MAUSAM, **53**, 4 (October 2002), 503-514

551.510 : 534

On variability of total ozone derived from TOVS data over peninsular Indian sub-continent and adjoining oceanic area

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(*Received 9 August 2001, Modified 24 January 2002*)

सार - अंतर्राष्ट्रीय टी.ओ.वी.एस. संसाधित पेकैज (आई.टी.पी.पी.) वर्शन 5.0 के वन स्टेप प्राकृतिक रूप से पुनः प्राप्त किए गए एलगोरिथम के माध्यम से एन.ओ.ए.ए. 12 उपग्रह के द्वारा टी.ओ.वी.एस. आँकड़ों से प्राप्त किए गए कुल ओज़ोन का उपयोग भूमध्यरेखा के प्रभावित क्षेत्र से 26° उ/60-100° पू. तक के क्षेत्र में 1998 के दौरान इनकी दैनिक, मासिक, अक्षांशीय तथा देशान्तरीय भिन्नताओं का पता लगाने के लिए किया गया है। इसमें अधिक उष्ण क्षोभसीमा तथा न्यून समतापमंडल के साथ अधिकतम कुल ओज़ोन के संपर्क को पुनः स्थापित किया गया है। इस अध्ययन में अत्याधिक शीत ऊपरी क्षोभमंडलीय तापमान जोकि विश्व के अन्यत्र स्थानों में पूरे वर्ष अधिकतम ओज़ोन सांद्रताओं के साथ सामान्यतः सहसंबंधित रहता है, इनका भी पता लगाया गया है किन्तु इनके संबंध प्रभावित क्षेत्र में दक्षिण पश्चिम मानसून के महीनों (जून-सितंबर) के दौरान प्रतिकूल पाए गए हैं। मानसून ऋतु के दौरान वायुमंडल में फैली हुई संवहनी अस्थिरता के कारण निचले क्षोभमंडल में अत्याधिक मात्रा में विद्यमान आर्द्रता के कारण वर्षा होती है तथा इस समय ऊपरी क्षोभमंडल में 500 हैक्टापास्कल के ऊपर केवल उर्ध्वाधर संवहन के लिए बहुत थोड़ी मात्रा में आर्द्रता विद्यमान रहती है। वर्षण प्रक्रियाओं द्वारा छोड़े गए गुप्त ऊष्मा मध्य तथा ऊपरी वायुमंडल को उष्ण बनाता है तथा इसे कुल ओज़ोन और ऊपरी क्षोभमंडलीय के (300 हैक्टापास्कल की उँचाई पर) तापमान के मध्य मानसून ऋतु में फैले हुए सकारात्मक सहसंबंध गुणांक का समर्थन मिलता है। न्यून अवक्षय से संबंधित मध्य और ऊपरी क्षोभमंडल की ऊष्णता और / अथवा ऊपरी क्षोभमंडल में अत्याधिक ओज़ोन के उत्पादन के कारण भारतीय प्रायद्वीपीय क्षेत्रों में अन्य ऋतुओं की अपेक्षा मानसून के महीनों में उच्चतर कुल ओज़ोन बन सकते हैं। जनवरी (226 डी.यू.) माह के दौरान 6° उ. में न्यूनतम सांद्रताओं तथा अगस्त माह के दौरान 18° उ. में अधिकतम (283 डी.यू.) सांद्रताओं का पता चला है। इस समय अक्षांशीय विविधताओं की अपेक्षा देशांतरीय विविधताएँ कम सुस्पष्ट पाई गई हैं।

ABSTRACT. The total ozone derived from TOVS data from NOAA 12 satellite through one step physical retrieval algorithm of International TOVS Processing Package (ITPP) version 5.0 has been used to identify its diurnal, monthly, latitudinal and longitudinal variability during 1998 over the domain Equator to 26° N / 60-100° E. The linkage of maximum total ozone with warmer tropopause and lower stratosphere has been re-established. The colder upper tropospheric temperature which is normally associated with maximum ozone concentration throughout the year elsewhere in the world has also been identified in this study but the relationship gets reversed during southwest monsoon months(June-September) over the domain considered. The moisture available in abundance in the lower troposphere gets precipitated due to the convective instability prevailing in the atmosphere during monsoon season and very little moisture is only available for vertical transport into the upper troposphere atop 500 hPa. The latent heat released by the precipitation processes warms up the middle and upper atmosphere. The warm and dry upper troposphere could be the reason for less depletion of ozone in the upper troposphere during monsoonal months and this is supported by the positive correlation coefficient prevailing in monsoon season between total ozone and upper tropospheric (aloft 300 hPa) temperature. The warmness in middle and upper troposphere which is associated with less depletion and/or production of more ozone in the upper troposphere may perhaps contribute for the higher total ozone during monsoon months than in other seasons over peninsular Indian region. The minimum concentration is observed during January (226 DU) over 6° N and the maximum (283DU) over 18° N during August. Longitudinal variability is less pronounced than the latitudinal variability.

Key words – Ozone, NOAA, TOVS, ITPP, Correlation, Troposphere, Tropopause, Stratosphere, Convective instability, Precipitable water vapour, Anthropogenic gases.

1. Introduction

The ultraviolet portion of the insolation is lethal for all forms of life on the earth. However the earth has developed its own protective shield enveloping the whole earth against this in the form of a thin layer of ozone which is a trace constituent in the stratosphere and upper troposphere. Ozone is formed by photochemical reaction of the oxygen of the

TABLE 1

Characteristics of TOVS channels used to estimate total ozone

Channel	Central wave number (cm^{-1})	Central wave length	Absorbing constituent	Level of peak energy (hPa)
HIRS/2 chl 1	668	15.00 μm	CO_2	30
HIRS/2 chl 2	679	14.70 μm	CO_2	60
HIRS/2 chl 3	691	14.50 μm	CO_2	100
HIRS/2 chl 4	704	14.20 μm	CO_2	400
HIRS/2 chl 8	898	11.10 μm	Window	Surface
HIRS/2 chl 9	1028	9.70 μm	O_2	25
MSU chl 4	1. 93	0.518 cm	O_2	90

atmosphere with the sun's ultraviolet radiation and the stratosphere is heated during this process. The differential heating in the vertical through differential absorption of solar radiation in the stratosphere by this trace gas determines the depth, static stability and to some extent the dynamics of the atmospheric motion (Asnani, 1993). Ozone not only protects the biosphere but is also a prime source of thermal energy and a useful tracer for stratospheric circulation (Dutsch, 1981). The total ozone is measured through ground based Dobson spectrophotometers throughout the Globe only at 150 stations and the measurement over oceanic area is almost nil [World Meteorological Organisation (WMO), 1992a]. It has been established by researchers that this thinner blanket of the ozone is hardly between 200 and 300 Dobson Unit (DU) (*i.e.*2 and 3 mm) and the total ozone over a unit area is between 200 and 500 DU (*i.e.* 2 and 5 mm) only (WMO, 1961). Drastic depletion of atmospheric total ozone during spring 1970 over the Antarctic has alarmed the scientific community. The reduction of ozone in the stratosphere by man made pollutants like chlorofluro carbon (CFC) was first suggested by scientists as early as in 1974. Large scale reduction of ozone was also reported throughout the world (WMO, 1981; Angell, 1987). Hence a need arose to augment the number of total ozone observations throughout the world to study the spatial and temporal variability of total ozone as the 150 and odd Dobson spectrophotometer is quite few in number and unable to cover the oceanic and remote areas. Polar orbiting satellite technology is one of the major solution to this problem as these satellites may provide data on Global scale.

Prabhakara *et al*. (1976) and Lovill *et al*. (1982) estimated total ozone through infrared emission measurements utilising the strong correlation between the meridional gradient of total ozone and the tropospheric wind velocity found out by Lovill (1972) and Prabhakara *et al*. (1973). The validation of TIROS Operational Vertical Sounder (TOVS) derived total ozone has been done by Planet *et al*. (1984) for a good number of stations throughout the world and the comparability of ozone measurements has been highlighted in Li *et al*. (1991), WMO (1992a and 1992b). As the validation of total ozone derived from NOAA satellites using International TOVS Processing Package (ITPP) had already been attempted by Gupta and Sharma (1996) for four Dobson spectrophotometer stations of India for the period November 1993 to April 1994 no validation has been attempted in this paper. However the ozone measurements through TOVS onboard NOAA 12 satellite over the peninsular Indian sub-continent and adjoining oceanic area has been analysed in this paper to find out seasonal and spatial variability, if any, and also to work out its correlation with tropospheric and lower stratospheric meteorological parameters.

2. Ozone retrieval through TOVS

The measured values of total ozone through Dobson spectrophotometer is regressed with approximately simultaneous satellite measured clear radiances which are in turn converted into brightness temperatures at selected spectral channels of High Resolution Infrared Sounder (HIRS). The characteristics of the selected HIRS spectral channels that are used to estimate total ozone are tabulated in Table 1. The regression coefficients thus developed have been utilised to check for their accuracy with independent ground based sounding values. The coefficients are stratified by month and latitude zones. Detailed description of the sounding retrieval has been well documented by Planet *et al*. (1984), Xia-Lin Ma *et al*. (1984). In this paper International TOVS Processing Package version 5.0 (ITPP 5.0) has been used to estimate the total ozone from radiance measured at wavelengths 15.0, 14.7, 14.5 and 14.2μ which have their peak contributions at 30, 60, 100 and 400 hPa. The 9.7μ channel peaks at maximum ozone contribution at stratosphere and the 11.1μ channel peaks at surface.

TABLE 2

Diurnal range between morning and evening total ozone soundings through TOVS on board NOAA12 satellite in the domain Equator/60 °E to 26 °N/100° E during 1998

Period	Morning soundings		Evening soundings		Mean Range Morning - Evening		Mean Range Morning - Evening	
	Mean (DU)	Std. Dev. (DU)	Mean (DU)	Std. Dev. (DU)	Value (DU)	Grid Freq.	Value (DU)	Grid Freq.
Jan'98	238.5	14.2	237.6	14.7	39.2	135	- 34.0	109
Feb'98	238.7	13.6	237.8	13.6	21.4	140	- 22.3	108
Mar'98	246.3	15.3	244.1	14.7	31.6	172	- 33.6	87
Apr'98	253.9	14.1	250.5	13.3	34.8	210	- 26.4	54
May'98	257.1	12.1	253.1	10.6	43.2	174	- 24.0	72
Jun'98	266.1	11.1	259.9	8.9	39.1	58	- 20.5	19
July'98	258.9	10.8	256.2	8.7	23.0	32	- 45.3	23
Aug'98	261.2	7.6	258.4	10.3	28.1	40	- 26.8	30
Sep'98	261.7	11.7	258.2	9.0	30.7	116	- 33.5	53
Oct'98	255.1	8.8	253.4	6.7	28.5	116	- 21.0	104
Nov'98	244.4	8.1	244.5	6.2	29.2	112	- 25.6	121
Dec'98	243.8	8.9	241.7	7.7	36.4	134	- 22.8	78

Note : DU - Dobson unit, Grid Freq. - Number of grid points

However as the ozone transmittance in 9.7µ is influenced both by water vapour and ozone, water vapour transmittance from 11.1µ is used instead of ozone transmittance and TIROS Atmospheric Radiance Module(TARM) developed by McMillin and Dean (1982) has been used for correcting limb darkening. The regression coefficients have been tuned accordingly. The guess ozone brightness temperature and radiance derivatives with respect to both temperature and brightness temperature are calculated. The peak and guess ozone profile are adjusted to obtain the calculated profile of ozone. The estimated total ozone from TOVS was found to be within 8% bias from the Dobson Spectrometer values (Planet *et al*., 1984; Li *et al*.,1991 and WMO, 1992a and 1992b). TOVS total ozone pictures on global scale are available in near real time in the website http://www.cpc.ncep.noaa.gov/products/stratosphere/tovsto.

3. Data

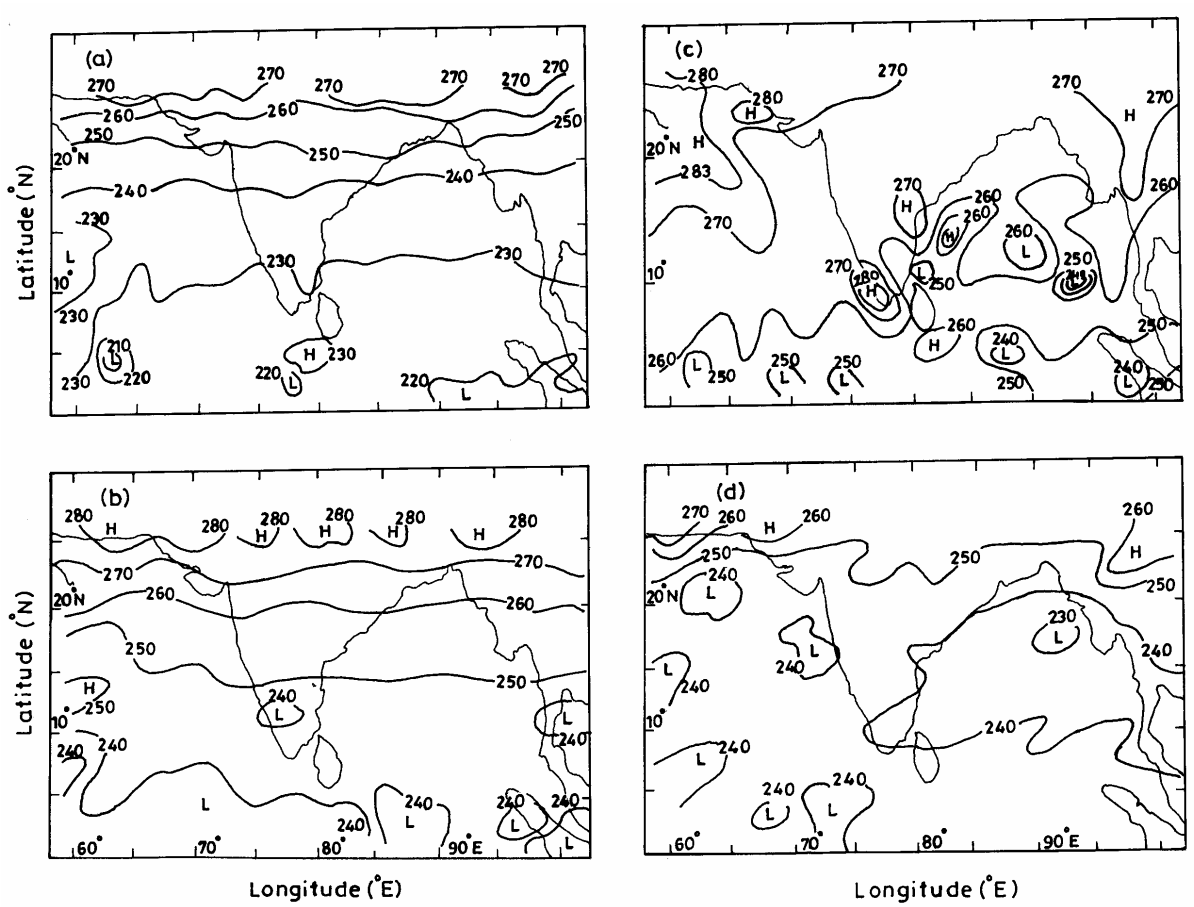
TOVS data received from NOAA 12 satellite at High Resolution Picture Transmission Direct Readout Ground station, Chennai during 1998 has been processed through ITPP 5.0 software over the area from the equator to 26° N and 60 to 100° E and used in this study to analyse the latitudinal, longitudinal and seasonal variability of total ozone. In order to validate the processing software for its accuracy in deriving its products, temperature, dew point, geopotential height at standard pressure levels obtained from Radio Sondes stations located in the above said domain have been considered. Rainfall data published by India Meteorological Department (IMD) for the year 1998 has also been considered for correlating with concentration of total ozone in the domain chosen.

4. Method of analysis

NOAA 12 satellite normally passes over the Chennai radio horizon between 2300 and 0200 UTC in the morning and between 1100 and 1330 UTC in the evening to cover the area from 60 to 100° E. As each pass provides soundings at an approximate area of 80 × 80 km in the sub-satellite points and at every 200 × 200 km at the end of scan, there are more than 350 soundings in the domain selected in this study. These data may at times contain noise also in which case the processing software package rejects such soundings.

4.1. *Diurnal variability*

Raw data received from all passes of NOAA 12 satellite during 1998 over the radio horizon of Chennai has been processed and the total ozone values were obtained. As there were two passes at morning and evening every day in the domain selected in this study, albeit the time difference between the consecutive passes is unavoidable,



Figs. 1(a-d). Distribution of mean total ozone(DU) over peninsular Indian sub-continent (a) January 1998, (b) April 1998, (c) July 1998 and (d) November 1998

there were innumerable sounding locations for each pass. However the morning and evening soundings are not obviously at the same locations. Hence the values obtained at every sounding location have been averaged over an even degree latitude and longitude grid for both morning and evening separately so that the values can be compared at grid points atleast. As such there are 273 grid points starting from 2° N / 62° E to 26° N/100° E. But even at these grid points also there had been occasions wherein soundings were not available on the same day at morning and evening due to the design of scan geometry. The grid point values have been carefully analysed to find out the presence of diurnal variation for each month. Mean, standard deviation and the diurnal range between morning and evening total ozone values for positive/negative values and their frequencies have been worked out and presented in Table 2. The analyses reveal that the morning ozone values were higher than that of the evening values on more grid locations. The highest diurnal range (Morning-Evening) was observed during May (+43DU) and (–45DU) during July 1998. As there are sizeable number of grid locations at which the evening total ozone is higher than that observed in the morning, the favourable time of peak ozone concentration can not be pinpointed with this data set. Also the mean morning and evening values are quite comparable and a maximum difference of 6DU has only been noticed during July 1998. The variability based on few hundreds of soundings in each month over various grid points suggests that ozone is a highly variable constituent and hence for further analysis we worked out the daily average to mask their diurnal variability.

4.2. *Monthly variability*

Monthly means of total ozone have been computed at every grid point locations for the year 1998 and depicted in Fig. 1 for January, April, July and November representing winter, pre-monsoon, southwest and northeast monsoon seasons. A common inference that can be made from these seasonal maps is that the total ozone is minimum very near to the equator and increases towards higher latitudes. This is in close agreement with earlier findings based on ground

TABLE 3

Latitudinal average of total ozone (DU) over peninsular Indian subcontinent in 1998

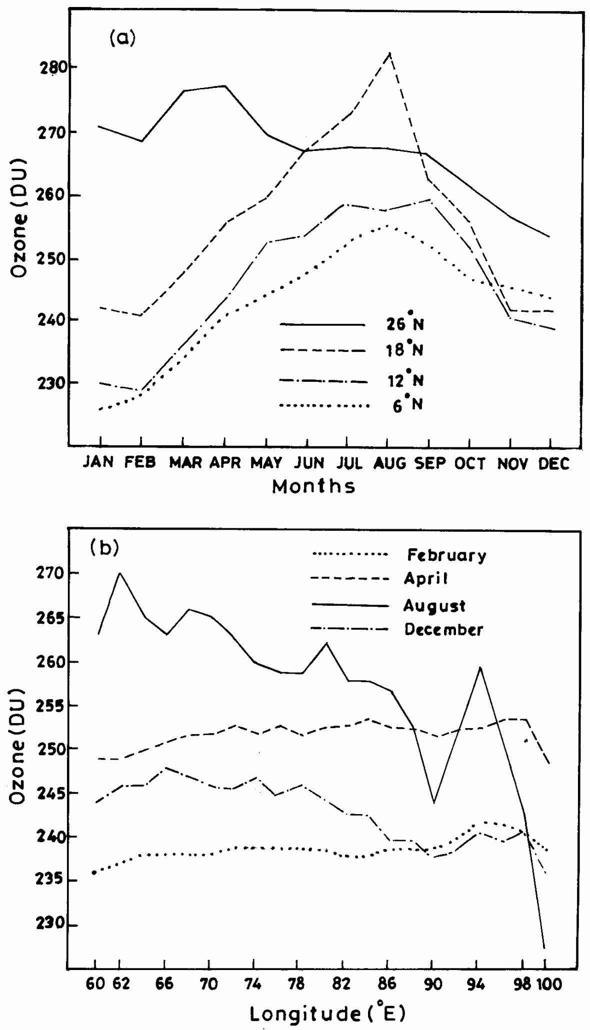
Lat. (°N)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
26	271	269	277	278	270	267	268	268	267	262	257	254
24	260	258	268	272	268	267	277	272	267	259	253	250
22	255	254	261	266	264	268	273	276	265	259	247	246
20	248	248	253	260	262	268	274	255	265	257	245	243
18	242	241	248	256	260	268	273	283	263	256	242	242
16	238	236	244	252	259	263	264	253	261	253	241	240
14	232	232	238	249	255	263	258	256	259	253	240	239
12	230	229	236	243	253	254	259	258	260	252	241	239
10	227	227	234	243	249	254	258	260	258	253	242	240
8	227	227	234	242	248	249	258	261	254	251	241	240
6	226	228	234	241	244	248	253	256	253	247	246	244
4	228	230	234	239	242	249	253	254	251	249	244	244
2	228	231	233	237	240	250	251	256	252	247	245	242

based Dobson spectrophotometer measured values (WMO, 1961). However the maximum ozone was observed during southwest monsoon months (July - September) rather than during the spring season as has been observed and documented in literature in extra-tropics and sub-tropical latitudes.

Asnani(1993) has ingeniously explained the cause of higher base of stratosphere (or the higher height of tropical tropopause) in the lower latitudes by interlinking the abundance availability of water vapour in the lower troposphere and lower value of ozone in the stratosphere at lower latitudes. According to him, the water vapour and ozone influences the formation of tropopause through radiative processes. Convective instability which prevails more in the tropical region than in the extra tropics causes the transport of water vapour into the stratosphere which tends to destroy the ozone which is believed to be available more in the stratosphere. Hence the stratosphere which is ozone regime has a higher base in the tropics than mid latitudes and extra tropics wherein the availability of water vapour in the lower troposphere is much lesser than that at tropics. However our ground based and satellite derived observation claims that the total ozone is more during southwest monsoon months wherein the availability of water vapour is quite high. This aspect will be discussed in the ensuing sections.

4.3. *Latitudinal variability*

The grid point mean values have been further averaged for each latitude and longitude to ascertain the presence of latitudinal and longitudinal variability, if any. The monthly latitudinal mean values averaged over longitudes have been furnished in Table 3. Latitudinal gradient of total ozone is very minimum at lower latitudes in comparison to higher latitudes. Steep increase in latitudinal gradient total ozone has been noticed north of 14° N and the increase is much pronounced during January - February. The variability is less during southwest monsoon months even at higher latitudes though some gradient is seen during other months. The highest mean value was 283DU in August, 278 in April and 271 in January. During northeast monsoon months the highest total ozone was observed to be 262DU only. Latitudinal average was higher (283DU) at 18° N followed by 274-278DU over 20-26° N latitudes. The minimum value (226DU) was seen at 6° N. This confirms the earlier theory that ozone is produced at stratosphere in the lower latitude and transported to higher latitude through stratospheric circulation (WMO, 1961). Fig. 2(a) shows the latitudinal variability of total ozone at select latitudes. The values shown in Table 3 and Fig 2(a) are in close agreement with preferred months of maximum ozone concentration over the Indian region as reported in WMO (1961). The



Figs. 2(a&b). Variability of total ozone (DU) over peninsular Indian sub-continent during 1998 (a) Latitudinal and (b) Longitudinal

monthly variability at 18° N is much pronounced and almost double the variability at 26° N. The range of variation is very high during January - April and minimum during September - December. The latitudinal mean range of total ozone computed for each month has been shown in Fig. 3.

4.4. *Longitudinal variability*

Longitudinal mean values for each month have been calculated and presented in Table 4. The inference from this Table is that the increase in ozone content is higher from May to June or June to July over different longitudes. However the intra month longitudinal variability is somewhat insignificant in comparison to latitudinal monthly variability except during southwest monsoon season. Maximum range of longitudinal variation was observed in

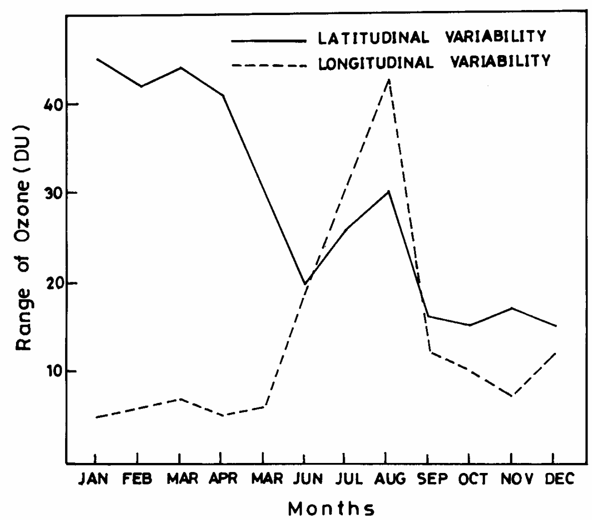


Fig. 3. Range of total ozone over peninsular Indian sub-continent

August and the minimum in January. The monthly variability was higher in 60-72° E longitudes and very less over 96-98° E. Fig. 2(b) depicts the longitudinal variability of total ozone in representative months of different seasons and the Fig. 3 shows the longitudinal mean range of total ozone.

5. Results and discussion

The southwest monsoon values of total ozone is of quite interest to researchers as their values are maximum in the domain considered and their variability is also significant and not conforming to the established variability elsewhere in the extra tropics. In order to analyse these aspects, overall mean of the total ozone for the entire domain has been computed and tabulated in Table 5. The highest mean value is observed during June when the southwest monsoon establishes and it is considerably higher than that observed during northeast monsoon season. The total ozone has been correlated with meteorological parameters and weather systems at tropospheric and stratospheric level (WMO, 1961).

5.1. *Validation of temperature retrievals*

As there are a lot of variations between the southwest and northeast monsoons in regard to other meteorological parameters such as moisture content, precipitation, vertical temperature distribution etc., temperature aloft 300 hPa, outgoing longwave radiation (OLR) were also retrieved from TOVS data. The temperature at 300, 200, 150 and 100 hPa have been validated with the collocated Radio sonde data (Radio sonde station located within 100km radius from the satellite sounding and within 3 hours of the

TABLE 4

Longitudinal average of total ozone(DU) over peninsular Indian sub-continent in 1998

Long (°E)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60	240	236	241	249	252	260	276	263	260	249	248	244
62	239	237	244	249	252	263	270	270	266	251	246	246
64	239	238	245	250	253	258	262	265	263	253	244	246
66	242	238	244	251	254	262	269	263	263	254	246	248
68	239	238	243	252	256	262	261	266	263	255	245	247
70	239	238	243	252	256	261	259	265	260	254	245	247
72	239	239	244	253	254	260	266	263	263	255	245	246
74	241	239	246	252	255	261	262	260	258	259	244	247
76	240	239	246	253	256	263	260	259	259	257	244	245
78	240	239	246	253	254	257	259	262	260	259	244	245
80	239	239	246	253	254	257	259	262	260	259	244	245
82	238	238	246	253	254	262	256	258	256	253	245	243
84	238	238	246	254	256	263	254	258	256	253	243	243
86	237	239	247	253	255	258	254	257	255	252	244	240
88	238	239	246	253	256	264	256	253	255	251	245	240
90	240	239	247	252	256	255	261	244	260	255	244	238
92	239	240	248	253	256	271	255	253	254	251	244	239
94	238	242	248	253	254	257	252	260	262	250	243	241
96	239	242	247	254	257	258	252	250	258	252	246	240
98	252	241	245	254	255	252	252	243	258	253	249	241
100	240	239	244	249	258	255	252	228	262	256	242	236

TABLE 5

Mean values of total ozone and associated meteorological parameters

Month	Ozone	OLR	T300	T200	T150	T100	PWV	GKI
Jan	239.2	263.9	- 32.0	- 42.2	- 54.4	- 68.9	32.7	16.0
Feb	239.0	267.8	- 31.4	- 41.6	- 53.8	- 68.6	31.5	14.4
Mar	245.5	277.4	- 31.7	- 41.9	- 54.0	- 68.8	33.3	16.5
Apr	252.2	280.5	- 30.9	- 41.2	- 53.3	- 68.5	38.3	20.1
May	255.0	269.9	- 31.1	- 42.4	- 55.6	- 72.3	46.9	26.2
June	260.4	258.0	- 32.0	- 43.9	- 57.8	- 74.6	51.9	30.5
July	259.7	254.9	- 30.1	- 40.5	- 52.7	- 67.2	52.1	31.8
Aug	260.0	265.5	- 29.7	- 40.4	- 52.8	- 66.9	49.8	30.1
Sep	259.6	264.2	- 29.9	- 40.4	- 52.7	- 67.0	47.2	28.7
Oct	253.8	262.6	- 30.6	- 41.0	- 53.4	- 67.9	42.7	25.1
Nov	244.8	264.0	- 32.0	- 42.2	- 54.4	- 68.7	37.7	21.2
Dec	243.3	258.7	- 33.0	- 43.1	-55.0	- 68.8	36.3	20.2

Note : Ozone in DU, OLR in Watts/ sq. m, PWV - Precipitable water content in mm;
GKI - George’s K index
T 300,T200,T150,T100 are temperatures at 300, 200, 150, 100 hPa level in ^{o}C

TABLE 6

Root mean squared biases (°C) between TOVS derived temperature and Radio Sonde values during 1998 over peninsular Indian sub-continent and adjoining oceanic area

Pressure (hPa)	Jan-Feb	Mar-May	Jun-Sep	Oct-Dec
1000	3.57	3.01	3.38	3.37
850	3.90	5.05	2.96	3.07
700	2.65	2.03	2.48	2.46
500	2.65	2.77	2.64	2.65
400	2.95	3.13	2.60	2.68
300	2.95	3.25	3.01	2.88
250	2.99	2.75	3.15	2.90
200	3.11	2.67	3.24	3.10
150	3.58	4.00	3.73	3.52
100	5.69	5.56	4.08	4.89

Radio Sonde observation time) in the domain considered. One step physical retrieval algorithm developed by University of Wisconsin, Madison (ITPP 5.0) has been used. Regression estimates obtained from HIRS channels at stratospheric level and MSU channels have been used as first guess profile as the MSU undergoes calibration at every scan and microwave radiation is well-nigh unaffected by the cloud contamination (Kidder and Vonder Harr, 1995; Cracknell, 1997). The results of validation have been summarised in Table 6. The results are comparable with similar validations done elsewhere even with the latest Advanced TOVS onboard NOAA15 satellites for tropical regions (Khanna and Kelkar, 1993; Hurrell *et al*., 2000; Jun Li *et al*., 2000). TOVS derived temperatures have been used to study the thermodynamic structure of the atmosphere during northeast monsoon season over peninsular India (Fig. 3) by Suresh and Raj (2001), Suresh *et al.* (2002) and to foreshadow cyclone movement by Suresh and Rengarajan (2001 and 2002). Since the TOVS ozone retrievals use temperature soundings and the TOVS derived temperature had been validated by many researchers, TOVS sounding retrievals are considered to be useful to further analyse the causes of variability of ozone in this study.

5.2. *Precipitable water vapour and convective instability analyses*

As it is normally expected that the total ozone has been correlated with other meteorological parameters, domain average of OLR, upper tropospheric temperatures have been done for further analyses. Precipitable water vapour from 1000 to 300 hPa has been independently computed from the TOVS derived meteorological parameters based on numerical methods for each retrieval as the TOVS derived precipitable water content appears to be slightly overestimating these values than that are normally derived through Radiosonde data. These values have been averaged for the domain as done for other sounding retrievals. As the convective instability mechanism is responsible for pumping water vapour into upper troposphere/lower stratosphere, the convective instability index defined by George (1960) has been computed. This index considers the overall stability of 850-500 hPa layer by subtracting the observed 500 hPa temperature from 850 hPa temperature and then introducing the contribution of high moisture content at low levels by adding 850 hPa dewpoint. A possible buoyancy reduction of cloud air parcels by evaporative cooling through entrainment is taken into account by subtracting 700 hPa dewpoint depression. Values in excess of 25 are associated with development of convective clouds in the tropical regions. Domain averaged values of all these parameters are listed in Table 5.

Precipitable water vapour was more during May-October than the other months over the domain considered. Also the convective instability was more during these months in the lower troposphere upto 500 hPa (more precisely upto 700 hPa). These two factors together caused the dense convective clouds formation. The precipitation realised during these months over the fifteen meteorological sub-divisions located in the domain supported the validity of the TOVS data (India Meteorological Department, 1999). But the question that remains still is when the water vapour which is transported to higher heights tends to destroy ozone, how the ozone values during monsoon months, more specifically during August, is higher than the non-monsoon months. One plausible answer to this question is that most

TABLE 7

Correlation matrix of total ozone with other meteorological parameters

Month	OLR	T300	T200	T150	T100	PWV	GKI	Freq.
Jan	- 0.45	- 0.90	- 0.86	- 0.66	0.78	- 0.78	- 0.18	271
Feb	- 0.56	- 0.91	- 0.84	- 0.49	0.82	- 0.73	- 0.01N	268
Mar	- 0.30	- 0.94	- 0.90	- 0.62	0.87	- 0.65	0.36	270
Apr	0.32	- 0.94	- 0.90	- 0.79	0.67	- 0.39	0.31	270
May	0.52	- 0.92	- 0.09N	- 0.09N	0.12N	0.02N	0.14	271
Jun	0.19	- 0.04N	0.53	0.46	0.20	0.13N	0.00N	186
July	0.36	0.57	0.65	0.61	0.33	0.38	- 0.14N	145
Aug	0.38	0.64	0.56	0.53	0.35	0.09N	- 0.24	138
Sep	0.24	0.58	0.60	0.60	0.39	- 0.17	- 0.28	247
Oct	0.08N	0.29	0.33	0.37	0.22	- 0.32	- 0.23	264
Nov	- 0.09N	- 0.53	- 0.40	0.05N	0.48	- 0.40	- 0.21	263
Dec	- 0.09N	- 0.46	- 0.32	- 0.02N	0.49	- 0.40	- 0.27	270

Note: N denotes correlation coefficient is insignificant at 5% level.
PWV - Precipitable water content ; GKI - George's K index ;
T 300,T200,T150,T100 are temperatures at 300, 200, 150, 100 hPa level;

of the water vapour might have been precipitated at the lower levels itself and might not have entered into higher levels during these months. Six meteorological sub-divisions reported positive side of the normal, eight sub-divisions reported excess and only one reported slightly negative side of normal rainfall (– 4%). (*i.e.*) Almost all meteorological sub-divisions have reported positive side normal/excess rainfall leaving very little moisture to enter into upper troposphere. Considering the month of August alone wherein the maximum mean total ozone was observed, nine meteorological sub-divisions reported excess, two reported positive side of normal and four reported negative side of normal rainfall. Though precipitation realised over the oceanic area is not available for analysis, the satellite imageries suggest there could have been very good precipitation. As such it is inferred that the destruction of ozone by water vapour could not have taken place and the maximum ozone observed during August could have been very much possible. The maximum total ozone concentration during August is in agreement with total ozone observed over Kodaikanal (10.2° N, 77° E) during the month of August (WMO,1961).

5.3. *Correlation analyses*

Simple correlation coefficients have been worked out for ozone with all the other parameters discussed above and the coefficients are furnished in Table 7. The number of grid points which have valid ozone data (as derived from the ITPP software) were only used to workout the correlation coefficients to avoid spurious results. In all there were 271 grid points (13 along latitude and 21 along longitude in every $2^o \times 2^o$ Lat. × Long. grid) available in the domain considered. Correlation coefficients which are not significant have been suitably marked.

5.3.1. *Total ozone vis-a-vis temperature*

The tropical tropopause is normally around 150-100 hPa. The 100 hPa temperature is positively correlated with total ozone throughout the year indicating warmer tropopause and lower stratospheric temperature are positively associated with total ozone. This is quite logical as the dynamic processes which cause warm/cold stratospheric air also cause maxima/minima of total ozone. This concept has been used in ozone retrieval algorithm by Xia-Lin Ma *et al*. (1984) and Planet *et al*. (1984). The temperatures at 300, 200 and 150 hPa levels are negatively correlated with total ozone during November to May suggesting that the colder upper tropospheric temperature are conducive for maximum ozone concentration. These findings are in agreement with the theory and already established results (WMO, 1961; WMO, 1992a). However it can be seen that there exists a positive correlation between 300 hPa temperature and total ozone during monsoon season (June–September) and the correlation remains positive during October when the monsoon retreats in the domain considered. The 300 hPa positive correlation from

TABLE 8

Mean temperature gradient (10 – 25 °N) over peninsular India and adjoining oceanic area during 1998

Month	60°E	65 °E	70 °E	75 °E	80 °E	85 °E	90 °E	95 °E	100 °E
			Temperature gradient between 700 and 500 hPa ($T_{700} - T_{500}$)						
Jan	15.65	15.70	15.65	14.90	14.50	14.40	14.65	14.70	14.40
Apr	17.20	17.80	17.40	17.60	17.40	18.25	17.55	16.75	17.05
Aug	19.55	18.40	15.65	13.75	13.90	14.35	14.55	14.40	14.95
Nov	21.45	14.65	14.75	14.60	14.80	15.30	15.95	15.30	14.55
			Temperature gradient between 700 and 400 hPa ($T_{700} - T_{400}$)						
Jan	26.65	26.60	26.35	25.20	24.70	24.30	24.50	24.60	24.10
Apr	29.50	29.95	29.45	29.35	28.60	29.45	28.95	27.85	28.20
Aug	27.80	26.80	24.80	23.60	24.05	25.00	24.60	24.40	24.95
Nov	26.60	26.40	26.20	25.25	25.30	26.50	25.90	25.85	25.05

June – October (Table 7) and 1 to 3° C warmness at 300 hPa in comparison to other seasons (Table 5) reveals that upper troposphere is relatively warmer in monsoon season than the other seasons which may be contributing to the maximum total ozone observed during monsoon.

The positive correlation observed during monsoon season between 200 and 150 hPa temperature and ozone could be due to the fact that the atmosphere at these levels are warmer (by 1 to 2° C) than the other months (Table 5). The 500 hPa temperature during monsoon season is warmer by 6 to 10° C / 5 to 7° C / 2 to 5° C than winter/pre-monsoon / post monsoon seasons respectively. Similarly at 400 hPa level, monsoon months are warmer by 6 to 10° C / 6 to 8° C / 4 to 6° C than the other seasons. The reasoning that the dynamic processes which cause warm / cold air also cause the maxima/minima of total ozone at the stratosphere as mentioned earlier may perhaps also hold good for explaining the upper tropospheric ozone (which contributes for the total ozone) during monsoon months over the domain considered. In order to explain the distinct complex relationship, temperature gradient in the middle atmosphere over the domain considered has been computed and presented in Table 8 for January, April, August and November to represent winter, pre-monsoon, monsoon and post-monsoon season respectively. The gradient is lower (by 1 to 5° C), especially over land areas, and hence the middle and upper atmospheric layers are in relatively more stable stratification during monsoon than in other seasons. The reason for low gradient can be attributed to the release of latent heat by the monsoonal precipitation processes (from low and medium clouds) which warms up the middle atmosphere. As explained in para 5.2, since most of the water vapour available in the lower troposphere upto 500 hPa precipitates during monsoon and since the temperature gradient aloft 700 hPa is relatively low, very little moisture could have been transported to the upper troposphere. As such the quantum of ozone present in the atmosphere could not have been depleted by the water vapour during monsoon season whereas due to relatively higher temperature gradient prevailing in the other seasons and in the absence of precipitation processes there is every chance that upper tropospheric ozone could be destroyed by the water vapour transport from lower and middle troposphere into upper troposphere. Thus the warmer upper troposphere (causing relatively more ozone in those levels) together with lower temperature gradient in the middle troposphere could possibly contribute for the maximum total ozone during monsoon months.

5.3.2. *Total ozone vis-a-vis precipitable water vapour*

The negative correlation of tropospheric precipitable water vapour supports the existing theory of ozone (Asnani, 1993; WMO, 1981). However, here again, the positive correlation during southwest monsoon could be due to a complex relationship between precipitable water, convective instability and total ozone concentration. The ozone concentration has been related with weather systems (WMO, 1961 ; Gupta and Sharma, 1996). The monsoonal convective clouds precipitate the water vapour and cause transport of warm dry air and/or less water vapour into tropopause averting depletion of ozone. This explains the positive correlation coefficient of precipitable water vapour with total ozone during August. There had been considerable increase in ozone concentration from May to June/June to July over different longitudes. However the correlation coefficients between precipitable water vapour and George's K index and ozone were not all significant albeit their numerical values were very high during these months. This point needs further analyses to find out their relationship with total ozone.

5.3.3. *Total ozone vis-a-vis OLR*

In the case of OLR, the correlation coefficients are negative during January-March when maximum ozone is reported at higher latitudes and positive correlation during April-September is associated with higher ozone concentration in middle latitudes. Similar change of sign of correlation between different periods have been reported in WMO(1961) for the tropopause height with ozone over Tromso (69.7° N, 18.9° E). The relationship between OLR and total ozone is yet to be understood.

6. Scope for future work

With the available one year data, the nature and degree of relationship between total ozone and various meteorological parameters influencing the production and destruction of ozone could not be fully explained as the southwest monsoon during 1998 was quite good over the domain considered. The exact relationship can be better established by analysing few more years of ozone data especially when the monsoons are dry and intermediary. Granier *et al*. (1996) used a global three dimensional chemical transport model to investigate possible causes for the reduction in carbon monoxide (CO) and opined that the changes in total ozone could be responsible for global decrease of CO by about 20% in northern hemisphere. Inter Governmental Panel on Climate Change (IPCC, 2001) reported that the tropospheric ozone has increased by 36% since 1750 primarily due to anthropogenic emissions of several ozone forming gases. Tropospheric ozone could be attributed to processes like downward transport from the stratosphere or *in situ* photochemical production from the oxidation of hydrocarbons or CO in the presence of the catalyst NO_x (Tang *et al.*, 1998). The role of anthropogenic gases, more specifically the CO and NO_x, to the tropospheric ozone over the peninsular India may have to be studied to understand further to the cause of maximum total ozone concentration during monsoonal months over peninsular India. The OLR values derived from TOVS are yet to be validated for Indian region. On receipt of data, these works can be taken up.

7. Conclusions

(*i*) Positive correlation coefficient between total ozone and temperature at 100 hPa level can be used to estimate ozone concentration throughout the year as this relationship does not get changed throughout the world during the past 30 years.

(*ii*) The latitudinal variability is more pronounced during January-April and quite less during September - December. The between months variability of total ozone is more at 18° N and less at 26° N.

(*iii*) Except during June-September, the latitudinal gradient gets built up north of 14° N.

(*iv*) The longitudinal variation of ozone is very less except during southwest monsoon months, precisely during August, compared its latitudinal variability. The range of monthly variability is more over 60-72° E and less over 96-98° E.

(*v*) Positive correlation exists between total ozone and upper tropospheric (aloft 300 hPa) temperature during southwest monsoon season while negative correlation prevails during other seasons over the domain considered.

(*vi*) Domain average (Equator to 26° N / 60 to 100° E) of total ozone is the highest during southwest monsoon season. Since the available moisture precipitates exploiting the instability prevailing in the lower troposphere, very little moisture escapes to the upper troposphere and hence very little depletion of ozone could be taking place during monsoon season. Considering other things being equal in all seasons, the less depletion of upper tropospheric ozone and the warmness in these layers contribute for the maximum total ozone during monsoon season than the other seasons over the peninsular India and adjoining oceanic areas.

(*vii*) The diurnal variability of ozone could not be pinpointed due to the fact that the diurnal range (morning–evening) varies from +43DU to –45DU in different months. However considering the frequencies of positive and negative values of diurnal range an inference can be drawn to the effect that the morning ozone concentration was higher than that of evening values except during March, July and September, 1998.

Acknowledgements

Facilities extended by the Deputy Director General of Meteorology, Regional Meteorological Centre, Chennai is gratefully acknowledged. Thanks are due to Shri M. Bharathiar and Shri N. Selvam for tracing the diagrams. Assistance extended by S/Shri M. Srinivasan and V. Aravindan in preparation of the manuscript is acknowledged with thanks.

References

Asnani, G. C., 1993, "Tropical Meteorology", Vol I and II, 822, Sindh Colony, Aundh, Pune 411007, India, p1202.

Angell, J. K., 1987, "Seasonal differences in the trend of total ozone and contributions from tropospheric and stratospheric layers", *Mon. Wea. Rev*., **27**, 91-97.

Cracknell, P. A., 1997, "The Advanced Very High Resolution Radiometer(AVHRR)", Taylor & Francis Int. Ltd., Great Britain, p534.

Dutsch, H. U., 1981, "Ozone research - Past, Present, Future", *Bull. Amer. Meteor. Soc*., **62**, 213-217.

George, J. J., 1960, "Weather Forecasting for Aeronautics", Academic Press, New York, p673.

Granier, C., Muller, J. F., Madronich, S. and Brasseur, 1996, "Possible causes for the 1991-93 decrease in the global tropospheric CO abundance: a three dimensional study", *Atmospheric Environment*, **30**, 1673-1682.

Gupta, H. V. and Sharma, A.K., 1996, "Comparison of total ozone retrieved from NOAA satellite and measured from Dobson spectrophotometer over Indian region", *Mausam*, **47**, 2, 125-132.

Hurrell, J. W., Trenberth, K. E., Brown, S. J. and Christy, J. R., 2000, "Comparison of Tropospheric Temperatures from Radiosondes and Satellites: 1979-98", *Bull. Amer. Meteor. Soc*., **81**, 9, 2165-2178.

India Meteorological Department, 1999, "Rainfall figures (mm) for each month and season as a whole (June - September) ", *Mausam*, **50**, 3, p314.

Intergovernmental Panel on Climate Change(IPCC), 2001, "Summary for policy makers", A report of working group I of the IPCC, p20 (available in website : www. ipcc. ch)

Jun, Li, Wolf, W. W., Paul Menzel, W., Wenjian Zhang, Hung-Lung Huang and Achtot, T. H., 2000, "Global Soundings of the Atmosphere from ATOVS Measurements : The algorithm and Validation", *J. Appl. Meteor*., **39**, 8, 1248-1268.

Khanna, P. N. and Kelkar, R. R., 1993, "Temperature sounding of the atmosphere over the Indian region using satellite data", *Mausam*, **44**, 2, 167-174.

Kidder, S. Q. and Vonder Harr, T. H., 1995, "Satellite Meteorology - An introduction", Academic press, San Diego, p466.

Li , J. Y. and Lynch, M. J., 1991, "Preliminary results for total ozone using ITPP3.0", Sixth International TOVS study Conference, 305-315.

Lovill , J. S., Ellis, J. S., Luther, F. M., Sullivan, T. J. and Weichel R. L.,. 1982, "Defense meteorological satellite measurements of total ozone", *Geophys. Res. Lett*., **9**, 105-108.

McMillin, L. M. and Dean, C., 1982, "Evaluation of a new operational technique for producing clear radiances", *J. Appl. Meteor*., **21**, 1005-1014.

Planet, W. G., Crosby, D. S., Lienesch, J. M. and Hill, M. L., 1984, "Determination of Total Ozone Amount from TIROS Radiance Measurements", *J. Clim. Appl. Meteor*., **23** , 308-316.

Prabhakara C., Rodgers, E. B., Conrath, B. J., Hanel, R. A. and Kunde, V. G., 1976, "The Nimbus 4 infrared spectroscopy experiment 3. Observations of the lower stratosphere thermal structure and total ozone", *Geophys. Res*., **81**, 6391-6399.

Suresh, R. and Raj, Y. E. A., 2001, "Some aspects of Indian northeast monsoon as derived from TOVS data", *Mausam*, **52**, 4, 727-732.

Suresh, R. and Rengarajan, S., 2001, "Validation of TOVS data and its utility in foreshadowing cyclone movement", Proc TROPMET2000, Cochin University of Science and Technology, Cochin, 309-314.

Suresh, R., Sankaran, P. V. and Rengarajan, S., 2002, "On thermodynamic structure of northeast monsoon over Tamilnadu and adjoining Bay of Bengal using TOVS data", *Mausam*, **53**, 1, 75-86.

Suresh, R. and Rengarajan, S., 2002, "On forecasting cyclone movement using TOVS data", *Mausam*, **53**, 2, 215-224.

Tang, X., Madronich, S., Wallington, T. and Calamari, D., 1998, "Changes in tropospheric composition and air quality", *Journal of photochemistry and Photobiology: B:Biology*, **46**, 83-95.

World Meteorological Organisation, 1961, "Ozone observations and their meteorological applications", WMO No. 108-TP-46, WMO Tech. Note No.**36**, WMO, Geneva, p48.

World Meteorological Organisation, 1981, "Modification of the ozone layer due to human activities and some possible geophysical effects", WMO, Geneva.

World Meteorological Organisation, 1992a, "Global ozone research and monitoring project", WMO report No. 18, WMO, Geneva.

World Meteorological Organisation, 1992b, "WMO and the ozone issue", WMO, Geneva.

Xia Lin Ma, Smith, W. L. and Woolf, H.M., 1984, "Total Ozone from NOAA Satellites - A Physical Model for Obtaining Measurements with High Spatial Resolution", *J. Clim. Appl. Meteor*., **23**, 1309-1314.