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Recalculation of 11-year total ozone of Brewer spectrophotometer 115

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[1] Ground-based total ozone (O_3) has been measured by Brewer 115 at Hong Kong (Cape D'Aguilar, 22°13′N, 114°15′E, 64 m above mean sea level). Long-term observations between 1995 and 2005 show that the sensitivity of outdoor spectrophotometers exhibit long-term drift. Despite the undesirable sensitivity shift, high-quality total ozone observations can still be achieved so long as the spectrophotometer is well maintained and calibrated regularly, and appropriate corrections applied to the data. The recalculated ground-based total ozone also shows good agreement with the satellite (Total Ozone Mapping Spectrometer (TOMS) version 8) data and Brewer 61 (Chengkung: 23°05′, 121°21′). The procedures and experience of a total ozone trend analysis using multiple linear regression that account for upper level temperatures, QBO, AOD, sun spot activities, and El Niño were reported for future reference. It can be concluded that no ozone depletion was observed over Hong Kong in this time period.

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1. Introduction

[2] Since the first World Meteorological Organization (WMO) consultation meeting in Arosa [*WMO*, 1991], many Brewer Spectrophotometers have been installed all over the world. The addition of Brewer Spectrophotometers to the Global Ozone Monitoring Network strengthened ground observations of total ozone, which have long been carried out by Dobson Spectrophotometers [*London et al.*, 1976]. Comparing against the Dobson, the Brewer has strengths and weaknesses. The Brewer is fully automatic and the daily observation schedule can be programmed [*Kerr et al.*, 1985]. Hence stations located at remote monitoring sites which have little manpower or expertise can also contribute to WMO routine observations. Another strength of the Brewer is that it is more versatile. It can perform UV spectral scanning and report UV index, SO_2 column and aerosol optical depth (AOD). On the other hand, the Brewer is more difficult to maintain due largely to its being installed outside in all weather conditions. As for other spectrophotometers, it is sensitive to humidity. Particularly in tropical and subtropical regions, the sensitivity of the Brewer might change considerably after a few years of operation. Regular replacement of desiccant allows operating a Brewer at a stable calibration even under humid conditions. At present, about 200 Brewers have been sold in the world but the number of stations reporting Brewer total ozone data to the World Ozone and Ultraviolet Radiation Data Center (WOUDC) is less than 50. The aim of this article is to share the Brewer 115 experience with the Brewer community in order to encourage more Brewer stations to recalculate their total ozone measurements and submit them to WOUDC. Furthermore, the search for ozone recovery in the long-term ozone data records is of special interest today. After the XX Quadrennial Ozone Symposium 2004, the International Ozone Commission defined three stages of ozone recovery. The ozone community would be interested to see whether stratospheric ozone shows a statistically significant slowing of the downward trend or even an upward trend after removal of all other known influences such as the solar cycle or volcanic aerosols. The objectives of this paper are (1) to publish the 11-year (January 1995 to December 2005) total ozone acquired by Brewer 115 so as to offer the satellite community an opportunity to compare their data with a good ground reference, and (2) to share the experience on a total ozone trend analysis at 22°N.

2. Instrument

[3] The Brewer spectrophotometer MKIV 115 (SCI-TEC Instruments Inc.) was installed at Cape D'Aguilar, Hong Kong in January 1995. The location of the station is 22°13′N, 114°15′E and 64 m above mean sea level. The Brewer spectrophotometer contains a modified Ebert f/6 spectrometer with a 1200 line/mm holographic diffraction grating operating in the third order for ozone and SO_2. The spectrophotometer is described in more detail by *Kerr et al.* [1980]. The station information is presented in detail by *Lam et al.* [2002].

[4] The original calibration was provided by the manufacturer in January 1995. Since then, the Brewer 115 has been maintained regularly by International Ozone Services Inc. (IOS) and all subsequent calibrations were done by IOS using the traveling standard Brewer 017. Since 1999 calibrations have been carried out annually, except for 2003, when the annual exercise was interrupted by the SARS

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Table 1. Calibration History of Brewer 115[a]

Year	Start Day	ETC O_3	ETC SO_2	R6	R5
1995	001	3147	3424	1926	3730
1996	316	3161	3455	1955	3790
1999	099	2957	2936	1720	3260
2000	099	2735	2650	1500	2975
2001	093	3330	3730	2125	4080
2002	092	3550	4070	2370	4480
2004	056	3030	3105	1798	3388
2005	062	3005	3050	1770	3335
2006	033	2968	2915	1750	3265

[a]ETC: extraterrestrial constants.

epidemic. The calibration dates and extraterrestrial constants (ETC) are listed in Table 1.

3. Stability of the Instrument

3.1. Standard Lamp Tests

[5] Table 1 also shows the standard lamp ratios R5 and R6 recorded during each calibration. The standard lamp test is carried out two times a day. This test is designed to detect and record the changes in the spectral sensitivity of the instrument. It is done by taking a series of measurements at the operating wavelengths using a standard internal halogen lamp as a source. The two most important results of the test are the ratios R5 and R6 representing SO_2 and O_3 respectively. The time series of R5 and R6 ratios are shown in Figure 1. R6 is shown as the red curve on the left vertical axis whereas R5 is shown as the green curve on the right axis. Calibration visits by IOS are marked as timelines in Figure 1. The standard lamp was replaced twice by IOS during annual maintenance on 9 April 2000 and 24 February 2004. The replacement of standard lamp never changed the R5 and R6 ratios of Brewer 115 so it did not affect the recalculation of total ozone. If the R ratios do change after a standard lamp replacement, one needs to apply the difference as an offset for future extraterrestrial constants corrections so that the difference does not affect the calibration.

[6] According to the changes in standard lamp ratios, the 11-year history of the spectrophotometer can be separated into four periods:

[7] 1. In the first 3 years from 1995 to 1997, the spectrophotometer exhibited excellent stability.

[8] 2. Since the beginning of 1998, the sensitivity started to change. The maintenance trip on day 099 in 1999 discovered that the photomultiplier filter ($NiSO_4$/UG11) combination had deteriorated. This filter was subsequently replaced on day 099 in 2000.

[9] 3. From 2000 up to 2003, the sensitivity of the spectrometer continued to shift but in the opposite direction. The new filter was not behaving as expected. The performance of the spectrophotometer was monitored more closely and annual calibrations were maintained. The photomultiplier filter was replaced a second time on day 056 in 2004.

[10] 4. From 2004 onward the stability of the spectrophotometer was restored.

[11] During the past 11 years, only the main power supply, mercury lamp, standard lamp and the photomultiplier tube filters have been replaced. To date, all other internal parts including all electronics, motors, iris, lens, filters and gratings have continued to functioning normally. The most common errors causing loss of data include power failure, serial cable communication fault, software suspension caused by ‘‘division by zero’’, and errors of time caused by various reasons such as inaccurate PC clock.

3.2. Mercury Lamp (HG) Test

[12] The mercury lamp test is designed for wavelength calibration. It is designed to ensure that all observations are aligned at the correct wavelengths. The test is performed by scanning a Hg spectral line and comparing the measured scan with a laboratory scan. The manufacturer suggests repeating this test every time when the internal instrument temperature changes by 3 degrees Celsius. In practice, this test was carried out many times everyday irrespective of the temperature change. The mercury lamp test was carried out after each UV scan. Analysis of the 11-year record shows no problems in the performance of this test. This means that the instrument was usually making direct sun measurements at the proper wavelengths. The micrometer screw never showed any shift. The pushrod was checked and lubricated as necessary during servicing checks each year.

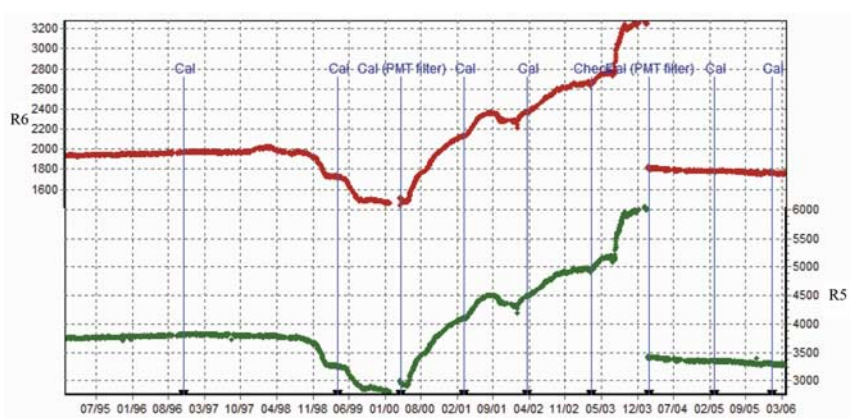

Figure 1. Standard lamp ratios of Brewer 115.

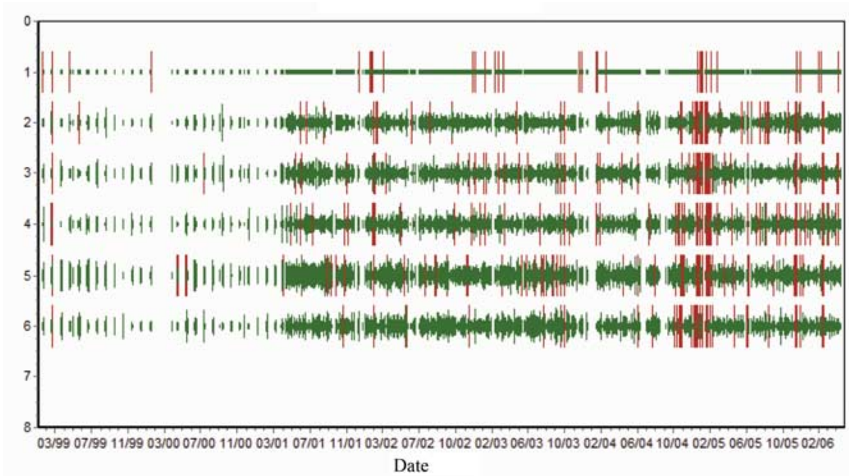

Figure 2. Run-stop test of Brewer 115.

3.3. Run-Stop (RS) Test

[13] The RS test checks the ability of the detection system to operate in the dynamic mode when the system switches among five operating wavelengths with high speed during direct sun mode. The criteria for the test are the ratios between photon counts accumulated in the dynamic mode and those in the static mode. Figure 2 shows the 11-year record of these test results. The green marks represent acceptable (as described by the manufacturer) results and the red lines mark the occasional results outside the prescribed limits. Since the test failed only occasionally, it does not represent any instrumental problem. The more frequent occurrence of poor RS results around 2005 was caused by a communication fault. The weatherproof cable connector of the serial signal cable that is attached to the bottom of the tracker had aged after over 10 years of service. Data transmission between the Brewer 115 and the computer was interrupted every now and then. This fault was particularly difficult to identify because the communication error occurred only momentarily in random and all operations returned to normal afterward. The problem was fixed by replacing the signal cable.

4. Ozone Absorption Coefficient

[14] Another important characteristic that is established at the time of a calibration is the instrument's ozone absorption coefficient. This is achieved by measuring the dispersion curve of the instrument and using this curve for calculating the exact operating wavelengths and the slit functions, which are then used for calculations of the effective ozone absorption coefficient. A typical value for Brewers is around 0.34. The Brewer 115 has shown a remarkable stability in its monochromator performance. The absorption coefficient has always measured between 0.3413 and 0.3417.

5. Data Recalculations: Establishing the ETC

[15] A total of 3683 Brewer data files, known as b-files, have been analyzed. Each file contains all the records for

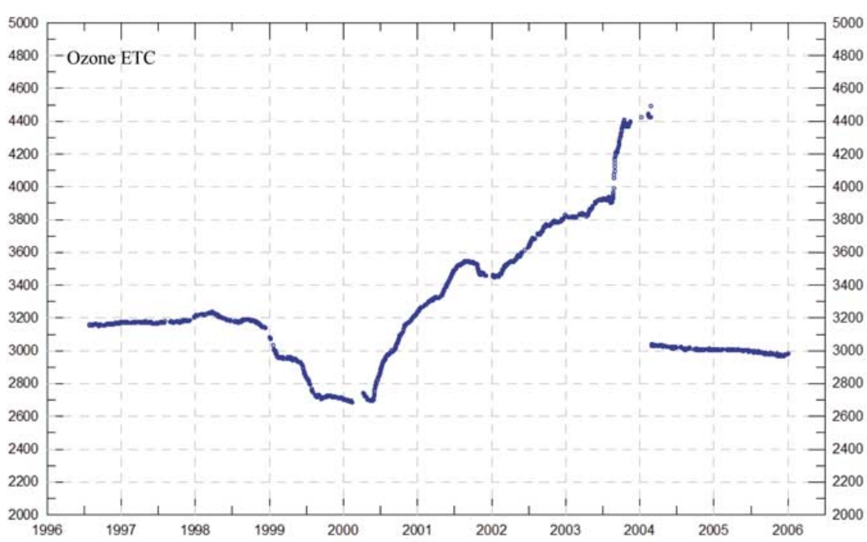

Figure 3. Ozone extraterrestrial constants (ETC) values used in final processing.

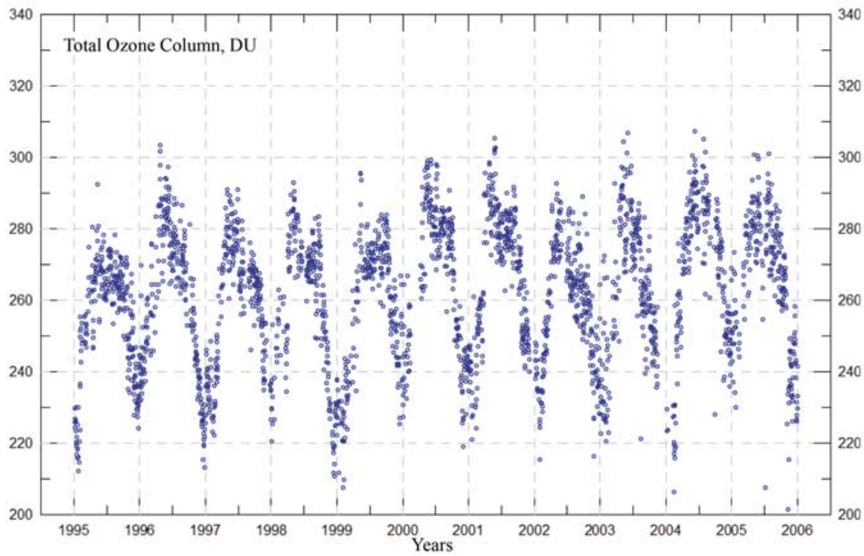

Figure 4. Total ozone values acquired by Brewer 115.

1 day of operations. The instrument experienced a great shift in sensitivity between 1998 and 2003. All total ozone data had to be recalculated. The extraterrestrial constants (ETC) established during each calibration visit along with the standard lamp (SL) test results provided the necessary data for correcting the ozone values between each calibration.

[16] ETC constants are usually calculated by comparing a calibrated reference instrument and the instrument to be calibrated. At the time of a calibration, not only are the ETC's calculated, but also the SL test results are recorded as a reference. Any change in the SL R6/R5 values should be applied as a correction to the ETC constants that were established at the last calibration. Often, at the next calibration it is confirmed that the SL correction is all that is needed to bring the ozone values to those of the reference instrument, but sometimes, especially when the SL R5/R6 values are changing rapidly, an additional correction is needed. This was exactly the situation with the Brewer 115. The photomultiplier filter started to deteriorate in 1998 and continued doing so until 2004. Throughout this period, the R5/R6 values were very unstable and the total change was unusually large. This called for a special technique to combine the results of the calibrations with those of the SL test.

[17] For that, two processes were combined: First, a linear interpolation of the calibration results between calibrations and second, a 3-day running average of the daily changes in SLR5/SLR6 from the day of the latest calibration. These two processes yield ETC's for each day that are continuous and have no stepwise behaviour at the calibration dates, except as mentioned above for the two calibrations when the PMT filter was replaced. Figure 3 shows the actual ozone ETC used in the final reprocessing. An identical process

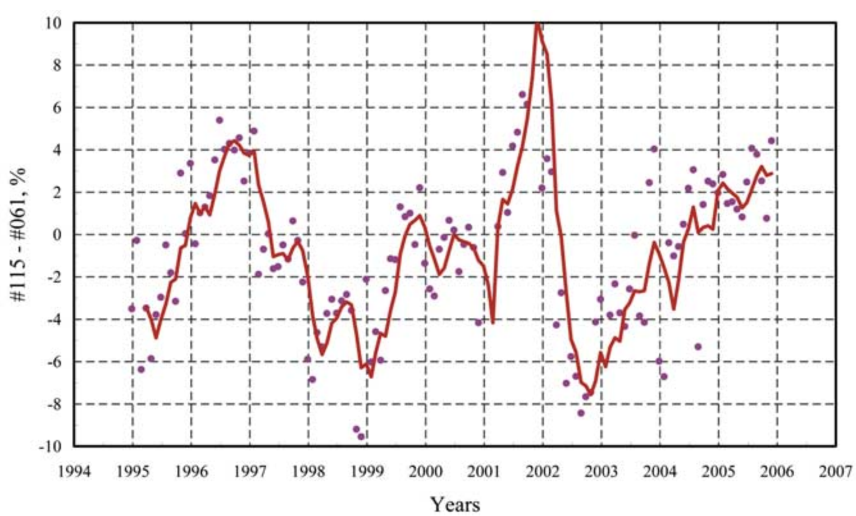

Figure 5. Percentage difference between Brewer 115 derived and Brewer 061 derived total ozone.

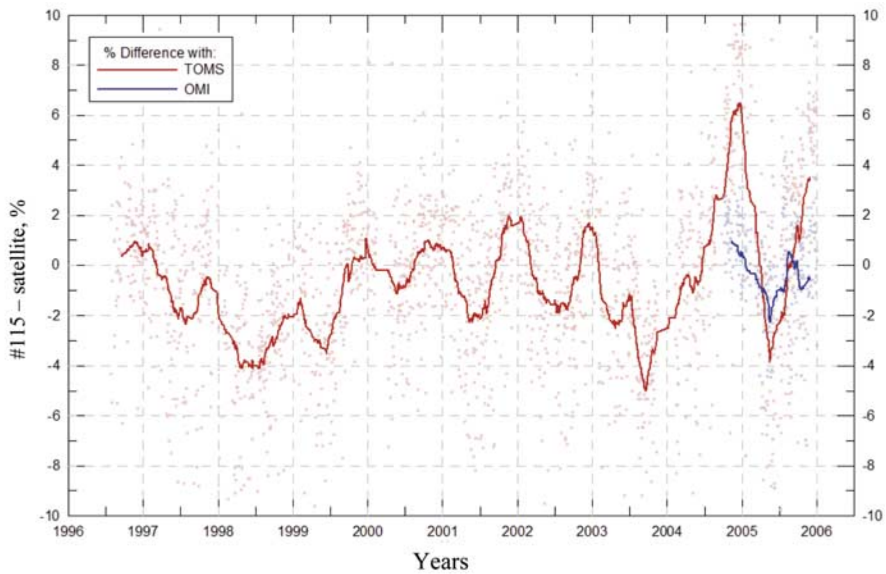

Figure 6. Percentage difference between Brewer-derived and satellite-derived total ozone.

was repeated for the SO_2 ETC. Figure 3 shows good agreement with Figure 1.

6. Final Total Ozone Observed at Cape D'Aguilar

[18] Using the corrected ETC's all files for the 11-year period were reprocessed. It was found that regular calibrations and maintenance of the Brewer 115 helped to sort out the effects on the data of the changing instrument. The total ozone could be recalculated with high precision. Figure 4 shows the final results for daily mean total ozone.

7. Comparison of Brewer 115 Total Ozone With Brewer 61 and Satellite Data

[19] The first quality assurance procedure was to compare the Brewer 115 with another Brewer located in a similar latitude. The Brewer 61 installed at the Chengkung station (23° 05′N) is about 800 km from Hong Kong. Brewer 61 is one of the best kept instruments within the Brewer community. Annual comparison with traveling standard Brewer 017 and servicing have been carried out by IOS since 1993 (except 1996). The differences (in percentage) between total ozone as measured by the Brewer 115 and the Brewer 61 are shown in Figure 5. The lines represent a 4-month running average of the difference (in percentage). The total ozone (monthly averages) characteristics observed at Chengkung are very similar to those observed at Hong Kong (data available at http://www.cwb.gov.tw/V5/climate/o3/Data/o3-y.htm). The annual cycles are almost identical [*Liu and Chang*, 2001]. Overall, the Chengkung total ozone was about 1.7 DU, or less than 1%, higher than the Brewer 115. The standard deviation of their differences was about 10 DU which is less than 4% of the overall mean of the Brewer 115. A long-term variation at about the 5-year cycle was observed in Figure 5.

[20] The total ozone of the Brewer 115 was then compared with the overpass data from the Total Ozone Mapping Spectrometer (TOMS) (version 8) and OMI satellite systems. It is now known that the TOMS data quality deteriorated dramatically sometime in 2004 and OMI has now assumed the place as the main data source for the global coverage for ozone. Still, in Figure 6, which shows the differences between total ozone as measured by the Brewer 115 and the satellites, we plotted all available data from TOMS, including the questionable quality data for 2004–2006. In Figure 6, the lines represent a 2-month running average of the differences (in percentage) between daily mean ozone from Brewer 115 and the overpass satellite data.

[21] The graph shows good overall agreement with TOMS for the periods when that system was operating as designed and also very good agreement with the OMI data. Overall, the TOMS total ozone was about 2.1 DU, or less than 1% higher than the Brewer 115. The standard deviation of the differences was about 10 DU which is less than 4% of the overall mean of the Brewer 115. The seasonal variation in the differences are very well known, but not fully understood. This is consistent with the world ground-based total ozone network performance. *Fioletov et al.* [1999] used data in the World Ozone and Ultraviolet Radiation Data Center and found that the standard deviations of the monthly mean difference between Brewer and TOMS is less than 2.2%.

[22] Results of the linear regressions of the two total ozone data sets against the Brewer 115 are listed in Table 2. The two regressions are statistically significant at the 95% confidence level. TOMS exhibits excellent correlation with the Brewer 115; the slope of the regression line was unity. The good correlations between satellite and the second ground station indicate that the recalculation of the Brewer 115's total ozone values has been successful.

8. Trends

[23] Simple Linear regressions of the 11-year time series were first carried out, and the results are listed in Table 3.

Table 2. Results of Linear Regressions Between Different Total Ozone Data Sets Against Total Ozone of Brewer 115[a]

	m	b	p-Value	R^2
Brewer 061 versus Brewer 115	0.92 ± 0.05	23.47 ± 13.65	0.000	0.70
TOMS versus Brewer 115	1.00 ± 0.01	1.60 ± 3.40	0.000	0.77

[a]y = mx + b, R^2 = coefficient of determination. TOMS: Total Ozone Mapping Spectrometer.

The seasonal cycles of total ozone were removed using two methods: (1) The daily/monthly data was transformed into yearly averaged data and the data set reduced to only 11 data points, and (2) a low-pass filter was applied of 365 days running smoothing which truncates the data set by 1 year, but the data intensity remains at the daily interval. For the yearly averaged data, both the Brewer 115 and the Brewer 61 time series exhibited small positive trends (Table 3). The Brewer 115 trend is statistically significant at $\alpha = 0.05$ level. The same trend is also seen for the Chengkung station but the trend is weaker (only about 0.4 DU per year) with a very small correlation coefficient and is statistically insignificant. The TOMS yearly averaged time series showed a statistically insignificant decreasing trend but this trend cannot be used because it has been announced officially that TOMS data since 2002 should not be used for trend analysis. For the 365 days smoothed data, the slope of the Brewer 115 total ozone was +0.0026 DU/day which is equivalent to about 0.95 DU/year. The total ozone over Hong Kong has increased by about 9 DU in the last decade which is about 4% per decade.

[24] To further investigate the total ozone trend measured by the Brewer 115, multiple linear regressions were carried out. The conventional multiple regression using the deseasonalized time series together with the seven explanatory variables listed in equation (1) was then carried out. The statistical model followed that used by *Bojkov et al.* [1990], *Staehelin and Kegel* [1998], or *Svendby and Dahlback* [2004]. The model applied to the data set of the monthly mean of total ozone was formulated as

$$\begin{aligned} O_3(t) = {} & b + mt + \gamma_1\Omega_i + \gamma_2(\mathrm{AOD})_t \\ & + \gamma_3(\mathrm{QBO\ index})_t + \gamma_4(\mathrm{sunspot\ index})_t \\ & + \gamma_5(\mathrm{El\ Niño\ index})_t + \gamma_6(T_{300})_t + \gamma_7(T_{100})_t \\ & + \gamma_8(T_{50})_t + N_t \end{aligned} \quad (1)$$

where

- $O_3(t)$ the Brewer 115 total ozone mean of month t where t goes from 1 to 132
- m trend of total ozone
- b constant
- Ω_i ozone mean of month i (average values from 1995 to 2005) where i goes from January to December
- γ_j coefficients corresponding to explanatory variables
- N_t residual noise series
- AOD stratospheric aerosol optical depth [*Barnes and Hoffman*, 1997] (provided by J. Barnes, unpublished data, 2006)
- QBO index the zonally averaged winds at 50 mbar over the equator. (http://www.cpc.ncep.noaa.gov/data/indices/qbo.u50.index)
- Sunspot index sunspot number (http://sidc.oma.be/sunspot-data)
- El Niño index (standardized Tahiti−standardized Darwin) sea level pressure (http://www.cgd.ucar.edu/cas/catalog/climind/SOI.signal.ascii)
- T_{300}, T_{100}, T_{50} upper air temperature at 300, 100 and 50 mbar respectively. (Extracted from radiosonde data of Hong Kong Observatory)

[37] Initial regression analysis revealed two problems: (1) Autocorrelation exists in the noise term N_t and (2) heteroscedastic residuals. The autocorrelation coefficient ρ of the residuals was 0.40 and the Durbin-Watson statistic d was 1.20. The correlation problem was solved by using an autoregressive model. $O_3(t)$ was transformed to $O_3(t) - \rho O_3(t - 1)$ and similarly all predictor variables x_t were transformed to $x_t - \rho x_{t-1}$ [*Chatterjee et al.*, 2000]. The model presumes N_t depends on its previous values: $N_t = \rho N_{t-1} + e_t$ where e_t is the new noise term after transformation. After one-lag transformation, the Durbin-Watson statistic d increased to 1.89 and ρ reduced to 0.01. The weighted least square method was continued to overcome unequal variances in the residuals. It is well known that ozone is more variable in winter than during the summer at high-latitude stations but in this case the seasonal difference was not obvious. It was assumed that different months have different residual variances. The 12 weighting factors C_j^2 for each month j were found by the ratio $\left[\sum_{i=1}^{11} e_i^2/11\right] / \left[\sum_{t=1}^{132} e_t^2/132\right]$. The transformed model is $\frac{y_{t,j}}{C_j} = \frac{b}{C_j} + \frac{m}{C_j} + \gamma_2\frac{x_{1t,j}}{C_j} + \ldots\gamma_9\frac{x_{1t,j}}{C_j} + \varepsilon_t$ and it is a no-intercept model.

[38] The results from six statistical runs are presented in Table 4.

[39] It is shown in Table 3 that the p-values of both the yearly averaged and 365 days running average time series satisfied the $\alpha = 0.05$ significance level and support a positive trend. The R^2 values were 0.39 and 0.32 respectively. When the seasonal cycle was treated as an explan-

Table 3. Linear Trend Analyses of TOMS, Brewer 115 and 61 Total Ozone Time Series[a]

	Trend m, DU Per Decade ± SD	R^2	p-Value
Brewer 115 Hong Kong (1995–2005)			
Reduced yearly averaged data	11.2 ± 4.6	0.394	0.039
365 days running average	9.6 ± 0.2	0.321	0.000
Brewer 61 Chengkung (1995–2005)			
Reduced yearly averaged data	4.4 ± 5.1	0.077	0.409
TOMS (1997–2005)			
Reduced yearly averaged data	−0.23 ± 0.38	0.050	0.563
365 days running average	−0.13 ± 0.02	0.012	0.000

[a]y = mx + b, R^2 = coefficient of determination.

Table 4. Multiple Linear Regression Results From Statistical Runs Calculated From Equation (1)

Run	Explanatory Variables Used	R^2	Ozone Trend m: DU Per Decade ± SD	γ_2 to γ_8	p-Values of γ_i
1	all seven variables not used	0.846	6.76 ± 2.78	trend	0.016
2	T50	0.858	6.60 ± 2.73	trend	0.017
				T50 1.10 ± 0.44	0.014
3	T50	0.869	7.39 ± 2.67	trend	0.006
	QBO			T50 1.32 ± 0.43	0.003
				QBO 0.30 ± 0.11	0.006
4	T50	0.871	8.29 ± 2.71	trend	0.003
	QBO			T50 1.22 ± 0.44	0.006
	AOD			QBO 0.27 ± 0.11	0.017
				AOD −804 ± 510	0.117
5	T50	0.880	8.61 ± 2.62	trend	0.001
	QBO			T50 1.33 ± 0.42	0.002
	AOD			QBO 0.21 ± 0.11	0.055
	T100			AOD −1100 ± 499	0.029
	T300			T100 0.88 ± 0.42	0.039
				T300 −0.65 ± 0.47	0.165
6	T50	0.881	9.00 ± 2.66	trend	0.001
	QBO			T50 1.44 ± 0.43	0.001
	AOD			QBO 0.25 ± 0.11	0.026
	T100			AOD −1106 ± 507	0.031
	T300			T100 1.12 ± 0.46	0.016
	sunspot			T300 −0.68 ± 0.47	0.148
	SOI			Sunspot −0.02 ± 0.03	0.629
				SOI 0.55 ± 0.36	0.126

atory variable, the R^2 improve to 0.85 (run 1 in Table 4); that is the trend and the seasonal cycle already explained 85% of the variance in the total ozone time series. The addition of all seven explanatory variables improved the R^2 to 0.88. Out of the seven explanatory variables, the upper temperature at 50 mbar and the AOD are the two most influential parameters. In contrast, there is no evidence showing that the sunspot activities and El Niño events have any influence on the total ozone column. A speculated explanation is that the 11-year time series is too short for the 11-year solar cycle to exert a discernible influence. Similarly, there has been no strong El Niño episode since 1997.

[40] In summary, a small statistically significant increasing trend in total ozone has been observed by the Brewer 115. This increasing trend was also observed by the Brewer 61 but to an even lower extent. Furthermore, the satellite data cannot be used for trend analysis. Thus the evidence for a long-term increase in total ozone in the subtropical region is not strong. Actually, the standard deviations in establishing the trends for the Brewers are quite large (∼50–100%). In fact, the positive trend is the resultant of two distinct types of years: 1995, 1997–1999, and 2003 with relatively low ozone values, and the remaining years (1996, 2000, 2001–2005) with higher ozone. This means that depending on how many years one takes into account one can have different trend and this is why the standard deviation is so high. *Svendby and Dahlback* [2002], have emphasized that even 20 years is still too short a period to allow conclusive statements about long-term ozone trends. On the other hand,

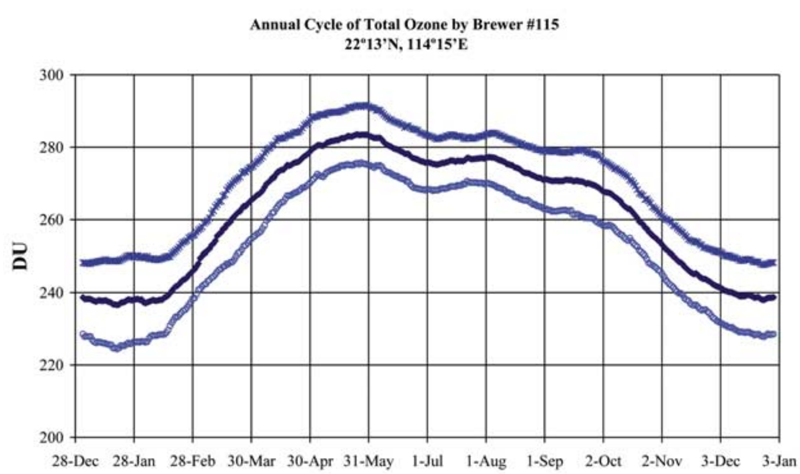

Figure 7. Eleven years averaged annual cycle of total ozone by Brewer 11.

the converse can be confidently stated, that there is no total ozone depletion at 22°N at least in this observation period.

9. Annual Cycle of Total Ozone at 22°N

[41] Since the trend of an increasing total ozone over Hong Kong is very small, it is possible to construct an annual cycle for reference in forecasting operations. The 11-year averaged annual cycle of total ozone observed by the Brewer 115 is shown in Figure 7. The total ozone shows a mild seasonal variation between 220 DU and 300 DU. The mean is 263 DU. In December and January, the total ozone remained at a low value of about 230 DU. Total ozone started to rise in February until it reached a maximum of about 290 DU in May. It remained high in summer at about 270 DU. It started to fall in October and reached a minimum in winter. The averaged annual cycle is quite precise, the 95% confidence interval is about 10 to 20 DU. The amplitude of the QBO ozone anomalies is 10 to 20 DU which is 4 to 8% of 263 DU. This annual cycle could be used as a reference for ozone forecasting which is a prerequisite for UV forecasting.

10. Conclusions

[42] The original Brewer data were recalculated to account for the changes in the SL ratios. The final data set agrees very well with the satellite data, and the Chengkung Brewer data within an expected deviation. Despite considerable shifts in sensitivity, high-quality total ozone observations can still be achieved so long as the equipment is well maintained and regularly calibrated, and appropriate corrections applied to the data. For total ozone long-term monitoring, ground-based observations achieve higher precision and good data capture rates when compared with satellite data. Ground-based stations are thus indispensable platforms complementing space-based and balloon-based remote sensing. The experience on maintenance, data reevaluation and trend analysis of a Brewer Spectrophotometer are documented and shared for future reference.

[43] **Acknowledgments.** This project was supported by the Hong Kong Research Grants Council (grant B-Q682) and PolyU internal grant (grant S023). Special thanks are due to the John Barnes of the Mauna Loa Observatory for the personal communication of stratospheric aerosol optical depth data. We thank the following institutions for making data publicly available: (1) NASA Goddard Space Flight Center for TOMS data, (2) Central Weather Bureau for Chengkung data, (3) Climate Prediction Center, NOAA, for QBO index, (4) Solar Influence Data Analysis Center, Belgium, for sunspot data, (5) Climate and Global Dynamics, NCAR, for SOI index, and (6) Hong Kong Observatory for Ozonesonde data. We thank Martin Stanek of the Solar and Ozone Observatory, Czech Hydrometeorological Institute, for the provision of Brewer software to Brewer users.

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