THE ROLE OF VERTICAL MOTIONS IN OZONE-WEATHER RELATIONSHIPS

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ABSTRACT

The relative importance of horizontal advection and vertical motion in producing the day-to-day changes in total ozone amount is calculated, and the manner in which these two factors combine to produce the well-known ozone-weather relationships is explained. The calculations show that at most one third of the range of daily values is attributable to vertical motions, the remainder presumably being the result of horizontal advection.

1. Introduction

From the time of Dobson's early measurements, it has been known that the total ozone amount undergoes large day-to-day fluctuations. Data from stations in many parts of the world have revealed that these fluctuations are everywhere greatest in winter and spring, while in any one season they are greater at high than at low latitudes. Figs. 1 and 2 illustrate these statements on the basis of data from two representative stations: Arosa, Switzerland, and Tromso, Norway. The figures show the frequency of occurrence of various per-cent departures of the daily ozone amounts from the monthly means.

However, the day-to-day changes of total amount are not only of interest because of their amplitude—which, incidentally, is nearly as large as the amplitude of the seasonal variation—but also because of the relationships which have been established between them and various meteorological quantities.

Dobson and collaborators (1928) have shown that maximum positive deviations of daily values from the monthly means are generally found to the rear of surface low-pressure areas, while maximum negative deviations are found to the rear of surface highs. More recently, on the basis of more extensive measurements, Dobson and collaborators (1946) have refined the earlier results and found that for many occlusions the maximum positive deviations occur directly over the surface low rather than to the rear.

Tonsberg and Olsen (1943) have related the deviations of total ozone amount to surface fronts. In general, they found that the surface cold or occluded front is the dividing line between positive and negative departures.

In addition to the ozone-weather relationships discussed above, significant correlations have been obtained by Meetham (1937) between total ozone amount and various meteorological quantities in the upper atmosphere. In particular, he found that the total amount correlates positively with the temperature and potential temperature in the lower stratosphere and negatively with the density and the height of the tropopause.

Since the day-to-day variations are now known to have their origin principally in the regions between 5 and 20 km, where photochemical effects are negligible (Wulf and Deming, 1936, 1937; Dütsch, 1946; Craig, 1949), the preceding ozone-weather relationships are today attributed either to the effects of horizontal advection or large-scale vertical motions, or a com-

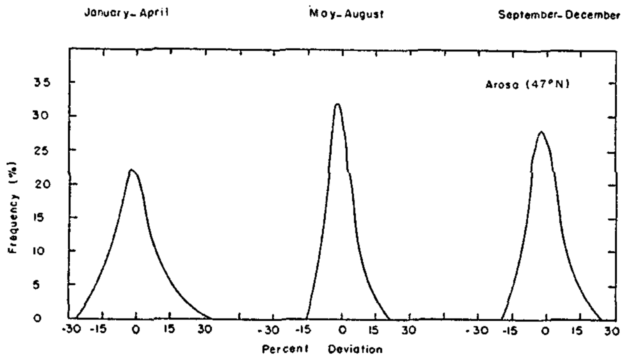

FIG. 1. Frequency of occurrence of variousp er-cent ozone deviations during three different seasons at Arosa, Switzerland (47°N).

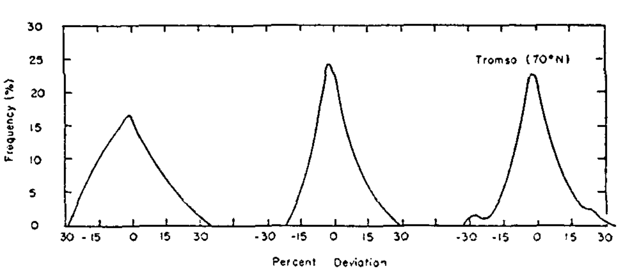

FIG. 2. Frequency of occurrence of various per-cent ozone deviations during three different seasons at Tromso, Norway (70°N).

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[1] This paper is based on a doctor's thesis written by the author at the Massachusetts Institute of Technology in June 1949.

bination of both. The horizontal-advection theory is based on the circumstance that, on the average, the total ozone amount increases northward. As a consequence, northerly advection over a station may be expected to produce an increase, and southerly advection a decrease, in ozone amount.

The vertical-motion theory is based on the fact that, due to the compressibility of the atmosphere, air parcels experience an increase in density as they descend. For those atmospheric gases which normally increase in density downward, no local change of concentration results from a downward displacement. But since the density of ozone normally increases upward in the lower stratosphere, a downward displacement has the effect of greatly increasing its concentration at any one level. Conversely, upward motion produces a local decrease of ozone concentration.

In the past, the relative importance of horizontal advection and vertical motions in producing the day-to-day variations has been the subject of considerable debate. In recent years, calculations of the vertical-motion effect have been made by Nicolet (1945) and Dütsch (1946), so that the question is now settled to a large extent.

The object of the present paper is to repeat the computations of Nicolet and Dütsch, employing a simpler and more accurate method. The results of these computations establish quite definitely the magnitude of the vertical-motion effect, and comparison of this magnitude with the observed size of the day-to-day changes indicates the importance of horizontal advection. After estimation of the relative contribution of each of these factors to the day-to-day fluctuations, it is shown schematically how they combine to produce the well-known ozone-weather relationships.

2. The vertical-motion effect

To compute the vertical-motion effect, it is necessary to select an observed curve of the vertical ozone distribution and to assume that this represents the initial distribution in a vertical air column. Next, in conformity with observational evidence, a distribution of vertical displacements or vertical velocities is allowed to operate within the column. As explained previously, the vertical motion has the effect of changing the ozone concentration at the various heights within the column. As a result, a new curve of ozone concentration versus elevation is obtained. Comparison of the areas under the initial and final curves gives the increase or decrease in total amount of ozone.

Previous methods for carrying through the above procedure have dealt with vertical ozone distributions expressed in terms of cm km^{-1}, a unit[2] which is equivalent to density. Because of the compressibility of the atmosphere, it has been necessary to take into account the horizontal divergence which accompanies vertical displacements. However, if the vertical distribution is expressed in terms of the ozone mixing ratio instead of cm km^{-1}, the upward and downward displacements can be made without any additional considerations and the final result obtained with greater ease and accuracy. This use of the ozone mixing ratio as a conservative property is entirely permissible in the present problem, since the day-to-day fluctuations have their origin, as stated above, in the region of non-equilibrium ozone. Furthermore, the conversion of conventional cm km^{-1} curves into mixing ratio curves presents no difficulty. Multiplication of the values of points on the former curves by 2.14×10^{-8} converts the ozone density into the standard unit of g cm^{-3}. Division by the air density then gives the desired dimensionless ratio.

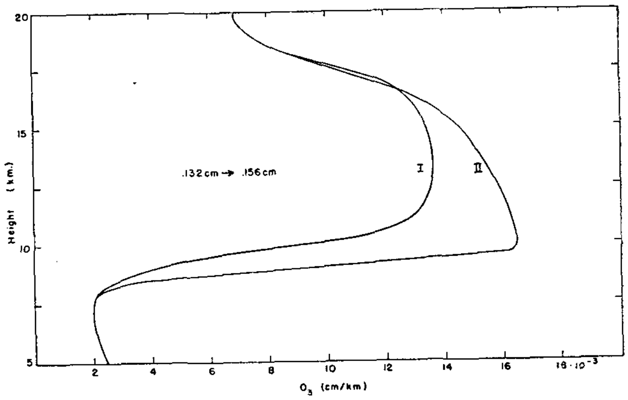

FIG. 3. Curve I is ozone concentration as function of height before subsidence, Curve II the same after subsidence.

The foregoing discussion will now be illustrated by an example. Curve I in fig. 3 represents the assumed initial vertical ozone distribution in the region between 5 and 20 km for a total amount of .320 cm, the amount in the section under consideration being .132 cm. The curve itself is patterned after the *Umkehr* curve given by Götz (1944) for a total amount of .340 cm. The maximum at about 13 km is a secondary maximum, a common feature for high total amounts. The primary maximum would be found in the vicinity of 26 km, if the curve were extended to that height.

On the other hand, curve I in fig. 4 gives the same vertical distribution in terms of mixing ratio, air densities for the U. S. Standard Atmosphere being used to make the conversion. This latter curve is next assumed to be displaced downward, and a new curve, curve II in fig. 4, is obtained. The lengths of the ordinates included between the two curves indicates the assumed displacements.

Reconversion of this second curve into cm km^{-1}, again using air densities for the U. S. Standard Atmos-

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[2] According to this usage, the term "cm" refers to the thickness of ozone which would result if the ozone in a vertical column 1 km in length were brought to standard temperature and pressure.

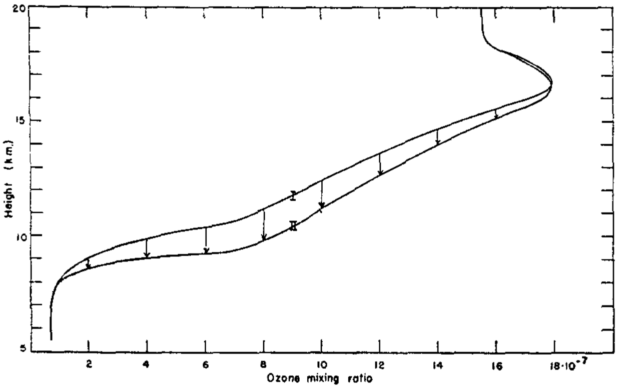

FIG. 4. Curve I is ozone mixing ratio as function of height before subsidence, Curve II the same after subsidence.

phere, gives curve II in fig. 3, the ozone distribution after subsidence has occurred. Finally, the total amount in the region between 5 and 20 km for this latter curve is obtained by summing the abscissae at 1 km intervals. In the present case, this amount is found to be .156 cm, an increase of .024 cm over the initial amount of .132 cm.

To calculate the positive deviations due to subsidence and the negative deviations due to lifting, it is necessary in the one case to determine the distance that air particles in a moving column may in practice sink below their normal elevations, and in the other case the vertical distance that they may rise. Various methods suggest themselves for determining these distances from high-level meteorological data. One such method, the one used in the preceding example, is based on certain simple considerations concerning the temperature field in the lower stratosphere.

In winter, north of 40 deg lat, the horizontal temperature-gradient at these heights is, on the average, very small (see Hess, 1948). Thus, the strong temperature fields which are a characteristic feature of synoptic charts of the lower stratosphere, for example the 200-mb chart, can be attributed almost entirely to the adiabatic heating and cooling that accompanies descent and ascent, respectively, of stratospheric air currents. To gain an idea, then, of the possible extremes of the displacements, it is only necessary to compare the mean sounding for the season in question with individual soundings that show extremely low and extremely high temperatures over a large height-interval in the lower stratosphere. The height differences are determined by taking points on the mean sounding and tracing upward or downward along a dry adiabat until the extreme curves are intersected, and noting the height intervals traversed.

By this method it can be concluded that an upward or downward displacement of 1.5 km is nearly an extreme value. Since in the illustrative example a maximum displacement of 1.4 km was assumed, and since, in addition, the other factors entering into the computations were chosen so that they would give a large value, the computed deviation of +.024 cm must be close to the upper limit attainable from the vertical motion effect.

From the ozone and temperature observations, other combinations of vertical ozone distributions and vertical displacements may be selected, and the pertinent deviations calculated. None of these, however, will significantly change the above upper limit.

It is now possible to state with some assurance the relative importance of vertical motion and horizontal advection in the day-to-day changes. As noted, the maximum positive deviation due to vertical motion is about .024 cm. On the other hand, the maximum negative deviation will be somewhat smaller, since low ozone values occur in stratospheric air which has been advected from more southerly regions where the ozone content is initially smaller. Application of the previous scheme of vertical displacements, upward now instead of downward, to a curve for a total amount of .260 cm discloses that −.017 cm is a reasonable, large value for the negative deviation. Thus, the total deviation possible from the vertical-motion effect is approximately .040 cm. Because of the various assumptions made, this amount may be considered representative of the maximum conditions at a middle-latitude station in late winter or early spring. The observed total range of deviations for such a station during these seasons is about .120 cm. Thus, vertical motions account for at most one third of the range, and the remainder must presumably be produced by horizontal advection. At higher latitudes, where the total range is considerably larger, the role of vertical motions must be even less.

3. Explanation of ozone-weather relationships

Pressure troughs in the lower stratosphere are characteristically observed to be areas of warmth, while ridges are observed to be areas of cold. Furthermore, these warm and cold areas do not move with the speed of the winds. Instead, they move with the speed of the pressure systems, which, as a rule, progress much more slowly than the wind component in their direction of motion. In other words, the high-level winds blow through the accompanying pressure and temperature patterns. From this it follows that the warm and cold areas must be dynamically produced as a result of subsidence and lifting, respectively, the maximum of warmth in the troughs and cold in the ridges indicating that the downward and upward displacements are greatest in these regions. The vertical-motion effect, therefore, produces maximum positive deviations in high-level troughs and greatest negative deviations in ridges.

At the same time, because of the approximate coincidence of trajectories and isobars at high levels, the air moving through stratospheric troughs is air which has undergone a maximum southward displacement from its previous position, while the reverse is true for the air in ridges. Since, on the average, the ozone amount increases northward, the southward displacement of air into the trough brings above normal amounts or positive deviations into that region, and similarly the northward advection into the ridge produces negative deviations there. The joint effect, then, of vertical motions and horizontal advection is to produce positive deviations in high-level troughs and negative deviations in high-level ridges.

The foregoing considerations are entirely in agreement with Meetham's correlations. According to empirical evidence, the high-level trough is a region of warm temperature, high potential temperature and low tropopause. It will be recalled that Meetham found that high ozone amounts are associated with all these conditions.

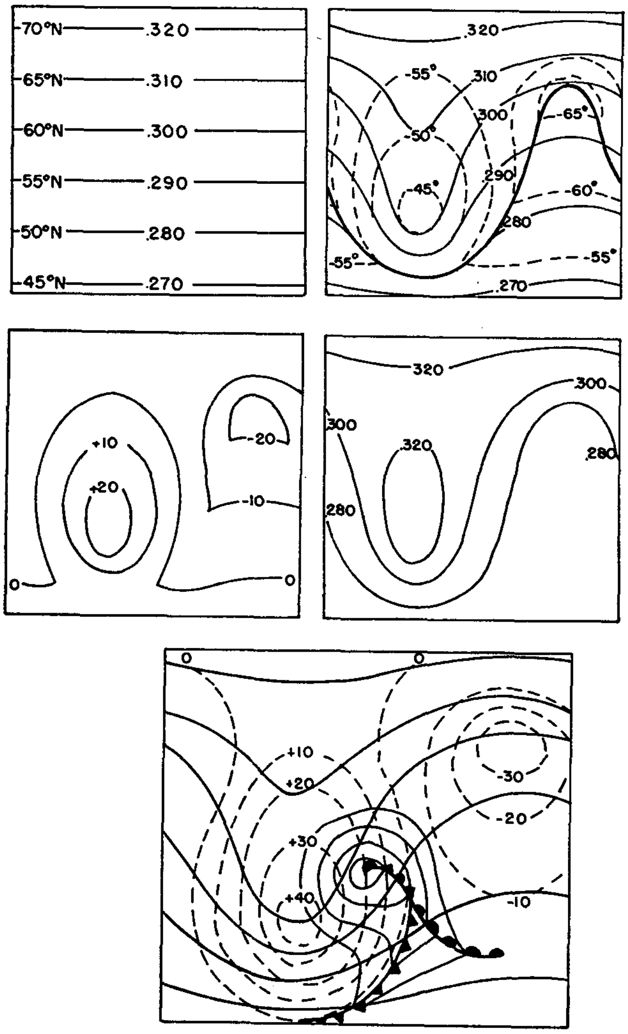

FIG. 5. Schematic diagram of ozone-weather relationships. Upper left (a): assumed initial, undisturbed, meridional distribution of total ozone amount in cm. Upper right (b): disturbed state; thin solid lines give ozone distribution resulting from horizontal displacement only and represent approximate 200-mb contours; dashed lines are 200-mb isotherms; solid line is intersection of tropopause with 200-mb surface. Middle left (c): ozone deviations (cm·10^3) due to vertical displacements. Middle right (d): final distribution of total amount, taking account of both horizontal and vertical displacements. Bottom (e): heavy solid lines are high-level contours; thin solid lines are sea-level isobars; surface fronts depicted according to usual convections; dashed lines are total ozone deviations (cm·10^3).

The relationships between the ozone deviations and the surface weather-situation follow as a natural consequence of the observed relationships between high- and low-level pressure systems. Generally, the upper-level systems are displaced to the rear of the surface systems. Thus, the positive deviations should appear to the rear of the surface cyclone and the negative deviations to the rear of the sea-level anticyclone. Newly formed lows ordinarily have a steeper vertical tilt than old occlusions, the latter frequently exhibiting nearly vertical structures. This explains the tendency, noted by Dobson, for the positive deviations to be directly over some occlusions. Furthermore, the surface cold- or occluded-front lies, on the average, about midway between the high-level trough and ridge. Therefore, the surface front should lie in the region between the positive and negative deviations.

The increase in magnitude of the ozone deviation with latitude can be accounted for by the increased intensity of storm systems at high latitudes and the concomitant stronger vertical motions and greater amplitudes of the horizontal flow at these latitudes. Also, the diminution of the deviations in summer may be attributed to the weakening of storm activity during that season.

The foregoing ideas are summarized with the aid of fig. 5. Fig. 5a represents an assumed initial state with a north–south ozone gradient, similar to the average gradient for March, and with east–west air flow. Next, a disturbance is assumed to form in the zonal flow so that the air is displaced southward into the trough and northward into the ridge. The thin solid lines in fig. 5b represent the new ozone distribution and also, roughly, the flow and isobaric patterns. Although the values for the total amounts are attached to these lines, it should be noted that only that portion of the total amount contained in the lower stratosphere is varying significantly. To bring out the high-level meteorological conditions which accompany such a disturbance, a schematic temperature field (dashed lines) and tropopause (solid line) at the 200-mb level are included in the figure.

Thus far, no account has been taken of the effects of vertical motion. This deficiency is remedied in fig. 5c, where a pattern of ozone deviations consistent with the temperature field in the preceding figure is shown. In the figure, these deviations are expressed in thousandths of cm.

The addition of the deviations in fig. 5c to the total amounts in fig. 5b gives the ozone distribution represented in fig. 5d, which can be considered the final distribution of total amount as a result of the combined effects of advection and vertical motion.

In conclusion, fig. 5e depicts on a single diagram the high-level isobaric pattern (heavy solid lines), sea-level pressure system (usual convention), and the total deviations (dashed lines). The latter were determined by graphically subtracting the ozone amounts in fig. 5a, which represent the normal values for the season, from the disturbed amounts in fig. 5d. The agreement between this picture and the observed features of the ozone-weather relationships is evident.

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