn.

If we assume an absorbing layer responsible for the dependence of λ_0 of the height h of the sun, there will — when we remember that the path-length of light through the layer is approximately inversely proportional to sin h — by the discovery of Cornu be established a connection between the shortest wavelength λ_0 and the thickness of the absorbing layer, being the ozone layer.

The wavelength limit λ_0 on the plate is influenced both by atmospheric and photographic conditions, of which the invariable do not matter at all. The variations of scattering and transparency of the atmosphere may be approximately eliminated when we omit observations unless the sky is clear, and extend the time of exposure far beyond the necessary limit. We fixed 10 minutes, although 5 minutes were sufficient.

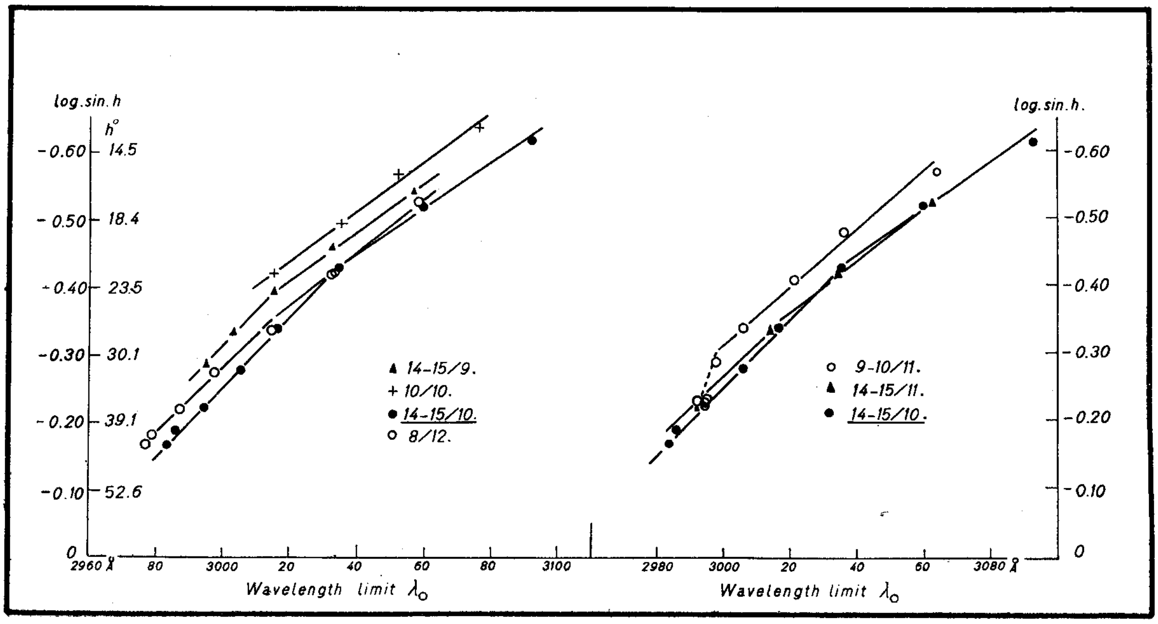

Fig. 10. "Cornu"-lines of moonlight.

Now to determine the thickness of the ozone layer according to the method of the shortest wavelength we proceed as follows. By means of a series of moonlight spectra taken at different altitudes of the moon, and the corresponding ozone value otherwise determined, we get a "Cornu"-line with its corresponding ozone value, or even more a "Cornu"-diagram (fig. 10) to read off ozone values. For an arbitrary moonlight spectrum we should determine log sin h and the wavelength limit λ_0, then on the diagram read off that one to λ_0 on the "Cornu"-line corresponding log sin h, the difference of the two log sin h determines the logarithmical difference between the two ozone layers and thus the difference between the thickness of the layers themselves.

To be able to check the ozone values red off on the "Cornu"-diagram, a number of "Cornu"-lines with corresponding ozone values would be required. We only succeeded, however, in getting one *single "Cornu"-line* with corresponding ozone value from sunlight observations. This happened on the 13. to 15. of October 1935 in the following order. On the 13. two sunlight measurements at about noon gave 0.196 cm. and 0.205 cm. of ozone, mean value 0.201 cm., then during the night of 14. to 15. a successful series of moonlight spectra, the "Cornu"-line of which is drawn twice on fig. 10, and at last on the 15. between 11 and 13 o'clock five sunlight measurements which gave 0.204, 0.201, 0.197, 0.196, 0.196 cm. of ozone, mean value 0.199 cm. Thus the corresponding ozone value to the "Cornu"-line of 14. to 15. of October was put equal to 0.200 cm., assuming the atmospheric ozone to remain constant between the 13. and 15., an assumption which of course may by doubtful, but a least supported by fairly steady weather conditions.

Further to verify the moonlight observations we give the table below of some adjacent sunlight and moonlight values.

Some corrections are considerable, the smallest are connected to the shortest time-differences. *It is possible, however, that the moonlight values ought to be lifted some 0.005 to 0.010 cm.*

Date	Ozone sun	Ozone moon	Correction		Observational time-difference
			+	—	
1936 1/9 ...	210	196	14		14 Hours
2/9 ...	206		10		10
5/9 ...	199			19	15
6/9 ...	216	218		2	9
30/9 ...	196	182	14		14
1/10 ..	179			3	10
1938 9/3 ...	256	250	6		10
10/3 ...	260	258	2		9
11/3 ...	276		18		15
1939 1/3 ...		259	18		12
2/3 ...	277	271	6		7
3/3 ...	273		2		17

Another source of error is the possible uncertainty of say 5 A in the reading off of the wavelength limit λ_0. The resulting error will be about 6 %, that means 0.012 cm. for an ozone value of 0.200 cm. and 0.018 cm. for a value of 0.300 cm.

Considering fig. 10 where our 6 observational series are plotted, two irregularities are evident. For one thing some scattering of interdependent points along the recorded lines, probably caused by errors in the determination of λ_0, may also be affected by real changes in the ozone content. If the latter be the case we should expect some regular lifting or sinking of the points, compare the series of 9—10/11. Secondly we notice that every ,,Cornu"-line has got a crack corresponding to a height of the moon of about 22°, just in accordance with previous observations (18, 20). Whatever the explanation may be — perhaps insufficient time of exposure — we should not rely on observations below a height of the moon of say 22°.

Although the method of the shortest wavelength is an approximate one we hardly believe that either the starlight or the spectrophotometric measurements will give results of a higher accuracy during the darkest winter season at Tromsø.

Notes to the Table of Ozone Values.

The table gives the daily mean ozone values of unit 0.001 cm. in the column headed *M*. The two other columns headed *N* and *R* contain respectively the daily number of observations and the daily range, or the difference between the highest and lowest ozone value during the day. It should be noticed, however, that *N* does not *necessarily* mean the total number of observations during the day, strictly speaking it means the number of hour-periods during which observations have been made. If for instance three observations have been made between 11 and 12 o'clock, their mean contributes to the daily mean value *M* and the number *N* as but a single observation. In a similar way *R* means strictly speaking the difference between the highest and lowest hourly mean value. When *N* is a relatively high number *R* will generally follow up, indicating that observations have been performed to very low sun and reduced accuracy. The daily mean ozone values *M* have been simply calculated from the number *N*, without attempts to centre them at noon. In this way *M* may sometimes — mainly on days when "Umkehr"-observations have been made — be somewhat displaced to local noon. We have, however, preferred to calculate the daily mean value from the actual hourly values instead of introducing arbitrary rules of selection.

During the four first years of ozone measurements the direct sunlight values are supplied by some starlight and moonlight values, respectively marked with *St* and *M* in the table. Further on in the table — from 23/8 1939 when the spectrophotometer came into use — the letter *c* has been added to the majority of values, this indicates that the observation has been made on *cloudy* zenith sky. Where nothing is added the values refer to observations on the clear zenith sky.

Direct sunlight values by the spectrophotometer have not been allowed for either in the mean value *M* or in the number *N*. Regarding them as check-measurements they are always connected to observations on the clear zenith sky, which should be equal in accuracy.

Some large gaps which are evident in the ozone table are caused by absence of observer except for the darkest season of the year. As to the latter period we should rank the observations in quality, starting with those of 1939/40 and 1942/43 being relatively the best, next follow the observations of 1940/41 and at last those of 1941/42, when the instrument was temporarily difficult to read off because of bad quality of the high tension batteries.

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	July 1935			Aug. 1935			Sep. 1935			Oct. 1935			Nov. 1935			Dec. 1935			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	–			–			–			155	3	1	–			–			1
2	–			–			196	2	8	175	1		–			–			2
3	247	1		–			205	1		–			–			–			3
4	–			–			212	1		175	1		–			–			4
5	–			–			222	1		171	2	3	–			–			5
6	–			–			204	1		–			–			193 M			6
7	–			–			199	1		162	2	2	187 M			–			7
8	–			–			195	3	2	144	5	16	–			187 M			8
9	261	2	25	–			196	2	0	153	3	12	184 M			–			9
10	224	2	2	208	1		215	1		168 M			191 M			–			10
11	–			–			202	2	23	–			–			–			11
12	–			–			199	2	4	–			–			–			12
13	–			220	1		190	3	9	201 196 M	2	9	191 M			–			13
14	–			–			183 M			200 M			193 M			–			14
15	–			–			186	3	13	200 M 199	3	8	–			–			15
16	234	1		210	1		178	2	4	–			–			–			16
17	–			207	2	9	190	2	11	–			–			–			17
18	–			208	2	6	184	2	9	–			–			–			18
19	219	2	10	206	3	5	192	1		–			–			–			19
20	231	1		201	3	13	–			–			–			–			20
21	–			205	1		–			176	1		–			–			21
22	–			195	2	16	215	1		179	1		–			–			22
23	222	1		196	2	17	184	2	15	147	1		–			–			23
24	–			201	2	1	183	2	5	–			–			–			24
25	–			–			194	1		137	2	3	–			–			25
26	–			192	1		201	1		152	1		–			–			26
27	222	1		191	1		–			144	1		–			–			27
28	–			187	2	5	186	1		–			–			–			28
29	–			188	2	3	–			–			–			–			29
30	–			178	1		187	2	3	–			–			–			30
31	–			183	2	8	–			–			–			–			31
Mean	**233**			**199**			**196**			**167**			**(189)**			**(190)**			Mean

Day	Jan. 1936			Feb. 1936			March 1936			April 1936			May 1936			June 1936			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	–			289 M			290 M			–			301	1		274	1		1
2	–			285 M			–			384	1		289	3	4	281	2	5	2
3	–			264 M			–			–			293	1		–			3
4	195 M			–			284 M			366	2	2	274	9	22	264	1		4
5	–			–			–			–			290	1		289	1		5
6	–			–			303	1		361	2	14	279	3	10	267	1		6
7	–			–			–			318	2	29	276	1		–			7
8	159 M			–			336	1		263	1		282	1		266	1		8
9	213 M			–			–			326	2	18	–			274	1		9
10	–			–			282	1		367	2	7	268	1		259	1		10
11	–			–			298	3	4	292	6	31	256	1		249	1		11
12	–			215 St			284	1		–			261	2	11	237	3	29	12
13	200 St			–			–			315	2	1	228	2	1	236	4	18	13
14	170 St			100 St			286	1		340	1		243	5	8	240	2	7	14
15	135 St			–			–			345	3	9	259	6	27	234	1		15
16	120 St			–			316	1		355	1		236	1		227	2	12	16
17	240 St			–			276	3	9	354	1		245	1		238	2	2	17
18	–			120 St			269	1		291	1		287	1		234	3	8	18
19	110 St			–			–			–			281	1		–			19
20	–			–			–			277	2	4	306	1		235	2	3	20
21	–			–			–			295	4	22	297	1		217	1		21
22	–			110 St			294	2	16	295	1		300	1		247	1		22
23	–			–			320	2	4	308	3	14	265	2	1	240	2	11	23
24	–			–			326	2	1	282	1		278	1		–			24
25	–			–			320	1		266	1		–			–			25
26	–			–			–			258	1		–			–			26
27	–			–			–			242	1		264	1		255	1		27
28	–			–			267	1		277	2	10	280	1		263	1		28
29	–			–			–			262	2	13	283	1		268	2	9	29
30	–			–			298	1		272	2	4	276	2	1	253	1		30
31	–			–			–			–			289	1		–			31
Mean	**(171)**			**(198)**			**297**			**308**			**275**			**252**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	July 1936			Aug. 1936			Sep. 1936			Oct. 1936			Jan. 1937			Feb. 1937			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	267	1		233	1		210 196 M	1		179	2	3	–			–			1
2	264	1		221	2	3	206	1		–			–			–			2
3	252	2	6	225	2	0	216	1		203	2	6	–			–			3
4	251	1		194	1		210	1		–			–			–			4
5	–			219	2	3	199			–			–			–			5
6	–			–			216 218 M	1		–			–			–			6
7	–			–			204	1		173	2	3	–			–			7
8	246	2	3	219	2	3	191	1		–			–			–			8
9	241	2	10	218	1		200	1		160	2	3	–			–			9
10	235	1		227	1		203	1		–			–			–			10
11	243	1		237	1		–			–			–			–			11
12	233	1		223	1		–			208	1		–			–			12
13	230	1		250	1		195	1		207	2	4	–			–			13
14	219	1		222	1		–			210	1		–			–			14
15	234	1		210	1		–			197	2	3	–			–			15
16	224	1		206	1		190	1		204	2	2	–			–			16
17	248	1		206	1		–			–			–			–			17
18	–			204	1		–			215	2	2	–			–			18
19	241	1		204	1		213	1		192	1		–			–			19
20	–			202	1		–			186	1		260 M			–			20
21	237	1		210	1		–			196	1		237 M			–			21
22	228	1		208	1		193	1		–			224 M			–			22
23	233	2	2	238	1		–			–			–			–			23
24	226	1		195	1		222	1		–			–			–			24
25	229	2	1	214	1		221	1		–			237 M			–			25
26	213	1		222	2	5	203	1		–			–			356	2	4	26
27	233	1		–			–			227 M			–			–			27
28	237	1		–			–			–			244 M			301	1		28
29	237	1		216	1		–			–			290 M			–			29
30	–			205	1		196 182 M	1		152 M			–			–			30
31	223	2	1	201	1		–			–			–			–			31
Mean	**237**			**216**			**205**			**195**			**(249)**			**(329)**			Mean

Day	March 1937			April 1937			May 1937			June 1937			July 1937			Aug. 1937			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	–			–			–			–			–			–			1
2	322	2	2	261	2	2	–			–			–			210	2	12	2
3	304	1		257	2	5	–	–		264	1		215	1		208	1		3
4	–			250	1		–			–			220	1		212	1		4
5	–			–			231	1		261	1		215	1		203	1		5
6	328	1		231	1		–			–			219	1		206	1		6
7	359	1		–			248	1		237	1		218	1		206	1		7
8	–			265	1		244	1		245	1		215	1		–			8
9	297	2	6	266	1		237	1		227	1		215	1		214	1		9
10	328	1		272	1		254	2	6	235	1		205	1		–			10
11	351	1		262	1		241	1		–			222	1		–			11
12	325	1		–			256	1		–			231	1		208	1		12
13	304	1		242	1		256	1		–			228	1		–			13
14	–			–			255	1		208	1		232	1		210	1		14
15	302	1		246	2	2	–			228	1		222	1		208	1		15
16	281	1		241	1		275	1		–			219	1		219	1		16
17	285	1		240	1		255	1		–			208	1		198	1		17
18	312	1		250	1		250	1		223	1		–			198	1		18
19	324	1		259	1		249	1		233	1		203	1		201	1		19
20	325	1		267	2	20	264	1		228	1		211	1		192	1		20
21	311	1		283	1		240	1		236	1		203	1		186	1		21
22	316	2	8	277	1		–			228	1		206	1		–			22
23	–			291	1		–			229	1		204	1		207	1		23
24	–			292	1		–			–			210	1		–			24
25	–			–			–			232			216	1		200	1		25
26	313	1		282	1		232	1		256	1		227	1		–			26
27	–			271	1		–			–			216	1		202	1		27
28	–			290	1		–			249	1		217	2	0	196	1		28
29	–			–			–			264	1		217	1		–			29
30	–			241	1		–			232	1		215	1		208	1		30
31	–			–			–			–			214	1		219	1		31
Mean	**316**			**263**			**249**			**237**			**216**			**205**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	Sep. 1937			Oct. 1937			Nov. 1937			Dec. 1937			March 1938			April 1938			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	224	1		–			–			–			–			360	1		1
2	217	1		205	1		–			–			–			–			2
3	215	1		204	1		–			–			–			358	1		3
4	216	1		–			–			–			–			357	1		4
5	218	1		–			–			–			–			343	1		5
6	214	1		–			–			–			–			295	1		6
7	201	1		–			–			–			–			310	1		7
8	–			–			–			–			267	1		–			8
9	215	1		–			–			–			256 250 M	1		266	1		9
10	–			–			–			–			260 258 M	1		–			10
11	–			–			–			–			276	1		286	1		11
12	212	1		–			–			–			–			–			12
13	221	1		–			–			–			–			276	1		13
14	191	1		–			–			192 M			–			–			14
15	197	1		–			–			219 M			263	1		–			15
16	197	1		–			159 M			–			283	1		–			16
17	203	1		–			154 M			195 M			268	1		321	1		17
18	196	1		–			164 M			–			–			–			18
19	–			–			200 M			197 M			272	1		280	1		19
20	–			–			–			–			256	1		–			20
21	178	1		–			–			–			281	1		–			21
22	184	1		–			–			–			–			366	1		22
23	–			–			–			–			263	1		–			23
24	196	1		–			–			–			–			286	1		24
25	199	1		–			–			–			–			–			25
26	199	1		–			–			–			324	1		318	1		26
27	201	1		–			–			–			311	1		–			27
28	–			–			–			–			339	1		304	1		28
29	183	1		–			–			–			314	1		311	1		29
30	–			–			–			–			338	1		286	1		30
31	–			–			–			–			352	1		–			31
Mean	**203**			**(205)**			**(169)**			**(201)**			**290**			**313**			Mean

Day	May 1938			June 1938			July 1938			Aug. 1938			Sep. 1938			Oct. 1938			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	301	1		249	1		–			224	1		201	1		–			1
2	312	1		273	1		–			252	1		–			–			2
3	–			272	1		–			232	2	16	–			–			3
4	–			255	1		–			–			–			–			4
5	–			–			222	1		–			–			–			5
6	291	1		230	1		231	1		–			–			–			6
7	283	1		245	1		230	1		–			–			–			7
8	281	1		251	1		–			205	1		–			–			8
9	293	1		251	1		–			204	1		200	1		176	1		9
10	295	2	15	244	1		–			211	1		–			198	1		10
11	–			–			200	1		206	1		–			–			11
12	279	1		–			–			–			–			215	1		12
13	–			–			202	1		205	1		236	1		199	1		13
14	277	1		254	1		226	1		206	1		–			–			14
15	299	1		255	1		211	1		218	2	2	–			–			15
16	271	1		–			233	1		–			–			–			16
17	281	1		266	1		–			201	1		218	1		–			17
18	286	1		283	1		219	1		217	1		–			–			18
19	–			283	1		213	1		–			–			–			19
20	284	1		246	1		221	1		215	1		200	1		–			20
21	–			–			217	1		237	1		–			–			21
22	275	1		225	1		–			234	1		–			–			22
23	–			255	1		198	1		220	1		–			–			23
24	–			233	1		–			223	1		–			–			24
25	261	1		–			–			221	1		–			–			25
26	–			–			207	1		216	1		–			–			26
27	–			–			–			210	1		–			–			27
28	266	1		237	1		200	1		227	1		–			–			28
29	245	1		242	1		208	1		208	1		–			–			29
30	–			–			217	1		210	1		–			–			30
31	255	1		–			225	1		211	1		–			–			31
Mean	**281**			**252**			**216**			**217**			**211**			**197**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	March 1939			April 1939			May 1939			June 1939			July 1939			Aug. 1939			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	259 M 277	 1		–			324	1		261	1		239	1		213	1		1
2	271 M			278	1		315	1		294	1		234	1		226	1		2
3	273	1		275	1		306	1		279	2	4	220	1		223	1		3
4	–			–			301	1		263	1		227	1		–			4
5	–			248	1		305	1		257	1		244	1		–			5
6	284	1		263	1		307	1		–			235	1		–			6
7	261	1		274	1		277	1		253	1		229	1		192	1		7
8	259	1		287	1		282	1		275	1		226	1		192	1		8
9	–			302	1		264	1		256	1		239	1		184	1		9
10	281	1		–			266	1		260	1		239	1		192	1		10
11	–			257	1		–			–			234	1		197	1		11
12	–			249	1		–			258	1		224	1		203	1		12
13	–			232	1		–			–			236	1		210	1		13
14	308	1		243	1		–			263	2	6	228	2	2	200	1		14
15	315	1		251	1		–			260	1		245	1		201	1		15
16	270	1		236	1		–			254	1		235	1		195	1		16
17	268	1		–			–			220	1		225	1		–			17
18	–			267	1		255	1		219	1		218	1		178	1		18
19	–			–			256	1		219	1		221	1		191	2	1	19
20	–			291	1		246	1		263	1		223	1		207	1		20
21	245	1		–			–			–			215	1		204	1		21
22	250	1		271	1		239	1		238	1		211	1		190	1		22
23	251	1		298	1		249	1		251	1		204	1		211 C	1		23
24	254	1		295	1		–			235•	1		214	1		206 C	1		24
25	261	1		282	1		241	1		–			201	1		194	2	8	25
26	272	1		307	1		262	1		–			191	1		205 C	2	1	26
27	263	1		305	1		252	1		256	1		199	1		201	2	1	27
28	260	1		286	1		272	1		263	1		211	1		200	2	15	28
29	–			287	1		–			240	1		209	1		208 C	1		29
30	271	1		306	1		264	1		231	1		214	1		–			30
31	272	1		–			261	1		–			227	2	0	206 C	3	16	31
Mean	**270**			**275**			**273**			**253**			**223**			**201**			Mean

Day	Sep. 1939			Oct. 1939			Nov. 1939			Dec. 1939			Jan. 1940			Feb. 1940			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	191	3	8	198 C	1		167 C	1		–			–			410 C	1		1
2	184 C	3	3	221	1		176 C	1		290 C	1		–			315 C	1		2
3	188 C	1		234 C	2	6	175 C	1		260 C	1		–			–			3
4	188 C	2	9	–			177	1		250 C	1		140	1		305 C	1		4
5	186 C	1		185 C	1		186 C	1		150 C	1		160	1		302 C	1		5
6	188 C	1		180 C	1		154	2	8	–			160	1		253	1		6
7	184	2		190 C	2	3	150 C	1		135 C	1		–			–			7
8	189 C	1		183 C	1		190 C	1		–			–			237	1		8
9	197 C	1		194 C	1		203 C	1		165	1		–			277 C	1		9
10	200 C	1		204 C	1		190 C	1		175	1		–			335 C	1		10
11	198	2	10	212 C	1		168 C	1		–			–			312 C	1		11
12	179 C	1		195	1		238 C	1		–			220 C	1		–			12
13	200 C	1		219	1		302 C	1		–			280 C	1		336 C	1		13
14	186 C	1		229	1		185 C	1		175	1		250 C	1		–			14
15	207	2	0	217	1		202	1		–			–			–			15
16	212 C	2	2	246 C	1		256 C	1		–			300 C	1		364 C	1		16
17	207 C	1		248 C	1		290 C	1		–			–			354 C	1		17
18	206 C	1		268 C	1		265 C	1		–			270 C			–			18
19	201 C	1		212 C	1		242 C	1		–			255 C	1		–			19
20	–			198 C	1		222 C	1		160 C	1		330 C	1		–			20
21	229	2	4	185 C	1		220 C	1		160 C	1		330	1		–			21
22	260 C	1		203 C	1		288 C	1		135 C	1		335	1		322	1		22
23	235	1		210 C	1		240 C	1		260	1		275 C	1		300 C	1		23
24	221	1		218 C	1		275 C	1		145	1		–			303	1		24
25	231	1		298 C	1		232 C	1		170	1		390	1		334 C	1		25
26	224 C	1		223 C	1		232 C	1		215	1		–			–			26
27	204	1		180 C	1		220 C	1		–			345 C	1		294	1		27
28	197 C	1		174 C	1		237 C	1		–			400 C	1		–			28
29	196 C	1		189 C	1		195 C	1		100	1		–			402 C	1		29
30	203 C	1		230 C	1		232 C	1		160	1		355 C	1		–			30
31	–			230 C	1		–			200	1		–			–			31
Mean	**203**			**212**			**217**			**184**			**282**			**320**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	March 1940			April 1940			May 1940			June 1940			July 1940			Aug. 1940			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	284 C	1		334 C	2	3	301 C	1		308 C	1		222 C	1		248 C	1		1
2	331 C	1		350 C	2	0	293	1		–			245 C	1		242 C	1		2
3	344 C	1		336 C	2	16	293 C	1		287 C	1		249 C	2	2	252	1		3
4	340 C	1		317 C	2	23	–			302 C	1		255 C	1		245 C	1		4
5	358	1		323 C	2	13	–			305 C	1		242	1		257 C	1		5
6	314 C	1		303 C	1		302	1		298 C	1		280 C	1		235	1		6
7	361	1		266 C	1		303	1		304 C	1		268 C	1		253 C	1		7
8	332	2	8	300 C	2	4	342	1		–			245 C	1		258 C	1		8
9	307	2	6	343 C	1		303 C	1		–			263 C	1		240	8	22	9
10	317	1		327	1		302	1		298 C	1		260 C	1		245	3	3	10
11	313 C	1		–			322 C	1		269 C	1		218 C	1		248 C	1		11
12	336 C	1		–			–			260	1		230 C	1		244 C	1		12
13	331 C	1		–			–			252	5	5	220 C	1		230 C	1		13
14	314	2	6	–			291	1		249	8	11	260 C	1		227	8	30	14
15	335	1		–			296 C	1		241	1		275 C	1		233 C	2	9	15
16	331 C	1		346 C	1		288	1		–			252 C	1		235 C	1		16
17	369 C	1		346 C	1		286	1		264 C	2	33	256	5	5	250 C	1		17
18	327 C	1		341 C	1		313 C	1		253 C	1		256	1		238 C	1		18
19	–			370	1		290 C	1		227	1		268 C	1		245 C	1		19
20	–			370 C	1		270 C	1		–			254 C	1		224 C	1		20
21	–			372 C	1		287 C	1		268 C	1		248 C	1		228 C	1		21
22	–			314 C	1		271	2	0	270 C	1		256 C	1		233 C	1		22
23	–			334 C	1		272	14	12	272 C	1		256 C	1		230 C	1		23
24	–			341 C	1		269	10	17	268 C	1		266 C	1		250 C	1		24
25	318 C	1		342 C	2	12	269	11	13	240 C	1		260	2	6	245	2	10	25
26	304 C	1		303 C	1		258	6	21	238	1		270 C	1		221	1		26
27	312	1		282	1		260	9	15	281 C	2	10	252 C	1		252 C	1		27
28	302	4	6	–			272 C	1		273 C	2	25	262 C	1		238 C	1		28
29	306	3	6	293 C	1		278	2	0	–			252 C	1		231 C	1		29
30	306 C	1		296 C	1		280 C	1		–			252 C	1		240 C	1		30
31	317 C	2	14	–			287 C	1		–			251	1		238 C	1		31
Mean	**324**			**327**			**288**			**271**			**253**			**240**			Mean

Day	Sep. 1940			Oct. 1940			Nov. 1940			Dec. 1940			Jan. 1941			Feb. 1941			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	234 C	1		202 C	1		171 C	1		120 C	1		175	1		350	1		1
2	222 C	1		237 C	1		205 C	1		–			–			340 C	1		2
3	236 C	1		223 C	1		196 C	1		190 C	1		–			358	1		3
4	214	3	10	183 C	1		188 C	1		215	1		–			318 C	1		4
5	215 C	1		179 C	1		202 C	1		275	1		–			252	1		5
6	226 C	1		194 C	2	9	184 C	1		130 C	1		–			258	1		6
7	212	2	4	214 C	2	4	190 C	1		180	1		–			269 C	1		7
8	224 C	1		202	3	8	234 C	1		–			215 C	1		294 C	1		8
9	223 C	1		208 C	2	6	210 C	1		230 C	1		–			278 C	1		9
10	240	2	1	212 C	1		238	1		–			–			289 C	1		10
11	240 C	2	12	204 C	1		200 C	1		190 C	1		190 C	1		293 C	1		11
12	237 C	1		207 C	1		138	1		–			145 C	1		316 C	1		12
13	223	7	4	186	1		122	1		–			120 C	1		336 C	1		13
14	215	5	21	220 C	1		242 C	1		80 C	1		200 C	1		300 C	1		14
15	209	6	4	217	3	13	202 C	1		75 C	1		160 C	1		275	1		15
16	203	3	4	234 C	1		196 C	1		200 C	1		200 C	1		319 C	1		16
17	212 C	1		236 C	1		205 C	1		125 C	1		240	1		292	3	10	17
18	243 C	1		221 C	1		–			–			240 C	1		302	9	24	18
19	218	4	6	238 C	1		182	1		140 C	1		330	1		314	9	12	19
20	220	5	14	213	1		100	1		–			360	1		325	7	56	20
21	214 C	3	4	212	5	8	160	1		–			245 C	1		379	2	1	21
22	243 C	1		206 C	1		255 C	1		–			230 C	1		396 C	4	16	22
23	242	2	3	190 C	1		168	1		–			370 C	1		384	6	14	23
24	230	5	7	183 C	1		112 C	1		190 C	1		–			361	4	29	24
25	221	5	5	195 C	1		90 C	1		220 C	1		250 C	1		364	3	16	25
26	230	3	12	200	5	7	140	1		—			250 C	1		363	7	16	26
27	205	10	18	197 C	1		125 C	1		230 C	1		370 C	1		422	8	40	27
28	198	5	10	197 C	1		180 C	1		60 C	1		400 C	1		375	4	13	28
29	177 C	1		197 C	1		–			110 C	1		325 C	1		–			29
30	183 C	1		216 C	1		140 C	1		–			325 C	1		–			30
31	–			190 C	1		–			220 C	1		350 C	1		–			31
Mean	**220**			**207**			**178**			**167**			**259**			**326**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	March 1941			April 1941			May 1941			June 1941			July 1941			Aug. 1941			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	369	10	74	340 C	2	6	267	9	11	294 C	2	4	221	9	15	257 C	3	32	1
2	355	8	28	357	7	29	297 C	2	14	284 C	3	20	246 C	3	27	228 C	1		2
3	394	9	63	375 C	2	18	305 C	2	8	275 C	2	5	229 C	3	18	252 C	1		3
4	400	10	58	369 C	1		316	2	0	286 C	1		215 C	3	6	259 C	3	12	4
5	387	2	1	392 C	1		326	3	23	314 C	2	17	233 C	5	22	245 C	3	6	5
6	364	5	34	355 C	1		328 C	2	8	316 C	2	14	257	3	34	239 C	3	16	6
7	400 C	1		358 C	1		331 C	2	19	289 C	3	1	261 C	3	15	255 C	3	10	7
8	366 C	5	25	348 C	1		349 C	2	19	302 C	2	7	251	5	23	246 C	2	12	8
9	362 C	1		315 C	1		325 C	3	6	320 C	2	28	266 C	3	12	230 C	3	13	9
10	378 C	3	31	313 C	1		362 C	1		311 C	2	12	259 C	3	26	247 C	2	17	10
11	361	2	5	301	2	4	281	3	1	305	6	5	236 C	4	10	241 C	3	2	11
12	360 C	1		298 C	1		299 C	2	10	275 C	3	14	240 C	5	45	227	4	8	12
13	316 C	3	14	313	3	15	311	2	8	268 C	3	15	252 C	2	40	214	3	16	13
14	318 C	2	24	321 C	2	10	306 C	2	8	296 C	4	42	252 C	4	32	211	4	5	14
15	320 C	1		320 C	1		314 C	3	26	307 C	3	2	234	5	7	206	5	11	15
16	310 C	1		319 C	1		318 C	3	6	287 C	2	8	221	7	10	218 C	3	17	16
17	328 C	2	15	321	8	17	344 C	2	27	289 C	3	20	228	8	7	229 C	1		17
18	306 C	2	0	326 C	3	14	337 C	2	15	279 C	2	9	222	10	10	214	4	17	18
19	323	8	28	329 C	2	8	320 C	2	0	257 C	2	23	225	4	12	216	6	12	19
20	309	11	23	308	2	7	311 C	3	15	259 C	3	17	234	3	3	202	6	5	20
21	324 C	2	3	302	9	15	288 C	2	16	282 C	3	22	229	4	12	205	4	5	21
22	358 C	1		298 C	2	8	272	5	12	275 C	3	15	225	5	14	210	5	6	22
23	350 C	1		321 C	2	10	289	9	17	255 C	2	0	230	5	8	213	6	3	23
24	341 C	2	18	314 C	2	5	272	6	3	234	8	9	225	7	9	208	2	12	24
25	336	11	11	316 C	3	12	272 C	3	10	235	5	9	225	7	9	213	8	13	25
26	318	4	7	304 C	2	4	258	13	6	241	11	21	215	3	11	207	3	8	26
27	338	8	19	275 C	2	1	265	16	27	227	12	10	222	11	15	209	5	10	27
28	338	8	21	279 C	3	3	281	3	15	227	7	12	217 C	3	17	209	3	4	28
29	340	6	10	281 C	2	3	290 C	3	21	224	4	5	204	4	10	217	7	18	29
30	357	8	22	313 C	3	14	281 C	2	26	219	3	6	218	4	20	234 C	3	5	30
31	277 C	1		–			280 C	2	3	–			230	2	0	220	2	2	31
Mean	**345**			**326**			**303**			**275**			**233**			**225**			Mean

Day	Sep. 1941			Oct. 1941			Nov. 1941			Dec. 1941			Jan. 1942			Feb. 1942			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	218 C	2	2	207 C	3	8	186 C	1		240 C	1		–			280	1		1
2	221	3	1	247 C	2	6	201 C	2	8	180 C	1		–			289	2	1	2
3	209	4	13	256 C	1		215 C	2	12	240	1		–			280 C	2	8	3
4	227 C	2	1	257 C	1		223 C	3	5	–			–			298	1		4
5	225 C	1		246 C	1		199	2	18	200 C	1		–			306 C	1		5
6	235 C	2	1	222 C	2	25	181	2	6	170 C	1		–			331 C	1		6
7	228 C	2	3	–			194 C	2	4	185	1		–			284 C	1		7
8	231 C	2	8	260 C	3	9	192 C	1		–			145	1		381 C	1		8
9	232 C	3	10	246 C	3	32	160 C	2	8	275	1		–			270 C	1		9
10	243	2	10	234 C	4	2	147 C	2	4	250 C	1		–			287 C	2	8	10
11	214	3	10	215 C	2	13	160 C	2	2	275	1		–			414 C	2	12	11
12	199 C	2	14	195 C	2	10	147	2	12	160 C	1		–			390 C	1		12
13	206 C	2	6	209	4	23	196 C	2	2	180	1		–			344 C	3	22	13
14	248 C	1		196	10	16	193	1		250	1		–			353 C	3	22	14
15	218 C	1		193	11	5	240 C	1		195 C	1		350 C	1		334 C	1		15
16	210 C	1		185	11	9	170 C	1		255 C	1		302 C	1		291	2	2	16
17	206 C	2	1	171	7	12	210 C	1		–			145 C	1		303 C	3	13	17
18	178 C	2	18	193	8	21	185	1		–			260 C	1		325 C	2	5	18
19	180 C	1		202	2	4	245	1		–			230 C	1		311 C	2	4	19
20	180 C	2	12	207 C	4	18	195 C	1		–			270	1		301	3	24	20
21	184 C	2	11	195	6	6	225	1		–			275	1		325 C	2	6	21
22	209 C	2	1	208 C	3	11	250 C	1		–			150	1		352 C	2	9	22
23	188 C	2	10	190 C	3	9	215 C	1		210 C	1		205	1		388	5	33	23
24	220 C	2	28	179 C	1		250	1		–			225	1		398	5	11	24
25	203 C	6	14	224 C	2	2	260 C	1		–			290	1		433 C	4	20	25
26	199 C	10	11	253 C	1		200 C	1		–			280	1		424	4	25	26
27	202	7	10	205	2	5	160 C	1		–			239	2	2	402	1		27
28	193 C	2	0	211	4	2	155 C	1		–			280	2	4	392	4	14	28
29	206	6	8	209 C	3	7	200 C	1		–			244	2	7	–			29
30	204	6	8	220 C	3	7	220 C	1		–			268 C	1		–			30
31	–			212 C	3	4	–			–			268	2	12	–			31
Mean	**211**			**215**			**199**			**218**			**246**			**339**			Mean

OZONE TROMSØ

Table of Ozone Values.

Unit 0.001 cm.

M. = diurnal mean, N. = number of observations, R. = diurnal range.

Day	March 1942			April 1942			May 1942			June 1942			July 1942			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	403	2	5	380 C	3	31	302 C	4	3	274 C	4	12	249 C	4	7	1
2	401 C	2	2	359 C	2	13	328	4	16	299 C	4	10	248 C	5	4	2
3	392	3	42	337 C	1		331	3	17	279 C	4	21	245 C	4	6	3
4	341 C	3	17	340	4	9	316	5	8	268 C	4	12	255 C	4	11	4
5	379 C	4	42	336	2	1	326	5	25	276 C	4	12	234 C	3	5	5
6	380 C	5	32	332	3	4	316 C	4	2	266 C	4	25	244 C	4	32	6
7	380 C	4	51	327	3	13	311 C	4	17	258	3	5	231	5	9	7
8	362	2	36	339 C	2	27	305 C	3	7	264	3	3	231 C	4	9	8
9	386	5	30	365 C	3	12	314 C	4	20	261	4	9	232 C	4	27	9
10	409	7	18	336 C	8	64	336 C	3	9	266 C	4	10	226 C	4	2	10
11	432 C	3	30	378 C	4	12	333 C	4	16	263 C	4	12	227 C	4	9	11
12	411	9	17	325 C	3	17	331	4	11	258 C	3	4	235 C	4	17	12
13	378	9	25	294 C	4	42	333	5	9	255	4	3	239 C	4	6	13
14	357	7	23	310 C	4	26	333	4	5	266 C	3	26	221 C	4	15	14
15	366	3	3	315 C	4	17	333 C	4	16	269 C	4	17	221 C	4	7	15
16	357	6	19	294 C	4	36	331 C	4	14	278 C	3	8	217	4	9	16
17	315	6	62	278 C	4	21	299	5	3	241 C	4	33	226	4	7	17
18	302	7	28	240 C	4	12	262	6	6	227 C	4	8	224	4	10	18
19	303	5	16	253 C	3	12	274 C	6	16	252 C	4	9	223	3	11	19
20	312 C	4	26	348 C	4	26	262	4	6	258 C	4	33	236 C	3	10	20
21	318 C	2	3	337 C	4	13	276 C	4	16	264 C	3	15	221	4	6	21
22	351 C	2	2	328	4	6	289 C	4	16	249 C	4	20	228 C	4	3	22
23	323 C	5	9	336 C	4	13	295 C	4	10	250 C	3	3	240 C	4	16	23
24	314 C	4	22	324 C	4	37	298 C	3	5	243 C	3	13	253 C	4	16	24
25	334 C	4	11	321 C	3	17	284 C	3	5	258 C	4	12	250 C	4	4	25
26	341 C	5	11	289 C	3	11	286 C	4	4	257 C	4	5	252	4	7	26
27	348 C	4	16	277 C	4	7	268 C	4	5	250	3	10	265 C	4	14	27
28	362 C	3	22	275 C	3	3	278 C	5	25	252	3	8	257 C	3	4	28
29	408 C	2	25	276 C	3	37	301 C	6	15	245 C	4	10	258 C	3	10	29
30	384 C	5	38	274 C	3	6	273 C	7	33	250 C	4	14	262 C	4	5	30
31	381 C	4	14	–			254 C	3	9	–			251 C	4	10	31
Mean	**362**			**317**			**303**			**260**			**239**			Mean

Day	Aug. 1942			Sep. 1942			Oct. 1942			Nov. 1942			Dec. 1942			Day
	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	M.	N.	R.	
1	263 C	2	0	206 C	3	6	186	3	7	205	2	1	245 C	1		1
2	262 C	2	3	211 C	3	10	203 C	3	9	197	1		280 C	1		2
3	268 C	3	14	230 C	3	15	224 C	2	6	160	2	10	200 C	1		3
4	243 C	4	10	200	3	3	235 C	3	10	167 C	2	8	215 C	1		4
5	244 C	4	8	225 C	2	9	248 C	3	25	155 C	1		230	1		5
6	248 C	4	5	203 C	2	6	253 C	2	6	249 C	1		215 C	1		6
7	241 C	4	3	232 C	3	7	265 C	2	2	160	1		220	1		7
8	228 C	4	7	236 C	3	3	199 C	3	9	163 C	1		240	1		8
9	222	3	5	193 C	3	6	184 C	2	4	128 C	1		175 C	1		9
10	219	4	5	225 C	3	7	199 C	5	14	138 C	1		130 C	1		10
11	244	3	6	232 C	3	7	200 C	2	6	270 C	1		190 C	1		11
12	220 C	4	8	240 C	3	6	210 C	2	6	165 C	1		170 C	1		12
13	216 C	4	18	237 C	3	16	208	2	6	139 C	2	2	70	1		13
14	223 C	4	21	231 C	3	7	212	2	2	212 C	1		120	1		14
15	215 C	4	10	223	3	4	227 C	2	1	137 C	1		110	1		15
16	220 C	3	12	219 C	2	6	229 C	2	12	152 C	1		50 C	1		16
17	225 C	3	1	201 C	4	9	203 C	2	2	210 C	1		160	1		17
18	228	3	10	214	3	2	201	2	2	140 C	1		150	1		18
19	244 C	2	15	230 C	3	6	192	5	10	190 C	1		210 C	1		19
20	211 C	3	5	227 C	2	10	183	3	7	225 C	1		140	1		20
21	207	3	2	225 C	3	13	179	2	2	170 C	1		125 C	1		21
22	212 C	3	5	233	4	3	195 C	2	12	195 C	1		130 C	1		22
23	212 C	3	35	236 C	2	14	205	2	4	185 C	1		50 C	1		23
24	214 C	3	5	244 C	2	5	207 C	2	0	135 C	1		–			24
25	206 C	3	10	242 C	3	10	206	2	2	175 C	1		130 C	1		25
26	207 C	3	4	241 C	2	6	206 C	2	8	190 C	1		50 C	1		26
27	231 C	2	3	209 C	2	13	210 C	2	4	175 C	1		60 C	1		27
28	218 C	3	21	190 C	2	4	229 C	2	4	275 C	1		160 C	1		28
29	234 C	2	8	170 C	2	10	254 C	2	10	200 C	1		135 C	1		29
30	228 C	3	23	190	2	2	210	2	4	115 C	1		200	1		30
31	214 C	3	2	–			203	2	2	–			100	1		31
Mean	**228**			**220**			**212**			**176**			**155**			Mean

The Mean Ozone Values.

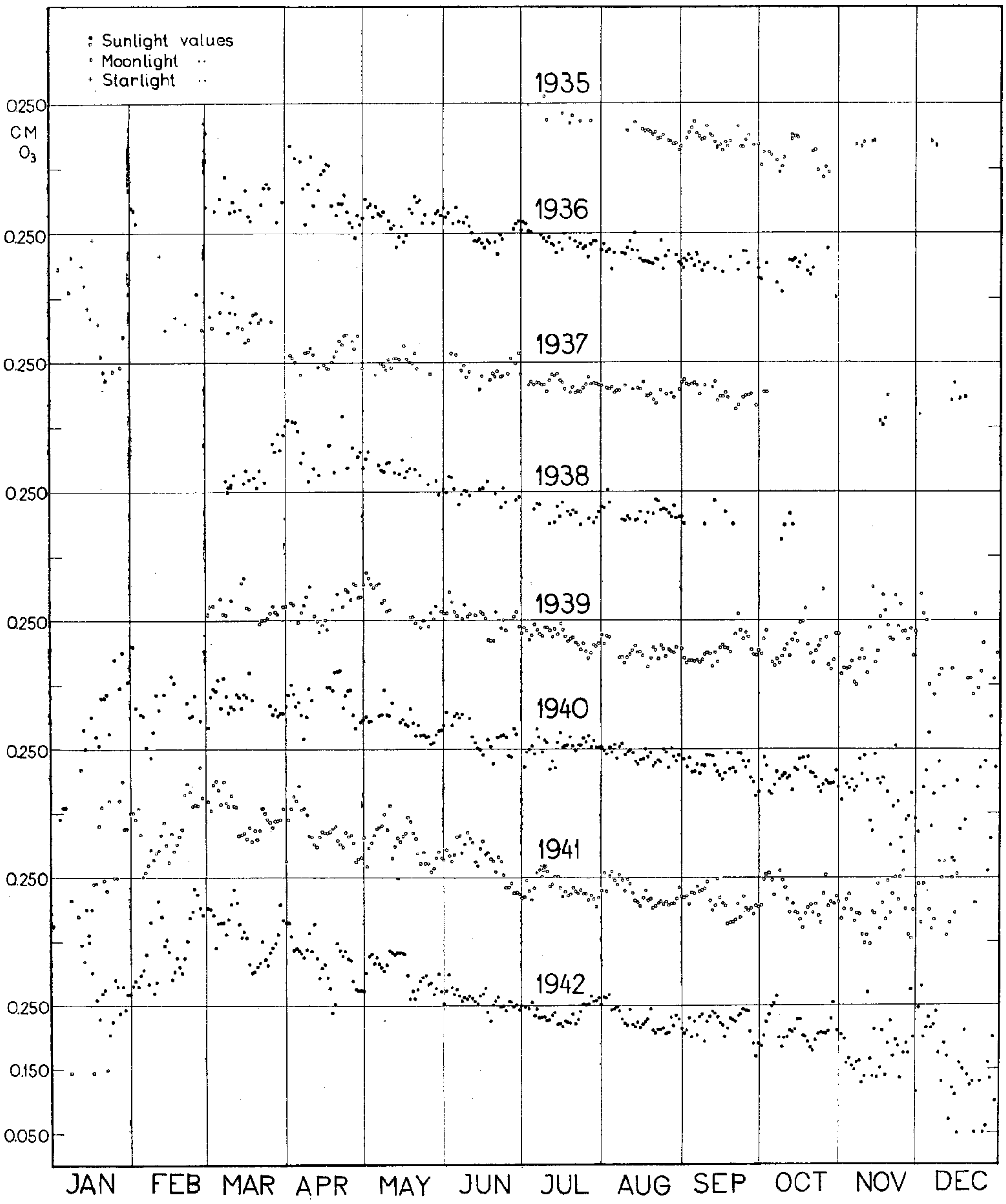

Fig. 11. The daily mean ozone values plotted against time.

We should also present the monthly mean ozone values in a table.

Month	1935	1936	1937	1938	1939	1940	1941	1942	Mean
Jan.	–	–	–	–	–	282	259	246	(262)
Feb.	–	–	–	–	–	320	326	339	(328)
March........	–	297	316	290	270	324	345	362	315
April.........	–	308	263	313	275	327	326	317	304
May	–	275	249	281	273	288	303	303	282
June.........	–	252	237	252	253	271	275	260	257
July	233	237	216	216	223	253	233	239	231
Aug.	199	216	205	217	201	240	225	228	216
Sep.	196	205	203	211	203	220	211	220	209
Oct.	167	195	–	197	212	207	215	212	201
Nov.	–	–	–	–	217	178	199	176	(193)
Dec.	–	–	–	–	148	167	218	155	(181)
Mar.-Oct. mean	–	248	241	247	239	266	267	268	254
Annual mean ..	–	–	–	–	–	256	261	255	–

For one thing we learn from the table that March or April has the highest monthly mean value and December generally the lowest one. Secondly there is evidence for a considerable difference in the annual mean values, a relation which is illustrated on fig. 12.

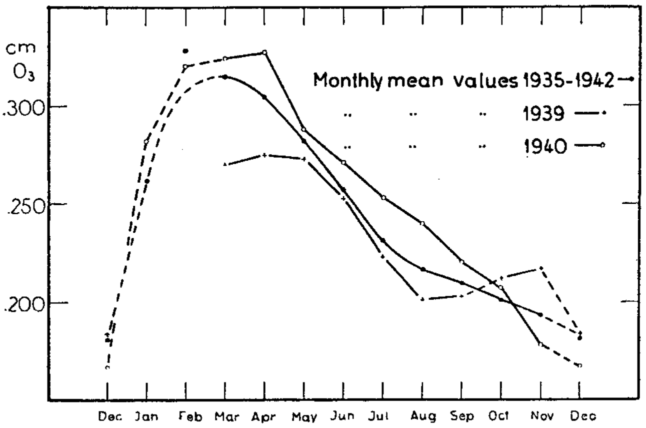

Fig. 12. Annual curves of monthly mean ozone values.

We have selected the neighbouring years of 1939 and 1940 as extremities, although 1942, especially in the spring, exhibits a greater deviation from the normal course than 1940.

II. Vertical Distribution.

Method A.

Two different methods — called A and B — are available for an approximate numerical calculation of the vertical distribution of atmospheric ozone. Both methods — founded on spectrophotometric observations on the blue zenith sky — have been developed by Götz, Meetham and Dobson (22, 19). Method B was used both for Arosa and Tromsø (26), while method A only for Arosa. Now we have extended method A to Tromsø as well. For a closer comparison of the results, and in some extent to save time, we have in our calculations dealt with just the same numerical examples as had earlier been chosen.

In order to give at once an idea of method A, let us briefly state. By observations on the clear zenith sky the dial readings of the spectrophotometer give the values of log I/I' (I and I' respectively the intensities of 3110 A and 3300 A), just plotted against μ on fig. 5 (page 8) in this paper. Or more accurate, the dial readings give the values of log I/I' (I being always minor to I') plus an unknown constant C of instrumental origin. That constant varies with the amount of ozone. Denoting the observed log-values on fig. 5 (p. 8) by L, we may write:

$$\log I/I' + C = L \quad \text{or} \quad I' - I \cdot 10^{(C-L)} = 0, \quad C > L$$

The above equation will in its form to the left be used to determine C — the future link between observations and calculations — for any given ozone value, and in its form to the right be used to determine the vertical distribution of ozone itself.

As to I' and I each one will be calculated by means of a formula, containing amongst others, an expression for the path-length of light through the ozone layer, depending on its thickness. As to L it will be read off on the chart of fig. 5 (p. 8).

Regarding fig. 5 it is evident that for any ozone curve log I/I' is decreasing with increasing μ or sinking sun to a certain point where log I/I' passes a minimum to rise again with sinking sun as far as observations have been possible. This "Umkehr"-effect was detected by Götz during observations on Spitzbergen (20), and was the inspiration to the present method of deducing the vertical distribution of atmospheric ozone from observations on the clear zenith sky, because a logical explanation of the "Umkehr" effect (21) will involve an assumption of a characteristic distribution of the ozone in the atmosphere.

Another striking feature of the ozone curves on fig. 5 is the displacement of the "Umkehr" point in relation to μ with increasing ozone, an indication of changes in the vertical distribution with changes in the total ozone content.

Returning in some words to the above mentioned logical explanation of the "Umkehr" effect, let us remember the fact that the ratio of intensity I/I' of the direct solar beam is continually decreasing with sinking sun, because the light-path through the absorbing ozone region is increasing continually with μ (sec Z). As to the light from the zenith sky it has been scattered downwards by the atmospheric particles on all heights. The scattered zenith light reaching the instrument from the points B and B' on fig. 13, will depend on the scattering power at B and B' and the absorption before and after scattering. The scattering power, being proportional to the density of air, will increase downwards, while the absorption power will increase with increasing μ, and the wavelength 3110 A will be more rapidly absorbed than 3300 A, the latter being but slightly affected by ozone. Thus the lower region of the atmosphere around B will contribute mainly to the intensity of scattered light from above until the sun becomes so low that the short wavelengths in question but for a small portion can penetrate the rapidly increasing air-path, especially for 3110 A ozone-path, in the lowest atmosphere. With still lower sun the higher region around B', in spite of its weak scattering power, will contribute more and more to the total intensity, particularly of 3110 A but also of 3300 A, now received at the instrument.

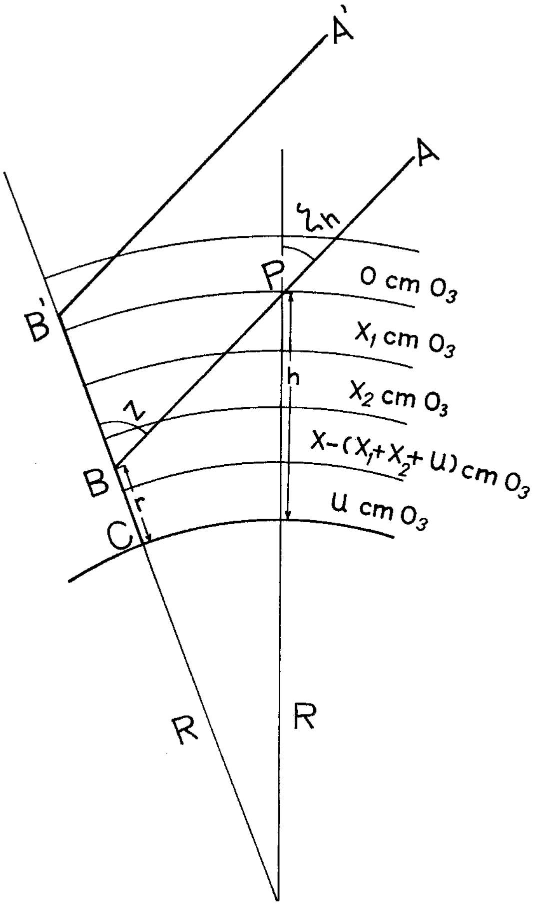

Fig. 13. Light beams and ozone content in a vertical section through the atmosphere.

Estimating the main atmospheric ozone to be present in a layer say between B and B', then with increasing μ, a still increasing part of the scattering of 3110 A will have to take place above most of the ozone, while 3300 A — depending far less on the ozone — will mainly be scattered lower down in the atmosphere. When 3110 A is scattered in the upper part of the ozone region it has suffered but little absorption before scattering, and afterwards it is passing vertically downwards through the shortest possible ozone path. Thus it may be understood and made possible that the intensity ratio 3110 A to 3300 A after passing through a minimum value may slightly rise again and form the characteristic "Umkehr" curve. According to this explanation of the "Umkehr" effect the displacement of the "Umkehr" point (minimum) should indicate that the decisive high region scattering sets in still earlier as the amount of ozone increases, again an indication of ozone concentration still lower down with increasing ozone.

And now let us briefly put the theoretical base of method A in mind.

The intensity of light of an arbitrary wavelength reaching point B on fig. 13 after suffering by absorption and scattering along its air path-length will be:

$$I_0 \cdot 10^{-\int_r^{\infty}\left(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0}\right)\sec\zeta_h\, dh}, \qquad \frac{\beta}{H}\frac{\varrho_h}{\varrho_0} = \beta_h$$

I_0 is the intensity at the entrance of the atmosphere.
X_h is the amount of ozone at the height h.
α is the absorption coefficient.
β is the scattering coefficient of the whole atmosphere of homogeneous height H.
ϱ_0 and ϱ_h are the density of air at the ground and at a height h respectively.
ζ_h is the zenith distance as seen from a point at the height h.

The *secondary scattering* has so far been neglected.

The amount scattered vertically downwards at B will be:

$$K\varrho_r(1+\cos^2 Z)\, I_0 \cdot 10^{-\int_r^{\infty}\left(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0}\right)\sec\zeta_h\, dh}, \qquad K = \frac{3}{16\pi}\frac{\beta}{H\varrho_0}$$

The amount reaching C from B will be:

$$dI = K\varrho_r(1+\cos^2 Z)\, I_0 \cdot 10^{-\int_r^{\infty}\left(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0}\right)\sec\zeta_h\, dh} \cdot 10^{-\int_0^{h}\left(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0}\right) dh}$$

The total amount reaching C scattered vertically downwards from all heights will be:

$$I = K\,(1 + \cos^2 Z)\,I_0 \int\limits_o^{\infty} \varrho_h \left[10^{-\int\limits_h^{\infty}(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0})\sec\zeta_h\,dh} \cdot \right. \left. \cdot\, 10^{-\int\limits_o^{h}(\alpha X_h + \frac{\beta}{H}\frac{\varrho_h}{\varrho_0})\,dh} \right] dh$$

Separating scattering and absorption we may shortly write:

$$I = K\,(1 + \cos^2 Z)\,I_0 \int\limits_o^{\infty} \varrho_h\, 10^{-\beta S} \cdot 10^{-\alpha Y} \cdot dh$$

S being the air-path and Y the ozone-path. S is determined by the expression:

$$S = \frac{\varrho_h}{\varrho_0}\left[f(z) - 1\right] + 1$$

$f(z)$ (earlier in this paper denoted by "m") is the modefication of sec Z, when the curvature of the earth and the atmospheric refraction are allowed for. $f(z)$ is considered independent of the height of the scattering point.

The ozone-path Y is a function of the amount of ozone X and its arbitrarily selected sub-components.

Dealing practically with method A the atmosphere is divided into five concentric sections (see fig. 13), being 0 to 5 km., with ozone content u cm. or $u/5$ cm per km., 5 to 20 km. with ozone content $X - (X_1 + X_2 + u)$ cm., 20 to 35 km. with ozone content X_2 cm., 35 to 50 km. with ozone content X_1 cm. and 50 to 65 km. with negligible ozone content. The ozone in each section is assumed to be distributed uniformly.

The ozone content u in the lowest section is estimated to 5 % of the totale amount of ozone X (presupposed known) or 1 % per km.[1]) Thus with a partition of the atmosphere into 5 sections we get 2 unknowns X_1 and X_2 in the expression of the ozone path Y, and a greater number of unknowns would enormously increase the difficulties of a numerical solution of the equations in question.

The ozone path Y, being the sum of PB and BC (fig. 13), is calculated in steps of 1 km. PB is easily found trigonometrically. And the ozone path in each section is determined as an average of the different paths, usually 15. The mean paths for $Z = 80°$ and $Z = 86°.5$ are given in the table below.

Mean ozone path Y in cm.

Section	$Z = 80°$	$Z = 86°.5$
65 — 50 km.	X	X
50 — 35 km.	$2.45\,X_1 + X$	$6.93\,X_1 + X$
35 — 20 km.	$4.36\,X_1 + 2.45\,X_2 + X$	$10.04\,X_1 + 6.93\,X_2 + X$
20 — 5 km.	$1.59\,X_1 + 1.91\,X_2 + 3.45\,X - 2.45\,u$	$0.80\,X_1 + 3.11\,X_2 + 7.93\,X - 6.93\,u$
5 — 0 km.	$-0.62\,X_1 - 0.35\,X_2 + 5.48\,X - 1.66\,u$	$-4.33\,X_1 - 2.87\,X_2 + 12.18\,X - 2.50\,u$

The air-path S is calculated in steps of 1 km. as well, and the different values of the expression $\varrho_h \cdot 10^{-\beta S}$ are summed up for each section to a constant. These constants are given below for $Z = 80°$ ($f(z) = 5.60$) and $Z = 86°.5$ ($f(z) = 13.75$). We have calculated with $\beta' = 0.37$ and $\beta = 0.47$. The values of ϱ_h, will be discussed later.

Hence the result of the numerical integrations above for any wavelength λ and any zenith distance Z will be a sum of 5 expressions corresponding to the five sections. If the integrations are performed for the wavelengths 3110 A and 3300 A for an arbitrary value of Z, we shall have an expression of I/I', which besides the two unknowns X_1 and X_2 contains a couple of constants (see page 24) β/β' and I_0/I'_0 which return in a second expression of I/I' — for another value of Z — necessary for the solution of X_1 and X_2. These constants, however, being independent of Z and X, may be dropped as they will be included in the "link" constant C (in the equation $\log I/I' + C = L$ on page 23) between calculated and observed values of I/I'.

Section	$\int \varrho_h \cdot 10^{-\beta' S}$		$\int \varrho_h \cdot 10^{-\beta S}$	
	$Z = 80°$	$Z = 86.°5$	$Z = 80°$	$Z = 86.°5$
65—50 km.	2.28	2.28	1.79	1.78
50—35 km.	22.62	22.01	17.88	17.29
35—20 km.	185.94	148.40	142.52	107.48
20— 5 km.	642.02	162.47	393.73	84.33
5— 0 km.	98.25	0.64	34.94	0.08

Now to determine C we calculate I/I' for a rather small value of Z, making use of the fact that

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[1]) Some recent measurements made at Nordlysobservatoriet of the *low* ozone support the validity of this assumption.

when Z is less than say 60° the value of I/I' will depend mainly on the *amount* of ozone and not appreciably on its *distribution*. Hence for the ozone-path we suppose a uniform distribution from the ground up to 50 km. A very pretty value for calculations would be $Z = 0$, but for that value we have no readings L (except extrapolated) of $\log I/I'$ on the chart of fig. 5 (p. 8). To join up with Meetham and Dobson (26) we have dealt with $Z = 60°.75$, and are giving the results below for an ozone value of 0.280 cm.

$Z = 60°.75$			$Z = 80°$		$Z = 86°.5$	
Log I/I' Calculated	Log I/I'+ $C = L$ Red off	C	$(C-L)$	$10^{(C-L)}$	$(C-L)$	$10^{(C-L)}$
—0.738	2.336	3.074	1.370	23.44	1.490	30.90

The expression $10^{(C-L)}$ is the final link in the distribution equation $I' - I \cdot 10^{(C-L)} = 0$ (p. 23) now to be given for $Z = 80°$ and $Z = 86°.5$ for the solution of the two unknowns X_1 and X_2.

It is necessary to know the absorption coefficients for 3300 A and 3110 A, being respectively 0.09 and 1.26.

I. $Z = 80°$

$$
\begin{aligned}
&2.28 \cdot 10^{-0.09 \cdot 0.28} + 22.62 \cdot 10^{-0.09\,(2.45\,X_1 + 0.28)}\\
&+ 185.94 \cdot 10^{-0.09\,(4.36\,X_1 + 2.45\,X_2 + 0.28)}\\
&+ 642.02 \cdot 10^{-0.09\,(1.59\,X_1 + 1.91\,X_2 + 0.93)}\\
&+ 98.25 \cdot 10^{-0.09\,(-0.62\,X_1 - 0.35\,X_2 + 1.51)}\\
&- 23.44\,[1.79 \cdot 10^{-1.26 \cdot 0.28} + 17.88 \cdot 10^{-1.26\,(2.45\,X_1 + 0.28)}\\
&+ 142.52 \cdot 10^{-1.26\,(4.36\,X_1 + 2.45\,X_2 + 0.28)}\\
&+ 393.73 \cdot 10^{-1.26\,(1.59\,X_1 + 1.91\,X_2 + 0.93)}\\
&+ 34.94 \cdot 10^{-1.26\,(-0.62\,X_1 - 0.35\,X_2 + 1.51)}] = 0
\end{aligned}
$$

II. $Z = 86°.5$

$$
\begin{aligned}
&2.28 \cdot 10^{-0.09 \cdot 0.28} + 22.01 \cdot 10^{-0.09\,(6.93\,X_1 + 0.28)}\\
&+ 148.40 \cdot 10^{-0.09\,(10.04\,X_1 + 6.93\,X_2 + 0.28)}\\
&+ 162.47 \cdot 10^{-0.09\,(0.80\,X_1 + 3.11\,X_2 + 2.12)}\\
&+ 0.64 \cdot 10^{-0.09\,(-4.33\,X_1 - 2.87\,X_2 + 3.38)}\\
&- 30.90\,[1.78 \cdot 10^{-1.26 \cdot 0.28} + 17.29 \cdot 10^{-1.26\,(6.93\,X_1 + 0.28)}\\
&+ 107.48 \cdot 10^{-1.26\,(10.04\,X_1 + 6.93\,X_2 + 0.28)}\\
&+ 84.33 \cdot 10^{-1.26\,(0.80\,X_1 + 3.11\,X_2 + 2.12)}\\
&+ 0.08 \cdot 10^{-1.26\,(-4.33\,X_1 - 2.87\,X_2 + 3.38)}] = 0
\end{aligned}
$$

Any of the equations will, in a plot between X_1 and X_2, give a curve (fig. 14) and the point of intersection of the two curves will be the numerical solution of the equations. To be able to check this solution we have dealt with $Z = 89°$, and got a third curve, which does not run exactly through the first point of intersection.

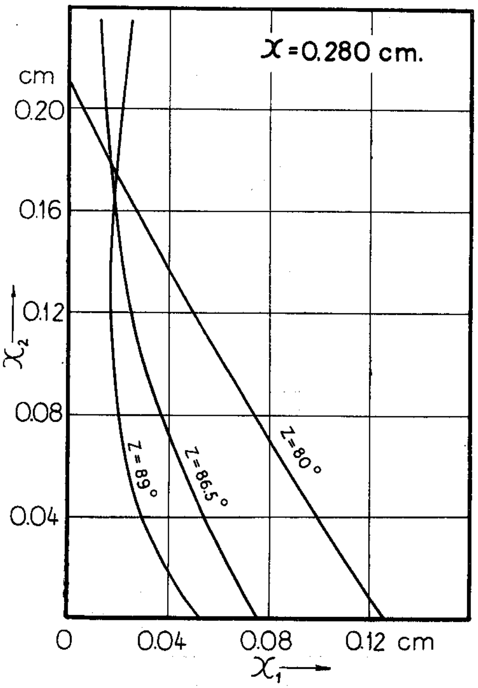

Fig. 14. Graphical solution of distribution equations.

Regarding the course of the curves (fig. 14) we may deduce that X_1 is approximately independent of X_2 when Z is very great. This means that the readings of the instrument when the sun is very low are governed mainly by the absorption and scattering high in the ozone region, say above 35 km.

Results.

The vertical distribution has been calculated for five different values of the total amount of ozone. The results are given below in cm. of ozone in the different sections, and in cm. of ozone per km.

Sections	$X = 0.160$		$X = 0.220$		$X = 0.280$		$X = 0.340$		$X = 0.400$	
	0_3	0_3/km.	0_3	0_3/km.	0_3	0_3/km.	0_3	0_3/km.	0_3	0_3/km.
50 — 35 km...........	0.018	0.0012	0.013	0.0009	0.016	0.0011	0.020	0.0013	0.018	0.0012
35 — 20 km...........	0.112	0.0075	0.155	0.0103	0.180	0.0120	0.187	0.0125	0.192	0.0128
20 — 5 km...........	0.022	0.0015	0.041	0.0027	0.070	0.0046	0.116	0.0077	0.170	0.0113
5 — 0 km...........	0.008	0.0016	0.011	0.0022	0.014	0.0028	0.017	0.0034	0.020	0.0040

Height	$X = 0.160$		$X = 0.220$		$X = 0.280$		$X = 0.340$		$X = 0.400$	
	O_3/km.	$R \cdot 10^6$	O_3/km.	$R \cdot 10^6$	O_3 km.	$R \cdot 10^6$	O_3/km.	$R \cdot 10^6$	O_3/km.	$R \cdot 10^6$
45 km	0.0003	2.14	0.0003	2.14	0.0003	2.14	0.0003	2.14	0.0003	2.14
40 km................	0.0012	3.91	0.0012	3.91	0.0012	3.91	0.0012	3.91	0.0012	3.91
35 km................	0.0045	6.84	0.0045	6.84	0.0055	8.36	0.0060	9.12	0.0060	9.12
30 km................	0.0082	5.59	0.0112	7.64	0.0132	9.00	0.0133	9.07	0.0136	9.28
25 km................	0.0083	2.91	0.0112	3.93	0.0133	4.67	0.0137	4.81	0.0140	4.92
20 km................	0.0035	0.62	0.0065	1.15	0.0090	1.58	0.0112	1.97	0.0127	2.24
15 km................	0.0014	0.11	0.0027	0.21	0.0050	0.39	0.0095	0.74	0.0124	0.97
10 km................	0.0012	0.04	0.0021	0.07	0.0032	0.11	0.0070	0.24	0.0122	0.43
5 km................	0.0014	0.03	0.0021	0.04	0.0027	0.05	0.0033	0.06	0.0040	0.07
0 km................	0.0017	0.02	0.0023	0.02	0.0029	0.03	0.0035	0.03	0.0042	0.04

These values are plotted to the left on fig. 15, which illustrates the vertical distribution in "blocks", and by smooth curves drawn in such a way that the ozone content in each section has been kept equal to that in the corresponding "block". Reading off the smooth curves we obtain the ozone content per km. on all heigths, and are able to calculate the ratio volume of ozone to air, determined by the formula $R = 10^{-5} \cdot X_h \cdot \varrho_0/\varrho_h$, where X_h is the ozone content per km. at the height h. The two series of results are tabled above, and the latter is shown to the right on fig. 15.

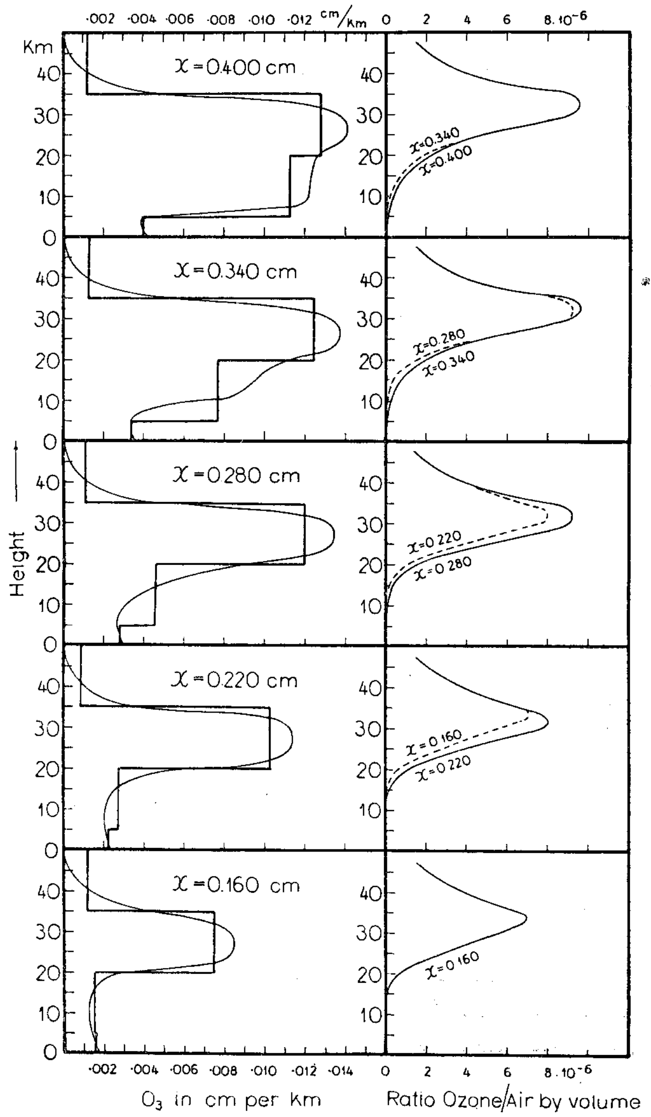

Fig. 15.

The position of the centre of gravity of the ozone layer may have some interest, and has been determined from the "block"-distribution for the five different amounts of ozone dealt with.

Ozone	0.160 cm.	0.220 cm.	0.280 cm	0.340 cm.	0.400 cm.
Height of centre of gravity	26.7 km.	25.7 km.	24.7 km.	23.0 km.	20.8 km.

A similar slight decent of the centre of gravity with increasing ozone appeared in Arosa as well.

Accuracy and Sources of Error.

As mentioned above the mean "Umkehr" curves on fig. 5 (p. 8) have been used to read off the observed values of log I/I' (denoted L in the equations). The mean curves should be fairly reliable, but some error concerning the level of the ozone value, as well as inaccurate drawing may be present. As to the ozone "level" we have trusted in constant ozone throughout days with steady meteorological conditions, and have made no allowance for a possible diurnal variation in the ozone content, which — if existing — is of no considerable amount. Some recent observations on the matter have not yet given any decisive answer, but are continued.

The mean curves, however, are based on a considerable number of individual observations besides on in all 63 successful series of "Umkehr" observations. Among the series 43 have been taken during the period Feb. to Apr., 10 during the period May to Aug. and 11 during Sep. and Oct. The curves representing the high ozone values in the spring should therefore be the relatively best founded ones, what is really necessary as they show the greatest individual deviations (highly reduced intensity of 3110 A), and particularly appreciable displacements of the "Umkehr" point. A circumstance, however, which may be due to actual variations in the vertical distribution of ozone in spite of unchanged ozone content. A definite answer to this pending question ought to be given for Tromsø, if bad weather do not continuously prevent us from making "Umkehr" observations during this springtime, upp till now indicating very low ozone values compared with the extreme high values of the last three years dealt with here.

To illustrate the quality of the "Umkehr" observations 6 series are to be seen on fig. 16. It is evident that the accuracy of measurement is considerably decreasing within the "Umkehr" region, actually more rapidly than fig. 16 may go to show.

Let us roughly estimate the actual deviations of log I/I' (L) from the mean "Umkehr" curves to be respectively 0.010, 0.015 and 0.020 at $Z = 80^\circ$, $86^\circ.5$ and 89°. An inaccuracy of that amount will introduce a maximum error in the ozone content of 8 % in the section 50 to 35 km., 3 % in the section 35 to 20 km. and 5 % in the section 20 to 5 km.

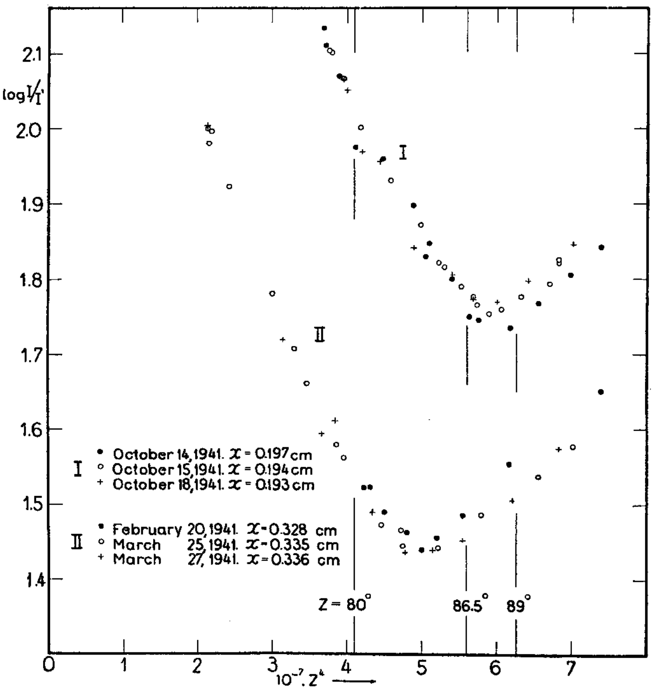

Fig. 16. Series of "Umkehr" observations.

Taking consequence of the fact that the inaccuracy of measurement is rapidly increasing with increasing Z in the "Umkehr" region, we have in the graphical solution always selected the point of intersection between the Z_{80}-curve and the $Z_{86.5}$-curve for determination of X_1 and X_2, calculating at the same time, however, the checking Z_{89}-curve that does not usually run through the previous point of intersection (compare fig. 14). This is not due to any inaccuracy in the mathematical determination of the curves, which is in fact very accurate.

The deviations of the points of intersection — simply read off — correspond to errors of the following order of magnitude:

Section 50 to 35 km.: 10 % of the ozone content.
Section 35 to 20 km.: 10 % of the ozone content.
Section 20 to 5 km.: 20 % of the ozone content.

The above errors may be regarded as a *quantitative measure of the inaccuracy of method A*, concerning observations and assumptions. In this error-bag may be included for one thing the error caused by inaccurate drawing of the "Umkehr" curves, roughly dealt with above, secondly an error due to secondary scattering not allowed for, and thirdly an error introduced by the rough partition of the atmosphere into but five sections with uniformly distributed ozone.

As to the secondary scattering Götz, Meetham and Dobson (22) have made valuable determinations and considerations, the outcome of which is that the ratio of secondary scattered light to the primary scattered is very nearly a constant, which is approximately independent of Z and X for each wavelength. This again means that the effect of secondary scattering already has been approximately accounted for in the determination of the link constant C between observations and calculations. That constant originally declared to be of instrumental origin, is in reality of atmospheric origin as well.

After the detection of a nearly constant ozone content in the section 50 to 35 km. for any ozone value, we have like Götz (19) taken advantage of it, and devided the interval 35 to 5 km. now into *three* sections, 35 to 25 km., 25 to 15 km. and 15 to 5 km. An expectation to gain further important details in the vertical distribution has so far been disappointing, there has however for Tromsø too appeared traces of a new feature in the distribution — particularly for the higher ozone values — with *two* pronounced maxima, one in the section 35 to 25 km., the other in the section 15 to 5 km. But the inaccuracy in these solutions appear to be so high that we should trust more in the earlier results. The possibility of two pronounced maxima of the atmospheric ozone should however in some cases not be excluded.

In the expression for the calculation of I and I' we are met with the density of air ϱ and the scattering coefficient β, two somewhat uncertain constants.

As to ϱ values are required every km. from the ground to 65 km. above. An extract of the densities used at Tromsø and Arosa is given below in unit gr. /cm$^3 \cdot 10^{-6}$.

Height in km.	0	10	20	30	40	50	60
Tromsø ...	1296.0	370.7	73.60	19.00	3.98	0.85	0.18
Arosa	–	403.4	90.12	18.10	3.68	1.11	–

The densities above 20 km. assumed at Arosa are based on results of the investigations of Whipple on the reflection of air waves from the stratosphere, suggesting an increase in temperature above 30 km. The Tromsø — densities up to 20 km. are average values measured during the *spring*, above 20 km. they are those of Chapman and Milne (7), assuming a constant temperature of 219° A (— 54° C) in the stratosphere and a completely intermixed atmosphere. Any error in the vertical distribution of density, however, will introduce but a small error in the vertical distribution of ozone. Using the Arosa-densities above 40 km. against our own, we get the alterations below for the ozone value of 0.280 cm.

Section 50 to 35 km.: 30 % increase in ozone.
Section 35 to 20 km.: 2 % decrease in ozone.
Section 20 to 5 km.: 2 % alteration in ozone.

The Rayleigh values of the scattering coefficients β and β' are 0.41 and 0.32 respectively, the "Dobson" values (12) (taking into account scattering by *all* particles small compared to the wavelength) used by us are 0.47 and 0.37. Calculating with the Rayleigh values we get the alterations below for an ozone value of 0.280 cm.

Section 50 to 35 km.: 20 % decrease in ozone.
Section 35 to 20 km.: 3 % decrease in ozone.
Section 20 to 5 km.: 2 % increase in ozone.

The real error caused by inaccuracy or variation in the scattering coefficient is probably still less. We see, however, that the error in the vertical distribution of ozone introduced by errors in β and ϱ are small except for the section 50 to 35 km., where the ozone content is relatively diminutive.

Summing up all errors above, calculated for an ozone value of 0.280 cm., we get:

Section	Ozone in cm. per km.	Maximum error in cm. per km.	Maximum error in percent
50—35 km.	0.0011	0.0004	40
35—20 km.	0.0120	0.0018	15
20— 5 km.	0.0046	0.0011	24

The corresponding error in the heigh of the centre of gravity will be ± 1.5 km.

Remarks.

The schematic picture of the vertical distribution of ozone over Tromsø presented here ought to be a fairly reliable one. We should emphasize, however, that the smooth distribution curve through the "blocks" on fig. 15 (p. 27) indicates a higher accuracy than is actually present. Method A cannot give any detailed picture of the distribution (similar to method B), but it involves no subjective assumptions (contrary to method B), to be regarded as very important. Since possible error by the method will influence the distribution uniformly for any ozone value, it seems to hold true that the vertical distribution of ozone does not change uniformly with changes in the total ozone content. Further, to illustrate the matter we refer to fig. 15 (p. 27) and the table below showing the distribution of ozone among the different sections in per cent.

Section	$X = 0.160$	$X = 0.220$	$X = 0.280$	$X = 0.340$	$X = 0.400$
65–50 km.	0 %	0 %	0 %	0 %	0 %
50–35 km.	11	6	6	6	5
35–20 km.	70	70	64	55	48
20– 5 km.	14	19	25	34	42
5– 0 km.	5	5	5	5	5

The most striking feature in the table is the great alterations in the ozone content between 5 and 20 km., without doubt of considerable meteorological interest, further to be dealt with in the next section of the present paper.

In order to compare our results with those derived by method B (26), we should refer to fig. 17. In addition to the Tromsø-curves will be seen the Arosa-curves by method B, which are in good agreement with the Arosa-curves by method A. The considerable difference in ozone distribution between the Tromsø-curves by method A and B, may perhaps be due to failure in the assumptions of method B, that the distribution is changing uniformly with the total amount of ozone, and that the ozone contents in the two lowest layers (0 to 10.2 km. and 10.2 to 17,8 km.) are equal for every given ozone value. Considering the results of method A these assumptions hardly seem to hold true.

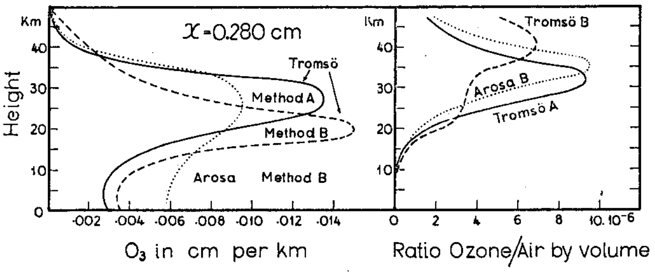

Fig. 17. Comparison of method A and B.

The "volume"-curves by method A and B are very different indeed (fig. 17). The maximum value at about 40 km. on the *B*-curve is due to the higher ozone content at that height found by method B than by method A. This disagreement, however, is hardly very serious when remembering the great inaccuracy — by method A ± 40 % — in the determination of the ozone content at 40 km.

A comparison between the distribution curves of Arosa and Tromsø (fig. 17), gives two marked differences, a greater maximum content at Tromsø between 20 and 35 km., and a far lower content between 5 and 20 km. As to the "volume"-curves they are very similar, and differ but a couple of km. in height and are — according to Penndorf (29) — in the best agreement with the distribution-theory of R. Mecke (25).

The average height of the centre of gravity at Tromsø has by method A been determined to 24.2 ± 1.5 km., or about 2 km. higher than found for Arosa. The result of method B at Tromsø was 20.8 km. And the height is slowly decreasing with increasing ozone content, contrary to the result of method B which was constant height for any ozone content.

The disagreements above may express the inaccuracy attached to the two different methods of deducing the vertical distribution of ozone.

III. Ozone Variations during Passage of Cyclones.

Introduction.

In some fundamental works, Dobson and collaborators (13, 14, 15, 16) have shown the close connection between the amount of atmospheric ozone and different meteorological characteristics of the atmosphere. The correlations found between the amount of ozone and the surface pressure distribution and also between the amount of ozone and various meteorological characteristics of the lower stratosphere, are later confirmed and extended by Meetham (27).

Making use of the ozone values of Tromsø from June 1935 to April 1940 a method has been developed to study the marked variations in atmospheric ozone at high latitudes during the passage of cyclones. The principal source for studying the weather-situation has been the daily weather-maps at 8 o'clock from "Vervarslinga på Vestlandet" in Bergen, which, among other desired meteorological material, kindly was put to our disposal by the director of "Vervarslinga for Nord-Norge" in Tromsø. The meteorological symbols, terms and theories used in this investigation originate from the well known works of *V. Bjerknes*, *J. Bjerknes*, *H. Solberg* and *T. Bergeron* (2, 8).

Taking the results obtained into account a further attempt has been made to explain the changing from year to year of the annual variation of atmospheric ozone.

Working Principle.

The year-diagrams of ozone values in the present paper (fig. 11, p. 22) illustrate the marked annual variation, which for the following investigation should be represented by a smooth curve through the scattered points. All ozone deviations dealt with here are relating to such smooth curves, otherwise drawn on fig. 12 (p. 23).

For methodical reasons we will at first consider the period March to May. In this period the greater number of polar front cyclones are approaching Northern-Norway from a south-westerly direction. The centre of the cyclones is most frequently passing south of Tromsø and the majority of cyclones being in some stage of occlussion when reaching Norway. In the period considered the arctic front is situated sometimes south and sometimes north of Tromsø. For generalizing purposes it was found convenient to restrict the classification of cyclones to two main groups:

1. Cyclones in a medium stage of development (with open warm sector).
2. Occlusions. Including warm front and cold front occlusions.

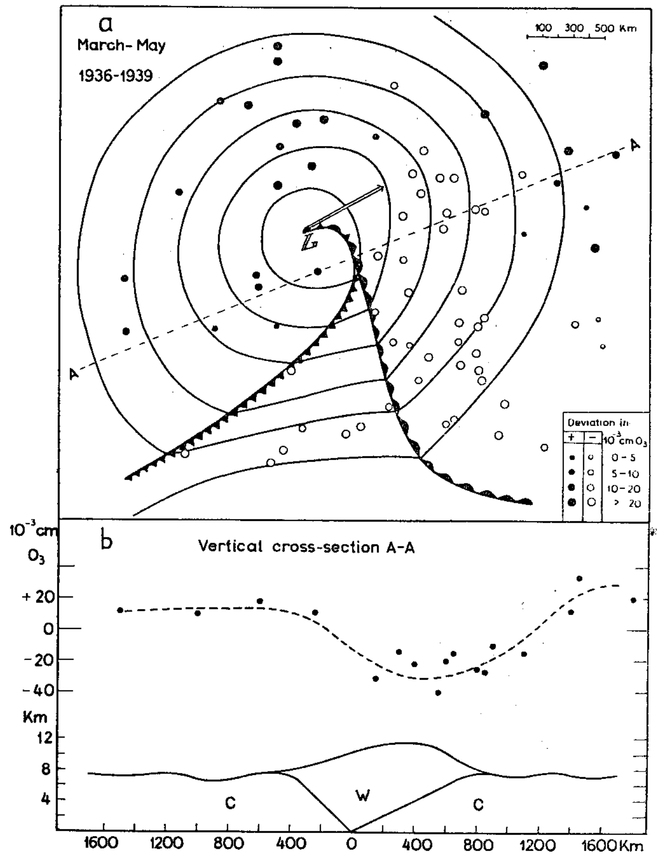

Fig. 18 a and b.

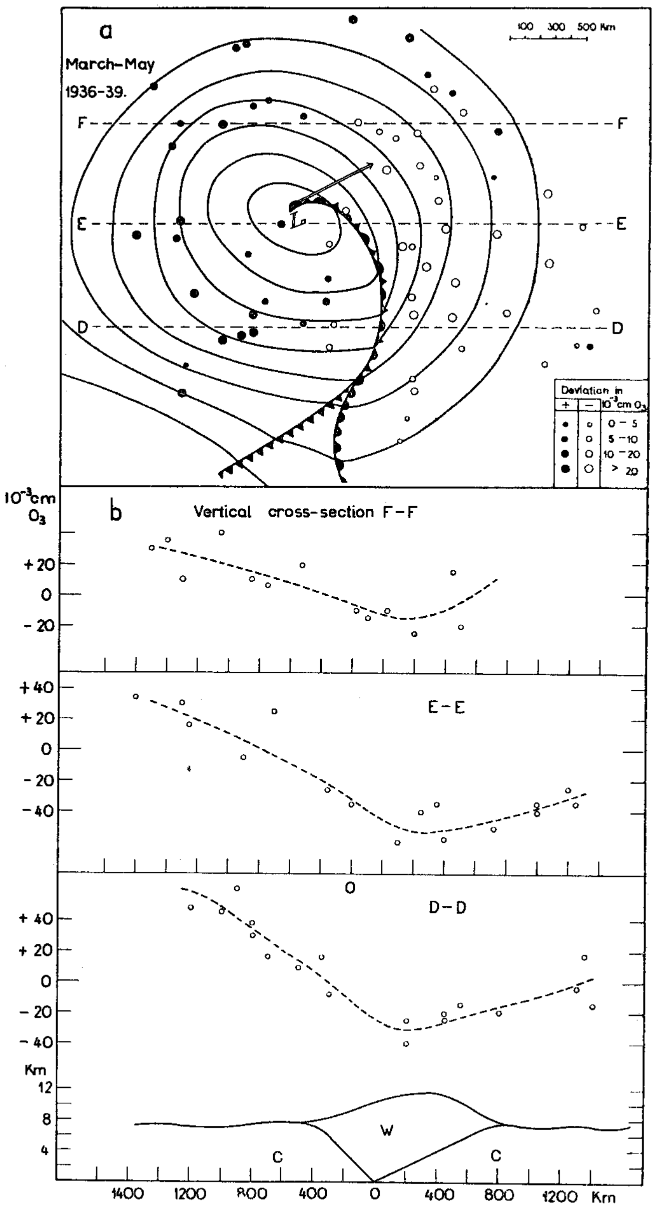

Fig. 19 a and b.

Fig. 18 a and 19 a. Ozone deviations relative to the position of front lines and depression centre of a cyclone model.
Fig. 18 b and 19 b. Ozone deviations in vertical cross-sections through the cyclone model.

Our cyclone models are shown on fig. 18 a and 19 a, on which the position of each individual circle, open or closed, are determined in the following way:

The cyclone model drawn on a tracing paper was placed upon the map in such a way that depression and corresponding frontlines on map and model were in the closest agreement. The observational place, Tromsø, now just determines the position of the actual circle on the model paper. If agreement is not obtained between both the warm front and the cold front on map and model, we let the front line nearest to Tromsø cover each other on map and model. The open and closed circles stand for negative and positive ozone deviations respectively. A scale of magnitude between circle areas and deviations is given on the figures.

When there was a difference in time between the ozone observation and the actual weather-map, the position of the cyclone in the moment of observation was determined by means of the preceding and subsequent maps. We have preferred this procedure to a correction of variable ozone values to standard hours for meteorological observations, regarding the latter method to be far more problematic. The total number of points (circles) in fig. 18 a and 19 a are 137, among which 67 come from April 1936—39 and the remaining 70 from March and May the same four years. The greater majority of the points belongs to polar front cyclones. In this representation we have included all observations *taken within a closed pressure area around the cyclone centre. We have rejected all cases with indistinct fronts and also cases when the weather situation was otherwise complicated.*

It is evident from the construction method, that the cyclone centre on fig. 18 a and 19 a should not move individually in any appointed direction in relation to the observational place. Considering, however, the frequent cyclone track from SW to NE, we have indicated the mean direction of movement towards NE by an arrow through the depression-centre.

On fig. 18 b and 19 b we have given a picture of ozone variations along various vertical cross-sections through the cyclone models. The ozone values dealt with were situated on or close to a section line. At the bottom of each figure is drawn a schematical picture of a cross-section through the front surfaces and the tropopause. For simplification the section plane *A—A* is placed vertically to the warm front and through the occlusion point of the cyclone. The section plane *E—E* cuts through the centre of depression, while *D—D* and *F—F* are placed about 600 km. to each side of *E—E*.

Discussion of Figs. 18 and 19.

Before drawing any conclusion we should call attention to some sources of error by the working method.

1. A front line is theoretically a line of intersection between a horizontal plane and a surface of discontinuity. On a weather map we are always met with a frontal zone between two different air masses, but all the same the drawing of the front lines is ruled by accepted conventions. We may estimate an inaccuracy in the recording of a cold front on the map to about 50—100 km. In the recording of a warm front or an occlusion we must allow for a possible error of about 100—200 km.
2. The estimation of the position of the front at the moment of observation may imply an error of about 100 km.
3. As to the ozone values, the error may be estimated to about 3 percent.
4. The greatest inaccuracy is probable due to the very variant structure of the cyclones and the pressure systems.

We should emphasize that the position of each circle on fig. 18 a and 19 a is rather accurate as to the distance from the depression centre and from the nearest front line. It is obvious that the majority of the circles necessarily belong to cyclones in different stages of development. Hence the picture of the circles should be regarded but as a schematical one, illustrating the changes in atmospheric ozone by passage of cyclones during the spring. The variations appearing in the different cross-sections should especially be regarded as approximate pictures. Further it should be remembered that a polar front cyclone is a dynamical phenomenon, and that the figures are giving the observed ozone deviations at different positions of the cyclones relative to Tromsø. The figures do not necessarily represent the general ozone distribution around an individual cyclone.

In spite of the inaccuracies implied by the construction of the figures, we may deduce:

a. The deviations in ozone content seem to be closer related to the position of the front lines than to the position of the depression centre. The differences in ozone deviations in direction *along* a front line are evidently small compared with those in direction *perpendicularly* to it, a circumstance in favour of regarding the cross-section pictures on fig. 18 b and 19 b — based on deviation values close to the actual cut-line — as representative of the development of ozone changes by passage of cyclones during the spring.

b. The marked rise in the ozone content in the rear of a cold front and also in the rear of an occlusion appears to begin about simultaneously with the passage of the front at the ground.

c. Relatively high ozone values seem to be present in the whole region dominated by the polar or arctic outbreaks of cold air in the troposphere. We are not able to decide whether the ozone value has a pronounced maximum in some definite distance relative to the depression centre or not.

d. The low ozone values appear in the warm sector and in the region probably covered by the warm front surface.

e. The characteristic fall in the amount of ozone may occur in a region more than 1000 km in advance of the warm front or the occlusion. This means practically that the passage of a warm front or an occlusion at the ground, may be forecasted at least 24 hours before it occurs. A further experience on this relation should perhaps be of prognostical value for the weather-forecasting.

Selected Examples of Ozone Variations in Connection with Movements of Individual Cyclones.

We have just seen that especially in the vicinity of a front, the ozone content will depend highly on the distance between the actual front and the place of observation. Ignoring the ozone variation along the front we are on fig. 20 giving a schematical representation of four examples on the subject in question.

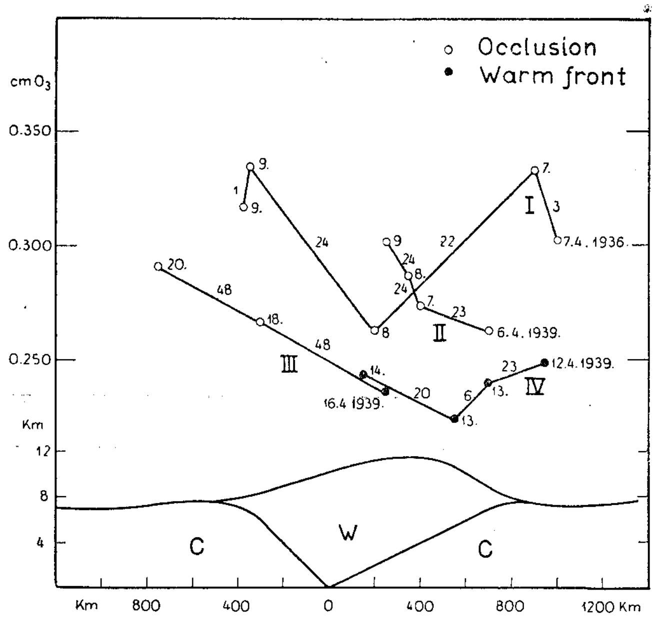

Fig. 20. Ozone variations during passage of individual cyclones.

The observed ozone values are plotted against the actual distance between Tromsø and the occlusion-front (marked ○) or the warm front (marked ●). The points are dated and the numbers between them give the time interval in hours between successive observations. The four curves on fig. 20 are selected among several others showing very varying ozone variations. The characteristic development in variation, however, being always present. More frequent observations should of course have been desirable.

Curve I shows the variation in the amount of ozone during the passage of an entirely occluded cyclone (like the model fig. 19 a). On April 7. the centre of the cyclone is situated about 1300 km. WNW to Tromsø and is moving towards ESE. The pre- and post-frontal cold air is polar, and the lifted warm air is probably old reversed maritime polar air. On April 8. when warm air should be present in the higher troposphere, the ozone value has fallen about 0.080 cm.

Curves II, III and IV belong to April 1939, when daily radiosounding ascents were carried out at "Vervarslinga for Nord-Norge" in Tromsø. These observations have been dealt with by H. Johansen (24). The upper air data in the discussion of the three curves are taken from this paper.

Curve II is showing a very interesting rise in the amount of ozone in the vicinity of an occlusion. An old polar front cyclone with entirely occluded fronts is slowly approaching Northern-Norway from SW, gradually slowing down and disintegrating before reaching Tromsø. The ascent data of April 6. indicate polar air at the ground and tropical air from about 4 dyn km. In the ascent data from April 8. and 9. the polar front indications are absent, and it is difficult to decide whether the air masses in the troposphere above Tromsø should be characterized as polar air or tropical air. If the air is of tropical origin, the transition to polar air should have proceeded so completely that we can not distinguish it from real polar air. The second possibility should be a gradual replacement of the tropical air by polar air. As seen from curve II the rise in the ozone value is going on paralell to the changes of air masses in the troposphere. It seems reasonable to suppose that the rise in the amount of ozone is caused by these and similar changes of air masses in the lower stratosphere. To this subject we shall return later on.

Curve III illustrates the rise in the ozone content in the rear of an occlusion. On April 16. a warm front is situated 250 km. SW of Tromsø and the ascent data indicate tropical air above a height of about 2 dyn km. The front is passing

Tromsø the next day, now as an occlusion, and the tropical air is replaced by a strong outbreak of polar air reaching a considerable height. This airstream is still continuing on April 20., when the occlusion is situated 750 km east of Tromsø. The rise in the amount of ozone is proceeding rather slowly compared to its more sudden jump on curve I. It seems to be some relation between the speed of ozone variations and the speed of the cyclone movements.

Curve IV gives the ozone variation in the proregion of a warm front approaching from SW. From the ascent data of April 13. we are able to deduce: No trace of any front, but a lifted tropopause and low temperature at the tropopause, which indicate an invasion of tropical air in the upper troposphere. The following day tropical air is present above Tromsø down to 2 dyn km. It should be noted that the day with lowest ozone content, April 13., has the highest tropopause and coldest lower stratosphere among the three days in consideration.

There is reason to believe that decreasing ozone content is due to an invasion of tropical air in the lower stratosphere. The ozone observations suggest that this invasion may take place before the warm front surface is present in the troposphere. Considering the results from fig. 18 and 19 we should suppose that the marked fall in the ozone content about 1000 km. in advance of the warm front is occurring simultaneously with the first invasion of tropical air masses in the lower stratosphere. Bjerknes and Palmén (1) have shown that such an invasion frequently has the character of a cold front phenomenon in the lower strata of a previous polar stratosphere. Such changes of air masses in the lower stratosphere will explain the observed ozone variation in advance of an approaching cyclone.

The four examples above (fig. 20) of ozone variations during passage of cyclones show rather different pictures of development, a fact which underlines the average character of the similar pictures on fig. 18 and 19 (p. 31). In this connection we should not forget the difficulty in a close pursuit of the ozone variations connected to cyclones from one observational station alone.

It seems doubtles, however, that ozone observations frequently may give valuable information about the meteorological conditions in the lower stratosphere. The ozone tendency, the rise or fall in the amount of ozone during the last — say 3 — hours, ought to be of future interest in the weather forecasting service.

Ozone Variations during Passage of Cyclones at Different Seasons of the Year.

Owing to shortage of simultaneous ozone observations and weather-maps for the four wintermonths, November to February, we are not able to investigate this interesting period in detail. As a single example, however, we will deal with the ozone values measured by Barbier, Chalonge and Vassy at Abisko (68°.3 N, 18°.8 E. Gr.) during January and February 1935 (4). For the remaining 8 months the table below gives the mean deviations in cm. from the smooth annual curves of ozone, and the same deviations in per cent of the monthly mean values.

Period 1935—41	March	April	May	June	July	Aug.	Sept.	Oct.
Monthly means	0.307	0.302	0.278	0.257	0.230	0.241	0.207	0.199
Mean deviations	0.018	0.024	0.014	0.013	0.007	0.008	0.010	(0.016)
Mean deviations in per cent	6	8	5	5	3	4	5	(8)

It is evident that the mean day to day variations of ozone from a maximum in spring are falling off to a minimum in summer only to rise again in autumn. Relatively few ozone values are available from September and October, and the mean ozone variation in summer is but slightly greater than the error of observation. The activity of cyclones at the polar front is more intense in spring and autumn than in summer. In addition, the discontinuities once existing in a cyclone over the sea in summer, will usually become rather indistinct at the ground when arriving over the continent. Owing to these facts the working method employed should fail to be as useful for the period June—October as for the period March—May, dealt with here.

This assumption is confirmed on fig. 21, where (compare fig. 20) any ozone values are plotted against the distance to the actual frontline. The closed circles (points) to the right and left of the occlusion point (marked 0 km.) indicate respectively observations in the pro-region of a warm front and in the rear of a cold front. The open circles refer to occlusions. The scattering of the points is considerable, but we should remember that they belong to different cyclones. Probably more distinct curves might have been plotted for individual cases. The six examples on fig. 21 are selected among all available from the years 1936—39 as representative in an attempt to characterize the seasonal variation. The Abisko-curve should only be regarded as a striking example of the marked ozone variation that may occur during passage of cyclones in January and February. It should not be considered as a characteristic curve for the ozone variation in connection with occurrence of winter-cyclones. As seen from the curve of annual variation (fig. 12 p. 23) the mean ozone value increases very rapidly during January and February, a rise which hardly can be explained by the activity of cyclones alone.

The previously dicussed period, March—May, is represented by the curve from April 1936. This figure needs no further explanation. It is worth attention, however, that the use of absolute ozone values gives a similar picture of the variation in spring as earlier stated, where we used deviations from smooth annual curves. During the period June—October, the connection between ozone variation and passage of cyclones being obviously less marked than in spring. The low ozone values in the pro-region of a warm front seem to be present in June but can hardly be pointed out from July to October. A slight rise in the ozone values in the rear of a cold front is indicated in the autumn.

The less marked connection between ozone variation and passage of cyclones during summer time might partly be explained as due to a looser connection between tropospheric and stratospheric processes within a cyclone during this period. Meanwhile the seasonal variation illustrated on fig. 21 should also be regarded as an argument in favour of the advection theory for the ozone variations dealt with later on.

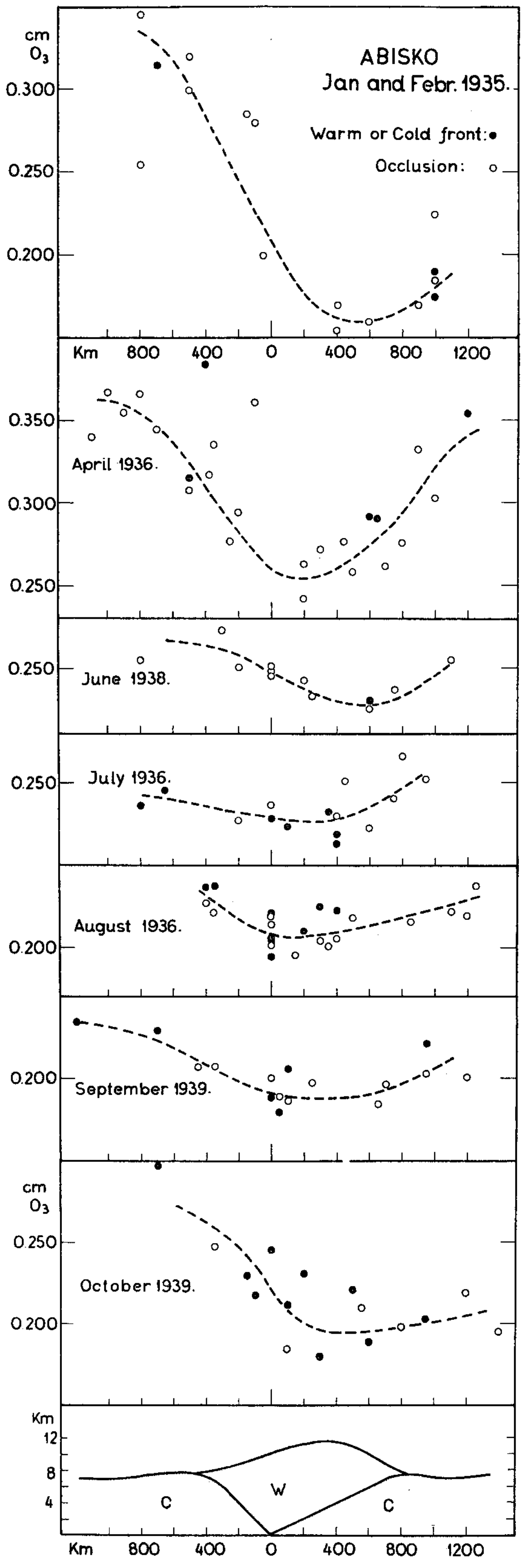

Fig. 21. Ozone values plotted against the actual distance from the nearest front line.

The Difference from Year to Year in the Annual Variation of Atmospheric Ozone.

It is well known that the monthly mean values of atmospheric ozone may differ considerably from year to year. An attempt to throw some light on this problem will be made here.

Of the monthly mean values of Tromsø from 1935 to 1941 we are calculating the average values for each month. Deviations in the monthly mean values from this "standard" values prove a surprisingly high correlation with the direction of the dominating flow of air. For this investigation we will only distinguish air masses from a northerly direction (0—8 and 24—32 meteorological scale) and a southerly direction (8—24). As the wind direction in Tromsø is affected by local peculiarities it should be taken from the weather-maps. When — for instance — a depression is approaching from NW, a primary NW-wind may frequently be recorded as SW-wind in Tromsø. The number of days with respectively northerly and southerly wind are counted for each month, and the excess of northerly (+) or southerly (—) wind calculated in per cent of the number of days in consideration (all days with ozone observations). If these monthly values are plotted against the corresponding ozone deviations, we find the rather high correlation pictured in fig. 22. The correlation coefficient being + 0.71 when all months from March to October in the period 1935—1941 are taken into account. Considering the period March to May only, the correlation coefficient is slightly higher, viz. + 0.79.

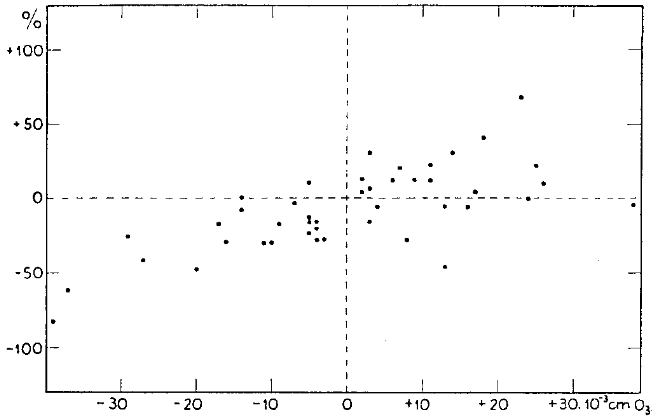

Fig. 22. The correlation between excess of northerly wind (+) or southerly wind (—), and the deviations in monthly mean ozone values from year to year. As "standard" ozone values are used the average values for the months March-October of the period 1935—1941.

In several periods the correlation is very striking. For instance during the extraordinarily warm spring and summer 1937 showing a considerable excess of southerly wind (April: — 82 %) and correspondingly very low ozone values (April: — 0.039 cm).

In view of this correlation and the above found relation between the ozone content and the position of the polar front, we may put forward the suggestion that the main cause of the observed differences from year to year in the annual variation of atmospheric ozone, is of meteorological origin.

The found correlation probably indicates a connection between air currents in the troposphere and the lower stratosphere. If we adopt an advection-theory behind the ozone variations, this means that a southerly wind in the troposphere causes a transport of air masses of low ozone content towards north, and a northerly wind should bring air masses of high ozone content towards south. Meanwhile this is not always true, some irregularities may be present. An outbreak of polar air, for instance, frequently reaches merely a height of a few km., while the air above may be of another origin. In average during a month, however, an excess of air transport towards north respectively south in the troposphere is apparently present in the lower stratosphere simultaneously. Although the main direction of air flows in the lower stratosphere in high latitudes probably is from west to east.

Discussion and Conclusions.

Especially from the works by Dobson and Meetham we have learned that the correlation coefficients between the amount of ozone and meteorological elements are very high in the lower stratosphere and in the highest troposphere, but rather small or hardly present in the lower troposphere. Among the number of investigated correlations with the ozone variations we should emphasize the following:

1. The high positive correlation with the potential temperature at heights of about 18 km. (Meetham: $r = + 0.8$.)
2. The high negative correlation with the height of the tropopause. (Dobson and Meetham: $r = - 0.7$.)
3. The relation to the surface pressure distribution. (Dobson.)

4. The relation to the origin of air currents in the upper troposphere. (Dobson.)

These correlations may probably differ considerably from place to place and from season to season. The present treatment of the variation in the amount of ozone during passage of cyclones at different seasons of the year, indicates that the above given correlations do vary considerably with the season at high latitudes.

According to Dobson, we allow for three possibilities of ozone variation above a given locality:

A. By transport of air masses from regions where the amount of ozone is normally large to regions where it is normally small (and vice versa).
B. By vertical movements in the atmosphere. (Convection currents or vertical displacements of air masses.)
C. By actual formation or decomposition of ozone above the area in question.

As to the last possibility we should remark that the ozone content in unchanged air remains persistingly constant. Both formation and decomposition of ozone seem to be slow processes, and it should be particularly noted that any daily variation in atmospheric ozone has not yet been recorded. Consequently possibility (C) alone can hardly explain the great and rapid deviations from the annual curve. But it may perhaps contribute to variations connected with possibility (B).

The theories of a photo-chemical ozone-equilibrium in the atmosphere (19) learn that a sinking of air in the lower stratosphere will cause a rise in the ozone. Conversely a lifting of air in the lower stratosphere will be accompanied by a fall in ozone. These effects are probably present during the passage of cyclones.

Normally there is an upward displacement of air in the warm sector and in the region covered by the warm front surface. These movements are connected with a divergence of the upper air. The upward displacement being suppressed with increasing height in the stratosphere. There is a downward displacement of the tropical air in the lower stratosphere and upper troposphere on the eastern (leeward) side of the moving polar air tongue, and also in the tropical air normally being present above the spreading and sinking polar air tongue. This descending motion is connected with a convergence of the upper air.

The above mentioned air movements may contribute respectively to the fall in the ozone values observed below the lifted warm air and to the marked rise in the rear of the cold front, but according to Meetham (27) they cannot solely explain the observed ozone variations. His assumption of an appreciable amount of vertical circulation in the stratosphere, which would highly increase the ozone content in a given column of air, should be considered, but owing to the small lapse-rates present in the stratosphere it is hardly to believe that a vigorous convection-process is going on there.

Thus we find it necessary to take possibility (A) into consideration, perhaps still being regarded as the most important cause of ozone variations. Any large mass of air might be expected to drift about carrying with it its own ozone. Such large air currents are well known from the general circulation in the troposphere and are also present in the lower stratosphere. Any discussion of the latter theory, however, requires an intimate knowledge of the geographical ozone distribution and also of the manner in which replacements of air in the ozone layer take place.

As to the distribution, earlier measurements have given increasing ozone values with increasing latitude (16). Because of considerable differences in the monthly mean values from year to year, it should hardly be justifiable to compare values from different years in attempts to determine the ozone variation with latitude. Corresponding curves in a diagram ozone against latitude (fig. 23) will differ considerably from year to year, why fig. 23 should only be regarded as an individual picture of ozone variation with latitude, being based merely on 2 years

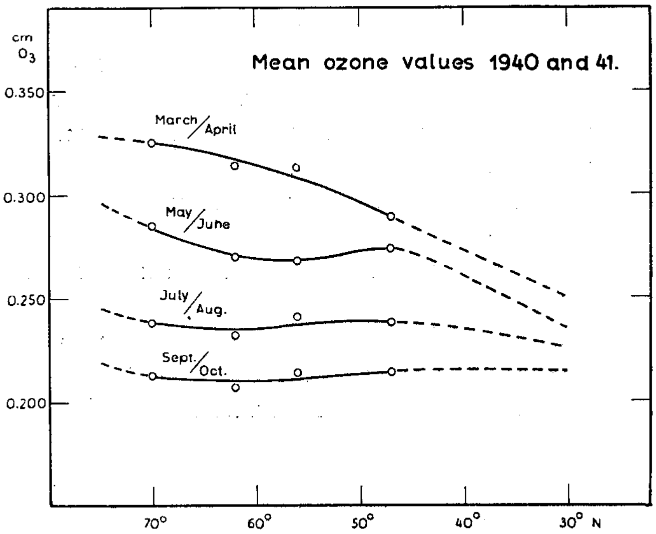

Fig. 23. Ozone variation with latitude. Mean curves for the years 1940 and 1941.

monthly mean values observed 1940 & 41 at Tromsø (69°.7 N, 18°.9 E. Gr.), Dombås (62°.1 N, 9°.1 E. Gr.), Århus (56°.2 N, 10°.2 E. Gr.) and Arosa (46°.7 N, 9°.6 E. Gr.). The dotted prolongations of the curves rely on earlier measurements.

In the present state of information about atmospheric ozone in polar regions it is difficult to test the advection theory as to the high ozone values found in connection with outflows of polar air. We may, however, emphasize the following points in favour of the advection theory as the main cause of the ozone variations:

1. The distribution of low ozone values in connection with passage of cyclones (fig. 18 and 19), and especially the probable coincidence between the marked fall in the amount of ozone about 1000 km in advance of the warm front and the first invasion of tropical air in the lower stratosphere.
2. The correlation between ozone deviations and height of the tropopause. Polar air brings a low tropopause and tropical air brings a high tropopause.
3. The seasonal variation in the relation between ozone deviations and passage of cyclones. In the period March to June, when the monthly mean values are obviously greater at 70° latitude than at 30° (taken as locality for the main production of tropical air), Tromsø observes relatively low ozone values in the region covered by the warm front surface (fig. 21). The same relation is evidently not present in the period July to October when the ozone content at 70° is about equal to that at 30° (see fig. 23).
4. The correlation found between the dominating wind direction and the deviations in monthly mean ozone values from "standard" monthly values, especially in spring (fig. 22).
5. The variation in the vertical distribution of ozone above Tromsø.

   The greatest changes in the ozone content appear in the layer 5 to 20 km. (fig. 15 and table p. 27). A fall in the amount of ozone in spring from say 0.340 to 0.280 cm., may very well be due to an invasion of tropical air somewhere in the layer 5 to 20 km. The ozone content of this tropical air — assumed remaining unchanged during the drive towards north — may be calculated to 0.0045 cm. per km. as an average, the calculation being based on a total ozone content of 0.250 cm., and the assumption of a vertical distribution similar to that of Arosa. This value (0.0045 cm. per km.) agrees with the ozone content in the same layer above Tromsø when the total amount of ozone is 0.280. cm. (see table p. 26).

As already remarked by Dobson there is at least one strong argument against the advection theory:

At a given place we may observe an ozone value that is considerably greater than the average values at places in higher latitudes at the same time of the year. We may also observe an ozone value that is considerably smaller than the average values at places in lower latitudes.

In spite of such accidents the advection theory should not be dropped. We should prefer to explain many of the discrepancies as a result contributed to by all air movements considered. In every attempt to explain ozone variations it should be necessary to know the actual (and not average) ozone distribution over a large area, extending both N—S and E—W. Further we should know the mechanism of air displacements and replacements within the ozone layer. Reasonably the advection theory cannot be proved or rejected by discussing the total amount of ozone only. It should also be necessary to have an intimate knowledge of the vertical distribution of ozone.

As to the extreme low and high ozone values in high latitudes they can be but partly governed by meteorological factors.

Otherwise, it seems advisable to wait for the results of further simultaneous ozone and aerological investigations before attempting to decide between the different theories.

Whatever the cause of the ozone variations may be, a further investigation on the relation between ozone deviations and passage of cyclones appears to be of considerably interest for meteorology.

LIST OF PAPERS

1. J. Bjerknes and E. Palmén: Investigations of Selected European Cyclones. Geof. Publ. Vol. XII No. 2, 1937.
2. V. Bjerknes, J. Bjerknes, H. Solberg und T. Bergeron: Physikalische Hydrodynamik. Berlin 1933.
3. D. Barbier, D. Chalonge et E. Vassy: Mesure de l'épaisseur réduite de l'ozone atmosphérique pendant l'hiver polaire. C. R. *201,* 787, 1935.
4. D. Barbier, D. Chalonge et E. Vassy: Nouvelles méthodes pour la mesure nocturne de l'ozone atmosphérique et l'étude de la répartition de l'énergie dans les spectres stellaires. Rev. d'optique *13,* 1934.
5. D. Chalonge et E. Vassy: Spectregraph astigmatique à prisme objectif. Rev. d'optique *13,* 113, 1934.
6. D. Chalonge: Recherches sur les spectres continus de l'atome et de la molécule d'hydrogène. Thèses à l'Université de Paris 1933.
7. S. Chapman and E. A. Milne: The Composition, Ionisation, and Viscosity of the Atmosphere at Great Heights. Quart. J. Roy. Met. Soc. XLVI, 196, 1920.
8. S. P. Chromow: Einführung in die synoptische Wetteranalyse. Berlin 1940.
9. A. Cornu: Sur la limite ultraviolette du spectre solaire. C. R. *88,* 1879.
10. A. Cornu: Sur la limite ultraviolette du spectre solaire. C. R. *111,* 1890.
11. G. M. B. Dobson: A Photoelectric Spectrophotometer for Measuring the Amount of Atmospheric Ozone. Proc. Phys. Soc. *43,* III, 324, 1931.
12. G. M. B. Dobson: Instruction for Use of Dr. Dobson's Spectrophotometer.
13. G. M. B. Dobson and D. N. Harrison: Measurements of the Amount of Ozone in the Earth's Atmosphere and its Relation to other Geophysical Conditions. Proc. Roy. Soc. *110,* 660, 1926.
14. G. M. B. Dobson and D. N. Harrison: Part II. Proc. Roy. Soc. *114,* 521, 1927.
15. G. M. B. Dobson and D. N. Harrison: Part III. Proc. Roy. Soc. *122,* 456, 1929.
16. G. M. B. Dobson and D. N. Harrison: Part IV. Proc. Roy. Soc. *129,* 411, 1930.
17. Chr. Fabry et H. Buisson: Étude de l'extrémité du spectre solaire. J. de physique *2.* 197, 1921.
18. F. W. P. Götz: Das atmosphärische Ozon. Ergebnisse der kosmischen Physik Band I, S. 180.
19. F. W. P. Götz: Die vertikale Verteilung des atmosphärischen Ozons. Ergebnisse der kosmischen Physik Band III.
20. F. W. P. Götz: Zur Strahlungsklima des Spitzbergensommers. Strahlungs- und Ozonmessungen in der Königsbugt 1929. Gerl. Beit. z. Geophys. *31,* 119, 1931.
21. F. W. P. Götz: Über die Deutung des Umkehreffektes bei Messungen des atmosphärischen Ozons. Z. f. Astrophys. *8,* 1934.
22. F. W. P. Götz, A. R. Meetham, and G. M. B. Dobson: The Vertical Distribution of Ozone in the Atmosphere. Proc. Roy. Soc. *145,* 416, 1934.
23. L. Harang: Filteraufnahmen von Polarlicht. Geof. Publ. Vol X, No. 8.
24. H. Johansen: Eine aerologische Untersuchung mittels Radiosondierungen in Tromsø während der Zeit 31. März—30. April 1939. Meteorologiske annaler B. I, No. 2.
25. R. Mecke: Zur Deutung des Ozongehaltes der Atmosphäre. Zeits. f. phys. Chem. Bodensteinfestband, 392, 1931.
26. A. R. Meetham and G. M. B. Dobson: The Vertical Distribution of Atmospheric Ozone in High Latitudes. Proc. Roy. Soc. *148,* 598, 1935.
27. A. R. Meetham: Correlation of Atmospheric Ozone with other Geophysical Phenomena. Quart. J. Roy. Met. Soc. Supplem. to *62,* 59, 1936.
28. Ny Tsi-Ze et Choong Shin-Piaw: L'absorption de la lumière par l'ozone entre 3050 et 3400 A. C. R. *195,* 309, 1932.
29. R. Penndorf: Beiträge zum Ozonproblem. Spezialarbeiten aus dem Geophysikalischen Institut und Observatorium Leipzigs B. VIII Heft. *4,* 1936.
30. E. Tønsberg und F. W. P. Götz: Ozon in der Polarnacht. Naturwiss. *23,* 354, 1935.
31. L. Vegard: Investigations of the Auroral Spectrum based on Observations from the Auroral Observatory, Tromsø. Geof. Publ. Vol. X, No. 4, 1933.

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the path-length accurately, taking into account both the curvature of the earth and the refraction. Thus the relative path-length of light through the whole atmosphere will be given by Bemporade's corrected values of sec z, by Dobson denoted by m, and the relative path-length of light through the ozone region — with its centre of gravity 25 km. above — will be given by the corrected values of sec y, by Dobson denoted by μ. With these new designations the ozone equation is written:

$$x = \frac{\log I_0/I'_0 - \log I/I' - (\beta - \beta')\, m}{(\alpha - \alpha')\, \mu.}$$

A further examination of the various terms of the equation will follow.

Sunlight Observations.

The instruments used were an "old" Dr. Dobson spectrograph from 1935 to 1939, and a "new" Dobson — the spectrophotometer — later on.

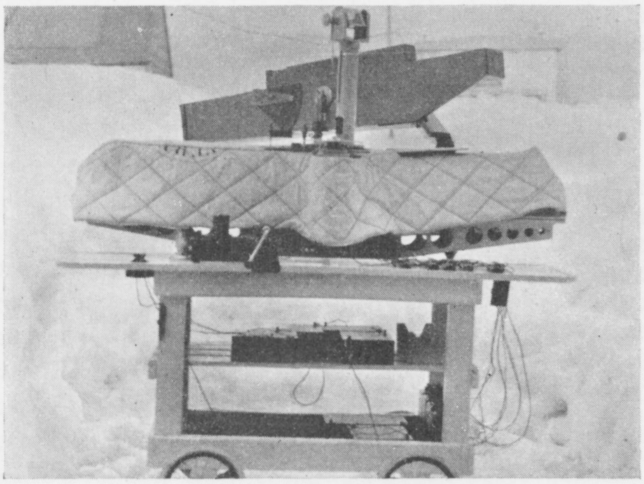

Fig. 2. Dr. Dobson's "new" and "old" ozone instruments.

The "old" Dobson spectrograph was constructed especially for ozone measurements from photographs of the sun in the wavelength region 3300 A to 2900 A. A detailed description of the apparatus in construction and use is given by Dr. Dobson (13). The instrument is an excellent one, giving photographs free from fogging and of high sharpness. The dispersion corresponds to about 14 A units per mm. in the actual region. An enlargement of a photograph is seen on fig. 3. It is evident that the light has passed through an optical wedge before falling on the plate.

For relative intensity measurements (determination of log I/I') of the selected wavelengths we have used a visual photometer of the P. P. Koch pattern (23) with two photo-electric cells, the second one serving as a grid leak cell. The measuring accuracy of the photometer has proved satisfactory.

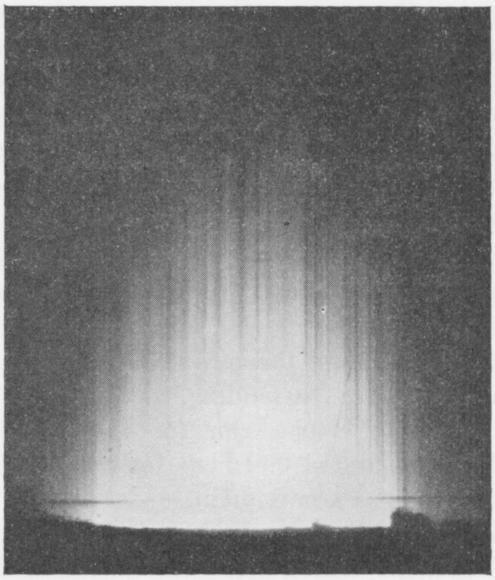

Fig. 3. Enlargement of an "old" Dobson photograph.

Just before sending the spectrograph from Oxford Dr. Dobson took 12 trial photographs, and simultaneously measured the amount of ozone by means of his spectrophotometer. Besides the 12 photographs we got a list of selected wavelengths with all necessary constants and coefficients. Thus a definite test of our intensity measurements was possible. This test proved satisfactory, giving ozone values not differing more than 0.006 cm. as a maximum from the true ones (determined by the spectrophotometer), the mean difference being 0.002 cm.

Consequently we should have reason to believe that the ozone values of Tromsø were directly comparable with those of Oxford, so far as the spectrograph had remained unchanged. This requirement, however, was not quite fulfilled, as it was found desirable already in August 1935 to try an adjustment of the spectrograph to obtain the highest possible sharpness of the spectral lines. But it is not likely that this slight alteration has affected the ozone values by any considerable amount, so far as some measurements simultaneously undertaken between this instrument and the spectrophotometer the chart on fig. 7 we get ΔL, which added to L_c gives L_b, which again from the chart on fig. 5 gives the ozone value.

We cannot of course expect the same accuracy from measurements on the cloudy zenith sky as from those on the clear, and particularly for very low sun the "cloud correction" is not quite satisfactorily determined. But this does not matter so much after all, the "cloud correction" for very low sun always being relatively small.

As to the error introduced by the inaccuracy of the "cloud correction" we should estimate it generally to be less than 0.010 cm. in the ozone value, unless for rapidly drifting and changing clouds; and no marked annual variation is present.

Observations on days when the sky is evidently or actually hazy, although clear, have been dealt with as "cloud" observations. The "cloud" correction in the ozone value will generally amount to no more than 0.005 cm. This procedure means that we believe it to be right to fix a certain standard reading for every value of "m" (fig. 6 page 10), which should be reached on the blue sky, and if not lifted to it.

Starlight Observations.

It has found to be possible to use both starlight and moonlight for ozone measurements provided the suitable apparatuses were at hand. A very good star spectrograph was constructed by Chalonge & Vassy (5). A picture of the instrument is seen on fig. 8.

Measurements undertaken by the French at Abisko in North Sweden during the winter season of 1934/35 brought the first ozone values from the polar night (3). To obtain more similar values the spectrograph was kindly put to our disposal for the winter season of 1935/36. We got several star spectra, which were sent Dr. Chalonge for evaluation. By far the majority, however, were unfortunately too weak or fogged by aurorae to give reliable ozone values. The few values obtained will be found in the ozone table marked by St.

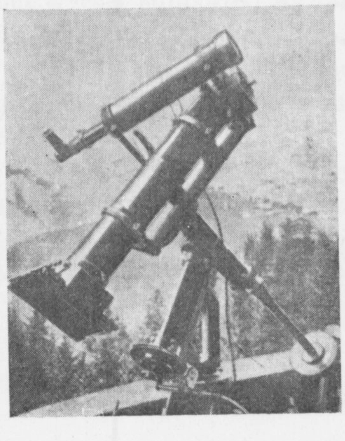

Fig. 8. The French star spectrograph.

As to the method of evaluation of the star spectra it is simply the same as for direct sunlight spectra. For details we refer to papers of Barbier, Chalonge and Vassy (3, 4).

Some important features in the construction of the spectrograph should however be emphasized here. By placing the camera lens aslope in the direction of the parallel light beams from the prism, the spectral light *points* of the star will be drawn out to *lines* of some height on the photographic plate, and thus enable us to obtain reliable photometric measurements. It is evident that the height and intensity of the spectral lines will depend upon the angle of slope of the lens, which may be regulated. In the actual wavelength region the spectrograph has a dispersion which corresponds to about 17 A per mm.

The telescope is an indispensable part of the spectrograph, one may say that its filament is the slit of the spectrograph. And during an exposure the spectrograph must be moved in such a way that the star is kept closely on a selected point of the filament.

Every plate must be provided with an intensity scale, which is obtained by means of an artificial star, being a hydrogen tube (6) giving a continuous spectrum of nearly constant intensity in the actual region of wavelengths. The graduation of the intensity scale is obtained by means of diaphragms of different apertures. Thus it is important that the plane where the diaphragms alternate is *uniformly* illuminated.

Let us mention that a similar star spectrograph of that of Chalonge and Vassy has been built at Nordlysobservatoriet. We have, however, not yet succeeded in obtaining sufficiently reliable fundamental constants to present the results of observation here. The main difficulty by the series of observation is the fogging of the spectra caused by auroral displays which suddenly occur.

Moonlight Observations.

Our first attempts on ozone determinations by means of the moonlight were carried out during the winter season of 1934/35 (30). The spectrograph used (31), seen on fig. 9, has a dispersion which corresponds to about 14 A per mm. in the actual region of wavelengths. Through a lens a picture

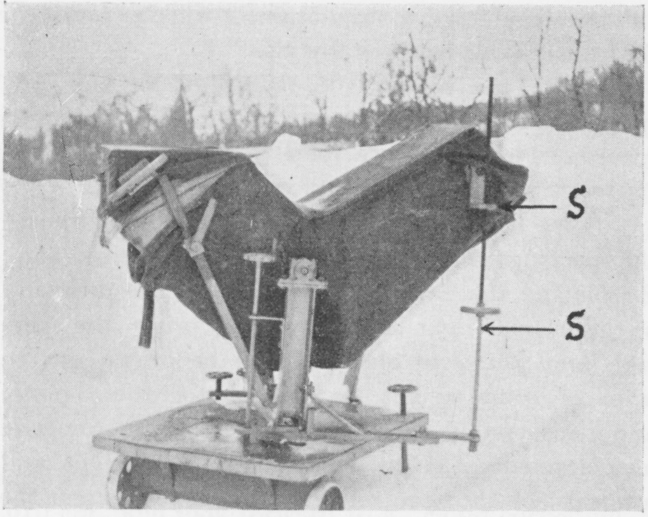

Fig. 9. The spectrograph used for moonlight observations.

of the moon was thrown on the slit, and during the exposure kept there by means of the auxiliary bar or screw marked SS on fig. 9. The height of the moon was measured by a theodolith, and refers to the middle of the exposure.

For determination of the ozone values we made use of *the method of the shortest wavelength* λ_0, developed by Dr. Götz (18, 20), while based on earlier observations by A. Cornu (9, 10). This method is not an independent one, as we need at least one otherwise determined ozone value — a reference value — in connection with a successful series of spectra taken at different heights of the moon. But the method is very simple indeed, it requires no intensity measurement, one simply has to read off the shortest wavelength λ_0 visible on the plate.

The observations of Cornu mentioned above led to the discovery of a connection between the shortest visible wavelength λ_0 in the sun's spectrum and the height h of the sun. If for an observational series λ_0 were plotted against log sin h, the points fell approximately on a straight line, a "Cornu" line (fig. 10). The "line", however, showed parallel displacements from one day to another and above all from season to season, moving against ever shorter wavelengths from summer to autumn.

If we assume an absorbing layer responsible for the dependence of λ_0 of the height h of the sun, there will — when we remember that the path-length of light through the layer is approximately inversely proportional to sin h — by the discovery of Cornu be established a connection between the shortest wavelength λ_0 and the thickness of the absorbing layer, being the ozone layer.

The wavelength limit λ_0 on the plate is influenced both by atmospheric and photographic conditions, of which the invariable do not matter at all. The variations of scattering and transparency of the atmosphere may be approximately eliminated when we omit observations unless the sky is clear, and extend the time of exposure far beyond the necessary limit. We fixed 10 minutes, although 5 minutes were sufficient.

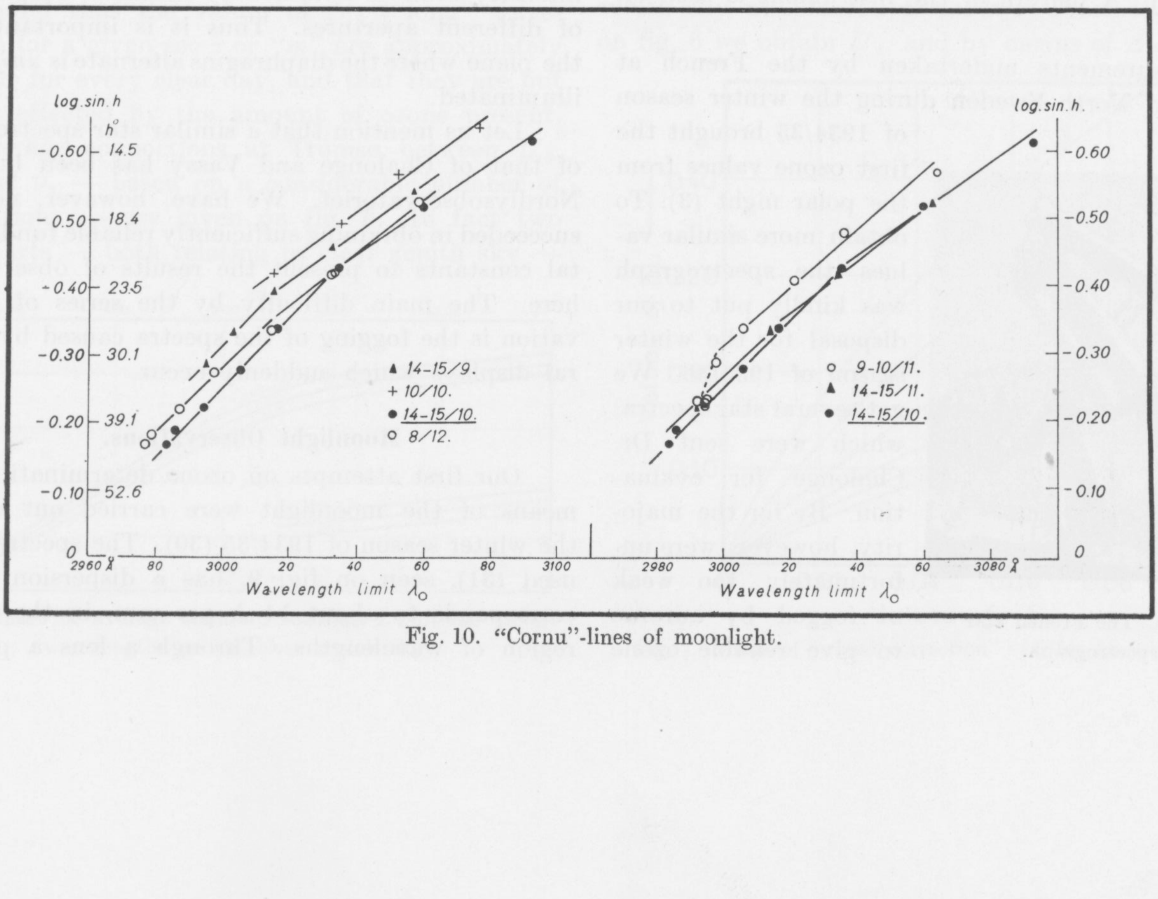

Fig. 10. "Cornu"-lines of moonlight.