A Case Study of the Vertical Distribution of Atmospheric Ozone[1]

John G. Breiland
The University of New Mexico, Albuquerque

(Manuscript received 23 October 1964)

ABSTRACT

Vertical distributions of ozone observed at Albuquerque, New Mexico, and at Fort Collins, Colorado, on 5, 6 and 7 May 1963 by means of the chemiluminescent ozone-sonde are compared with the structure of the wind and temperature fields during this period. The comparison indicates that during the passage of an upper trough, accompanied by a trough in the conventionally defined middle tropopause, the increase in partial pressure of ozone with altitude begins at a level considerably lower than the level of the tropopause. In general, secondary maxima in the partial pressure of ozone between the level of the main ozone maximum and the level of the middle tropopause at the time of the sounding are associated with tongues, or layers, of polar or middle-latitude stratospheric air injected into tropical air. Tongues of tropical air injected into higher-latitude stratospheric air are associated with a decrease in the partial pressure of ozone. Small-scale features as well as large-scale features of such interpenetrations of polar or middle-latitude stratospheric air and tropical air, as indicated by the temperature field, are substantiated by the ozone soundings.

1. Introduction

During the period 29 April to 10 May 1963, observations of the vertical distribution of atmospheric ozone were made daily with balloon-borne chemiluminescent ozone-sondes (Regener, 1964) at eleven stations in North America as a part of a research project initiated in January 1963 by the Air Force Cambridge Research Laboratories. In this paper, the vertical distribution of ozone on 5, 6 and 7 May 1963 and its day-to-day variation during this period at two middle-latitude stations, Albuquerque, New Mexico, and Fort Collins, Colorado, are discussed. The atmospheric structure during this same period is discussed by means of 200-mb constant pressure charts, time and space cross sections depicting the temperature and wind fields, and temperature soundings from individual stations. Locations of stations are shown in Fig. 1. The line extending from El Paso (ELP) northward to Canada indicates the orientation of the vertical cross sections shown in subsequent figures.

2. Typical ozone soundings

In a previous paper (Breiland, 1964), it was pointed out that variations in the vertical distribution of ozone are associated with variations in the height and structure of the tropopause. At Albuquerque, located at 35N, the structure of the atmosphere in the winter and spring frequently is characterized by a double tropopause. This feature is especially prominent in the spring. At this time, the middle tropopause frequently extends southward beyond Albuquerque at the same time that the higher-level tropical tropopause extends well to the north of the station. Under such circumstances, a secondary maximum in the partial pressure of ozone generally is observed in the region between the middle tropopause and the tropical tropopause, indicating an intrusion of a layer of polar or middle-latitude stratospheric air, rich in ozone, into the tropical troposphere. But during the summer and autumn, the middle tropopause frequently does not extend southward to Albuquerque, while the tropical tropopause extends far northward. The partial pressure of ozone is then small at all levels below the tropical tropopause in regions where the middle tropopause is absent.

In Fig. 2 are shown two ozone soundings and the corresponding temperature soundings, both sets slightly smoothed, illustrating the two cases described in the foregoing paragraph. Both sets of observations were

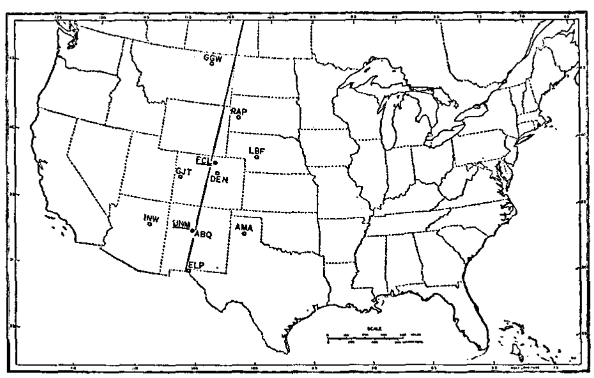

Fig. 1. Locations of stations. Line extending from El Paso (ELP) northward indicates orientation of cross sections shown in Figs. 7, 8 and 9. University of New Mexico (UNM) and Fort Collins (FCL) are ozone-sonde stations.

[1] A part of this paper was presented on 2 September 1964, at the International Atmospheric Ozone Symposium, Albuquerque, N. Mex.

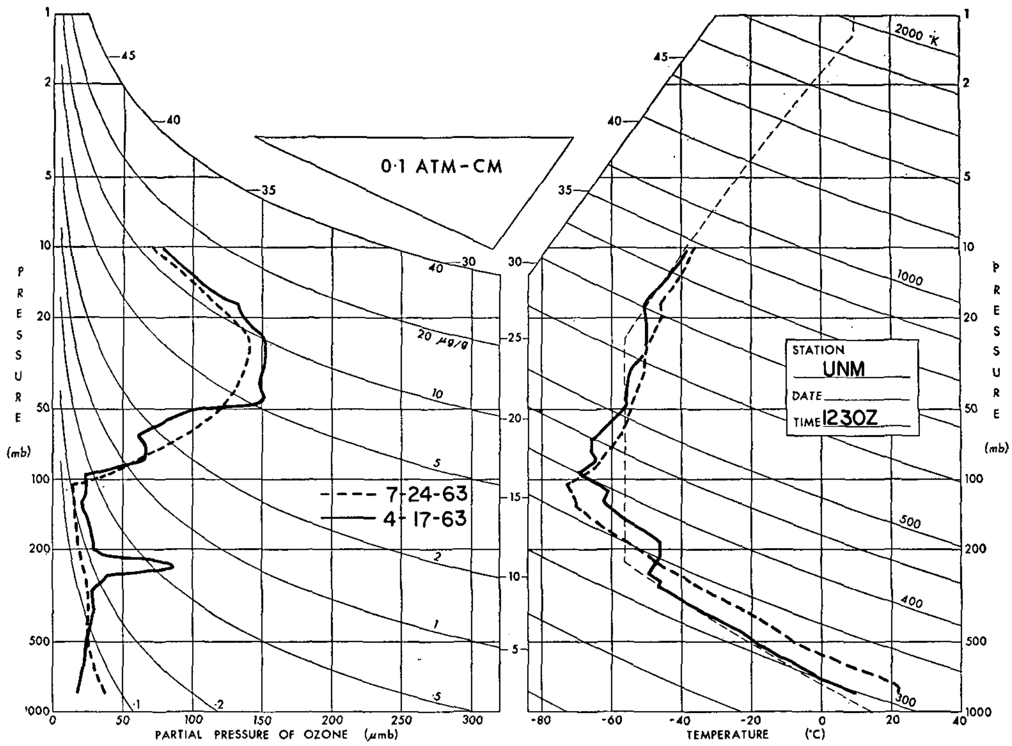

FIG. 2. Comparison of the vertical distribution of ozone and temperature shown by a typical summer sounding through a tropical air mass (dashed curves) with the vertical distribution of ozone and temperature shown by a sounding through a double-tropopause (middle and tropical) structure in the spring (continuous curves).

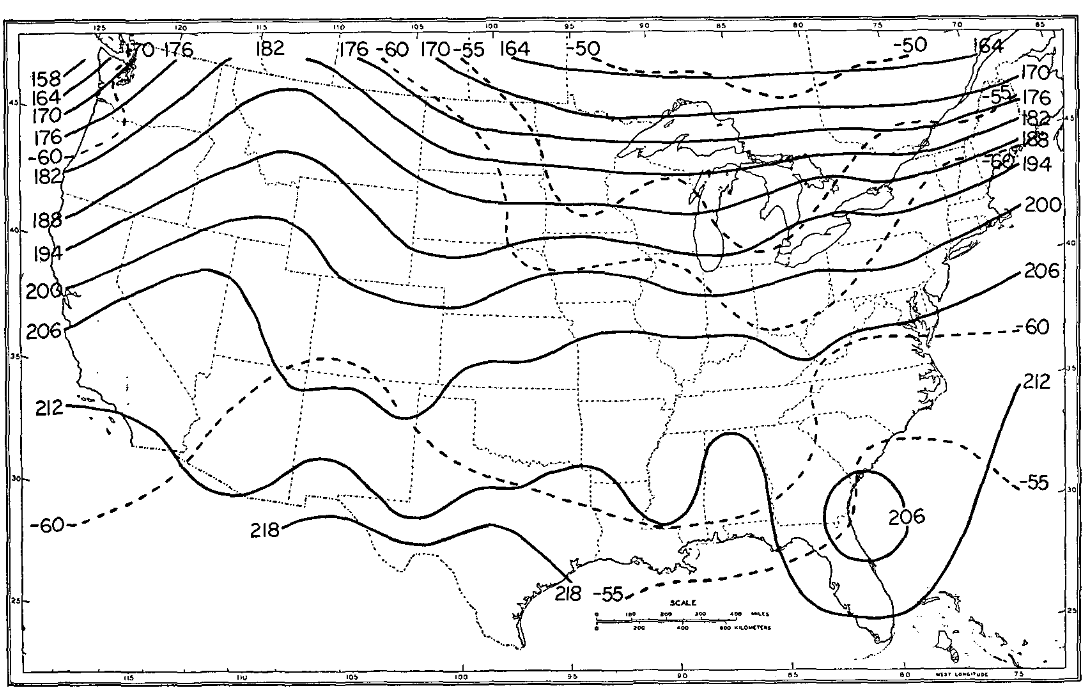

FIG. 3. 200-mb chart, 1200 GMT 5 May 1963. Continuous lines are contours (decameters); dashed lines are isotherms (C).

taken at the University of New Mexico (UNM), Albuquerque, one in the summer and the other in the spring. The dashed curves represent an ozone sounding and a temperature sounding taken on 24 July 1963 through a tropical air mass. The temperature sounding indicates that there is a single, well-defined tropopause at about the 105-mb level above the station at this time. This is called the tropical tropopause. The ozone sounding shows that immediately above this tropopause the partial pressure of ozone increases rapidly with altitude.

The continuous curves show the vertical distribution of ozone and temperature at the time of a double-tropopause structure. The temperature curve shows that in this case there are two air masses above the station. A polar or middle-latitude air mass, with a middle tropopause, extends from the surface up to about the 200-mb level; above this level there is a tropical air mass, with a tropical tropopause.

The middle tropopause is at the 260-mb level, but there is also a thin, stable layer at the 290-mb level. It should be noted that the partial pressure of ozone shows a significant increase with altitude beginning at this lower level, although it increases more rapidly immediately above the 260-mb level. In the transition layer between the upper tropical air mass and the lower polar or middle-latitude air mass the partial pressure of ozone decreases rapidly with altitude to a small value in the tropical troposphere.

As is indicated by the temperature curve, the tropical tropopause, coinciding with the level of minimum temperature, is located at about the 95-mb level. But there are also two secondary minima in the temperature curve near this level, one at about the 125-mb level and the other at about the 65-mb level. The stratified structure of the air that is indicated by this temperature distribution is also well indicated by the corresponding ozone sounding, which shows minima in the partial pressure of ozone corresponding to the temperature minima. Such phenomena have also been observed in several other cases. This suggests that when a tropical air mass with its cold tropical tropopause is displaced northward, an injection of tropical air into warmer polar or middle-latitude stratospheric air may take place in a multiple-layer fashion. In a study of cross sections of mean temperature along 80W, Kochanski (1955) points out that a separate tropopause leaf seems to exist in the vicinity of the tropical tropopause at 40 to 50N. He shows that this feature is substantiated by daily temperature soundings. Newton and Persson (1962) also have shown the existence of multiple tropical tropopauses.

3. Analysis of data

On 4 May 1963 a minor trough of low pressure began to develop in the upper troposphere over southwestern United States. The trough intensified on 5 and 6 May and moved southeastward. Figs. 3, 4 and 5 show the contours of the 200-mb constant pressure surface on 5, 6 and 7 May. The development of this trough took place in conjunction with the development of a ridge of high pressure to the northwest of the trough associated with a northeastward displacement of a

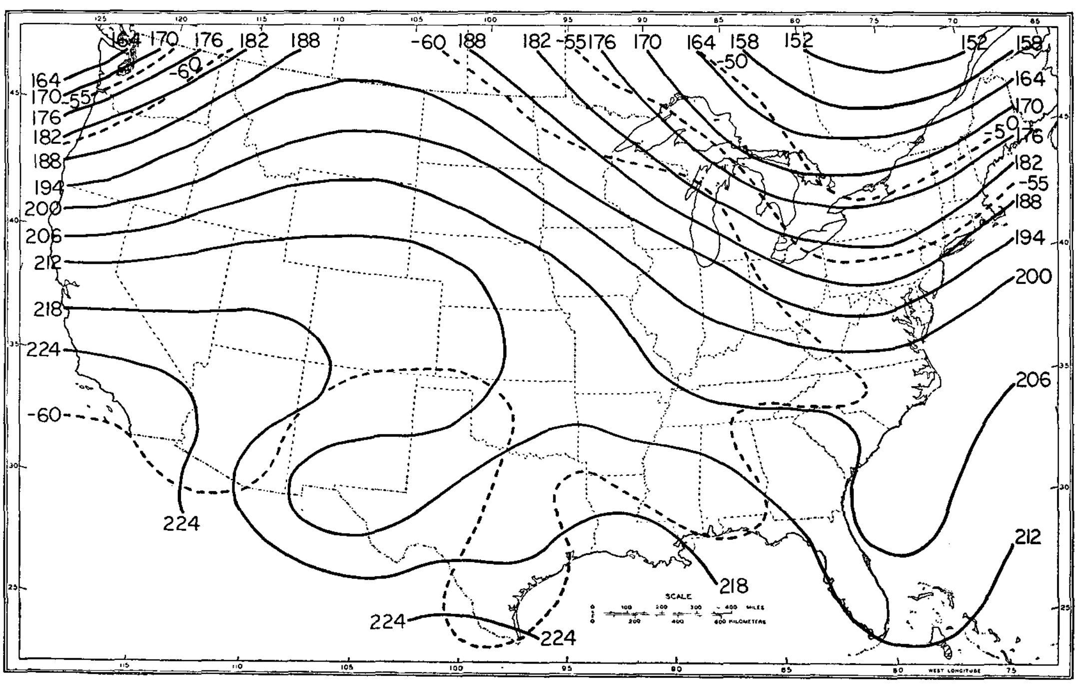

FIG. 4. 200-mb chart, 1200 GMT 6 May 1963. Notation as in Fig. 3.

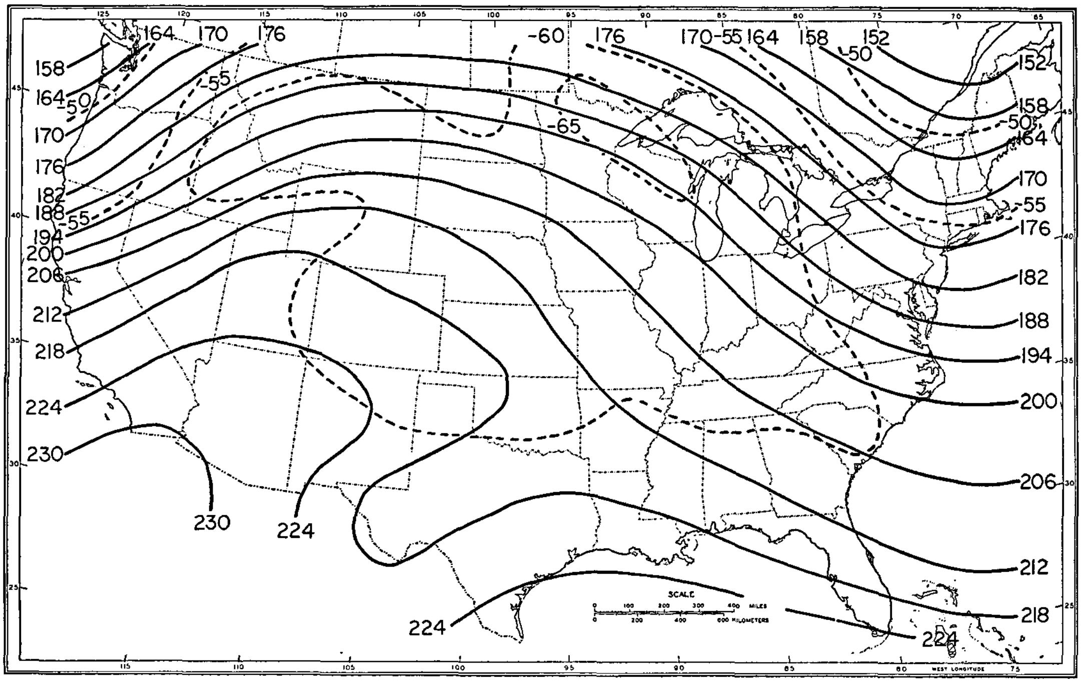

FIG. 5. 200-mb chart, 1200 GMT 7 May 1963. Notation as in Fig. 3.

subtropical air mass having a high and cold middle tropopause.

Fig. 6 is a time section for Albuquerque showing the vertical distribution of wind and temperature observed at 12-hourly intervals from 4 May to 10 May 1963. The dots indicate the height of the middle tropopause according to the definition adopted by the U. S. Weather Bureau. In the layer between the 30-mb level and the 50-mb level the temperature shows very little change during the time interval covered by the time section. The largest change in temperature is observed at about the 150-mb level, where the temperature decreases from −57C on 5 May to about −72C on 8 May. In the upper troposphere the winds change from westerly to northeasterly and back again to westerly as the trough-ridge system passes the station. At about the 75-mb level the temperatures remain rather low during the entire period of the time section, probably owing to a northward displacement of cold tropical air. Immediately above this layer of cold tropical air, the temperature increases rapidly with altitude, resulting in a layer of very stable air between the 70-mb level and the 50-mb level. Above this stable layer the winds are mostly light easterlies.

In the left part of Fig. 7 is shown a vertical cross section for 5 May 1963 extending from ELP northward into Canada along the line indicated in Fig. 1. In Fig. 7 are also shown ozone and temperature soundings for FCL and UNM. Wind observations at UNM taken simultaneously with observations of ozone and temperature are plotted on the same diagram as the ozone sounding. Temperature soundings from nearby U. S. Weather Bureau stations also are shown. Ozone and temperature observations at UNM and FCL generally are taken approximately one hour later than the 1200 GMT U. S. Weather Bureau observations. On 5 May, however, the observations at FCL were approximately three and one-half hours late, and therefore are not strictly comparable with observations taken at UNM.

Certain main features, however, may be discussed. The FCL temperature sounding shown in Fig. 7, taken simultaneously with the ozone sounding, indicates that there is a fairly well-defined middle tropopause at about the 200-mb level at the time of the sounding. Immediately above the tropopause, there is a layer of stable polar or middle-latitude stratospheric air. The ozone sounding indicates that this stable layer is rich in ozone. In the less stable air of tropical characteristics above this layer, the partial pressure of ozone is smaller except for a thin layer of air of high partial pressure of ozone at about the 100-mb level. A thin layer of high partial pressure of ozone also shows up on the ozone sounding for UNM, at about the 110-mb level. A close examination of the vertical cross section and the individual temperature soundings shown in Fig. 7 reveals that this ozone-rich layer corresponds to a tongue of warm polar or middle-latitude stratospheric air injected into colder tropical air.

As indicated by the temperature field shown in the cross section in Fig. 7, there is a depression, or trough, in the middle tropopause between Denver (DEN) and ABQ at the time of the observations. This trough is associated with the trough of low pressure in the upper troposphere. The tropopause in such troughs often is

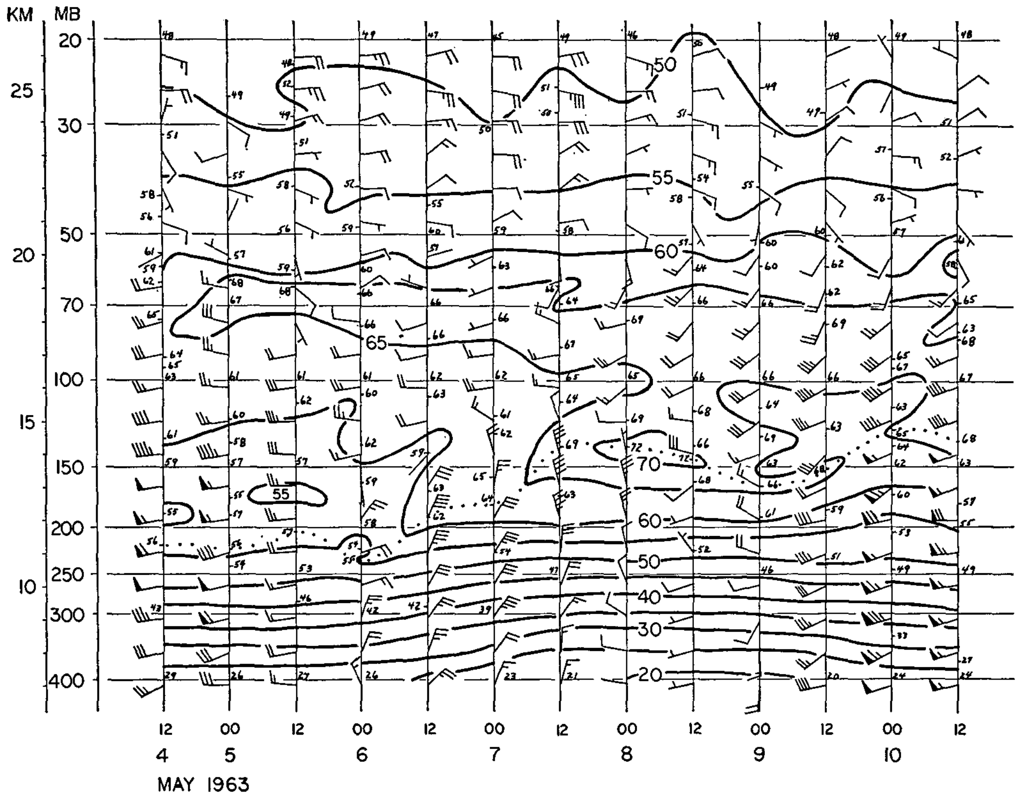

FIG. 6. Time section for Albuquerque for the period 1200 GMT 4 May 1963 to 1200 GMT 10 May 1963. Plotted values are temperatures (C), minus signs omitted. Continuous lines are isotherms. The tropopause is shown by dots. Winds are shown by conventional symbols; each pennant represents 50 knots, full line 10 knots, half line 5 knots.

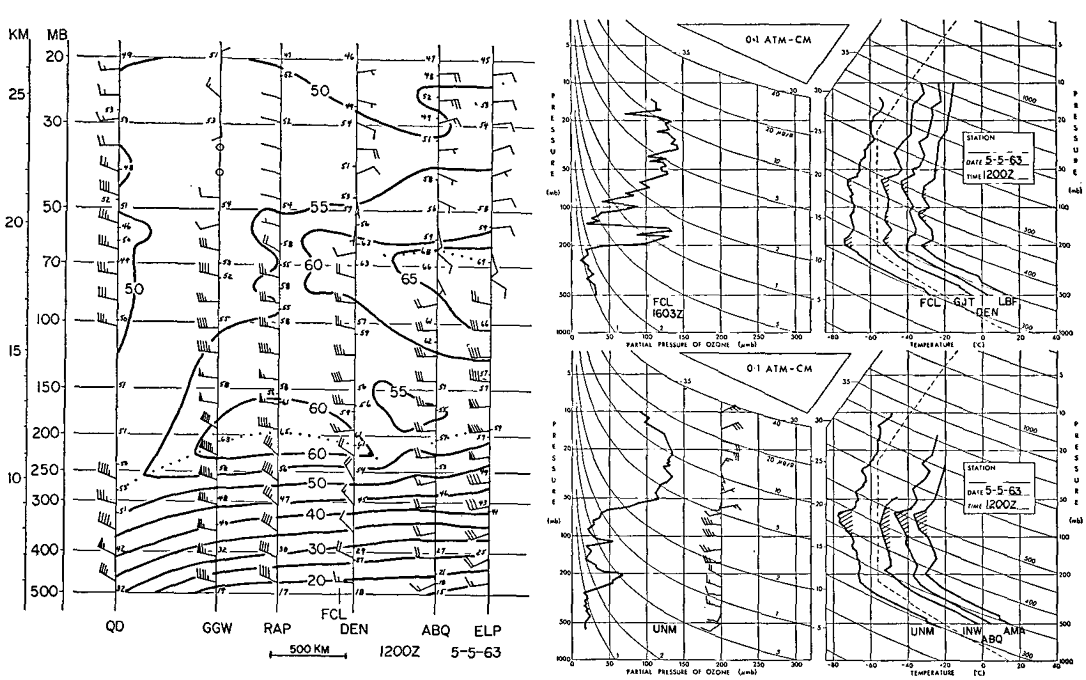

FIG. 7. Vertical distribution of ozone, wind, and temperature 5 May 1963. See Fig. 1 for locations of stations. The temperature curves are displaced horizontally, for clarity; the area to the left of the −60C isotherm for each temperature sounding is shown by hatching. Notation in the cross section as in Fig. 6.

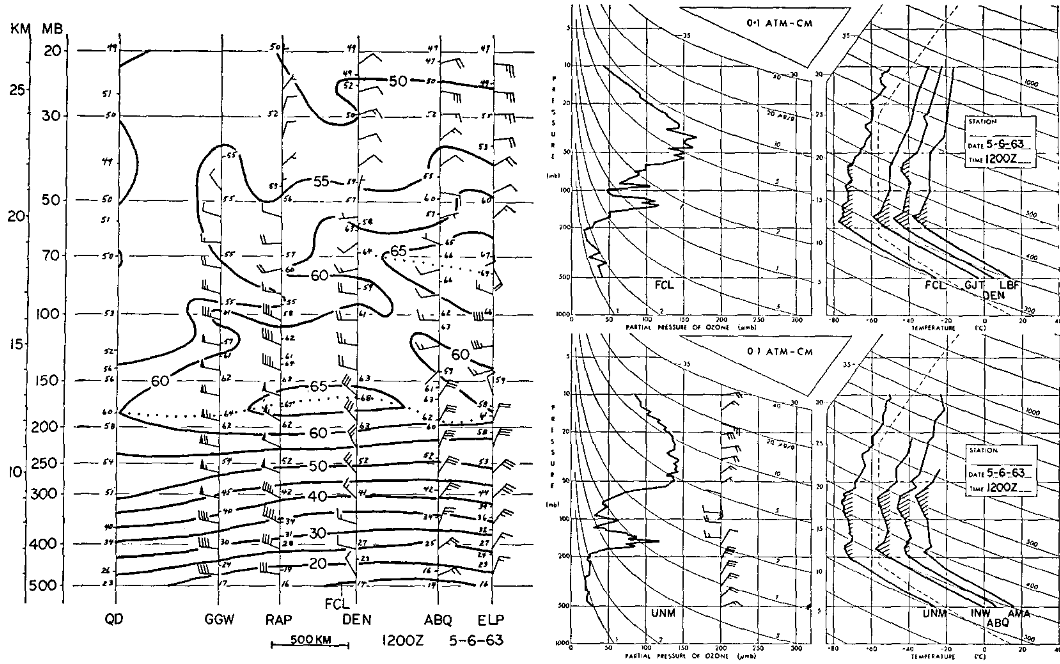

FIG. 8. Vertical distribution of ozone, wind, and temperature 6 May 1963. See Fig. 1 for locations of stations. Notation as in Fig. 7.

indefinite (Sawyer, 1955). It has also been shown (Reed, 1955; Reed and Danielsen, 1959; Staley, 1960) that in such troughs there may be air of stratospheric origin at levels below the conventional tropopause. The temperature sounding for Amarillo (AMA) shown in Fig. 7 indicates that at the time of the observation (1200 GMT) there is a well-defined tropopause at about the 200-mb level at this station. At ABQ, the conventional tropopause is also at about the 200-mb level at this time, but the tropopause there is less definite than it is at AMA. It is even more indefinite one hour later, as indicated by the UNM sounding. At this time, although there is a temperature minimum at the 200-mb level, the conventional tropopause is located at about the 240-mb level. But there is also a significant change in hydrostatic stability at about the 300-mb level, where the temperature lapse rate changes from a nearly dry-adiabatic lapse rate to one associated with a more stable air mass. It seems significant that the partial pressure of ozone begins to show a rather large rate of increase with altitude at this level, not at the level of the conventional tropopause, which at this time is located at a higher level. Apparently, stratospheric air, rich in ozone, extends down to the 300-mb level over UNM at this time.

The effect of a northward displacement of tropical air in reducing the partial pressure of ozone over a station is clearly evident in the ozone sounding for UNM shown in Fig. 7. In the layer of uniform and fairly strong westerly flow of tropical air between approximately the 180-mb level and the 65-mb level, except for the thin layer of polar or middle-latitude air of higher partial pressure of ozone referred to previously, the partial pressure of ozone is relatively small. But immediately above the 65-mb level, the partial pressure of ozone increases extremely rapidly with altitude through a stable layer of air in which the temperature changes very abruptly from very cold tropical air to warmer air. The winds also change abruptly at this level from a uniform westerly flow to easterlies.

The ozone soundings for 6 May (Fig. 8) show a layer of high partial pressure of ozone at about the 100-mb level over UNM and at a slightly higher elevation over FCL. This layer also shows up on the cross section as a tongue of warm polar or middle-latitude stratospheric air with colder tropical air above and below. At FCL there is a layer of air of high partial pressure of ozone immediately above a rather well-defined middle tropopause. The middle tropopause over ABQ is much more definite than on the previous day, since, as is seen from Fig. 4, the trough at this time has been displaced toward the southeast. The ozone sounding shows a large rate of increase in partial pressure of ozone beginning at about the 200-mb level, where the change in temperature lapse rate is sufficiently large to mark this level as the middle tropopause in accordance with the conventional definition of tropopause, although a sharp temperature minimum occurs at a higher level. The temperature soundings show clearly the twofold air-mass structure, a cold tropical air mass above a polar or middle-latitude air mass. As on the previous day, the decrease in partial pressure of ozone, apparently

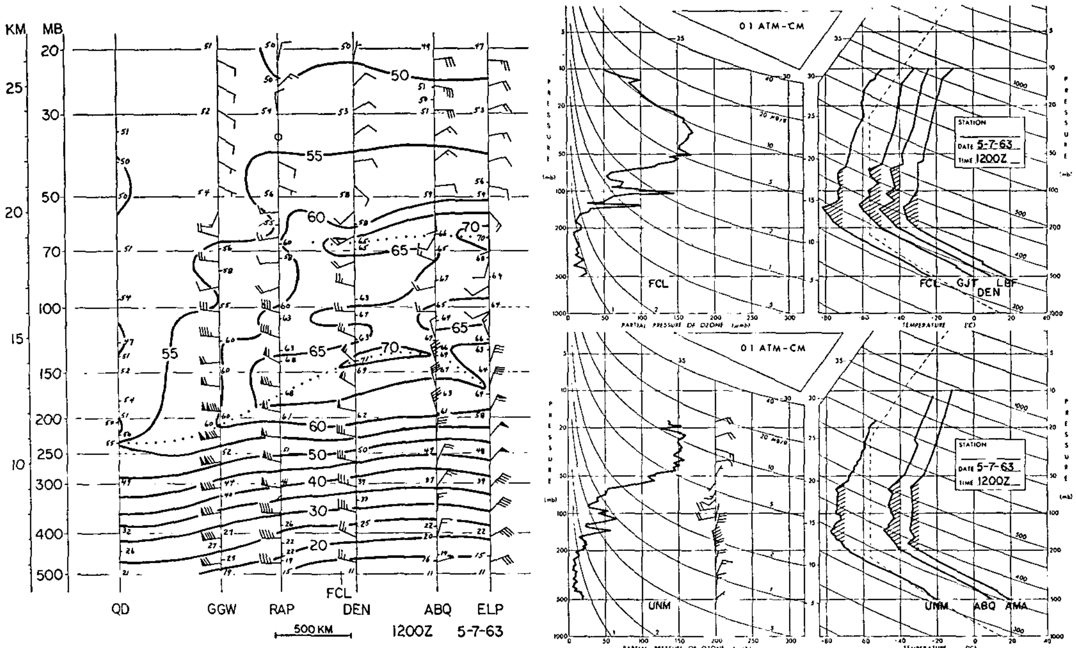

Fig. 9. Vertical distribution of ozone, wind, and temperature 7 May 1963. See Fig. 1 for locations of stations. Notation as in Fig. 7.

owing to a northward displacement of tropical air, is evident in the ozone soundings. This effect is more pronounced at UNM than at FCL.

On the 200-mb chart for 7 May (Fig. 5) a ridge of high pressure is seen extending over New Mexico, while the trough that was over New Mexico on 5 May has been displaced southeastward and now is over Texas. The middle tropopause is located well above the 150-mb level at both ABQ and FCL at this time. This is an unusually high level for the middle tropopause, and the temperatures at the tropopause level are abnormally low for this altitude and season. The ozone soundings show that the tongues, or layers, of ozone-rich stratospheric air injected into the tropical air above the middle tropopause now have decreased considerably in vertical thickness, especially at FCL, apparently owing to the inflow of subtropical air with a high middle tropopause.

4. Conclusion

The vertical distribution of atmospheric ozone at middle-latitude stations appears to be associated primarily with the origin and thermal structure of the air masses that are over the stations at the time of the soundings. In general, if the tropopause is well defined, the partial pressure of ozone is small in the troposphere, but increases rapidly with altitude immediately above the tropopause. In tropopause troughs, however, where the tropopause often is indefinite, ozone-rich air may be found at levels below the conventional tropopause.

In winter and spring, at middle-latitude stations there frequently will be a tropical air mass moving over a polar or middle latitude air mass. An ozone sounding through such a double-tropopause structure generally is characterized by a large-scale secondary maximum and a large-scale minimum in the partial pressure of ozone between the lower tropopause and the level of the main ozone maximum. The secondary maximum corresponds to what appears to be an intrusion of polar or middle-latitude stratospheric air, rich in ozone, into the tropical troposphere, while the minimum in partial pressure of ozone corresponds to the layer of tropical air.

Superimposed upon such large-scale maxima and minima in the vertical distribution of partial pressure of ozone there may at times be small-scale features that also show up in the temperature field. These features indicate that in regions where a tropical air mass comes in contact with a polar or middle-latitude stratospheric air mass, there may be interpenetrations of the two air masses resulting in a multiple-layer structure of relatively large horizontal extent.

Acknowledgments. The writer wishes to express his thanks to Dr. V. H. Regener and Mr. Luis Aldaz for their valuable comments, to Mr. H. Thomas May for assisting in the analysis, and to Air Force Cambridge Research Laboratories and the Albuquerque office of the Weather Bureau for furnishing data.

This research was supported by the Atmospheric Sciences Section, National Science Foundation, Grant GP-2394.

REFERENCES

Breiland, J. G., 1964: On the vertical distribution of atmospheric ozone and its relation to synoptic meteorological conditions. *J. Geophys. Res.*, **69**, 3801–3808.

Kochanski, A., 1955: Cross sections of the mean zonal flow and temperature along 80W. *J. Meteor.*, **12**, 95–106.

Newton, C. W., and A. V. Persson, 1962: Structural characteristics of the subtropical jet stream and certain lower-stratospheric wind systems. *Tellus*, **14**, 221–241.

Reed, R. J., 1955: A study of a characteristic type of upper-level frontogenesis. *J. Meteor.*, **12**, 226–237.

——, and E. F. Danielsen, 1959: Fronts in the vicinity of the tropopause. *Arch. Meteor., Geophys., Bioklim., A*, **11**, 1–17.

Regener, V. H., 1964: On the measurement of atmospheric ozone with the chemiluminescent method. *J. Geophys. Res.*, **69**, 3795–3800.

Sawyer, J. S., 1954: Day-to-day variations in the tropopause. *Geophys. Memoirs*, **11**, No. 92, Meteor. Office, London, 40 pp.

Staley, D. O., 1960: Evaluation of potential-vorticity changes near the tropopause and the related vertical motions, vertical advection of vorticity, and transfer of radioactive debris from stratosphere to troposphere. *J. Meteor.*, **17**, 591–620.