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The 1998-2000 SHADOZ (Southern Hemisphere ADditional Ozonesondes) Tropical Ozone Climatology: Comparison with TOMS and Ground-based Measurements

SHADOZ Team Author List
c/o Anne M. Thompson, NASA-Goddard Space Flight Center, Lab. for Atmospheres
Greenbelt, Maryland 20771 USA; thompson@gator1.gsfc.nasa.gov

Abstract: A network of 10 southern hemisphere tropical and subtropical stations, designated the Southern Hemisphere ADditional OZonesondes (SHADOZ) project and established from operational sites, provided over 1000 ozone profiles during the period 1998-2000. Balloon-borne electrochemical concentration cell (ECC) ozonesondes, combined with standard radiosondes for pressure, temperature and relative humidity measurements, collected profiles in the troposphere and lower- to mid-stratosphere at: Ascension Island; Nairobi, Kenya; Irene, South Africa; Réunion Island; Watukosek, Java; Fiji; Tahiti; American Samoa; San Cristobal, Galapagos; Natal, Brazil. The archived data are available to the community at: <http://code916.gsfc.nasa.gov/Data_services/shadoz>. SHADOZ supports studies of regional and global patterns in tropical ozone. In this paper, uncertainties and accuracies within the SHADOZ ozone data set are evaluated by analyzing: (1) imprecisions in individual profiles and in methods of extrapolating ozone above balloon burst; (2) comparisons of column-integrated total ozone from sondes with total ozone from the Earth-Probe/TOMS (Total Ozone Mapping Spectrometer) satellite and ground-based instruments; (3) possible biases from station-to-station due to variations in ozonesonde characteristics. The key results are: (1) Ozonesonde precision is 5%; (2) Integrated total ozone column amounts from the sondes are in good agreement (usually to within 5%) with independent measurements from ground-based instruments at five SHADOZ sites and with overpass measurements from the TOMS satellite (version 7 data). (3) Systematic variations in TOMS-sonde offsets and in ground-based-sonde offsets from station to station reflect biases in sonde technique as well as in satellite retrieval. Both stratospheric and tropospheric parts of the profile are affected. (4) There is evidence for a zonal wave-one pattern in tropical total and tropospheric ozone, but not in stratospheric ozone.

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The 1998-2000 SHADOZ (Southern Hemisphere ADditional Ozonesondes) Tropical Ozone Climatology: Comparison with TOMS and Ground-based Measurements

By Anne M. Thompson, Jacquelyn C. Witte (SSAI), Richard D. McPeters
NASA/Goddard, Atmospheric Chemistry & Dynamics Branch
Samuel J. Oltmans, Francis J. Schmidlin, Jennifer A. Logan, Masatomo Fujiwara, Volker W. J. H. Kirchhoff, Françoise Posny, G. J. R. Coetzee, Bruno Hoegger, Shuji Kawakami, Toshihiro Ogawa, Bryan J. Johnson, Holger Vömel, Gordon Labow

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In this first archival paper for the SHADOZ project, the sites and Co-Investigators (all are co-authors) are listed and characteristics of the data archive,<http://code916. gsfc.nasa.gov/ Data_ services/shadoz>, are described. SHADOZ is a network of 10 southern hemisphere tropical and subtropical stations that provided over 1000 ozone, temperature and relative humidity profiles (from surface to 30-35 km) during the period 1998-2000. Balloon-borne electrochemical concentration cell (ECC) ozone instrumentation was used with standard radiosondes at: Ascension Island; Nairobi, Kenya; Irene, South Africa; Réunion Island; Watukosek, Java; Fiji; Tahiti; American Samoa; San Cristobal, Galapagos; Natal, Brazil. This paper presents an evaluation of uncertainties and accuracy in the SHADOZ ozone data set. Specific analyses shown are (1) imprecisions in individual profiles and (2) biases and site-to-site variations in ozonesonde technique and instrumentation. The key results are: (A) Integrated total ozone column amounts from the sondes agree with overpassing TOMS measurements of total (and tropospheric) ozone. (B) Sonde total ozone agrees with co-located ground-based ozone instruments at five sites, suggesting that TOMS total ozone is 2-4% too high in the tropics. (C) With the first zonal view of equatorial ozone profiles available from SHADOZ, a zonal wave-one pattern seen by satellites is evident in total and tropospheric column ozone from the sondes, but not in stratospheric ozone.

1. Introduction: Background for SHADOZ

1.1. Requirements for Tropical Ozone Profiles.

Balloon-borne ozonesondes play an essential role in monitoring stratospheric and tropospheric ozone [Logan, 1994; WMO, 1998a], preparing climatologies [Logan, 1999a,b], developing satellite retrieval algorithms [Bhartia *et al.*, 1996; Chance *et al.*, 1996; Burrows *et al.*, 1999; Logan and McPeters, 1999], and for evaluating the accuracy of space-borne instruments, satellite data products and model calculations of ozone. During the 1990's at least a dozen southern hemisphere tropical and subtropical stations flew ozonesondes but sampling was often sporadic and geographical coverage uneven.

When balloon launches are coordinated with field campaigns, continuous records are lacking. For example, during SAFARI/ TRACE-A (Southern African Fire Atmospheric Research Initiative/ Transport and Atmospheric Chemistry near the Equator- Atlantic) more than fifty soundings were taken at five sites for a 6-week period in 1992 [Diab *et al.*, 1996; Kirchhoff *et al.*, 1996; Nganga, *et al.*, 1996; Thompson *et al*, 1996*a*]. By the end of 1993 only one of these stations remained operational. Three Pacific sites (American Samoa, Tahiti, Fiji) launched ozonesondes in conjunction with PEM-Tropics, 1966-1999 (Pacific Exploratory Mission; Oltmans *et al*, 2001). Two others (Christmas Island; San Cristobal, Galapagos) started during SOWER (1998-1999; Soundings of Ozone and Water in the Equatorial Region; Hasebe *et al.*, 2000). Soundings began in 1992-1993 in the western Indian Ocean (Réunion Island; Baldy *et al.*, 1996; Taupin *et al.*, 1999; Randriambelo *et al.*, 2000) and over Indonesia [Komala *et al.*, 1996; Fujiwara *et al.*, 2000]. Natal, Brazil (6S, 35W) is the only tropical ozonesonde station that has operated continuously since the late 1970's [Logan and Kirchhoff, 1986; Kirchhoff *et al.*, 1988; 1991].

Gaps in ozonesonde operations limit the profile data base for satellite algorithm and trends research in the tropics. This is surprising given that ozone changes are expected as a consequence of economic growth and land-use and forestry/vegetation changes. In-situ ozone data that can resolve features in tropical ozone variability related to climate and dynamics, e.g. the Quasi-Biennial Oscillation (QBO), El Niño-Southern Oscillation (ENSO) and the zonal wave-one feature seen in satellite ozone [Shiotani, 1992; Shiotani and Hasebe, 1994; Fujiwara *et al.*, 1998], are limited to a few stations. New retrievals of satellite tropospheric ozone have increased the demand for tropical ozonesonde data for validation purposes [Fishman and Brackett, 1997; Ziemke *et al*, 1998; Thompson and Hudson, 1999; Thompson *et al.*, 2001]. A proliferation of global chemical-transport models for interpreting satellite data and predicting future ozone has highlighted the sparseness of tropical ozone profiles for evaluation of model simulations.

1.2. Initiation of SHADOZ. Station Selection.

The SHADOZ project was initiated to remedy the lack of consistent tropical ozonesonde observations through the augmentation of ozone balloon launches at operational sites (Section 2). One guiding principle of SHADOZ is the enhancement of sonde launches at existing facilities on a cost-share basis with international partners. A second criterion was a zonal distribution of sites suitable for studying the wave-one pattern that has been observed in equatorial total ozone [Shiotani, 1992; Kim *et al.*, 1996; Ziemke *et al*, 1996; Hudson and Thompson, 1998]. The SHADOZ archive includes four Pacific islands: Fiji, Tahiti, Galapagos and American Samoa. Two sites are in the Atlantic region: Natal (Brazil) and Ascension Island. Four other sites span the region from Africa across the Indian Ocean and maritime continent (Nairobi; Irene, near Pretoria, South Africa; Réunion

Island; Watukosek, Java, Indonesia). Location coordinates appear in Table 1.

A third principle of SHADOZ site selection is a commitment to open, rapid distribution of the data in a central archive. This is based on assumptions that: (1) wide dissemination and interaction among sonde data users will leverage local funding to maintain infrastructure and operations; (2) evaluation of the data by users will assist in quality assurance and support correlative ozone measurements. From time to time, ozonesonde data from intensive campaigns at other tropical locations are archived in SHADOZ. Campaigns may also lead to more concentrated launches at the regular SHADOZ stations.

1.3 Scope of Paper

At the end of 2000, over 1000 ozone, temperature and relative humidity profiles had been archived at the SHADOZ website <http://code916.gsfc.nasa.gov/ Data_services /shadoz>. The 1998-1999 data have been transmitted to the World Ozone and Ultraviolet Data Center (WOUDC) in Toronto <http://woudc.ec.gc.ca> to further enhance unrestricted distribution of data. The present paper is an introduction to SHADOZ with several goals:

(1) Publicize the data set to a wider set of potential users, including atmospheric chemists, tropical climatologists, meteorologists, and satellite remote sensing specialists.

(2) Evaluate the precision (Section 3) and accuracy (Section 4) of the SHADOZ ozonesondes through analysis of profile statistics and comparison of sonde-derived column ozone amounts with ground-based and satellite ozone data. In turn, use the sondes to detect satellite biases and possible inaccuracies in total and upper stratospheric ozone.

(3) Describe technical variations among stations in the ozone, temperature and humidity data (Appendix). Even though the same basic instrument is employed at all sites, differences in ozonesonde technique among the stations affect certain uses of the data. Although all ECC (electrochemical concentration cell) techniques currently used in SHADOZ were evaluated recently in laboratory chamber experiments [WMO, 1998b; H. Smit, personal communication, 2000; Johnson *et al.*, 2001], these tests represent half a dozen simulated flights with idealized profiles. The SHADOZ dataset allows us to evaluate instrument performance and technical bias (Sections 3-5) with better statistics and under tropical operating conditions.

2. Experimental Summary & SHADOZ Archive

2.1. Regular SHADOZ Sites

Table 1 lists the SHADOZ Co-Investigator and station personnel responsible for each site. Figure 1 shows a map similar to the one on the SHADOZ website, with a sample header file describing the current data format. The nominal sampling schedule at all stations is once-per-week, usually but not always, mid-week. Balloon-borne ozonesondes are coupled with a standard radiosonde for data telemetry transmitting air pressure, air and pump temperatures, relative humidity, and ozone to a ground receiving station. Some of the ground receiving stations also track and record wind speed and direction using GPS, although these are not archived at the SHADOZ website. ECC sondes [Komhyr, 1967; 1986; Komhyr *et al.*, 1995] are used at all SHADOZ sites with an exception of Watukosek, Java, where prior to August 1999, MEISEI sondes were used [Kobayashi and Toyama, 1966; Komala *et al.*, 1996; Fujiwara *et al.*, 2000]. The Appendix summarizes the ECC technique and radiosonde type used at each station.

2.1.1 Ozone

Figure 2 gives an example of a typical sounding as it appears in the archive.

Although the SHADOZ project archives data in a uniform format, the initial analysis and calibration of data are done by the station Co-Investigator, who may re-process at any time: updates are given on the website. Some sites report data every 10 seconds during a flight, whereas other profiles are archived with 1-s frequency. Differences in data processing, as well as in sonde preparation, may contribute to systematic variations among some of the sites (Appendix, Section 5; see Johnson *et al.*, 2001).

In two respects, sonde total ozone in each SHADOZ data record (Figure 1) is uniform. First, no normalization is made to total ozone from another instrument, such as a satellite or a co-located ground-based total ozone sensor. Second, data from 7 hPa or balloon burst altitude, whichever is lower, is the uppermost data point used in computing integrated ozone. "Evaluated ozone residual" in the SHADOZ record is based on the extrapolation to the top of the atmosphere using the SBUV satellite climatology of McPeters *et al.* [1997]. Extrapolation by assuming a constant mixing ratio (CMR) for ozone above balloon burst is a standard technique that we use for some diagnostic purposes. However, it introduces errors in the total ozone calculation, *e.g.* > 20% when a burst occurs near the ozone maximum. In 1998-1999, 75% of SHADOZ launches reached 7 hPa, with eight stations having 60% or more of samples making this mark. For the other stations, good statistics (for Sections 3-5) are obtained by using profiles that reached 10 hPa. The header used for each data record (Figure 1, lower) shows integrated ozone from the sonde, the extrapolation "residual amount" and a TOMS overpass total ozone reading (from Level 2, version 7 data). Data from SHADOZ stations maintained at other archives may differ from SHADOZ in format, integration and extrapolation.

Table 1. SHADOZ Sites and Co-Investigators. Station operators and detailed procedures appear in the Appendix.

SHADOZ Sites	Lat./Long. (deg)		Co-I
Pago Pago, Am. Samoa	-14.23	-170.56	Samuel Oltmans (NOAA/CMDL)
Papeete, Tahiti	-18.00	-149.00	Samuel Oltmans (NOAA/CMDL
San Cristóbal, Galapagos	-0.92	-89.60	Samuel Oltmans (NOAA/CMDL
Natal, Brazil	-5.42	-35.38	Volker Kirchhoff (INPE)
Ascension Island	-7.98	-14.42	Francis Schmidlin (NASA/WFF)
Irene, South Africa	-25.25	28.22	Gerrie Coetzee (SAWB)
Nairobi, Kenya	-1.27	36.80	Bruno Hoegger (Méteo-Suisse)
La Réunion	-21.06	55.48	Françoise Posny (Univ. Réunion)
Watukosek, Indonesia	-7.57	112.65	Toshihiro Ogawa (NASDA/EORC)
Suva, Fiji	-18.13	178.40	Samuel Oltmans (NOAA/CMDL

2.1.2 Temperature and Humidity Measurements

Pressure, temperature and humidity are provided for each ozone sounding by a

meteorological radiosonde interfaced with the ozonesonde sensor and pump. Radiosondes produced by three manufacturers have been used at the SHADOZ sites (see Appendix), with seven sites of the ten using the Vaisala sonde. Temperature is measured quite accurately with all types of radiosondes (within 0.5°C). Humidity, on the other hand, is measured with less accuracy that is highly dependent on the ambient air temperature. Errors become large at air temperatures colder than -40°C and should be ignored at temperatures colder than -60°C or at any altitude in the stratosphere.

2.2. Additional SHADOZ Data Sets

Table 2 lists data from campaigns that are archived in SHADOZ. Fifty-four sondes were launched at the Kaashidhoo Observatory at Malé in the Maldives as part of INDOEX (Indian Ocean Experiment; Lelieveld *et al.*, 2001) in January through March 1999. SHADOZ also includes sondes taken during the same period under SOWER (Soundings of Ozone and Water in the Equatorial Region) at the Galapagos and at Christmas Island in the Pacific (2N, 157.5W) [Hasebe *et al.*, 2000]. A third augmentation of SHADOZ data is from the Aerosols99 cruise aboard the *Research Vessel Ronald H Brown*, on which 27 sondes were launched from Norfolk, Virginia, via Cape Town, South Africa, to Port-Louis, Mauritius, in January and February 1999 [Thompson *et al.*, 2000].

Table 2. Other Data Sets in SHADOZ archive.

SITE/CAMPAIGN	Lat./Long.	Responsible PI/Reference	Dates
INDOEX, Kaashidhoo	5N, 73E	S. J. Oltmans	Jan.-March 1999
SOWER - Christmas Is. --	2.0N, 157.5W	Hasebe *et al.* [2000]	March-Apr. 1999
Aerosols99 Cruise	31N-30S	Thompson *et al.* [2000]	Jan.-Feb. 1999

3. Sources of Uncertainties and Precision Estimates using SHADOZ Ozone Data.

The Appendix describes the theory and sources of error and uncertainty in the ECC ozonesonde measurements, but there is no easy way to evaluate the accuracy or precision of the SHADOZ data as a whole. First, each ozonesonde launched is a new instrument. Second, differences in technique among SHADOZ sites (Appendix and Section 5) mean the data may not be strictly comparable from station to station. Systematic errors affect trend evaluation when sonde methods are changed at an individual station. Third, variations in technique complicate comparisons with independent ozone measurements from satellite or ground-based or airborne instruments and comparison among stations, *e.g.* in evaluating the wave-one zonal ozone pattern. If satellite-derived total ozone is used as a well-calibrated reference, the goal of using the sondes to evaluate the satellite algorithm is compromised. Nonetheless, in Sections 4 and 5, we will show that by examining column ozone measurements from co-located ground-based instruments, TOMS and the SHADOZ data, it is possible to make some concrete statements about accuracy and possible systematic differences among SHADOZ stations.

In this Section, the precision of the ozone sounding is estimated. First, the impact of extrapolation of ozone above the balloon burst altitude is considered because this is a source of uncertainty. Second, we estimate the precision of a single instrument by examining statistics for a time-series of integrated ozone column amounts during campaigns in which stratospheric column ozone is expected to be nearly constant.

3.1 Upper Stratosphere Extrapolation

Data from INDOEX-Kaashidhoo (5N, 73E; late January-late March 1999) and

Aerosols99 (late January-February 1999) are used to estimate precision. As mentioned above, a climatology from SBUV is used for the extrapolated ozone amount above balloon burst. A typical Kaashidhoo profile is shown (Figure 3) with extrapolations based on constant mixing ratio. Definitions of the constant mixing ratio (CMR) vary in numerical formulation and in selection of data, e.g. degree of smoothing near burst. In our analysis, the uppermost points before 7 hPa are used with a formulation that adds a column amount up to 1 hPa.

In Figure 3, ozone partial pressure is shown as a function of pressure altitude, along with lines of constant volume mixing ratio. Extrapolation with a curve between 10 and 12 ppmv is closest to the end of the sounding. The total ozone integrals corresponding to these extrapolations are: 55 DU (10 ppmv), 66 DU (12 ppmv). For this particular sounding, the SBUV extrapolated amount, based on latitude and month of year, 36 DU, corresponds to a 6 ppmv CMR extrapolation. Which curve (if any) is correct and what imprecisions do the various extrapolations introduce into the integrated ozone column?

The CMR of 55 DU in Figure 3 (corresponding to the 10 ppmv smooth curve) is too high [see figures in McPeters *et al.*, 1997]. The 6 ppmv (36 DU) curve appears too low because deviations from the observed ozone start at 12 hPa where the ozone and radiosonde readings are still fairly reliable (this is less so above 10 hPa). These extremes, representing a +/-20 DU difference, probably bracket the uncertainty in a typical extrapolation. (See Section 5.3 for an assessment of the SBUV extrapolation based on SHADOZ statistics).

The different extrapolation treatments for Kaashidhoo campaign data are viewed in profile and in time-series of integrated stratospheric ozone. The 1- uncertainty in upper stratospheric ozone partial pressure over the Kaashidhoo campaign appears in Figure 4A, along with the mean of 41 soundings that reached 7.0 hPa; possible CMR extrapolation curves are also illustrated. The uncertainties are typically +/-5% of the mean partial pressure. The SBUV extrapolation for all the soundings is 34-37 DU. Figure 5 is a time-series of stratospheric ozone obtained by subtracting integrated tropospheric ozone from total ozone computed with SBUV (black) and with CMR (red-brown) for the 41 Kaashidhoo soundings represented in Figure 4A. For some soundings, CMR-based stratospheric ozone is less than the SBUV-based value; for three soundings the stratospheric ozone amounts coincide (overlapping). This is not surprising, given that each sonde instrument is new and the climatological SBUV value is only an estimate for the Kaashidhoo observing period. The variance (1-) of stratospheric ozone column is 9.54 DU with SBUV and 11.2 DU with constant mixing ratio (Table 3); this translates into 4.3% and and 4.7%, respectively, in total ozone. Results of daily launches that reached 7.0 hPa within 20 degrees of the equator on Aerosols99 [Thompson *et al.*, 2000] are similar to those at Kaashidhoo (Figure 4B; * in Figure 5). Thus, 5% imprecision appears to be a reasonable estimate for total column ozone from a sounding. This figure has also been deduced from laboratory and field tests [Barnes *et al.*, 1985; Johnson *et al.*, 2001].

3.2 Time-series at SHADOZ Sites.

Statistics for soundings that burst at 7.0 hPa and above for SHADOZ stations are similar to those for the Kaashidhoo and Aerosols99 campaigns, even though the observing period is longer. Table 3 summarizes statistics on CMR and SBUV for all 1998-2000 station soundings. Samoa has relatively small upper stratospheric ozone, small variance in the stratospheric column, and the 1- standard deviation for ozone above 7 hPa is 11% (5.28 DU standard deviation, 49.25 DU, CMR-calculated mean, Table 3). The effect on total

ozone uncertainty is only ~3%. The standard deviation at Nairobi is the smallest (4.5 DU) but is still 10% of the CMR ozone add-on. Table 3 shows that CMR extrapolations based on 7 hPa range from 44 DU (Irene) to 60 DU (Ascension).

4. Sonde Accuracy. Comparisons of SHADOZ Ozone with Independent Ozone Measurements

At five SHADOZ stations, ground-based instrumentation for total ozone also operates. Dobson total ozone spectrophotometers at four SHADOZ stations (American Samoa, Nairobi, Natal, Irene) were calibrated in during 1998-1999 to 2-3% accuracy with the world standard Dobson instrument (R. Evans, personal communication, 2000). The Brewer at Watukosek met the international Brewer standard in 1996 and 2000. Comparisons are made between instruments that measure total ozone and sonde total column amounts, using SBUV extrapolation and CMR for soundings that reached 7.0 hPa or 10 hPa (for Ascension, Natal, Réunion). TOMS overpass data, from the instrument onthe Earth-Probe satellite, are also compared to sonde ozone column integrals because the satellite is regularly calibrated and comparisons are possible at all sites (Table 3). The measurement of TOMS total ozone is considered accurate to 2-3% [McPeters and Labow, 1996].

4.1 Comparisons of SHADOZ and Ground-based Total Ozone with TOMS

For the Kaashidhoo total ozone values, comparison with TOMS total ozone measured during each day's satellite overpass appears in Figure 6. TOMS total ozone agrees with the sounding total ozone computed with CMR to within 0.3%; total ozone with SBUV is 7% lower than TOMS (Table 3). TOMS comparisons with total ozone from the Aerosols99 cruise (Table 3) are nearly identical to those for Kaashidhoo.

Comparisons of sonde total ozone with the TOMS overpasses for SHADOZ stations appear in Figure 7. Time-series of total ozone comparisons for the five SHADOZ stations with ground-based measurements are included (dots for Dobson and Brewer data). Total ozone from the sondes, computed with CMR ( ) and SBUV (*) extrapolation, are given with TOMS total ozone (solid line). Differences, relative to the total ozone sensor (TOMS, Dobson, Brewer), appear in the lower part of each frame. The summary of Dobson and TOMS means and differences with one another and with the sondes appear in Table 3. The difference between total ozone calculated using CMR instead of SBUV (7th and 8th columns, using 10 hPa statistics for Ascension, Natal and Réunion) ranges from 10-21 DU or ~3-8% of total ozone. If the calibrations of the Dobson and Brewer instruments are accurate to 2-3%, the ground-based instruments give total ozone at Natal, Nairobi and Irene as (270-278) DU +/-(14) DU, in good agreement with sonde total ozone and with the TOMS overpass data on average. The Dobson at Samoa (mean = 249 DU) and Brewer average at Watukosek (257 DU) are lower than the other three stations.

At Samoa (Figure 7A) sonde total ozone is 9% lower than TOMS with SBUV (Table 3) and the Dobson total ozone is 4% lower than TOMS. Section 5 and the Appendix discuss a possible instrument reason for the low sonde total ozone relative to the Dobson. The reason for high TOMS ozone relative to the Dobson and sondes is a known tendency for the TOMS ozone algorithm to overestimate total ozone over regions with tropospheric ozone column <20 DU (ref). In other words, the climatological ozone profile used in the TOMS algorithm assumes greater tropospheric ozone than is normally found over low-ozone stations like Samoa, Tahiti and Watukosek.

Table 3 Integrated Column Ozone from Sondes, Extrapolations, TOMS Overpass and Dobson or Brewer Spectrophotometer. Only Data to 7 hPa or higher burst used. All quantities except % in Dobson Units (DU). For stations with relatively few ascents to 7 hPa, statistics based on 10 hPa are also given. 22-MAY-2001

Site, SN	Int. O3 to Burst, 1-sig	Int. O3 - Trop O3, 1-sig	CMR Add. 1-sig	SBUV Add	Total O3, CMR, 1-sig	Total O3, SBUV, 1-sig	(CMR-SBUV) DU, 1-sig	TOMS Total O3 SN, 1-sig	TOMS-Tot O3, CMR, %	TOMS-Tot O3, SBUV, %	Dobson Total O3, SN, 1-sig	TOMS-Dobson %,1-sig
Kaash, 41	211.6, 8.4	147.8, 8.5	54.9, 5.3	35.2, 0.7	266.5, 11.2	246.8, 8.1	19.7, 5.5	266.0, 35, 4.8	-0.23	7.14		
Aer99, 21	215.0, 16,1	141.1, 11.4	49.8, 5.5	34.8, 1.5	264.8, 18.4	249.8, 15.9	15.0, 4.5	267.7, 19, 12.4	0.89	6.55		
Ascen, 4	215.5, 20.4	149.2, 15.4	60.1, 8.39	35.0, 1.5	275.6, 23.7	250.5, 19.7	25.1, 9.9	264.5, 4, 11.5	-4.06	5.36		
Ascen (10mb) 92	199.0, 19.3	114.8, 20.9	64.5, 11.4	48.5, 7.8	263.5, 21.6	247.5, 16.8	16.0, 7.3	269.5, 90, 11.0	2.20	8.14		
Fiji, 72	204.4, 17.9	148.1, 12.0	46.4, 5.2	34.8, 1.0	250.8, 18.8	239.0, 17.8	11.6, 5.0	264.0, 62, 12.9	4.78	9.13		
Irene, 38	232.3, 18.4	163.6, 20.3	44.0, 5.8	34.4, 0.5	276.3, 21.1	266.7, 18.5	9.6, 5.7	276.1, 35, 14.2	0.23	3.62	276.4, 33, 13.2	1.59, 1.23
Nair, 87	228.3, 13.7	163.6, 13,1	53.8, 4.8	35.0, 1.1	282.2, 15.2	263.3, 13.3	18.8, 4.7	268.2, 79, 12.6	-5.25	1.84	270.6, 45, 11.5	1.85, 1.25
Natal, 31	216.5, 24.2	149.6, 20.7	59.4, 13.2	35.1, 1.1	275.8, 31.8	251.6, 24.0	24.3, 13.1	275.2, 31, 8.0	-0.16	8.65	278.8, 13, 16.5	2.15, 1.56
Natal (10mb) 69	207.7, 23.18	134.1, 24.1	62.7, 14.1	41.7, 8.0	270.4, 29.2	249.4, 22.2	21.0, 11.7	272.4, 67, 9.3	0.52	8.35	274.8, 37, 13.8	2.38, 1.68
Reun, 19	221.0, 16.9	153.1, 11.6	54.1, 12.1	34.3, 0.5	275.1, 24.1	255.2, 17.0	19.8, 11.9	267.0, 18, 13.7	-2.88	4.46		
Reun. (10mb) 58	211.9, 18.9	135.9, 21.5	56.5, 10.9	42.9, 8.9	268.3, 21.4	254.7, 16.1	13.6, 9.8	271.5, 58, 14.8	1.10	6.14		
Samoa, 81	202.0, 13.4	147.6, 9.9	49.1, 5.4	34.9, 0.9	251.1, 15.3	236.9, 13.4	14.2, 5.0	259.7, 81, 9.7	3.30	8.77	248.8, 43, 10.4	3.93, 1.91

San C 86	205.7, 12.9	149.5, 9.1	47.4, 7.0	34.7, 0.9	253.0, 16.1	240.4, 12.6	12.6, 7.0	265.6, 84, 11.5	4.70	9.48		
Tahiti, 43	198.0, 13.0	143.3, 10.0	44.1, 5.4	34.4	242.1, 15.4	232.4, 13.0	9.8, 5.3	260.2, 43, 10.5	6.96	10.7		
Watu., 42	210.1, 12.29	149.9, 21.9	51.8, 10.2	34.6, 0.8	261.86, 20.98	244.7, 12.49	16.3, 11.3	260.6, 41, 7.0	-0.26	6.3	257.2, 15, 8.9	2.1, 1.32

Because Table 3 shows that the two stations with best agreement between TOMS and Dobson total ozone are Irene and Nairobi (both > 1 km in altitude), it is tempting to ascribe larger differences at other stations to tropospheric ozone algorithm effects. However, two tests show that this is not the case. First, if TOMS-sonde differences are due to tropospheric ozone, the differences should correlate with the amount of ozone in the lower troposphere and not with the stratospheric column. Using Samoa to represent a station where there is likely to be a tropospheric algorithm artifact, the sondes are integrated within the first two Umkehr layers and correlations examined between 0-10 km (most of the troposphere) and the Samoa TOMS-sonde offset and between layers 3-7 (10-35 km, representing the stratosphere) and the TOMS-sonde offset. Although correlation is 42% between the offset amount and the ozone in the troposphere, there is still 27% correlation with stratospheric ozone. Similar results are obtained at the other SHADOZ stations, with a few of them more highly correlated with the TOMS-sonde offset in the stratosphere than in the troposphere. Apparently, some of the total ozone difference comes from the stratospheric part of the profile. The second indication that stratospheric ozone contributes to the TOMS-sonde total ozone difference comes from comparison of tropospheric ozone measured by the satellite with tropospheric ozone determined from the sondes.

4.2 Tropospheric Ozone Satellite-Sonde Comparisons

Figure 8 compares integrated tropospheric ozone from six sites with the corresponding TOMS-based column tropospheric ozone determined by the modified-residual method [Hudson and Thompson, 1998; Thompson and Hudson, 1999]. For integration using the sonde, the tropopause is taken as the pressure altitude at which the steep gradient from the lower stratosphere crosses 100 ppbv ozone. (This chemically defined tropopause does not differ significantly from the location of the tropopause defined by the radiosonde thermal gradient. The chemical tropopause also tends to agree within +/- 1 km of standard published meteorological analyses). Agreement between the satellite and sonde tropospheric ozone averages 6-7 DU, comparable to the precision of the modified-residual technique and less than the corresponding discrepancies between sonde and TOMS total ozone in many cases (Table 3, columns 7 and 9).

5. Station-to-station Differences in SHADOZ Column Ozone and Implications for the Equatorial Wave-one

From Sections 3 and 4, we conclude that sonde precision for total ozone is 5%, slightly poorer than Dobson or TOMS precision. In addition to issues of instrument imprecision, the range of instrument techniques used at SHADOZ stations may result in station-to-station biases and systematic differences between ozone amounts determined from the sondes and from independent measurements. These are evident, for example, when looking at the zonal distribution of total ozone from the SHADOZ sondes. When plotted longitudinally over a short period of time (a month, for example), total ozone from the sondes fail to capture the persistent wave-one feature seen by TOMS. This appears to be a result of station-to-station variations in technique as well as precision limits. Given that assessment of comparative instrument performance is still underway (WMO, 1998b; H. Smit, personal communication, 2001), we cannot give a definitive evaluation of station biases in terms of instrument or technique used. Instead, we use observations from the large number of soundings within the SHADOZ dataset to investigate sonde performance under field conditions. In this section four parameters in the

SHADOZ data set are examined.

5.1 Comparisons of Sonde Ozone with Dobson and TOMS Total Ozone.

Offsets of total ozone from the sondes and Dobson, with respect to TOMS, are summarized in Figure 9. Three features are noteworthy. First, the Dobson total ozone leads one to conclude that TOMS total ozone is overestimated up to 4%, depending on location (cf Table 3). Second, although TOMS reads ~4% too high over the Samoa Dobson, TOMS is 9% greater than total ozone from the Samoa sondes (with SBUV). Third, offsets between total ozone and the independent ozone data vary from station to station, although there is some consistency with longitude. The stations over the Pacific are very low in sonde total ozone with respect to TOMS. Three stations (Nairobi, Irene and Réunion) are highest (relative to TOMS).

That the four Pacific sites (Fiji, Samoa, Tahiti and San Cristobal) are similar to one another is not surprising. Ozone climatology shows that these stations are generally similar in stratosphere and troposphere and in seasonal behavior (Tables 3 and 4; see Oltmans *et al.*, 2001). Furthermore, all four Pacific sites use the same sonde solution type, hardware, measurement and processing techniques (Appendix, Table A-1). Based on preliminary results from JOSIE 2000 and other tests [Johnson *et al.*, 2001], there is a suggestion that the type of ozonesonde instrument used in the Pacific stations gives systematically lower total ozone than the instrument used during the Aerosols99 cruise and Kaashidhoo sampling. Offsets in the latter datasets are 2-3% less than at the Pacific stations where the same sonde preparation and data processing were used (CMDL method, Appendix). (The same instrument bias might also explain different offsets between sondes and TOMS at Irene and Nairobi where the same preparation is used with different instrument. However, other SHADOZ data are ambiguous concerning instrument type ozone biases [Appendix].)

A definitive evaluation of instrument accuracy and station-to-station instrumental effects requires examination of sonde profiles and is beyond the scope of this paper. However, we attempt to learn more about potential sources of variability in SHADOZ data by considering three aspects of the stratospheric portion of the profiles.

5.2 Stratospheric Ozone Variability

On average, stratospheric ozone is uniform among the tropical SHADOZ stations (Table 4). Figure 10 shows the measured stratospheric ozone column to 7 hPa obtained by subtracting integrated tropospheric ozone from the sonde-measured total (Table 3, 3rd column). Measured mean stratospheric ozone falls within 11 DU (43 DU [Tahiti] to 153 DU [Reunion]) at all but two stations: Irene and Nairobi. Higher stratospheric ozone at Irene is explained by a higher frequency of mid-latitude air (signified by a tropopause height 2-3 km lower than for the other stations, not shown). Reasons for higher stratospheric column ozone at Nairobi are less clear. A strong response to the QBO, a 20 DU increase in stratospheric ozone for ~1/3 of the SHADOZ record, was detected at Nairobi but was not unique to this station [Logan et al., 2000]. Nairobi shows a tendency toward relatively higher ozone in the uppermost part of the measured profile, above the ozone maximum (not shown). This is depicted in one of the highest CMR extrapolations (shown relative to SBUV, Figure 11) compared to all the stations. Figure 12 shows that Nairobi has no bias relative to other stations in the lower stratosphere/ upper troposphere ("UT/LS," represented by the 15-20 km column integral). In Figure 12, as expected, Irene has the highest mean value (23 DU). All other stations average between 10 and 15 DU so the UT/LS ozone column is uniform over the tropical stations. The implications for the wave-one pattern in equatorial ozone are discussed in Section 5.4. Other variations among stations that are displayed in Figures 13 suggest

relatively high upper stratosphere ozone at Natal and Ascension (high CMR relative to SBUV) and relatively low upper stratospheric ozone at Fiji, Tahiti, San Cristobal and Samoa. This contrasts with similar column amounts for all of these stations in the UT/LS. Note, however, that the 15-20 km integrated ozone is a small fraction of the stratospheric column.

Table 4. Mean ozone column amounts averaged from SHADOZ soundings taken in 1998-2000. Number of samples is given. Lower part of table based on soundings taken in March-April-May (MAM) and September-October-November (SON).

STATION	#NUM	TOTAL [DU]		STRAT [DU]		TROP [DU]	
		Mean	1sigma	Mean	1sigma	Mean	1sigma
Samoa	111	236.1	12.8	216.8	9.5	19.0	6.2
Tahiti	68	237.8	15.2	216.3	12.0	21.5	6.3
Galapagos	125	240.2	13.9	216.3	11.8	25.2	4.4
Ascension	109	249.6	15.1	213.1	10.1	37.9	7.1
Natal	82	249.5	21.2	217.5	16.3	32.0	8.4
Nairobi	130	260.2	14.0	231.2	11.6	29.6	5.3
Reunion	78	253.2	15.9	219.5	10.7	37.7	8.2
Kaash(99)	48	246.0	8.6	217.7	8.2	28.3	5.1
Fiji	116	240.5	16.9	218.8	11.4	21.5	7.6
Watukosek	68	240.2	20.9	217.0	19.6	29.1	5.5

STATION	#NUM	TOTAL Mean		STRAT Mean		TROP Mean	
	MAM, SON	MAM	SON	MAM	SON	MAM	SON
Samoa	33, 19	229.2	252.2	212.4	228.5	18.9	23.0
Tahiti	24, 17	225.8	256.7	208.3	230.0	17.6	26.7
Fiji	35, 24	232.6	259.7	215.0	231.3	17.6	28.4
Galapagos	38, 41	236.6	246.1	216.1	218.8	20.5	28.4
Ascension	29, 30	242.4	262.7	209.7	219.5	35.3	44.6
Nairobi	29, 38	256.9	265.8	228.4	234.9	28.5	32.3
Reunion	18, 20	243.3	269.6	212.9	228.6	34.0	45.2
Watukosek	4, 24	232.6	241.8	211.0	217.0	27.2	26.9
Natal	20, 22	242.4	268.8	209.7	227.4	35.3	41.3

5.3 Evaluation of the SBUV Add-on for the SHADOZ Region

With the statistics in Table 3 (and Figures 9-12) based on hundreds of soundings, there is enough data to evaluate the SBUV climatology, assuming that discrepancies between sonde total ozone and the total ozone instruments are due to extrapolation errors. If the Dobson and/or Brewer data are taken as a group, Figure 9 suggests that TOMS total ozone is 2-4% too high, depending on location, and that sonde total ozone computed with SBUV is 4-11% lower than TOMS. (An exception is Nairobi where the sonde and Dobson totals are identical, on average). To bring the sonde totals into agreement with the ground-based instruments at Natal, Samoa, Irene and Watukosek, would require 2-7% more ozone (5-17.5 DU, assuming a 250 DU mean total ozone; Table 4). Because of the calibration of SBUV instrument, a 17.5 DU figure for extrapolation from 7 hPa is likely to be too high. Adding 5-7 DU to the SBUV add-on would be reasonable, however, and would bring sonde total ozone closer to the range

suggested by the ground-based instruments. Note that if a low-ozone instrument bias affects the Pacific stations (Fiji, Tahiti, Samoa, San Cristobal), as Johnson *et al.* [2001] believe, the sonde-Dobson ozone offset at Samoa would be reduced.

5.4. Zonal Distribution of Ozone and the Equatorial Wave-one.

A number of studies [Shiotani and Hasebe, 1994; Kim et al., 1996; Ziemke et al., 1996; Hudson and Thompson, 1998] have attempted to isolate the location of the equatorial wave-one pattern in total ozone, i.e. is it in the troposphere, the stratosphere or both? With the assumption that the excess Atlantic ozone is located in the lower stratosphere, satellites, usually at poorest precision at these altitudes, are of limited use. Consequently, the longitudinal coverage of SHADOZ was designed to observe the zonal structure of tropical ozone profiles for the first time. Figures 10-12 do not support a picture of a stratospheric wave-one. The measured total stratospheric column (Figure 10) is zonally invariant if the Nairobi and Irene (not really tropical in character) sondes are omitted. The 15-20 km ozone column is the same at all tropical stations, within uncertainties (Figure 12), ie no lower stratospheric wave-one appears.

How do the uncertainties and possible biases of sondes affect interpretation of equatorial wave-one pattern? Precision limits (5%) and natural variability (up to 10% of total ozone annually; Figure 7) do not show a total ozone wave-one with the SHADOZ data as a whole. This is clear when total ozone (+/- 1) from Table 4 is plotted as a function of longitude (not shown). Seasonally averaged column amounts can be used to look at the wave-one, however, because on this time-scale total ozone data variability approaches the 5% sonde uncertainty. Figures 13 and 14 present the seasonal means (to +/- 1) for total, stratospheric and tropospheric column ozone, respectively, for March-April-May (MAM) and September-October-November (SON), respectively. The wave-one in total ozone is more clearly observed, with Natal, Ascension, Nairobi and Réunion spanning the regions of maximum ozone. During MAM and SON, lower total ozone occurs at the four Pacific stations and Watukosek, although the relatively lower total ozone at Fiji, Samoa and Tahiti is not as pronounced during SON, when these sites are subject to ozone pollution transported from Africa, SE Asia and/or Australia [Oltmans *et al.*, 2001].

Table 5 shows total, stratospheric and tropospheric ozone averaged over the sets of four stations, Natal-Ascension-Nairobi-Réunion (representative of the ozone maximum region) and Watukosek-Fiji-Tahiti-Samoa-San Cristobal (representing the ozone minimum). An estimate of wave-one magnitude is obtained by subtracting the two means. Total ozone shows a wave-one amplitude equal to 15 (+/-5) DU in both March-April-May and September-October-November. Stratospheric ozone shows a small (not statistically significant) wave or none at all. In both MAM and SON there is a tropospheric wave, 13-14 (+/-5) DU. The tropospheric wave-one in MAM occurs during an annual minimum in southern hemisphere biomass burning [Thompson *et al.*, 2001], evidently for dynamical reasons. A smaller amplitude dynamically driven wave, enhanced by (mostly) pyrogenic ozone concentrated between eastern South America and Africa, is presumably responsible for the SON wave-one [Thompson *et al.*, 1996b; Fishman *et al.*, 1996; Moxim and Levy, 2000]. The concept of zonally invariant stratospheric ozone, an underlying wave-one in tropospheric ozone and an "excess ozone" signal is used to derive tropospheric ozone from TOMS in the modified-residual method [Thompson and Hudson, 1999].

Besides capturing the persistent wave, Figures 13 and 14 depict seasonal variations in total, stratospheric and tropospheric ozone. Total ozone is 10-25 DU greater in SON than in MAM (cf Table 4, lower). At stations with little pollution ozone (Nairobi, for example, under

normal conditions), total and stratospheric ozone show similar seasonal differences. The impact of seasonal transport of mid-tropospheric ozone from biomass burning has been documented at Natal [Logan and Kirchhoff, 1986; Kirchhoff *et al.*, 1991; 1996], Ascension [Fishman *et al.*, 1992; Olson *et al.*, 1996; Thompson *et al.*, 1996b], Watukosek [Komala *et al.*, 1996; Fujiwara *et al.*, 1999; 2000] and Réunion [Baldy *et al.*, 1996; Taupin *et al.*, 1999]. More remote from source regions are the Pacific sites, where persistent high-ozone layers introduced by biomass burning have been described by Newell *et al.* [1999] and Oltmans *et al.* [2001]. The lack of a clear seasonal difference in tropospheric ozone at Watukosek may seem surprising in view of ozone pollution detected in sondes following the 1997 El-Niño-related fires [Fujiwara *et al.*, 1999]. However, Thompson *et al.* [2001] determined that over the maritime continent in general, approximately half the 1997 tropospheric ozone increase was dynamical, not photochemical in origin. The apparent lack of tropospheric ozone seasonality in the 1998-2000 Watukosek data may be an artifact of the noisier instrument used for about half the record. Using only data from the ECC period, August-November tropospheric ozone at Watukosek averaged 24 +/- 8.3 DU compared to 19 +/- 7.5 DU in April-July 2000. Table 5 (and Figures 13 and 14) show small seasonal differences at Nairobi, where pollution influences are not consistently strong. For example, in early September 2000, Nairobi soundings averaged ~30 DU tropospheric ozone whereas tropospheric ozone from soundings at Lusaka, Zambia, in the midst of urban and rural burning, averaged 45 DU (A. M. Thompson, unpublished results, 2000.)

Table 5. The wave-one amplitude based on average 1998-2000 column-integrated sonde amounts from SHADOZ (Table 4). Stations between 40W and 65E are used to represent the ozone maximum region; stations between 110E and 90W represent the ozone minimum.

Season	Nat-Asc-Nai-Reu	Wat-Fij-Sam-Tah-San Cris	Difference	Mean)
March-April-May				
Total Ozone	246.3 DU	231.4 DU	14.9 DU	5.5 DU
Strat. Ozone	215.3 DU	212.5 DU	2.8 DU	5.5 DU
Trop. Ozone	33.3 DU	20.4 DU	12.9 DU	3.6 DU
September-October-November				
Total Ozone	266.7 DU	251.3 DU	15.4 DU	3.1 DU
Strat. Ozone	227.4 DU	227.6 DU	-0.2 DU	6.4 DU
Trop. Ozone	40.85 DU	26.7 DU	14.1 DU	5 DU

6. Summary

The SHADOZ project has been described, including background and goals, archive status and issues of sonde technique that may affect interpretation of the data. Noting that each sonde launched is a different instrument, statistics from three years of ozone data from 10 sites and 2 campaigns are used to estimate uncertainties in the SHADOZ data set and to assess the impact of variations in sonde technique and hardware among the stations. Further insight into possible instrument biases and sonde accuracy comes from comparisons of column ozone

amounts with ground-based and satellite ozone data. The key results are:

–> The imprecision in total ozone column measured by an ozonesonde is ~5%.

–> Good agreement (within 2-4%) is found between total ozone from TOMS and colocated ground-based instruments at Natal, Nairobi, Irene, Watukosek and American Samoa. For total ozone from the sondes and TOMS, the agreement may be poorer (2-11%, using sonde extrapolation with SBUV). Satellite total ozone is higher than ozone from the ground-based instruments and the sondes.

–> The best sonde-Dobson-TOMS agreement in total ozone is at the two sites with highest terrain (Nairobi and Irene). Although this could be interpreted as evidence that TOMS insensitivity in the lowest troposphere is the main cause for sonde-satellite discrepancies, several tests show that this is not the case. Discrepancies evidently arise also from the stratospheric part of the ozone profile.

–> Agreement with TOMS tropospheric ozone and integrated tropospheric ozone from the sondes is very good. Typical mean discrepancy is 6-8 DU - the precision limit of the TOMS tropospheric ozone - and is comparable at all stations within 15 degrees of the equator.

–> Station-to-station differences in the total ozone TOMS-sonde-Dobson agreement are sometimes consistent with biases in sonde technique or in TOMS. In other cases, sonde samples do not follow the behavior expected for the instrument:

- The sensor instrument model used at the four Pacific stations may explain why total ozone at Samoa from the sondes is 4-5% lower than the Dobson ozone total.
- Similarly, the TOMS algorithm assumes several percent too much ozone over the Pacific. When the latter two factors are taken into account, total ozone from TOMS-Dobson-sondes are in agreement with one another at 1-2%.
- Two different types of ECC instruments were used at Ascension, Galapagos, Natal and Réunion during the 1998-2000 period. The Réunion and Galapagos samples sorted by instrument type resemble results of laboratory tests, but there was no apparent effect of a hardware change at Ascension and Natal.
- The column amount difference between total ozone with the two types of instruments that have been used at Watukosek is consistent with recent chamber tests with ozonesonde instruments but not within parts of the profile.

–> On average, the stratospheric ozone column is the same at all but two sites (within 10 DU). The exceptions are at Irene (which frequently receives mid-latitude air) and at Nairobi.

–> Due to station-to-station biases and natural ozone variability, the wave-one pattern in total ozone cannot always be observed with the sondes. However, seasonal means show a statistically significant wave-one pattern in total ozone, a tropospheric wave of the same magnitude (~15 DU) and a longitudinally uniform stratosphere (no wave).
The uniformity of equatorial stratospheric ozone validates the assumption made in several residual-type tropospheric ozone retrievals that the tropical stratosphere is zonally constant. A follow-on paper will discuss the structure of the tropospheric wave.

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and the University of Réunion Island (France). SHADOZ has benefitted greatly from JOSIE-2000 and WMO workshops on ozone instrumentation (sponsored by M. Proffitt and H. Smit) and we appreciate the opportunity to participate.

Appendix: Techniques and Characteristics of Individual SHADOZ Sites

Although all SHADOZ sites use electrochemical concentration cell (ECC) technology [Komhyr, 1967], various stations prepare their sondes and process the raw data differently. There are two reasons for this. First, sonde technology is continuously evolving [Barnes *et al.*, 1985; Beekmann, *et al.*, 1994; Komhyr *et al.*, 1995]. Manufacturer recommendations for sonde preparation and processing as well as evaluations of instrument performance by users dictate changes in method from time to time. Second, because all stations were operational at the initiation of SHADOZ (one with data since 1978), it was impractical to specify a uniform procedure. To aid the reader and SHADOZ data user, we give a brief description of how the ECC measurement leads to an ozone value (Section A.1). This is followed by a summary of techniques used at the SHADOZ sites (Section A.2), including comparisons of data collected at the SHADOZ sites that switched instrumentation during the 1998-2000 period.

A.1 The Electrochemical Concentration Cell (ECC) Ozonesonde

The main principle of an ECC sensor is simple. An potential difference is set up between two cells of different strength of KI (potassium iodide) solution [Komhyr, 1967]. The amount of ozone present, as partial pressure, is given as follows:

$P_{ozone} = 4.307x10(-4) \times (I-I_{bg}) \times T(pump) \times t(flow) \times C_{eff} \times C_{ref}$

The current, I, that develops due to electrochemical reactions from introducing ozone into the sensor is given relative to a "no-ozone" background value, I_b, measured in the laboratory prior to the balloon flight. The first term on the rhs is a units conversion that incorporates the gas constant and the Faraday constant to give the ozone partial pressure, which is reported in each profile data record. The other terms are the flow rate, measured in the laboratory prior to launch, and two correction terms. The flow rate accounts for a slowdown in the efficiency of the ozonesonde pump as higher altitudes and lower temperatures are encountered. This is most critical above 25 km. The second correction is to normalize the entire column amount to an independently determined total ozone column, either from satellite or from a co-located total ozone instrument (usually a Dobson or Brewer). The latter step is omitted from the sonde profiles in SHADOZ data files.

Uncertainties are the flow rate (1-2% at the ground), extrapolation to the top of the atmosphere, which is based on climatology (the balloon only reaches 4-7 hPa; see Section 3.1), the pump efficiency correction and the response time of the solution. The pressure, determined by the radiosonde, becomes noticeably more uncertain with altitude. Temperature uncertainties are 0.5K. The humidity determination is deemed reliable to several percent up to ~12 km. The pump efficiency correction is the greatest source of uncertainty in the profile as a whole (10-15% above 25 km) [Komhyr, 1986; DeBacker and DeMuer, 1991]. An additional uncertainty comes from the strength of the KI solution used and whether or not the solution is buffered [Boyd *et al.*, 1998; WMO *et al.*, 1998; Johnson *et al*, 2001].

Differences among ozonesonde technique are not easy to resolve. A test-chamber sponsored by ForschungZentrum (FZ)-Jülich and the World Meteorological Organization (WMO) has been used on two occasions to compare sonde performance in a controlled environment that simulates the atmosphere [WMO, 1998b; <www.fz-juelich.de/icg/icg2/forschung/Josie>]. Of the groups participating in SHADOZ, only the NOAA/CMDL ECC system used at the four SHADOZ sites in the Pacific was tested in the 1996 comparison (JOSIE= Jülich Ozonesonde

Intercomparison Experiment). During JOSIE-1996 [WMO, 1998b] the NOAA sondes appeared to read higher than the standard ozone "tropical stratospheric" profile and not significantly different in the "tropical troposphere." After that time, NOAA sonde preparation and processing procedures were modified and Samoa, Tahiti and Fiji data from 1995-1998 were re-processed [Johnson *et al.*, 2001; Oltmans *et al.*, 2001].

Chamber tests performed at FZ-Jülich in September 2000 (JOSIE-2000) were conducted by 4 SHADOZ groups and included all methods currently used in the network. The results and impact on SHADOZ data are currently being analyzed. A limitation of the chamber approach is that model profiles are highly idealized compared to the layering typically found in the tropics [Newell *et al.*, 1999]. In addition to chamber tests, field comparisons need to be conducted, ie with several instruments flown simultaneously on a single balloon [Hilsenrath *et al.*, 1984].

A.2 Summary of Ozonesonde Procedures at SHADOZ Stations

The procedures used to collect SHADOZ data at the end of 2000 appear in Table A-1. All of the SHADOZ sites are subject to re-processing and a website caveat reminds users that the data are subject to change. Note that each station (Table 1) processes the raw data for SHADOZ in the way that has been customary for the site, so that data are not strictly comparable from one station to the next. Data users are urged to contact the station Co-Investigator (addresses and email at the SHADOZ website) for details on current operating characteristics and re-processing.

Four SHADOZ stations changed sonde instrument during the 1998-2000 period. Data at Réunion and a small set of San Cristobal samples reveal systematic differences between ozone determined with the different procedures. At San Cristobal, 11 ENSCI samples were taken mixed in the otherwise-SPC data. Ozone from SPC averaged 2 DU lower than TOMS total ozone, whereas total ozone from ENSCI data was 18 DU (~7%) higher. For Réunion, inspection of Figure 7F (lower panel) reveals sonde-derived ozone from the SPC-6A instrument lower than from ENSCI data. Measured column amounts to 10 hPa are:

Réunion ENSCI: 217.7 +/- 17.4 DU (43 samples)
Réunion SPC: 196.8 +/- 13.1 DU (16 samples).

These differences agree with laboratory tests as described by Johnson *et al.* [2001] and with a possible lower-ozone tendency for SPC when SHADOZ Pacific data are compared to the Aerosols99 and Kaashidhoo soundings (Section 5.1). At Natal and Ascension (Figures 7C, G), however, instrument switches did not lead to noticeable differences. Measured to 10 hPa:

Ascension ENSCI: 195.5 +/- 20.0 DU (25 samples) Natal ENSCI: 206.6 +/- 18.6 DU (18 samples)
Ascension SPC: 200.2 +/- 18.9 DU (67 samples) Natal SPC: 208.0 +/- 24.8 DU (51 samples).

(Note, that for Natal, the change in instrument type change was accompanied by a recommended sensor solution change, so some of the 1998-1999 data have been reprocessed to be consistent with other Natal data. The modified data are available at the SHADOZ website.) At Watukosek, the Meisei RSII-KC79D instrument was flown from the start of ozonesonde launches in 1993 until July 1999, when an ENSCI ground station was installed. Figure A-1 shows a comparison of mean ozone (partial pressure) and temperature profiles from the 1993-1999 record at Watukosek, labeled "Meisei-All " and based on 129 sondes. A subset of 28 Meisei profiles were taken in the first part of the SHADOZ period, from January 1998-July 1999. Mean temperature and ozone mixing ratio appear in Figure A-1. The mean profiles from ENSCI sensor data from July 1999-December 2000 (57 soundings) are also shown in Figure A-1. Integrated column ozone for the mean Meisei ozone profile is 13% lower than for the corresponding ENSCI column amount. Nearly all of this difference is due to stratospheric discrepancies because tropospheric column amounts average 23 DU for both sets of profiles. For the lower stratosphere, JOSIE-1996 [WMO, 1998b] showed that Meisei readings can be lower than ENSCI due to a slower response time of the Meisei instrument. This does not appear to explain the

lower Meisei values in the upper stratosphere in Figure A-1, where JOSIE-1996 found Meisei ozone to be higher than the ozone standard. JOSIE-2000 may offer further insight into Meisei-ENSCI differences.

Table A-1. Station Operation and Technical Summary on next page.

Table A-1. Sites	Station/Data Managers	Sensor Type	Radiosonde Type	Solution Strength	Pump Efficiency Curves
Natal, Brazil	F. Raimundo da Silva (INPE[1])	Ensci Z SPC 6A	Sippican Inc.	0.5% buffered until 03/99 1% buffered since 04/99	NASA/WFF[2]
Ascension Is.	E. T. Northam (NASA/WFF)	Ensci Z SPC 6A	Sippican Inc.	1% buffered	NASA/WFF
Irene, South Africa	A. Phahlane, D. Esterhuyse (SAWB[3])	SPC 6A	Vaisala	1% buffered	Komhyr table, 1986
Nairobi, Kenya	W. Kimani (KMD[4]) G. Levrat (SMA[5])	EnSci 2Z	Vaisala	1% buffered	Komyhr table, 1994
Watukosek-Java	S. Kawakami (NASDA/EORC[6]) S. Saraspriya and staff (LAPAN[7])	MEISEI until 07/99	MEISEI until 07/99	4e-2% until 07/99	MEISEI table
		EnSci 2Z since 08/99	Vaisala since 08/99	2% no buffer since 08/99	NOAA/CMDL[8]

[1]INPE= Instituto Nacaional de Pesquisas Espaciais

[2]WFF = Wallops Flight Facility

[3]SAWB = South African Weather Bureau

[4]KMD = Kenyan Meteorology Department

[5]SMA = Swiss Meteorological Agency

[6]NASDA/EORC = National Space Development Agency/Earth Observation Research Center

[7]LAPAN = Atmospheric Research and Development Center, National Inst. of Aeronautics and Space, Indonesia

[8] NOAA/CMDL = National Oceanography and Atmospheric Admin./Climate Monitoring and Diagnostic Laboratory, as reported in Johnson *et al.* [2001].

Table A-1. Sites	Station/Data Managers	Sensor Type	Radiosonde Type	Solution Strength	Pump Efficiency Curves
La Réunion	F. Posny J-M. Metzger (Univ. La Réunion)	Ensci Z SPC 6A	Vaisala	1% buffered until 04/98 0.5% buffered since 05/98	Komyhr table, 1994
Suva, Fiji	K. Koshy (Univ. So. Pac.) B. Johnson(NOAA/CMDL)	SPC 6A	Vaisala	1% buffered until 04/98 2% no buffer since 05/98	NOAA/CMDL
Tahiti	P. Simon (Meteo France)	SPC 6A	Vaisala	1% buffered until 05/05/98 2% no buffer since 05/06/98	NOAA/CMDL
Am Samoa	B. Johnson	SPC 6A	Vaisala	1% buffered until 04/16/98 2% no buffer since 04/17/98	NOAA/CMDL
San Cristobal	H. Vömel (NOAA/CMDL)	SPC 6A	Vaisala	1% buffered until 04/16/98 2% no buffer since 04/17/98	NOAA/CMDL
Kaashidhoo, Maldives	J. Lobert	EnSci 2Z	Vaisala	2% no buffer	NOAA/CMDL
Aerosols99 Cruise	A. M. Thompson (NASA/GSFC)	EnSci 2Z	Vaisala	2% no buffer	NOAA/CMDL

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9 June 01 – FIGURE CAPTIONS

FIG #	CAPTION
1	SHADOZ sites. Header description on SHADOZ data files. Although individual stations may extrapolate ozone above 7 mb or balloon burst in different ways, "residual" ozone to top of atmosphere in SHADOZ files are determined from climatology [McPeters *et al*, 1997]. Station latitude-longitude information is in Table 1.
2	Typical profile from website, showing data in partial pressure (ozone, on left) and temperature from radiosonde (also left), with ozone volume mixing ratio on right. Example is for a sounding on 22 Sept. 1999 from Ascension Island. High ozone peaks below 10 km originate from African regions with biomass burning.
3	A typical sounding from Kaashidhoo (Male, during INDOEX) along with curves that represent a constant volume mixing ratio above the maximum ozone region.
4	The mean profile from soundings that reached 7.0 hPa with the 1 σ standard deviation based on 0.25 km averages. (A) Kaashidhoo during INDOEX (February-April 1999); (B) Aerosols99 cruise (January-February 1999 in tropical Atlantic). Constant-mixing ratio isolines are illustrated. The corresponding mean CMR above-7.0 hPa is given in Table 3.

5 Stratospheric ozone computed from soundings at Kaashidhoo (Male, during INDOEX) and from Aerosols99 cruise (launches to +/- 20 degrees). Stratospheric column amount computed by subtracting integrated tropospheric ozone from the sonde total ozone. The fact that the stratospheric column amounts assuming SBUV and constant-mixing-ratio extrapolation sometimes identical (not theoretically possible) illustrates limitations in the SBUV climatology and in sonde precision.

6 Comparison of integrated total ozone computed by CMR ( ) and SBUV (*) for Kaashidhoo launches, compared to TOMS overpass data (January-March 1999).

7 A comparison of integrated total ozone from sondes (TCO) plus CMR or SBUV, TOMS satellite (Level 2, version 7) overpasses, and total ozone from co-located Dobson instruments at (A) Samoa; (B) Nairobi; (C) Natal; (D) Irene. TOMS overpass and sonde ozone at (E) San Cristobal; (F) Réunion; (G) Ascension; (H) TOMS overpass, sonde and Brewer total ozone at Watukosek. Data to 7 hPa used for all stations except Natal, Réunion, and Ascension. % deviation relative to TOMS and ground-based instrument in lower panels.

8 Integrated tropospheric ozone for six SHADOZ sites (*) with 9-day averaged tropospheric ozone for the corresponding location derived from TOMS by the modified-residual method [Thompson and Hudson, 1999]. Nine-day running averages of TOMS data are used to minimize equatorial data gaps, scan angle artifacts and aerosol effects. The modified-residual method is restricted to tropical air masses, which are defined as being within the zone of the wave-one feature in total ozone - usually at +/-20 degrees from the equator. (A) Natal, (B) Nairobi, (C) Ascension, (D) Samoa, (E) San Cristobal, (F) Watukosek.

9 Comparisons of total ozone differences between TOMS and sondes and between TOMS and Dobsons for SHADOZ data sets. Measurements from early 1999 field campaigns (Aerosols99 data from 20N-20S over the Atlantic and Kaashidhoo Observatory during INDOEX) are shown with station data.

10 Zonal view of stratospheric column ozone computed by subtracting integrated tropospheric ozone from total ozone computed by SBUV extrapolation. Bars indicate 1-)standard deviation. Irene stratospheric column is relatively higher because mid-latitude stratospheric conditions frequently prevail.

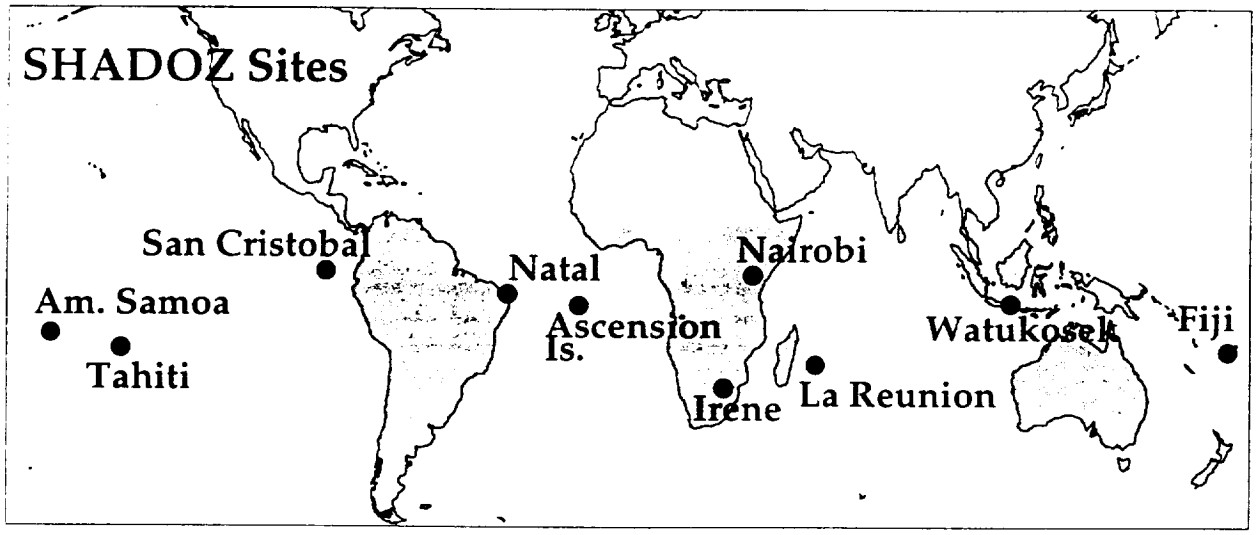
11 Zonal view of average CMR extrapolations for SHADOZ stations and Kaashidhoo data with 1-)standard deviation.

12 Zonal view of integrated column ozone (DU) between 15 and 20 km, with 1-)standard deviation. Irene, with typically lower tropopause, is ~50% greater than the other sites.

13 Seasonally averaged (MAM=March-April-May) total ozone column, stratospheric ozone column and tropospheric ozone column from 1998-2000 SHADOZ data. Integration for total ozone based on SBUV add-ons and stratospheric ozone is obtained by subtracting the integrated tropospheric ozone column from total ozone. Mean and 1-)standard deviation are shown.

14 Same as Figure 13 except that SON averages are shown. Note scale difference for tropospheric ozone compared to Figure 13.

Fig A-1 - A comparison of ozone and temperature profiles taken at Watukosek with Meisei and EN-SCI type sondes. All refers to 1993-July 1999 data; Meisei, 98-99 are in SHADOZ.



Data Format

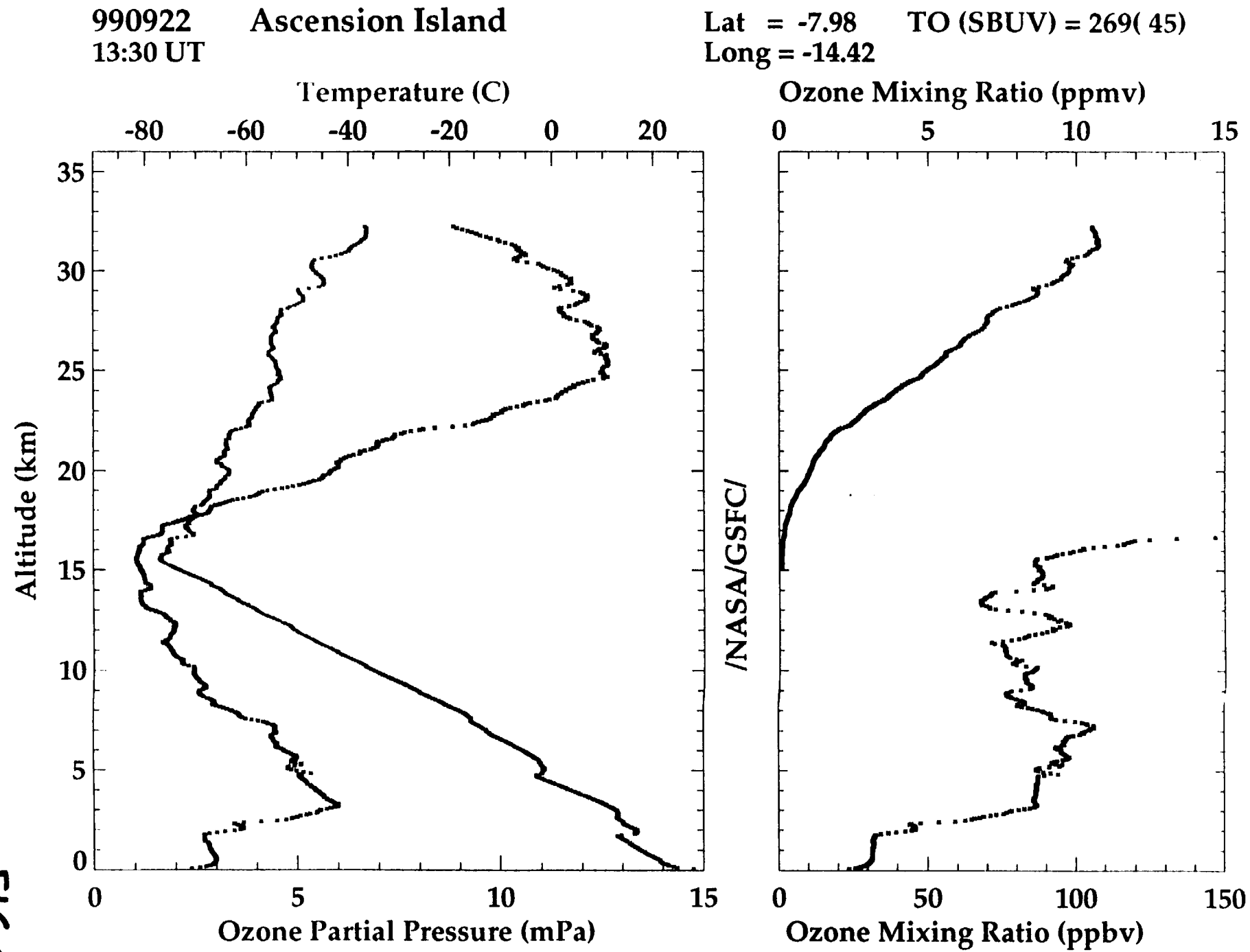
Integrated ozone up to @ Xmb
Sonde total+O3 Residual = Total Column Ozone

SBUV climatology extrapolation from sonde total to the top of the atmosphere. [McPeters et al., JGR 102, pp 8875-8885, 1997]

```
12
Ascension Is.
Location                        : 7.98   S 14.42  W
Launch date                     : 990922
Launch time                     : 13:30 UT
Sonde total (DU) @ 8mb          : 224.02
Evaluated O3 Residual (DU)      : 45.4
Dobson total (DU)               : 9999
TOMS (DU)                       : 287.0

Press      Alt     Temp     RH       O3        O3
hPa        km      C        %         nbar      ppmv
1004.510   0.079   28.010   96.70   23.820   0.0237
 998.340   0.133   24.790   96.70   25.840   0.0259
 992.010   0.188   24.070   97.60   27.330   0.0276
 986.820   0.234   23.150   98.40   28.370   0.0287
```

FIG 1


990922 Ascension Island
13:30 UT
Lat = -7.98 TO (SBUV) = 269(45)
Long = -14.42
Temperature (C)
-80 -60 -40 -20 0 20
Ozone Mixing Ratio (ppmv)
0 5 10 15
Altitude (km)
35 30 25 20 15 10 5 0
/NASA/GSFC/
0 5 10 15
Ozone Partial Pressure (mPa)
0 50 100 150
Ozone Mixing Ratio (ppbv)

716 2

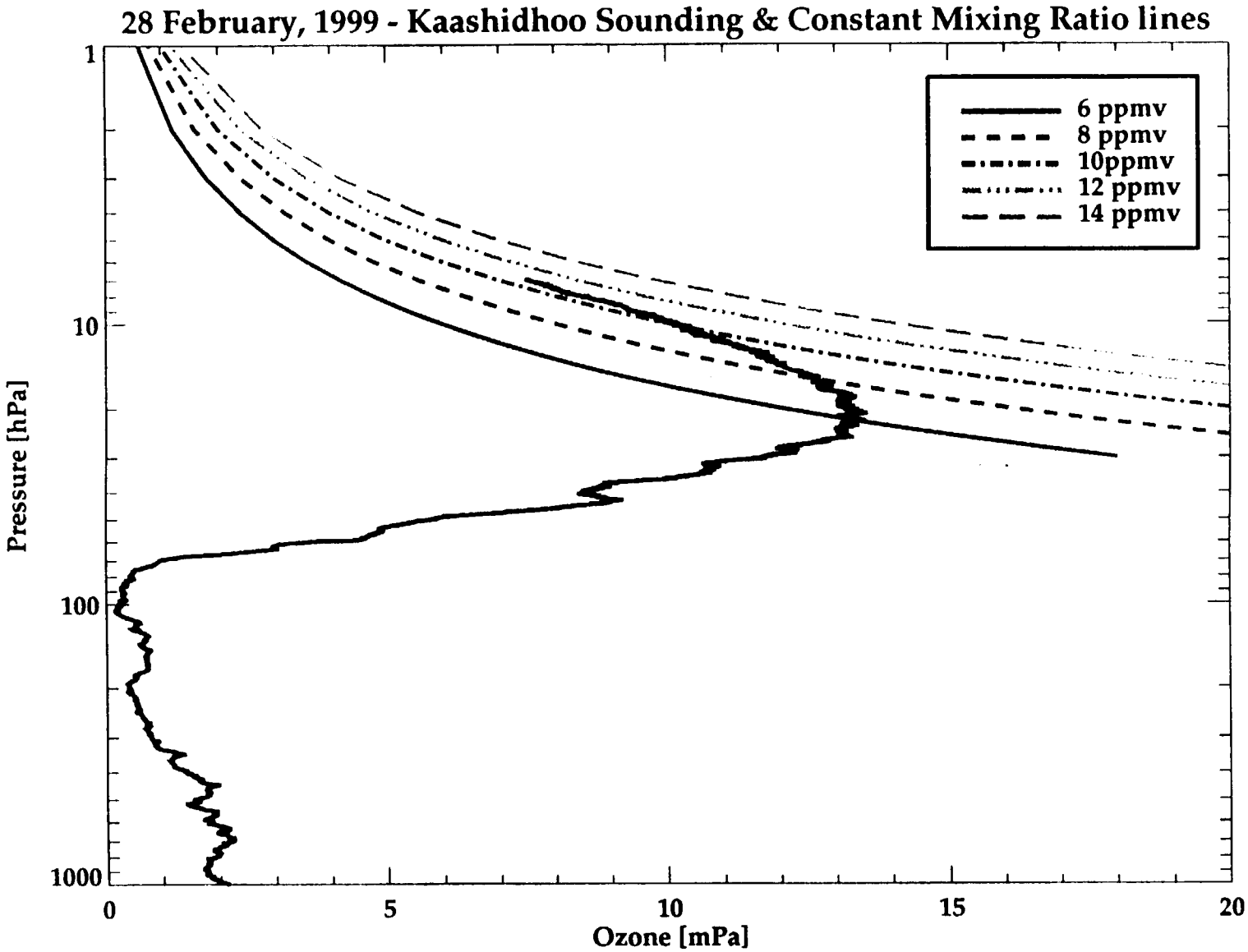

28 February, 1999 - Kaashidhoo Sounding & Constant Mixing Ratio lines
6 ppmv
8 ppmv
10ppmv
12 ppmv
14 ppmv
Pressure [hPa]
1
10
100
1000
0
5
10
15
20
Ozone [mPa]

Fig 3

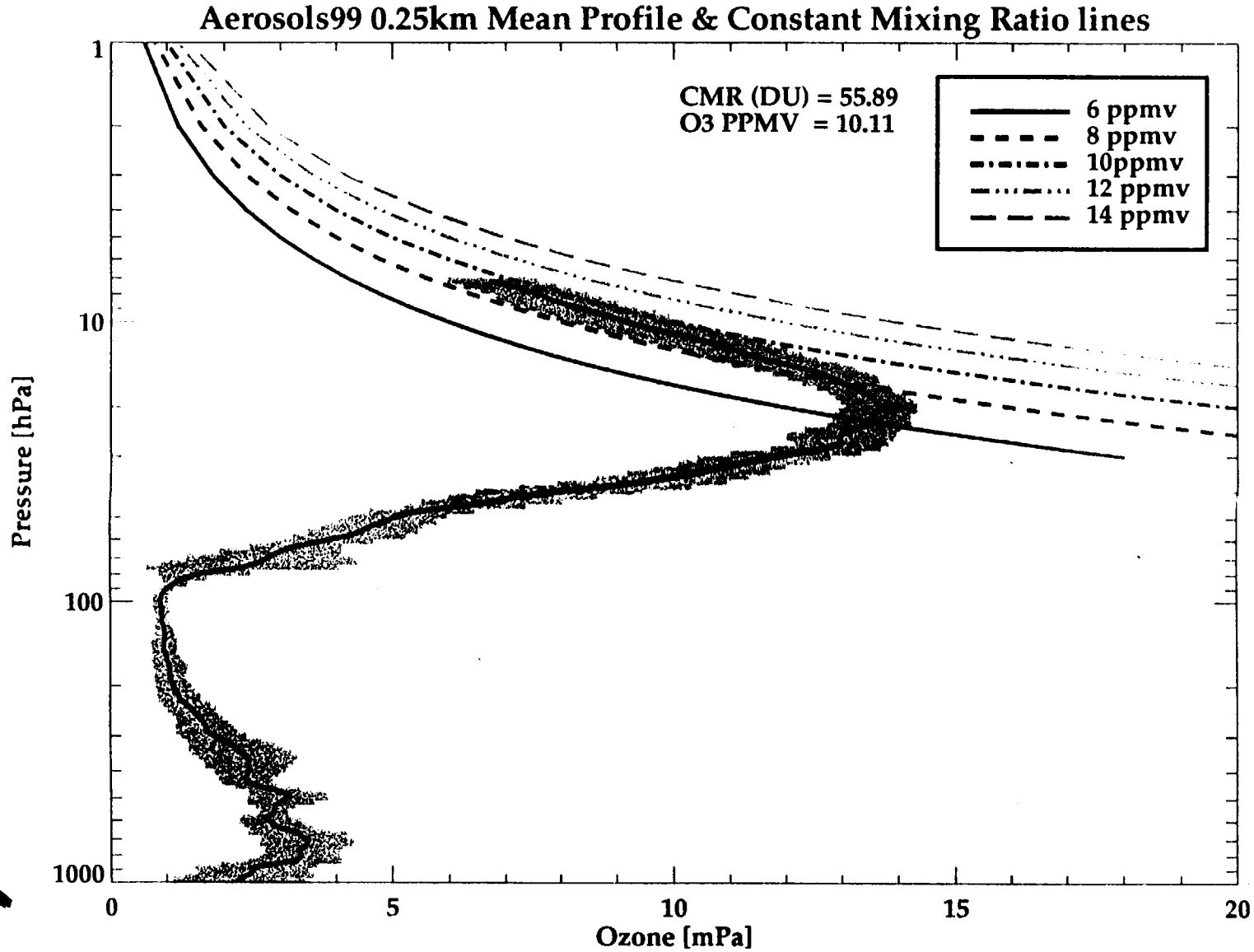
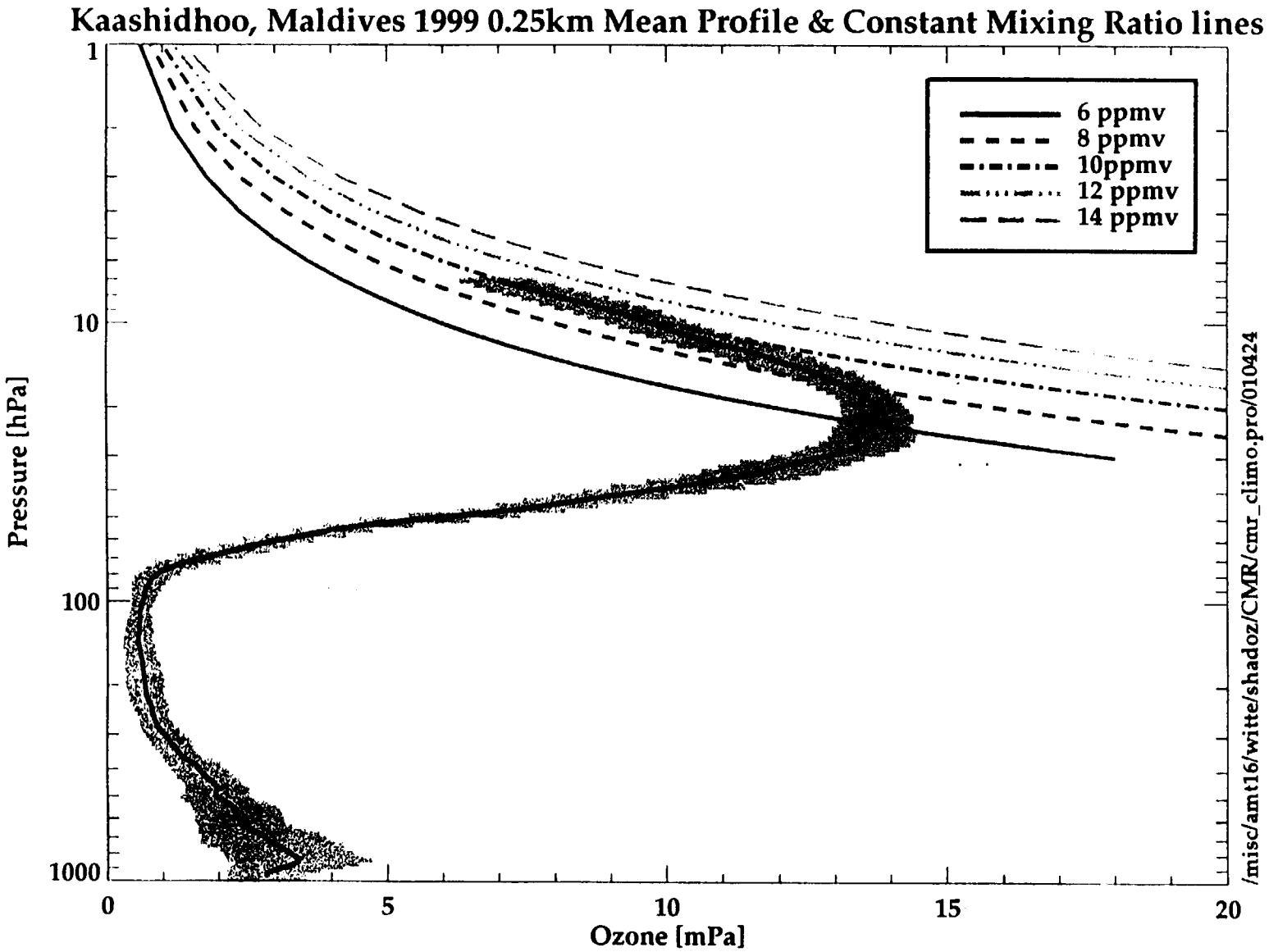

Aerosols99 0.25km Mean Profile & Constant Mixing Ratio lines
CMR (DU) = 55.89
O3 PPMV = 10.11
6 ppmv
8 ppmv
10ppmv
12 ppmv
14 ppmv
Pressure [hPa]
1
10
100
1000
0
5
10
15
20
Ozone [mPa]

Fig 4B


Kaashidhoo, Maldives 1999 0.25km Mean Profile & Constant Mixing Ratio lines
6 ppmv
8 ppmv
10ppmv
12 ppmv
14 ppmv
Pressure [hPa]
1
10
100
1000
0
5
10
15
20
Ozone [mPa]
/misc/amt16/witte/shadoz/CMR/cmr_climo.pro/010424

4 of 4

SHADOZ Campaigns, 1999
Sonde Stratospheric Ozone [DU]
280
260
240
220
200
180
160
20
40
60
80
-Feb-
-Mar-
-Apr-
Day of Year
Δ Kaashidhoo (#41)
* Aerosols99 (#10)
SBUV
CMR

FIG 5

FIG 5

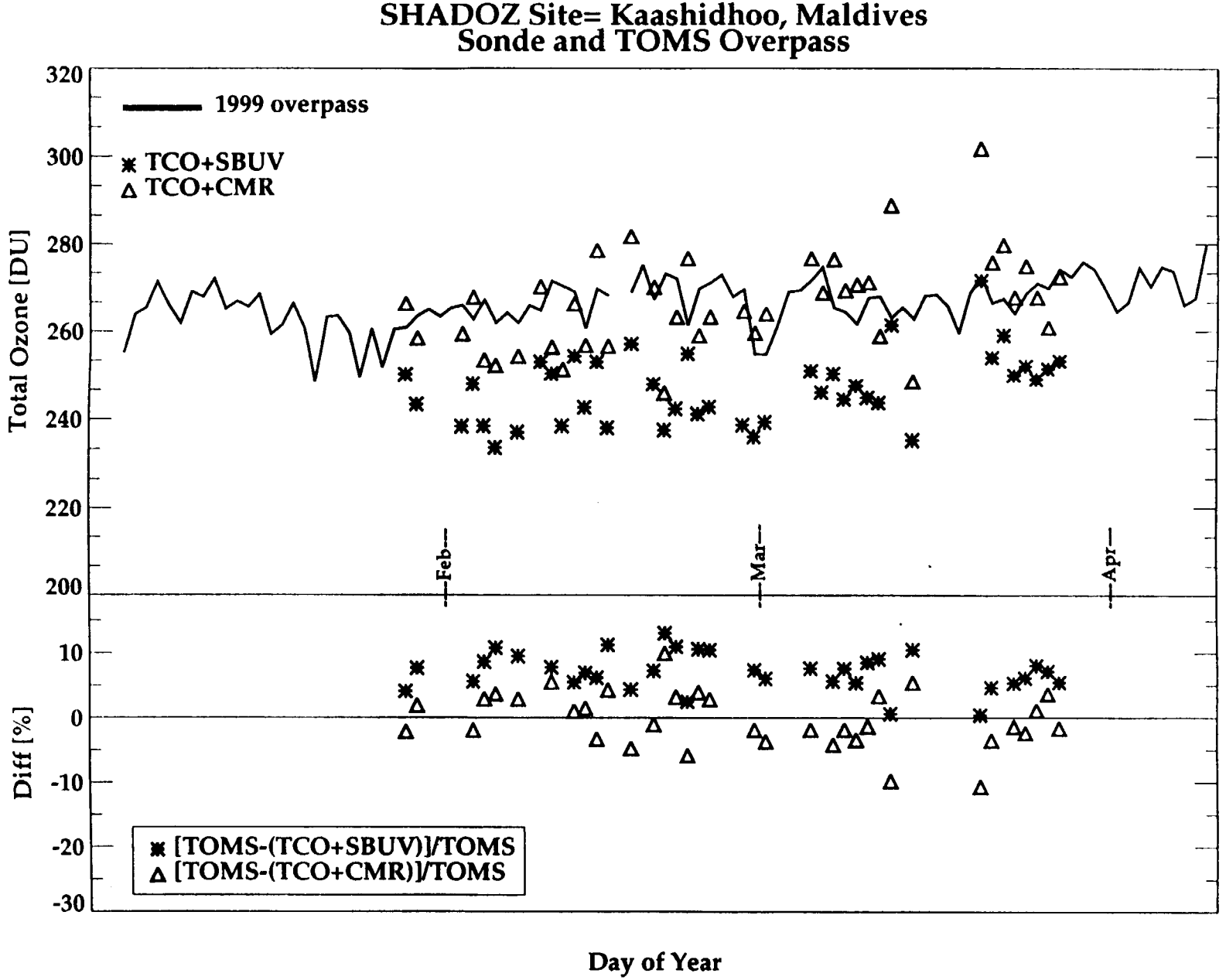
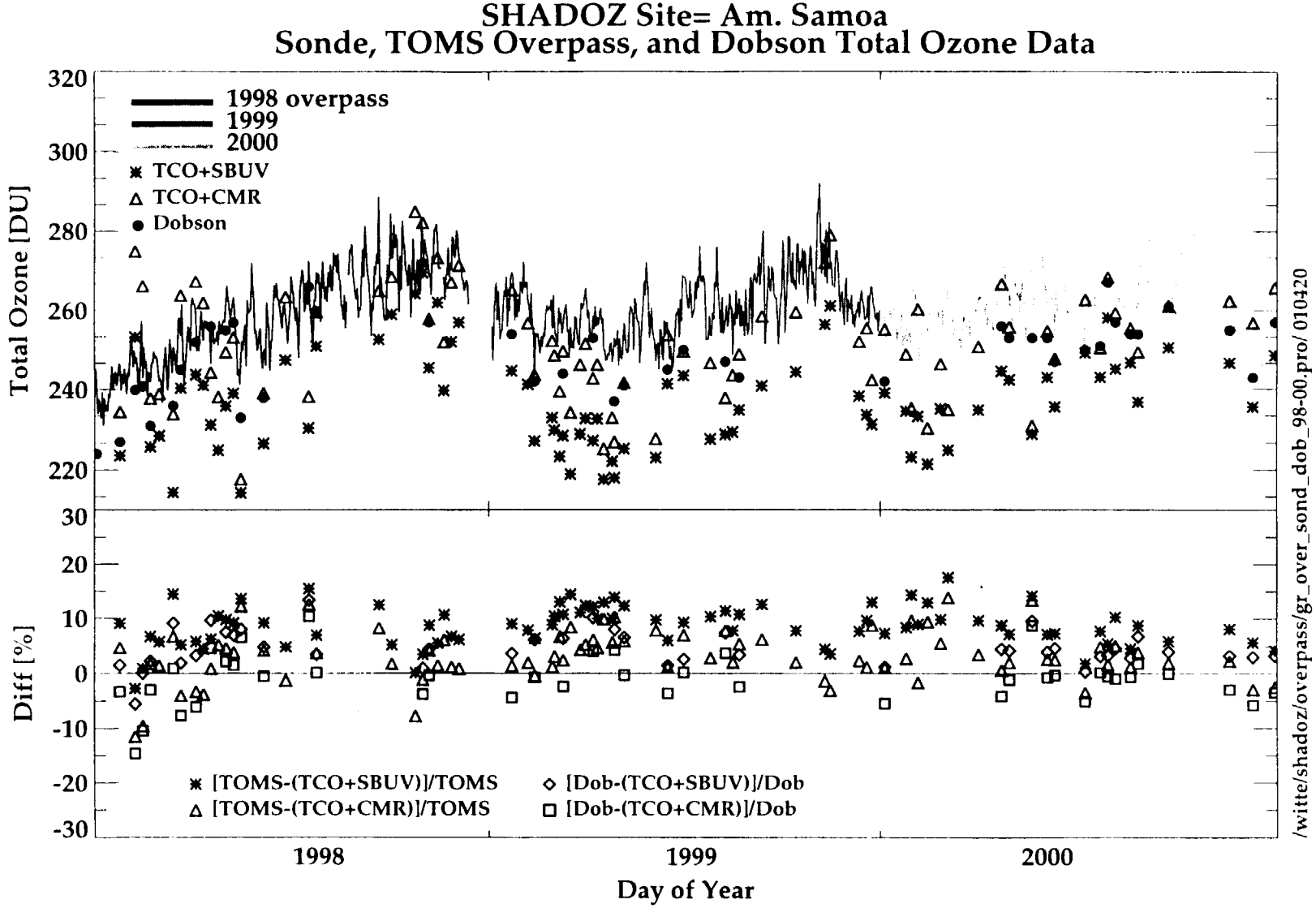
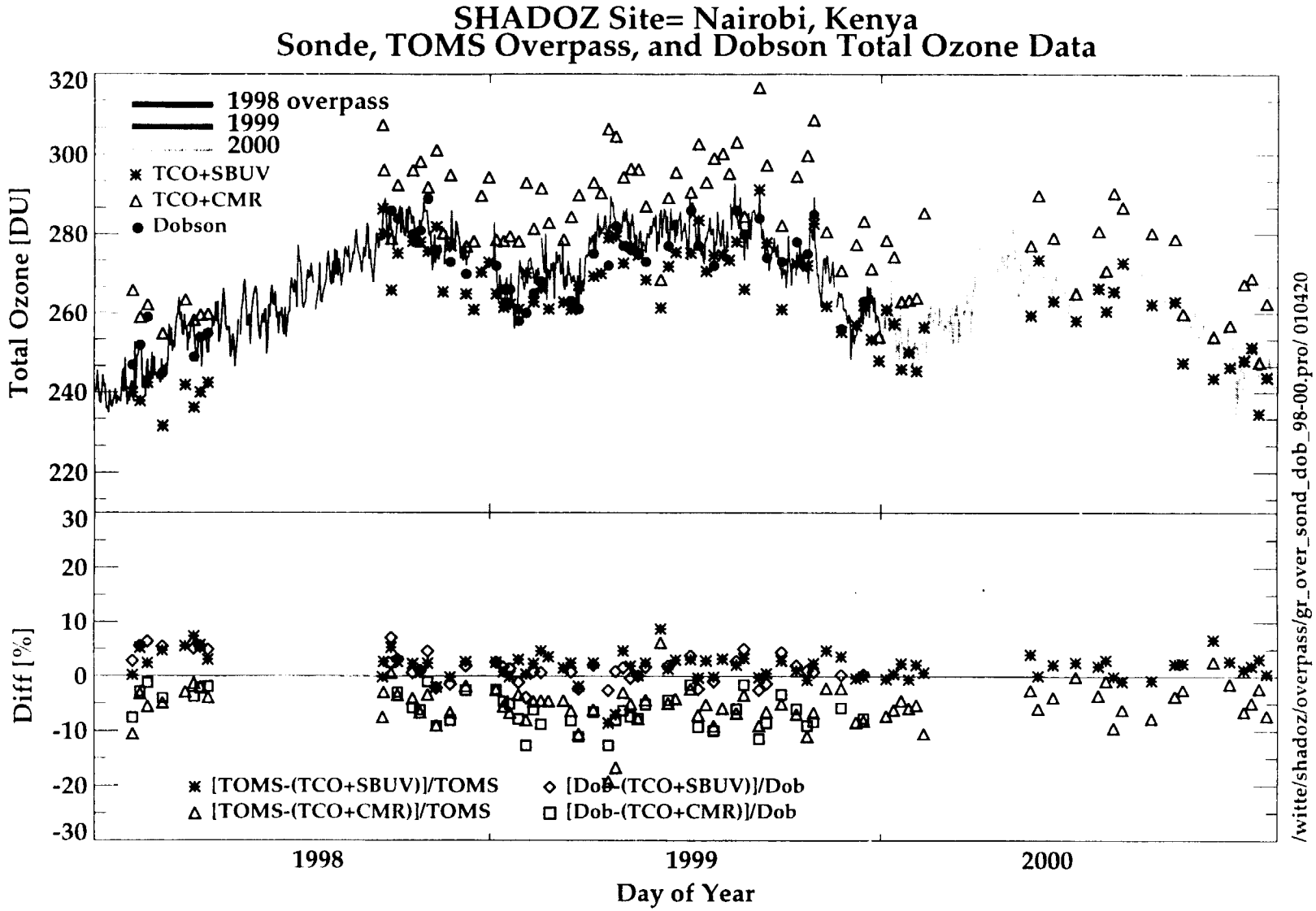

SHADOZ Site= Kaashidhoo, Maldives
Sonde and TOMS Overpass
1999 overpass
TCO+SBUV
TCO+CMR
Total Ozone [DU]
320
300
280
260
240
220
200
Feb
Mar
Apr
10
0
-10
-20
-30
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
Day of Year

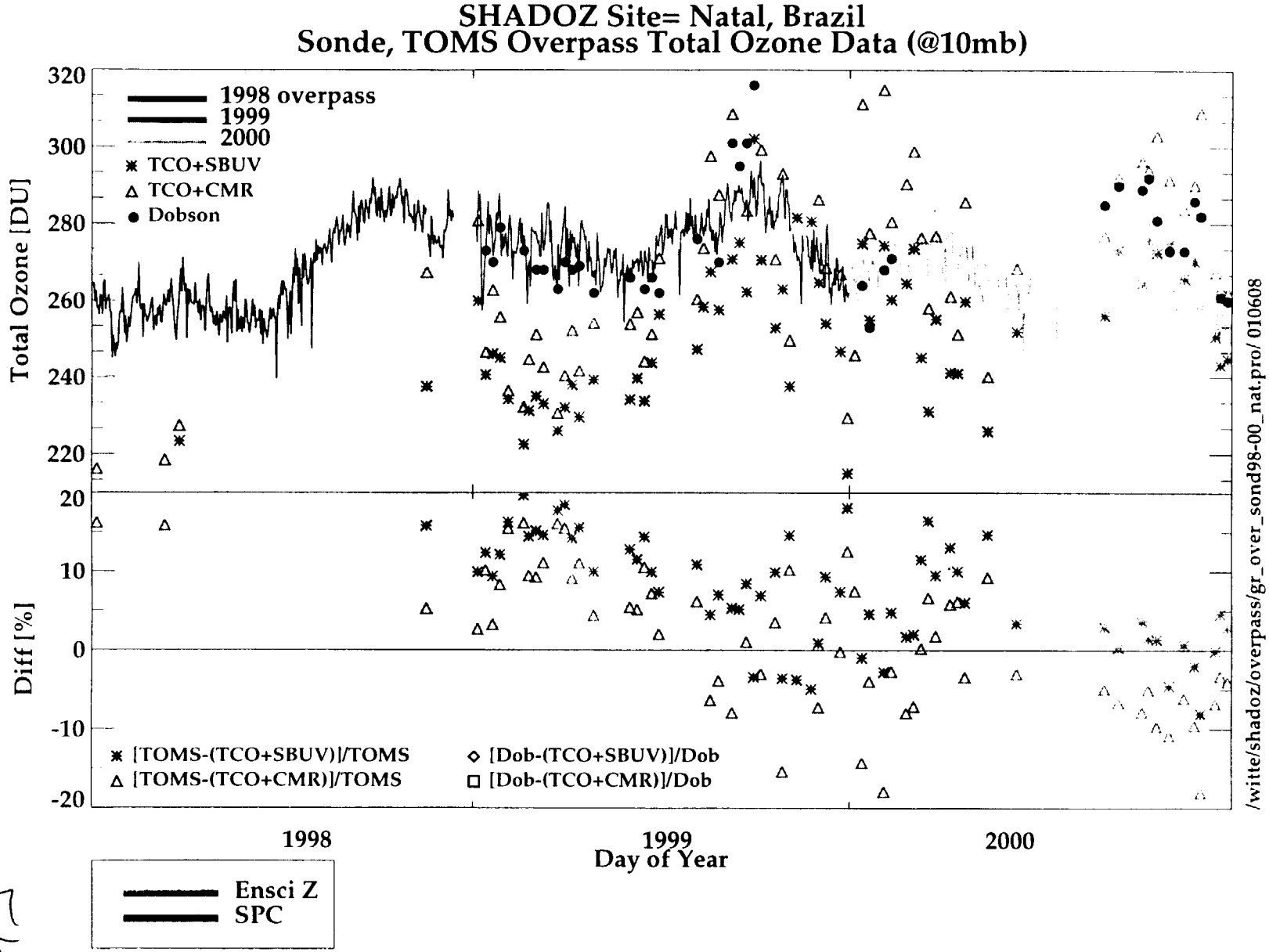
Fig 6


SHADOZ Site= Am. Samoa
Sonde, TOMS Overpass, and Dobson Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Dobson
Total Ozone [DU]
320
300
280
260
240
220
30
20
10
0
-10
-20
-30
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[Dob-(TCO+SBUV)]/Dob
[Dob-(TCO+CMR)]/Dob
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_dob_98-00.pro/ 010420

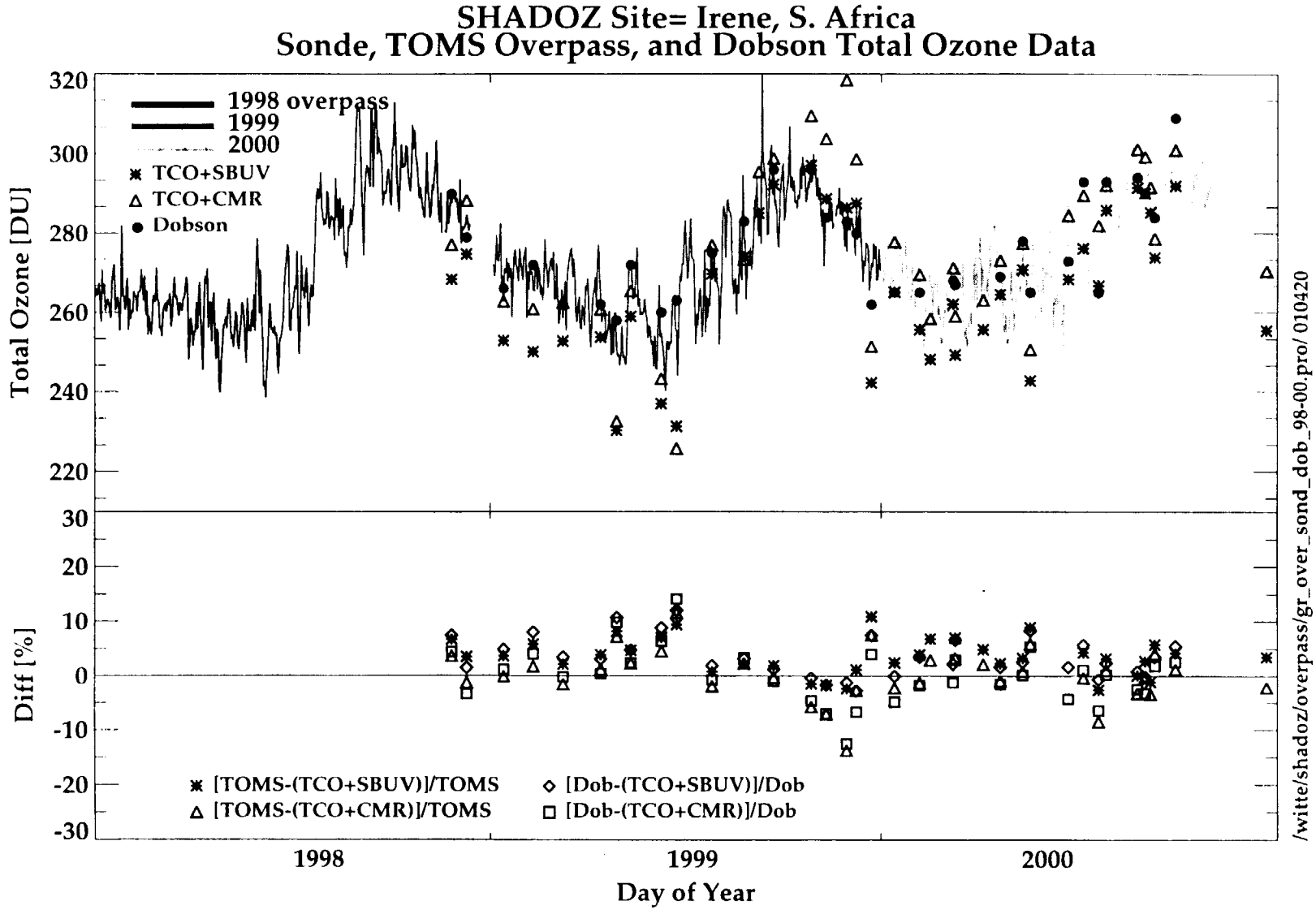
716 714


SHADOZ Site= Nairobi, Kenya
Sonde, TOMS Overpass, and Dobson Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Dobson
Total Ozone [DU]
320
300
280
260
240
220
30
20
10
0
-10
-20
-30
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[Dob-(TCO+SBUV)]/Dob
[Dob-(TCO+CMR)]/Dob
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_dob_98-00.pro/ 010420

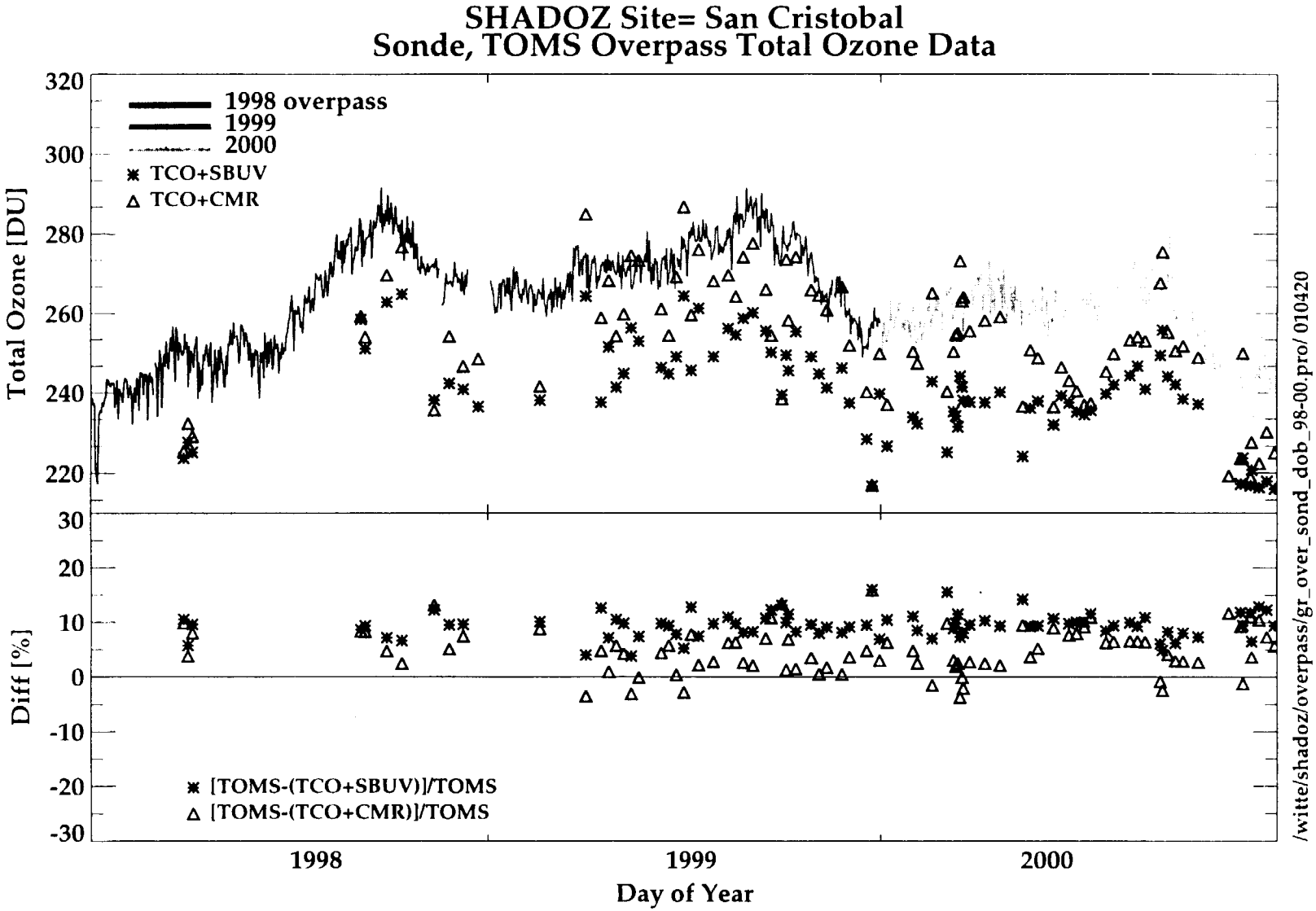
F16 7E


SHADOZ Site= Natal, Brazil
Sonde, TOMS Overpass Total Ozone Data (@10mb)
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Dobson
Total Ozone [DU]
320
300
280
260
240
220
Diff [%]
20
10
0
-10
-20
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[Dob-(TCO+SBUV)]/Dob
[Dob-(TCO+CMR)]/Dob
1998
1999
2000
Day of Year
Ensci Z
SPC
/witte/shadoz/overpass/gr_over_sond98-00_nat.pro/ 010608

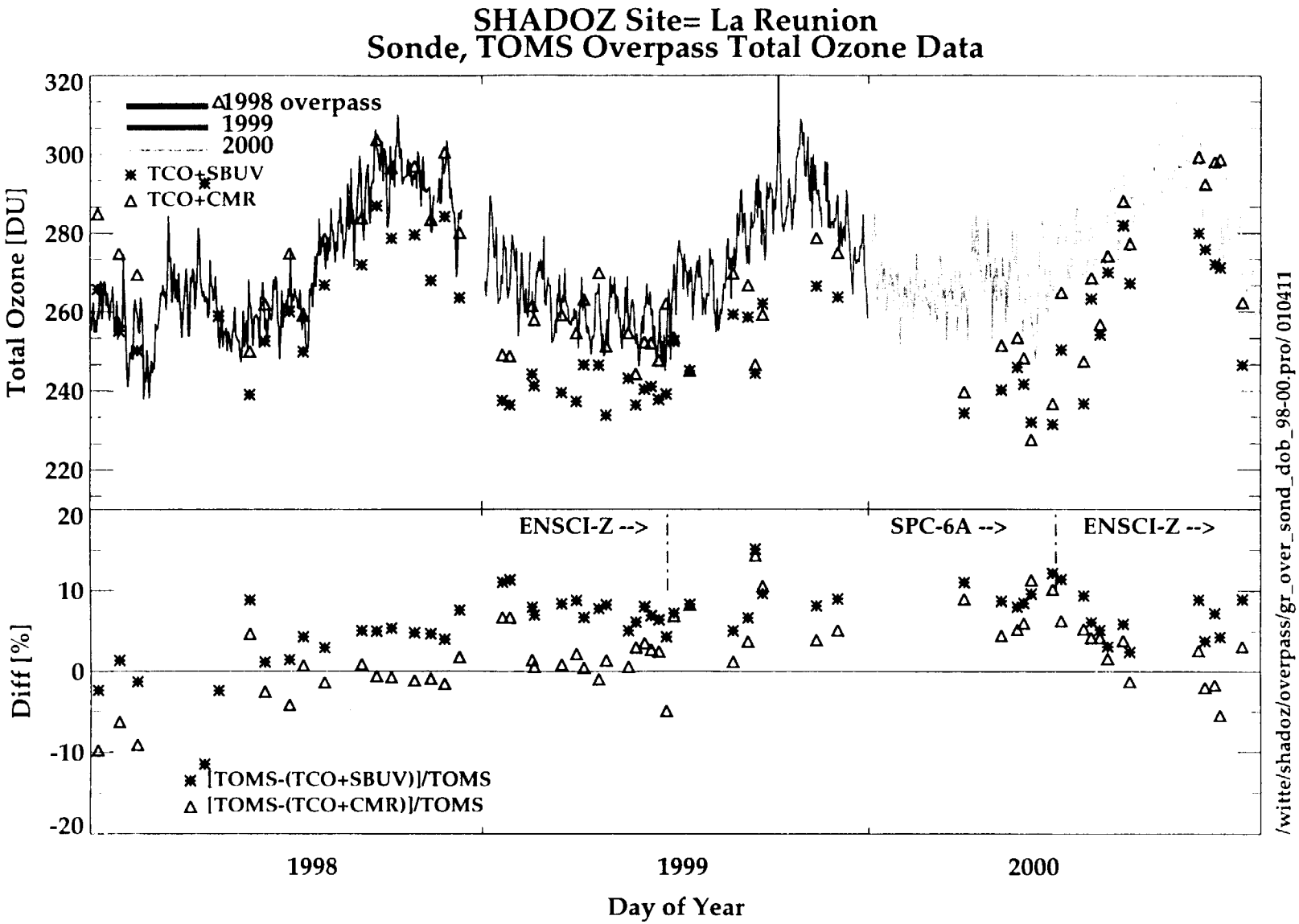
F167C


SHADOZ Site= Irene, S. Africa
Sonde, TOMS Overpass, and Dobson Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Dobson
Total Ozone [DU]
320
300
280
260
240
220
30
20
10
0
-10
-20
-30
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[Dob-(TCO+SBUV)]/Dob
[Dob-(TCO+CMR)]/Dob
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_dob_98-00.pro/ 010420

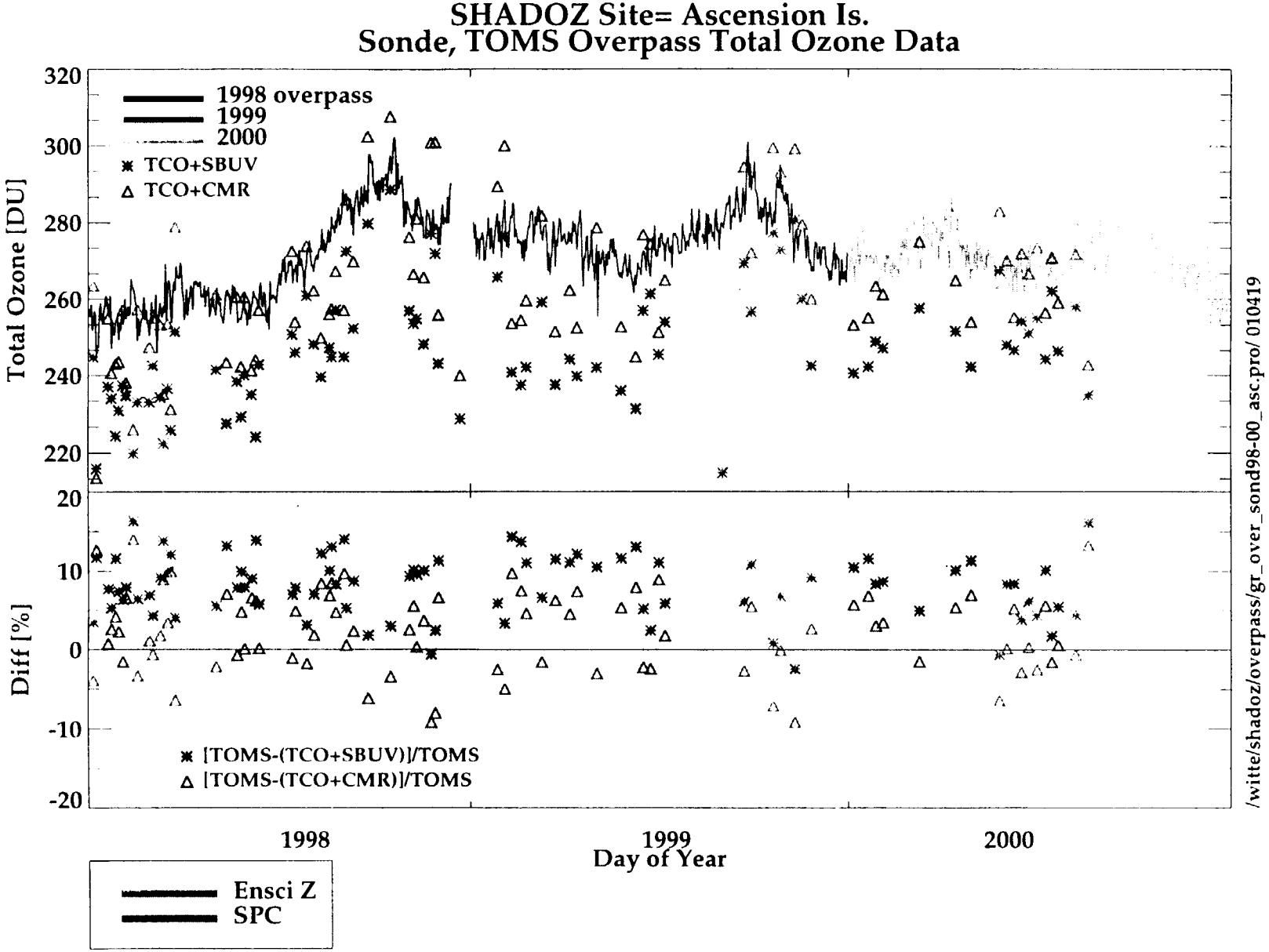
F1679


SHADOZ Site= San Cristobal
Sonde, TOMS Overpass Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Total Ozone [DU]
320
300
280
260
240
220
30
20
10
0
-10
-20
-30
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_dob_98-00.pro/ 010420

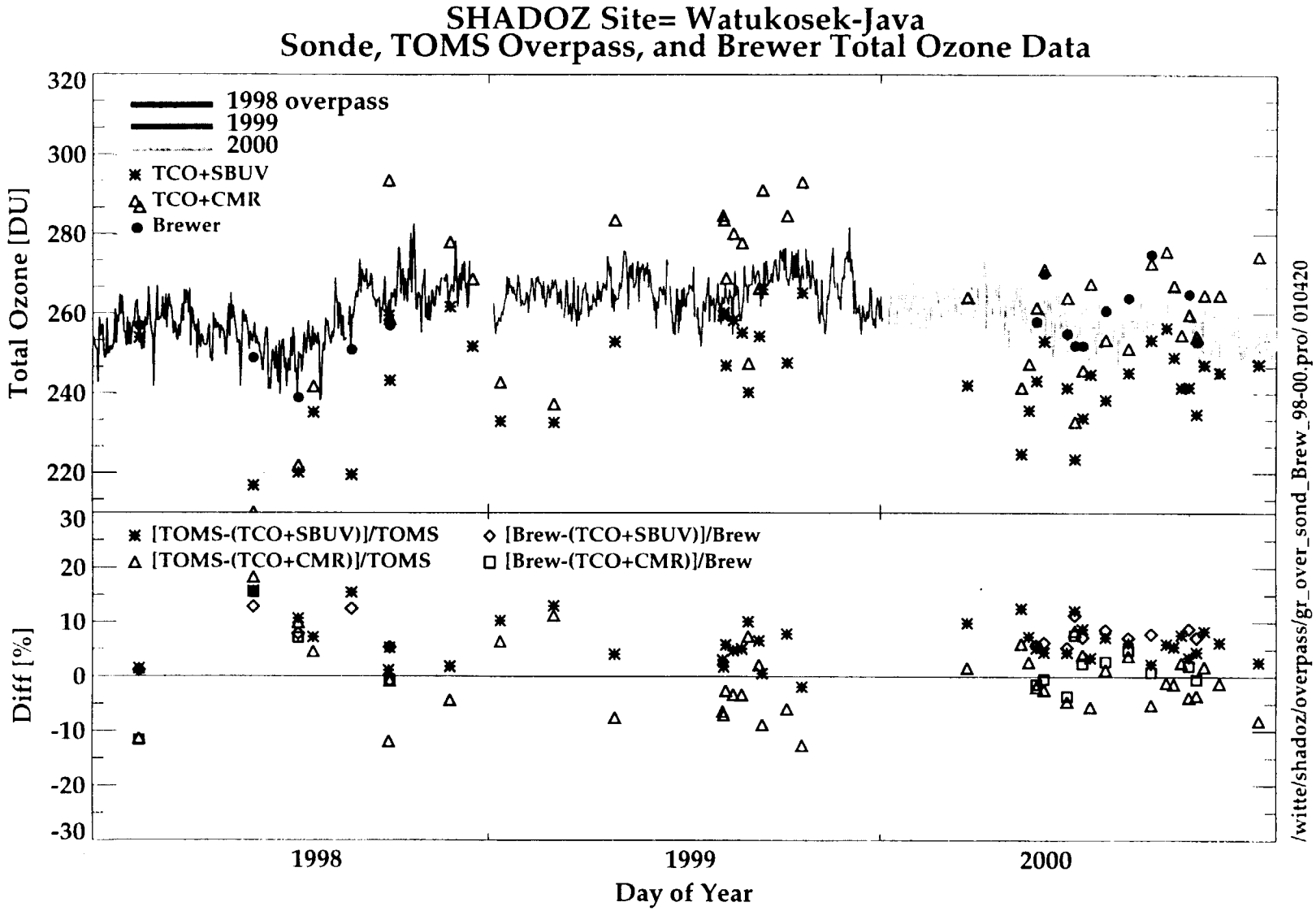
F/G 7E


SHADOZ Site= La Reunion
Sonde, TOMS Overpass Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Total Ozone [DU]
320
300
280
260
240
220
ENSCI-Z -->
SPC-6A -->
ENSCI-Z -->
Diff [%]
20
10
0
-10
-20
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_dob_98-00.pro/ 010411

TL 9/4

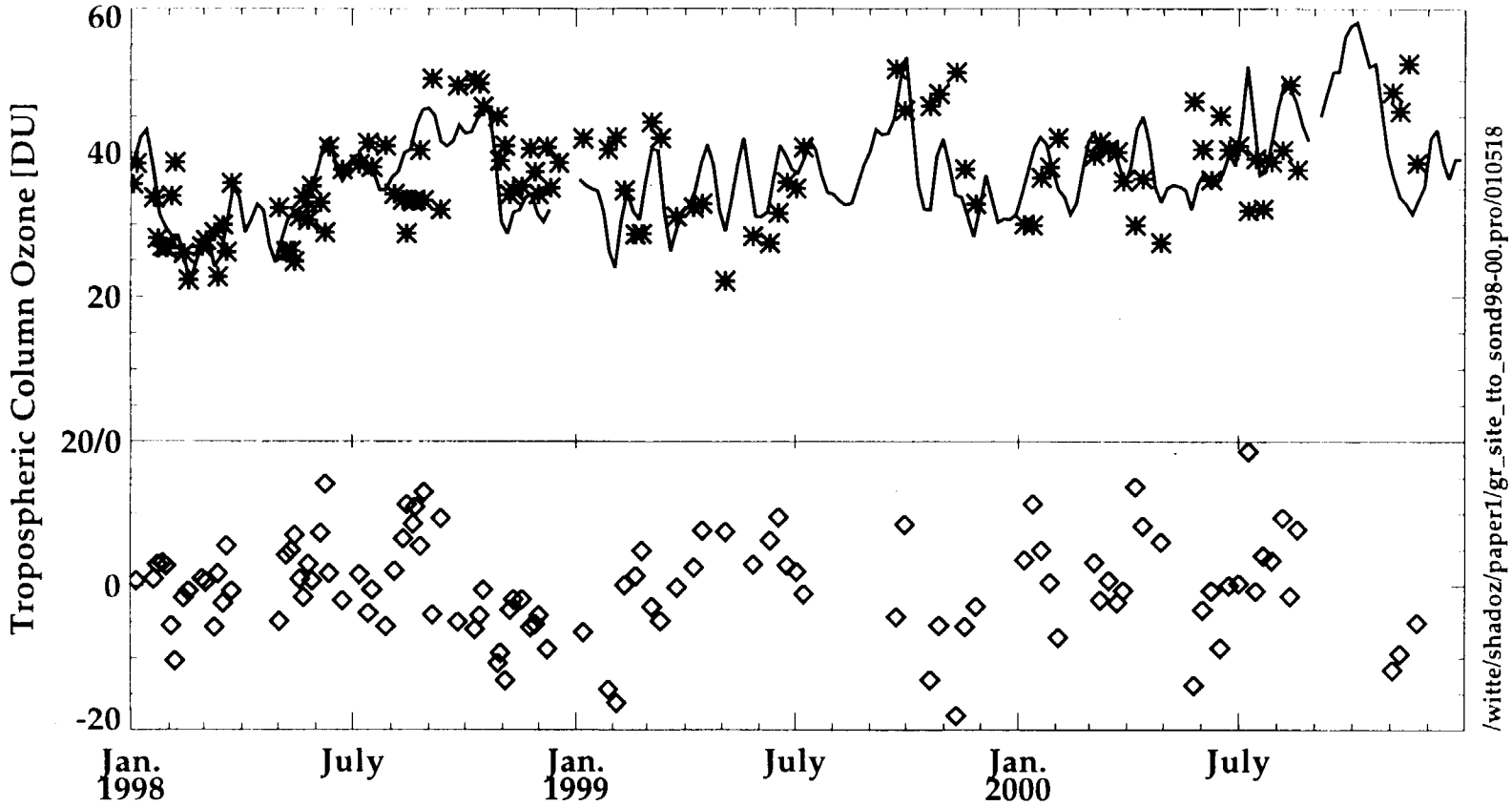

SHADOZ Site= Ascension Is.
Sonde, TOMS Overpass Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Total Ozone [DU]
320
300
280
260
240
220
20
10
0
-10
-20
Diff [%]
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond98-00_asc.pro/ 010419
Ensci Z
SPC

GL 917


SHADOZ Site= Watukosek-Java
Sonde, TOMS Overpass, and Brewer Total Ozone Data
1998 overpass
1999
2000
TCO+SBUV
TCO+CMR
Brewer
Total Ozone [DU]
320
300
280
260
240
220
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[Brew-(TCO+SBUV)]/Brew
[Brew-(TCO+CMR)]/Brew
Diff [%]
30
20
10
0
-10
-20
-30
1998
1999
2000
Day of Year
/witte/shadoz/overpass/gr_over_sond_Brew_98-00.pro/ 010420

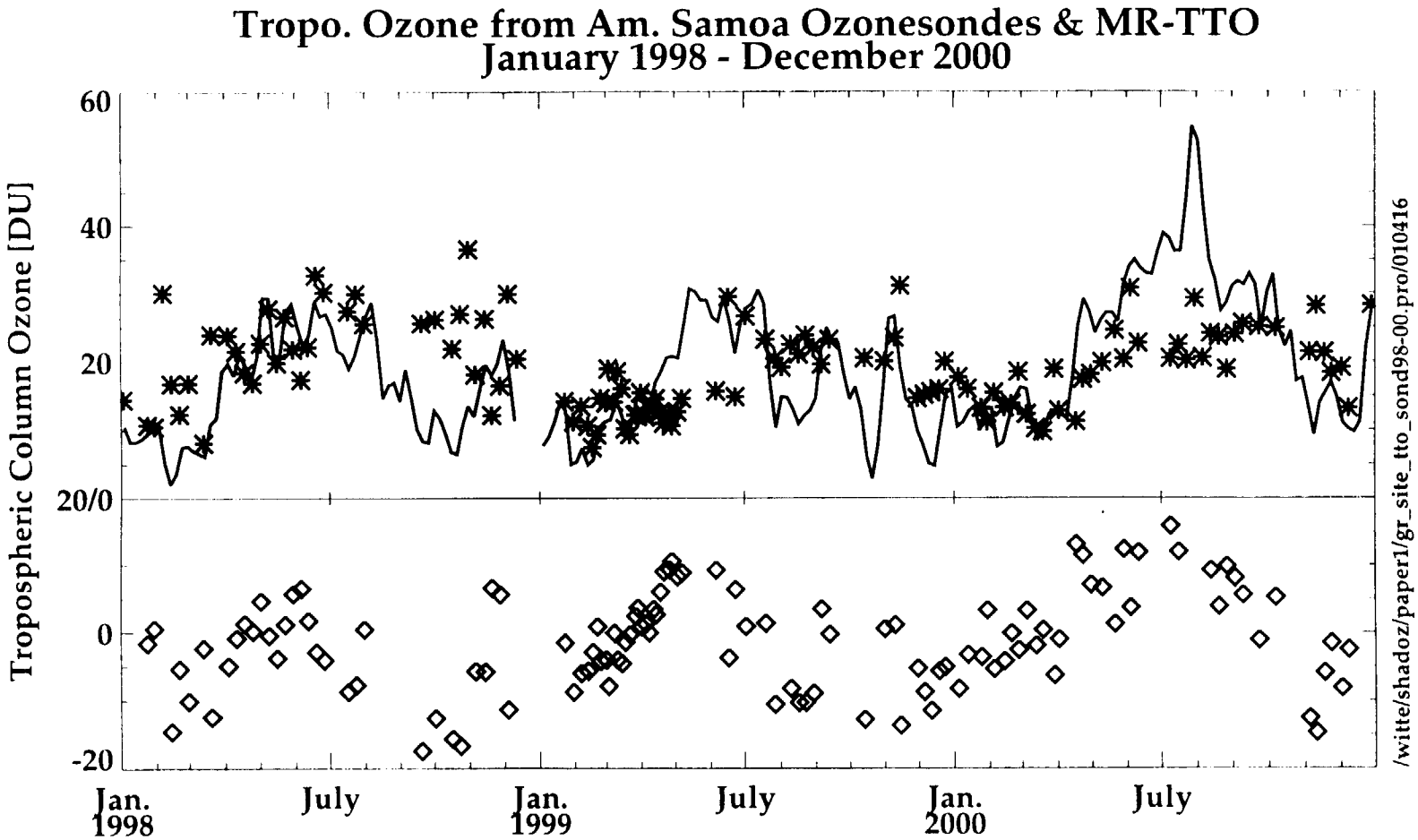
HL 9/17

Tropo. Ozone from Ascension Is. Ozonesondes & MR-TTO
January 1998 - December 2000



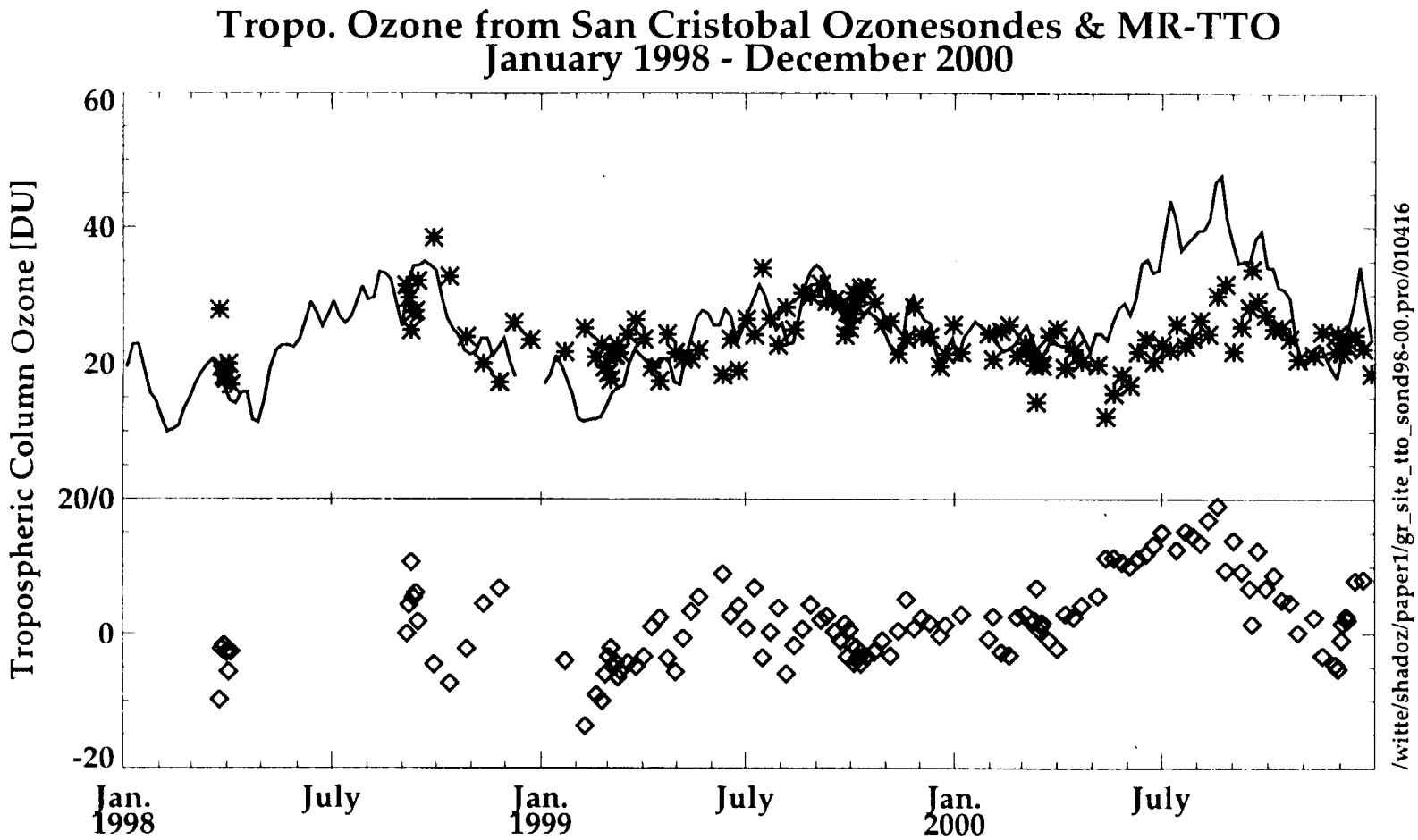
Line -- Tropo. Ozone from MR Method
Stars -- Tropo. Ozone from Ascension Is. Ozonesondes
Diamonds -- Difference (MR-Sonde)
RMS DEV. = 6.8 D.U.

F/6 8C



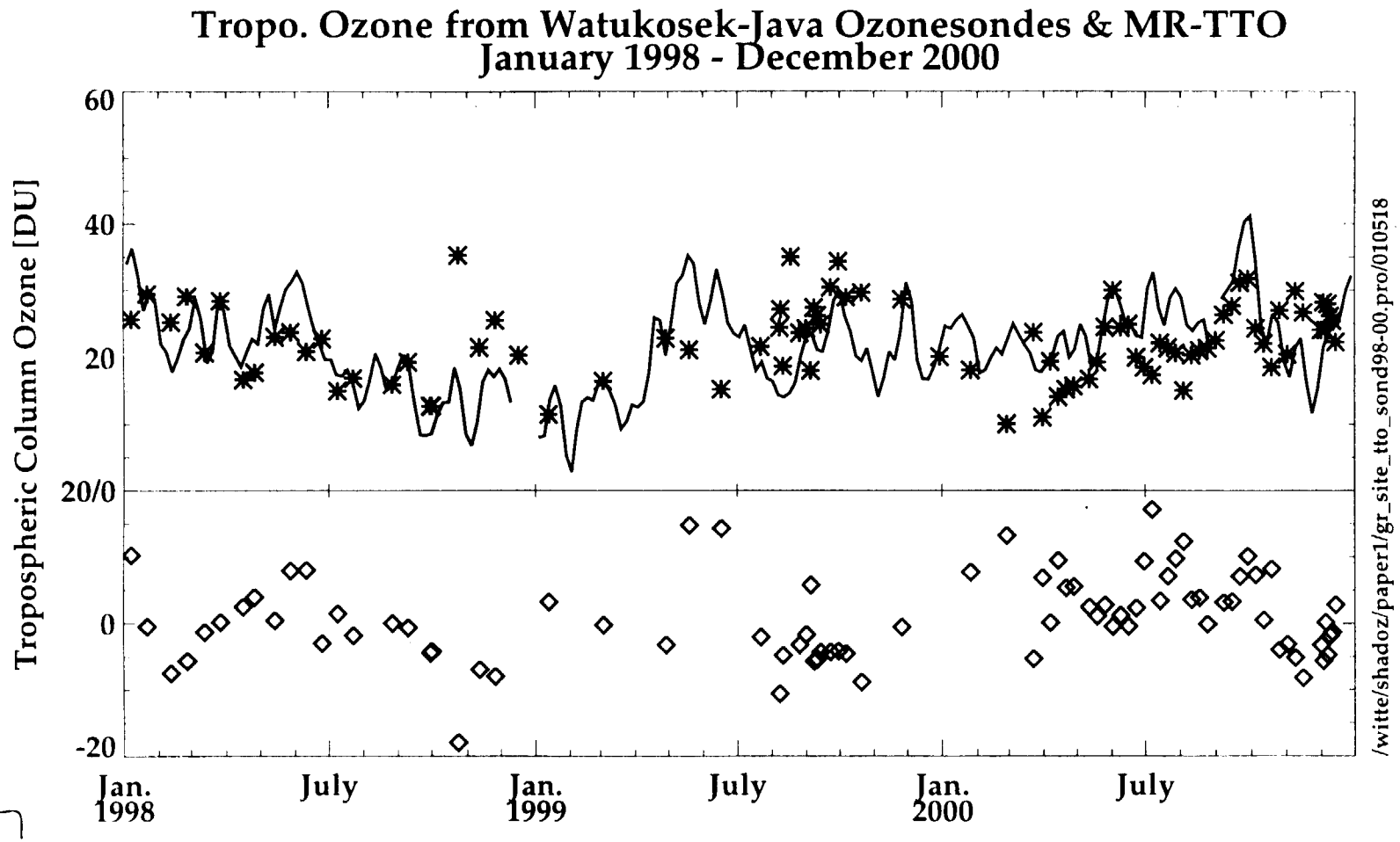
Line -- Tropo. Ozone from MR Method
Stars -- Tropo. Ozone from Am. Samoa Ozonesondes
Diamonds -- Difference (MR-Sonde)
RMS DEV. = 7.4 D.U.

GB 914



Line -- Tropo. Ozone from MR Method
Stars -- Tropo. Ozone from San Cristobal Ozonesondes
Diamonds -- Difference (MR-Sonde)
RMS DEV. = 6.5 D.U.

38 9/7



Line -- Tropo. Ozone from MR Method
Stars -- Tropo. Ozone from Watukosek-Java Ozonesondes
Diamonds -- Difference (MR-Sonde)
RMS DEV. = 6.4 D.U.

FIG 8F

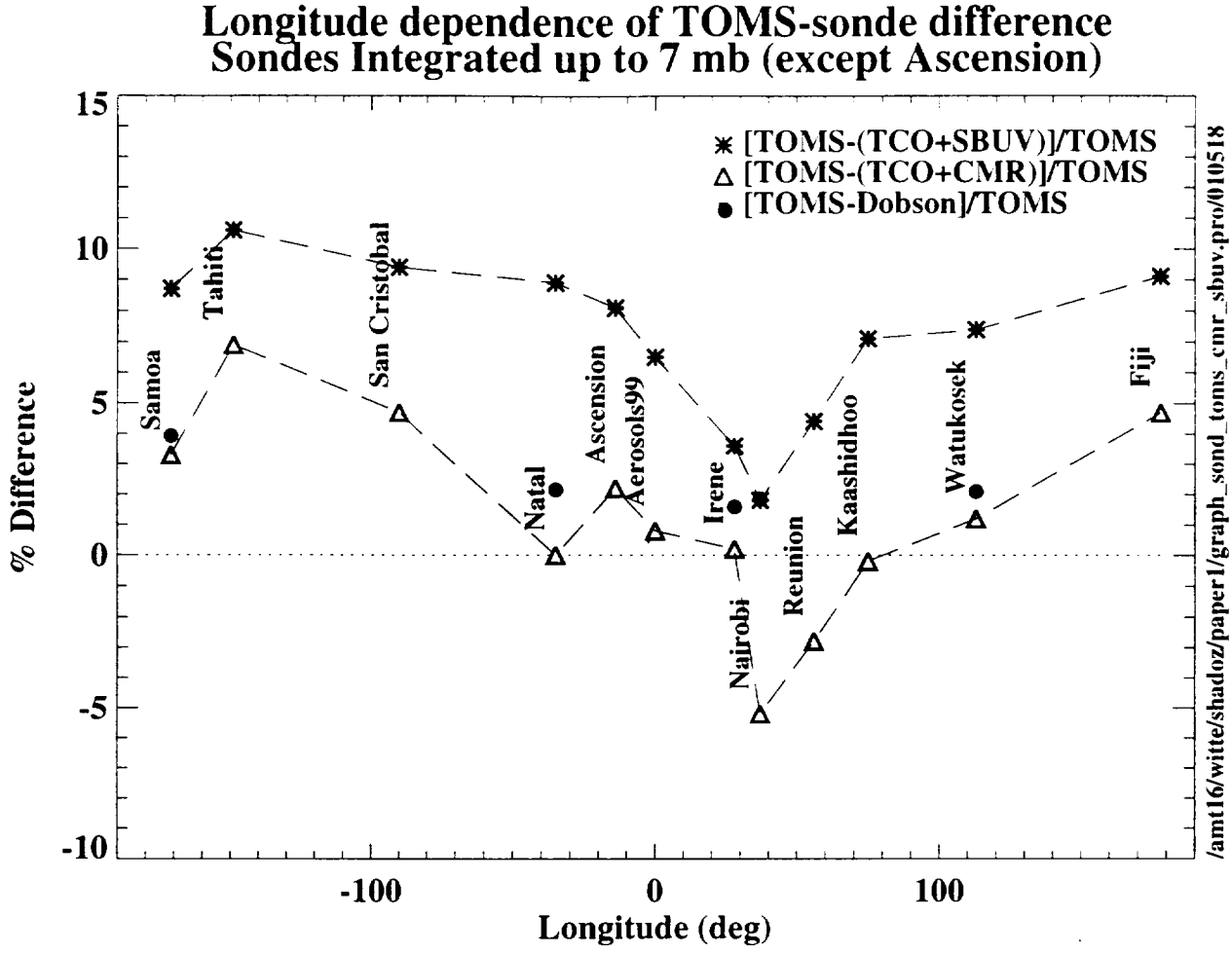

Longitude dependence of TOMS-sonde difference
Sondes Integrated up to 7 mb (except Ascension)
[TOMS-(TCO+SBUV)]/TOMS
[TOMS-(TCO+CMR)]/TOMS
[TOMS-Dobson]/TOMS
% Difference
Longitude (deg)
15
10
5
0
-5
-10
-100
0
100
Samoa
Tahiti
San Cristobal
Natal
Ascension
Aerosols99
Irene
Nairobi
Reunion
Kaashidhoo
Watukosek
Fiji
/amt16/witte/shadoz/paper1/graph_sond_toms_cmr_sbuv.pro/010518

FIG 9

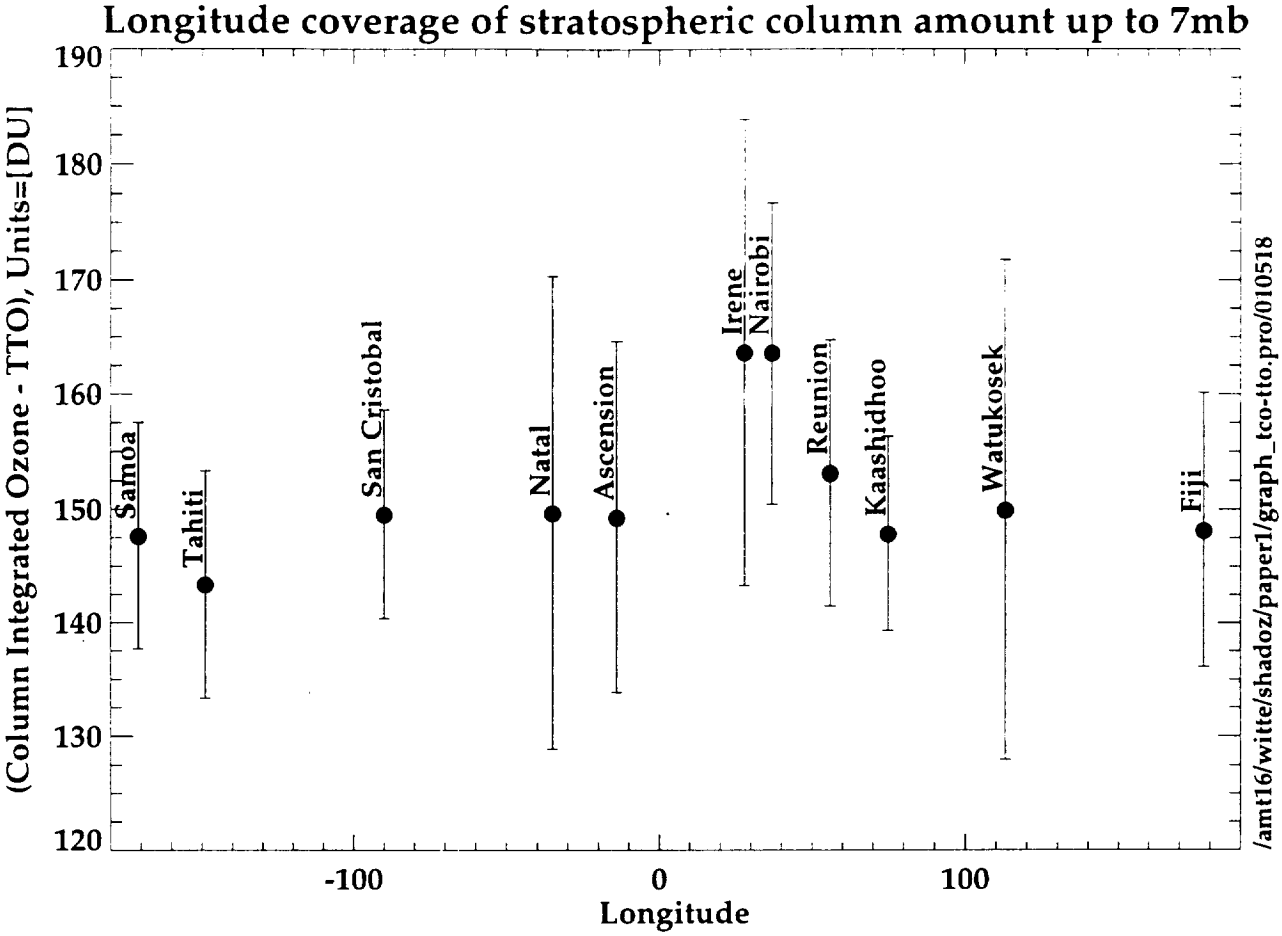

Longitude coverage of stratospheric column amount up to 7mb
(Column Integrated Ozone - TTO), Units=[DU]
190
180
170
160
150
140
130
120
-100
0
100
Longitude
Samoa
Tahiti
San Cristobal
Natal
Ascension
Irene
Nairobi
Reunion
Kaashidhoo
Watukosek
Fiji
/am16/witte/shadoz/paper1/graph_tco-tto.pro/010518

FIG 10

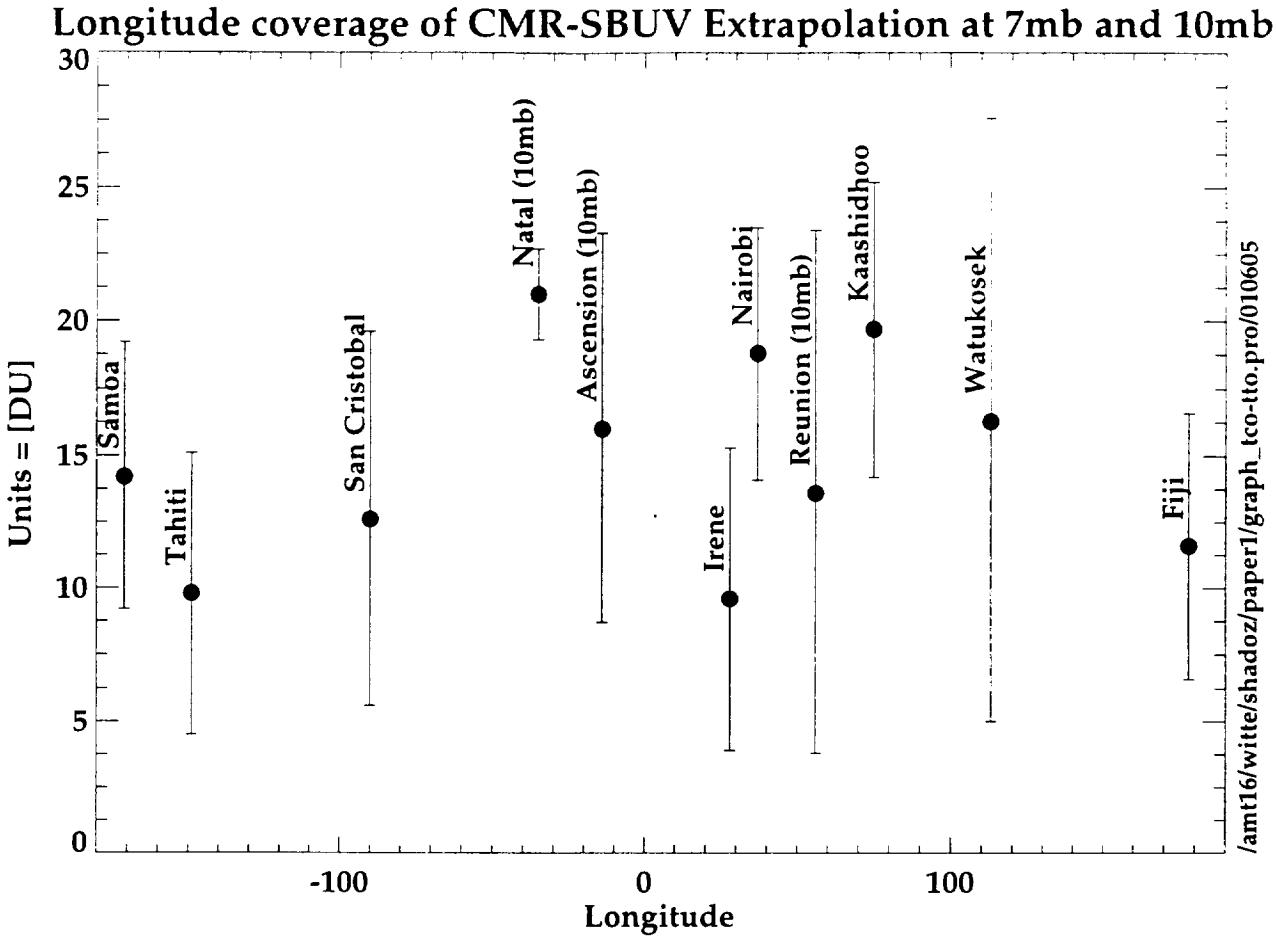

Longitude coverage of CMR-SBUV Extrapolation at 7mb and 10mb
Units = [DU]
30
25
20
15
10
5
0
-100
0
100
Longitude
Samba
Tahiti
San Cristobal
Natal (10mb)
Ascension (10mb)
Irene
Nairobi
Reunion (10mb)
Kaashidhoo
Watukosek
Fiji
/amt16/witte/shadoz/paper1/graph_tco-tto.pro/010605

FIG 11

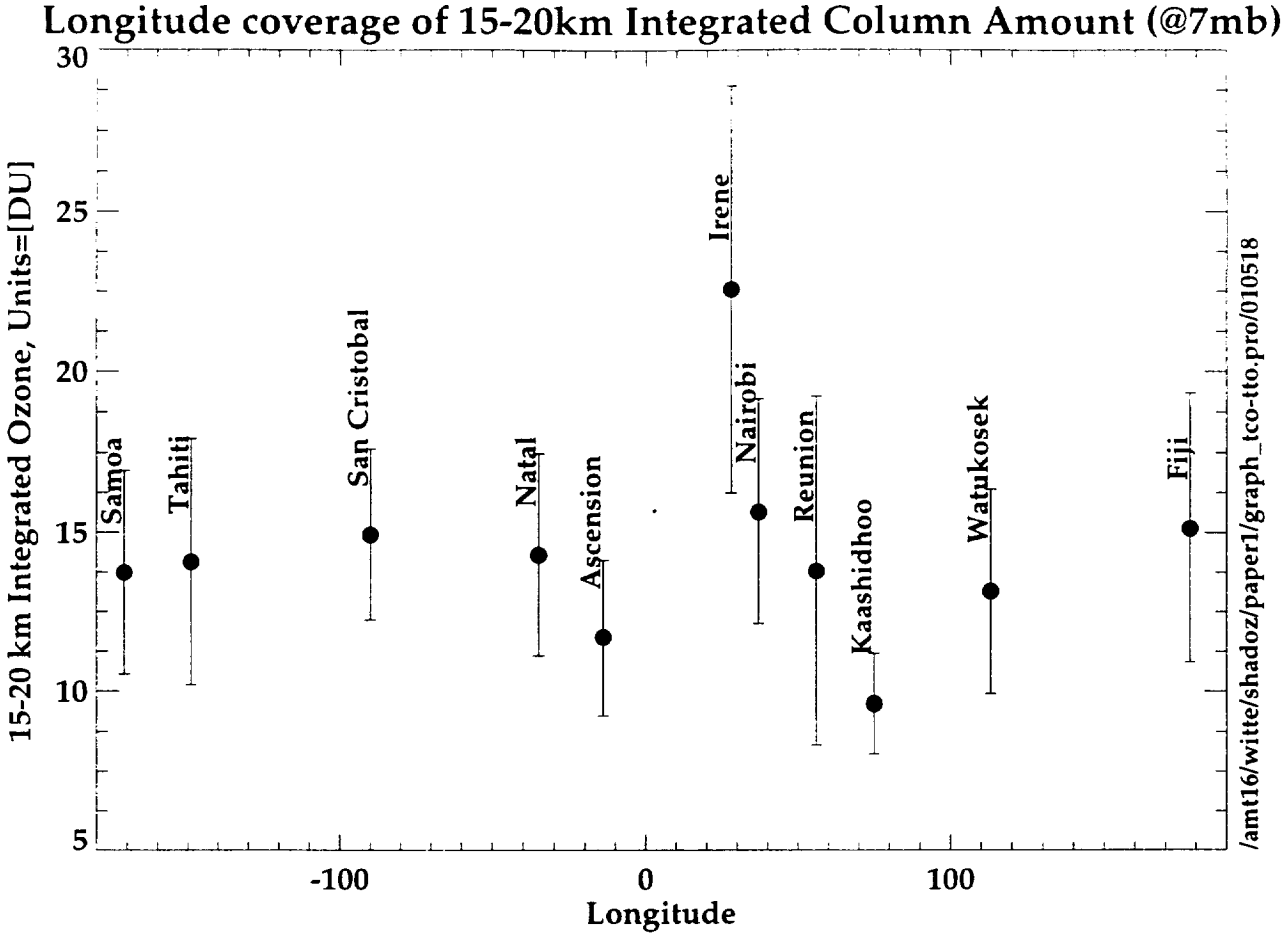
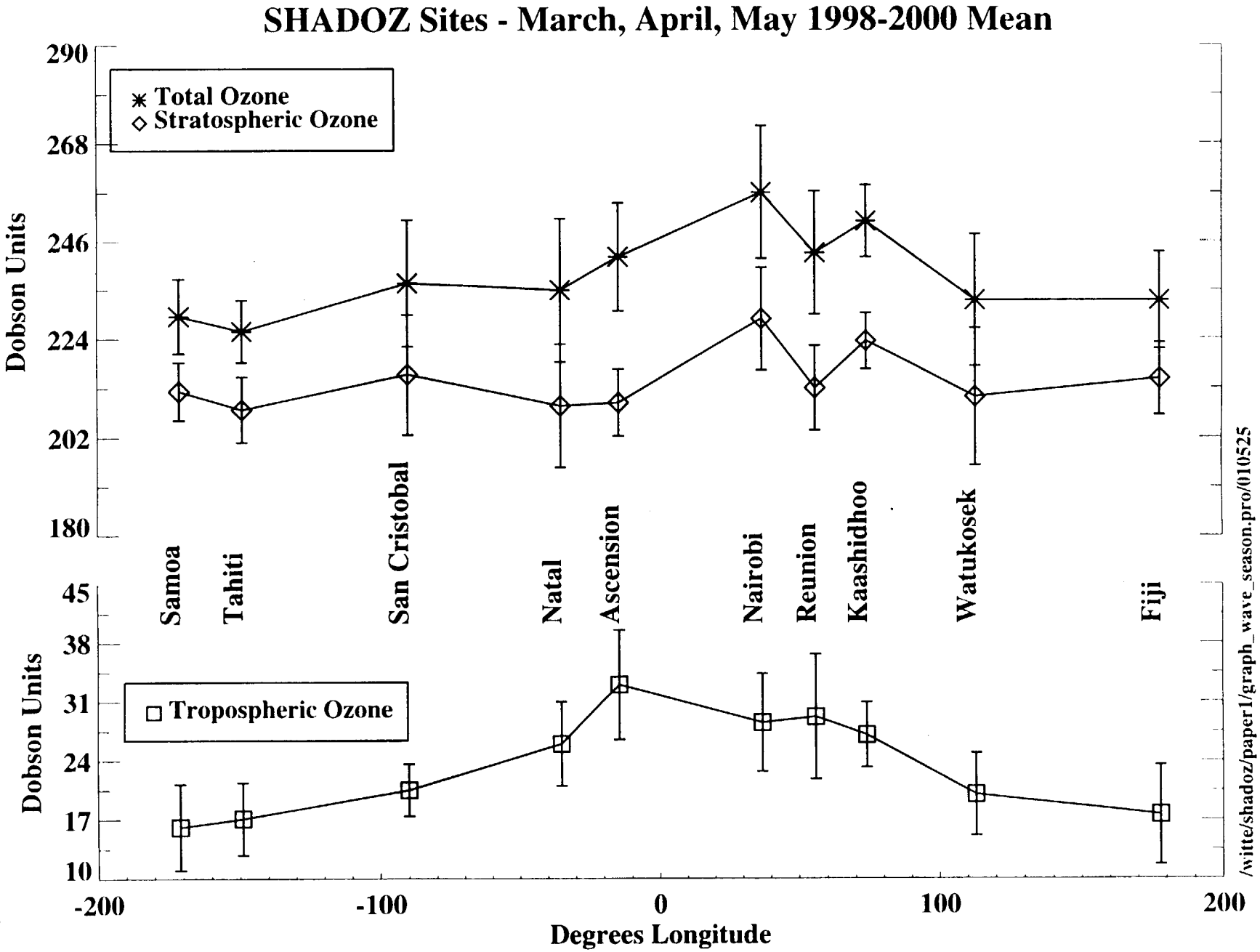

Longitude coverage of 15-20km Integrated Column Amount (@7mb)
15-20 km Integrated Ozone, Units=[DU]
30
25
20
15
10
5
-100
0
100
Longitude
Samoa
Tahiti
San Cristobal
Natal
Ascension
Irene
Nairobi
Reunion
Kaashidhoo
Watukosek
Fiji
/amt16/witte/shadoz/paper1/graph_tco-tto.pro/010518

FIG 12


SHADOZ Sites - March, April, May 1998-2000 Mean
Total Ozone
Stratospheric Ozone
Dobson Units
290
268
246
224
202
180
Samoa
Tahiti
San Cristobal
Natal
Ascension
Nairobi
Reunion
Kaashidhoo
Watukosek
Fiji
Tropospheric Ozone
Dobson Units
45
38
31
24
17
10
-200
-100
0
100
200
Degrees Longitude
/witte/shadoz/paper1/graph_wave_season.pro/010525

F16 13

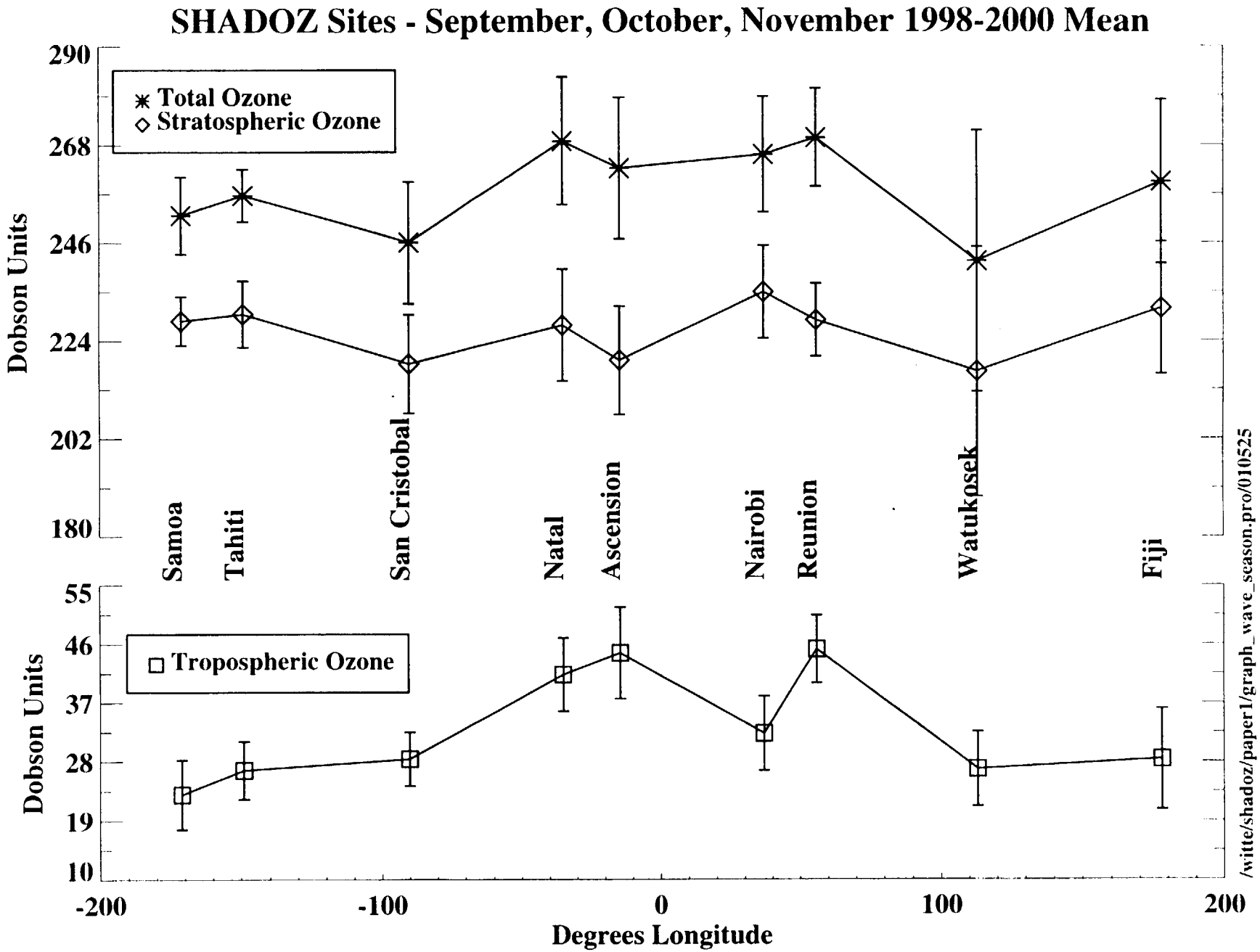
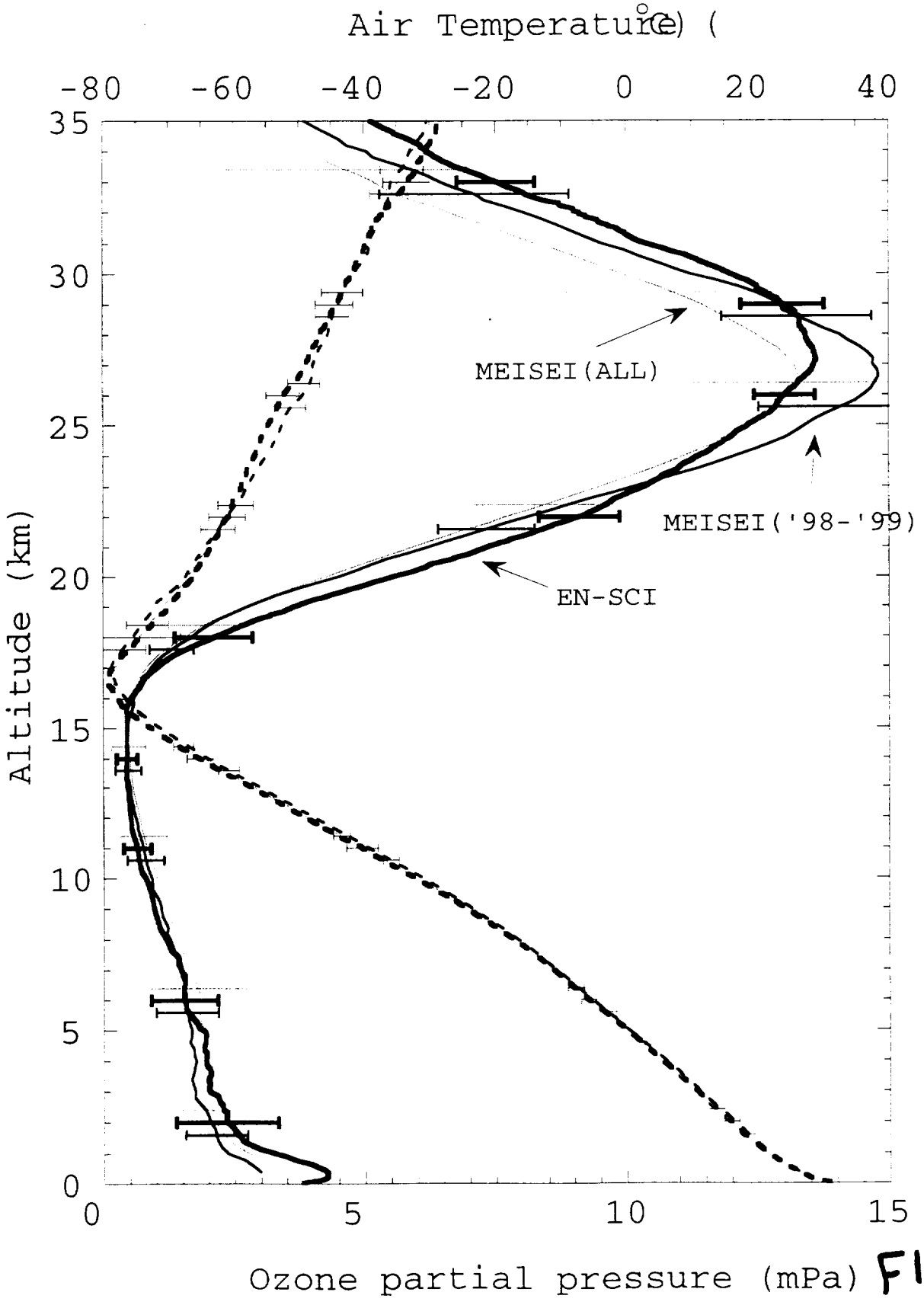

SHADOZ Sites - September, October, November 1998-2000 Mean
Total Ozone
Stratospheric Ozone
Tropospheric Ozone
Dobson Units
290
268
246
224
202
180
55
46
37
28
19
10
Samoa
Tahiti
San Cristobal
Natal
Ascension
Nairobi
Reunion
Watukosek
Fiji
-200
-100
0
100
200
Degrees Longitude
/witte/shadoz/paper1/graph_wave_season.pro/010525

Fig 14


Air Temperature (°C)
-80
-60
-40
-20
0
20
40
35
30
25
20
15
10
5
0
Altitude (km)
MEISEI(ALL)
MEISEI('98-'99)
EN-SCI
0
5
10
15
Ozone partial pressure (mPa)

FIGA-1