

SHORTER CONTRIBUTION

LARGE-SCALE EDDY FLUX AS A MECHANISM FOR VERTICAL TRANSPORT OF OZONE

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(Manuscript received 13 February 1953)

Introduction.—In a previous paper, the writer (1951) undertook a quantitative analysis of the two most commonly proposed mechanisms for vertical ozone transport, namely, meridional circulation and turbulent mass exchange. The main conclusion derived from the analysis was that, according to our present state of knowledge concerning the physical characteristics of the atmosphere, there is reason to doubt whether either mechanism, acting by itself, can satisfactorily explain the observed behavior of ozone. Although this conclusion cannot be considered final, it does raise the interesting possibility that other processes may be of equal or perhaps even greater importance than the foregoing.

One such mechanism has been suggested previously by the writer (1949). This is large-scale vertical eddy flux, in which the turbulent elements are supposedly the broad ascending and descending currents associated with cyclones and anticyclones (or troughs and ridges). It is a well known fact that substantial exchange of atmospheric properties, such as sensible heat and momentum, is accomplished by means of the horizontal wind components accompanying weather systems. The term *gross austausch* is often applied to this mode of transfer. It therefore seems worthwhile to explore the possibility that the vertical motions in atmospheric disturbances constitute a vertical gross austausch, capable of producing significant downward flux of ozone.

The purpose of the present paper is to make a quantitative estimate of the average magnitude of the flux across a certain level due to the large-scale eddy motions, and to compare it with the observed increase in ozone below. Since little is known concerning vertical motions at levels much above 200 mb (11 km), no attempt will be made to evaluate the downward transport in the critical region above 25 km, where ozone has its source in photochemical processes. Instead, we shall confine our attention to the flux near the tropopause, and hence be concerned chiefly with the origin of tropospheric ozone.

Computations.—The amount of ozone transported across a unit horizontal area in unit time is given by the product qw , where q is the ozone density and w the vertical velocity. Following a familiar method of analysis, we now write

$$q = \bar{q} + q', \quad w = \bar{w} + w'. \quad (1)$$

Here the bars refer to time averages over a period of

months, and the primes denote "instantaneous" deviations from these means.

Forming next the product qw , and averaging with respect to time, we obtain

$$\overline{qw} = \bar{q} \bar{w} + \overline{q'w'}. \quad (2)$$

Physically, (2) expresses the fact that the average vertical transport may be divided into two components. The first, $\bar{q} \bar{w}$, gives the transfer by mean vertical motion and therefore represents the meridional circulation effect studied previously. The second, $\overline{q'w'}$, signifies the flux due to large-scale eddy motion and represents the process now under consideration.

Since, by definition of the quantities involved,

$$\overline{q'w'} = \sigma(q) \sigma(w) r(q, w), \quad (3)$$

where the σ 's refer to standard deviations of the quantities and r is the correlation between them, an upper limit to the magnitude of the large-scale eddy flux may be established immediately by assuming a perfect correlation between q and w . This step will reveal whether the process in question is potentially strong enough to warrant further investigation.

The following computation applies to the flux near 10 km, during the winter months in middle latitudes. On the basis of measurements of vertical ozone distribution presented by Tonsberg and Olsen (1944), $\sigma(q)$ is assumed to be 5×10^{-11} g/cm³. A study by Fleagle (1947) suggests a value of 1 cm/sec for $\sigma(w)$. Hence, with $r = 1$, (3) gives $\overline{q'w'} = 5 \times 10^{-11}$ g cm⁻² sec⁻¹.

This figure may be compared with an average increase of ozone in the layer below 10 km of roughly 5×10^{-12} g cm⁻² sec⁻¹, also based on Tonsberg and Olsen's data. A first conclusion, therefore, is that the mechanism in question is potentially a powerful one. It can by itself account for the observed flow of ozone across the tropopause, even if the correlation between q and w is as small as 0.1.

This of course raises the crucial question of just how highly q and w are correlated, if indeed they are at all. Since simultaneous measurements of the quantities are unavailable, a direct answer to this question is not possible. However, by setting up an idealized physical model, involving known relationships between weather systems and vertical velocities and ozone amounts, we may achieve an independent calculation of the eddy flux without making explicit use of the correlation coefficient.

The following features are incorporated in the model:

1. At a given locality in middle latitudes, a high-level trough-ridge system is assumed to pass overhead once every four days. In accordance with results of Namias (1947), the trough speed is assumed to be 10 deg long per day. It follows that the assumed wavelength is 40 deg long.

2. Vertical velocities are considered to be zero at trough and ridge lines, and at a maximum midway between. Fleagle (1947) shows this to be the usual condition.

3. Positive and negative ozone deviations are assumed to be greatest 2 deg long to the west of trough and ridge lines, respectively. This assumption is based on Meetham's statistics (1937), which imply that the maximum positive ozone deviation is roughly 200 km to the west of the upper pressure trough. (Some doubt exists concerning the accuracy of Meetham's results; nevertheless, the idea that the maximum ozone deviation lags behind the pressure trough, which is essential to the argument, does seem a sound one. It is equivalent to saying that the lag of greatest temperature anomalies behind pressure troughs and ridges is a logical consequence of the average north-south temperature gradient, if, for the purpose of analogy, we consider horizontal gross Austausch.)

4. Vertical velocities and ozone deviations are assumed to vary sinusoidally with time, at a fixed spot.

The foregoing conditions are expressed mathematically as follows:

$$q' = Q \sin \frac{\pi}{48} (t - 20), \quad w' = W \sin \frac{\pi t}{48}, \quad (4)$$

where Q and W are the amplitudes of the variations. In integral form, $\overline{q'w'}$ may be written

$$\overline{q'w'} = P^{-1} \int_0^P q'w' dt, \quad (5)$$

P being the period of oscillation, measured in hours. Hence, from (4),

$$\overline{q'w'} = \frac{WQ}{96} \int_0^{96} \sin \frac{\pi t}{48} \sin \frac{\pi}{48} (t - 20) dt. \quad (6)$$

By means of suitable trigonometric transformations, (6) may be integrated to give

$$\overline{q'w'} = \frac{1}{2} WQ \cos 5\pi/12. \quad (7)$$

In a sinusoidal distribution, the amplitude factor is $2^{1/2}$ times the standard deviation of a variable. Therefore,

$$\overline{q'w'} = \sigma(w) \sigma(q) \cos 5\pi/12 \quad (8)$$

and using the previously selected values of $\sigma(w)$ and $\sigma(q)$, we finally obtain

$$\begin{aligned} \overline{q'w'} &= 1 \times 5 \times 10^{-11} \times 0.26 \\ &= 13 \times 10^{-12} \text{ g cm}^{-2} \text{ sec}^{-1}. \end{aligned}$$

This result suggests that the correlation between q and w lies between 0.2 and 0.3, sufficiently large to give an appreciable flux of ozone. It also points to the desirability of obtaining a more precise measurement

of the average phase lag between the high-level pressure and ozone waves.

Concluding remarks.—From the foregoing analysis, it is apparent that large-scale vertical eddy flux may be an important mechanism for transporting ozone from the stratosphere to the troposphere. How important this process is at higher levels is a question which cannot be answered until more is known concerning vertical velocities in the stratosphere, but it is a matter which warrants considerable attention. Tonsberg and Olsen's (1944) measurements reveal that variations in total amount of ozone are mainly the results of changes in ozone content below the 20-km level. This may be interpreted as an indication that the seasonal and latitudinal variations are determined primarily by the transfer of ozone across that level. If it is the large-scale vertical eddy flux associated with weather systems which effects that transfer, it should be expected that ozone amounts increase most rapidly in winter, when cyclonic activity is most pronounced. Furthermore, it should be anticipated that highest ozone amounts occur on the average at latitudes between 50 and 60°N, where the interdiurnal variability of pressure change is greatest (Klein, 1951). As regards these requirements:

1. There can be no doubt that the ozone content of the atmosphere increases most rapidly in winter.
2. Ozone measurements at high latitudes are still too scanty, and in some cases too inaccurate, to state positively the character of the latitudinal variation; but observations taken during months of high sun, when measurements are most reliable, do indicate a maximum in the 50 to 60°N range.

In conclusion, it should be pointed out that if large-scale eddy flux proves to be of importance for the vertical transport of ozone, it will no doubt assume an equally significant role in the horizontal transport.

Acknowledgment.—The writer wishes to thank Prof. V. P. Starr for helpful suggestions.

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