A Case Study Using Ozone to Determine Structure and Air Motions at the Tropopause

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ABSTRACT

Data from an instrumented U-2 aircraft, an ozonesonde and standard radiosondes provided detailed meteorological and ozone data on 2 October 1963 in the vicinity of the tropopause over a stretch of several hundred miles. These observations are used to describe the small-scale structure and motions of the tropopause in a region removed from the jet stream.

The tropopause surface appeared to have a wave-like structure which was identifiable over a 2-hr period as the wave moved with the winds at the tropopause level. Furthermore, descending motion of 1.5 cm per sec was computed on the stratospheric side of the more inclined portion of the tropopause, while on the tropospheric side the air maintained constant height.

1. Introduction

The U. S. Air Force Cambridge Research Laboratories' ozone network program (see, Hering[1]) is supported by an instrumented U-2 airplane containing a meteorological package which includes a Regener ozone meter. The plane's research package has been described by Kahle[2], and the first ozone observations produced by the U-2 were discussed by Penn.[3]

Measurements of wind, pressure, temperature, ozone, and of the navigational variables were available at one minute intervals. Available information on absolute errors to the 95 per cent confidence limits are 0.4C for temperature, and 0.85 mb for atmospheric pressure. The analysis in the present paper is concerned largely with point-to-point or relative values, and the relative errors appear to be significantly less than the errors given above. In regard to the accuracy of the ozone measurements, it is estimated that the errors are less than 10 per cent of the indicated values. An estimate of the reliability of the meteorological data to be discussed in this paper was possible because aircraft data were produced in the vicinity of five radiosonde stations. At 120 mb (approximate tropopause) the average absolute difference in temperature was 1.2C, and at 150 mb the difference was only 0.4C. Reliability of the ozone data was established by comparing at the same locations measurements obtained on the forward and return legs of the flight. In addition data were compared with the measurements obtained at the same time from an ozonesonde. The comparisons did indeed indicate that the data were very reliable. The wind data appeared to be reasonably good but no quantitative comparison would not be needed. On the basis of the above considerations, we feel confident about the reliability of the data used in this study.

Our objective, in connection with the flight to be discussed in this paper, was to investigate the detailed structure of the tropopause in a region removed from the jet stream. Subsequent analysis revealed that the tropopause surface appeared to have a wave-like structure, and this feature maintained continuity in time and apparently moved with the wind. The height of the tropopause was in the vicinity of 50,000 ft (120 mb). The broad synoptic picture near tropopause level is shown by the 100-mb map in Fig. 1.

2. Observations on 2 October 1963

The U-2 airplane on 2 October was based in Bedford, Mass. (about 10 mi northwest of Boston). The flight plan called for horizontal traverses near 50,000 ft (120 mb), 40,000 ft (200 mb), and 30,000 ft (300 mb) from northern Maine to the vicinity of Washington, D. C.; in addition, the plan included vertical probes 30,000–50,000 ft near Washington, New York City, Boston, and central and northern Maine. A cross-sectional analysis of the observations of ozone, potential temperature, and wind speed is shown in Fig. 2.

Before trying to interpret the cross section, let us

[1] Hering, W. S., 1963: On the measurement and analysis of the vertical ozone distribution over North America. Presented at IUGG XIIIth General Assembly, Berkeley, Calif., August.

[2] Kahle, D. A., 1963: The instrumentation of a special research aircraft for the collection of meteorological data. Presented at Conference on Stratosphere-Mesophere Structure, El Paso, Tex.

[3] Penn, S., 1963: Preliminary aircraft observations of ozone in the stratosphere. Presented at Seminars on the Stratosphere and Mesosphere and Polar Meteorology, Stanstead, Quebec, July.

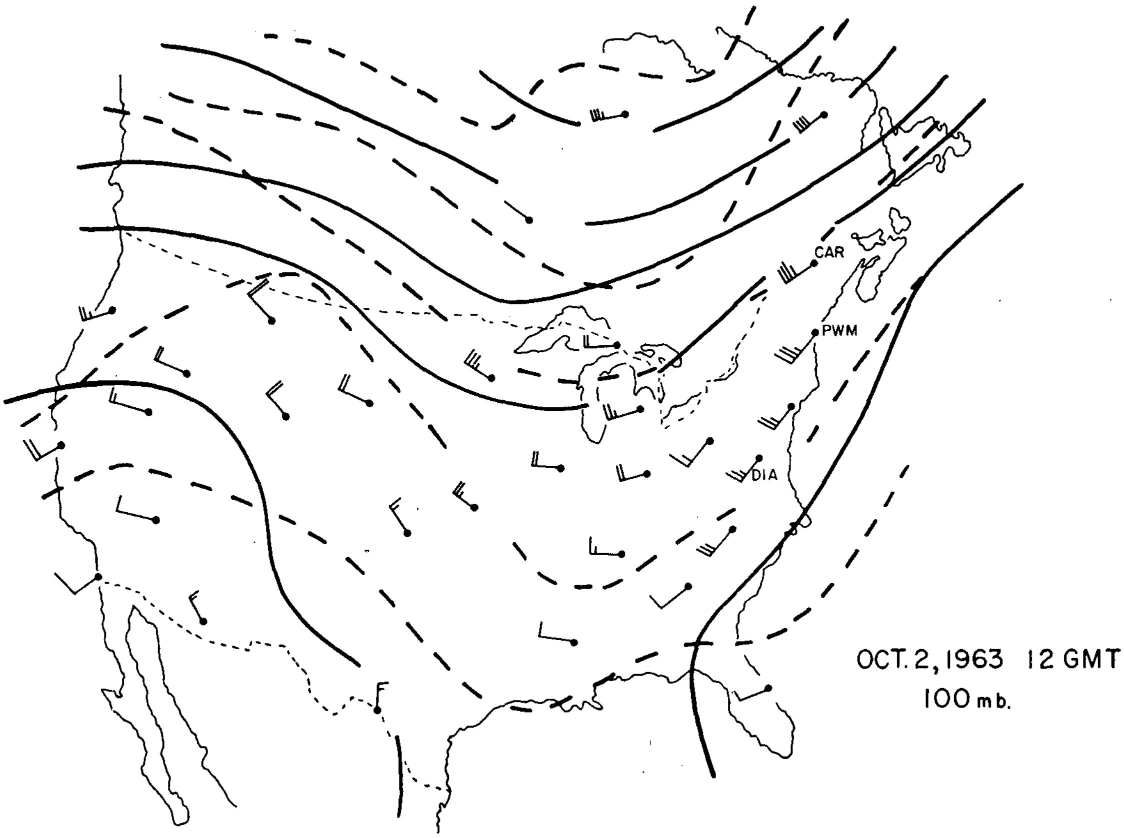

FIG. 1. 100-mb map for 1200 GMT 2 October 1963.

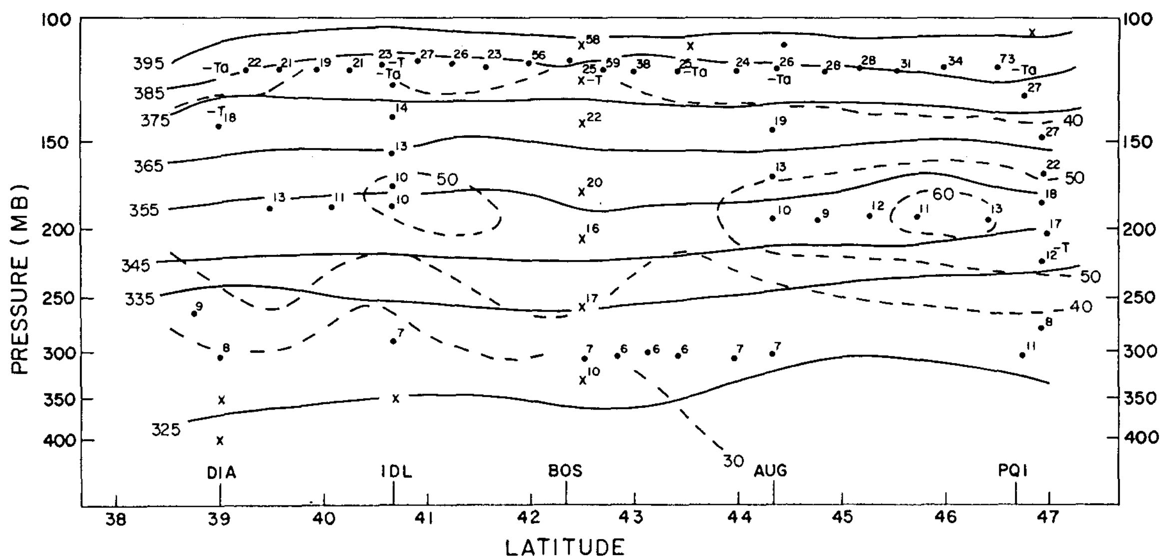

FIG. 2. Vertical cross section on 2 October. Aircraft data identified by a dot and balloon data by an x. Tropopause from aircraft data identified by Ta, and tropopause based on balloon data by T. Solid lines are isentropes, and dashed lines are isotachs. Numbers in the figure refer to ozone concentration in μmb.

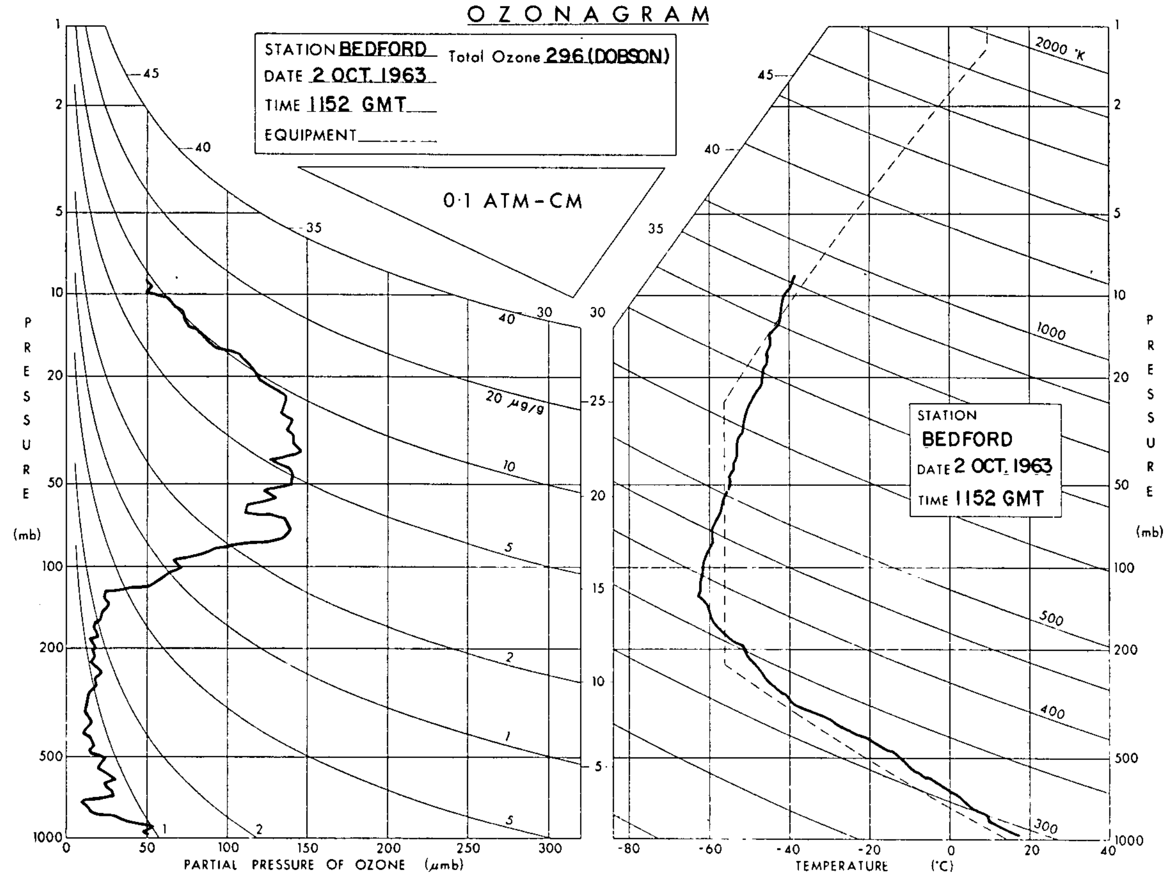

Fig. 3. Profiles of ozone and temperature at 1200 GMT 2 October 1963 at L. G. Hanscom Field, Bedford, Mass.

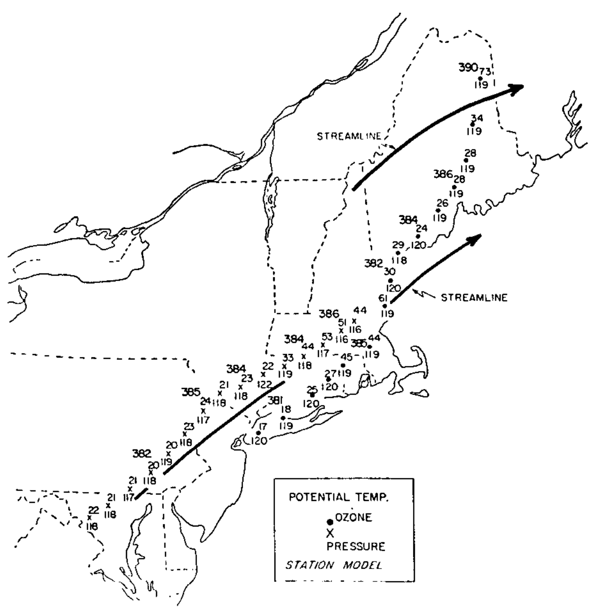

Fig. 4. Ozone (μmb), potential temperature (deg K), and pressure (mb) data are shown along the 50,000-ft flight segments. The data shown represent less than 25 per cent of total at 50,000-ft level. Points marked with an x are those on forward leg Boston to Washington, and points identified by a dot are on the return leg from New York to Presque Isle, Me.

first direct our attention to the balloon sounding from Bedford (BED) at the time of the flight. These data are presented in Fig. 3. The temperature profile indicates a tropopause near 122.5 mb, and at this level the ozone concentration starts to increase rapidly with height. From 300 mb to the tropopause, ozone concentrations[4] increase from about 13 to 23 μmb—fairly typical values in the upper troposphere. Between the tropopause and 115 mb, concentrations increase rapidly to about 55 μmb. This increase in ozone by a factor of two over a 7-mb interval is significant when one considers that the ozone observations are reliable within 10 per cent. Because of the ozone lapse rate in the lower stratosphere, it is apparent that ozone can be a promising tracer in this region of the atmosphere. It also follows that a sharp distinction can be made between air parcels with tropospheric and stratospheric ozone concentrations.

Returning to the cross section in Fig. 2, we find a weak jet in northern Maine; however, from the maximum wind chart (not shown here) it was clear that the major jet was located near 50N lat. Tropopause pressures (heights) are shown as determined from radiosondes and

[4] Partial pressure of ozone is related to mass mixing ratio by $r(\mu g\, g^{-1}) = 1.657 p_3\,(\mu mb)/p(mb)$.

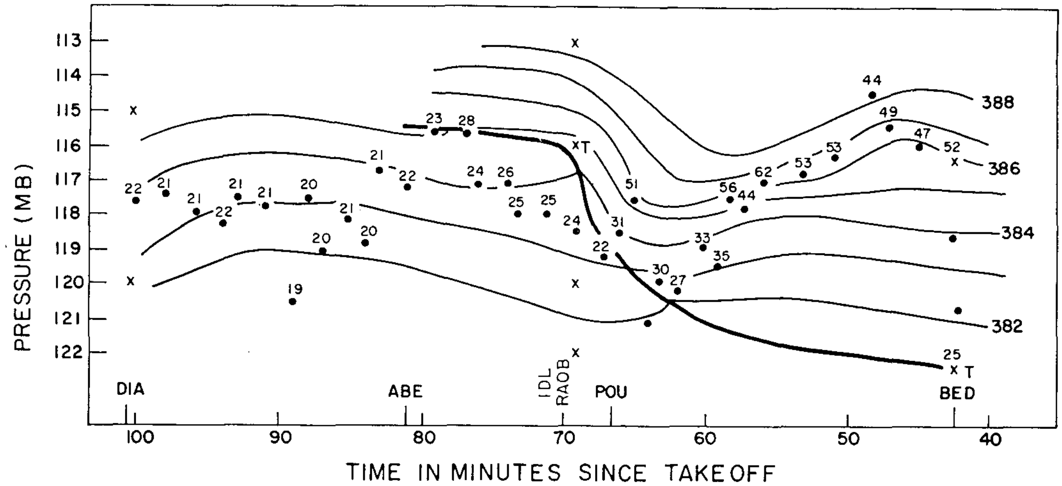

FIG. 5. Analysis of data between Bedford and Washington. Heavy line is tropopause profile, thin lines are isentropes, and numbers are ozone amounts (μmb). Tropopause positions which were determined from temperature considerations are identified by a "T".

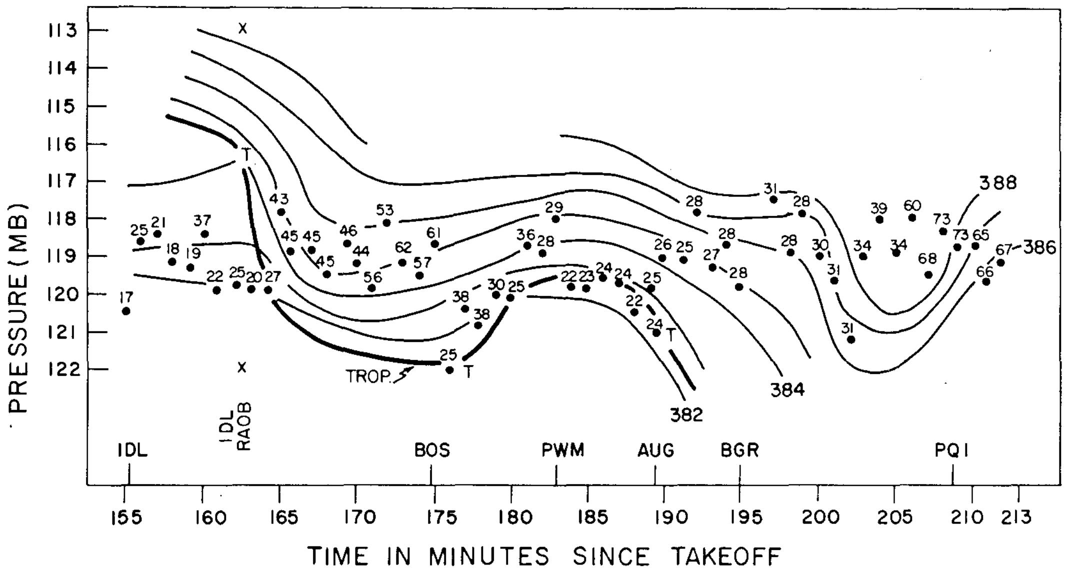

FIG. 6. Same as Fig. 5, but applied to return leg data from New York to Presque Isle.

the U-2 temperature sensor. The indicated heights do not agree over Washington and northern Maine; however, over most of the cross section the agreement is good and tropopause pressures range from 122 to 116 mb. Since there is as much as 3 hours between the two types of measurements, the differences may well represent real changes. In Fig. 2 we see that horizontal variations in ozone are small in the troposphere, while in the vicinity of 120 mb the amounts vary by a factor of two. An important point is that a detailed examination of the data revealed the ozone amounts were in the middle to upper 20's at indicated tropopause pressures except at the ends of the cross section where apparently complicated changes were taking place. This fact regarding the ozone concentration at the tropopause will be used as a guideline in the analysis of the data in the section which follows.

3. Interpretation of data

Fig. 4 presents the observations along the tracks of the flight at 50,000 ft. It is evident that both tropospheric and stratospheric ozone amounts are to be found at the same pressure level and on the same isentrope. It is also seen that the flight tracks are along the streamlines south of Boston but partially across the wind flow in Maine. The tracks are roughly parallel in southern New England with a separation of about 40 miles ex-

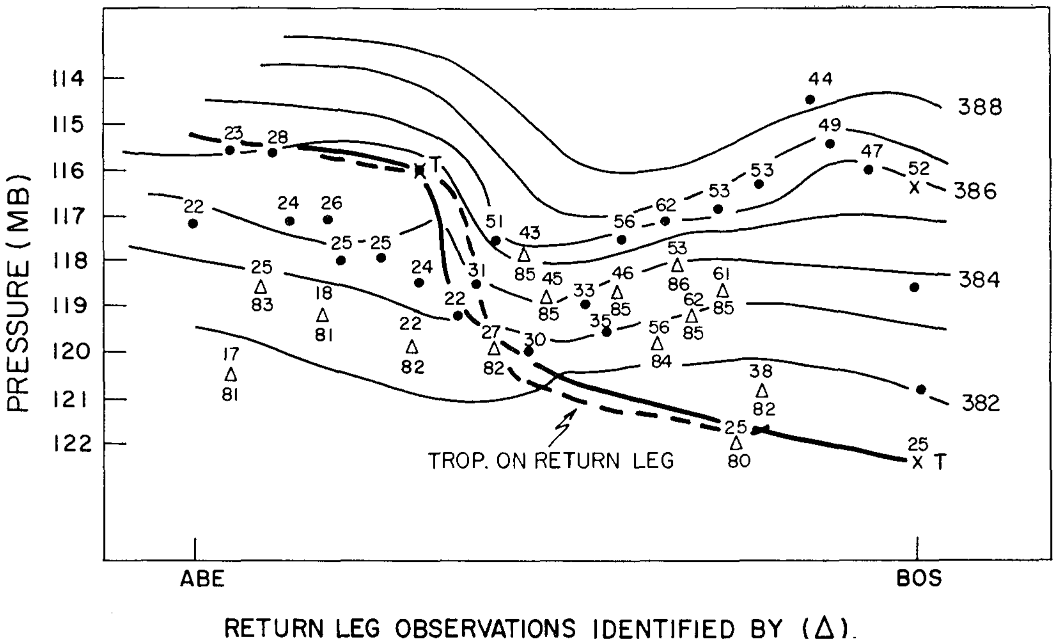

Fig. 7. Repeats a section from Fig. 5, between Boston and Allentown, Pa. The tropopause profile (dashed line) and observations from a section of the return flight (identified by Δ) are shown at computed upstream locations. Data below each Δ is potential temperature with first digit (3) omitted. Balloon data location identified by x.

cept over eastern Massachusetts where the separation narrows to about 10 miles. The separation in time is about 83 minutes in southeastern New York, and about 134 minutes in the Boston area. With these observations we shall try to describe the 1–2 hour history of air parcels at the tropopause.

The fine scale character of the tropopause surface is examined in cross sections where ozone and potential temperature are analyzed in detail as functions of pressure. The cross section for the forward leg is shown in Fig. 5 and that for the return leg in Fig. 6. The BED and New York (IDL), radiosondes are used in Fig. 5, and the IDL radiosonde in Fig. 6. The radiosondes were moved with the wind at 120 mb so as to locate the radiosonde data at the time of the U-2 observations. The resulting tropopause analyses seem to be consistent with nearly all of the data. Since the high tropopause at IDL is important to the analyses in both cross sections, let us see what basis there is for accepting the IDL indication. First of all, the tropopause was sharply defined on the radiosonde report at 116 mb; second, the Nantucket Island radiosonde showed a well defined tropopause at 115 mb. In addition of course, the ozone data in Fig. 5 suggests a tropopause at 115–116 mb a little southwest of IDL.

In both cross sections the tropopause profile suggests a wave-like structure along the wind. Because of the exaggerated vertical scale the slopes of the profiles may be misleading. In the apparently steeply-sloped regions the slope is about 1:300. The data were not complete enough in Fig. 6 to define the cross-wind character of the tropopause. A wave-like structure in the isentropes was looked for at 30,000 and 40,000 ft, but the data were too sparse for confident analyses.

Since the two tracks as shown in Fig. 4 are only 40 mi or less apart in the New York-southern New England region, we shall assume that the spatial variations in ozone and potential temperature may be neglected between the tracks. If we further assume conservation of the two variables, we are then in a position to compute the 1–2 hour histories of air parcels at the tropopause. Accordingly, backward horizontal trajectories were computed for the observations on the return leg using a time interval (to a second approximation) appropriate to the location along the track. The time interval ranged from 78 minutes in the vicinity of New York City to 122 minutes near Boston; this was equivalent to displacements of 47 and 73 miles at New York and Boston, respectively. Fig. 7 presents part of the forward leg cross section (from Fig. 5), and return leg data is shown at computed locations. The striking feature is that the tropopause profiles match very well. Another significant feature is that potential temperatures on the stratospheric side of the inclined portion of the tropopause have increased by about 2 deg. This represents a downward displacement of about 2 mb over an interval of about 2 hours. Downward motion is confirmed by the general increases in ozone at a given level. Most of the ozone changes would indicate descent of about 2 mb. At the 120-mb level the above-mentioned descent is equivalent to about 1.5 cm per sec. Of further interest is the fact that air on the tropospheric side of the tropopause seems to have remained at a constant level.

4. Summary

Through the use of detailed observations of ozone and potential temperature we were able to construct a picture regarding the fine scale structure and motions of the tropopause on 2 October 1963. The tropopause appeared to have a wave-like character along the streamlines. The wave amplitude was 5–7 mb; the wavelength was more uncertain and was estimated at 270 mi. The more inclined section of the wave had a slope of 1:300. The wave-like pattern was identifiable over a 2-hr period and appeared to move with the wind. During the 2-hr period the stratospheric air ahead of the inclined portion of the tropopause descended about 2 mb, while the tropospheric air on the rear side remained at a constant level.

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