On the Annual and Meridional Variation
of
the Atmospheric Ozone

by

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Abstract

The mass distribution of atmospheric ozone on the earth was calculated assuming that distributions of ozone on the northern and southern hemispheres are approximately the same only with a half year difference of phase. Results showed that the total mass of ozone is always constant. On the other hand, calculated amount of ozone by our previous theory decreases rapidly with increasing sec Z . Therefore, meridional distribution of photochemically formed ozone and that observed are quite different, but the total mass is equal to the latter and it becomes also constant on the whole earth. We considered that initial distributions are decided photochemically and actual distributions are formed secondly by pole-ward transports of ozone in the stratosphere. The speed and direction of the transport and their seasonal variations were estimated by which the annual and meridional variation of ozone could be explained reasonably.

Introduction

Up to the present day, the problem on the peculiar annual and meridional variations in the amount of the atmospheric ozone is one of the difficult questions in the meteorology. It seems that it will not be solved by considering only the change of photochemical equilibrium or temperature in the upper atmosphere. The recent studies on this problem have been inclined toward the conclusion that it is impossible to explain them unless the pole-ward flow of ozone is considered.

But, the precise wind direction and its seasonal variation in the upper atmosphere especially in the ozone layer which extends from about 20 km to 40 km above the ground have not yet been accurately observed. Therefore, it may be said that the effort to make clear the annual and meridional variations of ozone is not only for the ozone problem itself, but also one of valuable ways, though indirect, to conjecture the conditions in the upper air.

Chapter 1

The mass distribution of ozone on the earth and the constancy of its total amount.

It is a custom to express the amount of ozone by its vertically integrated thickness x reducing to the normal state. This expression is convenient to compare the ozone amount among several observation points or to obtain the seasonal variation at a certain point. But, it is unsufficient to consider a distribution of ozone quantity over a certain area. Assuming that x is constant everywhere on the same latitude and varies only on meridional direction a mass of ozone M on a narrow latitudinal zone $\Delta\varphi$ around the earth is given by the next formula,

$$(1) \quad M_{\varphi} = \frac{2m}{V} \cdot \varphi \cdot \pi \cdot R^2 \cdot \cos \varphi \cdot \Delta\varphi$$

where, R is the radius of the earth; m , the molecular weight of ozone; V , the molar volume at N.P.T. and φ is the latitude. Some examples of the calculation of the mass distribution of ozone on the whole earth are given by dotted lines in Fig. 1, where it is assumed that values of x on the southern hemisphere are approximately symmetrical to those on the northern hemisphere only with a half year

Fig. 1 Meridional mass distribution of ozone

difference of phase.

As shown in Fig. 1, the form of the mass distribution is considerably different from the well known distribution of x . M is larger in the temperate zone and decreases toward the pole, on the contrary x shows the minimum near the equator and the maximum at about the latitude, 55° .

The total mass of ozone on the earth is obtained easily by integrating the above formula over the range from $-\pi/2$ to $\pi/2$. The result shows that the total mass of ozone is almost constant all the time as shown in Table 1.

It seems that though there is a remarkable seasonal variation in M on each hemisphere but the increase on one side is compensated by the decrease on the other side and the total mass becomes always constant. The above result seems to support the idea to assume the presence of meridional flow of ozone between two hemispheres.

Table 1. The total amount of ozone on the earth and its annual variation. unit: 10^8 ton

	N—Hemisphere		S—Hemisphere		Total	
	obs.	calc. *	obs.	calc. *	obs.	calc. *
Jan.	1.26	0.70	1.36	1.64	2.62	2.34
Feb.	1.35	0.85	1.20	1.62	2.52	2.47
Mar.	1.40	1.11	1.16	1.50	2.56	2.61
Apr.	1.39	1.36	1.19	1.24	2.58	2.60
May	1.35	1.65	1.17	0.94	2.52	2.59
June	1.27	1.72	1.19	0.71	2.47	2.43
July	1.36	1.64	1.26	0.70	2.62	2.34
Aug.	1.20	1.62	1.35	0.85	2.52	2.47
Sept.	1.16	1.50	1.40	1.11	2.56	2.61
Oct.	1.19	1.24	1.39	1.36	2.58	2.60
Nov.	1.17	0.94	1.35	1.65	2.52	2.59
Dec.	1.19	0.71	1.27	1.72	2.47	2.43

* See Chapter 2

Chapter 2

The annual variation and the meridional distribution of photochemically formed ozone.

1. The variation of α with the altitude of the sun.

When the solar altitude changes, the change in thickness of ozone in the state of photochemical equilibrium takes place, and it can be calculated by our previous theory.¹⁾ Our fundamental formula expressing the photochemical equilibrium of the atmospheric ozone is as follows;

$$(2) \quad [O_3]^2/[O_2]^3 = K \cdot p \cdot \alpha q / \beta q'$$

where $[O_3]$ and $[O_2]$ are respectively the partial pressure of ozone and oxygen; p , the total pressure, α and β are the light absorption coefficients of oxygen and ozone; q and q' are the number of effective light quanta to produce and decompose ozone and K is the reaction velocity constant. The number of light quanta q_λ and q'_λ with each definite wave length arriving at a certain altitude are given by the next formula, where Z is the zenith angle of the sun and λ and λ' are the wave lengths.

$$(3) \quad q_\lambda = q_{0\lambda} \cdot \exp \left[- \int_h^\infty \alpha_\lambda \cdot \sec Z [O_2] \cdot dh \right]$$

$$(4) \quad q'_\lambda = q_{0\lambda'} \cdot \exp \left[- \int_h^\infty \beta_{\lambda'} \cdot \sec Z [O_3] \cdot dh \right]$$

$q_{0\lambda}$ and $q_{0\lambda'}$ are the number of light quanta at the outer atmosphere respectively with the wave lengths λ and λ' . In the next place, q_λ and q'_λ are integrated over a certain range of wave lengths for different $\sec Z$ taking into account the change

Chapter 3

The meridional circulation of ozone.

About twenty years ago Dobson²⁾ suggested that the only possible way to explain the annual and meridional variations of ozone is to assume a meridional circulation in the stratosphere. Brewer³⁾ estimated the velocity of horizontal flow toward the pole in the lower stratosphere a little more quantitatively by which he ex-

of α and β according to the wave lengths. In this way, q and q' at every heights at intervals of 5 km are calculated. Thus, x is obtained by summing up $[O_3]$ at every altitudes as follows,

$$(5) \quad x = \int_0^{\infty} [O_3] \cdot dh$$

At present, the velocity constant K can not be obtained theoretically since the heats of activation in the relating chemical reactions are not yet known exactly. Therefore, it is estimated empirically so as to make the calculated total quantity

of ozone being equal to the actual amount on the earth. The result of calculation shows that amount of photochemically forming ozone decreases rapidly with increasing $\sec Z$ (Fig. 2). That is to say, the most of the ozone production takes place in the neighborhood of the equator, on the other hand, only a little amount of ozone is formed photochemically near the pole. Thus, the calculated, annual and meridional variation of x can be obtained and it is also easy to convert x to the mass distribution. Examples of the meridional and annual variations in photochemically calculated M are given in Fig. 1 by full lines which are quite different from

Fig. 2 The relation between x and $\sec Z$ the actual distribution. But, the total mass becomes also constant (see Tab. 1) and almost equal to the actual mass when an appropriate value of K is chosen ($K^{1/2} = 4.2$). From the above results, it might be not unreasonable to consider as follows.

1. The actual total amount of ozone on the whole earth is always constant and it is equal to the amount produced by the photochemical formation. It is however, to be noted that a part of ozone will be lost by absorbing infra-red ray and by coming into contact with reducing substances. But, now, for the sake of simplicity, such reducing effects are neglected,

2. The total quantity and the initial meridional distribution of ozone are decided by the intensity of the solar radiation and secondly the meridional flow brings about the actual distribution. The annual and meridional variations of both effects having each different phase superpose on each other, consequently, the peculiar variations in ozone may be resulted.

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plained the drier air above the tropopause layer. He considered the existence of the general circulation in the stratosphere in which air enters the stratosphere near the equator, then it flows toward temperate and polar regions and sinks again into the troposphere. According to him, the mean horizontal flow of about 0.5 m/sec is allowable just above the tropopause where the eddy diffusion coefficient is of the order, $10^2 \sim 10^3$. Dütsch⁴⁾ tried to explain the annual variation of ozone by introducing the assumption of the vertical flow of the air in the stratosphere which must be compensated by the horizontal flow of about $10^1 \sim 10^2$ m/sec. He asserted that it might not be improper.

The eddy diffusion coefficients above the tropopause layer can be roughly estimated by the vertical gradient of wind speed and the degree of separation of oxygen, helium⁵⁾ and heavier nitrogen isotopes⁶⁾ at different heights. It seems to increase rapidly above 20 km, reaching as large as the order, 10^5 at 30 km and $5 \cdot 10^5$ at 40 km. Therefore, if Brewer's suggestion may be extended above 20 km where the most of ozone is distributed, more speedy circulation will be possible than Brewer's estimation.

In our calculation, the amount of photochemically formed ozone is always larger in the vicinity of the equator, therefore, ozone must be transported to the higher latitude by the meridional flow until it takes an actual distribution. For instance, in summer on the northern hemisphere, the center of gravity of photochemically formed ozone shifts to the same side, but on the contrary, the actual amount becomes larger on the opposite hemisphere. Thus, a part of ozone should be transported from the northern hemisphere to the south passing across the equator. As Dütsch said, it seems reasonable, because, on the southern hemisphere it is colder

Fig. 3 Annual variation of transport velocity of ozone

Fig. 4 The velocity of meridional mass transport of ozone

and a considerably large pressure gradient is formed in the upper atmosphere, especially above 20 km, decreasing toward the south, *vice versa* in the winter on the northern hemisphere.

Now let the speed of the meridional transportation of ozone be u and the mass of ozone be M , then, the time change of ozone mass on a certain latitude φ is given by the next formula.

$$(6) \quad dM/dt = \partial M / \partial t - u \partial M / \partial \varphi - M \partial u / \partial \varphi,$$

where the first term on the right side is the change in the mass of photochemically produced ozone with time. Here, the influence of temperature upon the reaction velocity is neglected since we have considered tri-molecular reactions in the fundamental equation. The above equation may be rewritten in the next form replacing M into x .

$$(7) \quad dx/dt = \partial x / \partial t + u(x \cdot \ln \varphi - \cos \varphi \partial x / \partial \varphi) - x \cos \varphi \partial u / \partial \varphi$$

It is to be noted that physical meaning of flowing speed, u is somewhat complicated. It is not the speed of horizontal flow itself, because, the vertical displacement of ozone also brings about the change in x by contraction or dilatation of air. Therefore, u may be regarded as a resultant speed which consists of true horizontal transportation and a change due to the vertical flow. In other words, it may be said that it is only an apparent speed of transportation of ozone on the meridional

direction.

Using the observed data concerning $\partial x/\partial \varphi$ and the calculated value $\partial x/\partial t$, we can evaluate the speed u approximately. Here, it is assumed that the initial state brought about by the photochemical equilibrium changes into the observed, monthly mean distribution in a half month. The results of estimation of u are given in Fig. 3. The average speed of the apparent flow u in each month is from 1.2 m/sec to 2.9 m/sec, which is a little larger than Brewer's estimation, but it seems to be allowable since the prevailing wind speed is larger than 50 m/sec at higher altitude than 20 km. In Fig. 4 the meridional variation of the apparent transportation speed during a half year are given. As shown in the figure, ozone is transported from the summer hemisphere, as far as from the latitude 40° into the winter hemisphere, and the speed increases with increasing latitude until about 55° . For the latter half of a year, it may be obtained approximately by reversing the direction of the former half. As stated above, though, the speed of apparent transportation u might have an intimate relation to the pole-ward wind speed in the stratosphere, but they are by no means the same things. However, it might give an approximate measure of wind velocity in the stratosphere especially above 20 km.

In considering on the earth as a whole, the absolute mean speed is largest in January and July and smallest in April and October. At a certain latitude, the speed becomes largest in winter and smallest in midsummer, and at a definite time it increases with the latitude until it reaches the maximum at about 55° . According to recent observations of the wind above 18 km in the temperate region, the strong

Fig. 5 Annual variation of reversing point in transport direction

westerly changes into the easterly at the beginning of May and the latter continues until the beginning of September. Generally speaking, it means the presence of the southward component during the summer on the northern hemisphere which is in good agreement with our results in which the reversing of the transport direction takes place respectively in June and August on 30° N as illustrated in Fig. 5.

References

- (1) Miyake Y. and Saruhashi K. 1950: Geophys. Mag., **21**, 99.
- (2) Dobson G. M. B. 1929: Proc. Roy. Soc., A **122**, 484.
- (3) Brewer A. W. 1949: Quart. J. Roy. Met. Soc., **75**, 351.
- (4) Dütsch H. U. 1946: Photochemische Theorie des atmosphärischen Ozons unter Berücksichtigung von Nichtgleichgewichtszuständen und Luftbewegungen, Inaugural-Dissertation, Univ. Zürich. p. 101.
- (5) Paneth G. A. 1939: Quart. J. Roy. Met. Soc., **65**, 304.
- (6) McQueen J. H. 1950: Phys. Rev., **77**, 100, Nature, **166**, 100.