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Intercomparison of the NIMBUS 7 SBUV/TOMS Total Ozone Data Sets With Dobson and M83 Results

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Total ozone measurements made by the SBUV and TOMS instruments on the NIMBUS 7 spacecraft are compared with measurements from 62 Dobson and 18 M83 stations. On the average, TOMS ozone values are 6.6% smaller than Dobson and 9.1% smaller than M83; corresponding SBUV biases are 8.3% and 11.3%, respectively. Use of SBUV or TOMS as a transfer standard reveals an apparent bias between the Dobson and M83 networks of 3.0 or 2.5%, respectively. Major portion of the bias between the space and ground measurements is attributed to uncertainties in the ozone absorption coefficients used in processing the measurements. Precision of total ozone retrieved from either the SBUV or the TOMS instrument is shown to be better than 2%, which is comparable to that of a well run Dobson station. Precision of a typical Dobson measurement is estimated at about 2% and that of an M83 measurement is estimated to be 4%. Apparent station to station biases of up to 11.2% for Dobson and 15.5% for M83 are shown. Daily and seasonal variations of ozone measured by the satellite over selected Dobson stations are found to be in excellent agreement with the ground observations. An instrumental drift is found in the SBUV/TOMS total ozone measurements that is essentially linear with time and has a rate of 0.5% per year for the first year of data. A better understanding of instrument changes is expected to help reduce any further drift.

1. INTRODUCTION

The Total Ozone Mapping Spectrometer (TOMS) and the Solar Backscattered Ultraviolet (SBUV) instrument aboard the NIMBUS 7 satellite make high precision total ozone measurements using the backscattered ultraviolet (BUV) technique [*Dave and Mateer*, 1967]. From a nearly polar, sun-synchronous orbit, TOMS scans in a plane perpendicular to the orbital plane to produce daily global ozone measurements at between 50 and 150 km resolution [*Heath et al.*, 1978]. SBUV measures ozone with 200 km resolution in the nadir direction only. It has additional wavelength bands to measure vertical ozone profiles [*Heath et al.*, 1978]. SBUV and TOMS measure total ozone in a similar manner using nearly identical wavelength bands. Their total ozone retrieval algorithms [*Fleig et al.*, 1982*a*, *b*] were developed from the NIMBUS 4 BUV total ozone algorithm [*Klenk et al.*, 1982] and are identical except that the TOMS algorithm accounts for the variation in the scattered and absorbed ultraviolet radiation as a function of view angle.

Two years of SBUV/TOMS data spanning the period November 1978 to October 1980 have been processed and compared with ground-based ozone measurements made at 62 Dobson and 18 M83 ozone stations. Comparisons between satellite ozone measurements and ground-based ozone measurements are useful for several reasons. They provide a check on the satellite's ozone retrieval technique, they allow estimating the systematic and random errors in the satellite and the ground station retrieval techniques, and they allow the use of the satellite as a standard for intercomparing the performance of ground stations. The ground-based ozone data used for these studies were obtained on tape from the Atmospheric Environment Service, Downsview, Ontario, and includes corrections published through volume 22, number 2 (March/April 1981) of *Ozone Data for the World* [*Atmospheric Environment Service*, 1981]. The ground station data can be more accurately compared to the TOMS data than the SBUV data owing to the high spatial resolution and daily global coverage of TOMS. For this reason the TOMS comparisons have been much more extensively studied and will be the primary subject of this paper.

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2. COMPARISON TECHNIQUES

In matching TOMS ozone data to a ground station, the TOMS sample closest to the station location was used. The separation between the center of the TOMS field of view (FOV) and the ground station averaged about 0.2 arc degrees, with the station almost always within the TOMS FOV. The time difference was found to average about 1 hour. For SBUV, where the closest measurement can be up to 13° in longitude away from the ground station, SBUV measurements on each side of the ground station and on the same day as the ground measurement were interpolated to the ground station longitude using the inverse squares of the separation as weighting functions. The separation in latitude was at most 1°.

For each matched pair of satellite/ground station measurement a difference was computed as a percent of the ground station value. A daily time series of such differences obtained from one year of TOMS and Dobson data (November 1978 to October 1979) is plotted for Arosa in Figure 1. A negative percent difference means that the TOMS ozone was less than Dobson. Figure 1 shows a negative bias of approximately −4% indicating that the TOMS retrieved ozone values are systematically less than the Arosa Dobson values. Such behavior is typical for TOMS and SBUV comparisons with the other ground stations. Similar plots for the other stations have been published by AES, Canada [*Fleig et al.*, 1982*c*]. For each

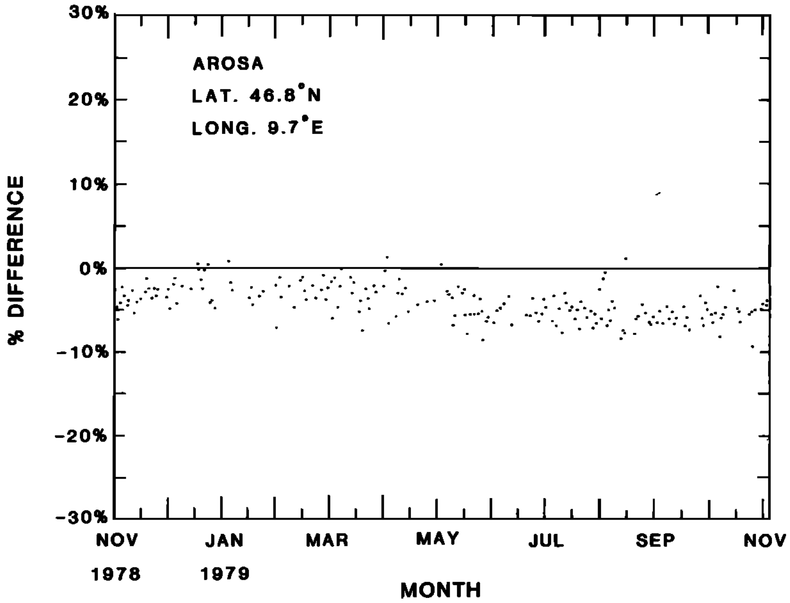

Fig. 1. Percent difference between TOMS ozone and Dobson ozone measured at Arosa versus time during the first year of TOMS operation. All Arosa measurements are 00 code measurements.

station, the daily percent differences were averaged to obtain the "percent bias" between the satellite and the ground station. A correction was then applied to this bias to account for the ozone that may be present between the station altitude and the average terrain altitude in the satellite field of view. On the basis of ozonesonde data we estimate that roughly 0.8% of the total ozone is present in each kilometer of the lower troposphere. Using this value we find that of the 80 stations, only 11, shown in Table 1, require corrections exceeding 0.5%. Mauna Loa, located on a narrow mountain in the Pacific, requires the largest bias correction of −2.7%.

Percent biases between TOMS and 62 Dobson stations are listed in Table 2; a similar set of comparisons for 18 M83 stations are given in Table 3. The stations are arranged by latitude starting at 90°S and moving northward. Results are given separately for Dobson codes 00 and for all the Dobson codes combined. Dobson stations assign 00 code to a measurement made by using the AD double pair in the direct sun viewing mode. This viewing mode provides the most reliable Dobson ozone measurement and is preferred unless the

TABLE 1. Stations in the Ground Ozone Network With Bias Adjustments Due to Terrain Height Exceeding 0.5%

Station	Latitude	Longitude	Adjustment to Bias, %
Alma-Alta	43.2	76.9	0.6
Kodaikanal	10.2	77.5	−1.4
Mount Abu	24.6	72.7	−0.8
Mauna Loa Observatory	19.5	−155.6	−2.7
Arosa	46.8	9.7	−0.9
Mont-Louis	42.5	2.1	−0.6
Ashkhabad	38.0	58.3	0.7
Syowa	−69.0	39.6	0.8
Huancayo	−12.0	−75.3	−1.1
Mexico City	19.3	−99.2	−0.7
Sestola	44.2	10.8	−0.7

A negative adjustment effectively decreases the TOMS ozone value in the computation of the bias.

sun is obscured by clouds. Wavelength pairs other than AD are often used by high latitude stations for low solar elevation angle measurements. TOMS data used in these comparisons were not edited in any manner and include all available TOMS measurements taken over a station in the first year of instrument operation (November 1978 through October 1979).

TOMS/station biases given in Tables 2 and 3 represent systematic errors in the two measurement schemes. A negative bias indicates that, on the average, TOMS ozone values are lower than the station values. The two tables also show the random errors in the comparisons as represented by the standard deviations of TOMS/station differences. In the following section we will examine the implication of these differences in understanding the quality of the total ozone data sets.

3. Analysis of Comparison Statistics

An overall summary of comparison of the two satellite instruments with the two types of ground based instruments is given in Table 4. Column 4 of this table gives the unweighted average of the individual station biases followed by an uncertainty estimate (one standard error) obtained by dividing the interstation variability of the biases (given in column 5) by the square root of the number of stations. Both SBUV and TOMS measure significantly smaller ozone amounts compared to those measured from the ground. Recently it has become evident that a substantial part of the satellite/ground bias is due to inconsistencies in the ozone absorption coefficients used by both the satellite and the ground station retrieval algorithms. All four types of instruments being compared here measure the absorption of solar ultraviolet radiation by ozone; however, their wavelength bands are different, and they do not use a common ozone absorption spectrum. The ozone absorption coefficient in effect determines a scale for measuring ozone; the one used by SBUV/TOMS is based on *Inn and Tanaka*'s [1959] room temperature measurements, converted to −44° using *Vigroux* [1953] temperature coefficients [*Klenk*, 1980]. Dobson total ozone measurements are based exclusively on the values derived by *Vigroux* [1967]. As discussed in a recent WMO report [*World Meteorological Organization*, 1980] the

TABLE 2. TOMS/Dobson Comparison Statistics

			00 Codes			All Codes		
Station	Latitude	Longitude	Number of Matches	Bias, %	Standard Deviation of Differences, %	Number of Matches	Bias, %	Standard Deviation of Differences, %
Amundsen-Scott	−90.0	−24.8	47	−4.0	2.2	114	−3.9	2.8
Syowa	−69.0	39.6	69	−1.8	2.6	151	−1.9	2.8
Macquarie Island	−54.5	159.0	41	−3.2	3.2	237	−5.2	6.0
Invercargill	−46.4	168.3	85	−4.7	3.0	233	−6.0	4.6
Hobart	−42.9	147.3	51	0.5	5.9	234	−0.8	5.9
Aspendale	−38.0	145.1	156	−7.0	2.0	286	−7.0	2.3
Buenos Aires	−34.6	−58.5	114	−5.2	3.8	127	−5.4	3.7
Perth	−31.9	115.8	209	−6.3	1.7	299	−6.7	2.2
Brisbane	−27.5	153.0	120	−5.7	2.5	277	−4.6	3.7
Cairns	−16.9	145.7	151	−7.7	3.7	267	−6.5	3.9
St. Helena	−15.9	−5.6	83	−6.1	2.0	256	−6.0	2.5
Tuituila Island	−14.3	−170.6	170	−7.3	2.1	235	−7.3	2.8
Huancayo	−12.0	−75.3	236	−10.0	1.7	256	−10.0	1.9
Mahe. Seychelles Island	−4.7	55.5	168	−9.7	1.5	273	−10.6	2.2
Singapore	1.3	103.9	192	−8.6	1.9	192	−8.6	1.9
Kodaikanal	10.2	77.5	36	−8.5	1.3	175	−8.6	1.5
Manila	14.6	121.1	144	−7.2	3.0	190	−6.7	3.3
Poona	18.5	73.5	155	−4.3	1.4	235	−3.8	2.4
Mexico City	19.3	−99.2	152	−10.7	2.1	157	−10.7	2.1
Mauna Loa Observatory	19.5	−155.6	163	−5.5	1.7	200	−5.3	2.0
Mount Abu	24.6	72.7	157	−5.6	1.8	270	−5.6	1.8
Varanasi	25.4	82.9	53	−5.8	2.0	234	−6.8	2.1
Okinawaa	26.2	127.7	95	−5.9	1.8	275	−5.9	2.2
New Delhi	28.6	77.2	175	−5.8	1.6	287	−5.8	1.8
Cairo	30.1	31.3	134	−7.5	1.9	301	−8.0	2.2
Quetta	30.2	66.9	252	−6.4	4.3	260	−6.3	4.3
Tallahassee	30.4	−84.3	102	−8.2	2.8	160	−8.4	3.4
Kagoshima	31.6	130.6	74	−2.6	2.6	235	−4.0	3.2
White Sands	32.2	−106.4	216	−8.1	2.4	237	−8.3	2.4
Srinagar	34.1	74.8	96	−8.3	2.7	243	−8.3	2.6
Tateno	36.0	140.1	130	−5.9	2.3	290	−6.5	2.9
Nashville	36.3	−86.6	123	−9.4	2.9	161	−9.4	3.0
Wallops Island	37.8	−75.5	194	−5.6	1.8	256	−6.0	3.0
Lisbon	38.8	−9.1	84	−4.1	9.0	108	−4.4	9.0
Cagliari-Elmas	39.3	9.0	242	−3.9	2.9	296	−3.8	3.3
Shiangher	39.8	117.0	133	−6.2	2.8	134	−6.2	2.8
Boulder	40.0	−105.3	135	−7.5	2.5	200	−7.7	3.4
Vigna Di Valle	42.1	12.2	246	−7.2	2.7	290	−7.1	3.3
Mont-Louis	42.5	2.1	193	−8.8	3.0	193	−8.8	3.0
Sapporo	43.0	141.3	108	−4.3	2.2	280	−4.7	3.1
Toronto	43.7	−79.2	88	−7.2	2.2	219	−9.5	5.2
Sestola	44.2	10.8	160	−7.4	2.7	261	−7.7	4.0
Biscarrosse	44.4	−1.2	241	−6.0	1.9	293	−6.0	2.1
Bismarck	46.8	−100.8	123	−6.0	3.2	257	−6.3	3.2
Arosa	46.8	9.7	221	−4.3	2.6	221	−4.3	2.6
Caribou	46.9	−68.0	145	−6.2	2.5	268	−6.8	4.1
Hohenpeissenberg	47.8	11.0	209	−4.0	2.0	210	−4.0	2.0
Hradec Kralove	50.2	15.8	124	−5.3	3.3	282	−4.5	4.1
Uccle	50.8	4.3	84	−8.9	2.7	193	−9.2	2.9
Belsk	50.8	20.8	92	−8.8	2.4	274	−8.6	3.7
Bracknell	51.4	0.8	52	−7.7	2.9	207	−8.4	4.6
Potsdam	52.4	13.0	113	−6.5	2.2	260	−5.7	4.0
Goose	53.3	−60.4	22	−8.2	3.5	322	−8.7	4.2
Ed. Stony Plain	53.5	−114.1	71	−7.7	1.4	316	−7.7	3.0
Aarhus	56.2	10.2	0	—	—	263	−3.9	14.2
Churchill	58.8	−94.1	39	−6.5	2.3	317	−4.8	7.7
Oslo	59.9	10.7	20	−9.3	1.4	205	−8.8	4.8
Leningrad/Voeidovo	60.0	30.3	17	−7.8	1.7	237	−9.5	4.2
Lerwick	60.1	−1.2	48	−7.8	2.6	228	−8.4	5.8
Reykjavik	64.1	−21.9	88	−6.6	2.5	209	−6.1	3.2
Barrow	71.2	−156.4	52	−5.0	2.4	162	−6.6	4.7
Resolute	74.7	−95.0	46	−5.3	2.7	196	−7.7	4.9

two values of absorption cross sections differ significantly and are most likely the cause of the bias between the satellite and the Dobson ozone measurements. If the recent measurements made at the National Bureau of Standards [*Bass and Paur*, 1982] are applied to both the satellite and Dobson measurements, SBUV/Dobson bias would reduce to less than 1%. TOMS/Dobson bias would be larger but would still be less than 3%.

TABLE 3. TOMS/M83 Statistics

Station	Latitude	Longitude	Number of Matches	Bias, %	Standard Deviation of Differences, %
Ashkhabad	38.0	58.3	258	−5.4	3.6
Dushanbe	38.6	68.8	260	−7.8	2.9
Vladivostok	43.1	131.9	292	0.2	6.4
Alma-Alta	43.2	76.9	295	−10.5	4.8
Odessa	46.5	30.6	237	−8.9	3.9
Bolshaya Elan	46.9	142.7	250	−9.4	4.9
Kiev	50.4	30.4	224	−11.2	4.9
Irkutsk	52.3	104.3	268	−11.2	4.2
Kuibyshev	53.3	50.4	211	−11.8	5.3
Omsk	54.9	73.4	267	−8.2	4.6
Moscow	55.8	37.6	162	−10.2	4.6
Sverdlovsk	56.8	60.6	230	−10.6	4.0
Riga	57.0	24.1	211	9.9	4.8
Nagaevo	59.6	150.8	159	−9.7	6.9
Yakutsk	62.1	129.8	214	−5.6	10.0
Murmansk	69.0	33.0	191	−11.0	4.0
Dikson Island	73.5	80.2	125	−6.7	7.2
Heiss Island	80.6	58.0	117	−15.3	7.4

Table 4 also shows that, in addition to an overall bias between satellite and ground ozone values, there exists a smaller but statistically significant bias between the two satellite instruments as well as between the two types of ground instruments. Using Dobson as the transfer standard, TOMS ozone is found to be 1.7% higher than SBUV. As both SBUV and TOMS use similar wavelengths, this difference cannot be attributed to ozone cross-section errors and must therefore be either instrumental or algorithmic. Although the two instruments use conceptually similar observational techniques, the off-nadir scanning feature of TOMS introduces complexity in both the algorithm and the instrument design. Direct comparisons between SBUV and TOMS nadir measurements show that the two do not measure identical radiances and their total ozone differ in spite of the fact that their algorithms become similar for nadir viewing. TOMS instrument was designed primarily for measuring ozone at a very high spatial and temporal resolution and does not contain all the calibration features available for SBUV. Therefore, the SBUV/Dobson bias is probably more representative of the true bias in their respective ozone scales.

Using the satellite as a transfer standard, a bias of about 3% is found between the two types of ground-based instruments, with M83 higher than Dobson. Although errors in the M83 retrieval technique have long been known and are well documented [*Parsons et al.*, 1982], these intercomparisons provide the first quantitative estimate of their bias with Dobson under their actual operational environment. We suggest that these results be used in correcting the M83 ozone measurements before integrating them with the Dobson measurements as a part of the global ozone monitoring network.

Column 5 of Table 4 provides a measure of the interstation variability of bias among the various ground-based stations. Direct intercomparison between selected Dobson instruments have often shown large calibration-related errors [*Komhyr*, 1980], and it seems likely that most of the observed interstation variability can be attributed to such errors. Nevertheless, it is useful to examine whether other algorithm-related errors could contribute to such variability. Both Dobson and satellite retrieval schemes become less accurate at higher latitudes where average solar elevations are lower, signals are weaker, and observing conditions are highly variable. To examine whether such an effect may be contributing to the variability of biases, we show them as a function of station latitude in Figure 2. One observes that stations at similar latitudes differ from each other just about as much as they differ with stations at other latitudes. Some clustering of points in low latitudes does occur; the overall bias for the 11 low latitude stations (25°S to 25°N) is −7.6%, compared to the network average bias of −6.4%. Given the statistical uncertainty introduced by the interstation variability of bias, it cannot be determined whether the increase in bias for the low latitude stations is algorithmic or is simply a chance coincidence.

A bias between two stations could, however, occur if one of them is located near a large urban area with frequent episodes

TABLE 4. Overall Statistics

Type of Comparison	Total Number of Matches	Number of Stations	Satellite/ Ground Bias (Network AVG)	Interstation Variability of Bias (r.m.s.)	Standard Deviation of Satellite/ Station Differences (Median)
TOMS/Dobson(00)	7539	61	-6.4 ± 0.3%	2.1%	2.4%
TOMS/Dobson(ALL)	14504	62	-6.6 ± 0.3	2.1	3.1
SBUV/Dobson(ALL)	5749	58	-8.3 ± 0.3	2.2	4.4
TOMS/M83(ALL)	3982	18	-9.1 ± 0.8	3.3	4.8
SBUV/M83(ALL)	1992	17	-11.3 ± 0.7	2.9	5.9

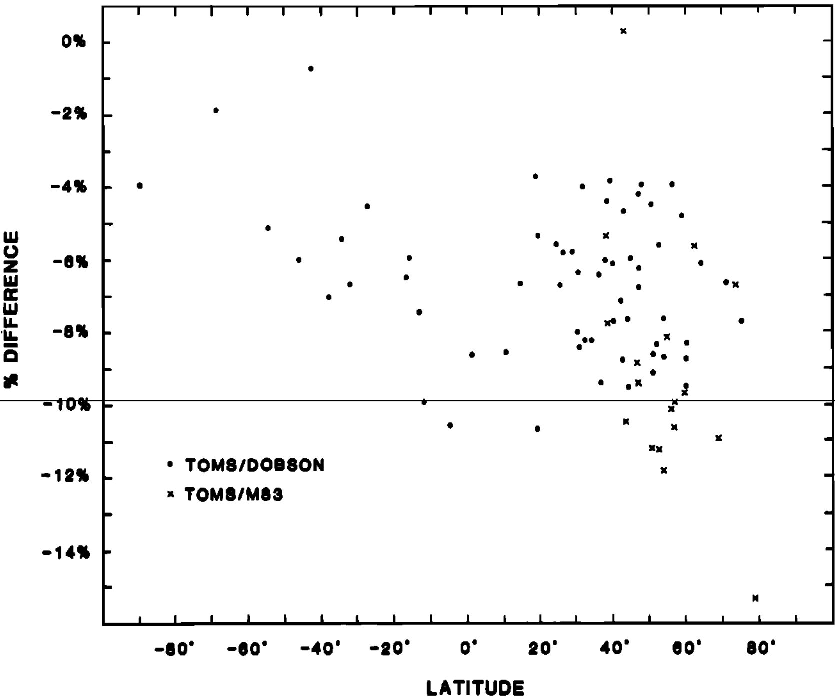

Fig. 2. Average percent difference (bias) between TOMS and the 62 Dobson stations (dots) and the 18 M83 stations (crosses) plotted versus station latitude.

of photochemical pollution. Such errors in Dobson measurements have been predicted by *Komhyr and Evans* [1980] and have been observed by *Evans et al.* [1981]. It has been suggested (C. L. Mateer, private communications, 1980) that persistence of such pollution over Mexico City may explain the difference in its bias with Mauna Loa and Poona.

Finally, one must consider the possibility that spatially varying errors may be present in SBUV/TOMS retrieval schemes. As pointed out by *Klenk et al.* [1982], the BUV technique is relatively insensitive to the ozone amount (and the pollution) present in the lower troposphere. The retrieval algorithm in effect depends on the standard ozone profiles to estimate lower tropospheric ozone amounts. The error introduced, however, is very small; typically, a 10% error in estimating tropospheric ozone may lead to 0.5% error in the total ozone. Although station to station differences of more than 50% in the yearly average tropospheric ozone density are being reported by balloonsondes, it appears that much of this difference is due to a bias between the two types of balloonsonde sensors currently in use operationally: the Brewer Mastsonde and the ECC Sonde. Using the ozonesonde data received from AES, Canada, we have compared the Garmisch-

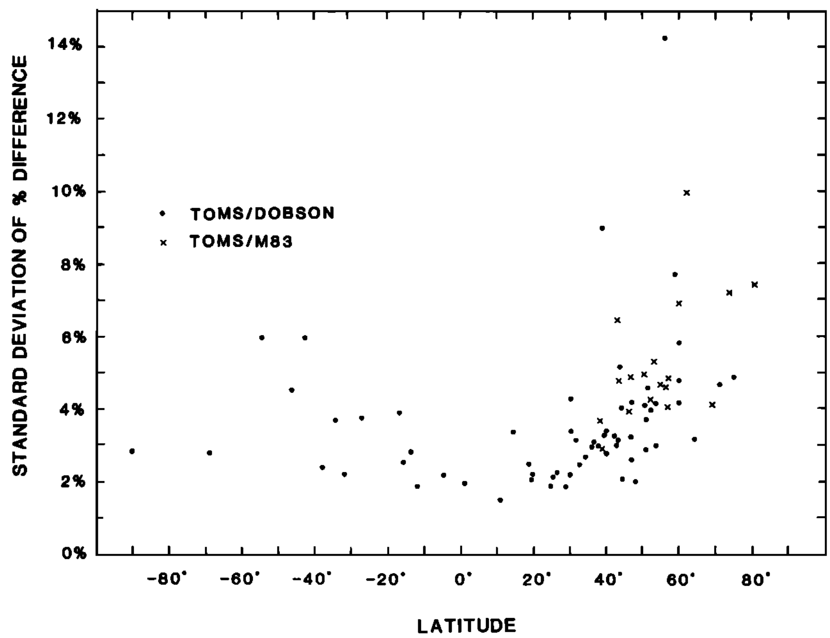

Fig. 3. The standard deviations of the difference for each Dobson station (dots) and for each M83 station (crosses) plotted versus station latitude.

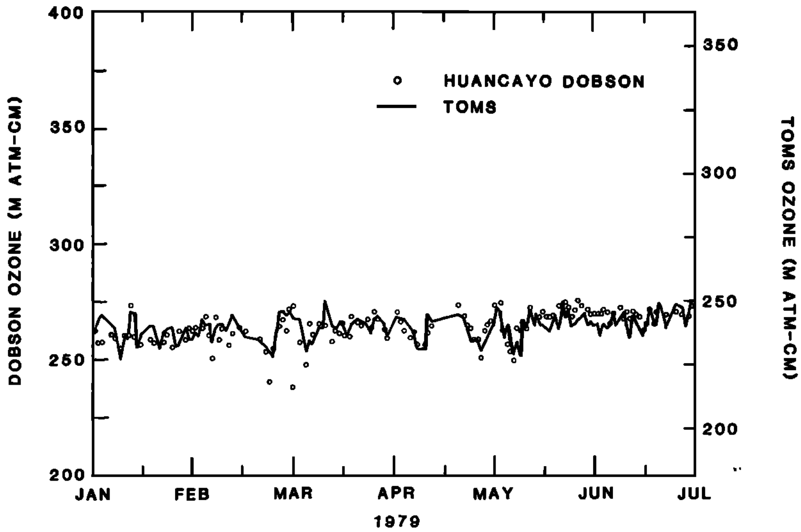

Fig. 4. Matched TOMS and Dobson ozone versus time for the Huancayo (12.0°S, 75.3°W) station. The scale used for TOMS ozone is shifted with respect to Dobson by 10% to remove the overall bias between the two.

Partenkirchen ECC's (49.5°N, 11.1°E) with the Hohenpeissenberg Mastsondes (47.8°N, 11.0°E) flown on the same day. On the basis of 25 matches in 1979, we find that the Garmisch-Partenkirchen ECC's measure 24% higher ozone on average than the Hohenpeissenberg Mastsondes between ground and 250 mbar. Since these two stations are less than 200 km apart, it is unlikely that these observed differences are due to a true systematic difference in their tropospheric ozone amounts. By comparison, tropospheric ozone amounts measured at the Hohenpeiseenberg Mastsonde station agree extremely well with a nearby Mastsonde station at Payerne (46.8°N, 7.0°E). Thus, it seems unlikely that systematic variations in tropospheric ozone could be the major cause of the interstation variability of bias between TOMS and the Dobson stations. Apart from this, we cannot, at present, identify errors in the SBUV/TOMS retrieval algorithm that will vary spatially, particularly with longitude.

Finally, to estimate the precision of the SBUV/TOMS ozone retrieval method, we look at the standard deviation of difference between the satellite and the station ozone amounts. This difference is caused by three random errors: satellite noise, station noise, and noise due to imperfect temporal and spatial coincidence in matching the two measurements. A plot of the standard deviations against station latitude, shown in Figure 3, shows considerable variation among stations at the same latitude. If we assume that the satellite noise and the coincidence noise does not vary with longitude, then the interstation variability of standard deviations will reflect variations in the quality of ozone measurements made by the various ground stations. Comparisons with 16 of the 62 Dobson stations show 00 code standard deviations of less than 2%. The median value of all station standard deviations are listed in the last column of Table 4. We can think of the medians as representing "typical values" of standard deviation of difference between each type of satellite measurement and station measurement. If we assume that a typical 00 code Dobson ozone measurement has a precision of 1% and that the coincidence noise is at least 1%, the estimated precision of TOMS must be better than 2%. The noise in all code measurements is larger, as expected. Most of this increase is likely due to a difference in the quality of the Dobson measurement for 00 code and all codes. Dobson stations use an empirically derived

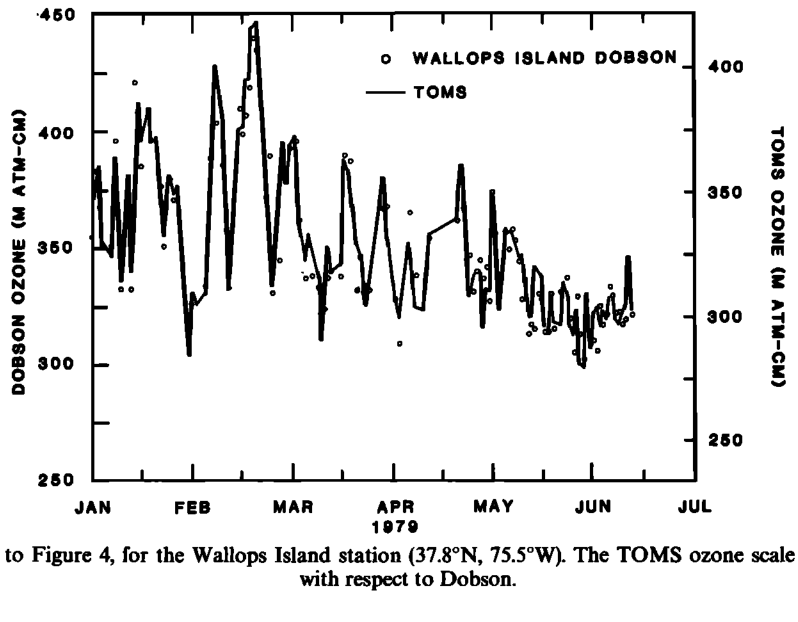

Fig. 5. Similar to Figure 4, for the Wallops Island station (37.8°N, 75.5°W). The TOMS ozone scale is shifted by 6.0% with respect to Dobson.

sky chart for their zenith sky measurements. Precision of ozone measurements made by using these charts under the presence of varying amounts of clouds has not been firmly established but has been shown to be significantly worse in comparison to the direct sun measurements [*Komhyr*, 1961; *Sullivan et al.*, 1961; *Kinisky et al.*, 1961]. Using the 2% precision estimate made for TOMS, we get roughly 2% as the precision of a typical Dobson all code measurement. Of course, this precision estimate will vary from station to station depending upon what percent of the station data is non 00 code and the applicability of the standard sky charts for that station. Detailed TOMS/Dobson comparison statistics for all the various Dobson codes has been compiled and is available from AES, Toronto, Canada [*Fleig et al.*, 1982c]. Using the 2% TOMS precision estimate we can also estimate that M83 stations have a typical precision of 4%, a value quite close to that obtained by direct intercomparison of a Dobson instrument with an M83 instrument at Wallops Island [*Parson et al.*, 1982]. Table 4 shows that the intercomparison noise for SBUV is much larger than for TOMS. This difference reflects the larger coincidence noise in matching an SBUV measurement to a Dobson measurement rather than any difference in the precision of SBUV and TOMS. Direct comparisons have been made between SBUV and TOMS for 2 weeks of data near the time of the vernal equinox in 1979. Each SBUV field of view (FOV) was matched with the weighted average of the appropriate TOMS FOV's. Along with an average bias between TOMS and SBUV, as already discussed, the comparisons showed a standard deviation of difference of only 1.2%, which is much smaller than the standard deviation of difference between TOMS and Dobson.

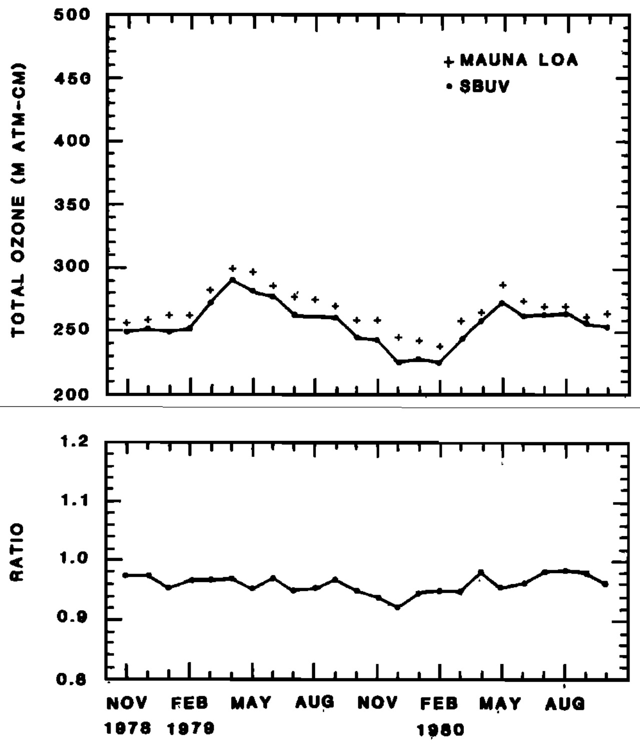

Fig. 7. Similar to Figure 6, for the Mauna Loa (19.5°N, 155.6°W) Dobson station.

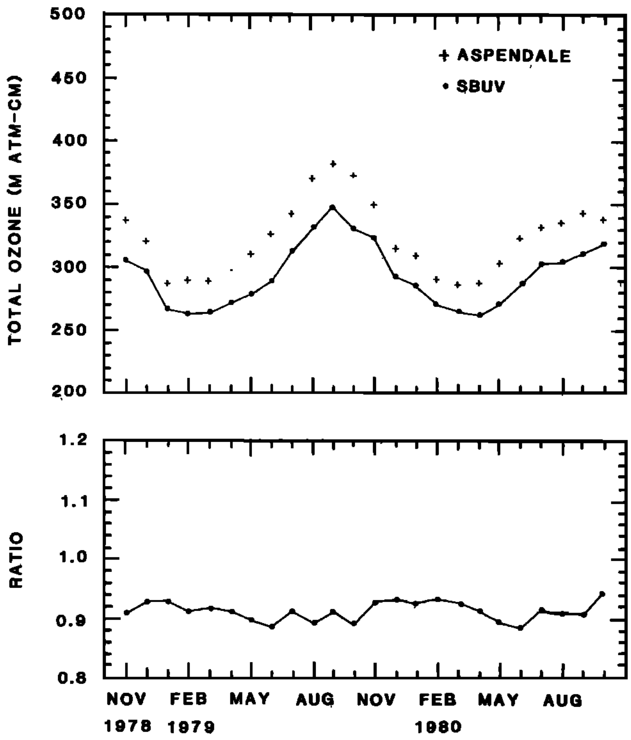

Fig. 6. Two year time series of monthly average ozone amounts for the Aspendale Dobson station (38.0°S, 145.1°E) compared to similarly averaged data from SBUV, measured in a box $\pm 1°$ in latitude and $\pm 15°$ in longitude centered over the station. The ratios of the monthly averages are also known.

4. Comparisons of Temporal Variations

SBUV and TOMS instruments were designed to measure changes in total ozone on a time scale varying from a day to several years. TOMS, owing to its high spatial resolution and complete global coverage, is ideally suited for studying day to day variations in ozone at any given location on the earth.

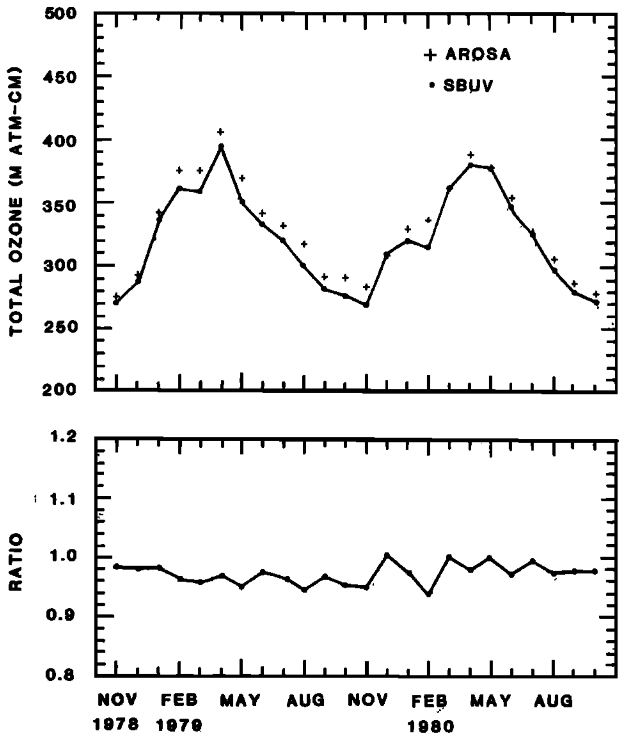

Fig. 8. Similar to Figure 6, for the Arosa Dobson station (46.8°N, 9.7°E).

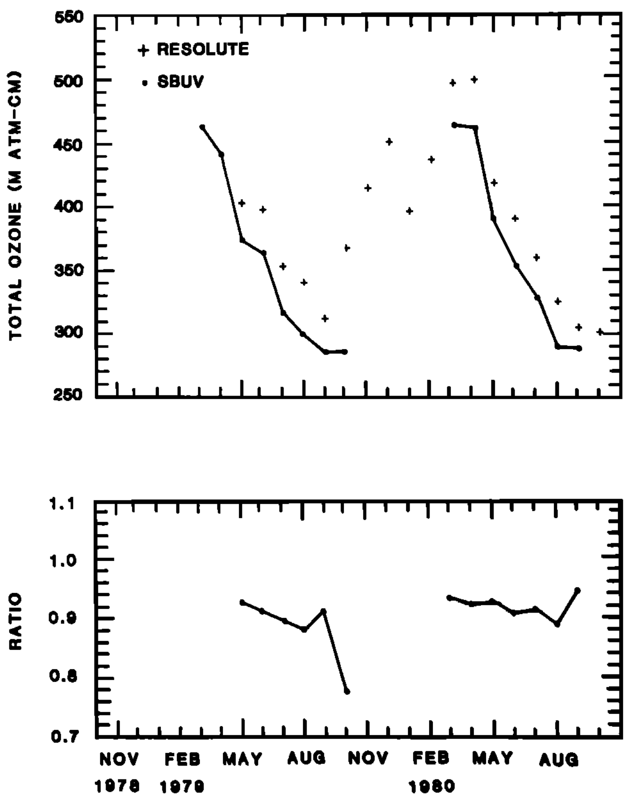

Fig. 9. Similar to Figure 6, for the Resolute Dobson station (74.7°N, 95.0°W).

This capability is demonstrated in Figures 4 and 5 where daily TOMS measurements taken during the first 6 months of 1979 over a Dobson station are compared with the measurements made by the station. Ozone variations observed over Huancayo are perhaps the smallest observed anywhere, yet the two measurements follow each other remarkably well. The Wallops Island station shows a typical mid-latitude ozone variation with changes of as much as 100 m atm cm in a period of 2–3 days. TOMS measurements follow these changes quite well showing consistency through the full range of ozone variations. It should be noted that these graphs use two different ozone scales to remove the overall bias between the two measurement techniques (the TOMS measurements were multiplied by 1.10 in Figure 4 and by 1.06 in Figure 5) to allow a better visual comparison between the two highly complex time series.

Given the large day to day variability, seasonal and secular changes in total ozone are more conveniently studied by using monthly averages. Since high spatial resolution is not required, SBUV data are well suited for such studies. Two year time series of monthly average ozone amounts observed by four Dobson stations are plotted in Figures 6–9. These stations were selected to represent typical variations of ozone observed over the globe. SBUV values are monthly averages of all measurements taken by the instrument in a box $\pm 1°$ in latitude and $\pm 15°$ in longitude centered over the stations. Typically, there is only one such measurement in any given day, although up to four measurements are possible when they occur near the corners of the box. Ratios of the monthly averages are also plotted with each graph. Apart from an overall bias, the two techniques show little systematic differences. At Aspendale, Mauna Loa, and Arosa, the two techniques show seasonal variations that agree even to minor details, and the ratios remain constant to within about 6%. Over Resolute (74.7°N latitude), SBUV cannot retrieve ozone in the winter months owing to very low sun elevation. In the nonwinter months, agreement is very good between the two techniques, except in October 1979 when the solar elevation is low and Resolute shows a large increase in total ozone not seen by SBUV.

Comparisons between the satellite and Dobson measurements are also useful for monitoring the long-term stability of both the satellite and the ground-based instruments. We have looked for drifts in the TOMS/Dobson biases using the first two years of TOMS data (November 1978 to October 1980) and the 53 Dobson stations that operated continually during this time period. Averaging the TOMS/station drifts obtained from these stations, we find that the TOMS ozone increased from the first year to the second year (with respected to Dobson) by $0.34 \pm 0.17\%$ (1σ). Although this change is barely significant at the 95% confidence level, there are reasons to believe that a small drift indeed is present in the TOMS and

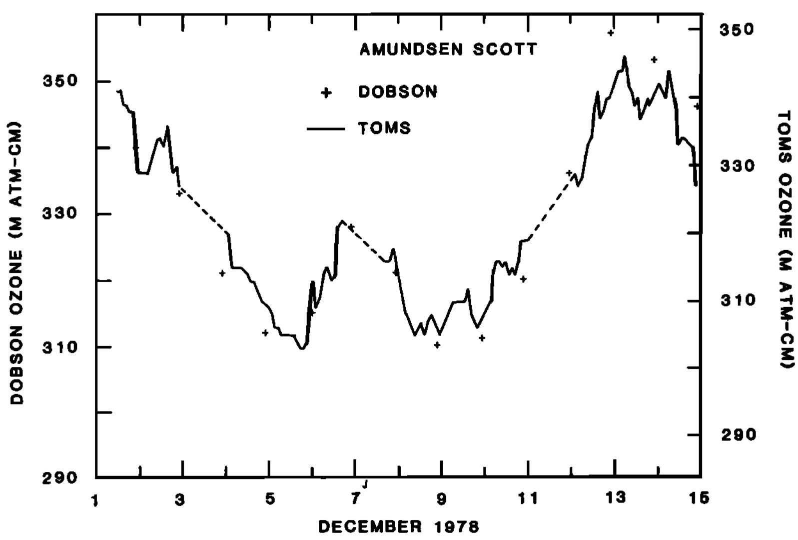

Fig. 10. TOMS ozone data taken over the south pole every orbit during December 1978 is shown with connected lines, with missing orbits shown as dashed lines. The daily Dobson measurements made at the south polar station Amundsen Scott are also shown.

SBUV data. On the basis of an independent analysis of the instruments calibration [*Fleig et al.*, 1982*a*, Addendum] it has been determined that the SBUV/TOMS total ozone began drifting downward at the rate of about 0.5% per year immediately after launch, owing to a wavelength dependent degradation of the aluminum diffusing plate used to monitor the solar flux. Before processing the second year data a technique was developed to monitor and correct most of this instrumental drift; therefore, the second year ozone drift should be less than 0.5%/year.

In the polar regions there is considerable overlap of the TOMS fields of view from one orbit to the next. When a pole is sunlit, TOMS takes an ozone measurement every 100 min, and these can be used to study short-term ozone variations. To show a typical such variation, TOMS data taken over the south pole during a 15-day period in December 1978 are shown in Figure 10. Also shown are the once a day measurements made by the Dobson instrument located at the south polar station Amundsen-Scott. Though one observes considerable variability in TOMS ozone during the day, the measurements agree well whenever they are compared with the temporally coincident Dobson measurements.

5. Summary and Conclusions

We have conducted a detailed comparison between the SBUV/TOMS total ozone data with those measured by the two types of operational ground-based ozone monitoring instruments: the Dobson spectrophotometer and the M83 filter photometer. Results show that the satellite ozone values are consistently smaller than those measured by the stations; most of this difference is likely due to an error in the currently accepted ozone absorption cross sections at ultraviolet wavelengths. Apart from this overall bias, which can be easily corrected and is of no consequence to studies of the dynamical behavior of ozone, Dobson derived ozone amounts agree extremely well with those derived from either of the two satellite instruments. Precision of TOMS measurements has been estimated to be better than 2% under all weather conditions, and no seasonally or spatially varying systematic errors have been detected in either data set. We note that the TOMS instrument is producing daily global ozone maps with between 50 and 150 km. resolution; each measurement on this map has accuracy and precision comparable to the best run stations in the Dobson network. Long-term stability of the ozone derived by the two instruments is expected to be better than 0.5% per year and will be monitored by similar comparisons with Dobson as more TOMS data become available. By the end of October 1982, SBUV and TOMS had completed 4 years of continuous ozone monitoring. They continue to operate satisfactorily at the time of this writing.

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