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ABSTRACT

The Backscatter Ultraviolet (BUV) instrument on the Nimbus 4 satellite is yielding a great quantity of information on the spatial and temporal variations of the high level ozone distribution and the total ozone amount. The latitudinal characteristics of the vertical ozone distributions are consistent with our earlier limited knowledge from rocket soundings and the total ozone variations agree with results from the network of Dobson spectrophotometers. However, the uniform sampling density and wide geographic coverage of the satellite system are resulting in a substantial global data base for the time period 1970 through 1973.

The zonally averaged BUV total ozone data for the period April 1970 - April 1971 show seasonal and latitudinal variations in generally good agreement with long-term average Dobson spectrophotometer results. However, the northern winter/spring increase began much earlier than in the Dobson average. The winter/spring increases in each hemisphere were accompanied by coincident losses in the tropics and a net loss of tropical ozone appears over this year of BUV data.

The total ozone changes are related to changes in the high level vertical distributions in the Northern Hemisphere. The zonal symmetry, which is found in the July 1970 ozone mixing ratio meridional cross sections, becomes disturbed in September and October. In January 1971 very high ozone mixing ratios were found near the border of the polar night between 1 and 20 mb.

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INTRODUCTION

Until recently, the only means for monitoring total atmospheric ozone has been from surface stations. Dobson spectrophotometers have been operated from about 100 sites of which on the order of 60 provide data routinely. Because of the distribution of land masses, it is not possible to implement a uniformly spaced network and the derived global ozone patterns have suffered from that uncertainty. Satellite systems offer the possibility of improved sample uniformity as well as internal consistency in observations.

A technique for inferring total ozone from atmospherically backscattered ultraviolet light was originally devised by Dave and Mateer (1967) and was implemented on the Nimbus 4 satellite (Heath, et al., 1973). The same instrument is also designed to make measurements from which the high level vertical ozone profile can be inferred in a technique suggested by Singer and Wentworth (1957). The combination of these techniques is proving to be a powerful tool for investigation of stratospheric processes.

The Backscatter Ultraviolet (BUV) instrument began acquiring data on April 10, 1970 and, in spite of a few moments of anomalous behavior, continues to produce data of uniformly high quality in February 1974. For example, in January 1974 a malfunction occurred affecting only the high gain state of the BUV photometer channel (used for surface reflectivity monitoring). Because the low gain state of the photometer is used for daytime operations (the normal data mode), it appears that the data quality will not be significantly affected.

BUV TOTAL OZONE RESULTS

The BUV total ozone data from all available orbits on each day have been processed to obtain zonal mean ozone amounts. Approximately 100 total ozone measurements are obtained over the daylight side of the earth along each of the 13.4 orbits per day. On the average, approximately 60% of the measurements have been recovered on each day with the losses resulting from "blind" orbits (i.e. out of the telemetry range) and technical problems in accessing raw data tapes. The data have been separated according to geographic latitude and averaged in 10 degree latitude bands. On each day about 50 points are available in each latitude band.

The BUV ozone determinations have been compared with near-simultaneous Dobson spectrophotometer data (Mateer, et al., 1971). Using surface reflectivity values determined with a 3800 Å photometer channel, the total ozone values from a 3125-3312 Å wavelength pair average 24 matm-cm lower than the Dobson results with a standard error of estimate of 20 matm-cm. The bias is believed to originate in the spectral dependence of the surface reflectivity. A simple linear regression relationship between Dobson and BUV data has been used to adjust the BUV total ozone data from which zonal mean values are computed.

The results of contouring the zonal mean values on a time-latitude plot are shown in Figure 1. The upper portion of the plot contains data from April 10, 1970 (BUV turn-on) through the end of December, 1970 and the lower portion shows the continuation from January 1, 1971 through April 9, 1971. The data have been contoured for intervals of 25 matm-cm ranging from 250 to 600 matm-cm. For the present purposes these contours have been subjectively smoothed to remove short-term, random fluctuations lasting only one to three days. However, we have attempted to retain the character of events which result in persistent changes in latitude gradients. The random "noise" which has been smoothed in Figure 1 varies with latitude and season, being smallest in the tropics (±1.5° in contour position) and largest in the spring at high latitudes (±5°). The daily zonal mean values, by themselves, show rather small variabilities. For example, the 20°N zonal average for the month of June 1970 is 290.6 matm-cm with a standard deviation of 2.4 matm-cm. This corresponds to a variability of 0.8% which is somewhat smaller than the variability in Dobson spectrophotometer measurements for individual stations at low latitudes (1-3%). For the same month (June) the variability in BUV zonal mean values increases to 2.8% at 40°N and to 3.0% at 60°N. During times of stronger meteorological activity the variability is, of course, higher. A detailed assessment of these variabilities is planned.

Many of the well-known general characteristics of total ozone, such as the equatorial minimum, the high latitude maxima and associated seasonal variations can be found in these data. Dutsch (1971) and Gebhart, Bojkov and London (1970) have published charts similar to Figure 1 derived from many years of conventional Dobson spectrophotometer data. Those analyses show a tropical minimum with values less than 280 matm-cm for latitudes less than about ±30° and, in that region, a small seasonal variation with a tendency for a maximum in May and June. The BUV data also show a tropical minimum with values less than 275 matm-cm between 10°N and 25°S in April 1970, and between 25°N and 30°S in April 1971.

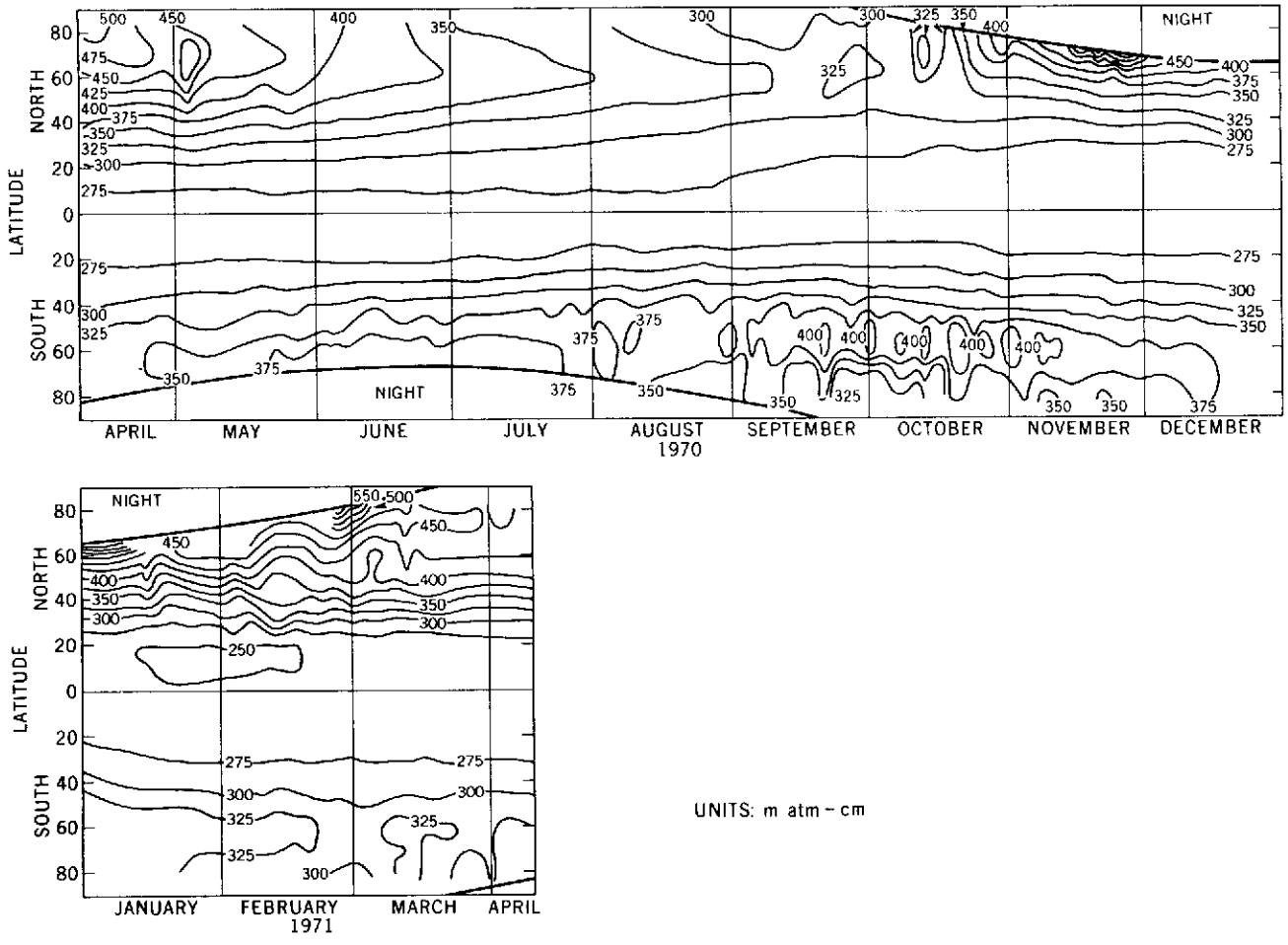


Figure 1. Zonally-averaged total ozone amounts (matm-cm) from the Backscatter Ultraviolet System on the Nimbus 4 satellite for the first year of operation (April 10, 1970 - April 9, 1971). The contours, which are shown from 80°S to 80°N, have been smoothed to remove fluctuations lasting less than 3 days. The data have been empirically corrected for surface reflectivity spectral variations.

NORTHERN HEMISPHERE OZONE

In the Northern Hemisphere, the long-term Dobson average shows an increase of total ozone with latitude to a polar maximum of greater than 440 matm-cm in March and April and, in the other months, to a plateau or slight ridge based near 60° to 70°N. The lowest amounts are found in September and October with values less than 300 matm-cm for latitudes greater than 75°N and values slightly greater than 300 matm-cm between 55° and 75°N. The rate of increase of ozone with time in the winter and spring (~ 22 matm-cm/month) is almost equal to the rate of decrease in the summer and fall (~ -21 matm-cm/month). The greatest rate of increase is found near the pole in late February (~ 50 matm-cm/month).

The Northern Hemisphere BUV results, although limited to latitudes illuminated with sunlight, show features similar to the conventional data in the spring, summer and early fall of 1970, but tend to differ in character after mid-October 1970. In April 1970 the ozone increases with latitude to a near polar maximum of 500 matm-cm at the beginning of observations, and is greater than 450 matm-cm for latitudes greater than 60°N throughout the month. In the months of May through August, the maximum values occur near 60°N with a poleward decrease of about 25 matm-cm. The amount at the hemisphere maximum decreases initially in May at the rate of about 50 matm-cm/month, and in August, at about 20 matm-cm/month. The smallest hemispheric amounts occur in September and early October, as in the Dobson data. Poleward of 75°, less than 300 matm-cm are found and between 40° and 75° the highest values are only slightly greater than 325 matm-cm.

After October 25, 1970, the ozone at latitudes greater than 50°N increased very abruptly (at a rate of approximately 225 matm-cm/month) and a steep poleward gradient was produced and maintained throughout the remaining fall and the winter months until finally, in mid-March, 1971, the gradient slackened beyond 60°N. The near terminator values remained greater than 400 matm-cm throughout the winter and spring months and became greater than 500 matm-cm for periods in late November, early January and in late February-early March. At latitudes below 50°N, very little increase was seen before mid-December. By the beginning of January the ozone at 50°N had increased to 400 matm-cm and values of that order were continued until the end of this data period in April 1971.

SOUTHERN HEMISPHERE OZONE

In the Southern Hemisphere, the long term Dobson zonal averages have been derived from a very limited number of stations relative to the Northern Hemisphere. However, it will be seen that relatively good agreement is found between Dobson and BUV zonal average data. The Dobson data show an increase

from the tropics to a maximum near 50°S in the fall and winter (April through September). The total ozone at the maximum increases by about 20 matm-cm/month ultimately reaching 400 matm-cm, during this time period. In the spring months (September through December) the latitude of the hemispheric maximum moves from 50°S to about 70°S and remains near 70°S through summer. The minimum annual amount, 300 matm-cm, occurs at the end of summer (March).

The satellite results for the Southern Hemisphere in Figure 1 show an increase in total ozone from the tropics to the vicinity of 60°S. In the fall and winter of 1970 (April through September) the maximum is at a latitude greater than 65°S and appears to be at the edge of or within the polar night as in the Northern Hemisphere winter. However, there is no indication of a steep increase beyond the 350 matm-cm contour into the polar night. In fact, the highest total ozone values (400 matm-cm) are found at the end of winter and in spring at about 55°S in September and shifting to 60°S by November. The magnitude and position of this maximum is in substantial agreement with the Dobson results. The southern springtime ozone is rapidly lost with the maximum amount being less than 350 matm-cm during the entire southern summer. During the late summer hemisphere minimum, the highest values were slightly above or slightly below 325 matm-cm and a polar minimum (< 300 matm-cm) was formed at the end of February 1971. These characteristics are nearly identical to those found in the Northern Hemisphere in September, 1970.

INTERHEMISPHERIC RELATIONSHIPS

While the ozone at mid-latitudes in each hemisphere is progressing through the annual cycle, little evidence is found for correlated changes between the two-hemispheres. However it is possible to see that the tropical regions experience changes apparently related to the winter and spring buildups in either hemisphere. While little change is found from April through August 1970, except for a slight increase in the southern tropics in late July, on August 28 a significant decrease in the northern tropics appears to be coincident with the springtime enhancement in the southern mid-latitudes. Further, at the time of the northern polar build-up in October, the southern tropics appear to be depleted of ozone. Finally, in mid-January, the southern tropics lose an additional amount of ozone and simultaneously, the lowest values of the year (< 250 matm-cm) appear between the equator and 20°N. The low northern tropical ozone amounts persist until mid-February.

These interrelated changes in ozone during the year April 1970 - April 1971 are suggestive of some general transport processes; during the first five months, April through August, ozone in the Northern Hemisphere mid-latitudes is lost slowly, presumably due to mixing into the troposphere where it is transported

to the surface and to photochemical destruction processes in the lower stratosphere. At the same time in the Southern Hemisphere fall and winter, the slight increase that is found can arise from gentle subsidence compensated by photochemical production. However, beginning at the end of August, the stronger increase of ozone in the southern mid-latitudes can apparently no longer be compensated by production as evidenced by a net loss of ozone in the tropics. The most unusual aspect is that the losses are found in the opposite hemisphere from the increases. To support this, an asymmetric Hadley circulation would be required since there is no evidence for horizontal advection.

A similar effect must take place in late October and again in mid-January when northern hemisphere increases are coincident with decreases in the southern tropics. However, in the mid-January case an additional loss is found in the northern tropics. These relationships appear to hold principally for the mid-latitude (40-60°) wintertime increases and no equatorial effects appear during the strong near-terminator increases observed in late November, early January and at the end of February.

LONG-TERM CHANGES

The content of ozone within the tropics is clearly smaller in April 1971 than it was in April 1970. Changes in tropical ozone with periods greater than one year have been found in conventional total ozone data. Ramanathan (1963) noted a biannual variation in tropical ozone. Komhyr, et al. (1971) have shown evidence for secular trends. Recently, Angell and Korshover (1973) have reviewed the evidence for these changes using essentially all the available conventional total ozone data. Because of the uniform, high sampling density of the satellite system it is expected that the full spectrum of periodicities and secular trends should become quite apparent.

VERTICAL OZONE DISTRIBUTIONS

In addition to total ozone determinations, the BUV measures the earth radiance at wavelengths that can be used to infer the high level vertical ozone profile. Although the climatological processing of total ozone data is further along than that of the high level vertical distribution data, we have attempted to explore the processes by which the total ozone is changed during the seasons. For visualization of dynamic effects on the ozone in the middle and upper stratosphere it has become convenient to use the ozone to air mass mixing ratio in mg/kg rather than ozone density (g/m^3). The ozone density varies exponentially by a factor of ~50 between 10 and 1 mb (30 and 50 km) and consequently 10-30% changes from a mean vertical profile appear as minor deviations which, on the other hand, can appear as organized features in a mixing ratio diagram.

At the present time, mixing ratio latitude-pressure cross sections have been prepared for only selected orbits. Figure 2 shows a set of mixing ratio cross sections from four orbits on a single day. These diagrams portray the ozone along the orbital track which is inclined 80° to the equator and therefore are pseudo-meridional cross sections rather than true meridional cross sections. The longitude of the equatorial crossing is designated above each cross section. At the left side of Figure 2 the cross section for both the Southern and Northern Hemispheres is shown while in the center and on the right, three other cross sections for the Northern Hemisphere only, spaced approximately 90° apart in longitude, are shown to illustrate the extent of zonal variability. For clarity, the regions where the mixing ratio exceeds 12 mg/kg have been shaded. At the bottom of the diagrams, the simultaneously determined total ozone amounts are shown in Dobson units (matm-cm). The values given here have not been corrected for the spectral variation of surface reflectivity and therefore are, on the average 24 matm-cm lower than the values in Figure 1.

In interpreting the high level mixing ratio diagrams it should be recognized that the inversion process yields information principally for the region between 10 and 1 mb. Outside these bounds the profile tends to converge to the first-guess profile, a parameterized function of air pressure. Mateer (1972) has discussed the properties of the inversion methods used for the BUV data. In the present context, because a single Rayleigh scattering model is assumed, radiance data for wavelengths that are returned from levels below the ozone density maximum cannot be used. Consequently, the profiles are not valid below the maximum (20-40 mb at low latitudes, 50-100 mb at high latitudes), and in fact tend to express the total ozone dependence of the parameterized starting function in the vicinity of the ozone density maximum. This interdependence must be recognized in interpretation of the total ozone variations from the mixing ratio cross sections.

JULY - SEPTEMBER CHARACTERISTICS

In July 1970, ozone was slowly being destroyed at latitudes greater than 20° in the Northern Hamisphere and was gradually increasing at low and mid latitudes in the Southern Hemisphere, as shown in Figure 1. Between 50°S and the terminator the ozone exhibited very little change from the minor increase that occurred in fall (April-May).

Figure 2 illustrates the mixing ratio patterns on July 20, 1973. The central core (mixing ratio >12 mg/kg) fills the region between approximately 12 and 3 mb and extends to $\sim 50°$N in each cross section. The gradients from this high mixing ratio core tend to be uniform both vertically and meridionally and the ozone decreases with latitude at all levels between 20 and 1 mb. The total ozone

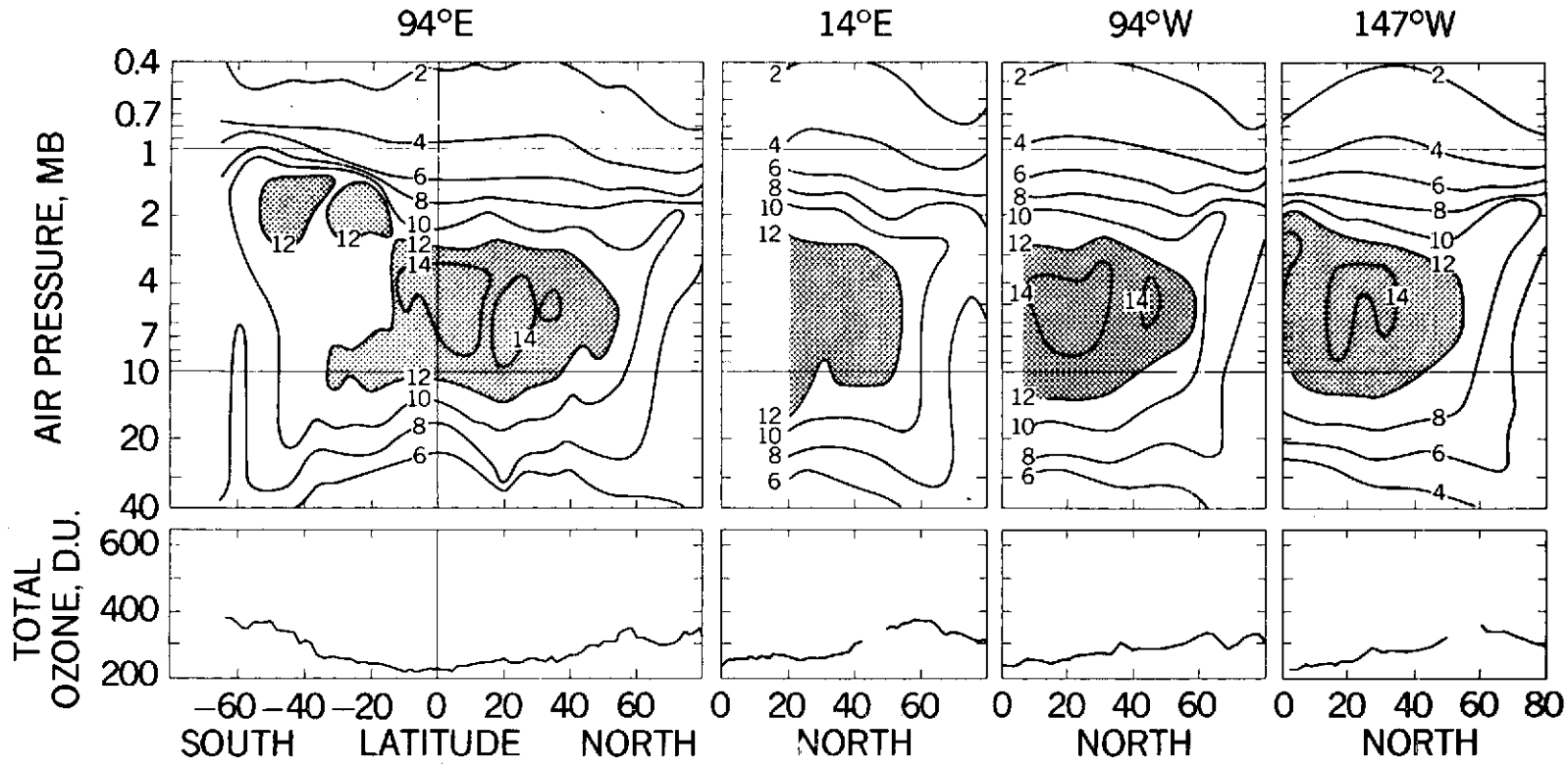


Figure 2. Pseudo-meridional cross sections of ozone mass mixing ratio in mg/kg for four sections of Nimbus 4 orbits on July 20, 1970. The orbits cross the equator at longitudes noted above each cross section. The mixing ratios are derived from the inversion of BUV earth radiance measurements. Simultaneously-determined total ozone amounts (uncorrected for spectral variation of surface reflectivity) are shown on the same latitude scale below each cross section.

variation with latitude is relatively featureless. In the Southern Hemisphere, the patches of higher mixing ratio air at mid-latitudes near the 2 mb level are elements of a persistent, fall and winter ring of ozone which has been previously noted (Krueger, Heath & Mateer, 1973). At lower altitudes the mixing ratios are greater than 10 mg/kg for much of the hemisphere. The wintertime total ozone increase seems possibly associated with an extension of the central core to levels below the 10 mb surface.

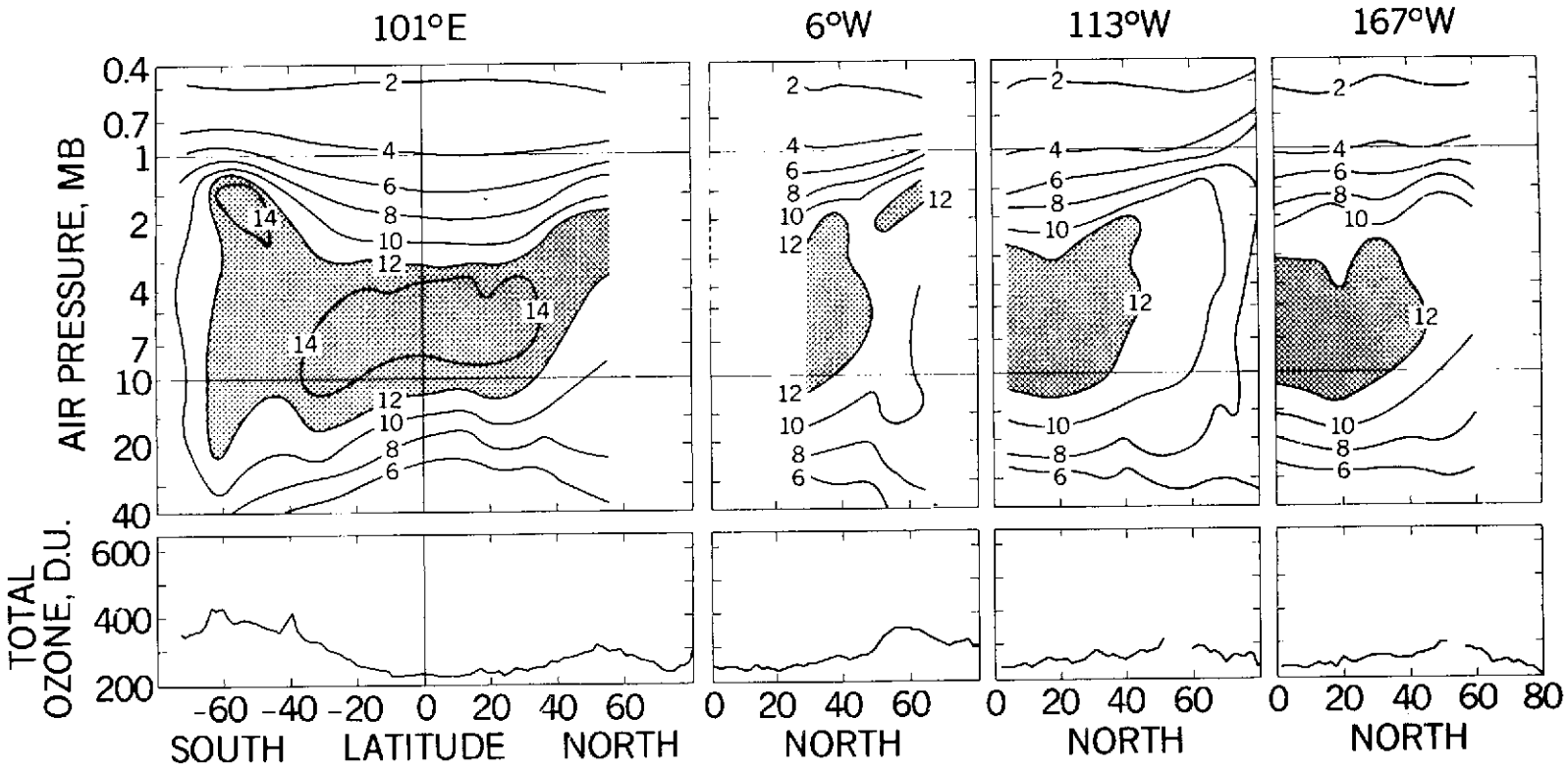
By mid-September, the Northern Hemisphere total ozone had fallen to its annual minimum, while the springtime maximum in the Southern Hemisphere was well developed. Figure 3 shows the mixing ratio cross sections that existed on September 17, 1970. The format of this figure is similar to Figure 2. Note that a zonal asymmetry has developed in the Northern Hemisphere. At altitudes above the 4 mb surface high mixing ratios are found beyond 55°N in the orbits at 101°E and at 6°W. The other two orbits show relatively small changes from the July conditions. The atmosphere below the 4 mb surface retains much of the zonal symmetry found in July.

In the Southern Hemisphere, the central core of ozone has expanded to fill much of the stratosphere to 60°S and tongues of high mixing ratio air extend well below the 10 mb surface at 30° and 60°S.

OCTOBER - JANUARY CHARACTERISTICS

In late October, 1970, the total ozone increased abruptly at latitudes greater than 50°N, the tropical ozone continued to decrease and the Southern Hemisphere mid-latitude maximum had drifted slightly poleward from its September position. Figure 4 illustrates the mixing ratio cross sections on October 28, 1970. In the Northern Hemisphere the bridging to the polar regions from the equatorial core is much more complete than in September. This core extends in three of the four quadrants (89°E, 18°W & 72°W) to levels higher than the 1 mb surface in the vicinity of 60°N. In those cross sections the contours also suggest a relative minimum centered along a surface intersecting the 10 mb level at 40° and 50°N and the 4 mb level near 60°N. The total ozone is relatively low under this surface but increases at higher latitudes. In the fourth quadrant (143°E) the total ozone reaches a maximum near 47°N and the mixing ratio pattern shows a corresponding projection of the equatorial core toward lower altitudes at that latitude.

In the Southern Hemisphere the mixing ratio enhancement at 2 mb at mid-latitudes has diminished and an isolated region of ozone-rich air appears below the 10 mb surface extending from 60° to 80°S. This region is associated with the large total ozone amounts at high latitudes.



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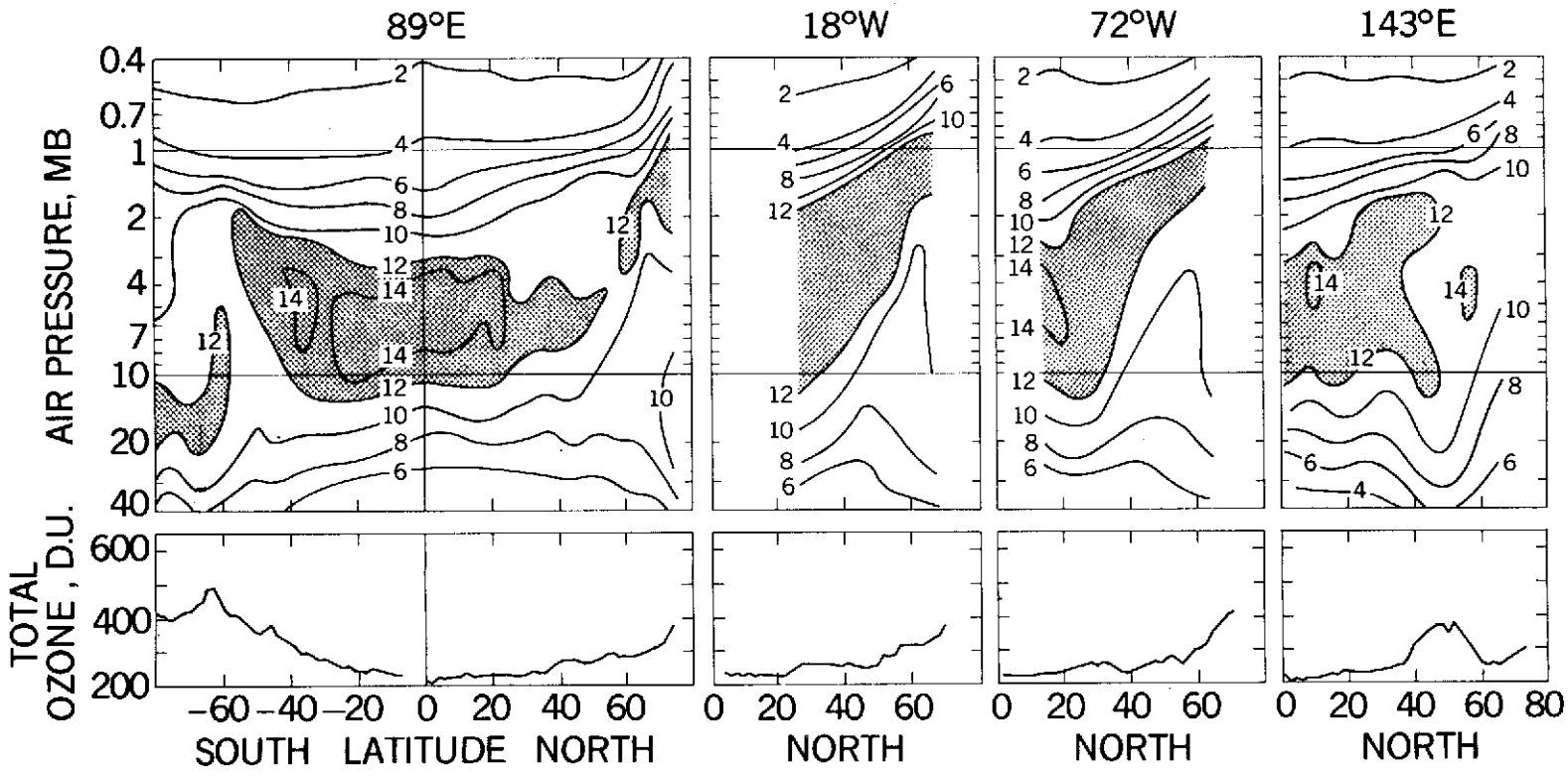

Figure 4. Pseudo-meridional cross sections of ozone mass mixing ratio in mg/kg for four sections of Nimbus 4 orbits on October 28, 1970. The orbits cross the equator at longitudes noted above each cross section. The mixing ratios are derived from the inversion of BUV earth radiance measurements. Simultaneously-determined total ozone amounts (uncorrected for spectral variation of surface reflectivity) are shown on the same latitude scale below each cross section.

In early January, 1971, the zonal mean data shows a strong gradient of total ozone from 30°N with an even steeper increase from 50°N to the terminator.. The tropical values were near their minimum and in the Southern Hemisphere, the ozone was slowly being depleted in the summertime circulation.

The mixing ratio cross sections observed on January 6, 1971 are shown in Figure 5. The pattern in the Northern Hemisphere has become very chaotic. The bridge from the equatorial core to high levels near the pole has been broken in three of the four quadrants (88°E, 18°W & 142°E). In those quadrants the high mixing ratios have been replaced by tongues of relatively low mixing ratio air, apparently extending downward from above the 1 mb surface. At the same time a ring of very high mixing ratio air appears bordering the terminator in all quadrants. This ozone-rich air is found at levels from 30 mb to less than 1 mb and protrudes to latitudes as low as 40°N. This circumpolar ring is highly unusual because it does not appear to be associated with the equatorial core and, in fact, contains mixing ratios greater than are usually observed in the tropics. The inversion results appear to be valid in that, although the solar zenith angles are large, similar conditions at other times of the year do not lead to such unusual results.

The ozone in this circumpolar ring can hardly be in photochemical equilibrium. It should be noted that the circulation was disturbed at the time with a major stratospheric warming occurring just prior to these observations. While the association with the warming event is not clear at the present time, the existence of such high ozone mixing ratios requires either a source of atomic oxygen or a depletion of the ozone catalysts. The most likely explanation requires advection of atomic oxygen-rich air at high levels into the polar night, followed by subsidence to the levels where the ozone is observed.

The other feature of interest on January 6 in the Northern Hemisphere appears at 35°N in the cross section at 99°W. The sharp increase of total ozone with latitude shows up as a very deep projection of the equatorial core of ozone toward higher latitudes. This pattern is quite similar to the one found on October 28 at 143°E. The Southern Hemisphere cross section on January 6, 1971 appears as a normal summer situation almost identical to the Northern Hemisphere cross sections of Figure 2.

CONCLUSIONS

As the processing of BUV data proceeds we are continuing to evaluate the relationship of the results with conventional data. The BUV zonal mean total ozone patterns for the period April 1970 through April 1971 show nearly all of the characteristics found in long-term averages of Dobson spectrophotometer data.

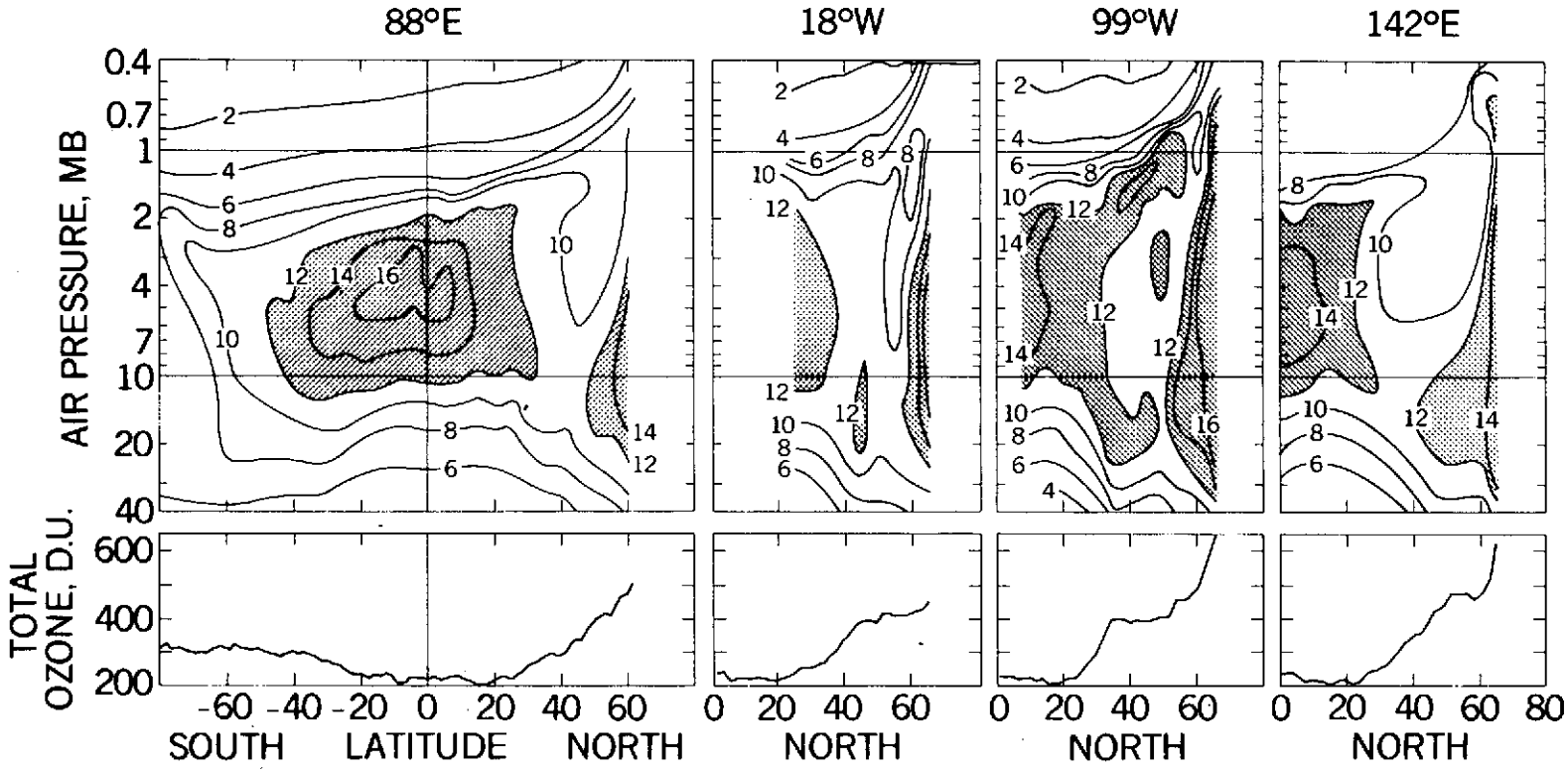

Figure 5. Pseudo-meridional cross sections of ozone mass mixing ratio in mg/kg for four sections of Nimbus 4 orbits on January 6, 1971. The orbits cross the equator at longitudes noted above each cross section. The mixing ratios are derived from the inversion of BUV earth radiance measurements. Simultaneously-determined total ozone amounts (uncorrected for spectral variation of surface reflectivity) are shown on the same latitude scale below each cross section.

In addition, with the greater and more uniform sampling density of the satellite system, it is possible to examine detailed, short-term changes in global fields for the first time. One of the most interesting findings in the 1st year of BUV data is the concurrent decrease of tropical ozone with mid- and high-latitude winter and spring increases. The Northern Hemisphere increase occurred at a very early date (late October) such that it was only 2 months after the Southern Hemisphere increase. Perhaps as a result, the tropical ozone content suffered a net loss during this year of observations.

Vertical ozone profile information, obtained simultaneously with the same instrument, are allowing us to examine the processes in the middle and upper stratosphere that are related to the total ozone changes. From analysis of selected ozone mixing ratio cross sections we find that the zonally-symmetric patterns of mid-summer begin to be distorted before the end of summer. By the beginning of the Northern winter increase in 1970, a bridge of high mixing ratio air had formed between the tropics and high levels near the pole. Total ozone increases seem associated with projections of the tropical, high mixing ratio core to higher latitudes.

Finally, in January 1971, when a great quantity of ozone was being deposited in the Northern Hemisphere, the mixing ratio cross sections point to the possibility of a non-photochemical ozone source in the polar night.

ACKNOWLEDGEMENTS

Work on the Nimbus 4 BUV experiment has been carried out in collaboration with my colleagues D. F. Heath of Goddard Space Flight Center and C. L. Mateer of the Atmospheric Environment Service, Downsview, Ontario. I wish to thank I. Eberstein for computation of the zonal mean total ozone amounts.

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