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Technical Memorandum 79696

(NASA-TM-79696) ASYMMETRIES IN OZONE
DEPRESSIONS BETWEEN THE POLAR STRATOSPHERES
FOLLOWING A SOLAR PROTON EVENT (NASA) 10 F
HC A02/MF A01 CACL 04A

N79-16477

G3/46 Unclas
13573

Asymmetries In Ozone Depressions Between the Polar Stratospheres Following A Solar Proton Event

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NOVEMBER 1978

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ABSTRACT

Ozone depletions in the polar stratosphere during the energetic solar proton event on 4 August 1972 were observed by the backscattered ultraviolet (BUV) experiment on the Nimbus 4 satellite. The observed ozone contents, the ozone depressions and their temporal variations above the 4 mb level (~ 30 km) exhibited distinct asymmetries between the northern and southern hemispheres. Since the ozone destroying solar particles precipitate rather symmetrically into the two polar atmospheres, due to the geomagnetic dipole field, it is suggested that these asymmetries may be explained in terms of the differences in dynamics between the summer and the winter polar atmospheres. In the summer (northern) hemisphere, the stratospheric and mesospheric ozone depletion and recovery are smooth functions of time due to the preponderance of undisturbed orderly flows in this region. On the other hand, the temporal variation of the upper stratospheric ozone in the winter polar atmosphere (southern hemisphere) exhibits large amplitude irregularities. These characteristic differences between the two polar atmospheres are also evident in the vertical distributions of temperatures and winds observed by balloons and rocket soundings.

The first observation of large-scale stratospheric ozone reduction due to precipitating energetic solar protons was made by the backscattered ultraviolet (BUV) experiment on the Nimbus 4 satellite during the solar flare event on 4 August 1972 (Heath et al., 1977). It was concluded that this ozone depression was due to solar protons because the observed ozone depression was preceded by the detection of high intensity solar protons and the latitude dependence of the observed ozone depletion was limited to the polar regions with geomagnetic latitudes higher than roughly 55° in both hemispheres. Prior to this observation, the reduction of stratospheric ozone during solar flare events was predicted by Crutzen et al. (1975).

The purpose of this letter is to describe the spatial and temporal asymmetries in the stratospheric ozone depletions occurring between the northern and southern hemispheres after the solar flare and discuss possible causes of these asymmetries.

In Figure 1(a,b and c),* the columnar contents of atmospheric ozone above the 4 mb level in the units of atmosphere-cm (atm-cm) obtained by the Nimbus 4 BUV are plotted against time for the period extending from day 180 to day 250 in 1972. The major solar flare erupted at about 06 UT on 4 August (Day 217) (Martes, 1973; Hakura, 1977). This flare event was the most intense on record in the last 26 years (Heath et al., 1977). Figures (a) and (b) correspond to the data at 70°N and 70°S , respectively. Figure (c) presents the latitudinal dependence of the observed ozone depression event in both hemispheres. From these figures, one can see the following: (1) The mean value of the ozone content above the 4 mb level prior to the solar event in the northern hemisphere (summer) is less than that of the southern

* The ozone data used in this investigation are from the original processing of the Nimbus 4 data from the BUV experiment. While the final processing is expected to improve the quality of the derived ozone data we have no reason to believe that it will alter the conclusions contained in this paper.

hemisphere (winter). (2) On a time scale of days, the ozone columns above the 4 mb level in the northern summer hemisphere are less disturbed than those in the southern winter hemisphere. (3) The reduction of ozone after the August 4 flare event ranges from a mean of 0.0138 atm-cm. for the pre-flare value to a mean of 0.0117 atm-cm, i.e., a 15.5% reduction at 70°N. On the other hand, at 70°S, it changes approximately from 0.017 to 0.011 atm-cm. which is more than 40%. (4) The recovery at 70°N is approximately monotonic with a time constant of the order of 20 days at the 4 mb level, although the ozone depletion in the band of 75°-80°N shows no evidence of recovery for a period of one month after the event, as can be seen from figure (c) (Heath et al., 1977). The time variation at high latitudes in the southern hemisphere indicates large fluctuations not only in the recovery period but also during the entire period of observation.

Due to the large temporal fluctuations of ozone in the southern hemisphere, one might initially question the validity of the data. In the following, however, we show that these fluctuations are real and can be explained on physical grounds. We also discuss the possible causes of the mean ozone asymmetries between the hemispheres which may be due to interhemispheric differences in the dynamics of the upper polar atmospheres, solar illumination and vertical temperature structure.

(1) Temporal Variations

The precipitation of solar flare particles, consisting mostly of protons of several tens of MeV, with a few alpha particles (of the order of 10% of protons) and a smaller fraction of heavy ions (Yates et al., 1973), should be symmetric between the two hemispheres, due to the geomagnetic control of these incident particles. Observations of the reductions in ozone and their temporal variations are, however, quite different in each hemisphere as can be seen in Figure 1. These differences can be attributed to the differing dynamical states of the

polar upper atmospheres in summer and winter as indicated by the thermal structure and its time dependence in Figure 2. This figure shows the vertical temperature distributions up to the 100 km level (a) in winter and (b) in summer as observed at Barrow, Alaska (71°N) from combined meteorological rocket soundings and radio-sonde observations during 1969 winter and 1971 summer periods (Smith et al., 1971, 1974; Theon et al., 1972). From these figures one can see that the winter polar atmosphere (Figure 2a) exhibits large disturbances in contrast to the summer polar atmosphere (Figure 2b). Correspondingly, instead of the monotonic recovery of depressed ozone in the summer stratosphere, the depleted ozone follows irregular variations as suggested by the vertical temperature variations in the winter stratosphere (Figure 2a). The variations are due to disturbances associated with planetary waves which propagate upward beyond the tropopause only during polar winter when the wind system in the lower stratosphere is moderately westerly (Charney and Drazin, 1961; Dickinson, 1968; Matsuno, 1970; Hirota, 1971, 1976; Austen et al., 1976). It should be noted that the presence of waves in the polar winter atmosphere and the relative lack of waves in the summer atmosphere is also reproduced by the numerical experiments of the general circulation model of Cunnold et al. (1975, Figure 10 for example). Such waves are also indicated by balloon and rocket soundings of the polar atmosphere (Theon et al., 1972). Internal gravity waves also contribute to the temporal structure of the polar winter atmosphere. Their amplitudes in the stratosphere are, however, not as large as those of planetary waves.

(2) Mean distributions

The higher mean ozone values in the winter stratosphere relative to those of summer (Figure 1) have been noted previously by Heath et al. (1974) and are also consistent with other OGO-4 ozone observations (London et al., 1977). These higher values are mainly due to the wintertime increase of the transmissivity of

the orographically excited planetary waves and the associated increase in eddy transports of ozone from the tropical upper stratosphere (where it is produced) to higher latitudes (Dutsch, 1971). Other smaller contributions to the higher winter mean ozone values are: (1) The nighttime enhancement of mesospheric ozone (Hunt, 1966, Reed, 1968; Maeda and Aikin, 1968; Hilsenrath, 1971), being greater in winter than summer, extends to the 4 mb level. (2) The net production of ozone in the cooler winter polar atmosphere is greater than that of the summer (Crutzen, 1974) since the production and destruction of ozone decreases and increases with temperature, respectively.

Finally, it should be noted that not only is the summer-winter ozone asymmetry (seasonal effect) produced by planetary waves but also the inter-hemispheric asymmetry of the total ozone content (ozone maximum is largest in the northern hemisphere). This can be ascribed to two factors: (1) The amplitudes of the orographically excited planetary waves are larger in the northern hemisphere than the southern hemisphere because of the larger continental surface area in the northern hemisphere in contrast to the dominance of smooth ocean surfaces in the southern hemisphere. (2) The transmissivity for planetary waves is largest in the late winter.

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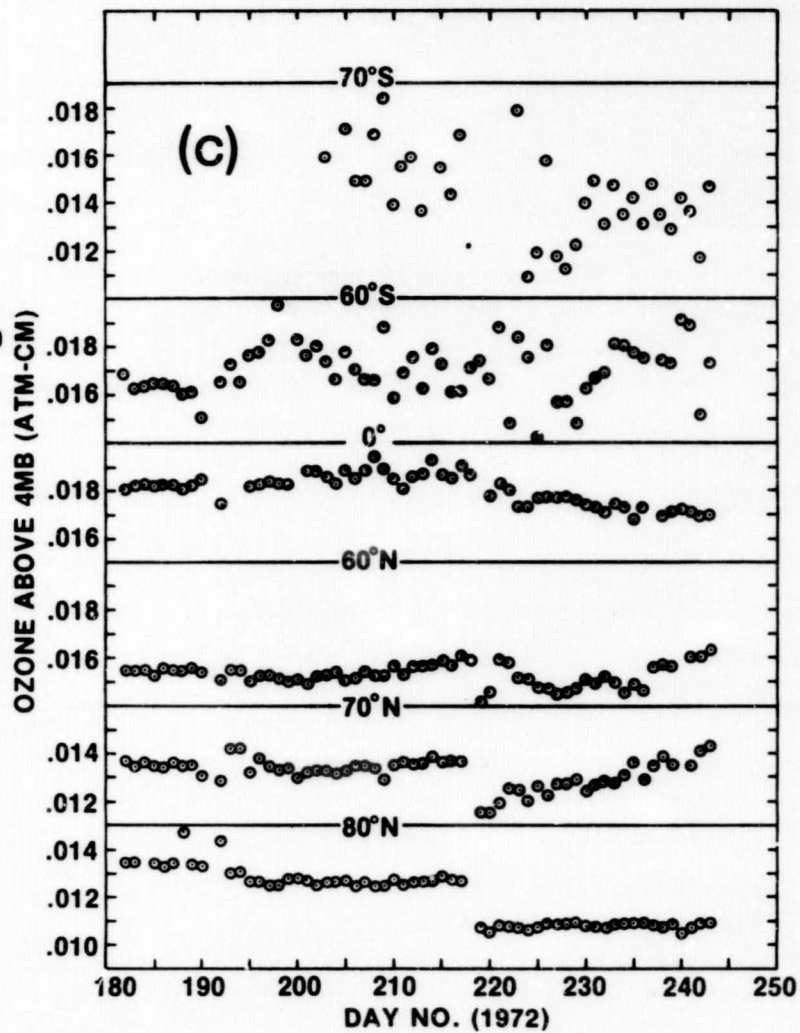
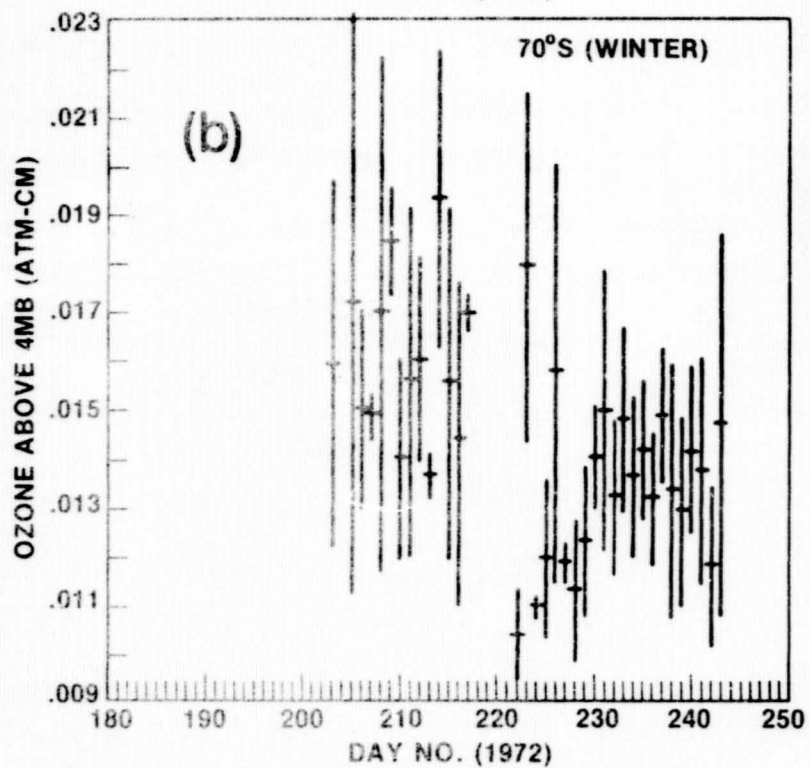
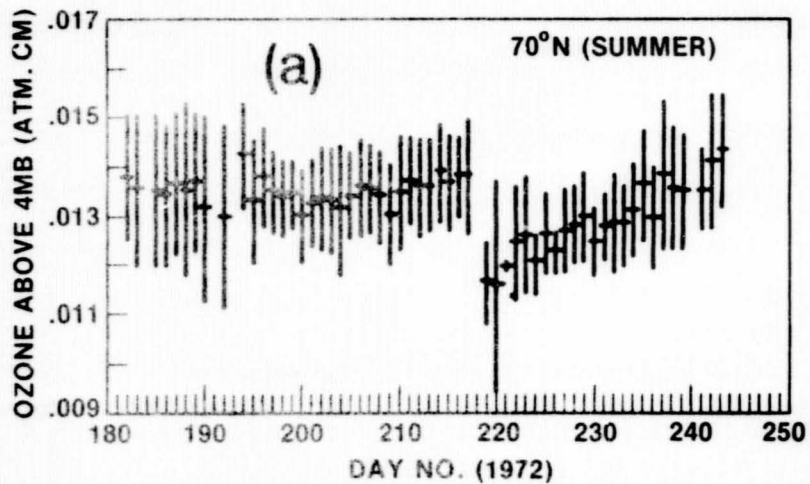
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FIGURE CAPTIONS

Fig. 1 Zonally averaged total ozone above the 4-mb level during July-August 1972. The solar proton event occurred on 4 August (day 217). (a) at 70°N, (b) at 70°S and (c) at 6-latitude bands, (70°S, 60°S, 0°, 60°N, 70°N and 80°N). The vertical bars for each data point in (a) and (b) indicate the standard deviations of all data obtained in the latitude band of that day.

Fig. 2 Vertical temperature distributions at Barrow, Alaska (71°N) observed by radio-sonde (up to around 35 km) and by sounding rocket, (a) in winter 1969 (data points marked by triangles, open circles and closed circles are 11 January 1015 UT, 19 January 2132 UT and 26 January 0500 UT, respectively, Smith et al., 1971), and (b) in summer 1971 (data points marked by triangles, open circles and closed circles are 24 June 1500 UT, 2 July 1959 UT and 12 July 1518 UT, respectively, Smith et al., 1974).



BARROW, ALASKA (71° N)

