On the Amount of Atmospheric Ozone and its Relation to Meteorological Conditions.

ON THE AMOUNT OF ATMOSPHERIC OZONE AND ITS RELATION TO METEOROLOGICAL CONDITIONS

BY

KAARE LANGLO

(Manuscript Received August 3rd, 1951.)

I. Introduction.

A review of the numerous papers on atmospheric ozone written before 1938 has been given by F. W. P. Götz.[1][2] In this introduction we only intend to mention some later works which have a direct bearing on the problems discussed in this paper. In 1939 E. Palmén[3] put forward the hypothesis that the topography of the tropopause, the temperature of the stratosphere, and the ozone distribution in a cyclone might be explained as the combined result of three different processes: 1) the horizontal advection, 2) the vertical air motion due to the cyclogenesis (the evacuation of air from the middle layer of the troposphere with the connected sinking of the tropopause), 3) the vertical air motions above the warm- and cold-front surfaces.

A close relation between the actual position of the front lines on the surface map and the amount of atmospheric ozone was found by the author using the Tromsø ozone values for the period 1935 to 1942.[4])

It was confirmed that the advection of air with different ozone content seems to be of importance and that the relation between the ozone variations and the passage of cyclones was dependent on the season of the year. A similar relation between the front lines on the surface map and the horizontal distribution of ozone was independently found by G. M. B. Dobson with A. W. Brewer and B. M. Cwilong.[5])

Dobson's conclusions in the paper cited are in brief that "the variation in the relative concentration of ozone and water vapour controls the broad, slow changes of temperature in the lower stratosphere, while the rapid changes both of ozone and temperature found at any given place in temperate latitudes are chiefly due to changes in the air mass."

In a theoretical work by H. U. Dütsch[6]) the various photochemical equilibrium theories for the atmospheric ozone is discussed and he

[1]) F. W. P. Götz: Das atmosphärische Ozon. Gerl. Beitr. Suppl. Bd. I, s. 180, 1931.

[2]) F. W P. Gotz: Die vertikale Verteilung des atmosphärischen Ozons. Gerl. Beitr. Suppl. Bd. III, s. 253, 1938.

[3]) E. Palmén: Über die dreidimensionale Luftströmung in einer Zyklone und die Ozonverteilung Union géodésique et géophysique int. VII assemblee générale, Procès-Verbaux II, De l'association de météorologie, Bergen 1940.

[4]) E. Tønsberg and K. Lan (Olsen): Investigations on Atmospheric Oz›‹ at Nordlysobservatoriet, Tromsø. Geof. Publ Vol. XIII, No. 12, 1944.

[5]) G. M. B. Dobson with A. W. Brewer and B. M. Cwilong. Bakerian Lecture. Meteorology of the Lower Stratosphere. Proc. Roy Met. Soc. A. Vol. 185, p. 144, 1946

[6]) Hans-Ulrich Dütsch: Photochemische Theorie des atmosphärischen Ozone unter Berücksichtigung von Nichtgleichgewichtzuständen und Luftbewegungen. Inaug. — Diss. Zürich 1946.

puts forward a theory from which he concludes that the ozone cannot be in a state of photochemical equilibrium in the whole atmosphere. By means of certain assumptions regarding the vertical "austausch" in the troposphere and lower stratosphere and by postulating an average meridional circulation of the atmosphere, he obtained a theoretical annual variation in the amount of ozone which apparently seems to fit the observed phase and amplitude of the annual variation at 60° N.

R. V. Karandikar and K. R. Ramanathan[7]) have given a brief survey of the distribution of ozone in the earth's atmosphere both in the horizontal and in the vertical and conclude that "the total amount of ozone over any place at a definite time is the sum of 1) the daily equilibrium amount produced by the photochemical action of sunlight and the recombination of ozone by collision processes with atomic oxygen and air molecules, and 2) the accumulated ozone below the region of photochemical ozone formation which, owing to low temperature, undergoes only very slow thermal decomposition".

The authors further express the view that the tropospheric convective processes, which carry water vapour and other particles into the upper part of the troposphere, apparently tend to destroy any ozone that might come down from the stratosphere. On the other hand E. Regener[8]) and others have shown that vertical turbulent mixing extending to great heights in the atmosphere will be favourable in bringing down ozone from higher levels and thus establishing a great total amount of atmospheric ozone.

It will be understood from the papers cited that there exists a fairly well established relation between the amount of atmospheric ozone and meteorological conditions, but many questions still lack an answer. In this paper an attempt will be made to throw some further light on the problems by means of the more extensive observational data now available and especially to investigate the relative importance of the different causes of ozone changes.

Some suggestions regarding the causes of the regular and irregular ozone variations will be put forward and an attempt be made to correlate the amount of ozone with the occurrence of Mother of Pearl clouds.

II. Observational Data.

"Det Norske Institutt for Kosmisk Fysikk", through its president Professor L. Vegard, has kindly placed at my disposal the daily observations of atmospheric ozone made at Dombaas (62°,1 N, 9°,1 E Gr) for the period 20th March 1940 to 18th June 1946. The ozone observations at Dombaas were undertaken by the late astronomer Sigurd Einbu and of his son Per Einbu. The instrument they used was the Dobson photoelectric spectrophotometer No. 8, which in 1939 was lent to Norway from the "International Union of Geodesy and Geophysics" as a chain in the planned international investigation on atmospheric ozone.

By permission of Dr. Dobson the instrument No. 8 was moved from Dombaas to Oslo in June 1946 and set up at "Det Norske Meteorologiske Institutt", Blindern, (59°,9 N, 10°,7 E Gr) under the supervision of the author. For Oslo are available daily observations for the period 19th July 1946 to 30th April 1949 and a great number of additional observations for certain chosen periods. The monthly mean values for Dombaas and Oslo are found in appendix I.

E. Tønsberg, Director of "Nordlysobservatoriet", Tromsø, has supervised the ozone work at Dombaas and has checked all the ozone values from that station. Further he has kindly given me copies of the monthly mean ozone values for Tromsø (69°,7 N, 8°,9 E Gr.) for the period January 1943 to April 1949 and a number of daily ozone observations for shorter periods.

The measurements of atmospheric ozone at Tromsø from 23rd August 1939 to May 1949 were made with the Dobson spectrophotometer No. 14. A summary of some of the Tromsø values are given in appendix II.

Helge Petersen, Director of "Det Danske Meteorologiske Institut" has kindly sent me a

[7]) R. V. Karandikar and K. R. Ramanathan: Vertical Distribution of Atmospheric Ozone in Low Latitudes. Proc. Ind. Acad. Sci. Vol. XXIX, p. 330, 1949.

[8]) E. Regener: Ozonschicht und atmosphärische Turbulenz. Met. Zeit. B. 60, Heft 8, p. 22, 1943.

copy of all available observations of atmospheric ozone made at Aarhus (56°,2 N, 10°,2 E Gr.) for the period April 1940 to January 1948. These measurements also originate from the same type of instrument as used at Tromsø and Oslo.

Professor F. W. P. Götz has kindly forwarded to me the monthly mean ozone values for Arosa (46°,7 N, 9°,6 E Gr.) for the period August 1926 to August 1949. During the last ten years of this period the observations at Arosa were also made with the Dobson spectrophotometer. A summary of these values is found in appendix III.

Last but not least, Sir Charles Normand and Dr. G. M. B. Dobson have generously placed at my disposal the daily observations of atmospheric ozone made at the British stations Oxford (51°,8 N, 1°,3 W Gr.), Eshdalemuir (55°,3 N, 3°,2 W Gr.), Aberdeen (57°,2 N, 2°,1 W Gr.) and Lerwick (60°,2 N, 1°,1 W Gr.) during 1941 and 1942 The British ozone measurements were also made with spectrophotometers of the Dobson type.

With regard to the observations of Mother of Pearl clouds, Professor Carl Størmer has kindly given me all available information about the occurrence of such clouds in the period 1939 to 1949.

III. Short Description of the Optical Method of Measuring the Total Amount of Ozone.

The method is based on the fact that the absorption coefficients of ozone are fairly well known in the ultraviolet part of the spectrum, close to the lower border of the sun's spectrum.

The shortest wave-length of the sun's spectrum which, normally being recorded at the earth's surface, is about 2900 Å.*) The ozone has a strong band of absorption between approx. 3300 Å and approx. 2000 Å with a maximum around 2550 Å.

The main principle of the method is to measure the intensity ratio between two selected wave-lengths of the sun's spectrum, for instance 3110 Å and 3300 Å, where the first wave-length is appreciably absorbed by the ozone while the second one is only very slightly absorbed.

*) 1 Ångström (Å) = 10^{-7} mm.

The method was first developed by Chr. Fabry & H. Buisson[9]) and later improved by G. M. B. Dobson and D. N. Harrison.[10])

In the first instance the earth is assumed to be flat. We suppose that the sun has a zenith distance Z as seen from the earth's surface and that the radiation of a certain wave-length has the intensity I_0 on the outside of the atmosphere and the intensity I_h at a height h above to ground. By passing from the height h to to the height $h - dh$, the intensity will be reduced to

$$I_h \cdot 10^{-k \cdot \sec Z \cdot dh},$$

where k is the absorption coefficient of the air in a layer of thickness dh.

The coefficient k is dependent on the density and composition of the air and will vary with height in the atmosphere.

By integration the intensity of the radiation at the surface of the earth (I) becomes:

$$I = I_0 \cdot 10^{-\sec Z \int_0^\infty k dh}$$

$$\text{hence } \log I = \log I_0 - \sec Z \int_0^\infty k dh$$

$$\text{or } \log I = \log I_0 - K \cdot \sec Z \qquad (3.1)$$

where $K = \int_0^\infty k dh$ represents the total loss of intensity due to absorption and scattering of a radiation which is passing vertically through the whole atmosphere.

It is practical for our purpose to divide K in the following way:

$$K = \alpha x + \beta + \delta.$$

Here α is the absorption coefficient for 1 cm of pure ozone at normal pressure and temperature and x will then be the total amount of ozone in the atmosphere. If all the ozone were concentrated in a layer of pure gas at normal pressure and temperature, then its thickness would be x cms. β is the scattering coefficient of the atmosphere due to air molecules and particles

[9]) Chr. Fabry et H. Buisson: Étude de l'extrémité du spectre solaire. J. de physique 2, 197, 1921.

[10]) 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. Part I, Proc. Roy. Soc. A. Vol. 110, p. 660, 1926.

which are small compared with the wave-length of light. It is assumed that this scattering approximately varies inversely as the fourth power of the wave-length. δ is the scattering coefficient of the atmosphere due to particles which are great compared with the wave-length of light (dust, water-droplets etc.). This scattering is assumed to be approximately independent of the wave-length, or at least approximately the same when the wave-lengths are chosen close to each other.

When using equation (3.1) to develop a practical formulae for the calculation of the ozone content, it is necessary to know both the relative path-length of sunlight through the whole atmosphere and also the relative path-length through the ozone region.

The relative path-length of sunlight passing through the atmosphere, by Dobson denoted by m, will be nearly proportional to the sun's Zenith distance (Z) as seen from the earth's surface. Bemporade*) has calculated accurately the values of m, allowing for the curvature of the earth and for refraction. (For $Z = 0$, $m = 1.0$).

The relative path-length through the ozone region will be proportional to the sun's zenith distance as seen from a height of about 22 km above the earth's surface (assumed to be the height of the centre of gravity of the ozone in the atmosphere). This path-length is by Dobson denoted by μ and owing to the curvature of the earth μ will be less than m.

For two different wave-lengths λ and λ' the equation (3.1) may be written:

$$\log I = \log I_0 - \alpha x\mu - \beta m - \delta m$$
$$\log I' = \log I'_0 - \alpha' x\mu - \beta' m - \delta' m$$

By subtraction we get the following expression for the ozone content:

$$x = \frac{\log I_0/I'_0 - \log I/I' - (\beta - \beta')\, m}{(\alpha - \alpha')\, \mu} \qquad (3.2)$$

If the constant $\log I_0/I'_0$ and the numerical values of $(\beta - \beta')$ and $(\alpha - \alpha')$ are known, it is possible to calculate the ozone amount in the atmosphere from equation (3.2) by means of a single measurement of $\log I/I'$.

The constant $\log I_0/I'_0$ is found experimentally by taking readings of $\log I/I'$ with direct sunlight at different values of m or μ and extrapolating for the value of $\log I/I'$, when m or $\mu = 0$. During this calibration the ozone amount x is supposed to be constant.

If the air is clear and a reading is taken directly against the sun, the equation (3.2) can be somewhat simplified. We assume that the observations are taken when the sun's zenith distance is relatively small and $\frac{m}{\mu}$ may then be put equal to a constant. Putting $\log I_0/I'_0 = 2.943$, $\alpha = 1.26$, $\alpha' = 0.09$, $\beta = 0.47$ and $\beta' = 0.37$ we get the simple formulae:

$$x = \frac{2.943 - \log I/I'}{1.17\, \mu} - 0.085 \qquad (3.3)$$

The value $\log I/I'$ is easily measured with a Dobson's photo-electric spectrophotometer. In brief this instrument contains a quartz monochromator which isolates the two desired wave-lengths and a photo-electric cell*) (with an amplifier) to measure the relative intensities of the wave-lengths.

The light from the two wave-lengths is made to fall on the photo-electric cell one after the other by means of a rotating shutter which interchanges the wave-lengths about 20 times a minute. The intensity of the wave-length which causes the greatest photo-electric current is reduced by means of an optical wedge until the amplifier gives the same current for both wave-lengths (zero-reading on an ampere-meter). The reading on an arbitrary scale connected to the optical wedge then gives a measure of the relative intensity of the two wave-lengths.

If the observations of $\log I/I'$ are made with the scattered light from a clear zenith sky, the ozone content can be found from empirical diagrams which give the amount of ozone as a function of μ and $\log I/I'$ measured against a blue zenith sky. These diagrams are based on numerous simultaneously taken measurements of $\log I/I'$, against the sun and against a clear zenith sky for different values of μ (or Z).

In addition to the fundamental measure-

*) See p. 201 of paper cited No. 1.

*) The existing instruments were rebuilt and improved during 1949—50. They are now equipped with a photo-multiplier which makes it possible to use the weak light from the moon to determine the ozone amount in the atmosphere.

ments with the pair of wave-lengths 3110 Å and 3300 Å simultaneous observations are also made with the pair of wave-lengths 3300 Å and 4450 Å where the absorption coefficient of ozone for the last wave-length can be regarded as equal to zero.

By means of this additional reading it is possible to find empirical corrections for the effect of clouds of different types on the magnitude of $\log I/I'$. Thus the ozone content can also be measured in overcast weather.

Sources of error.

The possible systematic and non-systematic sources of error involved in the method described are carefully discussed by G. M. B. Dobson and collaborators[11][12][13] and by E. Tønsberg.*)

Only a few remarks on some fundamental questions will be made here.

The method is based on the assumption that $\log I_0/I_0'$ is constant or in other words the ratio between the intensities of the wave-lengths 3310 Å and 3300 Å does not vary outside the earth's atmosphere.

As earlier stated, the value of $\log I_0/I_0'$ is found by extrapolating for the value of $\log I/I'$, when m or $\mu = 0$. Now the observed values as measured by the spectrophotometer give $\log I/I' + D$ where D is an undetermined constant which depends on the spectral sensitivity of the photo-electric cell, the relative slit-widths etc. This unknown constant D is also contained in the extrapolated value $\log I_0/I_0'$ but since it occurs twice with an opposite sign on the right side of equation (3.2), it may be neglected.

It may thus be concluded that any observed well based changes in $\log I_0/I_0'$, will be due either to changes in the instrument or to variations in the relative intensity of the two selected wave-lengths outside the earth's atmosphere, i. e., due to changes in the ultraviolet radiation from the sun. On the other hand, if no changes in $\log I_0/I_0'$ are recorded, it cannot be concluded that the radiation from the sun does not vary from time to time. It may only indicate that the ratio between the intensities of the two wave-lengths outside the earth's atmosphere remains constant.

From investigations on the conditions in the Ionosphere and other measurements[14] we have reason to believe that relatively great changes may occur in the ultraviolet radiation from the sun.

It is remarkable, however, that no changes in the constant $\log I_0/I_0'$, which could be interpreted as due to changes in the sun, have been discovered by any of the users of Dobson's spectrophotometer during more than ten years. Therefore, it seems reasonable to suppose that the changes in the ultra-violet radiation from the sun are not likely to alter the value of $\log I_0/I_0'$, and that probably no errors in the measured amount of ozone are introduced in this way.

The found ozone values are fundamentally dependent on the numerical figures we use for the absorption coefficient of ozone. It will be seen from equation (3.2) that the ozone amount is inversely proportional to $(\alpha - \alpha')$. So far as this difference is unchanged, and the same formulae used, it seems true that the found ozone values at different times and places are strictly comparable, although the calculated values should not be claimed as representing the exact absolute values of the ozone amount in the atmosphere. A number of the hitherto published values of atmospheric ozone are based on absorption coefficients of ozone which deviate from the coefficients used with Dobson's photoelectric spectrophotometer. Most of the ozone values measured before the last war therefore have to be corrected in order to make all the available observations comparable.

When developing the ozone-formulae (equation 3.2) it was assumed that the ozone layer

[11] G. M. B. Dobson: A Photoelectric Spectrophotometer for Measuring the Amount of Atmospheric Ozone. Proc. Roy. Phys. Soc. 43, III, 324, 1931.

[12] G. M. B. Dobson: Instructions for Use of Dr. Dobson's Spectrophotometer.

[13] F. W. P. Götz, A. R. Metham and G. M. B. Dobson: The Vertical Distribution of Ozone in the Atmosphere. Proc. Roy. Soc. 145, 416, 1934.

*) E. Tønsberg and K. Langlo (Olsen): loc. cit. (No. 4).

[14] G. M. B. Dobson: Measurements of the Sun's Ultra-Violet Radiation and its Absorption in the Earth's Atmosphere. Proc. Roy. Soc. London A. 104, p. 252, 1923.

was under "normal conditions", i. e. that the temperature in the layer was 0° centigrade and the pressure equal to 760 mm.

Actually the temperature in the greater part of the ozone layer (between 10 and 35 km) is somewhere between — 45° and — 75° centigrade, depending on the season of the year and the latitude, and the pressure varies with height from about 260 mbs. to about 6 mbs.

It has been shown*) that the absorption coefficients of ozone may be regarded as independent of pressure for the wave-lengths we are considering.

According to E. Vassy,[15]) however, the absorption coefficients of ozone are dependent on the temperature, in such a way that the coefficients for wave-lengths near the maxima of the absorption curve are uneffected, but the coefficients for wave-lengths near the minima are appreciably diminished.

It is therefore evident that the choise of wave-lengths for use in the described optical method is extremely important. From the paper by Vassy it seems true that the absorption coefficient for the wave-lengths 3110 Å will not be influenced when the temperature is changed from + 20° to — 80° centigrade. For the wave-length 3300 Å, however, the absorbtion coefficient seems to be slightly dependent on temperature.

The systematic error in the computed ozone value due to the fact that we are using absorption coefficients for the ozone under normal pressure and temperature, will, however, probably not be greater than 0,005 cm.

Further it may be said that both seasonal and day to day changes in the mean temperature of the main ozone region, although they may amount to 20° centigrade, probably will only cause changes in the measured ozone value of the order 0,002 cm, which is less than the accuracy of the ozone determination.

Some doubt as to the validity of the ozone values found by this method was raised twenty years ago by O. Hoelper and F. Linke[16]) on the basis that the scattering coefficient of the atmosphere due to particles which are great compared to the wave-length of light, is dependent on the wave-length and that this effect must be taken into account in equation (3.2). Further, they pointed out that the observed changes in the intensity ratio of the two wave-lengths might be due to changes in the transparency of the troposphere instead of changes in the amount of ozone.

It must be admitted that the simple division of the scattering of light in the atmosphere into two types, according to whether the particles are greater or smaller than the wave-length of light, is an approximation which will not be in accordance with the true conditions in the atmosphere.

This question has been thoroughly discussed by K. R. Ramanathan and R. V. Karandikar[17]) and it seems beyond doubt that the approximations regarding the scattering of light in the atmosphere are fully justified for this purpose. At middle and high latitudes the simple formulae (3.3) can be used with sufficient accuracy and the special haze conditions at low latitudes can be accounted for by means of the additional reading of the two longest wave-lengths (3300 Å and 4450 Å).

The second objection was based on the relatively few ozone observations available twenty years ago. It should be sufficient to mention that the investigations in Tromsø*) have shown that the relation between the air mass (passage of fronts and following change in transparency) and the amount of ozone has a marked annual variation. In summer and autumn, for instance, we may observe great changes in the transparency of the troposphere, but no changes in the measured amount of ozone.

*) See p. 256 to 258 of paper cited No. 2.

[15]) E. Vassy: Sur quelque propriété de l'ozone et leurs conséquences géophysiques.
Thèses, Série A, No. 1695, Paris 1937.

[16]) Rapport de la Réunion de l'ozone et de l'absorption atmosphérique. Gerl. Beitr. z. Geophysik. Bd. 23 und 24, p. 16 und 17, 1929.

[17]) K. R. Ramanathan and R. V. Karandikar: Effects of Dust and Haze on Measurements of Atmospheric Ozone made with Dobson's Spectrophotometer.
Quart. Journ. Roy. Met. Soc. Vol. 75, No. 325, p. 257, 1949.

*) E. Tønsberg and K. Langlo (Olsen): loc. cit. (No. 4).

In summing up this discussion we should like to state that — with the reservations already made — the discussed optical method scarcely gives the exact true value of the total amount of ozone in the atmosphere.

If the observations at different places, however, are made with calibrated instruments of the same type and using the same figures in the formulae when accounting for the absorption and scattering in the atmosphere, the simultaneously found ozone values are supposed to give a suitable basis for estimating the horizontal distribution of the total amount of ozone. Further we conclude that the observed changes are due to real changes in the amount of ozone provided due regard is taken to the accuracy of the observations.

Accuracy of the Observations.

When discussing the observational data it is important to keep in mind the maximum possible uncertainty in a single ozone determination due to limited ability of the instrument to measure weak light intensities.

For a single measurement against the blue zenith sky in the middle of the day we are showing in table 1 the *maximum* error which should be considered at different seasons of the year in Tromsø*) and in Oslo.

Table 1. The estimated maximum error in a single ozone observation made against the blue zenith sky in the middle of the day at different seasons.

Period	O_3 unit 0.001 cm	
	Tromsø	Oslo
$^1/_1$—$^{14}/_1$	60	40
$^{15}/_1$—$^{31}/_1$	40	30
$^1/_2$—$^{28}/_2$	25	20
$^{21}/_5$—$^{31}/_5$	15	10
$^1/_6$—$^{30}/_9$	5	5
$^1/_{10}$—$^{24}/_{10}$	10	10
$^{25}/_{10}$—$^{31}/_{11}$	20	20
$^1/_{11}$—$^{30}/_{11}$	40	30
$^1/_{12}$—$^{31}/_{12}$	70	50

To these figures we have to add a possible uncertainty of 0,005 to 0,010 cm in the basic values (the direct sun observations) and further an eventual error in the cloud correction amounting to about 0,010 cm. The figures in table 1 are somewhat dependent on the sensitivity of the actual instruments. The spectrophotometer in Tromsø has usually been more sensitive than the instrument used in Oslo. It should be emphasized, however, that the single observations of ozone for the month of December in Tromsø are very inaccurate and great care should also be shown when using the present available monthly mean values for Tromsø for that month.

*) E. Tønsberg and K. Langlo (Olsen): loc cit. (No. 4).

IV. Variations from Year to Year in the Annual Mean Amount of Ozone.

It is well known that the annual mean ozone content may vary considerably from year to year. In fig. 1 we illustrate this fact by means of the observations from the stations Tromsø, Dombaas, and Arosa for the period 1939 to 1948.

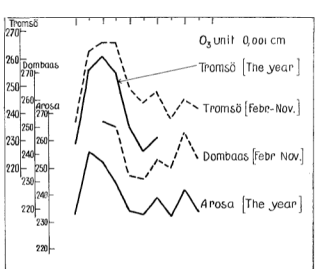

Fig. 1. Variations from year to year in the annual amount of atmospheric ozone at three stations in the northern hemisphere.

The annual mean is taken as the mean of the monthly mean ozone values. For Tromsø and Dombaas some of the months December and January are missing and therefore the means of the ten months February to November are used to illustrate the variations from year to year. (See appendix I and appendix II). The

points in parenthesis are less reliable than the others because one or two months are missing.

As will be seen from the figure, the changes in the annual mean at Tromsø may amount to 0.035 cm or about 15 % of the annual mean amount of ozone. Further, we may conclude from the figure that a marked parallelism exists between the changes at different stations. It may be noted that the rise in the annual mean ozone amount from 1939 to 1940 also was recorded at Zi-Ka-Wei, China (31°,1 N, 121° E Gr.)[18]) and that R. V. Karandikar[19]) found that the monthly mean ozone values at Delhi (28°,6 N, 77°,3 E Gr.) for the first three months of 1947 were markedly higher than for the corresponding months of 1946.

It should be remembered that the annual mean amount of ozone is largely dominated by the months with relatively high ozone values i. e., by the period January to May.

At first sight it seems reasonable that these world-wide changes from year to year must be due to changes in the radiation from the sun, but according to F. W. P. Götz[20]) no valid relation is established between the sunspot period and variations in the amount of ozone. As pointed out in chapter III the possibility of great changes in the ultraviolet radiation from the sun should not be excluded, but the established constancy of the fundamental constant $\log I_0/I_0'$ for the period concerned in fig. 1, at least indicates that the observed changes in ozone are not likely to be due to changes in the intensity ratio between the two wave-lengths outside the earth's atmosphere.

A second possibility is that variations in the ultraviolet radiation, which will not be discovered by checking the constant $\log I_0/I_0'$, will cause real changes in the equilibrium amount of atmospheric ozone. It seems difficult to understand, however, that such variations in the ultra-violet radiation from year to year are able to cause changes in the annual ozone amount of the order 0,035 cm in temperate latitudes but as far as we know no changes in equatorial regions.

The observations given in figure 1, support the idea that the whole ozone layer in the atmosphere cannot be in a state of photo-chemical equilibrium and that the changes from year to year may be due to variations in the annual amount of accumulated ozone which probably are closely related to changes in the meteorological conditions in the ozone incline region.*)

In order to explain the marked ozone changes occurring in the same year at wide-spread places in the northern hemisphere, it seems necessary to take into account the general circulation of the atmosphere. This point of view will be further developed in later chapters.

V. Variation with Latitude of the Amount of Ozone.

The first picture of the geographical distribution of ozone over the earth was given by G. M. B. Dobson[21]) by means of observations taken in different latitudes during the period 1927 to 1929. A revised representation of the amount of ozone as a function of latitude and season has been worked out by F. W. P. Götz.[22]) Considering the great changes in the ozone content from year to year, shown in fig. 1, it seems difficult to achieve a reliable and detailed picture of the distribution of ozone with latitude if we have to compare ozone values originating from different years. In this chapter we intend to give a new analysis of the variation with latitude of the ozone amount for individual years and for a period of years by means

[18]) M. Burgaud et Kiong Wei-zen. Notes de Météorologie physique, Fasc. X, Vapeur d'eau, trouble atmosphérique, ozone, radiation solaire, 1937—1944, p. 30, Shanghai 1948.

[19]) R. V. Karandikar. Studies in Atmospheric Ozone, Part II. Proc. Ind. Acad. Sci. Vol. XXVIII. p. 72. 1948.

[20]) F. W. P. Gotz und Werner Zünti. Die Aroser Ozonreihe. Conference on Atmospheric Ozone, Quart. Journ. Roy. Met. Soc. Suppl. Vol. 62, p. 73, 1936, and loc. cit. (No. 2).

*) The ozone incline region is defined as that part of the atmosphere were the amount of ozone normally increases with height (roughly between 10 and 25 km).

[21]) G. M. B. Dobson. Part IV (With Reports by H. H. Kimball and E. Kidson). Proc. Roy. Soc. A. Vol. 129, p. 411, 1930.

[22]) F. W. P. Götz: Der Stand des Ozon-problems. Vierteljahrsschrift der Naturforschende Ges. Zürich. 89, 1944.

of the greater observational data now available. In addition to the ten years' records from the stations Tromsø, Dombaas (or Oslo) and Arosa and the eight years' records from Aarhus, mentioned in chapter II, we have used the ozone observations from the following stations:

Table Mountain, California,
34,°4 N, 117,7° W Gr. (1928—29)*)
Zi-Ka-Wei, Shanghai, China,
31,°1 N, 121° E Gr. (1932—42)[23][24]**)
Helwan, Egypt, 29,°8 N, 31,2° E Gr. (1928—29)***)
Delhi, India, 28,°6 N, 77,°3' E Gr. (1945—47)***)
Bombay, India, 18,°9 N, 72,°9 E Gr. (1936—38)***)
Kodaikanal, India,
10,°2 N, 77,°5 E Gr. (1928—29)***).

Besides the geographical position of the stations the figures in brackets indicate the periods for which ozone observations are available. It may be noted that the stations Table Mountain, Zi-Ka-Wei, Helwan, Bombay and Kodaikanal have used Dobson's "old" spectrograph and therefore the ozone amount is only measured on days with a visible sun. The observations from Zi-Ka-Wei originate from selected days with an atmosphere as far as possible free from dust and clouds. A summary of the Zi-Ka-Wei ozone-values is given in appendix IV.

The monthly mean ozone values for Table Mountain, Helwan, Bombay and Kodaikanal are all reduced by 12 per cent in order to make them comparable with the other observations, because the original calculations of the ozone content for these stations are based on other values of the absorption coefficients of ozone than are used at the other stations.

The monthly mean ozone values for Delhi are lifted 0,010 cm partly because the slightly different ozone-formulae used at that station gives ozone values which on an average are some 0,003 cm lower than the values obtained with formulae (3.3), Chapter III, and partly because the optical wedge of the instrument used at Delhi has been recalibrated.*)

In fig. 2 we have tried to illustrate the mean distribution with latitude of the annual amount of ozone in the northern hemisphere.

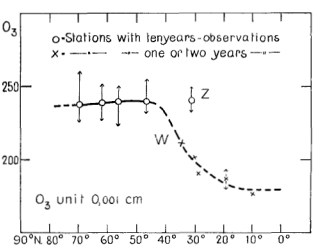

Fig. 2. The mean annual distribution of ozone with latitude in the northern hemisphere. The curve *W* gives the approximate variation along the west side of the continents. *Z* stands for the station Zi-Ka-Wei, Shanghai. The points of the arrows indicate the greatest and smallest observed values of the annual mean ozone value during a 10 year period.

Remembering the geographical positions of the stations we find it justified to draw a smooth curve through the stations situated on the west side of the continents including also the stations in lower latitudes where the variations from year to year are small. The only station falling outside this curve (*W*, fig. 2) is the Observatory Zi-Ka-Wei at Shanghai which is situated on the east coast of the continent. Considering the fact that the point in fig. 2 representing Zi-Ka-Wei (*Z*) is based on eleven years observations, we find it reasonable to assume that the annual amount of ozone probably is greater on the east side of the continent than on the west, at least around 30° N. More observations are, however, desired to check this assumption.

From the figure we may draw the conclusion that for a certain period the mean annual amount of ozone is remarkably constant between 70° and 45° N. More observations are, however, desired to check this assumption.

*) G. M. B. Dobson: loc. cit. (No. 21).

[23]) R. P. Pierre Lejay: Mesures de la quantité d'Ozone contenue dans l'atmosphère. Janvier 1932—Décembre 1933. Notes de météorologie physique. Fasc. III, Zi-Ka-Wei, Shanghai.

[24]) R. P. Pierre Lejay: Mesures de la quantité d'Ozone contenue dans l'atmosphère à l'Observatoire de Zô-sè. 1934—1936. Notes de météorologie physique, Fasc. VII, Shanghai 1937.

**) M. Burgaud et Kiong Wei-zen: loc. cit. (No. 18).

***) R. V. Karandikar: loc. cit. (No. 19).

*) R. V. Karandikar: loc. cit. (No. 19).

more uncertain but it seems probable that a relatively rapid fall in the annual amount of ozone must take place somewhere between 45° and 25° N., depending on the longitude. It should be noted that this zone approximately coincides with the transition zone between the region with a relatively low polar tropopause and the region with a relatively high tropical tropopause. Besides the very interesting task to obtain reliable ozone-measurements from the Polar Region farther north than 70° N, especially during the winter season, it would be worth while to investigate the synoptic variations in the ozone amount at some stations situated between 45° and 25° N on the west side of a continent and some in the same latitude at the east side of the same continent. Between 25° N and equator the variation in ozone seems to be very small.

In figure 2 we have indicated by means of arrows the observed maximum deviations from the given mean curve for some of the stations. The points of the arrows indicate the greatest or smallest annual mean ozone amount at the station for the periods given at the beginning of this chapter.

In fig. 3 the full or broken smoothed curves give a similar illustration of the mean distribution with latitude for each month of the year. The actual distribution for individual years is indicated by the points of the arrows and the thin broken lines between them.

Comparing fig. 3 with the curves given by G. M. B. Dobson*) and F. W. P. Götz**) we may firstly draw attention to the observed but partly uncertain low mean ozone values in high latitudes during the period August to January and, secondly, to the occurrence of a slight secondary maximum between 40° and 50° N. When considering the possibility of an appreciable variation in the mean ozone amount with longitude this last result should not necessarily be taken as representative for the distribution with latitude in other parts of the world.

As seen from figure 3, the values representing Zi-Ka-Wei (*Z*) are higher than the values found in higher latitudes during the period

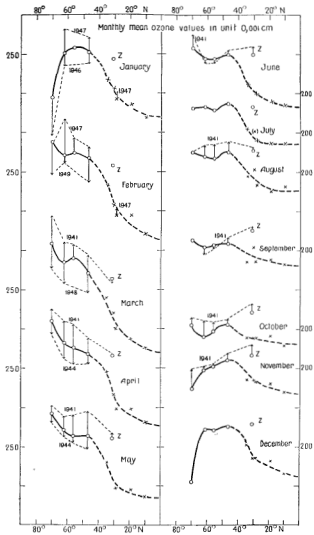

Fig. 3. The mean distribution of ozone with latitude for each month of the year. *Z* stands for the station Zi-Ka-Wei, Shanghai. The observed variation with latitude for some selected months are indicated by the thin broken lines through the points of the arrows.

September to December. This might indicate that all the values from Zi-Ka-Wei are somewhat too high. If, however, the Zi-Ka-Wei values are corrected down to the level of the stations in higher latitudes during this period, they will still for most months of the year be appreciably higher than the values representing Egypt and India in the same latitude as Zi-Ka-Wei.

The mean ozone content for selected months illustrated in figure 3, give, as a whole, a similar picture as shown in figure 1 for the annual amount of ozone. For instance, during the ab-

*) G. M. Dobson: loc. cit. (No. 21).
**) F. W. P. Gotz: loc. cit. (No. 22).

normal cold winter and spring of 1941, very high ozone values were observed at the high and middle latitude stations. For the discussion in the later chapters it is important to bear in mind that a very high ozone gradient normally exists between high and low latitudes in the period February to May. On the other hand, only small differences in the monthly mean amount of ozone are found in high and middle latitudes during the summer and autumn. In September and October the average variation with latitude between 70° N and the equator is remarkably small.

As mentioned in chapter IV, some observations indicate a probable relation between ozone changes in middle and low latitudes but the available material is very scanty and no safe conclusions can be drawn at the present time.

Figure 3 illustrates, for instance, that the monthly mean ozone amount at Zi-Ka-Wei (31° N) for March 1941 was slightly lower than the normal value for the month in question and April was only 0.002 cm higher than the "normal". During the rest of the year the monthly mean ozone values for Zi-Ka-Wei were permanently higher than the "normal" and with the greatest deviations in June and November.

According to G. M. B. Dobson*) and others the distribution of ozone with latitude may be regarded as the main cause of the relatively high temperatures found in the ozone incline region in middle and high latitudes compared with the temperatures in the same region at the equator.

Dobson assumes that on an average for a year there is about 0,130 cm more ozone at 60°—70° N than over the equatorial regions, and that the annual mean temperature in the lower stratosphere (the level not specified) is about 30° centigrade higher at 60°—70° N than at the equator. From fig. 2, however, it follows that on an average there is probably only about 0.060 cm more ozone at 60°—70° N than at the equator and that if the mentioned hypothesis is correct 0,002 cm ozone would be sufficient to cause an increased temperature of 1° centigrade. As realized by Dobson we have here neglected a probable difference between the amount of water vapour in the ozone incline region at 60°—70° N and at the equator. Further the actual distribution of ozone with height in the atmosphere has not been taken into account in the discussion.

An important argument against the suggested explanation of the observed horizontal temperature gradient in the ozone incline region must be the fact that the annual mean temperature in this region at 60°—70° N is not subject to such great variations from year to year as should be expected from the observed variations in ozone according to figure 1. If the ozone amount is some 0,035 cm higher in a maximum-year than in a minimum-year, we should expect that the temperature in the ozone incline region above a certain place should be some 17° centigrade higher in the first case than in the second. This is very far from the observed changes in the annual mean temperature for a certain level in the lower stratosphere at 60°—70° N.

It seems therefore unlikely that the increase in temperature in the ozone incline region when passing from the equator to the poles is due to the variation with latitude in the amount of atmospheric ozone.

Any complete theory of the ozone layer in the atmosphere must explain the fact that the distribution of ozone with latitude is very irregular and subjected to marked changes from year to year. Further the possibility must be taken into account that the amount of ozone may be dependent on the longitude.

Considering that the irregular shapes of the distribution curves found are based on long series of observations, it seems difficult to explain this distribution by a simple theory assuming the whole ozone layer to be in a state of photo-chemical equilibrium.

The modified photo-chemical theory by H. U. Dütsch*) gives a distribution with latitude which, however, is not fully in accordance with the observed variation given in fig. 2 and 3 of this paper.

*) G. M. B. Dobson with A. W. Brewer and B. M. Cwilong: loc. cit. (No. 5).

*) H. U. Dütsch: loc. cit. (No. 6).

The additional assumptions which must be made to bring the photo-chemical theory in agreement with the observations, will be further discussed in chapter X.

VI. The Annual Period in the Amount of Ozone.

The atmospheric ozone has a well established annual period with a maximum in spring in both hemispheres and a minimum in autumn. In high latitudes the annual variation is remarkably greater than in lower latitudes as will be seen from figure 4.

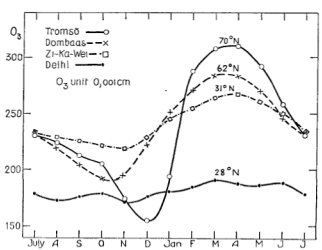

Fig. 4. The mean annual variation in ozone at four stations in the northern hemisphere based on long series of observations.

In this figure we illustrate the smoothed, mean annual variation at the following four different places in the northern hemisphere: Tromsø (period 1940—49), Dombaas (period 1940—49), Zi-Ka-Wei (period 1932—42) and Delhi (period 1945—47)*).

Having in mind the geographical positions of the four stations we should like to draw attention to the observed but very uncertain low mean ozone values at 70° N from November to January and to the marked difference between the curves for the two stations Zi-Ka-Wei and Delhi, situated in approximately the same latitude.

The annual period in the amount of ozone has been one of the strongest arguments in favour of a photo-chemical equilibrium theory for the ozone layer.*) If the given results from Zi-Ka-Wei and Delhi are verified by further measurements, however, they will strongly support the idea that the annual period mainly is dominated by the seasonal variations in the meteorological conditions in the ozone incline region for the stations in question.

Further, if the total amount of ozone in the atmosphere were mainly dependent on the intensity and duration of the incoming ultraviolet radiation from the sun, we should expect that the rapid increase in the amount of ozone in the winter season at middle and high latitudes should occur approximately at the same time

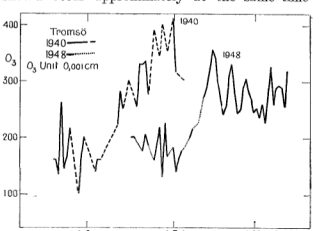

Fig. 5. Illustrating that the great seasonal rise in the amount of ozone at Tromsø occurred around one month later in 1948 than in 1940.

each year. It will be seen from figure 5, however, that this is not in accordance with the observations. As illustrated in the figure the approximate starting point for the great seasonal rise in the amount of ozone at Tromsø may be displaced as much as one month when comparing different years. At Dombaas and Oslo the seasonal increase may occur so early as at the end of December or so late as at the end of February. An approximate simultaneous seasonal rise at Tromsø and Oslo has also been observed, for instance, 1st to 14th February 1947 and 7th to 11th February 1949.

These observations also support the opinion that the annual period in the amount of ozone

*) For the geographical positions of the stations see chapters II and V.

*) See for instance: H. U. Dütsch: loc. cit. (No. 6).

must be chiefly dominated by changes in the meteorological conditions in the ozone incline region and not only by seasonal variation in radiation from the sun.

A more detailed illustration of the ozone variations in high latitudes during the interesting period November to January is given in fig. 6.

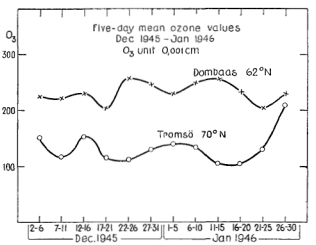

Fig. 6. The smoothed variation in ozone at 62° and 70° N during the darkest season of the year illustrated by means of five-day mean ozone values.

Due to the inaccurate ozone values from Tromsø during the darkest period, we have used five-day mean ozone values to characterize the possible ozone variations. The distance between the two stations Tromsø and Dombaas is around 1000 km.

As seen from the figure, a very high ozone gradient seems to exist between 62° N and 70° N during mid-winter. As far as may be judged from the present unsatisfactory observations, however, there seems to be no direct relation between the ozone changes at the two stations during the period of extra low ozone values at Tromsø.

It may be noted that such an isolated region of low ozone content over the North Pole and down to around 65° N during mid-winter, will be in good agreement with the opinion that the polar stratosphere is relatively stagnant during this period and consequently appreciably cooled by radiation down to the observed temperatures of — 60° to — 80° C. On the other hand, the observed phenomenon may also be due to inaccuracies in the Tromsø-values for the darkest period.

Before attempting to draw any safe conclusions with regard to the causes of the peculiar ozone variations in high latitudes, it seems wise to wait for the results of some years simultaneous ozone measurements at Tromsø and Spitsbergen with the improved Dobson spectrophotometer.

VII. Studies of the Horizontal Transport (Advection) of Ozone in the Atmosphere and Related Problems.

The advection of air with different ozone content has long been regarded as an important cause of ozone variations but very little is known about how this transport of ozone actually takes place. During a period of hours or from day to day a recorded change in ozone content may be due to a simple advection of air from a region with ozone content different from that above the observing place. During periods of weeks or months, however, the recorded long period ozone variation may be regarded as a result of a large-scale horizontal "Austausch" between areas with high and low ozone contents. For a station at temperate latitude this "Austausch" will be caused by the different ozone contents in the air-masses connected to the moving polar front cyclones and also by the large-scale advection of air-masses directed by relatively stagnant pressure systems. Both these effects forms a part of the term "general circulation" of the atmosphere and it is our first aim in this chapter to study the effect of this circulation on the long-period ozone variations.

Of the numerous papers on the general circulation in the atmosphere we will just mention a work by "Staff Members of the University of Chicago[25]) and a short rewiew given by J. van Mieghem.[26]) Other interesting information

[25]) Staff Members of the Department of Meteorology of the University of Chicago. On the General Circulation of the Atmosphere in Middle Latitudes. Bull. Am. Met. Soc. Vol 28, No. 6, June 1947.

[26]) J. van Mieghem: Progrès récents en aérologie synoptique. Extrait de bulletn "Ciel et Terre" de la Société belge d'astronomie, de météorologie et de physique du Globe, Bruxelles, No. 1—2, 1950.

about the winds in the lower stratosphere is found in a book by R. Scherhag.[27])

C. E. P. Brooks and collaborators[28]) have published charts of upper winds over the world by means of the two parameters, the vector mean wind V_r and the standard vector deviation σ of the individual winds about the vector mean. These charts are given for each of the four seasons for different pressure levels up to 130 mb (around 16 km).

In order to illustrate the actually observed winds in the ozone incline region in a suitable latitude and at a time for which ozone observations are available, we have extracted some data from one year's continuous radar wind observations made at the Ocean Weather Station "*M*" (66° N, 02° E Gr.).

The upper wind observations made at Lerwick (60,2° N, 1,1° W Gr.) and at Stockholm (59,3° N, 17,9° E Gr.) for the same period have also been studied, but the observations from the highest levels for these stations are more scanty than for station "*M*". Because of the lack of high level radiosondeobservations we have found it difficult to draw trajectories in pressure surfaces up to 100 mb as would be desirable in order to study the true air flow in the ozone incline region.

On the basis of our present knowledge about the general circulation in the atmosphere, we should like, however, to put forward some suggestions regarding the effect of this circulation on the horizontal distribution of ozone.

It will be seen from tables 2 and 3 that

Table 2. Some results of one year radar wind measurements at Ocean Weather Station "M". The figures are mean values for the 15000 meter level. n is the number of observations.

Station "M" 66° N, 02° E Radar wind 15000 meter level	n	Monthly Scalar mean wind speed V_s Knots	Magnitude of vector mean wind speed V_r Knots	Vector mean direction in degrees	Steadiness (Constancy) in per cent $\frac{V_r}{V_s} \cdot 100$	West-east component V_x Knots	South-north component V_y Knots
January 1949	39	81,0	70	282	87	68	—14
February 1949	37	59,8	52	265	87	52	5
March 1949	36	49,8	42	291	85	39	— 15
April 1949	55	44,5	38	259	86	37	7
May 1949	43	17,4	8	226	46	6	6
June 1949	53	14,5	5	295	35	5	— 2
July 1949	41	14,4	10	286	69	10	— 3
August 1949	58	24,7	21	248	85	20	8
September 1949	56	25,5	20	252	79	19	6
October 1948	51	31,4	28	276	89	28	— 3
November 1948	36	40,8	36	287	88	35	—10
December 1948	52	43,2	36	259	83	35	7

The monthly mean values given in table 2 are based on the special radar wind ascents which were made twice a day. The obtained annual mean top height for these ascents was around 15000 meters and therefore we believe that the monthly mean values for the 15000 meter level may be regarded as fairly representative; similar data for the 18000 meter level are given in table 3.

above a certain place at 66° N the steadiness*) of the wind in the lower stratosphere in remarkably high during the winter season October to March and much less during the summer months.

Further it may be deduced from the tables that the zonal component of the monthly vector mean wind speed is appreciably greater than the meridional component during the winter and spring. It should be noted, however, that the

[27]) Richard Scherhag: Neue Methoden der Wetteranalyse und Wetterprognose, Berlin 1948.

[28]) C. E. P. Brooks, C. S. Durst, N. Carruthers, D. Dewar and J. S. Sawyer: Upper Winds over the World. Geophysical Memoirs No. 85, London 1950.

*) Steadiness is defined as the ratio percentage between the magnitude of vector mean wind speed and the scalar mean wind speed.

Table 3. Some results of one year radar wind measurements at Ocean Weather Station "M". The figures are mean values for the 18000 meter level. n is the number of observations.

Station "M" 66° N, 02° E Radar wind 18000 meter level	n	Monthly Scalar mean wind speed V_s Knots	Magnitude of vector mean wind speed V_r Knots	Vector mean direction in degrees	Steadiness (Constancy) in per cent $100 \cdot \frac{V_r}{V_s}$	West-east component V_x Knots	South-north component V_y Knots
January 1949	11	81,7	73	265	89	73	6
February 1949	22	67,8	61	269	90	61	0,5
March 1949	9	57,4	52	285	91	50	—14
April 1949	43	38,5	32	257	83	31	7
May 1949	27	8,9	3	190	34	1	4
June 1949	46	10,0	1	137	10	— 0,5	1
July 1949	25	5,2	4	264	77	4	0,5
August 1949	51	15,1	12	250	80	11	4
September 1949	45	16,5	13	266	79	13	1
October 1948	16	31,3	28	280	90	28	— 5
November 1948	15	33,8	31	294	89	28	—13
December 1948	28	39,2	35	265	89	35	3

Table 4. A comparison between the monthly mean ozone values in three different latitudes and the vector mean wind speed in 15000 meters level at 66° N.

Month	Monthly mean ozone values in unit 0,001 cm.					Vector mean wind speed in knots	
	Year etc.	Tromsø 70° N	Oslo 60° N	Arosa 47° N	30° N	15000 m level 66° N	Year etc.
January	1949	No obs.	240	236		70	1949
	Ten year normal		251	252	200	30	Normal
	Percentage of normal		96 %	94 %		233 %	Percentage of normal
February	1949	245	261	258		52	1949
	Ten year normal	288	270	267	207	30	Normal
	Percentage of normal	85 %	97 %	97 %		173 %	Percentage of normal
March	1949	271	261	267		42	1949
	Ten year normal	308	284	271	210	28	Normal
	Percentage of normal	88 %	95 %	99 %		150 %	Percentage of normal
April	1949	309	277	253		38	1949
	Ten year normal	310	282	268	216	27	Normal
	Percentage of normal	100 %	98 %	94 %		141 %	Percentage of normal
May	1949	301	No. obs.	262		8	1949
	Ten year normal	292	271	263	207	24	Normal
	Percentage of normal	103 %		100 %		33 %	Percentage of normal

winter 1948 to 1949 was a period with exceptionally strong upper winds which is illustrated by the figures in table 4.

To the right in this table we have computed for the period January—May 1949 the deviations from the "normal" monthly vector mean wind speeds based on the mean charts of contour lines in the 130 mb surface printed in the paper by C. E. P. Brooks and collaborators.*)

To the left in table 4 is given the monthly mean ozone values in four different latitudes, the corresponding mean values for a ten year period and the actual value in percentage of the "normal". Although the used "normal" values of the monthly vector mean wind speed are somewhat uncertain, it cannot be doubted that the observed monthly means for January and February and perhaps also for March and April 1949, were appreciably greater than usual. According to table 4 relatively low mean ozone values were observed in middle and high latitudes during the same period. It may be mentioned, for instance, that the monthly mean ozone value for Oslo for March 1949 was the lowest mean value for the month March observed during the period 1940 to 1949. Judging from the remarkably mild weather which dominated the winter and spring of 1949 in North-Western Europe, it seems reasonable to assume that the strong westerlies in the ozone incline region on an average for a month have carried more air with low ozone content from middle latitudes (around 45° N) towards higher latitudes than normally is the case. On the other hand, it is difficult to explain in this way that the observed negative ozone-deviations may be greater at 70° N than at 60° N (Table 4, February and March). Therefore we will suggest that an abnormally strong zonal circulation between 50° and 70° N in the ozone incline region in winter and spring to some degree may prevent the normal formation of ozone in this region.

It should be realized that the observed deviation of the monthly mean ozone values from the "normal" values during periods of strong zonal circulation, for instance, the deviation of magnitude 0,023 cm at Oslo for March 1949 represents about 25 per cent of the total annual amplitude. Therefore, we have reason to believe that the seasonal changes in the pattern of the general circulation in the atmosphere must be of importance for the seasonal changes in the distribution of ozone with latitude.

According to tables 2 and 3 the steadiness of the wind in 15000 and 18000 meters level in a latitude with a great amount of ozone, decreases rapidly from April to May and June in good agreement with the marked fall in the amount of ozone at this time of the year. During the summer and early autumn the zonal circulation often breaks down into horizontal cells with a resulting greater possibility for the tropical air masses to be transported to higher latitudes than during the winter and spring.

Thus we suggest that the main effect of the general circulation in the ozone incline region during the late spring and summer, will be to reduce the total amount of ozone in middle and high latitudes. The ozone which is carried southwards from higher latitudes and happens to reach lower latitudes than around 45° N is assumed to be relatively rapidly decomposed by chemical actions in the ozone incline region or in the troposphere due to the presence of dust and water droplets.

Turning now to the question whether or not the advection of air with different ozone content alone can explain the rapid day to day variations in ozone, we will first study the mean horizontal distribution of ozone in zonal and meridional direction.

For this purpose we have used the simultaneous observations of the total amount of ozone above the stations Lerwick, Dombaas and Tromsø*) for the period March to September 1942. The distance between Lerwick and Dombaas is around 600 km and between Dombaas and Tromsø approx. 1000 km. For each month we have computed the mean "ozone gradient" pr. 100 km in the two directions and disregarded the sign of the gradient. The results are given in table 5.

The table indicates the interesting result that the mean zonal "gradient" of the total ozone amount is greater than the meridional "gradient" in 5 of 7 months and, as a whole, the mean "ozone-gradients" are of about the

*) C. E. P. Brooks, C S. Durst, N. Carruthers, D Dewar, and J. S. Sawyer: loc. cit. (No. 28).

*) For the locations of the station see chapter II.

Table 5. The mean "ozone-gradient" in zonal and meridional direction. Unit 0.001 cm pr. 100 km.

Direction of "ozone-gradient"	March	April	May	June	July	August	September
Zonal	5,5	4,7	3,0	2,9	2,7	2,8	4,0
Meridional	6,4	4,3	4,3	1,6	1,3	1,5	2,7

same order of magnitude in the two directions.

Remembering the statement above that the zonal component of the monthly vector mean wind speed is appreciably greater than the meridional component, especially in winter, it seems justifiable to stress the importance of the actual zonal distribution of ozone for the day to day changes in the amount of ozone caused by advection. It may further be of interest to study the mean distribution of ozone with latitude compared with the observed ozone variations at a certain place.

frontal cyclones and these variations will be discussed in the next chapter.

As to the variation of wind speed with height in the lower part of the main ozone layer it may be said that the wind speed usually has a maximum near the tropopause and decreases upwards to, let us say, 20 to 25 km. Higher up it usually increases again to higher values than at the tropopause or the wind speed may also increase steadily upwards above the tropopause.

This picture is confirmed by the results given in figure 7 originating from radar wind

Table 6. The mean meridional distribution of ozone compared with the maximum 24 hours change in ozone at 62° N.

Ten year mean ozone values O_3 Unit 0,001 cm	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct	Nov.	Dec.
Diff. Tromsø–Dombaas (ca.1000 km)	— 57	18	24	28	21	13	— 1	5	9	13	— 23	— 67
Diff. Dombaas-Arosa (ca 1700 km)	— 1	3	13	14	8	— 5	— 5	— 6	— 5	— 14	— 13	— 4
Max 24 hours change at Dombaas	70	50	55	70	45	35	50	35	40	40	45	75

In table 6 the differences are given between the monthly mean ozone values at Tromsø and Dombaas and also those between Dombaas and Arosa compared with the observed maximum variation in ozone at Dombaas during 24 hours. These last figures represent the average of the maximum ozone variation during 24 hours measured each year of a ten-year period.

It seems evident that the mean variation of ozone with latitude is quite insufficient to explain the day to day changes in the amount of ozone. Although a number of cases with greater or smaller ozone variation with latitude than that given in table 6 certainly occur, we believe that the actual zonal distribution of ozone will be of greater importance for the day to day changes in ozone than will the meridional distribution.

The most marked irregular changes in the amount of ozone occur during the passage of

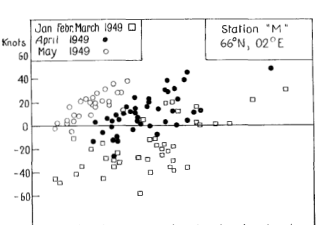

Fig. 7. The difference between the scalar wind speed at 12000 and at 18000 meters plotted against the scalar wind speed at 12000 meters.

observations made at Ocean Weather Station "M". Here we have plotted individual measurements of the difference between the scalar wind speed

at the 12000 meter level and the 18000 meter against the scalar wind speed at the 12000 meter level.

The figure indicates that in 70 % of all available cases in the given periods the wind speed at 18000 meter was deviating more than 10 knots from the wind speed at 12000 meter and that the wind speed at 18000 meter may be 40 knots greater or smaller than the wind speed at 12000 meter.

This picture of the variation of wind speed with height in the ozone incline region may be of importance for the ozone changes caused by advection. It has been suggested*) that the irregular ozone variations may be explained as mainly due to changes in the accumulated ozone which we may assume to be situated between 10 and 20 km. If a great amount of accumulated ozone normally is situated lower down in the atmosphere than a small amount, we have to take into account that the advection of air masses in the ozone incline region may cause overlapping of accumulated ozone layers. In this way greater ozone changes may be recorded than would be expected from the total amount of ozone. A study of the relative importance of the different possible causes of the day to day ozone changes, will be made in the next chapter.

VIII. Studies of the Irregular Ozone Variations and their Relation to the Topography of the Tropopause and to the Passage of Air Mass Fronts.

In order to investigate the effects of marked, fast moving tropopause troughs on the amount of ozone, we have studied the maps of contour lines of height of tropopause printed in "Daily Aerological Record" of the Meteorological Office, London, for the years 1947, 48 and 49. From these maps we have selected all cases (48 in all) with simultaneously made ozone observations at Oslo and at Tromsø, where the actual position of the centre of the tropopause trough at the hour the ozone observations were made could be found with sufficient accuracy, and where the ozone content at Tromsø was less or equal to the ozone amount at Oslo.

*) R. V. Karandikar and K. R. Ramanathan: loc. cit. (No. 7).

The result is given in figure 8 where we have plotted the ozone deviation from the smoothed annual curve against the actual distance

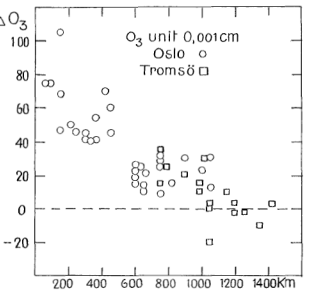

Fig. 8. Ozone deviations from the smoothed annual curve plotted against the corresponding horizontal distances to the centre of the tropopause trough at the moment the ozone content was observed.

between the ozone observing station and the centre of the tropopause trough on the map.

A simple advection of air with higher ozone content from higher latitudes may here be excluded as the main cause of the high ozone values judged from the observations at Tromsø. We will regard this figure as a strong support for the hypothesis put forward by E. Palmén in 1939*) and conclude that the rise in ozone content must be due to descending motions of the air combined with a convergence in the lower stratosphere.

The highest ozone values during the passage of a polar front cyclone is found near the centre of the tropopause trough belonging to the cyclone, if such a marked trough exists.

It has been shown**) that in the period February to May a marked correlation exists between the amount of ozone and the position of the front-surfaces belonging to well developed, moving polar front cyclones. Because of the approximations used when plotting the observations on figs. 18 and 19 of the paper cited it

*) E. Palmén: loc. cit. (No. 3.)

**) E. Tonsberg and K. Langlo (Olsen): loc. cit. (No. 4).

was not possible, however, to decide whether the amount of ozone had a maximum somewhere behind the cold front, indicating that other processes than pure horizontal advection must be present, or the high ozone values were distributed in such a way that they might be caused solely by advection of air with higher ozone content.

We have just shown that such a maximum of ozone very probably exists near the centre of a closed and moving tropopause trough connected to a polar front cyclone. Three individual cases are discussed below.

Case 1. 9th to 11th March 1948.
Fig. 9 and fig. 10.

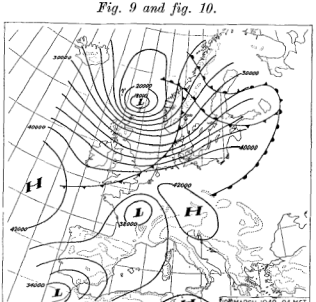

Fig. 9. The topography of the tropopause (heights in feet) and the position of the fronts on the surface map at 04 MET 10th of March 1948.

Fig. 9 gives the topography of the tropopause (contour lines in feet a. s. l.) and the position of the surface fronts at 04 MET, 10th March 1948. A cold front is situated just west of Oslo and has a deep and fast moving tropopause trough in the rear.

In fig. 10 we have illustrated the observed changes in total ozone and air pressure at Oslo and also indicated the variation of the height of tropopause above Gardermoen (60 km North of Oslo). For comparison the observed heights of tropopause the 10th of March above Sola

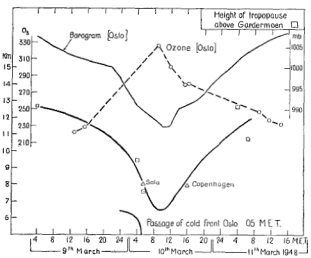

Fig. 10. The variations in sea level pressure, the total amount of ozone and the height of the tropopause from 9th to 11th of March 1948.

and Copenhagen are also included. It should be noted that the ozone content above Tromsø (70° N) retained a relatively steady value around 0,290 cm during the three days in question.

According to figure 10 we may assume that the great rise in ozone between the 9th and the 10th of March above Oslo is related to the passage of the marked tropopause depression. The first measurement of ozone on the 10th of March was made at $8^h\ 54^m$ MET but the exact hour for the occurrence of the ozone maximum is not known. It may be concluded, however, that the maximum of ozone probably occurred a few hours before the passage of the tropopause trough.

The centre of the tropopause depression moved with an approximate speed of 60 knots. If the high ozone amount were caused by accumulation of ozone in the ozone incline region due to a downward motion of air combined with a horizontal convergence, say some 900 kilometers west of Oslo, we may assume that this accumulated ozone has been transported eastward at an appreciably greater speed than that of the tropopause trough. Judging from the observations of upper winds at Lerwick on the 10th of March, we may estimate the wind speed in the ozone incline region above Lerwick to around 90 knots and from a direction between 270 and 300 degrees. According to this

rough estimate, the maximum of ozone should be recorded at Oslo around three hours *before* the passage of the tropopause depression.

From the earlier investigations at Tromsø*) it seems true that the rise in the amount of ozone may occur some hours before the passage of the cold front at the surface. This result has been confirmed by further studies, for instance the front passages at Oslo on 14th of April 1947 and on 1st of April 1948 which are not dealt with here.

By studying the upper air charts from 9th and 10th of March 1948 (Case 1) no support can be found for the idea that the great rise in the ozone content above Oslo between the mentioned days can be caused by pure advection of air from higher latitudes. It seems justifiable to regard these facts as an argument in favour of the opinion that the high ozone values in the rear of a cold front are mainly dependent on a descending motion of the air combined with a horizontal convergence. This descending motion seems to occur in connection with a marked tropopause trough, and in this case with an approximately west-east transport of the accumulated ozone.

If the observed ozone content at Tromsø (0,290 cm) can be regarded as representing the maximum value which in this case could be reached at Oslo by pure advection of air from higher latitudes, we may conclude, according to figure 10, that the magnitude of the vertical motion effect must lay somewhere between 0,040 and 0,100 cm.

Case 2. 20th March 1948. Fig. 11 and fig. 12.

Fig. 11 shows, as in case 1, the contour lines of the tropopause and the position of the fronts on the surface map. At 04 MET an occlusion is situated to the east of Oslo and a cold front is approaching from west. The height of the tropopause decreases northwards from the high pressure area above Northern France but no marked tropopause trough is present.

As seen from figure 12 the amount of ozone above Oslo is practically uneffected by the passage of the marked cold front but, on the other hand, no changes in the height of the tropopause has been recorded above Gardermoen and Sola in Southern Norway. The observations at Tromsø show a rise in the amount of ozone from around 0,274 cm on the 19th to around 0,304 cm on the 20th of March.

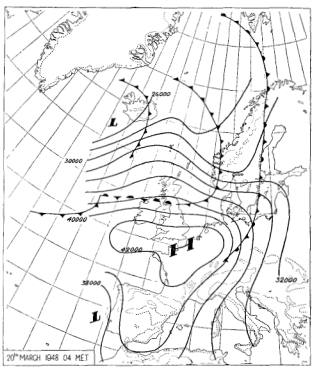

Fig. 11. The topography of the tropopause (heights in feet) and the position of the fronts on the surface map at 04 MET 20th of March 1948.

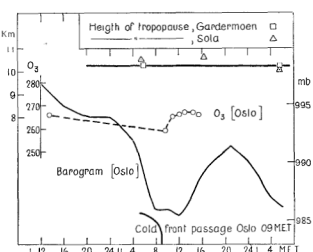

Fig. 12. The variations in the height of the tropopause, the total amount of ozone and the sea level pressure on the 19th and 20th of March 1948.

*) E. Tønsberg and K. Langlo (Olsen): loc. cit. (No. 4).

We believe that the observed constancy of the ozone content above Oslo during the cold front passage primarily must be due to the lack of any descending motion of the air in the ozone incline region, and, secondly, to the fact that the higher ozone content north of Oslo on the 20th of March could not be transported appreciably southwards because of the direction of the upper air flow.

Further we should like to point out that according to figures 10 and 12 it is difficult to believe in any firm correlation between the amount of ozone and the pressure variations at the earth's surface as found by H. Johansen.[29]) This positive correlation may be high for a selected, short period but in individual cases the changes in surface pressure may be quite dominated by processes which do not cause any changes in the amount of ozone. An increase in the surface pressure may also occur simultaneously with a fall in the amount of ozone.

Case 3. 21st to 22nd April 1949. Fig. 13.

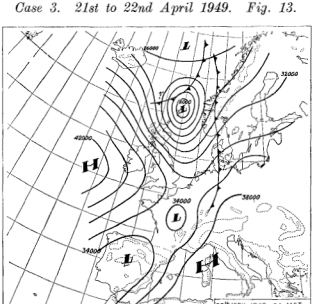

Fig. 13. The topography of the tropopause (heights in feet) and the position of the fronts on the surface map at 04 MET 22nd of April 1949.

The weather situation is illustrated by figure 13, which shows the topography of the tropopause and the position of the surface fronts at 04 MET, 22nd April 1949.

The cold front to the right on the map passed Oslo at 07^h and the next and faster moving cold front reached Oslo at around 14^h. It is difficult to trace the motion of the marked tropopause depression but it presumably moved eastward with approximately the same speed as the second cold front and made the tropopause very low above Oslo around noon. The ozone amount above Oslo at around 13^h rose from 0,276 the 21st to 0,352 cm the 22nd. At Tromsø, however, the variations in the amount of ozone were small, only from 0,309 to 0,324 cm on the 21st and from 0,319 to 0,325 cm on the 22nd.

Judging from the 300 mb chart and the radar wind measurements at Station "M", Lerwick and Stockholm, there are no reasons to believe that any appreciable transport of air from higher latitudes have taken place during the days in question. For illustration an extract of the radar wind measurements from the cited three stations are given in table 7.

We are left with the only reasonable possibility that the main part of the 0,076 cm increase in the amount of ozone above Oslo must be due to a downward component of the air motion, combined with a horizontal convergence, in connection with the tropopause depression.

IX. Atmospheric Ozone and Mother of Pearl Clouds.

Professor Carl Størmer has kindly put at my disposal a complete list of all observed cases of mother of pearl clouds in Norway from 1939 to 1949. For this period we have only found 20 cases where the total amount of atmospheric ozone has been measured on the same day as the clouds were observed. A review of these observations is found in table 8.

The first part of this table contains the information on the observed mother of pearl clouds, from left to right respectively the case number, the date, approximate hour and, as

[29]) H. Johansen: Eine aerologische Untersuchung mittels Radiosondierungen in Tromsø während der Zeit 31. Marz—30. April 1939. Met. Ann. Bd. 1, Nr. 2, Oslo 1942.

Table 7. Simultaneous upper wind measurements at three different stations on March 21st and 22nd 1949.

1949 Month Day MET	Station "M" 66° N, 02° E			Lerwick 60,2° N, 1,1° W			Stockholm 59,3° N, 17,9° E		
	Km level	Direction in degrees	Speed in knots	Km level	Direction in degrees	Speed in knots	Km level	Direction in degrees	Speed in knots
March	12	220	62	12	223	69	12	290	32
21st	15	210	64				15	260	13
16h	18	210	45				18	240	13
March	12	210	50	12	239	64			
21st	15	200	50	15	237[1])	54[1])			
22h	18	210	51						
March	12	210	37				9	260	43
22nd.....	15	230	40				10	240	57
4h	18	230	46						
March	12	250	35	12	283	55			
22nd.....	15	230	39	15	282	51			
10h	18	200	48						
March	12	260	38	12	281	57	8	200	80
22nd.....	15	200	46				9	200	97
16h	18	260	45						

[1]) Extrapolated values.

Table 8. Comparison between the occurrence of mother of pearl clouds and measurements of atmospheric ozone.

Observations of mother of pearl clouds				Nearest ozone station	Approx. distance between cloud and ozone station in km
Case no.	Date	Hour MET	Place		
1	22. 12. 1939	15^{30}—17^{05}	Helligskogen	Tromsø	150
2	24. 12. 1940	At Noon	Tromsø	Tromsø	170
3	18. 1. 1941	16^{25}—17^{00}	Narvik	Tromsø	400
4	19. 2. 1941	16^{30}—16^{55}	Narvik	Tromsø	400
5	2. 12 1943	13—14	Dombaas	Dombaas	150
6	10. 12. 1943	12—13	Dombaas	Dombaas	150
7	14. 12. 1943	At Noon	Dombaas	Dombaas	150
8	5. 1 1946	9—18^{20}	Oslo	Dombaas	250
9	7. 1. 1946	10	Vesteraalen	Tromsø	300
10	7. 1. 1946	8^{30} and 13^{30}	Aurdal and Trysil	Dombaas	250
11	8. 1. 1946	9—12	Tromsø a. o	Tromsø	30
12	15. 2. 1946	7—17^{50}	Trondheim, Oslo a. o.	Dombaas	180
13	2. 3. 1946	9^{45}	Narvik	Tromsø	300
14	13. 12. 1947	8—12	Oslo and Aurdal	Oslo	150
15	18. 1. 1949	8—9	Hornnes, Lillesand a. o.	Oslo	230
16	2. 2. 1949	9—10	Skibotn	Tromsø	200
17	3. 2. 1949	Evening	Lillehammer	Oslo	170
18	3. 2. 1949	7^{45}—8^{20}	Luleaa (Sweden)	Tromsø	580
19	4. 2. 1949	8—18^{45}	Lillehammer and Oslo	Oslo	170
20	5. 2. 1949	8—10	Skibotn.	Tromsø	200

Tab. 8 (continued).

Case no.	Observations of atmospheric ozone						Ozone deviation at the station nearest to the cloud	Max error of the ozone obs.
	Tromsø			Dombaas (Oslo)				
	Observed ozone Unit 0,001 cm	Hour MET	Deviation from ten year mean annual curve	Observed ozone Unit 0,001 cm	Hour MET	Deviation from ten year mean annual curve		
1	135	ca. 12	— 22	No observation			— 22	± 70
2	190	ca. 12	30	No observation			30	± 70
3	240	ca. 12	20	No observation			20	± 40
4	314	ca. 12	20	No observation			20	± 40
5	180	ca. 12	20	235	$12\underline{06}$	25	25	± 50
6	No observation			190	$12\underline{28}$	— 28	— 28	± 50
7	No observation			220	$12\underline{05}$	— 1	— 1	± 50
8	150	ca. 12	— 30	260	$12\underline{36}$	18	18	± 40
9	130	ca. 12	— 55	210	$12\underline{22}$	— 34	— 55	± 60
10	130	ca. 12	— 55	210	$12\underline{22}$	— 34	— 34	± 40
11	120	ca. 12	— 65	260	$12\underline{20}$	14	— 65	± 60
12	249	ca. 12	— 39	165	$12\underline{46}$	— 105	$\underline{-105}$	± 20
13	340	ca. 14	37	315	$12\underline{22}$	37	$\underline{37}$	± 15
14	No observation			190	$12\underline{37}$	— 29	— 29	± 50
15	No observation			231	$12\underline{14}$	— 23	— 23	± 30
16	183	ca 12	— 74	201	$12\underline{57}$	— 61	— 74	± 25
17	215	ca. 12	— 44	176	$13\underline{11}$	— 87	— 87	± 20
18	215	ca. 12	— 44	176	$13\underline{11}$	— 87	— 44	± 20
19	278	ca. 12	14	161	$13\underline{56}$	— 102	$\underline{-102}$	± 20
20	238	ca. 12	— 30	178	$12\underline{52}$	— 86	— 30	± 20
							$\overline{M} = -27$	

far as the space permits, the place from which the clouds were observed. Further to the right is indicated the name of the nearest ozone observing station and the approximate distance in km between this station and a point vertically beneath the cloud. For the cases where the accurate geographical position of the cloud is unknown, we have computed its approximate position by means of the approximate direction to the cloud as stated by the observer and by assuming that the height of the cloud a. s. l. be 25 km. The next part of table 8 gives the available ozone observations and their deviations from the ten-year mean annual curve. Next to the right in the table is given the ozone deviation at the station situated nearest to the position of the cloud. The assumed maximum uncertainty in the used ozone values are indicated in the last column.

The underlined ozone deviations in cases 11, 12 and 19 are believed to be the most reliable ones and, as a matter of fact, the observations of the mother of pearl clouds on these three days (8th Jan. 1946, 15th Febr. 1946 and 4th Febr. 1949) belong according to Professor Störmer, to the reliable cases. (On February 4th 1949 a number of photographs was taken of the clouds and their positions measured).

The mother of pearl clouds are a relatively rare phenomen. Several years might pass between the occasions the clouds are seen and, therefore, we have to realize that it may take a considerable time before a sufficient number of reliable observations are available for a statistical investigation of a possible relation between the occurrence of such clouds and the amount of ozone.

We have not found it possible to draw any definite conclusions from the relatively scanty material reproduced in table 8, but in view of the marked tendency which may be deduced from some of the more reliable observations, we have found justification for publishing these preliminary results in the hope that may be of some value for continued research in this field.

From table 8 it is seen that in 14 of the

20 cases the amount of ozone is less than should be expected from the smoothed annual curve of ozone variation and in 6 cases greater than this value. On an average, the ozone observations on days with mother of pearl clouds are 0,027 cm below the "normal" value. Selecting the 12 cases where the distance between the cloud and the ozone observing station presumably is less than 200 km, we find that 10 ozone values are smaller than the "normal" and only 2 higher. On an average for these 12 cases, the ozone amount is 0,041 cm below the "normal" but it should be remembered that this average value is much dominated by a few large negative deviations from the mean annual curve. It must also be remembered that in some cases there is an appreciable difference in time between the observation of the cloud and that of the ozone (max. 5 hours) but, on the other hand, the maximum error of each of the found positive ozone deviations is of the same order as the deviation itself. All circumstances considered, we may conclude that, according to the present material, the ozone content on days with mother of pearl clouds seems to be lower than the "normal" ozone value for the day in question.

It is unlikely that the presence of the ozone as such has any influence on the formation of mother of pearl clouds. During the months these clouds usually are observed — December, January and February — the ozone content is subject to very great changes. Thus in the cases discussed here the amount of ozone varies between 0,120 cm and 0,340 cm. It seems more realistic to suppose that both the measured low ozone values and the formation of mother of pearl clouds may have the same causes. If such causes could be found they might give valuable contributions to our knowledge both of the irregular ozone variations and of the formation of mother of pearl clouds.

The following points will be considered as possible causes of the negative ozone deviations:

1. A sufficiently strong upward component of the air flow in the lower stratosphere combined with a horizontal divergence.
2. A high content of water vapour in the lower stratosphere, preferably the presence of super cooled water droplets or ice particles combined with a sufficient amount of oxidizable impurities.
3. Advection of air with a small content of accumulated ozone.

With regard to the first point, the upward air motion may be identified with the vertical component of the air flow in the region near a wedge line of a semi-stationary wave in the contour lines of the 100 mb or a higher situated pressure surface.[30]) Such maps of the topography of the 100 mb surface are, however, not available for the cases in table 8 due to the lack of sufficient high level radiosonde observations.

Secondly an orographical lifting of the air in the troposphere due to a north-south located mountain ridge may cause "Føhn-waves" extending up in the lower stratosphere[31]) and, thirdly, a possible combined effect of the two causes must be considered.

A full discussion of these problems would be beyond the scope of this paper and therefore we will limit ourselves to discussing a single example given later in this chapter.

As to the second point, the water vapour content in the lower stratosphere, we know from recent measurements with the Frost-point hygrometer that the air in the lower stratosphere usually seems to be very dry.[32])

On the other hand, the formation of clouds at heights of around 25 km indicate the possibility that super-cooled water droplets and/or ice-crystals occasionally may be present at these heights i. e. at temperatures down to — 70° Centigrade.[33])

From laboratory experiments on the decomposition of ozone by absorption of ultraviolet light at normal pressure and temperature it is known that the quantum yield of ozone decomposition (number of molecules finally de-

---

[30]) See for instance. E. Palmèn and K. M. Nagler: The Formation and Structure of a Large Scale Disturbance in the Westerlies. Journ. of Met. Vol. 6, No. 4, August 1949.

[31]) H. Dieterichs: Zur Entstehung der Perlmutterwolken. Berichte des Deutschen Wetterdienstes in der US-Zone, Nr. 12, 1950.

[32]) H. C. Shellard: The Humidity of the Lower Stratosphere. Met. Mag. Vol. 78, No. 930, Dec. 1949

[33]) Helmut Weickmann: Die Eisphase in der Atmosphäre. Berichte des Deutschen Wetterdienstes in der US-Zone, Nr. 6, 1949.

composed divided by the number of quanta absorbed) may be as much as 15 times greater in the presence of water than in a pure mixture of ozone an dry air.[34])

Experimental studies of the photo-chemical decomposition of ozone are, however, very difficult because of its great reactiv power and the necessity of having a system free from all oxidizable impurities. It is hardly permitted to transfer these laboratory results to the conditions in the stratospheric ozone layer, and the effect on the ozone in the "protected region" of the ozone layer*) will probably be very small. When considering the accumulated ozone in the lower stratosphere it is most likely that this ozone will be much easier reduced due to chemical reactions with oxidizable impurities in the presence of water, than by photo-chemical reactions caused by the ultra-violet radiation.

Looking at table 8, cases 12 and 19 we find that the observed ozone content at around latitude 60° N is slightly smaller than the normal amount at the equator, where the chemical decomposition of the accumulated ozone very probably has its maximum. It may thus be concluded that other effects than the pure chemical decomposition of the accumulated ozone must be dominating in producing the observed extreme low ozone values at 60° N.

The two mentioned cases also illustrate that the third possible cause of the negative ozone deviations, the horizontal advection of air with smaller content of ozone from lower or higher latitudes, is unable to explain all the observed cases of low ozone in connection with mother of pearl clouds. In some cases, however, (cases 10 and 18) the effect of advection must probably be considered but, as a whole, the present material gives very little support for such an explanation of the low ozone values.

Just for illustration of the first point of the discussion, we give in fig. 14 a reproduction of a 500 mb chart of the North Atlantic region from 4th February 1949 at 16 MET.

On this day mother of pearl clouds were observed (and the positions measured) in Southern Norway from 8^h in the morning to $18^h\ 45^m$ in the evening. The ozone content above Oslo at $13^h\ 56^m$ was 0,161 cm, i. e., slightly lower than the normal amount at the equator.

Considering fig. 14 we assume that the marked wave-pattern of the contour lines also exists, although in a modified form, in a higher situated pressure surface, for instance the 100 mb surface. The actual wedge-line on the 500 mb chart may be drawn from Great Britain over Iceland to Greenland but neither the true position of the wedge-line on the 100 mb surface nor the trajectories in this surface is known. Although no proof can be given, the possibility of an effect on the total ozone above Oslo due to

[34]) G. S. Forbes and L. J. Heidt: J. Am. Chem. Soc. 56, p. 1671 and p. 2365, 1934

*) See chapter X, page 30.

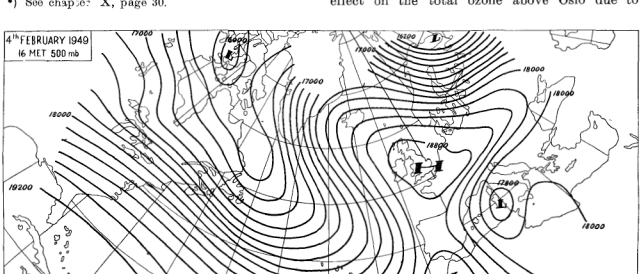

Fig. 14. Map of contour lines in the 500 mb surface at 16 MET 4th February 1949.

vertical motion connected to this wedge, should not be excluded. The other possible cause is the observed strong north-west wind in the troposphere across the main Scandinavian mountain ridge provided this wind is able to set up "Føhn-waves" extending high up in the stratosphere. "Føhn"-situations with winds from north-west are not uncommon in Norway but only in very few cases are mother of pearl clouds observed. Therefore, we should like to introduce the preliminary hypothesis that the formation of mother of pearl clouds is probably dependent on a certain successful combination of at least three of the discussed possibilities:

1. An upward motion connected to a semi-stationary wave in the contour lines of a stratospheric pressure surface provided the wave has a proper position relative to the mountain ridge.
2. An upward motion connected to a "Føhn-wave" caused by the mountain ridge itself.
3. The existence of a sufficient amount of water vapour to form the clouds.

As mentioned before, very few high-level radiosonde observations are available for the 20 cases discussed and earlier high level aerological data during mother of pearl cloud situations are also very scanty.*)

It may be of some interest to include here a short review of the existing ten aerological ascents made on the same day and at approximately the same place as atmospheric ozone and mother of pearl clouds were observed. Some extracts from these observations are found in table 9, where the upper part of the table contains from left to right the case number, the same information on the observed mother of pearl clouds as in table 8, name of radiosonde station, ascent hour and the distance between ozone station and radiosonde station.

The lower part of the table gives the measured temperature at 200 mb and at highest point reached, the highest point of the ascent in meters, a short note on the ascent curve, the monthly mean temperature above Tromsø for the given highest point for the month in question,[35]) the difference between the actual temperature and the monthly mean temperature and, finally, the ozone deviation found (see table 8).

As seen from table 9, the top heights for the ascents obtained are rather low and give very little information about the conditions in the stratosphere. It seems clear, however, that the actual temperature at the tropopause level as a whole is considerably lower than the mean temperature for the respective months of the year above Tromsø. This result tends in the same direction as the earlier aerological observations, i. e. that the lower stratosphere is exceptionally cold when the mother of pearl clouds are seen. If the advective temperature changes in the cases discussed are of minor importance, which seems not unreasonable, this cold stratosphere may be used as an argument in favour of a considerably upward displacement of the air as the main cause of the low ozone values.

X. Some Suggestions regarding the Ozone in the Atmosphere and the Causes of its Variations.

Wulf and Deming[36]) have introduced the idea that the main part of the total amount of ozone in the atmosphere may consist of ozone which is transported downwards to regions where it is to a great extent protected against decomposition due to the sun's ultra-violet radiation (protected regions). That part of the ozone which remains in a state of photo-chemical equilibrium may be relatively small and may only exist in the upper part of the ozone layer.

Several arguments may be put forward as a support for this idea.

In the paper by Dütsch[37]) a theoretical

*) H. Dieterichs: loc. cit (No. 31).

[35]) Extracted from: Harald Johansen: Mean Upper Air Data obtained from Soundings at Tromsø during the years 1941—44. Geofys. publ. Vol. XVII, No. 4, 1949.

[36]) O. R. Wulf and L. S. Deming: The Distribution of Atmospheric Ozone in Equilibrium with Solar Radiation and the Rate of Maintenance of the Distribution. Terr. Mag. Vol. 42, No. 2, p. 195, 1937.

[37]) H. U. Dütsch: loc. cit. (No. 6).

Table 9. Measurements of upper air temperatures on days with mother of pearl clouds.

Mother of pearl clouds observed				Radiosonde ascent		Distance between ozone- and radiosonde-station Km
Case no.	Date	MET	Place	Place	MET	
5	2. 12. 43	13—14	Dombaas	Kjeller	5	230
6	10. 12. 43	12—13	Dombaas	Kjeller	5	230
7	14. 12. 43	At Noon	Dombaas	Kjeller	5	230
9	7. 1. 46	At 10	Vesteraalen	Bardufoss	2	100
14	13. 12. 47	8—12	Oslo, Aurdal	Gardermoen	5	60
15	18. 1. 49	8—9	Hornnes, Lillesand o. a.	Sola	16	300
16	2. 2. 49	9—10	Skibotn	Skattøra	4	6
17	3. 2. 49	Evening	Lillehammer	Gardermoen	4	60
19	4. 2. 49	8—1845	Oslo, Lillehammer	Gardermoen	4	60
20	5. 2. 49	8—10	Skibotn	Skattøra	4	6

Case no.	Temp. at 200 mb C°	Temp. at highest point T_h	Highest point in meter	Remark on the ascent curve Tr = Tropopause	Monthly mean temp. above Tromsø T_m	Diff. $T_h—T_m$	Ozone deviation Unit 0,001 cm
5	— 56	— 56	11204	Tr, at 250 mb Temp. decreasing above Tr	— 57,6	1,6	25
6	— 63	— 63	11495	Tr. not reached	— 57,6	— 5,4	— 28
7	— 64	— 70	13390	No distinct Tr.	— 57,2	— 12,8	— 1
9		— 64	9690	Tr. not reached	— 59,–	— 5,0	— 55
14	— 61	— 63	14186	Tr. at 200 mb. Temp. decreasing above Tr.	— 57,1	— 5,9	— 29
15	— 56	— 60	13339	Tr. at 220 mb. Temp. decreasing above Tr.	— 60,–	0,0	— 23
16	— 69	— 71	11750	Tr. not reached	— 58,–	— 13,0	— 74
17	— 68	— 68	11649	Tr. not reached	— 58,–	— 10,0	— 87
19	— 66	— 69	12150	Tr. not reached	— 58,2	— 10,8	—102
20		— 66	10209	Tr. not reached	— 58,2	— 7,8	— 30

calculation is given of the so-called "reduzierte Abklingzeit" supposing that the state of equilibrium has been disturbed. This time will be nearly the same as the time of "half-restoration" computed by Wulf and Deming*). An extract of the figures found by Dütsch is given in table 10.

When transferring the time in hours in the table into number of days it should be noted that only the hours of the day for which the ozone layer is exposed to the sun's radiation must be taken into account. The figures for the time of "half-restoration" given by Wulf and Deming are appreciably smaller than those

*) O. R. Wulf and L. S. Deming: loc. cit. (No. 36).

Table 10. Approximate duration in hours of the process of "half-restoration" of the state of photo-chemical equilibrium (Converted from a table by Dütsch).

Height in Km	Equinox	Summer-solstice		Winter-solstice	
	$\varphi = 0$	$\varphi = 45°$	$\varphi = 70°$	$\varphi = 45°$	$\varphi = 60°$
50	0,9	1,0	1,1	1,5	2,1
40	5,3	6,8	7,4	$1{,}3\times10^{1}$	$2{,}4\times10^{1}$
35	$7{,}6\times10^{1}$	$6{,}5\times10^{1}$	$7{,}7\times10^{1}$	$2\,3\times10^{2}$	$3{,}9\times10^{2}$
30	$3{,}9\times10^{2}$	$2{,}9\times10^{2}$	$3{,}7\times10^{2}$	$1{,}2\times10^{3}$	$2{,}1\times10^{3}$
25	$1{,}7\times10^{3}$	$1{,}1\times10^{3}$	$1{,}4\times10^{3}$	$5{,}8\times10^{4}$	$1{,}0\times10^{4}$
20	$1{,}8\times10^{4}$	$4{,}7\times10^{3}$	$6{,}5\times10^{3}$	$2{,}3\times10^{4}$	$3{,}8\times10^{4}$
15	$1{,}6\times10^{5}$	$3{,}3\times10^{4}$	$4{,}5\times10^{4}$	$1{,}4\times10^{5}$	$1{,}0\times10^{5}$
10	$6{,}5\times10^{5}$	$3{,}1\times10^{5}$	$8{,}2\times10^{5}$	$1{,}4\times10^{6}$	$9{,}7\times10^{5}$

found by H. U. Dütsch, especially for the highest levels.

One of the reasons for this discrepancy is the fact that Wulf and Deming have made the assumption that the sun radiates as a black body of temperature 6000° Å in the actual ultra-violet part of the spectrum. According to measurements made with a V_2-rocket[37]) the border of the ultra-violet side of the sun's spectrum was around 2100° Å at a height of 55 km. This result indicates that in the ultra-violet the sun radiates as a black body of a lower temperature than 6000° Å, and thus the figures for the time of "half-restoration" given by H. U. Dütsch probably are the most appropriate ones.

It may be deduced from table 10 that the true amount of ozone above 30 to 35 km will not be far from the equilibrium amount at least in the summer. At around 25 km the condition changes and at 20 km and lower the amount of ozone is not able to take part in the seasonal changes of the height of the sun. If no air motions existed at these levels, the amount of ozone below 20 km would remain constant.

To some extent it is possible to compare this theoretical result with the direct measurements of ozone in the atmosphere and with the observed changes in the vertical distribution of ozone found by the "umkehr"-method.*)

Recently[38]) it has been shown by means of observations recorded during a Rocket-sonde flight, that the vertical distribution curve occasionally may have a secondary peak below the normal maximum. In this case the heights of the two maxima were found to be 17 and 25 km, respectively. The lowest maximum may be identified with the main part of the accumulated ozone layer and similar double maxima distributions may also be deduced from the "umkehr"-observations.**)

Turning now to the vertical distributions found by this method we illustrate in table 11

Table 11. The rough distribution of ozone with height in the atmosphere in low latitudes for different total amounts of ozone and given as the amount of ozone present in three different layers.

0_3 unit 0,001 cm Layer	Delhi 28,6° N Total amount of ozone				Poona 18,5°N Total 0_3		Mean
	155	175	200	217	164	174	
54–36 km	13	13	14	15	24	25	17
36–18 km	119	135	154	166	126	135	
18–0 km	23	27	32	36	14	14	

the computed amount of ozone in three different layers and for different total amounts of ozone in low latitudes. The figures are extracted from the cited paper by R. V. Karandikar and K. R. Ramanathan.*)

Table 12. The rough distribution of ozone with height in the atmosphere in high latitudes for different total amounts of ozone and given as the amount present in three different layers.

0_3 unit 0,001 cm Layer	Tromsø 69,7° N Total amount of ozone					Mean
	160	220	280	340	400	
50–35 km.....	18	13	16	20	18	17
35–20 km.....	112	155	180	187	192	
20– 0 km.....	30	52	84	133	190	

In table 12 we give the corresponding figures for a high latitude station found by the same method.**) As will be seen from the tables, a slightly different division of the atmosphere has been used in the two cases but this will not affect the main picture of the distribution.

Considering the maximum possible error in the amount of ozone found for the layer 50—35 km**) we may state that the true figures will not deviate more than 40 % from the figures in the table. Thus we may draw the conclusion that the amount of ozone above 35 km, which, according to the theory, will be in a state of equilibrium with the sun's radiation, must be relatively small compared with the total amount of ozone. Further, the figures indicate that this high-level ozone is probably approximately inde-

[37]) E. O. Hulburt: The Upper Atmosphere of the Earth. Journ. Opt. Soc. Am Vol. 37, No. 6, p. 405, 1947.

*) F. W. P. Götz: loc. cit. (No. 2).

[38]) Meteorological Office Discussion. Rocket sondes. Met. Mag. p. 69, March 1949.

**) F. W. P. Götz: loc. cit. (No. 22).

*) R. R. Karandikar and K. R. Ramanathan: loc cit., (No. 7).

**) E. Tønsberg and K. Langlo (Olsen): loc cit. (No. 4).

pendent of the total amount of ozone and probably also approximately independent of the latitude and season at least for the region between the equator and around 65° N*).

The layer between 35 and 20 km, normally containing the maximum of ozone concentration, may be regarded as a zone of transition between the state of equilibrium and the state of non-equilibrium (accumulated ozone).

From tables 11 and 12 is seen that the ozone content in the transitional-layer for low values of the total amount of ozone at high latitudes seems to correspond approximately with the ozone content in the same layer in low latitudes. For changes in the total ozone content between 0,280 and 0,400 cm at Tromsø the changes in the transitional-layer seem so be very small indicating that the major ozone variations at these high values must take place below 20 km. Finally, the great variations in the amount of ozone below 20 km, illustrated in table 12, are in agreement with the theoretical result that this ozone cannot be in a state of photo-chemical equilibrium.

It is further seen that reasonable changes in the amount of accumulated ozone are able to explain most of the observed day to day changes in the total amount of ozone. In order to explain the seasonal variation and the distribution with latitude, however, the changes in the transitional-layer must also be considered.

H. U. Dutsch**) has shown that the assumption of a photo-chemical equilibrium, taking into account the daily changes in the height of the sun and of the scattering of the radiation in the atmosphere, gives a maximum of ozone at the equator of the order 0,416 cm and appreciably smaller amounts in higher latitudes.

Considering the variation with latitude of the vertical "Austausch"*) in the atmosphere and in the vertical motions due to the expansion of the atmosphere in summer and the contraction in winter in high latitudes, he found that these effects approximately compensate for the theoretical maximum at the equator. On an average for a year the theory gave only around 10 percent greater ozone content in temperate latitudes than at the equator against the observed 33 percent (fig. 2), and the found annual amplitude at 60° N was only around 5 percent of the average value against the observed 40 percent.

By postulating an average meridional circulation of the atmosphere, however, Dütsch obtained a theoretical annual variation which was in fairly good agreement with the observed variation at 60° N. He assumed a downward motion of the air in the winter period October to March for all levels between 15 and 35 kilometers and an upward motion in the summer season April to September. The effects of an advection of air across latitudes were neglected in the theory. The proposed meridional circulation is neither in accordance with the estimated average circulation of air in vertical meridian planes given by A. H. R. Goldie[39]) nor with the picture of the general circulation described by C. G. Rossby.[40])

Referring to the discussion in chapter VII of this paper we suggest that the horizontal transport of ozone in the atmosphere must be taken into account when explaining the distribution with latitude and the annual variation in the ozone content. Further we suggest that the vertical motions connected to the development and movement of a polar front cyclone and the subsidence of air in high pressure areas must be taken into account. The observed change per unit time in the total amount of

*) It is realized that the figures in table 12 are based on mean "umkehr-curves" and that very little information is available about the actual vertical distribution of ozone at different seasons. The found distributions for the low total ozone contents originate, however, from observations made in the autumn and the distributions of the high total contents are based on observations made in the spring. Therefore, the figures in table 12 are supposed to be roughly representative for the seasonal variations in the vertical distribution of ozone.

**) H U. Dütsch: loc. cit. (No. 6).

*) This term takes into account the effects of all types of vertical turbulence, including also the large-scale convectional turbulence.

39) A. H. R. Goldie: The Upper Atmosphere. Estimated Distribution of Temperature, Pressure and Wind up to 45 km Level. M. R. P. 360 (unpublished paper of the Meteorological Research Committee. Met. Office, London.)

40) C. G. Rossby: The Scientific Basis of Modern Meteorology. Climate and Man. Yearbook of Agriculture, Washington D. C. 1941.

ozone above a certain place $\frac{d[0_3]}{dt}$ may be expressed by the following equation:

$$\frac{d[0_3]}{dt} = \frac{d[0_3]_e}{dt} + \frac{d[0_3]_a}{dt} + \frac{d[0_3]_v}{dt} + \frac{d[0_3]_h}{dt} \quad (10.1)$$

where

$\frac{d[0_3]_e}{dt}$ = the change per unit time in the theoretical equilibrium amount of ozone.

$\frac{d[0_3]_a}{dt}$ = the change per unit time in the theoretical amount of ozone destroyed or produced by the vertical "Austausch" in the atmosphere and by the vertical motions due to the expansion of the atmosphere in summer and the contraction in winter in temperate and high latitudes.

$\frac{d[0_3]_v}{dt}$ = the change per unit time in the amount of ozone destroyed or produced by vertical motions in addition to those included in $\frac{d[0_3]_a}{dt}$. (Vertical motions combined with convergence and divergence). The effect of the chemical decomposition of ozone caused by the additional vertical motions is included in the term $\frac{d[0_3]_v}{dt}$.

$\frac{d[0_3]_h}{dt}$ = the change per unit time in the contribution to the total amount of ozone caused by horizontal transport of air with different ozone content. The effect of the chemical decomposition of ozone due to the horizontal transport is included in the term $\frac{d[0_3]_h}{dt}$.

Considering the annual variation in ozone in a certain latitude as a smoothed curve through the monthly mean values, this variation may be characterized be equation (10.1) when substituting the monthly mean values in each of the terms, i. e.:

$$\frac{d\overline{[0_3]}}{dt} = \frac{d\overline{[0_3]_e}}{dt} + \frac{d\overline{[0_3]_a}}{dt} + \frac{d\overline{[0_3]_v}}{dt} + \frac{d\overline{[0_3]_h}}{dt} \quad (10.2)$$

According to the computations made by Dütsch the first two terms on the right hand side will roughly compensate each other (within 5 percent) and, therefore, the maximum and the minimum of the annual curve $\left(\frac{d\overline{[0_3]}}{dt} = 0\right)$ may be defined by:

$$\frac{d\overline{[0_3]_v}}{dt} + \frac{d\overline{[0_3]_h}}{dt} \approx 0 \quad (10.3)$$

Considering first the period November to March the monthly mean ozone value at for instance 60° N increases from around 0,197 cm in November to around 0,284 cm in March, i. e. approximately 0,090 cm.

Estimating from table 12, around 0,050 cm of this change may have taken place in the transitional layer and the rest, 0,040 cm, in the accumulated ozone layer.

According to the discussion in chapter VII we have reason to believe that the effect of advection at 60° N will be relatively small in the months November, December and January but will increase later in spring. Therefore an excess of downward motion of the air must be the main cause of the 0,090 cm increase from November to March. According to equation (10.3) the peak of the annual curve in March—April probably occurs when the increase in ozone due to the vertical motions in a period of a month is over-compensated by the invasion of air from lower latitudes with a lower content of ozone.

During the period April to October the monthly mean ozone value at 60° N decreases from 0,282 to 0,192 cm i. e. 0,090 cm. Estimating from table 12, approximately half of this change may have taken place in each of the two layers, the transitional- and the accumulated ozone layer respectively.

Referring to the discussion in chapter VII we suggest that the breaking down of the zonal circulation into horizontal cells be the main cause of the decrease in ozone during the late spring and summer. According to equation

(10.3) the minimum of the annual curve in October—November probably occurs when the decrease in ozone due to the advection of air from lower latitudes in a period of a month is over-compensated by the increase in ozone caused by the vertical-motion effect.

The greater amounts of ozone found in temperate and high latitudes than in low latitudes on an average for a year (fig. 2), can be explained by the assumption that on an average for a year the vertical-motion effect (excess of downward air motions) and the advection of air with relatively high ozone content will be of greater importance for the total ozone content in latitudes north of around 40° N than will the effect of advection of air from lower latitudes.

In a similar way the detailed distribution of ozone with latitude at different seasons of the year may be explained.

It is assumed that the chemical destroying of ozone in the troposphere and in the ozone incline region is appreciably greater in low latitudes than in high latitudes. Therefore we may suppose that the amount of ozone which is being chemically decomposed in the atmosphere is significantly greater in periods where the pattern of the general circulation is broken down in horizontal cells than in periods with more or less zonal circulation.

With regard to the observed changes from year to year in the annual amount of ozone, discussed in chapter IV, we suggest that these changes probably are due to the well-known irregular variations in the pattern of the general circulation from year to year.

A striking support for this hypothesis is the remarkably high monthly mean ozone values observed in temperate and high latitudes in Western Europe during the cold winters and springs of 1940 to 1942.

During these cold periods the Sibirian high pressure area was strongly developed and it may be anticipated that abnormal amounts of accumulated ozone was formed in this area by subsidence and connected convergence in the ozone incline region.

Turning now to the rapid irregular changes in the amount of ozone, the short period changes in the terms $\frac{d\,[0_3]_e}{dt}$ and $\frac{d\,[0_3]_a}{dt}$ in equation (10.1) could probably be neglected in most cases and the actual change in the ozone content be characterized by the simple relation:

$$\frac{d\,[0_3]}{dt} = \frac{d\,[0_3]_e}{dt} + \frac{d\,[0_3]_h}{dt} \qquad (10.4)$$

The term $\frac{d\,[0_3]_e}{dt}$ also includes a possible change in ozone due to chemical decomposition caused by the introduction of super-cooled water droplets, ice crystals and impurities in the ozone incline region. (Compare the discussion in chapter IX). The term $\frac{d\,[0_3]_h}{dt}$ also includes the effect of a possible overlapping of accumulated ozone layers.

For a middle latitude-station R. J. Reed[41]) has found that the sum of the positive (0,024 cm) and negative (0,017) deviation possible from the vertical-motion effect is approximately 0,040 cm. Further, he assumes that the total range of deviations for such a station during the late winter or early spring is about 0,120 cm. R. J. Reed concludes that the vertical motions account for at most one third of the range and that the remainder must presumably be produced by horizontal advection.

In chapter VIII we have found that the positive ozone deviations near the centre of a marked tropopause trough may be as great as 0,040 to 0,100 cm in cases where the effect of advection, due to the ozone distribution with latitude, probably is very small. Further we may conclude from the discussion in chapter VII (see table 6) that the "normal" ozone distribution with latitude can only account for a smaller part of the total 24 hours change in ozone at a temperate latitude-station, assuming reasonable values of the meridional wind-components in the ozone incline region. The maximum positive deviation of 0,024 cm found by R. J. Reed

[41]) Richard J. Reed: The Role of Vertical Motions in Ozone-weather Relation-ships. Journ. Met. Vol. 7, No. 4, 1950.

is based on static considerations, assuming a subsidence of the air in the ozone incline region amounting to maximum 1,5 km. We prefer to regard the rapid ozone variations as chiefly a dynamic problem in accordance with the hypothesis put forward by E. Palmén.*)

The results of the studies in chapter VIII support this view. A descending motion at the tropopause level is most probably accompanied by a convergence (inflow of air) above the descending air thus producing a greater total amount of ozone without necessarily postulating an instantaneous photo-chemical formation of more ozone than before. On the other hand, if the descending motion also takes place in the transitional and equilibrium ozone layer and continues several days, we may assume that the total amount of ozone may be increased due to the process of restoration, mainly in the equilibrium layer (compare table 10).

We do not yet know the exact magnitude of the terms $\frac{d\,[O_3]_e}{dt}$ and $\frac{d\,[O_3]_b}{dt}$ in equation (10.4) but some preliminary conclusions may be drawn from the present investigation. In order to explain the observed positive deviations greater than the calculated maximum deviation of 0,024 cm found by R. J. Reed,**) either the vertical displacements in the ozone incline region must be greater than 1,5 km or the effect of convergence in higher levels must have been omitted in his calculations. It is hardly possible that a rapid change in ozone content of the order 0,075 cm can be due to a meridional advection of air with higher ozone content unless a considerable overlapping of accumulated ozone layers takes place. According to the discussion in chapters VII, VIII and IX, it seems most reasonable that the vertical-motion effect will account for the greater part of the total day to day variation in ozone content.

*) E. Palmén: loc. cit. (No. 3)

**) R. J. Reed: loc. cit. (No. 41).

XI. Summary.

In the introduction a short review is given of some recent papers on atmospheric ozone which have a direct bearing on the relation between the amount of ozone and meteorological conditions.

The available observational data are summarized in chapter II and in chapter III a short description is given of the optical method of measuring the total amount of atmospheric ozone. Some of the fundamental questions regarding the sources of error involved in the described method are discussed with the conclusion that the used optical method scarcely gives the exact true value of the total amount of ozone in the atmosphere. If the observations at different places, however, are made with calibrated instruments of the same type and the same figures are used in the formulae when accounting for the absorption and scattering in the atmosphere, the simultaneously found ozone values are supposed to give a suitable basis for estimating the horizontal distribution of the total amount ozone. Further, it is concluded that the observed changes are due to real changes in the amount of ozone provided due regard is taken of the accuracy of the observations.

In chapter IV the causes of the observed variations from year to year in the annual amount of ozone are discussed and it is suggested that the general circulation of the atmosphere must be taken into account in order to explain these changes.

A revised picture of the variation with latitude of the ozone amount and the irregular changes in this distribution is given in chapter V. It is indicated that the annual amount of ozone probably is greater on the east side of the continents than on the west, at least around 30° N. Further, it seems difficult to explain the irregular distribution with latitude by a simple theory assuming the whole ozone layer to be in a state of photo-chemical equilibrium.

An objection has been put forward against the opinion that the increase in temperature in

the ozone incline region, when passing from the equator to the poles, is due to the variation with latitude of the amount of ozone.

In the chapter VI a study is made of the annual period in the amount of ozone, especially in high latitudes. The observations support the opinion that the annual period must be chiefly dominated by changes in the meteorological conditions.

The role of the horizontal transport (advection) of ozone in the atmosphere has been investigated (chapter VII) and it is concluded that the advection of ozone due to the general circulation of the atmosphere must be of importance for the seasonal changes in the amount of ozone. It is suggested that the main effect of the general circulation in the ozone incline region during the late spring and summer will be to reduce the total amount of ozone in middle and high latitudes. The importance of the actual zonal distribution of ozone for the day to day changes in the amount of ozone has been stressed and it is shown that the mean variation of ozone with latitude is quite insufficient to explain these changes. The given picture of the variation of wind speed with height in the ozone incline region may be of importance for the advective ozone changes due the possibility of the overlapping of accumulated ozone layers.

In chapter VIII it is shown that the highest ozone values during the passage of a polar front cyclone is found near the centre of the tropopause trough belonging to the cyclone. The study of individual cases of cyclone passages support the opinion that the greater part of a day to day variation in ozone is probably due to vertical motions of the air masses in the ozone incline region.

An attempt has been made to correlate the amount of ozone with the occurrence of mother of pearl clouds and it is suggested that the low ozone values observed on days with such clouds and the formation of the clouds may have the same causes. As a preliminary hypothesis it is proposed that the formation of mother of pearl clouds probably is dependent on a certain successful combination of at least three effects:

1. An upward motion connected to a semi-stationary wave in the contour lines of a stratospheric pressure surface provided the wave has a proper position relative to the mountain ridge.
2. An upward motion connected to a "Föhn-wave" caused by the mountain ridge itself.
3. The existence of a sufficient amount of water vapour to form the clouds.

In chapter X some suggestions are put forward regarding the ozone in the atmosphere and the causes of its variations.

It is stated that the upper part of the ozone layer, the equilibrium layer (above 35 km) contains only a small part (around 0,017 cm) of the total amount of ozone. This high level ozone is probably approximately independent on the total amount of ozone and probably also approximately independent on the latitude and season at least for the region between the equator and around 65° N. The layer between 35 and 20 km, normally containing the maximum of ozone concentration, is regarded as a zone of transition between the state of equilibrium and the state of non-equilibrium (accumulated ozone). Reasonable changes in the amount of accumulated ozone (below 20 km) are able to explain most of the day to day changes in the total amount of ozone. In order to explain the seasonal variation and the distribution with latitude, however, the changes in the transitional layer must also be considered.

The annual variation in ozone is discussed and the maximum and minimum of the annual curve is explained as the result of seasonal changes in the vertical air-motions and in the advection of air with different ozone content (the seasonal variations in the general circulation).

The distribution of ozone with latitude is explained by means of the same effects.

The changes observed from year to year in the annual amount of ozone are supposed to be due to the irregular variations in the pattern of the general circulation from year to year.

The rapid ozone variations from day to day is regarded as chiefly a dynamic problem and it is concluded that the vertical-motion effect will probably account for the greater part of these deviations.

Acknowledgments.

The author wishes to express his thanks to "Norges Almenvitenskapelige Forskningsraad" for a grant covering some of the expenses and to "Det Norske Meteorologiske Institutt" for giving me permission and support to undertake the work.

Thanks are also due to the institutions and persons mentioned in chapter II among whom E. Tønsberg should be especially remembered.

Appendix I.

Monthly Mean Ozone Values for Dombaas (March 1940 to June 1946)
and for Oslo (July 1946 to April 1949)
0_3 unit 0.001 cm.
n is the number of days with ozone observations.

	1940		1941		1942		1943		1944		1945		1946		1947		1948		1949		Mean (1940—49)
	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	
Jan..... ..							213	13			229	7	234	29	282	26	309	27	240	15	251
Feb.			306	6			226	9			270	4	245	17	317	24	266	25	261	20	270
Mar.	287	9	310	23	294	15	274	19	(267)	4	270	24	284	27	316	26	258	27	261	26	284
April	288	19	310	28	268	24	279	26	262	23	293	29	275	29	285	27	278	30	277	23	282
May	282	22	289	25	266	23	271	30	263	27	284	22	260	31	257	27	265	30			271
June	237	12	238	23	255	24	237	19	242	27	250	26	247	17	252	25	250	28			245
July	229	10	225	18	244	30	231	27	222	22	224	29	245	5	240	27	237	27			232
Aug.	224	20	234	25	221	28	222	25	198	20	214	30	(217)	3	207	26	232	23			219
Sept.	217	24	194	27	202	10	201	26	208	30	204	29	203	22	207	29	204	25			204
Oct.....	194	24	211	22			184	30	190	27	182	28	177	26	200	26	197	18			192
Nov.	213	6	(202)	3			198	26	198	23	186	24	192	21	203	25	191	10			197
Dec					202	10	224	22	215	17	230	22	213	23	248	26	(258)	4			222
Annual mean:	(241)		(252)		(250)		230		(227)		236		233		251		244				*239*
Feb. Nov. mean:	(241)		252		(250)		232		(231)		238		235		248		238				

Appendix II.

Monthly Mean Ozone Values for Tromsø 1939—1949

O_3 unit 0,001 cm.

n is the number of days with ozone observations.

	1939		1940		1941		1942		1943		1944		1945		1946		1947		1948		1949		Mean 1940—49
	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	O_3	n	
Jan.			282	17	259	22	246	18	206	31	132	19	166	31	145	25	123	15	186	11			194
Feb.			320	18	326	28	339	28	292	28	279	28	274	28	269	27	282	23	256	26	245	28	288
Mar.	270	21	324	25	345	31	362	31	304	31	296	30	293	31	309	31	301	31	278	31	271	29	308
April	275	24	327	24	326	30	317	30	303	30	294	30	318	30	313	30	297	30	298	30	309	29	310
May	273	21	288	27	303	31	303	31	295	31	281	31	292	31	283	31	286	31	287	31	301	20	292
June	253	24	271	23	275	30	260	30	253	30	247	30	263	30	245	30	253	30	257	30			258
July	223	31	253	31	233	31	239	31	334	31	220	31	222	30	220	29	233	31	229	31			231
Aug.	201	26	240	31	225	31	228	31	226	31	215	28	221	31	211	31	220	30	227	31			224
Sept.	203	29	220	30	211	30	220	30	208	30	216	30	217	30	201	29	215	30	210	30			213
Oct.	212	30	207	31	215	30	212	31	194	29	209	31	211	31	182	27	212	30	200	29			205
Nov.	217	30	178	28	199	30	176	30	177	23	184	27	165	30	151	18	153	27	181	9			174
Dec.	148	18	167	19	218	15	155	31	124	16	133	30	130	26			(108)	5					155
Annual mean:	(228)		256		261		255		235		226		231										*238*
Feb.—Nov. mean:	(236)		263		266		266		249		244		248		238		245		242				

Appendix III.

Monthly Mean Ozone Values for Arosa 1939—1949.

0_3 unit 0.001 cm.

n is the number of days with ozone observations.

	1939		1940		1941		1942		1943		1944		1945		1946		1947		1948		1949		Mean 1940—49
	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	
Jan.	227	14	274	20	256	19	283	19	239	15	213	20	267	23	238	24	271	25	242	20	236	14	252
Feb.	242	19	283	13	279	21	298	20	242	15	258	16	255	20	249	18	281	19	262	20	258	26	267
Mar.	272	12	295	26	294	22	264	20	272	29	272	13	255	23	269	26	278	21	246	27	267	26	271
April	146	11	303	24	289	21	288	18	257	26	255	21	264	26	256	25	261	25	257	26	253	27	268
May	270	6	285	23	295	22	266	24	247	22	247	24	266	28	251	25	256	27	250	28	262	23	263
June	240	16	274	21	255	26	246	21	249	22	248	25	249	29	243	22	242	24	245	23	251	29	250
July	235	22	245	19	247	23	231	24	238	21	227	24	233	29	225	24	237	25	244	21	238	28	237
Aug.	222	12	229	21	238	27	219	24	215	22	217	26	232	28	218	16	230	30	221	27	230	21	225
Sept.	204	14	220	19	217	25	202	27	199	24	207	24	211	22	197	22	218	28	212	16			209
Oct.	216	17	207	10	213	21	194	19	208	27	209	24	205	27	207	28	211	28	200	24			206
Nov.	202	20	214	17	219	21	212	19	215	13	212	15	210	23	211	24	198	19	203	22			210
Dec.	220	17	239	21	219	20	222	25	227	18	227	25	222	9	225	16	221	14	228	25			226
Anual mean:	233		256		252		244		234		233		239		232		242		234				240

Appendix IV.

Monthly Mean Ozone Values for Zi-Ka-Wei 1932—1942.

0_3 unit 0,001 cm.

n ist the number of days with ozone observations.

	1932		1933		1934		1935		1936		1937		1938		1939		1940		1941		1942		Mean 1932—42
	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	0_3	n	
Jan.	212	15	254	6	251	12	253	12	265	6	234	10			236	17	256	14	246	21	236	22	244
Feb.	243	15	(263)	4	248	12	275	6	269	7	252	9	267	11	239	10	268	12	250	13	265	7	258
Mar.	262	10	262	8	268	12	262	12	275	8	258	9	266	10	256	12	282	11	258	17	259	16	264
April	249	14	254	9	249	7	(262)	4	269	7	266	13	280	15	267	13	283	13	268	18	279	17	266
May	241	12	255	13	248	10	262	12	267	6	265	18	261	11	259	16	265	12	267	15	277	15	261
June	240	9	259	5	240	9	244	5	(209)	3	246	15	245	6	246	13	267	12	260	17	252	8	250
July	226	23	232	16	233	18	224	9	228	10	234	23	233	16	235	13	235	21	238	16	240	21	233
Aug.	229	14	239	16	225	10	(224)	3	232	12	222	22	226	22	220	17	238	18	231	16	222	7	228
Sept.	233	14	231	16	221	8	228	10	230	20	222	12	215	15	228	20	228	15	231	10	223	11	226
Oct.	226	14	212	5	216	16	219	12	223	21	218	19	215	16	224	12	223	16	233	20	226	15	221
Nov.	221	13	206	8	197	7	208	9	214	13	222	9	220	24	223	14	222	17	230	16	227	18	217
Dec.	219	15	231	11	218	9	224	10	221	5	237	14	235	15	235	24	234	17	232	15	(230)	4	229
Annual mean:	233		240		235		240		245		240		242		239		250		245		246		*241*

Printed in May 1952.
GRØNDAHL & SØNS BOKTRYKKERI, OSLO