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Statistical study of different solar activity features with total column ozone at two hill stations of Uttarakhand

Hema Bisht[1,$,*], Bimal Pande[2,#], Ramesh Chandra[2] & Seema Pande[1]
[1]Department of Physics, MBPG College, Haldwani 263 129, Uttarakhand, India
[2]Department of Physics, DSB Campus, Kumaun University, Nainital 263 002, Uttarakhand, India
E-mail: [$]hema.bisht15@yahoo.com; [#]pandebimal@yahoo.co.in

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This paper presents a statistical study of different solar activity features (DSAF), viz. sunspot number (SN), solar active prominences (SAP), solar flares (SF) and solar proton events (SPE) with total column ozone (TCO) amount using 28 years (1986-2013) data. The ozone data has been taken for two hill stations of Uttarakhand, viz. Nainital (29º23'N, 79º27'E) and Mussoorie (30°27'N, 78°06'E). The study reveals a positive correlation between yearly averaged TCO and DSAF. The value of linear correlation coefficient (r) for TCO-Nainital with SN, SAP, SF and SPE is found to be 0.51, 0.30, 0.49, and 0.54, respectively and for TCO-Mussoorie with SN, SAP, SF, SPE is found to be 0.45, 0.27, 0.44, and 0.51, respectively. This supports the fact that solar activity features contribute to the production of ozone. Also the trend in TCO over both the stations annually, monthly and seasonally has been studied. A negative trend is observed indicating a decrease in the ozone concentration over these stations in given time period.

Keywords: Total column ozone, Sunspot number, Solar flare, Solar active prominences, Solar proton events
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1 Introduction

There are a number of different features of solar activity such as: sunspot number (SN), solar active prominences (SAP), solar flares (SF) and solar proton events (SPEs). These are very important and crucial to understand the space weather. Hereafter, these mentioned different solar activity features are termed as DSAF. The variations in total column ozone (TCO) were found to be influenced by DSAF[1-8].

Ozone is highly reactive, naturally occurring ingredient of the stratosphere that is produced from oxygen by sunlight. It is one of the most important chemicals in both stratosphere and troposphere. Apart from absorbing the harmful ultraviolet radiation from the sun, it also plays an important role in determining the earth's climate. Total column ozone (TCO) is the total amount of ozone (or total number of ozone molecules) that is found in a column of air above the earth from its surface to the top of the atmosphere. It is the measure of the thickness of the ozone layer. It is numerically expressed in Dobson units (DU). The amount of TCO is controlled by some active species in the oxygen, hydrogen, nitrogen, chlorine and bromine families through photochemical reactions.

Solar variability affects ozone through radiative heating in atmosphere. Solar UV radiation is absorbed by atmospheric ozone. It is responsible for both the creation and destruction of ozone. Photochemical reactions occur between the incoming radiations and the molecules present in the atmosphere. There are observations which support the increase in solar ultraviolet radiation with increase in sunspot number[2] and hence, total ozone would be expected to vary more or less in phase with sunspot number[2-4]. The other features include solar flares (SF), solar active prominences (SAP) and solar proton events (SPEs).

The total ozone was found to be enhanced during magnetically disturbed conditions which are associated with peak solar activity period[9]. The results for different time periods are different. Angell & Korshover[1] concluded that there is nearly in-phase relationship between sunspot number and total ozone. According to them, the decrease in ozone from 1970 to 1974 is mainly due to the decrease in sunspot number following the sunspot maximum in 1969, and not due to anthropogenic effects. They predicted an upward ozone trend after the sunspot minimum in 1975. Angell[10] also observed such an upward trend in global total ozone. Moreover, after the sunspot maximum in 1979-80, they reported a downward trend more pronounced than during 1970-74. Isikwue *et al.*[3] studied the contributions of SN to the variations of stratospheric ozone concentrations in some cities in Nigeria during 1998-2005 and found significant positive correlation between both. Selvaraj *et al.*[6] studied the statistical relationship between surface ozone and solar activity for Tranquebar during the years 1996-2004 and obtained a strong positive correlation between SN and ozone content in the altitude range 20-30 km. However, Willet[7] presented a study for 27 years (1933-1959) and found a highly significant negative correlation between relative sunspot number and worldwide average of total atmospheric ozone.

McPeters & Jackman[11] and Jackman *et al.*[12] have observed a significant depletion in the ozone value after large solar proton events (SPE) and captured it in the dayside polar middle atmosphere using satellite measurement. Seppälä *et al.*[13] compared the concentration of NO_2 and O_3 after the solar proton events have taken place and found a strong negative correlation. Solar protons entering the earth magnetosphere are guided by the earth's magnetic field and they precipitate into the polar cap areas. Since the protons can have high energy up to tens of MeVs, hence, they deposit their energy in the mesosphere and stratosphere. Thus, they provide a direct connection between the Sun and the Earth's middle atmosphere.

The aim of the present study is to explore the possible relationship between the different solar activity features (SN, SAP, SF and SPE) and atmospheric ozone over two latitude regions of Uttarakhand, viz. Nainital and Mussoorie. These places being hill stations and not industrial areas, there are more chances of ozone being influenced by solar factors rather than anthropogenic activities. These sites have been chosen, as much work has not been done on these prominent hill stations, to figure out the relationship between solar activity and total column ozone.

2 Data sources and Analysis

The different solar activity features and atmospheric ozone data used in this study have been downloaded from the websites.

- The sunspot numbers and solar flares are taken from January 1986 to December 2013. Solar active prominences are taken from January 1986 to February 2008. The monthly mean values of sunspot number (SN) have been taken and then yearly mean value computed for 1986-2013. For SF, the total number is taken, first monthly and then summed to yearly during 1986-2013. For SAP also, data is taken first monthly and then summed to yearly values during 1986-2008. Sunspots, solar flares and SAP data are taken from the following sites:
  http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/;
  http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/h-alpha/;
  http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/prominencesfilaments/ filaments/.
- The solar proton events are taken from January 1986 to December 2013. SPE [1986-2013] data is obtained from: http://www.swpc.noaa.gov/ ftpdir/indices/. The total number of solar proton events have been taken first monthly and then summed them to yearly values for 1986-2013.
- Atmospheric ozone data [1986-2013]
  Total column ozone measurements from Total Ozone Mapping Spectrometer (TOMS) on board satellite Nimbus 7, Meteor 3, Earth Probe and OMI (Ozone Monitoring Instrument) have been used to determine daily data of column ozone over Nainital and Mussoorie. The data for atmospheric ozone is taken on the daily basis from January 1986 to December 2013 and then averaged monthly and yearly. During January 1995-July 1996, as no satellite was in place, no data were acquired and hence, the ozone data is missing. The ozone data from January 1986 to December 2013 is downloaded from the website http://ozoneaq.gsfc.nasa.gov/ozone_overhead_all_v8.md.

The detailed information about the ozone observations is given in Table 1. The data table including all the data of total column ozone-Nainital (TCO-NTL), total column ozone-Mussoorie (TCO-MUS) along with the standard error (SE), sunspot number mean [SN(M)], SF, SAP and SPE during 1986-2013 are provided in Table 2.

Table 1 — Characteristics of total column ozone content dataset

Satellites	Nimbus-7, Meteor-3, Earth Probe and OMI
Instrument	Total Ozone Mapping Spectrometer (TOMS)
Parameter	Total column ozone concentration
Temporal coverage	Jan 1986 to Apr 1993, May 1993 to Apr 1994, Jun 1994 to Nov 1994, Aug 1996 to Dec 2004 and Jan 2005 to Dec 2013
Temporal resolution	Daily data

Table 2—Data of TCO-NTL, TCO-MUS, SN (M), SF, SAP and SPEs during 1986-2013

S No	Year	TCO-NTL, DU	SE	TCO-MUS, DU	SE	SN (M)	SF	SAP	SPEs
1	1986	280.35	3.27	282.6	3.4	13.4	730	3095	4
2	1987	279.8	5.97	281.45	6.11	29.4	1627	4469	1
3	1988	274.47	2.14	276.39	2.18	100.2	4816	8246	9
4	1989	286.38	3.03	288.15	2.95	157.6	7711	10844	23
5	1990	283.03	3.62	284.56	3.49	142.6	6610	11575	12
6	1991	285.81	3.56	288.34	3.66	145.7	6495	11472	17
7	1992	279.58	4.79	280.59	4.75	94.3	3952	9913	6
8	1993	268.04*	3.36	268.5*	3.35	54.6	2541	9439	2
9	1994	279.08	3.65	281	4.1	29.9	1066	6083	2
10	1995	Nil	Nil	Nil	Nil	17.5	639	4044	1
11	1996	258.51*	4.68	260.77*	4.81	8.6	280	2238	0
12	1997	276.35	3.04	279.01	3.18	21.5	790	2506	2
13	1998	279.24	4.52	280.7	4.9	64.3	2423	1320	8
14	1999	273.32	3.35	274.72	3.2	93.3	3963	446	5
15	2000	278.46	4.15	279.4	4.17	119.6	4474	591	13
16	2001	281.27	4.13	282.33	4.34	111	3597	479	22
17	2002	276.49	3.4	278.51	3.05	104	3223	412	19
18	2003	282.55	4.02	284.19	4.21	63.7	1552	372	9
19	2004	276.79	2.98	277.98	3.09	40.4	728	165	6
20	2005	274.89	4.28	278.23	4.55	29.8	571	132	7
21	2006	274.9	3.59	276.83	3.48	15.2	159	102	2
22	2007	274.18	3.72	276.09	3.69	7.5	261	13	0
23	2008	272.51	2.66	274.53	2.64	2.9	24	10	0
24	2009	276.72	2.87	277.44	2.56	3.1	37	Nil	0
25	2010	281.34	4.26	286.48	5.44	16.5	390	Nil	1
26	2011	275.33	3.61	276.56	3.67	55.6	1805	Nil	7
27	2012	277.6	3.5	280.15	3.35	57.58	2177	Nil	13
28	2013	275.66	2.33	278.16	2.13	64.7	1826	Nil	7

2.1 Location

Nainital is a popular hill station in Uttarakhand. It lies in the Kumaon foothills of outer Himalayas at an altitude of 6837 ft above sea level. This region receives temperate summers with a maximum temperature of 27°C. In winters, it receives snowfall between December and February with temperature varying between 15°C and -3°C.

Mussoorie is a hill station in Dehradun district of Uttarakhand. It lies in the foothills of the Garhwal Himalayan range at about 6580 ft above sea level. It experiences warm summers with temperature varying between 30°C and 10°C and chilled winters with temperature ranging 10°C - 1°C.

Both the hill stations have subtropical climate. Location map of Nainital and Mussoorie is given in Fig. 1(a and b), respectively.

3 Statistical analysis of the data

3.1 Annual variation

The annual variation of DSAF with TCO for both stations, viz. Nainital and Mussoorie are presented in Fig 2. In order to analyze the trend, a linear curve fitting method is used. A decrease in ozone concentration is observed by -0.13 (±0.13)% per decade over Nainital, and 0.11(±0.13)% per decade over Mussoorie. The DSAF also experienced a negative trend during 1986-2013.

The decrease in the TCO values in 1993 is probably associated with major volcanic eruption of Mt Pinatubo (June 1991). Due to this volcanic eruption, huge quantities of particles (gas and ash) were injected into the stratosphere (eruption rate was 81,900 m^3 s^{-1}) resulting in the formation of sulphate aerosol. These aerosol particulates reflected sunlight away from the earth and caused global cooling. A 0.5°C of cooling was observed around the world. These sulphate aerosols temporarily accelerated the ozone depletion through a series of chemical reactions[14-18]. There has been no TCO measurement in the months of year 1995 (as mentioned earlier) and so the column for ozone is left blank for 1995. The low value of ozone in 1996 may be associated with the

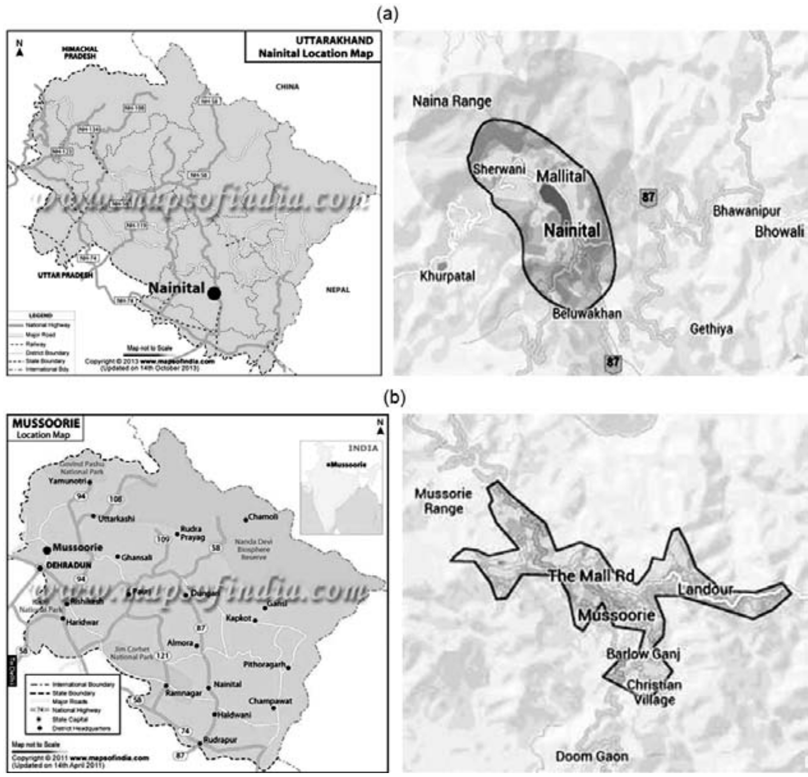

Fig. 1 — Location map of: (a) Nainital; and (b) Mussoorie (Uttarakhand)

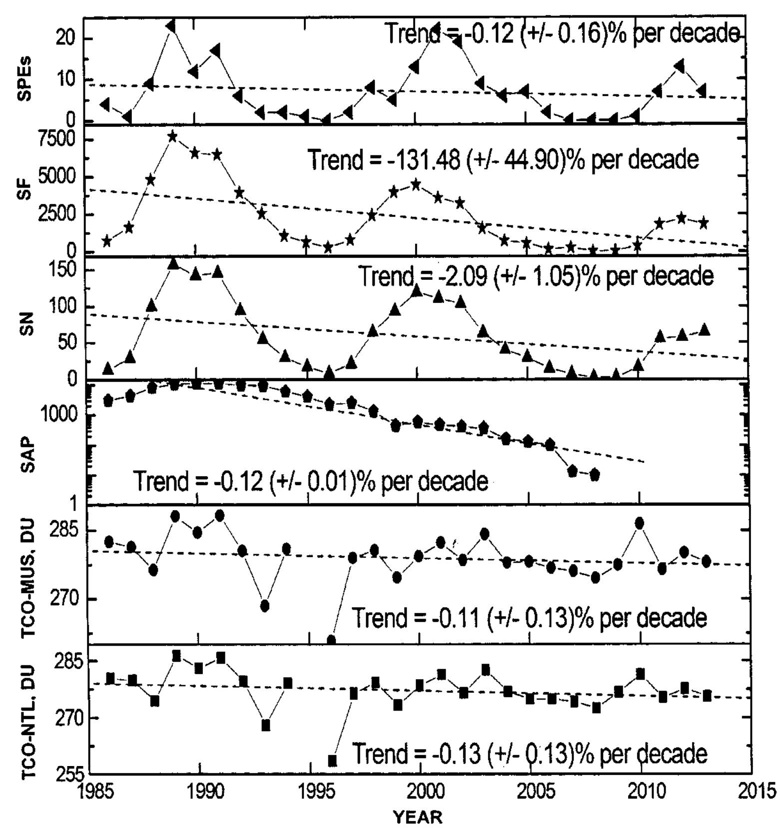

Fig.2 — Annual variation of TCO at Nainital and Mussoorie with DSAF for time period 1986-2013

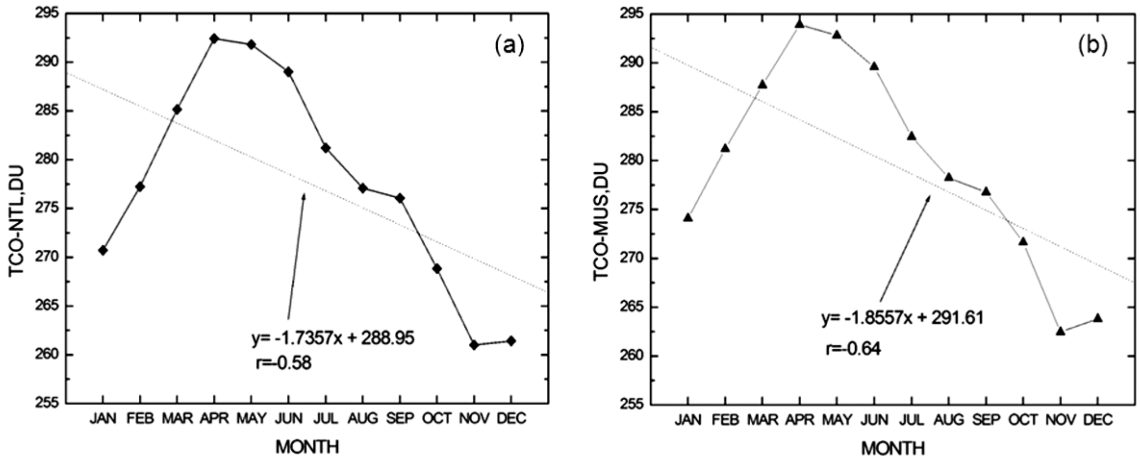

Fig. 3 — Monthly variation of TCO for time period 1986-2013 at: (a) Nainital; and (b) Mussoorie

solar minima in 1996. There may be one more reason for this decrease. No ozone data was measured by the TOMS instrument during January 1995-July 1996. Therefore, for the year 1996, only ozone data for August-December is available. Figures 3(a and b) show the monthly variation of ozone, which clearly depict the decreasing trend of ozone after August till December. This decreasing trend of ozone during August-December and the unavailability of ozone data for January 1996 - July 1996 may probably be the reason for such a low value of ozone.

3.2 Monthly variation

Figures 3(a and b) represent the monthly variation of TCO over Nainital and Mussoorie during 1986-2013. The data for a particular month (say January) is taken every year during 1986-2013, summed and then averaged. Similarly, the monthly data is prepared for both the stations (Table 3). There is an increase in TCO amount from January to April with the highest amount occurring in April. Thereafter, a decreasing trend begins with the lowest amount of TCO in November. A slight increase is observed after November till December. Apart from month to month variation, an overall decreasing trend is observed providing a correlation coefficient of -0.58 for Nainital and -0.64 for Mussoorie.

3.3 Seasonal variation

Both Nainital and Mussoorie have five seasons: spring time from March to April (MA), May to June (MJ) is summer, followed by the rainy season from July till September end (JAS), autumn season from October to November (ON), and chilled winters from December to February (DJF). The TCO shows variation in its value from one season to another.

Table 3—Data of monthly variation of TCO-NTL and TCO-MUS from 1986-2013

S No	Month	TCO-NTL, DU	SE	TCO-MUS, DU	SE
1	Jan	270.73	1.87	274.09	1.94
2	Feb	277.23	2.54	281.18	2.65
3	Mar	285.16	2.29	287.72	2.28
4	Apr	292.43	1.48	293.91	1.66
5	May	291.82	1.36	292.82	1.48
6	Jun	289.01	0.91	289.57	0.93
7	Jul	281.21	1.3	282.44	1.32
8	Aug	277.07	1.08	278.22	1.12
9	Sep	276.05	0.81	276.76	0.79
10	Oct	268.85	1.08	271.65	2.54
11	Nov	261.01	1.38	262.46	1.53
12	Dec	261.43	2.06	263.81	2.16

Most of it is created over the tropics and then transported into the polar region by the circulation in the stratosphere. The value of ozone near the equator is 260 DU, at mid-latitudes 300 - 350 DU and at poles it ranges 450-500 DU. Both the hill stations fall under sub-tropical climatic range. The threshold value for TCO is taken as 260 DU. The data of seasonal variation of TCO-NTL and TCO-MUS during 1986-2013 are provided in Table 4.

Figures 4(a and f) represent the plot of TCO for spring season for Nainital and Mussoorie. The peak value of TCO is 301.58 DU over Nainital and 304.70 DU over Mussoorie in 2001. It is observed that the TCO remains above the threshold value during spring time. Figures 4(b and g) represent the plots for summer season for Nainital and Mussoorie showing the ozone concentration above 260 DU for both the stations, with the highest value 301.44 DU over Nainital in 1992 and 302.31 DU over Mussoorie in

Table 4—Data of seasonal variation of TCO-NTL and TCO-MUS during 1986-2013

Year	TCO-NTL, DU					TCO-MUS, DU				
	MA	MJ	JAS	ON	DJF	MA	MJ	JAS	ON	DJF
1986	295.15	290.42	277.65	267.04	275.36	300.27	291.03	277.78	268.93	279.12
1987	297.6	299.3	282.92	259.75	265.2	298.45	302.31	285	260.32	266.76
1988	279.63	284.79	274.29	264.6	270.91	281.4	285.8	275.88	265.22	274.75
1989	300.16	294.96	287.67	271.42	280.15	302.13	295.29	288.4	272.27	284.41
1990	296.64	291.96	282.7	267.89	278.42	298.38	291.81	283.32	269.72	281.64
1991	299.71	299.19	287.06	272.58	275.21	302.99	301.3	288.18	272.93	280.39
1992	292.24	301.44	280.62	259.57	268.88	295.3	300.7	281.39	259.69	270.52
1993	276.83	285.01	268.21	255.12	259.33	279.3	282.99	270.18	252.85	260.38
1994	292.55	285.23	273.98	262.94	286.35	296.7	286.9	274	263.74	290.06
1995	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1996	Nil	Nil	268.47	255.28	245.05	Nil	Nil	270.84	257.3	247.57
1997	287.49	283.96	274.2	275.86	266.33	288.8	284.33	276.18	283.18	269
1998	298.28	290	279.4	256.81	274.17	299.86	292.33	280.93	255.27	276.91
1999	262.64	287.67	281.52	271.22	264.06	263.76	288.07	282.99	272.82	266.12
2000	293.45	290.13	280.82	258.69	271.49	294.27	289.49	281.79	258.83	274.08
2001	301.58	292.54	281.57	264.14	271.33	304.7	292.55	282.53	265.09	271.89
2002	284.39	289.55	281.12	270.66	261.76	284.84	289.28	283.99	271.6	266.23
2003	294.64	295.06	282.81	260.5	280.59	294.65	297.64	283.75	260.1	284.76
2004	277.65	289.44	282.73	270.22	266.24	281.69	289.48	284.53	270.07	266.57
2005	286.85	289.82	272.21	259.64	269.83	290.81	292.21	274.31	261.76	275.37
2006	286.09	288.06	277.83	270.72	258.5	289.25	288.91	278.72	272.4	261.55
2007	286.01	287.11	273.29	258.9	268.77	287.86	287.47	274.26	258.93	273.92
2008	280.61	281.6	274.42	264.31	264.6	283.12	282.48	275.89	266.26	267.67
2009	285.93	288.99	278.66	267.57	266.57	283.94	290.03	278.39	268.15	269.97
2010	289.75	296.7	279.12	264.03	279.25	290.74	297.79	276.3	292.91	282
2011	294.06	282.86	271.38	263.93	269.36	295.87	282.78	270.54	264.9	273.34
2012	288.5	295.12	273.72	269.6	267.87	291.46	296.31	274.98	272.62	272.05
2013	280.34	286.68	276.4	270.3	268.02	280.66	288.89	277.83	272.67	273.35

1987. The similar trend is seen in the rainy season also where TCO amount remains above the permissible threshold value. The maximum ozone value is 287.67 over Nainital [Fig. 4(c)] and 288.40 DU over Mussoorie [Fig. 4(h)] in 1989. Figures 4(d and i) show the variation of TCO in the autumn for Nainital and Mussoorie, respectively. A decrease is observed in the value of TCO and it falls below 260 DU at both the stations. The lowest value is 255.12 DU for Nainital and 252.85 DU for Mussoorie in 1993. The winter season also experiences reduction in the ozone value with the lowest 245.05 DU for Nainital [Fig. 4(e)] and 247.57 DU for Mussoorie [Fig. 4(j)] in 1996.

3.4 Total column ozone and Sunspot number (SN)

The yearly mean SN is plotted against yearly averaged TCO-NTL [Fig. 5(a)] and TCO-MUS [Fig. 5(b)]. By linear curve fitting method, the value of correlation coefficient is found to be 0.51 and 0.46, respectively. It shows moderate positive correlation. On plotting the graphs, it is observed that at both the hill stations, there are few points of TCO in 1993 and 1996, which are very far from the main stream. These are called outliers. These outliers are marked as '*' in data Table 2. On plotting the graphs again by removing these outliers for NTL [Fig. 5(c)] and MUS [Fig. 5(d)], a slight increase in the correlation coefficient (0.55 and 0.46, respectively) is found.

This positive correlation supports the previous studies, such as Angell[2] found a zero lag correlation of 0.48, significant at 1% level between SN and total ozone. Labitzke & Loon[4] got a positive correlation of 0.71 between TCO (taken over the area in the range 35°N-35°S) and SSC. Isikwue *et al.*[3] obtained a positive correlation between SN and ozone for five cities in Nigeria, namely Calabar, Nsukka, Lagos, Abuja and Sokoto as 0.748, 0.790, 0.790, 0.783 and 0.797, respectively.

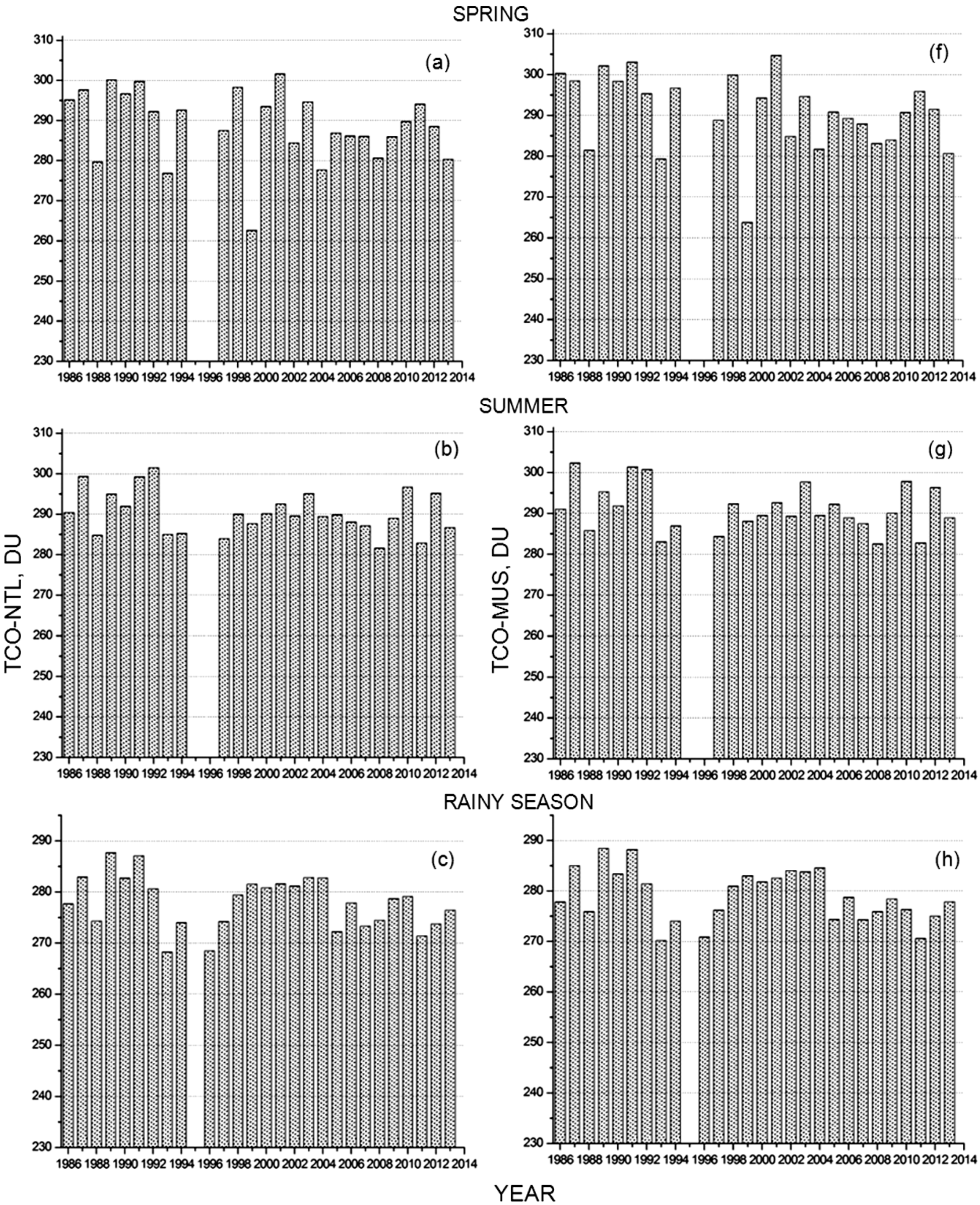

Fig. 4 — Seasonal variation of TCO over: (a-e) Nainital; and (f-j) Mussoorie [in spring (a and f); summer (b and g); and rainy season (c and h)] (Contd.)

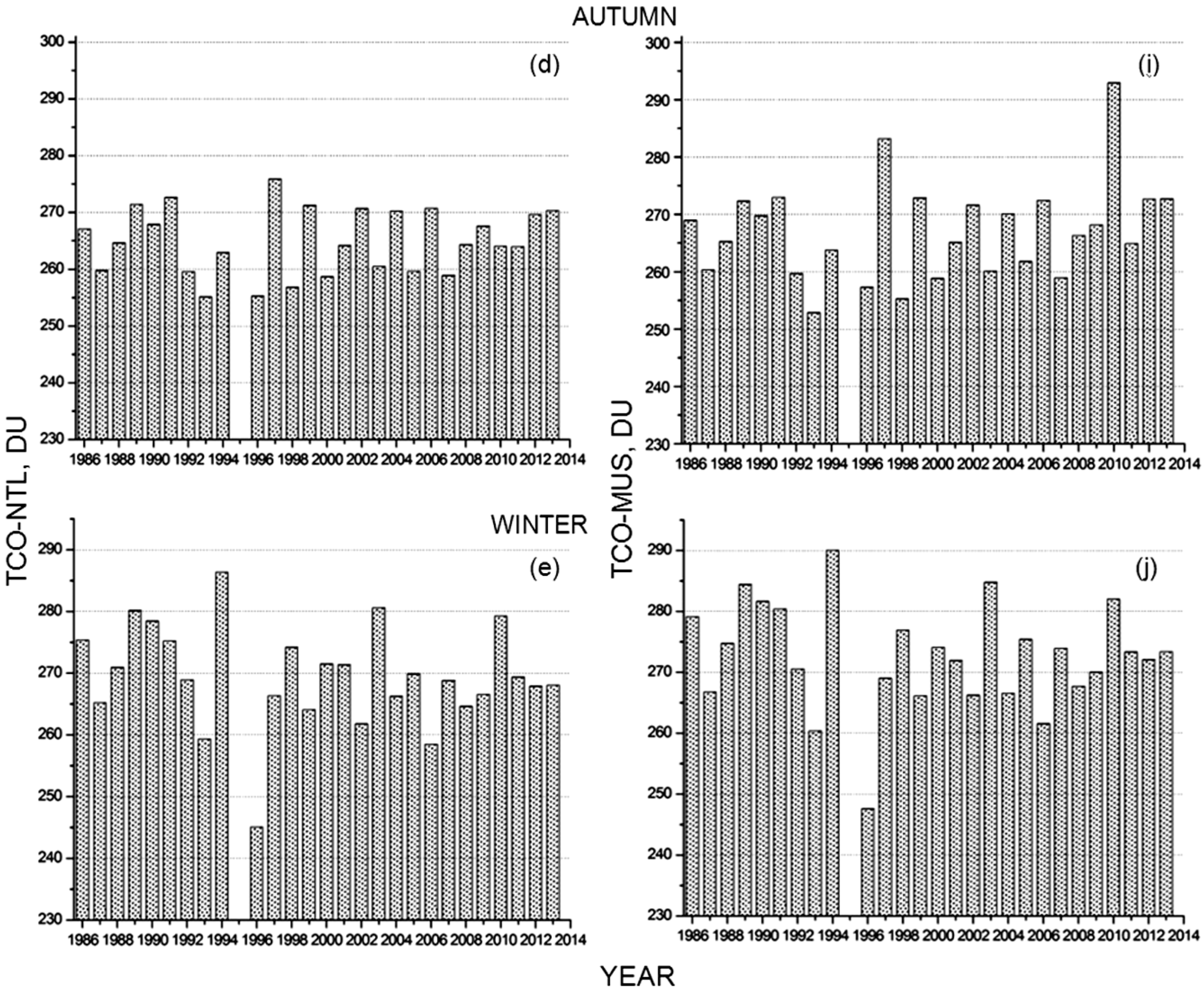

Fig. 4(Contd.) — Seasonal variation of TCO over: (a-e) Nainital; and (f-j) Mussoorie [autumn (d and i); and winter (e and j)]

The statistical results are shown in Table 5. The standard deviation (SD), Kurtosis (Kurt) and skewness (Skew) are also shown.

3.5 Total column ozone and Solar flares (SF)

The total number of flares on yearly basis is plotted against yearly averaged TCO-NTL [Fig. 6(a)] and TCO-MUS [Fig. 6(b)]. By linear curve fitting method, the value of correlation coefficient is found to be 0.49 and 0.44, respectively. It again shows moderate positive correlation.

Again similar to sunspot numbers, after removing the outliers (shown by ‘*’ in data Table 2) for NTL [Fig. 6(c)] and MUS [Fig. 6(d)], a slight increase in the correlation coefficient (0.58 and 0.50, respectively) is found. The statistical parameters after the comparison between solar flares and TCO are shown in Table 5.

3.6 Total column ozone and SAP

The total number of SAP on yearly basis is plotted against yearly averaged TCO-NTL [Fig. 7(a)] and TCO-MUS [Fig. 7(b)]. By linear curve fitting method, the value of correlation coefficient is found to be 0.33 and 0.31, respectively. It shows very poor correlation. Again, few outliers are noticed as indicated by ‘*’ in data in Table 2. On plotting the graphs by removing these outliers for NTL [Fig. 7(c)] and MUS [Fig. 7(d], a high increase in the correlation coefficient (0.63 and 0.64, respectively) is found. The result of the statistics between SAP and TCO is presented in Table 5.

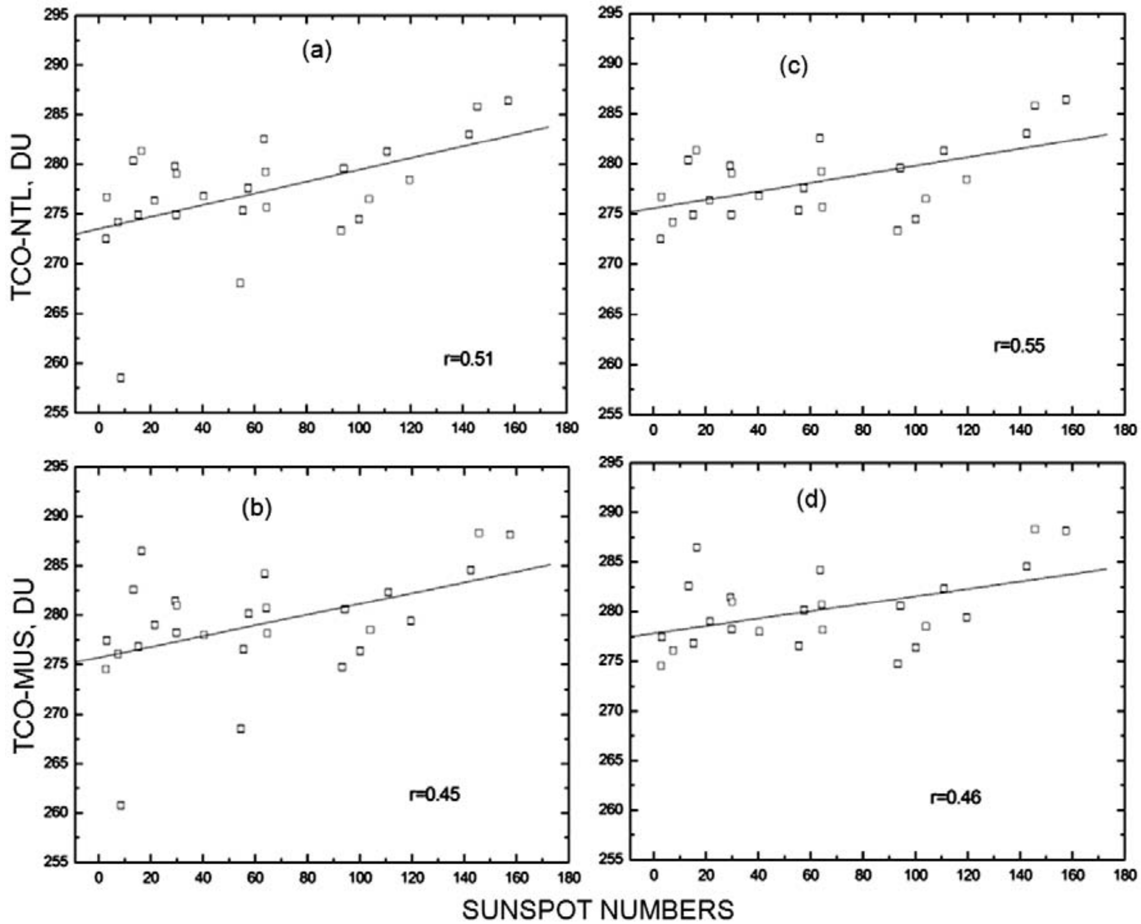

Fig. 5 — Scattered plot between TCO and sunspot number at: (a,c) Nainital; and (b,d) Mussoorie [correlation coefficients (r) indicated in the figure]

Table 5—Different statistical parameters at Nainital and Mussoorie

Statistical parameter		r	SD	Kurt	Skew
TCO with SN	NTL	0.50831	4.84518	-1.8089	-0.1879
	MUS	0.4526	5.16127	-1.8121	-0.1844
			After removing '*' values		
	NTL	0.54976	3.16889	-1.830	-0.1175
	MUS	0.46369	3.50727	-1.833	-0.1140
TCO with SF	NTL	0.49142	4.90002	3.3174	1.9804
	MUS	0.43828	5.2025	3.3201	1.9810
			After removing '*' values		
	NTL	0.57671	3.09918	3.0719	1.9239
	MUS	0.49604	3.43721	3.0746	1.9245
TCO with SAP	NTL	0.3307	5.8474	3.5437	2.1946
	MUS	0.3148	5.8918	3.5444	2.1948
			After removing '*' values		
	NTL	0.6336	3.1715	2.4585	1.9524
	MUS	0.6401	3.1147	2.4592	1.9526
TCO with SPE	NTL	0.54174	4.72909	-2.0671	0.0360
	MUS	0.50568	4.99344	-2.0670	0.0361

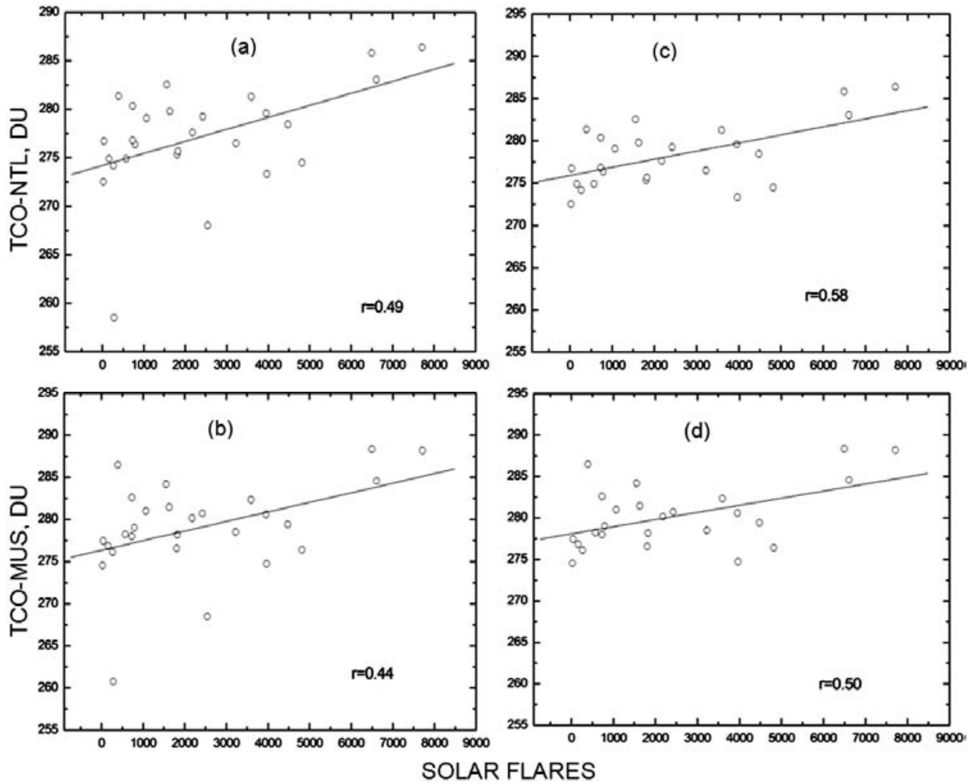

Fig. 6 — Scattered plot between TCO and solar flares at: (a,c) Nainital; and (b,d) Mussoorie [correlation coefficients (r) indicated in the figure]

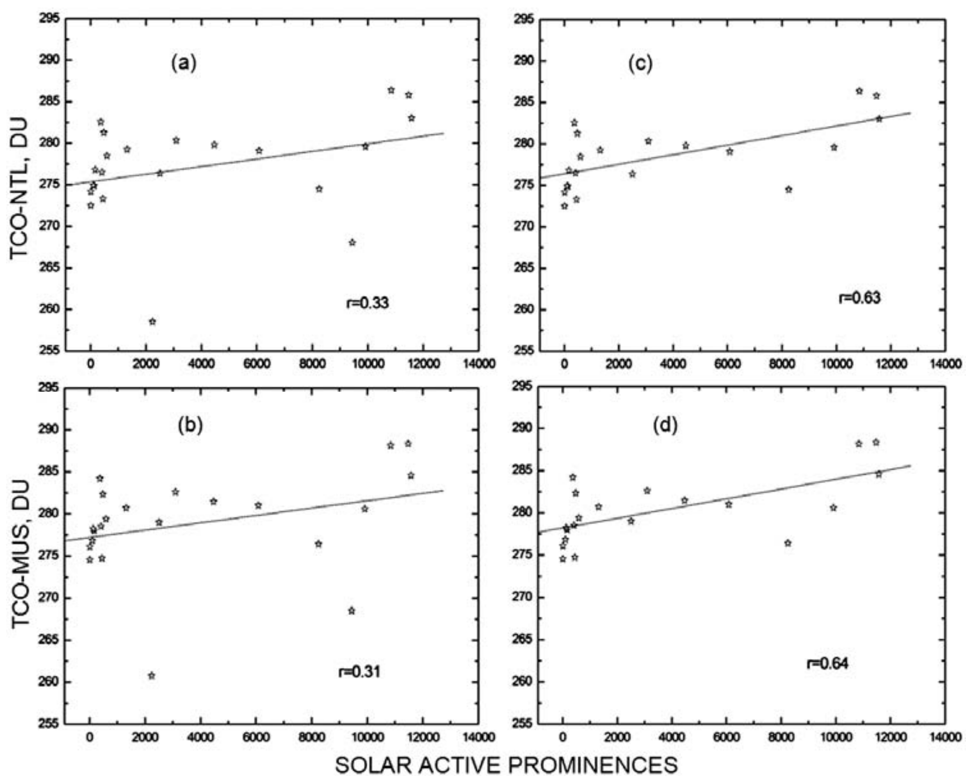

Fig. 7 — Scattered plot between TCO and solar active prominences at: (a,c) Nainital; and (b,d) Mussoorie [correlation coefficients (r) indicated in the figure]

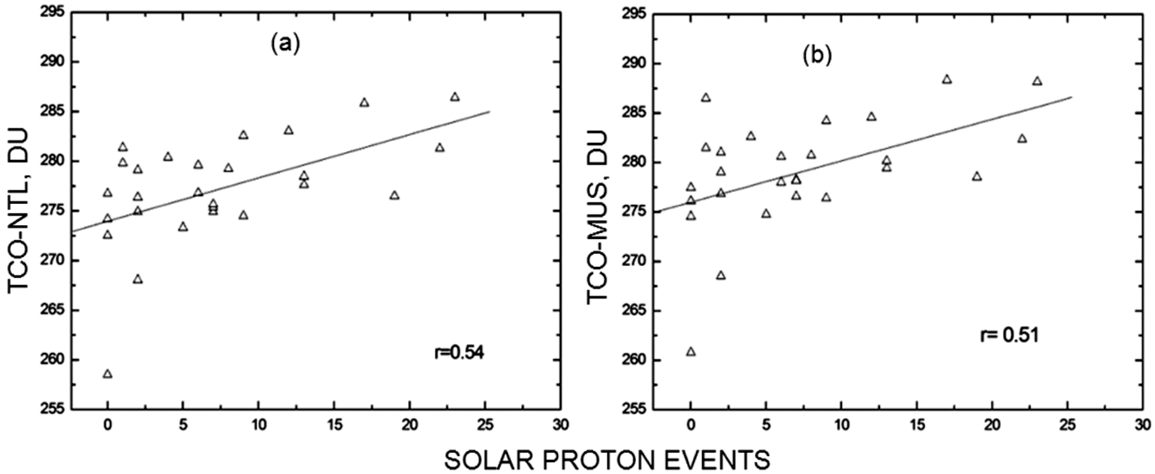

Fig. 8 — Scattered plot between TCO and solar proton events at: (a) Nainital; and (b) Mussoorie [correlation coefficients (r) indicated in the figure]

In Fig. 2, from 1999 to 2011, i.e. during solar cycle 23 and 24, a regular decrease is observed in the number of SAP. Joshi *et al.*[19] studied the distribution and asymmetry of solar active prominences during solar cycle 23 (1996-2007) and found that the SAP activity during this cycle was low in comparison to previous four solar cycles. Bankoti *et al.*[20] also reported less number of SAP observed in maximum phase compared to minimum phase of solar cycle 23.

3.7 Total column ozone and SPE

The total number of SPE on yearly basis is plotted against yearly averaged TCO-NTL [Fig. 8(a)] and TCO-MUS [Fig. 8(b)]. By linear curve fitting method, the value of correlation coefficient is found to be 0.54 and 0.51, respectively. It shows moderate positive correlation. On plotting the graphs, it is observed that at both the hill stations, there are not many outliers. The result of the statistics between SPE and TCO is presented in Table 5.

4 Summary

The statistical analysis of total column ozone annually, monthly, seasonally and with different solar activity features (SN, SAP, SF and SPEs) at two hill stations of Uttarakhand, viz. Nainital and Mussoorie has been done during 1986-2013. The yearly averaged value of TCO for Mussoorie is more than that for Nainital, which confirms the idea that the ozone increases with latitude[21-24]. The TCO over Nainital and Mussoorie experience a negative trend along with DSAF during 1986-2013. This negative trend clearly indicates that the amount of ozone is decreasing over these stations during given time period. In the monthly variation of TCO at Nainital and Mussoorie from 1986-2013, an overall negative trend is also observed with correlation coefficient of -0.58 for Nainital and -0.64 for Mussoorie. It is also observed that the highest amount of TCO over both the hill stations occur in the month of April and thereafter, it decreases from June to November. The lowest amount is observed during November for both the stations and then a slight increase in December, after which it continues to increase till the month of April. Solar activity as well as wind transport of ozone may be associated with these variations in TCO[22,25,26]. The in-depth analysis of these monthly variations requires some more investigation, which is beyond the scope of this paper. Seasonal variation of TCO over both stations revealed that the highest value of TCO occurs in spring and summer seasons indicating the production of ozone during these months, whereas lowest values are observed in autumn and winter months depicting thinning of ozone layer in these seasons.

A positive correlation is found between all DSAF and TCO for both Nainital and Mussoorie. It shows an increase in ozone with solar activities. It confirms the earlier studies that solar activity features are responsible for the production of ozone[1,6,9,10].

The correlation coefficients of TCO at Nainital and Mussoorie with SN (0.51 and 0.45, respectively), with SF (0.49 and 0.44, respectively) and with SPEs (0.54 and 0.51, respectively) are found to be nearly same and providing moderate correlation. While with SAP (0.30 and 0.27, respectively), it is very low. This poor correlation may be associated with low activity of SAP during solar cycle 23 and 24 (Refs 18 and 19). The correlation coefficient obtained is higher with

SN, SF, SAP and SPEs for TCO at Nainital than at Mussoorie except in Fig. 7(c) and Fig. 7(d). This exception is observed due to the missing parts of the data which affects the size of the correlation coefficients.

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