TAO, Vol. 10, No. 3, 619-632, September 1999

Ozone Trend over Taiwan from TOMS Data

Kuang-Jung Hsu[1] and Yuk Ling Yung[2]

(Manuscript received 24 September 1998, in final form 13 July 1999)

ABSTRACT

Ozone column data obtained from Nimbus 7 satellite instrument, TOMS, were analyzed. Total ozone data over Taiwan starts November 1978 till May 1993. Daily observations were changed into monthly data for trend analysis. First, spectral analyses were performed to find possible atmospheric movements. Significant peaks were found at periods of 6, 12, 19, and 29 months. The first two are due to seasonal variations. The last one corresponds to the quasi-biennial oscillation (QBO) in stratosphere. It is suggested that the 19-months period is the difference of the annual and the equatorial QBO frequencies.

A linear regression model (LRM) described by Yang and Tung (J. of Geophysical Res. 100, 9091, 1995) were adapted to the deseasoned ozone data. Besides the QBO, the solar flux and ENSO are known to affect the amount of ozone in the Earth atmosphere. The 30-mbar Singapore wind and F10.7-cm solar flux were chosen to represent variations of QBO and solar flux, respectively. The estimated total ozone decreasing trends due to anthropogenic activities are 0.92±0.46% and 1.77±0.52 % per decade over Taipei and Cheng-Kung, respectively. Increase in tropospheric production of ozone in Taipei may explain the lower trend in Taipei than that in Cheng-Kung. Estimated contributions from natural variables to the total ozone variations are: 3.2% and 2.8% from QBO maximum to minimum; 2.0% and 2.3% per 100 solar units for Taipei and Cheng-Kung, respectively. Influence from ENSO seems to be insignificant. Comparison with ground total ozone stations will be discussed.

(Key words: Total ozone, Trend)

1. INTRODUCTION

Ozone is one of the most important chemicals in both stratosphere and troposphere. It not only absorbs harmful ultraviolet radiation from the sun, but also important in determining the

[1]Dept. of Atmospheric Sciences National Taiwan University Taipei, Taiwan, ROC

[2]Division of Geological and Planetary Sciences California Institute of Technology Pasadena, CA 91125 USA

climate of the earth. Molina and Rowland (1974) first predicted that the man-made chlorofluorocarbons released into the atmosphere will eventually deplete the statospheric ozone. Such prediction remained as hypothesis till the discovery of the Antarctic ozone hole by Farman et al., (1985) and reports of a wintertime decrease in ozone at northern mid-latitudes (WMO, 1989). Earlier statistical analysis (Reinsel, et al., 1981), used only the ozone data itself, did not find significant trend, $(0.28 \pm 1.35)\%$. While Chandra (1984) used data from the Nimbus 4 satellite and found that the globally averaged ozone decreased by about 10-12 % in the upper stratsophere, and by about 1 to 3 % in the lower stratosphere. After the reports by Farman et al., many studies (Stolarski, et al., 1991; Stout and Rodgers, 1992; Bojkov et al., 1995) were devoted in finding the total ozone trend.

Over the years, variations of total ozone were found to be influenced by many parameters: solar UV flux changes (Chandra, 1984); quasi-biennial oscillation (QBO) (Brasseur and Simon, 1981; Yang and Tung 1995); El Nino-Southern Oscillation (ENSO) (Bojkov, 1987); volcanic eruption (Randel and Cobb, 1994), and the atmospheric increases in CH_4, N_2O, and CFCs.

The existence of equatorial quasi-biennial oscillation, QBO, was subjected to extensive investigations (Reed et al., 1961; Wallace, 1973; Lindzen and Holton, 1968). It is an irregular oscillation forced by equatorially confined waves propagating upward from the troposphere. The earlier decades showed somewhat shorter periods, of about 27 months, and the period during the last decades gives average of about 30 months.

It is apparently that the QBO signal not only exists in the equatorial region, it also exists in the extratropical stratosphere in variables such as water vapor (Mastenbrook and Oltamans, 1983); nitrogen dioxide (Zawodny and McCormick, 1991) and column ozone (Bojkov, 1986; Lait et al., 1989).

Bojkov, et al., (1990) studied the ozone variation in response to solar and quasi-biennial oscillation. They found a significantly more negative trends during the winter months (December - March) than during the summer month (May - August). The trends became more negative with increasing latitude. For latitudes of 35°N the trend in winter is -1.2% per decade. The summer trends are of the order of -0.6% per decade, with no apparent distinction as the latitude changes. They also found that regional trend varys at the same latitudes. The trends in Japan are considerably less negative than those in North America and Europe. Stolarski et al., (1991) used the TOMS data, studied the total ozone variations. The linear trend obtained from data averaged between 65N and 65S latitudes is $-0.26 \pm 0.14\%$ per year. The trend is near zero $(0.0002 \pm 0.2)\%$ per year at the equator and increases towards poles. The trend also showed a strong seasonal variation; at 50 N the trend is about -0.8% per year in winter and -0.2 % per year in summer.

Niu et al., (1992) using the TOMS data derived the trend of anthropogenic influences at different latitudes and seasons. According to their findings, trend of ozone decrease may differ a lot at the same latitude. Therefore, it is important to understand the local situation. Besides, it is important to compare the data from ground observation with the satellite ones. In this study, the anthropogenic influences of total ozone variations and its seasonal varitions were studied for both Taipei and Cheng-Kung during November 1978 till May 1993. The extent of solar cycle and QBO influences are estimated for both locations. Possible explanations will be proposed for the differences in trends between these two locations. The implications of the current trend for the variations on ultraviolet radiations will be discussed.

2. DATA ANALYSES

The total ozone data used in this study were obtained from the Total Ozone Mapping Spectrometer (TOMS) onboard the Nimbus 7 spacecrafts in late October of 1978. TOMS is an Ebert-Fastie monochromator which scans across the nadir track to provide a global map of the deduced ozone each day. It measures the ultraviolet albedo of the Earth at six wavelengths. Four of these: 312.5, 317.5, 331.2, and 339.8 nm, are used in pairs in combination with surface reflectivity measurements at 360nm and 380 nm. Herman, et al., (1991) developed a new method to calibrate the drift of the TOMS instrument, based on the internal consistency in ozonemeasured with different wavelength pairs. Therefore, the calibrated TOMS data set provided another independent data set in addition to the Dobsonnetwork. The reprocessed data set, version 7, are used in this study. Evaluation of the propagation of errors through the calibration and analysis indicated that the ozone measurements are precise to ±1.3 % between the beginning and the end of the record. It also confirmed by comparison to the World Standard Dobson Instrument (#83) during satellite overpasses, and by comparison to a composite of stations in the Dobson network (McPeters and Komhyr, 1991).

Daily measurements cover from November 1, 1978 through May 6, 1993, and averaged into grid cells covering 1 degree latitude by 1.25 degrees longitude. TOMS ozone data were also sorted out according to positions of ground stations for easier comparison. Taiwan is located between 119° 30' E and 122° E, 25° 38' N to 22° N with two ground total ozone monitoring stations: Taipei (25.05° N, 121.5° E) and Chengkung (23.10° N, 121.40° E).

Total number of the daily column ozone data at Taipei is 5174. Those data were then reorganized into monthly data. Figure 1 gave the monthly ozone data from November 1978 till May 1993. Annual variation can be clearly identified. The overall averages of the total ozone over Taipei are 271.26±22.03 D.U. which is higher than 265.98±22.70 over Cheng-Kung. This is consistent with literatures (Bojkov, 1987; Wayne, 1991) that higher latitudes have more ozone. Tables 1 and 2 list the monthly means for Taipei and Cheng-Kung, respectively. For both sites, ozone maxima occur at May, with values of 299.1 ± 7.4 D.U and 295.4±7.3 D.U., for Taipei and Cheng-Kung, respectively. Column ozone minima occur at winter time, December or January, with total average ozone of 245.4±9.4 and 239.3±9.4 D.U. for Taipei and Cheng-Kung, respectively. The annual variation for these two locations are between 50 and 60 D.U. Also listed in Tables 1 and 2 are the monthly trends derived using ordinary least-square fits for the whole period. It is clear that the total ozone variations are the largest in the wintertime, and the smallest in the summer. In fact, variation in total ozone are close to zero for the summer months in Taipei.

In order to derive the anthropogenic influences from the overall change, natural variations, such as solar cycle and QBO have to be separated. In the atmosphere, ozone formation depends on the photolysis of either molecular oxygens or nitrogen dioxides supplying the atomic oxygen. Variation in solar irradiance are known to affect the total ozone in the atmo-

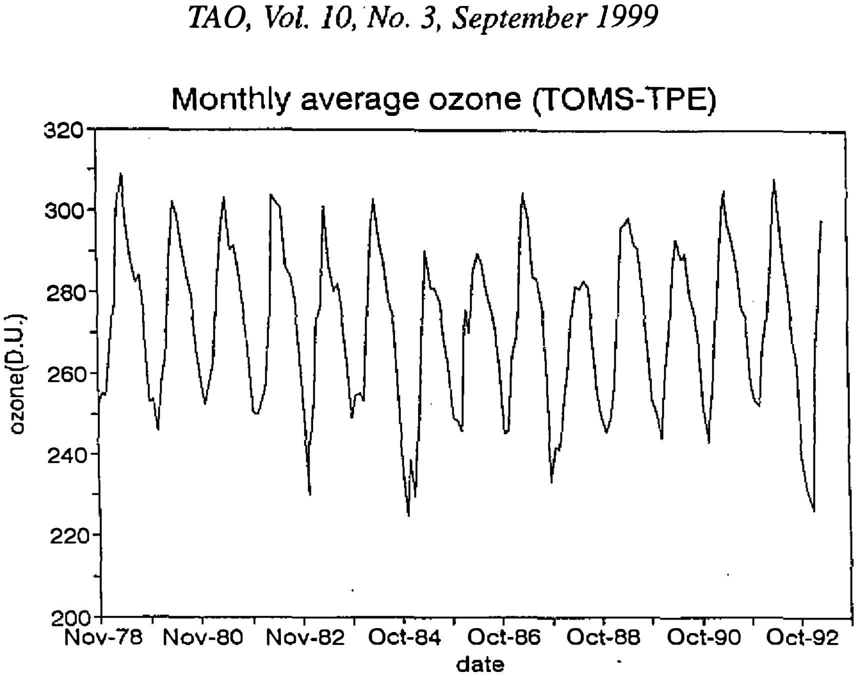

Fig. 1. Monthly column TOMS ozone over Taipei from November 1978 till May 1993.

sphere. In this study, the 10.7cm solar raido flux (F10.7) taken at Ottawa, Canada were used as the proxy of solar activity, since it correlates well with the EUV (10 - 100 nm) radiation absorbed in the mesosphere (Chandra, 1984).

Quasi-biennial oscillation was subject of many studies. As mentioned in earlier section, QBO not only exists in tropics, the total ozone QBO is strongest in the middle and high latitudes (Yang and Tung, 1995). The extratropical ozone QBO signal is out of phase with the equatorial ozone QBO which is in phase with the QBO in equatorial zonal wind. Tropical, midlatitudinal, and polar regions are three distinctive regions for its ozone QBO signal having a fairly constant phase with respect to latitude. The phase reversal between the equatorial and the extratropical region occurs at $\pm 12°$ of latitude symmetric about the equator. Evidence does not support a gradual phase propagation from the subtropical region to the high-latitude region. Earlier reports on this are probably caused by the artifacts of data processing.

In most studies, signals from the 30-mb or 50-mb Singapore wind were extracted from data by a least-square fit in order to find the extratropical ozone QBO signal. Sometimes, a filter admitting signal with frequency of the equatorial QBO was used. These analyses assumed that the extratropical ozone QBO should have the frequency of equatorial QBO, and they may significantly underestiamte the QBO signal (Tung and Yang, 1994). It is necessary to apply the spectral analysis to the whole period.

Results from the spectral analysis for data over Taipei are shown in Figure 2. Results obtained from data over Mauna Loa (19.53°N, 155.58°E) are listed for their similar latitude. Four significant periods are observed which correspond to 6, 12, 19, and 29 months. The former two are due to seasonal variations, and the last one confirms the existence of quasi-

Table 1. Monthly mean for column ozone over Taipei from November 1978 till May 1993.

Month	average ± S.D. (DU)	trend* ± S.D. (DU per year)
January	246.83 ± 7.56	-.823 ± .428
February	255.92 ± 12.6	-.768 ± .784
March	269.69 ± 8.24	-.554 ± .506
April	288.45 ± 9.12	-.568 ± .564
May	299.06 ± 7.37	-.406 ± .460
June	292.52 ± 6.66	-.050 ± .477
July	286.45 ± 4.11	.056 ± .294
August	282.03 ± 3.62	.028 ± .259
September	274.78 ± 4.64	-.556 ± .291
October	264.65 ± 4.96	-.121 ± .354
November	248.51 ± 6.53	-.344 ± .408
December	245.36 ± 9.43	-.615 ± .582

* results from simple regression, QBO, UV influences remain.

biennial oscillation. The near 20-month period was also observed by other study (Tung and Yang, 1994). It is suggested (Tung and Yang, 1994) that this period as the difference of the annual and the equatorial QBO frequencies; 1/12 - 1/30 = 1/20.

Seasonal trend was removed from the data set by substracting the monthly averaged data from individual monthly data, as shown in Figure 3. Average of deseasoned data is 3.31×10^{-6} with variance of 57.1682 for TOMS data over Taipei. The anthropogenic trend was estimated using the following equation according to Yang and Tung (1995):

$$O_3 = \alpha + \beta \cdot t + \gamma \cdot Q(t - lag) + \delta \cdot F(t) + noise$$

F(t) represents the 11-year cycle of solar irradiance, using the 13-month centered moving average of UV10.7cm. During this period, solar radiation varied about 140 solar unit.

$Q(t)$ is the modified 30 mbar Singapore wind, $Q(t) = U(t)$-mean($U(t)$). Where $U(t)$ is the 30 mbar Singapore wind data and the mean($U(t)$) is its mean value. The mean value is subtracted so that the resulting QBO index is more or less symmetric abou the zero line. As mentioned earlier, the extratropic QBO are out of phase with the tropical one and do not have gradual phase transition. Time lag between the extratropical QBO and the tropical one exists,

Table 2. Monthly mean for column ozone over Cheng-Kung from November 1978 till May 1993.

Month	average ± S.D. (DU)	trend* ± S.D. (DU per year)
January	239.31 ± 9.41	-1.080 ± 0.525
February	247.24 ± 12.0	-1.100 ± 0.707
March	261.48 ± 9.23	-0.745 ± 0.555
April	282.82 ± 10.9	-0.589 ± 0.684
May	295.44 ± 7.32	-0.313 ± 0.462
June	289.24 ± 6.67	-0.308 ± 0.469
July	283.70 ± 4.29	-0.246 ± 0.299
August	280.06 ± 4.26	-0.287 ± 0.294
September	273.39 ± 4.65	-0.529 ± 0.296
October	262.71 ± 4.91	-0.326 ± 0.339
November	245.43 ± 7.50	-0.520 ± 0.459
December	239.94 ± 8.50	-0.683 ± 0.511

* results from simple regression, QBO, UV influences remain.

represented by the Singapore winds. In order to find the most appropriate lag, null hypothesis was adopted in the chi-squared tests. The null hypothesis states that no correlation between two models if the χ^2 value is larger than the critical number at a desired significance level, 0.95 in this study. If the χ^2 value is less than that critical value, these two models are essentially the same and $A_{p+t} = 0$. In this case, lag length of 10 was derived for total ozone over Taipei.

Similar procedures were applied for total ozone data over Cheng-Kung, same lag was obtained. The Southern Oscillation Index (SOI) were added to the above model to examine the influences from El Nino-Southern Oscillation (ENSO). It is found that little influence on total ozone were due to SOI for both locations. The estimated parameters for ozone data over both sites are listed in Table 3. Units of variables used are in Dobson Unit per year, per wind unit (m/s), and per solar unit, respectively.

3. RESULTS AND DISCUSSIONS

Results from power spectra analyses showed that in addition to the annual and semi-annual signal and the equatorial QBO period, extratropical ozone contain major peaks at 20-

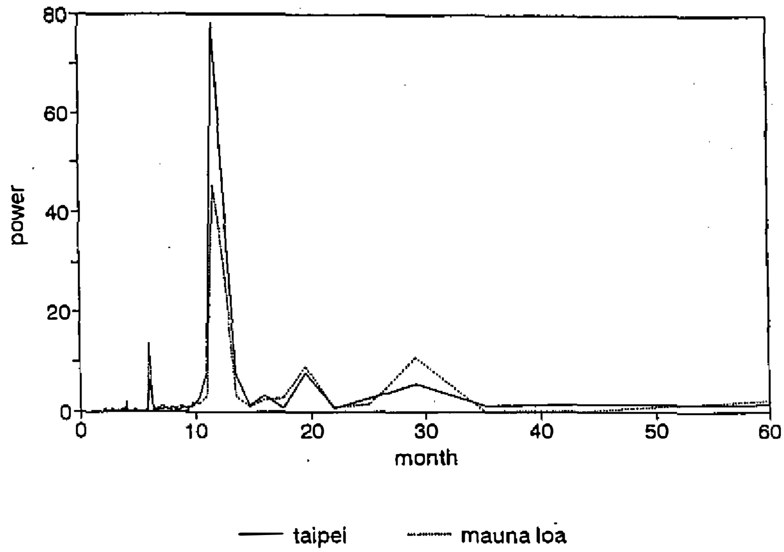

Fig. 2. Spectral analyses of the monthly ozone column TOMS data over Taipei and Mouna Loa.

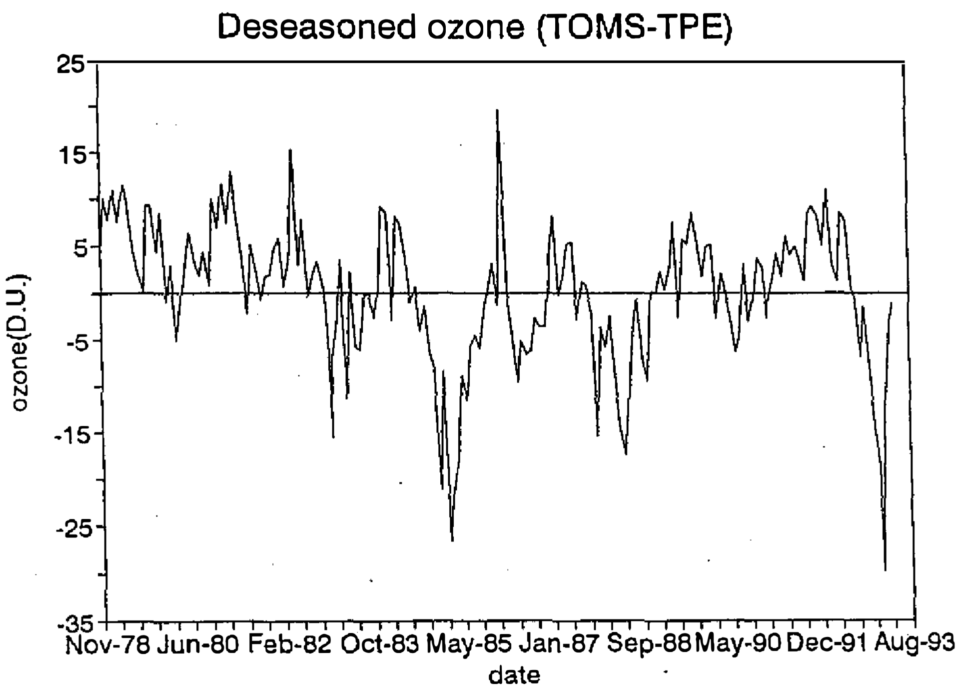

Fig. 3. Deseasoned TOMS ozone over Taipei from November 1978 till May 1993.

month. Tung and Yang (1994) used the 30 years data, 1958-1986, form Dobson stations in studying the QBO phenomena. The 20-month period was observed as one major component in total ozone. Tung and Yang suggested this period as the difference of the annual and the equatorial QBO frequencies; 1/12 - 1/30 = 1/20.

Trend: Reinsel et al., (1987) used data obtained from ground stations studying the ozone variation and its relationship with solar activities. With consideration of the solar cycle effects in their statistical model, they derived a global trend of (-0.260.92)% per decade, no significant overall trend, were estimated from the Dobson total ozone record over the period 1970 till 1984.

Reinsel et al., (1988) then applied a time series regression model to analyze the monthly averaged total ozone data set from the Nimbus 7 solar backscattered ultraviolet (SBUV). The seasonal components, a linear trend, an $F_{10.7}$ solar flux term, and an autocorrelated autoregressive noise term were included in their study. Results shown an average negative drift in SBUV data relative to Dobson data of about -0.4% per year. The global SBUV series were estimated to have a slightly negative trend, (-0.74±0.26)% per year.

Trend study by Stolarski et al., (1991) showed near zero at low latitudes but becoming more negative and statistically significant at middle to high latitudes in both hemispheres. TOMS data from November 1978 till May 1990 were used in their study. The trend averaged over 65S to 65 N are -3% over the 11.6 year. Reading from Figures 1 and 2 of their study, trend of total ozone is about -2% to -4% around 25N. Besides, a total ozone variation of 1.5% were found due to solar activities and about 1% change occurred over a QBO cycle.

The most comprehensive study concerning the trend of total ozone variation was made by Niu et al., (1992). They used the TOMS data to anaylze the trend of for each of the 10° latitude by 10° longitude blocks. The derived average trend at 25°N are -2.29±0.11% per decade, with maximum decrease of (-2.71±0.75)% and minimum of (-1.67±0.59)% per decade. According to their results, the estimated trend of total ozone vary significantly at the same latitude.

The derived trends of total ozone variation due to human influences are 2.5 to 4.7 D.U. decrease per decades for Taipei and Cheng-Kung, respectively. Those numbers correspond to decrease of -(0.92±0.46)% per decade for Taipei and -(1.77±0.52)% per decade for Cheng-

Table 3. Results from estimation for Taipei and Cheng-Kung from November 1978 till May 1993.

LOCATION	Trend (DU per decade)	QBO (DU per cycle)	Solar (DU per 100 solar units)
TAIPEI	−2.50 ± 1.24	8.73 ± 1.45	5.57 ± 0.97
CHENGKUNG	−4.70 ± 1.32	7.59 ± 1.56	6.21 ± 1.04

Kung.

The trend derived from this study for both Taipei and Cheng-Kung are in good agreement with most recent studies. From previous literatures, the trend of total ozone variation over Taipei should have a larger decrease than that obtained for Cheng-Kung, for its higher latitude. Our results do show a smaller decreasing trend in Taipei. Trend derived for Taipei, -(0.92 ± 0.46)% per decade, is lower than that obtained for Cheng-Kung. Differencemay be due to the fast increase of the tropospheric pollution in Taipei. Taipei is a crowded metropolitan area with more than 4 million population, while Cheng-Kung is a fishing village with dozens of streets. Using the ozonesonde data obtained by the Central Weather Bureau since January 1992, the tropospheric ozone variation can be examined. An increasing trend of 3.840 ± 0.94 \% per year were derived, with the total tropospheric ozone of 41.39 ± 10.12 D.U. (Hsu, et al., 1998) This trend cooresponds to an increase of total ozone by 0.58% per year. Since overlap between sonding data and TOMS data are small, the net contribution from tropospheric increase are not pursued further.

QBO influence: Bojkov (1987) suggested that the period of total ozone deficiency were mainly contributed by the circulation. The combination of QBO and very pronouced circulation change during the 1982/83 El Nino-Southern Oscillation (ENSO) caused total ozone of more than 10% below its normal. However, many earlier studies could not be confirmed this by the observational studies.

Tolson (1981) used a spherical harmonic model derived the QBO component of the total O_3 variation at 50°N were 12 ± 2 DU from minimum to maximum. However, the observed change derived form total ozone data were only 3-6 DU which were significantly less than the 60 DU annual change in total ozone between 1979 and 1985. Model studies by Gray and Pyle (1989) predicted the minimum to maximum changes at 50°S of 25 DU.

Earlier studies failed to derive QBO signal from observation maybe as a result from assuming the extratropical ozone QBO have the same frequency as the equatorial one. Because of the strong seasonal and interannual variability of dynamical quantities at high latitudes, the correlation between various quantities and equatorial QBO is relatively poor at high latitudes. Tung and Yang (1994) showed that variations of column ozone in the extratropics do have the QBO signal. The ozone QBO signal is actually strongest in the middle and high latitudes. There are additional signal in all extratropical latitudes with a period of 20 months due to the QBO modulating an annual cycle.

Yang and Tung (1994) found that at the tropical region, ozone QBO has an amplitude of about 6 Dobson Units (DU) and a period of about 30 months. The ozone QBO has an amplitude of about 12-14 DU at middle latitudes of Northern Hemisphere. At the middle and high latitudes in Southern Hemi-sphere, the ozone QBO has an amplitude of about 14-16 DU.The observed column ozone interannual variability in the extratropics contains at most 20% to 30%, 6-8 DU, is in the frequency range of equatorial QBO.

In this study, it is found that magnitudes of the quasi-biennial oscillation cycle can induce the column ozone variations of 8.7 and 7.6 D.U. over Taipei and Cheng-Kung, respectively. Those numbers correspond to 3.2% and 2.8% changes of the total ozone change in these two locations from a QBO maximum to minimum. Variations due to QBO is about 15 % annual ozone variations. The derived values are higher than global averaged value of 1% obtained by Stolarski et al., (1991). These numbers are in good agreement with model predictions and well within the range suggested by Yang and Tung(1994).

Solar influence: Ozone are formed by photochemical reactions of molecular oxygens or nitrogen dioxides. Over 90% of the ozone locate in the stratosphere. Its distribution are controlled by the availability of ultraviolet radiation from the sun and the molecular oxygen profile. The amount of UV radiation are closely related to the 11 years of solar cycle. Reinsel et al., (1988) studied the relationship between of total ozone variation and solar flux change. Global average of (0.97 $\pm$ 0.61)% per 100 solar flux units was reported using the data from solar backscattered ultraviolet (SBUV) over the period of November 1978 to September 1985.

Bojkov, et al., (1990) reported total ozone variation of 0.84% per 100 units of 10.7-cm flux, with a standard error 0.13% was due to solar activities. It corresponds to the ozone change of approximately 1.25% from solar minimum to solar maximum (150 solar units). Callis et al., (1991) examine data sets from SAGE, SAGEII, and Solar and backscattered Ultraviolet (SBUV) at 50° latitude in both hemispheres. Below 20 km and between 1979 and 1985, large local ozone depletion observed. It is found that solar UV flux changes contributed to 1.8% decline in global ozone.

In this study, the derived solar influence on total ozone variations contribute 5.57 DU per 100 solar units for Taipei. Cheng-Kung locates two degree south of Taipei, stronger solar influence is expected. The derived value for Cheng-Kung, 6.21 DU per 100 solar unit, is slightly larger than that in Taipei. Those correspond to the ozone change of approximately 2.8% and 3.2% from solar minimum to solar maximum (140 solar units).

ENSO influence: Studying the total ozone variation using the Nibmus 7 TOMS data, Shiotani (1992) found the ENSO cycle is one of the three dominant frequency components besides annual cycle and QBO cycle. Reid (1994) examined the characteristics of temperature variations using the radiosonde measurements of temperatures from several tropical stations. He concluded that the lower stratosphere is strongly influenced by the ENSO cycle as well as by the QBO. Randel and Cobb (1994) use TOMS total ozone data and the microwave sounding unit (MSU) channel 4 as the weighted mean temperature of the 150 to 50 mbar layer. They also found ENSO effect to be statistically significant.

Hasebe (1993) suggested that the tropopause effect and the advection effect are the two dynamic effects relating the equatorial total ozone variations to sea surface temperature (SST) changes. A higher tropopause results in a deeper layer with a characteristically low tropospheric ozone concentration and smaller amount of total ozone. The advection effects involves variations due to diabatically driven mean meridional circulation. Enhanced upward motion in the lower stratosphere will reduce the total ozone by countergradient vertical ozone advection. Higer SSTs activate higher tropopause and a stronger pward motion. At the time of high SSTs, total ozone tends to be lower. Shiotani and Hasebe (1994) later found that the maximum contributions to total column ozone takes place in the lower stratosphere, between 19 to 25 km. In this study, the chi-squared tests were ran on model including SOI with lag up to 48 months. The SOI influences on total ozone variation were found to be insignificant.

Comparison with ground stations: Bojkov, et al., (1988) compared the Nimbus 7 TOMS data with data from ground-based stations during the daily overpasses of the satellite. They found the TOMS-derived total ozone data decreased nonuniformly by an average of about 0.4% per year. Data obtained by two-thirds of 92 Dobson stations differed by less than 2% and about 20% of the Dobson stations show differences greater than 3%. The trend derived from OMS data were less negative than those derived from European ground-based stations by about 1.0% per decade; only small average differences for stations in North America and Japan.

Started July 1965, total ozone were monitored by the Central Weather Bureau (CWB) till now. The total ozone measurement at Cheng-Kung started February 1991. Data sets are not continuous due to malfunction of instruments occasionally, especially in the 80's. Therefore, the TOMS daily data were substracted from the CWB data over the period from January 1991 till May 1993. The difference plot is given in Figure 4 for Taipei station. Ordinary least squared fits applied to the difference data set. A trend of -2.23% per year were derived which corresponds to a -23% decrease of total ozone if the trend from TOMS data were included. The difference in total ozone trend between Taipei and Cheng-Kung was examined using CWB data from 1991 till 1996. A trend of 0.64±0.19% per year increase was obtained from the data set, (Taipei - Cheng-Kung). This number is in good agreement with radiosonding results, 0.58% per year (Hsu, et al., 1998). However, the overall trends in both locations are much larger than numbers in existing literatures. Longer data set and more detailed studies are re-

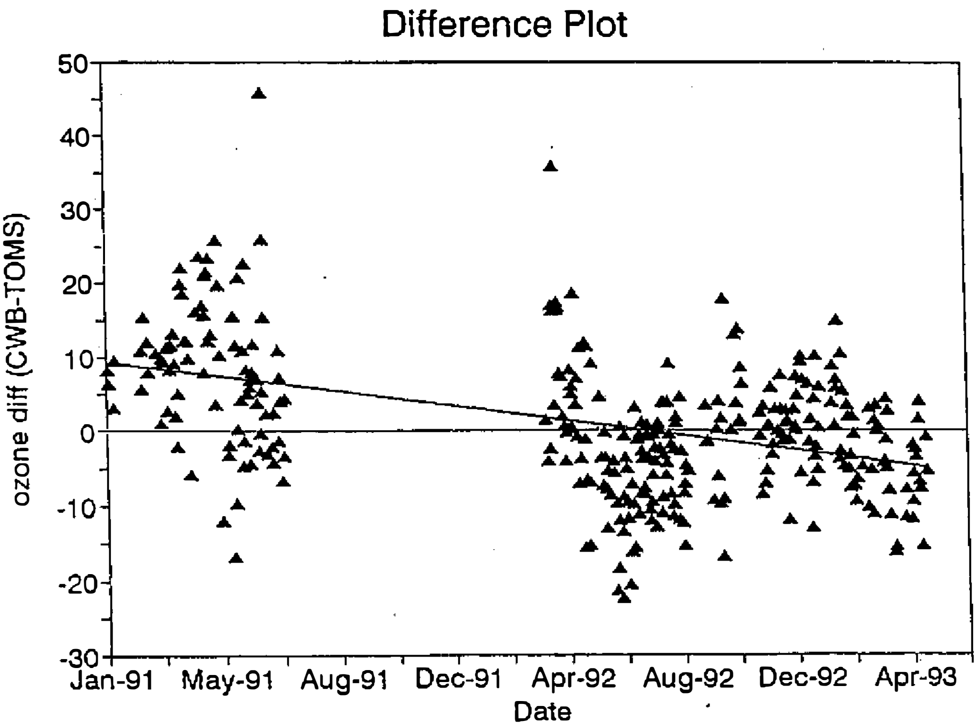

Fig. 4. Difference plot, CWB - TOMS, over Taipei from January 1991 till May 1993. Dashed line obtained by least squared fit.

quired in order to resolve the differences.

4. CONCLUSION

Data from the Total Ozone Mapping instrument onboard Nimbus 7 satellite were used in this study during November 1978 till May 1993. For data over Taipei and Cheng-Kung, total ozone variations are found to be caused by both natural and anthropogenic effects. The contributions from man-made CFCs, CH_4, and others induce the total ozone decreasing trends of 0.92% to 1.77 % per decade. Increase in tropospheric pollution in Taipei may be part of the reasons for the smaller decreasing trend over Taipei. Natural variables contribute to the total ozone variations are estimated: 3.2% and 2.8% from QBO maximum to minimum; 2.0% and 2.3% per 100 solar units. Influence from ENSO seems to be insignificant. Comparison with ground total ozone stations found unexplanable differences which needs further investigations. In this latitude, the anthropogenic contribution on total ozone change are smaller when compared with those natural ones. This study also showed that the local pollution may upset the decreasing trend by producing more ozone in the troposphere. With the success of Montreal Protocol, release of ozone depletion substances into atmosphere are dramatically reduced. It is expected that the anthropogenic trend will become smaller as time goes on.

Acknowledgements The authors would like to thank Prof. H. H. Hsu for many helpful discus-sions. This study is supported by National Science Council of Taiwan under the Grant NSC 88-2111-M-002-012.

REFERENCES

Bojkov, R. D., 1986: The 1979-1985 ozone decline in the Antarctic as reflected in ground level observation. *Geophys. Res. Lett.*, **13**, 1236-1239.

Bojkov, Rumen D., 1987: The 1983 and 1985 Anomalies in Ozone Distribution in Perspective. *Monthly Weather Review,* **115**, 2187-2201.

Bojkov, R. D., C. L. Mateer, and A. L. Hansson, 1988: Comparison of ground-based and total ozone mapping spectrometer measurements used in assess-ing the performance of the global ozone observing system. *J. Geophys. Res.*, **93**, 9525-9533.

Bojkov, R., L. Bishop, W. J. Hill, G. C. Reinsel, and G. C.Tiao, 1990: A statistical trend analysis of revised Dobson total ozone data over Northern Hemisphere. *J. Geophys. Res.*, **95**, 9785-9807.

Bojkov, R. D., L. Bishop, and V. E. Fioletov, 1995: Total ozone trends from quality-controlled ground-based data (1964-1994). *J. Geophys. Res.*, **100**, 25867-25876.

Brasseur, G., and P. C. Simon, 1981: stratospheric chemical and hermal re-sponse to long-term variability in solar UV irradiance. *J. Geophys. Res.*, **86**, 7343-7362.

Callis, L. B., R. E. Boughner, M. Natarajan, J. D. Lambeth, D. N. Baker, and B. Blake, 1991: Ozone depletion in the high latitude lower stratosphere: 1970-1990. *J. Geophys. Res.*, **96**, 2921-2937.

Chandra, Sushil, 1984: An Assessment of Possible Ozone - Solar Cycle Re-lationship Inferred from Nimbus 4 BUV Data. *J. Geophys. Res.*, **89**, 1373-1379.

Farman, J. C., Gardiner, B. G., and J. D. Shanklin, 1985: Large loses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature*, **315**, 207-210.

Garcia, R. R., S. Solomon, R. G. Roble, and D. W. Rusch, 1984: A numerical study of the response of the middle atmosphere to the 11-year solar cycle. *Planet. Space Sci.*, **32**, 411-421.

Heath, D. F., 1981: A review of observational evidence for short and long term ultraviolet flux variability. Proceedings of theInternational Conference on Sun and Climate, Centre National d'Etudes Spatiales, Toulouse, France.

Heath, D. F., and B. M. Schlesinger, 1986: The Mg 280-nm doublet as a monitor of changes in solar ultraviolet irradiance. *J. Geophys. Res.*, **91**, 8672-8682.

Hirota, I., 1980: Observational evidence of the semiannual oscillation in the tropical middle atmosphere - A review. *Pure Appl. Geophys.*, **118**, 217-238.

Holton, J. R., and R. S. Lindzen, 1972: An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076-1080.

Hood, L. L., J. L. Jirikowic, and J. P. McCormack, 1993: Quasi-decadal vari-ability of the stratosphere: influence of long-term solar ultraviolet varia-tions. *J. Atmos. Sci.*, **50**, 3941-3958.

Hsu, K.-J., Y. T. Lee, Y. L. Yung, 1998: The increase in tropospheric ozone over Taiwan using CWB data, in preparation.

Kane, R. P., Y. Sahai, and C. Casiccia, 1998: Latitude dependence of the quasi-biennial oscillation and quasi-triennial oscilation characteristics of total ozone measured by TOMS. *J. Geophys. Res.*, **103**, 8477-8490.

Krzyscin, Janusz W., 1996: UV controlling factors and trends derived from the ground-based measurements taken at Belsk, Pland, 1976-1994. *J. eophys. Res.*, **101**, 16797-16805.

Mastenbrook, H. J., and S. J. Oltamans, 1983: Stratospheric water vapor variability for Washington, D. C./Boulder, CO: 1964-82. *J. Atmos. Sci.*, **40**, 2157-2165.

McPeters, R. D. and W. D. Komhyr, 1991: Long-term changes in SBUV/TOMS relative to World Primary Standard Dobson Spectrometer 83. *J. Geophys. Res.*, **96**, 2987-2994.

Molina, M. J. and F. S. Rowland, 1974: Stratospheric sink for Chlorofluo-romethanes: chlorine atom catalyzed destruction of ozone. *Nature,* **249**, 810-812.

Niu, Xufeng, John E. Frederick, Michael L. Stein, and George C. Tiao, 1992: Trends in Column Ozone Based on TOMS Data: Dependence on Month, Latitude, and Longitude."J. *Geophys. Res.*, **97**, 14661-14669.

Lait, L. R., M. R. Schoeberl, and P. A. Newman, 1989: Quasi-biennial modu-lation of the Antarctic ozone depletion. *J. Geophys. Res.*, **94**, 11559-11571.

Lindzen, R. S. and J. R. Holton, 1968: A theory of the quasi-biennial oscilla-tion. *J. Atmos. Sci.*, **25**, 1095-1107.

Plumb, R. A. and R. C. Bell, 1982: A model of the quasi-biennial oscillation on an equatorial beta-plane. *Quart J. Roy. Meteor. Soc.*, **108**, 335-352.

Randel, William J. and Janel B. Cobb, 1994: Coherent variations of monthly mean total ozone and lower stratospheric temperature. *J. Geophy. Res.*, **99**, 5433-5447.

Reed, R. J., W. J. Cambell, L. A. Rasmussen, and D. G. Rogers, 1961: Evi-dence of the downward propagating annual wind reversal in the equatorial stratosphere. *J. Geophys. Res.*, **66**, 813-818.

Reid, George C., 1994: Seasonal and interannual temperature variations in the tropical stratosphere. *J. Geophys. Res.*, **99**, 18923-18932.

Reinsel, G. C., G. C. Tiao, M. N. Wang, R. Lewis, and D. Nychka, 1981: Sta-tistical Analysis of Stratospheric Ozone Data for the Detection of Trends. *Atmos. Environ.*, **15**, 1569-1577.

Reinsel, G. C., G. C. Tiao, A. J. Miller, D. J. Wuebbles, P. S. Connell, C. L. Mateer, and . J. DeLuisi, 1987: Statistical Analysis of Total Ozone and Stratospheric Umkehr Data for Trends and Solar Cycle Relationship. *J. Geophys. Res.*, **92**, 2201-2209.

Reinsel, G. C., G. C. Tiao, S. K. Ahn, M. Pugh, S. Basu, J. DeLuisi,C. L. Mateer, A. J. Miller, P. S. Connell, and D. J. Wuebbles, 1988: An analysis of the 7-year record of SBUV satellite ozone data: global profile features and trends in total ozone. *J. Geophys. Res.*, **93**, 1689-1703.

Stolarski, R. S., P. Bloomfield, R. D. McPeters, and J. R. Herman, 1991: Total ozone trends deduced from Nimbus 7 TOMS data. *Geophys. Res. Lett.*, **18**, 1015-1018.

Stout, J. and E. B. Rodgers, 1992: Nimbus-7 total ozone observation of west-ern Pacfic tropical cyclones. *J. Applied Meteorology*, **31**, 758-783.

Tung, K. K., and H. Yang, 1994: Global QBO in circulation and ozone. Part I: Reexamination of observational evidence. *J. Atmos. Sci.*, **51**, 2699-2707.

Yang, H. and K. K. Tung, 1994: Statistical significance and pattern of extra-tropical QBO in column ozone. *Geophys. Res. Lettes.*, **21**, 2235 -2238.

Yang, H. and K. K. Tung, 1995: On the phase propagation of extratropical ozone quasi-biennial oscillation in observational data. *J. Geophys. Res.*, **100**, 9091-9100.

Wallace, J. M., 1973: The general circulation of the tropical lower strato-sphere. *Rev. Geophys. Space Phys.*, **11**, 191-222.

WMO, 1989: Report of the International Ozone Trends Panel 1988. World Meteorological Organization Global Ozone Research and Monitoring Project - Report No., World Meteorological Organization, Geneva, Switzerland.

Wayne, Richard P., 1991: Chemistry of atmosphere. Oxford Science Publi-cation, New York. 2nd Edition.

Zawodny, J. M ,and M. P. McVormick, 1991: Stratospheric Aerosol and Gas Experiment II measurements of the quasi-biennial oscillations in ozone and nitrogen dioxide. *J. Geophys. Res.*, **96**, 9371-9377.