Long-term ozone decline and its effect on night airglow intensity of Li 6708 Å at Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W)

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A critical analysis has been made on the long-term yearly and seasonal variations of ozone concentration at Varanasi (25°N, 83°E), India and Halley Bay (76°S, 27°W), a British Antarctic Service Station. The effect of O_3 depletion on night airglow emission of Li 6708 Å line at Varanasi and Halley Bay has been studied. Calculations based on chemical kinetics show that the airglow intensity of Li 6708 Å line has also been affected due to the depletion of O_3 concentration. The yearly variations and seasonal variations of intensities of Li 6708 Å line for the above two stations are shown and compared. It has been shown that the rate of decrease of intensity of Li 6708 Å line was comparatively more at Halley Bay due to dramatic decrease of Antarctic O_3 concentration.

1. Introduction

Airglow is a natural chemi-luminescence phenomenon in the upper atmosphere (Midya and Midya 1993). Ions, atoms and molecules of the upper atmosphere by absorbing solar energy get excited to higher energy levels and while coming down to their ground levels, they emit radiation in the form of light which is known as airglow. Airglow can be classified into day, twilight and night airglow according to its time of occurrences. Green, red lines of oxygen, yellow lines of sodium and OH bands are the main emissions during day, twilight and night-time. Li 6708 Å is one of the important emissions of airglow spectrum.

Astronomical observations of elemental and isotopic abundances provide the ways to determine the origin of elements and to reveal their evolutionary pathways since the formation of Galaxy, approximately 15 billion years ago. The abundance of lithium is particularly important because, although some of it is to be primordial, most of it results from spallation reactions in which galactic cosmic rays break apart larger nuclei in the interstellar medium. Spallation reactions are crucial for the production of light elements, such as beryllium and boron (Reeves *et al* 1970; Meneguzzi *et al* 1971; Meneguzzi and Reeves 1975; Ramarty *et al* 1996; Lemoine *et al* 1998; Knauth *et al* 2000). Observation of lithium abundances can be used to test model predictions for light element synthesis. Abundance measurements of the light elements like lithium, beryllium and boron are playing increasing role in the study of stellar physics. Because these elements are easily destroyed in stars at temperatures $(2–4)\times10^6$ K, the abundances in the surface convective zone are diagnostics of the star's internal workings. Standard stellar models cannot

Keywords. Ozone depletion; airglow emission; excitation mechanism; intensity.

explain depletion patterns observed in low-mass stars, and so do not account for all the relevant physical processes. These processes have important implications for stellar evolution and primordial lithium production in big bang nucleosynthesis. Because beryllium is destroyed at slightly higher temperatures than lithium, observations of both light elements can differentiate between the various proposed depletion mechanisms (Brown 1998). Balachandran (1995) reported that depletion of lithium takes place in high-mass stars by the red giant phase and the depletion occurs during both the main sequence and giant phases. Lithium burning occurs in low mass giants also. Lithium airglow emission was measured by Dunn-Manring type photometer. Abundances of short-lived oxides of lithium can be calculated from lithium intensity following its excitation mechanism. Moreover, variation of ozone concentration at upper mesospheric region can also be predicted indirectly from the variation of lithium intensity.

Li line was detected by different investigators throughout the world (Midya *et al* 2001). Twilight emission of this line was also detected from Calcutta Observatory by Bhaumik *et al* (1996a). Strong atomic line of Li was observed by Slanger *et al* (2003) at San Jose from the Lick Observatory. The proposed excitation mechanism (Bhaumik *et al* 1996b) of lithium airglow line indicates that the intensity of Li 6708 Å line is affected by the variation of ozone concentration.

Ozone, though a very minor atmospheric constituent, plays an important role to control the chemical kinetics of troposphere, stratosphere and mesosphere. The global ozone assessment confirms that ozone is declining everywhere with smaller amount (Bojkov 1992). But Farman *et al* (1985) first reported that dramatic decrease of ozone concentration takes place at Antarctica during spring time causing an ozone hole. Afterwards, it was verified by different investigators throughout the world (Midya and Jana 2002).

Conventionally it is assumed that there is an ozone hole when the ozone abundance is $\leq$220 Dobson units (DU) (1 DU=0.001 atm cm) in a specific geographic place (WMO 2002). The 1997 monthly averaged column ozone from the total ozone mapping spectrometer (TOMS) is up to 25 DU lower than the TOMS climatological mean (1979–1996) and up to 20 DU below the previous record low values (Cordero and Nathan 2002). Kerr (1998) reported that the 1998 Antarctic ozone hole is the biggest one ever observed. Average area of ozone hole was 25.3×10^6 km^2 in September and 20.6×10^6 km^2 in October 1998. The area of Antarctic ozone hole (area of $O_3 < 220$ DU) increased (Uchino *et al* 1999) steadily from 1979 to 1998 and the 2000 ozone hole was the largest on record (Bodeker *et al* 2002). Averaged area of the Antarctic ozone hole, determined by the area enclosed by the 220 DU total ozone contour, increased (Madrigal and Peraza 2005) from 2.6×10^6 to 25.8×10^6 km^2 for the month of September and from 2.7×10^6 to 16.7×10^6 km^2 for the month of October, during 1982–2003. Several theories have been proposed for the Antarctic ozone hole. Chemical, dynamical and natural theories are mainly important and are explained in an earlier publication (Jana and Nandi 2005a, 2005b, 2005c). If ozone hole is created at any place in the atmosphere, O_3 concentration also decreases in other regions due to atmospheric diffusion and circulation (Midya *et al* 2001).

Ozone decline and its effect on night airglow intensity of OH (8, 3) for the period 1973–1984 have been presented by Midya (1994). It has been reported that Bates–Nicolet theory for the excitation of OH band is a predominant excitation process and the intensity of OH (8, 3) band was affected by the depletion of ozone. Jana and Nandi (2005a, 2005b, 2005c, 2006) and Jana *et al* (2006) have analyzed the depletion of ozone and its effect on night airglow intensity of Na 5893 Å at New Delhi (29°N, 77°E), Trivandrum (8.25°N, 76.9°E) and at Srinagar (34°N, 74.8°E), respectively from 1979 to 1998. They also concluded that the airglow intensity of Na 5893 Å line was affected due to ozone decline. On the basis of the observation of a solar eclipse event in the mesopause, lower thermosphere and ionosphere (MLTI) regions over equatorial latitudes, Vineeth *et al* (2008) reported the mesopause temperature enhancement and the enhanced thermospheric airglow intensity and its equatorward movement. They suggested that the enhancement in the thermospheric airglow intensity and its equatorward movement was due to the variations in neutral wind, ionization and neutral density. The mesopause temperature enhancement was attributed to the exothermic mesopause chemistry involving ozone. The enhancement in a narrow region around the magnetic equator had been conjectured to be associated with equatorial temperature and wind anomaly (ETWA) related vertical wind. Taori and Taylor (2010) studied the mesospheric O_2 airglow emission intensity and temperature data collected during January to February 2003 on 17 consecutive nights from Maui, Hawaii (20.8°N, 156.2°W). They observed that nocturnal data for the above period was dominated by terdiurnal tide-like wave. A quasi 5-day wave was also noticed with significant altitude. Taori *et al* (2010) studied the signatures of mesospheric waves during equatorial spread F events as characterized by their optical signatures in the thermospheric airglow layer, equatorial plasma bubbles (EPBs) by utilizing simultaneous monitoring of mesospheric and thermospheric airglow emissions over low

latitudes in Pacific sector. They observed significant differences in mesospheric wave growth during EPB nights compared to the nights of no EPBs. They also found that short-period gravity waves with periods less than 3 h exhibited larger wave growth between the OH and O_2 emission altitudes during the nights with EPBs.

From the excitation mechanism of Li 6708 Å, the volume emission rate of Li 6708 Å has been calculated. From the volume emission rate curve, the intensity of Li 6708 Å has been calculated. Following this process, the intensity of the same line of two stations namely, Varanasi (25°N, 83°E), India which has comparatively less depletion in ozone concentration and Halley Bay (76°S, 27°W), a British Antarctic Survey station which has comparatively more depletion in ozone concentration, have been calculated for other years, considering the depletion of O_3 concentrations. In this paper, the nature of variations of ozone trend and the intensity of Li 6708 Å line have been studied for the above stations.

2. Excitation mechanism

The excitation mechanism of Li 6708 Å as considered by Bhaumik *et al* (1996b) is given below:

$$\begin{aligned} \mathrm{LiO^* + O \overset{K_3}{\rightarrow} Li^* + O_2} \\ \mathrm{Li^* \rightarrow Li + hv\,(6708\,\text{Å})}, \end{aligned} \tag{1}$$

$\mathrm{LiO^*}$ may be produced by other ways:

$$\mathrm{Li + O + M \overset{K_2}{\rightarrow} LiO^* + M}, \tag{2}$$

$$\begin{aligned} \mathrm{Li + O_2 + M \overset{K_3}{\rightarrow} LiO_2 + M}, \\ \mathrm{LiO_2 + O \overset{K_4}{\rightarrow} LiO^* + O_2}, \end{aligned} \tag{3}$$

$$\mathrm{Li + O_3 \overset{K_5}{\rightarrow} LiO^* + O_2}. \tag{4}$$

where K_1, K_2, K_3, K_4 and K_5 are the rate coefficients having the numerical values $4\times10^{-11}\,\mathrm{cm^3 s^{-1}}$, $7\times10^{-33}\,\mathrm{cm^6 s^{-1}}$, $2\times10^{-33}\,\mathrm{cm^6 s^{-1}}$, $1\times10^{-11}\,\mathrm{cm^3 s^{-1}}$ and $K_5 = 6.5\times10^{-12}$ $\mathrm{cm^3\ s^{-1}}$, respectively and M represents a third body to carry away excess energy and momentum (Midya *et al* 2001). The values of reaction rate coefficients have been taken from Midya *et al* (2001).

According to reaction (2), the volume emission rate of LiO* is given by:

$$\mathrm{n(LiO^*) = K_2\ n(Li)\,n(O)\,n(M)}\,.$$

According to reaction (3), the volume emission rate of $\mathrm{LiO^*}$ is

$$\mathrm{n(LiO^*) = K_3K_4\ n(Li)\,n(O)\,n(O_2)\,n(M)}\,.$$

According to reaction (4), the volume emission rate of $\mathrm{LiO^*}$ is

$$\mathrm{n(LiO^*) = K_5\ n(Li)\,n(O_3)}\,,$$

Table 1. *Volume emission rates of Li 6708 Å.*

	Number densities (atoms/cc)					Volume emission rates		
Altitude (km)	n(Li)	$n(O)\times10^{-10}$	$n(O_3)\times10^{-8}$	$n(O_3)$ at Varanasi $\times10^{-8}$	$n(O_3)$ at Halley Bay $\times10^{-8}$	$n(Li^*)\times10^3$ Normal $cm^{-3}\ s^{-1}$	$n(Li^*)\times10^3$ Varanasi $cm^{-3}\ s^{-1}$	$n(Li^*)\times10^3$ Halley Bay $cm^{-3}\ s^{-1}$
80	3.73	1.4	1.4	1.44	1.67	1.9	1.96	2.26
81	3.94	2.84	1.3	1.34	1.55	3.78	3.89	4.5
82	4.15	4.28	1.2	1.24	1.43	5.54	5.71	6.59
83	4.37	5.72	1.16	1.19	1.38	7.53	7.76	8.96
84	4.59	7.16	1.08	1.11	1.28	9.22	9.5	10.97
85	4.82	8.6	1	1.03	1.19	10.77	11.09	12.81
86	5.02	11.78	1.02	1.05	1.21	15.68	16.15	18.65
87	5.22	15.8	1.04	1.07	1.24	22.3	22.97	26.53
88	5.42	18.1	1.06	1.09	1.26	27.03	27.84	32.15
89	5.62	21.6	1.08	1.11	1.28	34.08	35.1	40.54
90	5.82	24.5	1.1	1.13	1.31	40.78	42	48.51
91	5.64	29.9	0.85	0.88	1.01	37.26	38.38	44.32
92	5.51	35.2	0.6	0.62	0.71	30.25	31.16	35.98
93	5.29	39.8	0.5	0.52	0.59	27.37	28.19	32.56
94	4.96	44.3	0.4	0.41	0.48	22.85	23.54	27.18
95	4.63	45.4	0.3	0.31	0.36	16.39	16.88	19.5
96	4.27	48.5	0.27	0.28	0.32	14.53	14.97	17.28
97	3.91	48.66	0.24	0.25	0.29	11.85	12.21	14.09
98	3.55	48.8	0.21	0.22	0.25	9.45	9.73	11.24
99	3.23	47.6	0.18	0.19	0.21	7.19	7.41	8.55

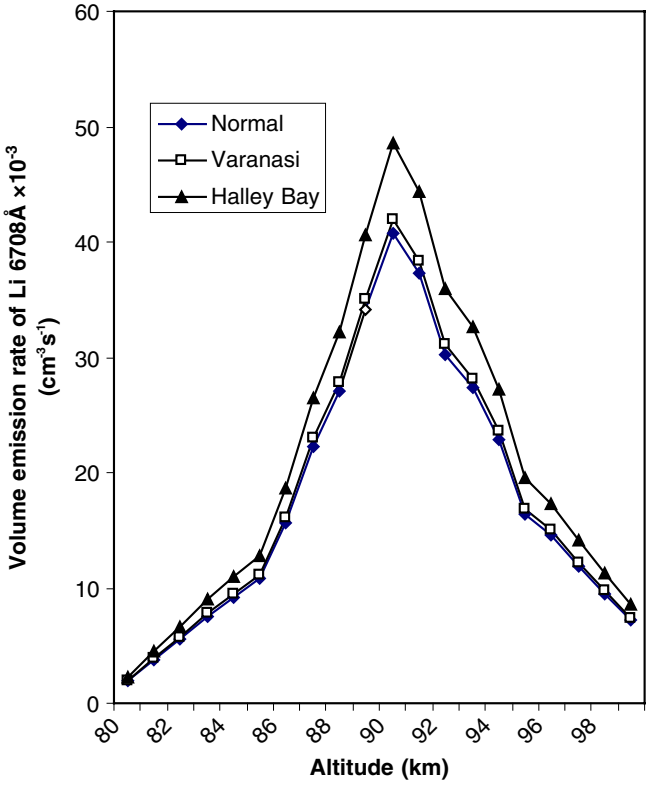

Figure 1. Volume emission rates of Li 6708 Å for normal, Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W).

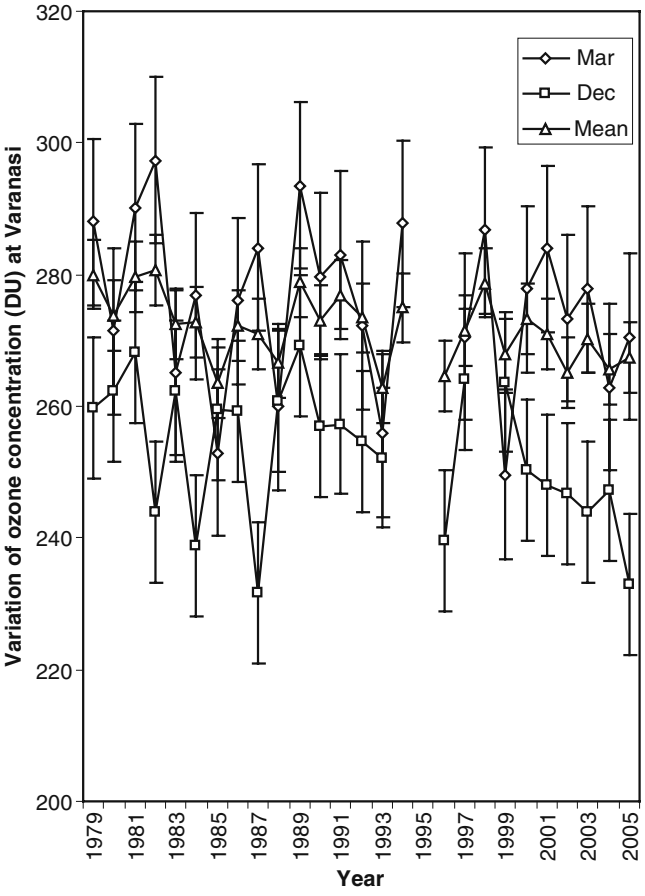

Figure 2. Variation of yearly mean concentration of ozone at Varanasi (25°N, 83°E) for the period of 1979–2005.

where $n(LiO^*)$, n(Li), n(O), $n(O_2)$, $n(O_3)$ and n(M) represent the number densities of LiO^*, Li, O, O_2, O_3 and M, respectively. So, the volume emission rate of LiO^* depends on the numerical values of K_2, K_3, K_4, K_5, n(Li), n(O), $n(O_2)$, $n(O_3)$ and n(M). The volume emission rate of LiO^* by reaction (4) is greater than those of reactions (2) and (3) because of the greater value of K_5 than K_2 or K_3K_4. Therefore, the reaction (4) is predominant over reactions (2) and (3). Thus, it may be concluded that O_3 plays an important role for the emission of Li 6708 Å line.

Ignoring the quenching terms, the rate of production of Li^* is given by the following equation:

$$\begin{aligned} n(Li^*) &= K_1 n(LiO^*) \times n(O)\,, \\ n(Li^*) &= K_1 K_5 n(Li)\, n(O)\, n(O_3). \end{aligned} \tag{5}$$

Using the number densities of Li, O and O_3, the volume emission rates of $n(Li^*)$ for different altitudes have been calculated with the help of the above equation. It attains maximum value at an altitude of 90 km. Altitudinal number densities of Li, O, O_3 and volume emission rates of $n(Li^*)$ have been shown in table 1. Intensity has then been calculated from the volume emission rate curve with the help of the following equation.

$$\text{Intensity} = \frac{1}{2}\big(\text{layer thickness} \times \text{peak volume emission rate}\big). \tag{6}$$

The value of layer thickness was 8.53 km and peak volume emission rate was 40.78×10^{-3} cm^{-3} s^{-1} for normal volume emission rate curve shown in figure 1. Thus, the intensity of Li 6708 Å became 17.4×10^{-2} R (Rayleigh) ($1\text{R} = 1.0\times10^5$ cm^{-2} s^{-1}). The number density of Li has been taken from Midya *et al* (2001), those for O and O_3 have been taken from Jacchia (1977) and Jana and Midya (1995), respectively.

3. Calculations and results

Ozone concentrations of different stations have been obtained from internet website http://jwocky.gsfc.nasa.gov published from NASA, USA. Monthly mean ozone concentrations have been calculated from daily average value of ozone in DU for the stations, Varanasi and Halley Bay. The yearly mean ozone concentrations have been calculated from monthly average value of ozone in DU.

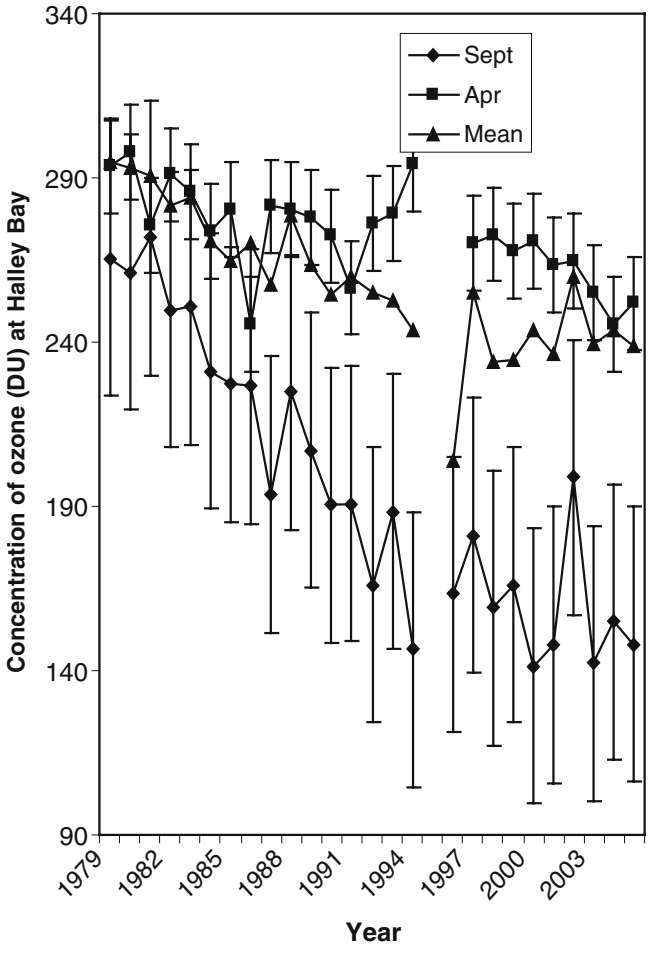

Figure 3. Variation of yearly mean concentration of ozone at Halley Bay (76°S, 27°W) for the period of 1979–2005.

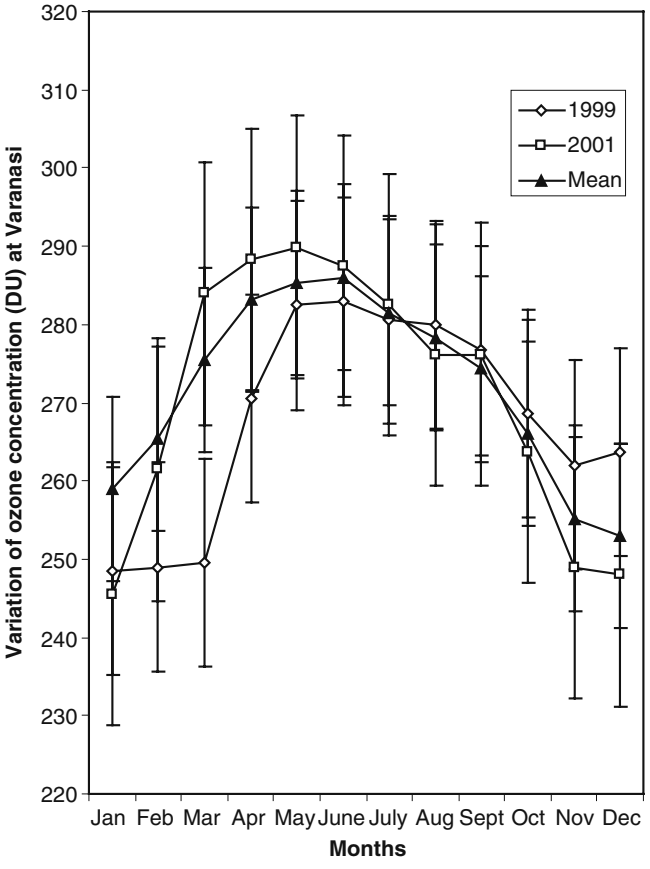

Figure 4. Seasonal variation of concentration of ozone at Varanasi (25°N, 83°E) for the period of 1979–2005.

Variations of yearly mean ozone concentrations at Varanasi and Halley Bay have been presented in figures 2 and 3, respectively, from 1979 to 2005. The nature of variations of ozone concentrations for each month for different years has been compared with the variation of yearly mean ozone concentrations. The coefficients of correlation between the variation of ozone concentrations for each month for different years and that of yearly mean ozone concentrations at both these stations have been shown in table 2. The correlation table 2, and figures 2 and 3 reveal that the variations of ozone concentrations for all months and variation of yearly mean ozone values followed nearly the same trend as the value of coefficient of correlations were high in all cases. The nature of variation of March ozone mean values from 1979 to 2005 was more similar with the variation of yearly mean ozone values for the same period than that of other months at Varanasi as the coefficient of correlation between March ozone mean values with yearly mean values was the maximum (0.84). The nature of variation of December ozone mean values from 1979 to 2005 was less similar with the variation of yearly mean ozone values for the same period than that of other months at Varanasi as the coefficient of correlation between December ozone mean values with yearly mean values was the minimum (0.31). The yearly mean ozone concentration as well as the concentrations of ozone for every month was gradually decreasing from 1979 to 2005 at different rates at Varanasi. The rate of yearly mean ozone depletion was 0.3044 DU per year. It was 0.348 DU and 0.5027 DU per year for the months March and December, respectively.

Table 2. *Coefficient of correlation between monthly mean concentration of ozone at Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W) from 1979 to 2005.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Varanasi (25°N, 83°E)	0.64	0.78	0.84	0.69	0.68	0.71	0.83	0.8	0.72	0.52	0.44	0.32
Halley Bay (76°S, 27°W)	0.81	0.74	0.62	0.53				0.87	0.89	0.83	0.82	0.85

But the in case of Halley Bay, the nature of variation of September ozone mean values from 1979 to 2005 was more similar with the variation of yearly mean ozone values for the same period than that for other months for the same period and the variation of April ozone values was less similar as the coefficient of correlation between September ozone mean values with yearly mean values was the maximum (0.89) and it was the minimum for April ozone mean values (0.53). The yearly mean ozone concentration as well as the concentrations of ozone for every month was gradually decreasing from 1979 to 2005 at different rates. The rate of yearly mean ozone depletion was 2.1785 DU per year. It was 4.6952 DU and 1.1466 DU per year for the months September and April, respectively.

Seasonal variations of ozone concentrations for the stations Varanasi and Halley Bay for the period 1979–2005 have been shown in figures 4 and 5, respectively. It has been observed that seasonal variations in each year and mean seasonal variation followed nearly the same trend. In case of Varanasi, the nature of seasonal variation of ozone mean values for the year 2001 among the years from 1979 to 2005 was more similar with the mean seasonal variation than that for other years. It has also been verified by the value of coefficient of correlation shown in table 3. The coefficient of correlation between the seasonal variations of ozone mean values for the year 2001 with mean seasonal variation was the maximum (0.98). It was the minimum for the year 1999 (0.66). Ozone concentration attained the maximum value for the months of May and June. The minimum ozone concentration occurred during the months of December and January. Ozone concentration gradually increased from the month of January, attained its maximum for the period of May and June, then gradually decreased and attained its minimum value for the month of December.

In the case of Halley Bay, the nature of seasonal variation of ozone mean values for the year 1997 among the years from 1979 to 2005 was more similar with the mean seasonal variation and the

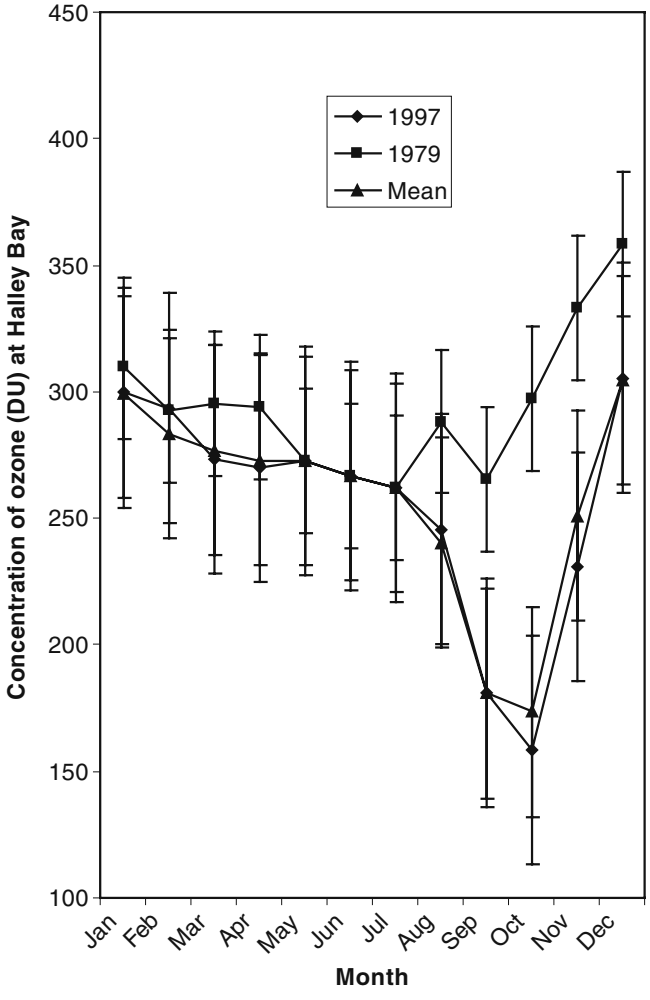

Figure 5. Seasonal variation of concentration of ozone at Halley Bay (76°S, 27°W) for the period of 1979–2005.

Table 3. *Coefficient of correlation between seasonal variation of O_3 with mean seasonal variation of O_3 at Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W) from 1979 to 2005.*

Year	Varanasi (25°N, 83°E)	Halley Bay (76°S, 27°W)
1979	0.95	0.36
1980	0.9	0.72
1981	0.88	0.52
1982	0.94	0.82
1983	0.91	0.84
1984	0.82	0.93
1985	0.68	0.91
1986	0.94	0.7
1987	0.93	0.94
1988	0.83	0.75
1989	0.89	0.97
1990	0.9	0.93
1991	0.96	0.95
1992	0.93	0.97
1993	0.92	0.92
1994	0.85	
1995		
1996		
1997	0.77	0.987
1998	0.84	0.82
1999	0.66	0.87
2000	0.92	0.97
2001	0.97	0.94
2002	0.9	0.76
2003	0.96	0.95
2004	0.91	0.93
2005	0.96	0.96

seasonal variation for the year 1979 among the years from 1979 to 2005 was less similar with the mean seasonal variation. It has been also verified by the value of coefficient of correlation. The coefficient of correlation between the seasonal variations of ozone mean values for the year 1997 with mean seasonal variation was the maximum (0.98). It was the minimum for the year 1979 (0.36). Ozone concentration attained the maximum value for the months of December and January. The minimum ozone concentration occurred at the months of September and October. Maximum ozone concentration occurred during the month of January, then gradually decreased, attained minimum for the month of September–October and then gradually increased.

Equation (5) clearly reveals that the volume emission rate of Li 6708 Å is directly proportional to the concentrations of Li, atomic oxygen and ozone. The concentration of ozone in stratosphere varies in considerable amount from year to year, as well as, from month to month. This stratospheric variation of ozone may influence the mesospheric altitudinal concentration of ozone. On the basis of recent study on inter-annual changes of dynamical structure in the lower stratosphere and contemporaneous changes of ozone observed by TOMS, Salby *et al* (2002) also concluded that inter-annual changes of ozone in the lower stratosphere is accompanied by coherent changes of ozone in the upper stratosphere and mesosphere. Rise in stratospheric ozone will enhance the mesospheric ozone through vertical transport of more ozone; fall in stratospheric ozone will accompany with less transport of ozone into the mesosphere through diffusion due to low density of ozone. As a result, the mesospheric ozone density will decrease. Percentage of ozone fluctuation for each year has been calculated from the mean of the yearly mean concentration of ozone during the period 1979–2005. The effect of variation of ozone has been considered in the calculation of volume emission

Table 4. *Yearly variation of intensity of Li 6708 Å line at Varanasi and Halley Bay.*

	Varanasi		Halley Bay		Peak volume emission rate of Li 6708 Å× $10^3 cm^{-3}s^{-1}$		Intensity of Li 6708 Å× $10^2 R$	
Year	Mean O_3 (DU)	O_3 fluctuation from mean (%)	Mean O_3 (DU)	O_3 fluctuation from mean (%)	Varanasi	Halley Bay	Varanasi	Halley Bay
1979	280	3	303.73	18.95	42	48.51	17.92	20.7
1980	273.81	0.72	301.75	18.18	41.07	48.19	17.53	20.56
1981	279.63	2.86	298.42	16.87	41.95	47.66	17.9	20.34
1982	280.64	3.23	286.09	12.04	42.09	45.69	17.96	19.49
1983	272.41	0.21	289.7	13.46	40.87	46.27	17.44	19.74
1984	272.76	0.33	272.28	6.63	40.91	43.48	17.46	18.55
1985	263.56	−3.05	263.72	3.28	39.54	42.12	16.87	17.97
1986	272.23	0.14	270.77	6.04	40.84	43.24	17.42	18.45
1987	270.98	−0.32	254.54	−0.31	40.65	40.65	17.34	17.35
1988	266.54	−1.95	282.24	10.53	39.98	45.07	17.06	19.23
1989	278.78	2.55	261.9	2.57	41.82	41.83	17.84	17.85
1990	273.1	0.46	250.39	−1.94	40.96	39.99	17.48	17.06
1991	276.96	1.88	257.21	0.73	41.55	41.08	17.73	17.53
1992	273.45	0.59	250.62	−1.85	41.02	40.02	17.5	17.08
1993	262.72	−3.36	247.82	−2.95	39.41	39.58	16.82	16.89
1994	274.97	1.15	233.48	−8.56	41.25	37.29	17.6	15.91
1995								
1996	264.67	−2.64	203.68	−20.23	39.7	32.53	16.94	13.88
1997	271.45	−0.15	250.84	−1.76	40.72	40.06	17.37	17.09
1998	278.76	2.54	222.62	−12.81	41.82	35.56	17.84	15.17
1999	267.87	−1.46	223.34	−12.53	40.18	35.67	17.15	15.22
2000	273.31	0.54	235.52	−7.76	41	37.62	17.49	16.05
2001	271	−0.31	226.23	−11.4	40.65	36.13	17.35	15.42
2002	265.16	−2.46	257.7	0.92	39.78	41.16	16.97	17.56
2003	270.28	−0.58	229.8	−10	40.54	36.7	17.3	15.66
2004	265.64	−2.28	235.4	−7.81	39.85	37.59	17	16.04
2005	267.35	−1.66	229.1	−10.28	40.13	36.59	17.11	15.61

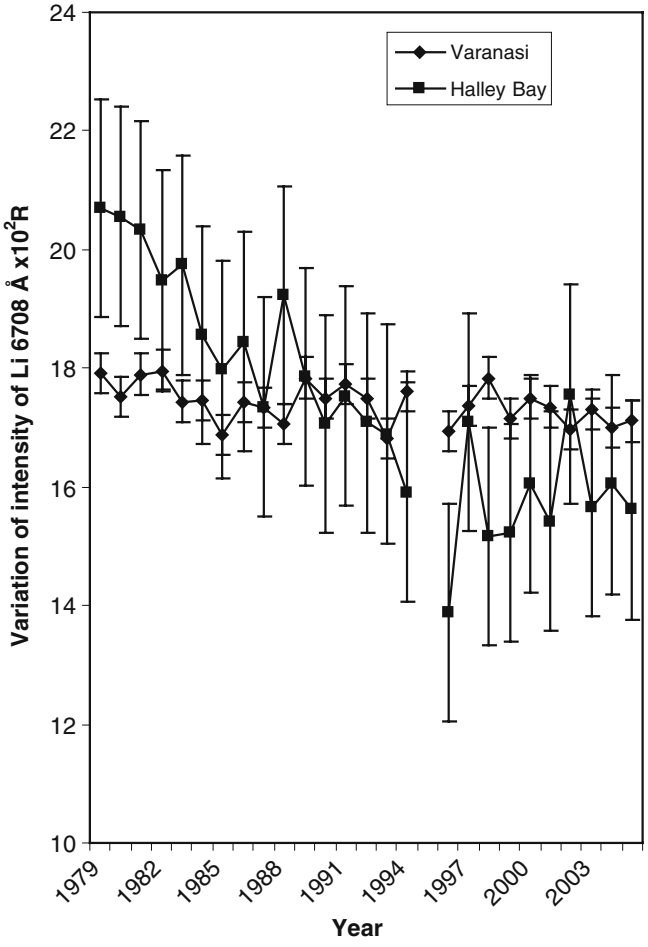

Figure 6. Yearly variations of intensity of Li 6708 Å at Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W) for the period 1979–2005.

rate and intensities of Li, assuming that the concentrations of Li and atomic oxygen remain constant.

Monthly mean ozone concentrations for the above stations have been collected from the website http://jwocky.gsfc.nasa.gov for the year 1979 to 2005. The yearly mean concentrations of ozone have been calculated from monthly mean values. The mean of the yearly mean values of ozone concentrations during the period 1979–2005 for the stations Varanasi and Halley Bay were 271.85 and 255.34 DU, respectively. Then percentages of variation of O_3 concentration from its mean have been computed for different years and have been shown in table 4. These were 3% and 18.95% for the year 1979 for Varanasi and Halley Bay, respectively. During this year altitudinal concentrations of ozone, volume emission rates and intensities of Li line were enhanced by 3% and 18.95% at Varanasi and Halley Bay, respectively, as shown in table 1. The altitudinal variations of volume emission rate for Varanasi and Halley Bay have been shown in figure 1. Intensities were 17.92×10^{-2}R (Rayleigh) and 20.7×10^{-2}R at Varanasi and Halley Bay, respectively, for the year 1979.

Following this procedure, the intensities for different years have been calculated for the period 1979 to 2005 and is shown in table 4. The yearly variations of intensities have been shown in figure 6. It is clear from figure 6 that the rates of decrease of intensities at Varanasi and Halley Bay were 0.0195×10^{-2}R and 0.194×10^{-2}R per year, respectively.

The mean of monthly mean ozone concentration for each month during 1979–2005 has been calculated and shown in table 5. Percentages of ozone fluctuation from the mean of January to December ozone values have been calculated for above stations. Then the intensities of Li line have been calculated considering the corresponding ozone fluctuation percentages. The variations of intensities

Table 5. *Seasonal variation of intensity of Li 6708 Å line at Varanasi and Halley Bay.*

	Varanasi		Intensity of Li	Halley Bay		Intensity of
Month	Mean O_3(DU)	Fluctuation from mean (%)	5708 Å at Varanasi $\times 10^2$R	Mean O_3(DU)	Fluctuation from mean (%)	Li 5708 Å at Halley Bay $\times 10^2$R
January	258.98	−4.77	16.57	299.44	16.5	20.27
February	265.36	−2.42	16.98	283.24	10.2	19.17
March	275.48	1.3	17.63	276.85	7.72	18.74
April	283.74	4.11	18.12	272.9	6.17	18.47
May	285.37	4.93	18.26	272.78	6.13	18.46
June	286.03	5.18	18.3	266.88	3.84	18.07
July	281.53	3.52	18.01	261.98	1.93	17.74
August	278.31	2.34	17.81	240.45	−6.45	16.28
September	274.31	0.87	17.55	180.74	−29.68	12.24
October	266.08	−2.16	17.02	173.56	−32.47	11.75
November	255.21	−6.16	16.33	250.99	−2.35	16.99
December	253.04	−6.95	16.19	304.48	18.47	20.61

for different months in a year for above two stations have been shown in figure 7. It clearly reveals that maximum intensity of lithium occurred for the month of May to June during summer and minimum intensity occurred for the month of December at Varanasi during winter in the northern hemisphere but in case of Halley Bay, maximum intensity occurred during the month of December during summer and minimum intensity occurred for the month of October during spring in the southern hemisphere. The minimum intensity of lithium during the month of October at Halley Bay was due to the dramatic decrease in ozone concentration at Halley Bay during spring time because of very low temperature, elevated concentrations of Cl and oxides of chlorine, fewer amounts of nitrogen oxides and large appearance of polar stratospheric clouds (Jana *et al* 2001). Yearly and seasonal variations of intensities of Li 6708 Å line can be verified from the experimental values of lithium intensities for the same period over these above places.

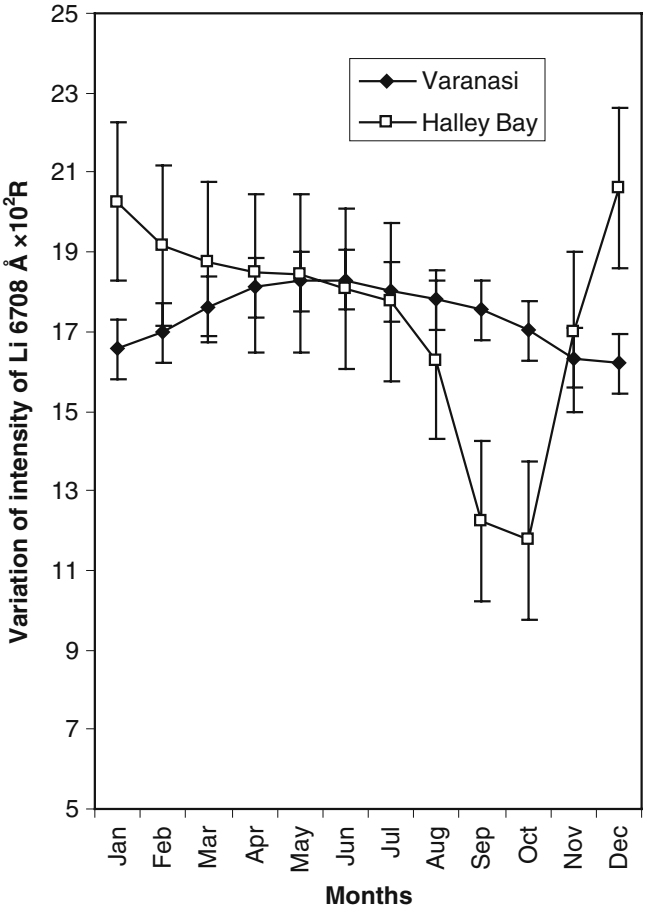

Figure 7. Seasonal variations of intensity of Li 6708 Å at Varanasi (25°N, 83°E) and Halley Bay (76°S, 27°W) for the period of 1979–2005.

4. Conclusions

The yearly variations of ozone concentration in DU at Varanasi and Halley Bay were mainly controlled by their March and September concentrations, respectively, because the nature of March and September ozone variations was the most identical with that of yearly ozone variations over these two stations, respectively, from 1979 to 2005. The rate of ozone depletion at Halley Bay was comparatively higher than that at Varanasi. The rate of ozone depletion attained maximum during September to October at Halley Bay due to predominant ozone destruction processes caused by comparatively lower temperature of about -80°C, higher concentrations of Cl and ClO radicals, lower amounts of oxides of nitrogen and appearance of larger polar stratospheric clouds at Halley Bay.

Observations of light element lithium in atmosphere provide the means to determine the origin of lithium, nucleosynthesis of other light elements, space radiation effects in satellites, the use of nuclear interactions in biology and medicine (Read and Viola 1984) and to investigate the effects of meridional circulation on the giant (Balachandran 1995). The volume emission rate of Li line attained maximum at an altitude of 90 km due to the maximum value of the product of $n(O_3)$, n(O) and n(Li). The volume emission rate and intensity of Li line at Halley Bay (76°S, 27°W) were comparatively higher than that at Varanasi in 1979 due to its higher percentage of ozone increase from its mean value. The intensity of Li line gradually decreased from 1979 to 2005 at both the stations, Varanasi and Halley Bay, but at different rates. The rate of yearly decrease in intensity was greater at Halley Bay due to higher loss rate of yearly mean ozone concentration from 1979 to 2005.

Intensity of lithium gradually increased from the month of January, attained its maximum during May and June, then gradually decreased and attained its minimum value in December at Varanasi. But for Halley Bay, maximum intensity of lithium occurred in December and January, then intensity gradually decreased, attained minimum in October, then intensity gradually increased due to same nature of ozone variation.

References

Balachandran S 1995 Lithium in first-ascent red giants; *Memorie della Societa Astronomia Italiana* **66** 387–394.

Bhaumik D, Chakraborty J N, Midya S K and Chakraborty S 1996a Morning twilight airglow emission of lithium 6708 Å and OH (7, 2) band at Calcutta and their co-variation; *Earth Moon Planets* **75** 169–175.

Bhaumik D, Chakraborty J N, Midya S K and Chakraborty S 1996b Evening twilight OH (7, 2) band emission at Calcutta and its covariation with Li 6708 Å; *Earth Moon Planets* **74** 115–121.

Bodeker G E, Struthers H and Connor B G 2002 Dynamical containment of Antarctic ozone depletion; *Geophys. Res. Lett.* **29** 14,206.

Bojkov R D 1992 Scientific assessment of ozone depletion; *WMO Bull.* **41** 171.

Brown E F 1998 Implication of a subthreshold resonance for stellar beryllium depletion; *Astrophys. J.* **495** 905–910.

Cordero E C and Nathan T R 2002 An examination of anomalously low column ozone in southern hemisphere mid-latitude during 1997; *Geophys. Res. Lett.* **29** 1123, doi: 10.1029/2001GL013948.

Farman J C, Gardiner B G and Shanklin J D 1985 Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction; *Nature* **315** 207–210.

Jacchia L G 1977 *SAO Special Report No. 375,* Smithsonian Institution Astrophysical Observatory, Cambridge, Massachusetts.

Jana P K and Midya 1995 A theoretical model of altitudinal distribution of sodium atom; *Earth Moon Planets* **71** 147–152.

Jana P K and Nandi S C 2005a Effect of solar parameters on Antarctic, artic and tropical ozone during the last solar cycle; *Indian J. Radio Space Phys.* **34** 114–118.

Jana P K and Nandi S C 2005b Depletion of ozone and its effect on night airglow intensity of Na 5893 Å at New Delhi (29°N, 77°E) and Halley Bay (76°S, 27°W); *Indian J. Phys.* **79(11)** 1313–1317.

Jana P K and Nandi S C 2005c Depletion of ozone and its effect on night airglow intensity of Na 5893 Å at Trivandrum (8.25°N, 76.9°E) and Halley Bay (76°S, 27°W); *Mausam* **57(2)** 350–354.

Jana P K and Nandi S C 2006 Ozone decline and its effect on night airglow intensity of Na 5893 Å at Dumdum (22.5°N, 88.5°E) and Halley Bay (76°S, 27°W); *J. Earth Syst. Sci.* **115** 607–613.

Jana P K, Midya S K and De U K 2001 Short-term ozone trend in India; *Indian J. Radio Space Phys.* **30** 176–180.

Jana P K, Nandi S C and Sarkar D 2006 Depletion of ozone and its effect on night airglow intensity of Na 5893 Å at Srinagar and Halley Bay; *Indian J. Radio Space Phys.* **35** 401–406.

Kerr A 1998 Deep chill triggers record ozone hole; *Science* **282** 391.

Knauth D C, Federman S R, Lambert D L and Crane P 2000 Newly synthesized lithium in the interstellar medium; *Nature* **405** 656–658.

Lemoine M, Vangioni-Flam E and Casse M 1998 Galactic cosmic rays and the evolution of light elements; *Astrophys. J.* **499** 735–745.

Madrigal M A and Peraza J P 2005 Analysis of the evolution of the Antarctic ozone hole size; *J. Geophys. Res.* **110** D02107, doi: 10.1029/2004JD004944.

Meneguzzi M and Reeves H 1975 Light element production by cosmic rays; *Astron. Astrophys.* **40** 99–110.

Meneguzzi M, Audouze J and Reeves H 1971 The production of the elements Li, Be, B by galactic cosmic rays in space and its relation with stellar observations; *Astron. Astrophys.* **15** 337–359.

Midya S K 1994 Ozone decline and its effect on night airglow intensity of OH (8, 3) band; *Earth Moon Planets* **65** 1–6.

Midya S K and Jana P K 2002 Atmospheric ozone depletion and its effect on environment; *Indian J. Phys.* **76B(2)** 107–138.

Midya S K and Midya D 1993 The effect of Antarctic O_3 decline on night airglow intensity of Na 5893 Å, O5577 Å, OH emissions and its correlation with solar flare numbers; *Earth Moon Planets* **61** 175–182.

Midya S K, Sarkar H and Manna A 2001 Antarctic O_3 depletion – its effect on the variation of Li 6708 Å emission line intensity at McMurdo and Halley Bay; *Czech. J. Phys.* **51** 609–614.

Ramarty R, Kozlovsky B and Lingenfelter R E 1996 Light isotopes, extinct radioisotopes and gamma-ray lines from low energy cosmic-ray interactions; *Astrophys. J.* **456** 525–540.

Read S M and Viola V E Jr 1984 Excitation functions for A≥6 fragments formed in ^{1}H and ^{4}He-induced reactions on light nucli; *Atomic Data and Nuclear Data Tables* **31(3)** 359–397.

Reeves H, Fowler W A and Hoyle F 1970 Galactic cosmic ray origin of Li, Be and B in stars; *Nature* **226** 727–729.

Salby M, Callaghan P, Keckhut P, Godin S and Guirlet M 2002 International changes of temperature and ozone, relationship between the lower and upper stratosphere; *J. Geophys. Res.* **107(D18)**, doi: 10.1029/2001JD000421.

Slanger T G, Cosby P C, Osterbrock D E, Stone R P S and Misch A A 2003 The high-resolution light-polluted night-sky spectrum at Mount Hamilton, California; *PASP* **115** 869–878.

Taori A and Taylor M 2010 Dominant winter-time mesospheric wave signatures over a low latitude stations Hawaii (20.8°N): An investigation; *J. Earth Syst. Sci.* **119(3)** 259–264, doi: 10.1007/S12040–010–0020.

Taori A, Makela J and Taylor M 2010 Mesospheric wave signatures and equatorial plasma bubbles: A case study; *J. Geophys. Res.* **115** A06302, doi: 10.1029/2009JA015088.

Uchino O, Bojkov R, Balis D S, Akagi K, Hayashi M and Kajihara R K 1999 Essential characteristics of the Antarctic spring ozone decline: Update to 1998; *Geophys. Res. Lett.* **26** 1377–1380.

Vineeth C, Pant T K, Thampi S V, Sridharan R, Ravindram S, Devasia C V, Kumar K K and Alex S 2008 Investigation of the response of equatorial MLTI region during a partial solar eclipse through ground-based daytime optical technique; *J. Geophys. Res.* **113** A03302, doi: 10.1029/2007JA012335.

World Meteorological Organization (WMO) 2002 *Scientific assessment of ozone depletion.*

MS received 4 April 2010; revised 20 October 2010; accepted 2 November 2010