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MEASUREMENTS OF ATMOSPHERIC OZONE AT SPITZBERGEN (78° N) AND TROMSÖ (70° N) DURING THE WINTER SEASON

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Abstract. In this paper, new results of measurement of total amount of atmospheric ozone at high latitudes (70° N and 78° N) are presented. These results, based on moonlight observations during an observing period of 8 years, do not support the suggestion of Götz that an "ozone gap" should exist in December at high latitudes, or even the often quoted minimum at this time of the year. A secondary rise in the annual period seems to appear during November. This may support the conventional view that differential solar heating of the ozone layer initiates a stratospheric jet stream in the Arctic.

1. Introduction. The result of Dobson's extensive ozone measurements during the years 1925—28 gave information on the seasonal and geographical distribution of ozone which have remained a fundamental source of facts. Nevertheless it was very desirable to extend the measurements to the highest possible latitudes, though in the summer season of 1929, observations were made at Spitzbergen by Götz. Five years later, in 1934, Dobson and Meetham made observations at The Auroral Observatory, Tromsö, and in July 1935 regular observations were started by means of a Dobson's spectrograph, kindly lent to the observatory. Since August 1939 a Dobson's spectrophotometer has been used. The observational data up to the end of 1942 have been published by Tönsberg and Langlo [1]. In the winter season of 1935, observations were undertaken at Abisko, in North Sweden, by Barbier, Chalonge and Vassy, using a star spectrograph [2]. They very kindly left behind a star spectrograph at The Auroral Observatory for observations next winter. Observations with a star spectrograph, for ozone measurements, which have been undertaken at Tromsö, have not been successful. In the winter season 1948—49 the author carried out several observations with a star spectrograph furnished with a prism-objective. This spectrograph was built at the observatory. The results derived were, however, uncertain and gave no detailed information. This work is described in a paper for a degree at the University of Oslo, presented by the author in 1950.

In 1950 the spectrophotometer in Tromsö (No. 14) was sent to DOBSON for recalibration. The instrument was back again in August the same year, together with an other instrument (No. 8) which DOBSON had kindly put at our disposal and witch had earlier been used for measurements at Dombås and in Oslo, Norway. They were now both furnished with a photomultiplier and thus were much more sensitive than earlier. Instrument No. 14 remained in Tromsö (70° N) as No. 8 was chosen for Spitzbergen (78° N). So, on initiative of TÖNSBERG, regular observations of atmospheric ozone were extended to Spitzbergen from September 1950. The observations at Spitzbergen were started and carried on in the first year by the author, and the observer later on has been engineer H. WELDE, the superintendent of the coal mines at Spitzbergen. The author has been responsible for all measurements at Spitzbergen and partly for the measurements in Tromsö in recent years, and the observational results have been regularly handed over to The International Ozone Commission as confidential information.

2. Observational results from ozone measurements at high latitudes. It is generally accepted that the atmospheric ozone in middle latitudes has a well established annual cycle with a maximum in spring or late winter, and a minimum in autumn. In high latitudes (up to 70° N) the annual variation is remarkably greater, and GÖTZ pointed out that the gradual decrease in the autumn terminated in an "ozone gap" at the end of December [3]. In recent years it has been discussed whether this "ozone gap" is real or not. In LANGLO's paper [4], a curve is presented showing smoothed mean annual variation of ozone at Tromsö based on measurements made in the years 1940—49. This curve shows a gradual decrease in the autumn which terminates in a well marked "ozone gap" in December as GÖTZ had pointed out. The observations, on which this characteristic winter part of the annual cycle is established, are zenith sky observations.

As will be known from the paper of TÖNSBERG and LANGLO [1], the basic method for optical ozone measurements is the direct sun observation. When the sun is very low, or in cloudy weather, one has depended on measuring scattered light from the zenith. The method is described in detail in the paper of TÖNSBERG and LANGLO and a short account of it will be given here.

In clear weather, observations of direct sunlight and scattered light from the zenith are taken alternately. The ozone amount is estimated from the sunlight observation. The instrumental readings N of the scattered zenith light are plotted against $f(z)$, where z is sun's zenith distance, and labelled with the ozone amount estimated from the sun observations. When a sufficient number of points are gathered, curves for zenith light can be drawn, each curve representing a certain ozone value. Assuming that the ozone value is steady during periods of quiet weather, observations have been carried on until the sun was very low or even with the sun below horizon, and curves labelled with ozone values, estimated when the sun was high enough, have been extended to values of $f(z)$ for $z > 90°$.

Once such empirical chart is produced, it can be used to deduce the amount of ozone from zenith light observations in clear weather. In cloudy weather, a correction is applied, based on an additional observation which correct the observed N to the value which would have been obtained on a cloudless sky. The correction is deduced from empirical cloud correction charts including the additional observations. The cloud correction charts are constructed from numerous observations made on days when the sky is partly clear and partly cloudy.

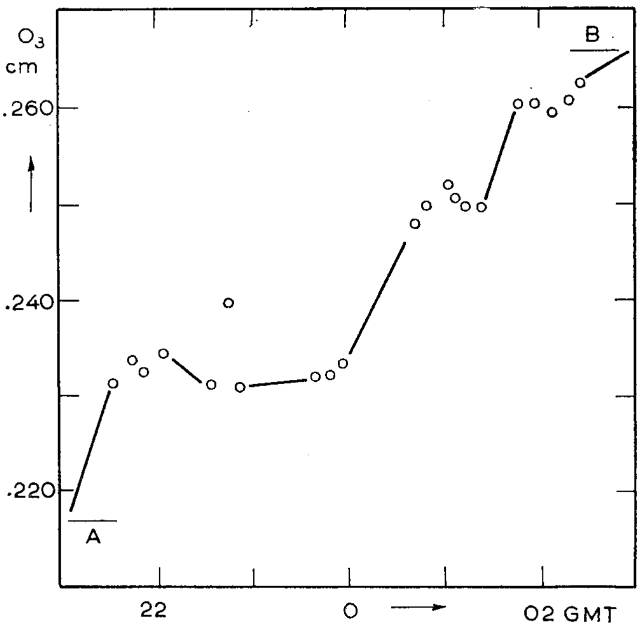

Fig. 1. O_3 values obtained from moon observations during one night. A and B denote the O_3 values on the day before and the day after.

The shape of the zenith curve will depend on the vertical distribution of the ozone, particular in that part of the curve obtained when the sun is low. In this region the curves approach each other, and the probable observational error increases due to the rapid fall in the light intensity. Hence one cannot expect a high degree of accuracy for zenith sky measurements at low sun, and fluctuation in the vertical distribution of the ozone make them still more uncertain.

When the sun is low, the direct sunlight which reaches the vertical air column over the instrument and is scattered vertically down-wards, has a long airpath and the main contribution of the scattered light entering the instrument will have its origin high up in the atmosphere.

It seems reasonable to assume that zenith sky measurements carried out during the polar night, where, in Tromsö, the sun is about 3° below the horizon at noon at winter solstice, will be much more affected by the upper than by the lower part of the atmospheric ozone region. In other words, the observed N values are not suitable for deducing a true total amount of ozone.

An increase of the high level ozone will, to a certain extent, effect the measured N value in such a way that the deduced change in the amount of ozone exceeds the true change. If, on the other hand, the high level ozone decreases, this also affects the measured $\mathcal{N}$ value, but may affect it in such a way that the deduced drop in the ozone value will be larger than the true change. This is a consequence of the dependence of the $\mathcal{N}$ value on the vertical distribution and the fact that our zenith curve chart implies a fixed vertical distribution for each ozone amount [5]. Such changes in the vertical distribution of ozone probably exist and the consequence would be deduced "ozone gaps" and sudden violent rises in ozone amount, on the base of zenith sky measurements.

The characteristic shape of the annual period of ozone amount at high latitudes with very low values in December, may not be real, and it should be of importance to try to check these results by introducing other methods of observation.

3. Moon measurements at Tromsö (70° N) **and at Spitsbergen** (78° N). When the DOBSON's spectrophotometer in 1950 had been furnished with a photomultiplier, it was well fitted for moonlight measurements due to its high sensitivity. In the observational work at Spitzbergen much importance has been attached to obtain good moon measurements which in turn should give information about the atmospheric ozone during the polar winter.

During the winter season 1955—56 observations have been made at Oxford to determine the error of observations using moonlight for different wavelength pairs and at various zenith distance of the moon. It was found that the standard error of a single observation is nearly 2 % of the ozone value actually measured when the zenith distance is between 30° and 67°, and for $z > 70°$, the standard error of observation increased rapidly. This is for the standard wavelength pair C $\lambda\lambda$.

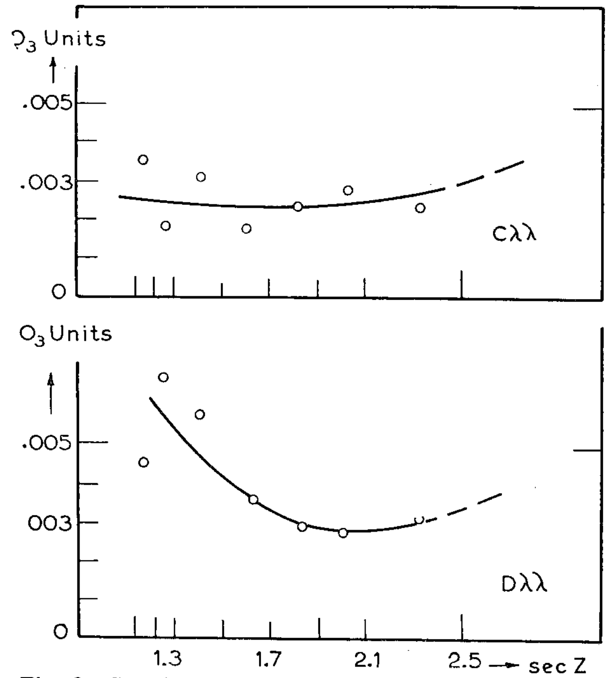

Fig. 2. Standard error of observation for moon measurements for two wavelength pairs (C and D).

If observations are made with an other wavelength pair, with smaller ozone absorption, the light intensity will increase. We will however have the surprising effect that the ozone measurements itself i less accurate when the moon is very high. The figures 1 and 2 show some of the results obtained at Oxford. The standard error of observation is given in units in which the total ozone amount is measured. The mean value

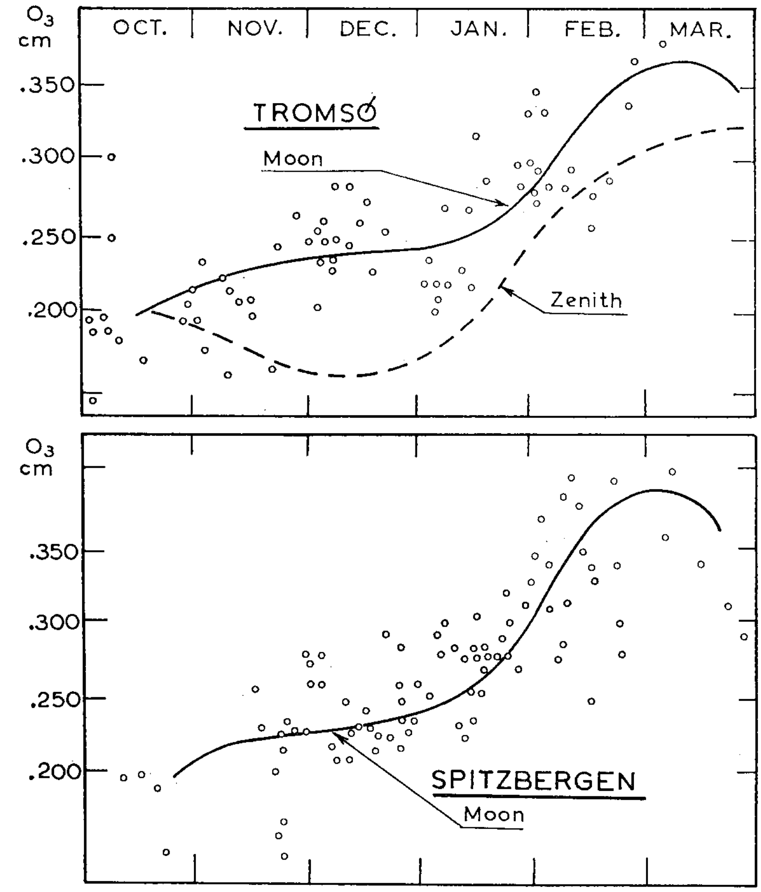

Fig. 3. The mean variation of the atmospheric ozone through the winter season for Tromsö and Spitzbergen based on moon measurements (solid lines).

of ozone during the period of observation was about 230 units (1 unit $= 10^{-3}$ cm 0_3 at N. T. P.).

From several moon series attempts were made to find a correction for the extraterrestrial constant by extrapolation. But no significant change from the constant for sun measurement could be deduced. There may be a difference, because the method of extrapolation is not very satisfactory until numerous observations have been made. Comparison between sunlight and moonlight observations shows however, a reasonable agreement between the two methods of observations, and the standard error of observation would probably not exceed 3—4 % with sun measurement as base.

The accuracy of moon measurements is therefore much better than the zenith measurement taken during the winterperiod in Tromsö which is said by LANGLO to have a probable error of about 30 % of the measured value.

Table 1. *Ozone values obtained by moon observations, given in cm 10^{-3}, at Tromsö 70° N.*

Year	Date	O_3	Year	Date	O_3	Year	Date	O_3
1950	28.9	225	1952	1.11	195	1954	9.11	223
	29.10	210		3.	175		11.	215
	23.11	245		29.11	265		7.12	233
1951	13.10	165		2.12	250		8.	229
	10.11	185		4.	255		9.	233
	14.	212		5.	258		12.	286
	15.	210	1953	28.1	287	1955	8.1	270
	16.	200		29.	302		1.2	335
	9.12	285		30.	300		2.	351
	12.	244		31.	282		3.	333
1952	5.1	221	1953	23.9	205	1957	7.10	185
	12.	230		25.	210		3.11	233
	14.	220		27.10	195		4.12	205
	5.2	283		22.11	166		6.	235
	9.	287		15.12	262		7.	251
	6.3	385		17.12	277		8.	251
	5.4	260		18.	230	1958	3.1	237
	6.	250		22.	255		4.	221
	2.10	193	1954	14.1	272		5.	203
	3.	190		16.	319		6.	208
	4.	194		19.	292		7.1	220
	5.	188		11.2	293		2.2	275
	6.	145		16.	258		4.	295
	31.10	215		17.	280		28.2	370

During the winter season, 1950—51, moon observations were carried out at Spitzbergen by the author, and during subsequent seasons by WELDE. Simultaneous moon measurements have been carried out at Tromsö. The results of moon measurements made at these two high latitude stations during the winter seasons from 1950—51 and 1957—58, are given in tables 1 and 2. They give daily means of the ozone amounts measured at Tromsö and Spitzbergen. The individual values are all based on measurements made with a moon's zenith distance less than 70°. In fig. 3 the tabulated values are plotted in two diagrams. Using the mean values for the individual moon periods as base, during which measurements are made, the mean variation of ozone through the winter has been estimated for Tromsö and Spitzbergen (solid lines). For comparison, LANGLO's mean ozone curve for Tromsö is drawn for the period of October—March (dashed line).

The moon measurement curves for Spitzbergen and for Tromsö are not very different, though the seasonal main rise in ozone amount probably starts earlier at Spitzbergen and it may reach a higher maximum value.

A very interesting feature is that there seems to be a slight secondary rise in the

Table 2. *Ozone values obtained by moon observations, given in cm 10⁻³, at Spitzbergen 78° N.*

Year	Date	O_3	Year	Date	O_3	Year	Date	O_3
1950	23.11	215	1952	1.12	277	1954	13.10	202
	24.	233		3.	261		14.	199
	25.	228		4.	281		16.	197
	26.	232		6.	315		7.12	214
	29.	231		24.	287		8.	207
	1.12	261		25.	248		10.	211
	24.	222		27.	228	1955	5.1	294
	25.	258		31.	258		6.	281
	26.	235	1953	2.1	253		7.	302
	27.	235		22.	292		9.	286
1951	16.1	280		23.	321		1.2	344
	18.	268		24.	298		3.	372
	19.	278		26.	270		4.	342
	20.	283		28.	315		5.	320
	21.	281		29.	332	1956	23.2	300
	16.2	333		21.2	395		24.	280
	17.	329		23.	340			
	10.12	252		26.3	296		19.10	155
	12.	230					16.11	255
	13.	235		21.11	202		17.	232
	15.	243		22.	158		17.12	229
1952	11.1	232		23.	150		18.	221
	13.	238		24.	172		19.	225
	14.	257		21.12	295		21.12	223
	7.2	275	1954	13.1	281			
	8.	285		14.	281	1957	11.1	225
	10.	316		15.	306		16.	255
	6.3	358		16.	281		10.2	386
	7.	400		16.2	251		11.	390
	30.11	282		15.3	342		12.	379
				16.	374		13.	348

ozone amount during November, at the time when the polar night starts. The very low values in the month of December which have been suggested previously, have not been found by moon measurements, but in October and November very low values do occur.

On the basis of these moon measurements we can say that the annual period of ozone has no "ozone gap" during the winter time at high latitudes, but a minimum in October, November.

The difference between the mean moon curve and the mean zenith curve may be a consequence of a systematic shift in the mean vertical distribution so that there are small amounts of ozone at higher levels during the polar night.

4. Remarks. Adequate knowledge about the seasonal variation of the total amount of atmospheric ozone at a large range of latitudes, together with more knowledge about the vertical distribution, should in time support the knowledge about the organization of the general circulation with respect to the ozone.

It has been shown that convergence and divergence associated with vertical motions serves to reorganize the ozone already present in certain regions of the atmosphere, and thereby contributes to variations of total ozone [6]. Martin [7], has suggested that we should consider vertical transfer as an integral part of the mechanism of latitudinal flux.

Reed suggested the very interesting theory that, to a certain degree, the ozone may be self-generating. Because of its radiative properties, strong temperature gradients, and hence strong thermal winds, may be produced in the shadow zone between the region of the polar night and the sunlit areas outside. The strong thermal winds may, in turn, produce sufficient austausch to transport ozone downwards and allow new ozone to form above.

In connection with the suggestion of Reed, one should pay attention to the paper of Lee and Godson [8] where it is stated that the existence of a high latitude winter stratospheric jet stream has been demonstrated on a synoptic basis for the North American sector. Its mean altitude and its latitudinal variation through the winter, as shown by a statistical study of the 100 mb temperature field, makes it probable that differential solar heating of the ozone layer is the primary physical process initiating the jet stream in the late autumn and intensifying it in the winter. The jet stream disappeared early in the spring.

The observational results obtained by moon measurements at high latitudes (70° N and 78° N) which show the main and sudden rise in winter, and a secondary slight rise in end of November, may contribute to achieve a greater understanding of the behaviour of the high latitude stratospheric westerly jet stream.

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