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Equatorial Ozone Profiles From the Ground to 52 km During the Southern Hemisphere Autumn

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We report the results of an ozone measurement campaign conducted at Natal, Brazil (5.9°S, 35.2°W) from March 25 to April 15, 1985. Seven profiles were obtained during this period, using ROCOZ-A and electrochemical concentration cell ozonesondes, standard U.S. meteorological radiosondes, and Super-Loki datasondes. Complete profiles of ozone, pressure, and temperature were obtained from the ground to 52 km, and all of the profiles correspond with site overpasses by ozone instruments on NASA and National Oceanic and Atmospheric Administration satellites. The profiles from this measurement series show reasonable agreement with established satellite climatologies. Stratospheric ozone variability was 2% or less during the 3 weeks of the measurement campaign, with stratospheric temperature and pressure variabilities half that amount. Low variability at a single location for this period implies comparable uniformity for ozone profiles over a large area around the measurement site. This condition at Natal removes the requirement of exact concurrence between satellite and local ozone measurements, allowing comparisons of larger sets of profiles and improving the precision of the intercomparisons. Regional ozone stability also allows an overall intercomparison of ozone measurements among the four satellites without the need for zonal mean averages. The auxiliary pressure and temperature profiles presented here allow the use of this data set as a transfer standard between satellite instruments with different fundamental ozone measurements. Finally, the low ozone variability in the stratosphere at Natal during this measurement series should provide an opportunity for high-quality intercomparisons of measured and modeled ozone concentrations in the equatorial stratosphere and lower mesosphere as well as a consistency check among satellite ozone measurements.

INTRODUCTION

In 1978 the Instituto de Pesquisas Espaciais (INPE) of Brazil and the National Aeronautics and Space Administration of the United States initiated a joint program to measure equatorial ozone profiles at Natal, Brazil (5.9°S, 35.2°W). A Dobson spectrophotometer (number 93) has also been in operation at Natal since 1978 as part of a collaboration between INPE and the National Oceanic and Atmospheric Administration (NOAA) of the United States. Analyses of atmospheric soundings with electrochemical concentration cell ozonesondes (ECCs) have been published [*Kirchhoff et al.*, 1981, 1983], and to date, more than 150 ECC ozone profiles have been collected. In a recent study, *Logan and Kirchhoff* [1986] used the ECC database to develop a climatology for ozone at Natal in the troposphere and the lower stratosphere, revealing a significant seasonal cycle in tropospheric ozone concentrations. In addition, an extensive set of Dobson measurements has been reported from Brazil [*Sahai et al.*, 1982].

We present here a set of ozone measurements from the ground to 52 km in the austral autumn as part of the continuing collaboration between INPE and NASA. Seven profiles were obtained at Natal over a 3-week period from March 25 to April 15, 1985, using ROCOZ-A and ECC ozonesondes, standard U.S. meteorological radiosondes, and Super-Loki datasondes. ROCOZ-A is a rocket-borne ultraviolet radiometer [*Barnes and Simeth*, 1986], and the ECC is a balloon-borne electrochemical ozone sensor [*Komhyr*, 1969; *Komhyr and Harris*, 1971]. This complete assembly of ozone and other atmospheric values should make a significant contribution to the published set of equatorial ozone measurements, which still remains sparse.

FLIGHT SUMMARY

The Natal measurement series described here was initiated for correlative support of ozone measurements from four NASA and NOAA satellites. The flight series was designed to check satellite retrievals of ozone profiles that are significantly different from those in the northern mid-latitudes. The measurements were made in conjunction with overpasses of the Solar Mesosphere Explorer (SME), of the Stratospheric Aerosol and Gas Experiment (SAGE II) instrument on the Earth Radiation Budget Satellite, and of the Solar Backscattered Ultraviolet (SBUV) instruments on Nimbus 7 and NOAA 9. These results also provide the first set of equatorial ozone profiles from the ground to 52 km in the southern hemisphere autumn.

Launch information for these measurements is given in

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TABLE 1. Launch Information for the Natal (5.9°S, 35.2°W) Measurement Series

Date (1985)	ROCOZ-A Launch Time, UT	Solar Zenith Angle, deg	Satellite Ozone Measurement Times, UT			
			Nimbus 7	NOAA 9	SME	SAGE II
March 25	1735	50[a]		1703		1948
March 27	1735	51		1642	1813	
April 4	1523	21	1420	1657		
April 5	1036	58				0812
April 6	1031	58				0825
April 13	1755	56		1702	1813	
April 15	1519	23	1412	1641		

[a] This is the solar zenith angle as the ROCOZ-A payload descended through 40 km.

Table 1. Each daily set of flights included atmospheric soundings from four instruments: a ROCOZ-A ozonesonde; a Super-Loki datasonde; and a balloon containing both a standard U.S. meteorological radiosonde and an ECC ozonesonde. The daily flight schedule for this measurement series had a balloon launch 2-hours before the ROCOZ-A flight and a Super-Loki datasonde launch immediately after the conclusion of the ROCOZ-A measurements.

The ROCOZ-A ozonesonde measures the solar ultraviolet irradiance over its four filter wavelengths as the instrument descends on a parachute. It is the third version in an instrument development sequence that started with a radiometer designed by A. J. Krueger and W. R. McBride for stratospheric soundings on an ARCAS rocket [*Krueger and McBride*, 1968*a*, *b*]. The amount of ozone between the ROCOZ-A radiometer and the sun is calculated from the attenuation of solar flux as the instrument falls, using the Beer-Lambert law. The fundamental measurement from ROCOZ-A is ozone overburden (column content) versus radar altitude from 20 to 53 km. The slope of these measurements gives ozone number density.

The ECC ozonesonde is a small, balloon-borne sensor developed at NOAA [*Komhyr*, 1969; *Komhyr and Harris*, 1971]. The sensor is based on an iodine/iodide redox concentration cell composed of two platinum electrodes immersed in neutral buffered iodide solutions of different concentrations in the anode and cathode chambers. An electric current is generated when air containing ozone is pumped into the cathode. Along with a measurement of air temperature within the instrument pump, this current is converted into ozone partial pressure (in nanobars), the primary output unit for the ECC ozonesonde.

The ECC is carried aloft, accompanied by a standard U.S. meteorological radiosonde that measures pressure and temperature from the ground to the burst altitude of the balloon [*Schmidlin et al.*, 1982]. Temperatures were also measured with rocket-borne Super-Loki datasondes [*Miller and Schmidlin*, 1971; *Schmidlin*, 1981] that were radar tracked from the top of the ROCOZ-A profiles down to about 20 km.

The flight series was conducted at Centro de Lancamento da Barreira do Inferno, the Brazilian Air Force rocket launch facility at Natal. The facility includes a French-built C band tracking radar (Thompson-CSF model TH.D.1216). Altitude measurements from this radar have an accuracy and a precision of the order of 50 m, equivalent to the quality of radar measurements from the C band radars at NASA's Wallops Flight Facility [*Barnes et al.*, 1986]. Limitations in the availability of the Brazilian radar facility for our measurements restricted radar tracking to only the ROCOZ-A and Super-Loki datasonde rocket flights. The ECC/radiosonde balloon ascents were not radar tracked, and altitudes for these flights were calculated from the radiosonde temperatures and pressures, giving altitudes in geopotential meters.

For this measurement series the tables of *List* [1963] have been used to convert the radiosonde altitudes to geometric meters. At 20 km the difference between geopotential and geometric altitude is 100 m at Natal. This correction is applied only to the seven ECC ozonesonde flights presented here. It is not part of the ROCOZ-A data reduction scheme [*Barnes et al.*, 1986], since auxiliary balloon flights for the project are radar tracked as a matter of practice.

Overcast conditions prevented Dobson direct-sun ozone measurements for two of the flight days in the Natal campaign. As a result, no Dobson results are presented here. In addition, the five remaining Dobson measurements were not used to normalize the ozone measurements from the concurrent ECC ozonesondes, although normalization to Dobson has been common practice with electrochemical sondes [*Attmanspacher and Dütsch*, 1981]. There is the possibility that this normalization might skew ECC ozone profiles with altitude, especially in the troposphere [*Barnes*, 1982; *Hilsenrath et al.*, 1986]. Also, presentation of unnormalized ECC profiles allows direct comparison of these measurements with the existing ECC data base at Natal [*Kirchhoff et al.*, 1981, 1983; *Logan and Kirchhoff*, 1986].

The ECC ozonesondes in this flight series used 1.5% potassium iodide sensing solutions, and the sampling pump efficiencies for the ECCs [*Torres*, 1981] were individually measured before flight. Estimates of the effect of the concentration of the ECC sensing solution on the instrument output have been published [*Barnes et al.*, 1985; *Hilsenrath et al.*, 1986]. The radiosondes in this flight series did not have hypsometers for high-altitude pressure measurements, decreasing the quality of the results from the balloon-borne instruments.

Estimates of Stratospheric Variabilities

For altitudes above 20 km the entire set of measurements shows remarkably low variability. This can be seen in the relative standard deviations listed in Tables 2 and 3. For the most part these tables give the results from seven flights. However, for the first flight set (March 25), radar did not locate the ROCOZ-A payload until it had descended to 43 km. For all other flights, radar acquisition of the ROCOZ-A and Super-Loki datasonde instruments occurred by payload apogee. As a

TABLE 2. Mean Ozone Measurements from the Flight Series

Geometric Altitude, km	Ozone Overburden, molecule/cm²	Relative s.d., %	Ozone Number Density, molecule/cm³	Relative s.d., %	Ozone Mixing Ratio, ppmv	Relative s.d., %
			ROCOZ-A Values			
52	1.67(16)	5.5[a]	3.96(10)	4.0[a]	2.25	3.5[a]
50	2.65(16)	4.6	6.05(10)	2.9	2.70	2.0
48	4.17(16)	3.8	9.31(10)	2.8	3.27	1.9
46	6.48(16)	3.6	1.42(11)	4.5	3.88	2.6
44	9.96(16)	3.9	2.10(11)	5.1	4.48	2.1
42	1.52(17)	3.8	3.27(11)	3.3	5.28	2.9
40	2.37(17)	3.2	5.46(11)	3.5	6.56	3.7
38	3.79(17)	2.7	9.03(11)	3.4	8.10	3.4
36	6.06(17)	2.6	1.39(12)	3.3	9.34	3.5
34	9.45(17)	2.7	2.02(12)	3.2	9.98	4.3
32	1.43(18)	2.7	2.83(12)	2.9	10.20	3.5
30	2.08(18)	2.6	3.73(12)	2.5	9.92	2.6
28	2.91(18)	2.4	4.51(12)	2.8	8.81	2.6
26	3.86(18)	2.2	4.88(12)	3.3	6.95	3.9
24	4.83(18)	2.1	4.59(12)	3.6	4.72	4.3
22	5.66(18)	2.0	3.53(12)	1.2	2.59	1.8
20	6.22(18)	1.9	1.87(12)	12.9	0.957	10.0
			ECC Values			
24			4.32(12)	6.0	4.43	6.3
22			3.45(12)	5.8	2.53	5.6
20			1.75(12)	14.3	0.897	15.7
18			6.35(11)	34.4	0.220	32.5
16			3.55(11)	26.3	0.086	26.8
14			2.89(11)	17.9	0.053	19.2
12			2.76(11)	22.3	0.041	21.7
10			3.09(11)	19.7	0.036	19.0
8			4.04(11)	20.1	0.038	19.8
6			5.01(11)	18.3	0.038	18.4
4			5.19(11)	12.1	0.032	12.8
2			4.38(11)	16.3	0.022	12.6

Read 1.67(16) as 1.67 × 10^{16}.

[a] The percentages represent one relative standard deviation. For altitudes below 43 km the relative standard errors of the means can be obtained by dividing the percentages by the square root of 7; for altitudes above 43 km by dividing by the square root of 6 (see text for details).

result, the data for altitudes above 43 km are derived from only six flights.

The data reduction procedure for ROCOZ-A measurements has been described previously [*Barnes et al.*, 1986]. For each flight series the ozone and atmospheric values from ROCOZ-A are averaged over 2-km intervals, centered at the reference altitudes. The mean values listed in Tables 2 and 3 are composed of the 2-km average values from the seven individual flights. ECC ozone values and auxiliary measurements from the balloon instruments are shown only to 24 km, since readings from the aneroid pressure transducers become more suspect at higher altitudes [*Schmidlin et al.*, 1982; *Parsons et al.*, 1984], as do the readings from the ECC ozonesondes [*Barnes et al.*, 1985; *Hilsenrath et al.*, 1986]. An arbitrary lower-altitude limit of 20 km has also been set for ozone measurements from ROCOZ-A, since there is a minimal contribution to ozone column content below this altitude [*Barnes et al.*, 1986]. In addition, multiple Rayleigh scattering introduces an error to the ozone overburden calculations below this altitude [*Holland et al.*, 1985].

These altitude ranges do not mark the absolute limits for measurements from either ROCOZ-A or ECCs. However, we feel that they mark the intervals over which the quality of the measurements from the instruments is well defined. Our purpose has been to present the best possible composite profiles for ozone, pressure, and temperature for this campaign, rather than to present a set of profiles extended to the altitude limits for each instrument.

Above 20 km the standard deviations of the ozone measurements are almost equivalent to the instrument-to-instrument repeatabilities of the ozone sensors. This is remarkable for a data set that has been collected over a period of 3 weeks and over a set of solar zenith angles from 20° to 60°. It reflects an exceptionally low variability in the equatorial stratosphere, at least during this southern hemisphere autumn.

The fundamental ozone measurement from the ROCOZ-A radiometer, as mentioned previously, is ozone overburden versus radar altitude. At one standard deviation the repeatability of these measurements from ROCOZ-A averages 2.4% and is independent of altitude [*Holland et al.*, 1985; *Barnes et al.*, 1986]. For the measurement series presented here the relative standard deviations averaged 3.1%, with a slight increase from 20 to 52 km (Figure 1).

From ROCOZ-A measurements, ozone number density is calculated as the slope of ozone overburden (column content) versus altitude. For ozone number density the instrumental repeatability averages 3.2%, with a significant increase in the variability between instruments at altitudes below the ozone

TABLE 3. Mean Auxiliary Measurements from the Flight Series

Geometric Altitude, km	Pressure, mbar	Relative s.d., %	Temperature, °K	Relative s.d., %	Total Density, *molecule/cm^3*	Relative s.d., %
			Super-Loki Datasonde Values			
52	0.65	2.3[a]	265.	1.3[a]	1.76(16)	2.1[a]
50	0.83	2.1	269.	1.3	2.24(16)	1.7
48	1.06	1.9	271.	0.6	2.85(16)	1.8
46	1.36	2.0	271.	1.4	3.65(16)	3.1
44	1.75	2.3	270.	1.4	4.70(16)	3.5
42	2.26	2.5	265.	1.4	6.18(16)	2.3
40	2.93	2.3	255.	0.9	8.33(16)	1.8
38	3.83	2.2	249.	0.9	1.11(17)	2.4
36	5.03	2.2	245.	1.2	1.49(17)	2.3
34	6.65	2.3	237.	1.0	2.03(17)	3.0
32	8.87	2.4	232.	1.3	2.77(17)	3.1
30	11.9	2.5	229.	0.7	3.75(17)	2.6
28	16.0	2.5	226.	0.7	5.12(17)	2.5
26	21.6	2.4	223.	0.5	7.03(17)	2.1
24	29.4	2.3	218.	0.8	9.74(17)	2.3
22	40.2	2.3	213.	0.6	1.36(18)	2.3
20	55.5	2.0	206.	1.0	1.95(18)	2.0
			Meteorological Radiosonde Values			
24	29.6	3.2	220.	1.1	9.74(17)	2.9
22	40.3	2.6	215.	0.7	1.36(18)	2.2
20	55.5	2.0	206.	1.0	1.95(18)	2.0
18	77.8	1.6	195.	1.8	2.89(18)	2.0
16	110.	1.4	195.	0.7	4.11(18)	1.1
14	155.	1.2	205.	0.6	5.48(18)	0.9
12	212.	0.9	221.	0.7	6.94(18)	0.5
10	285.	0.7	238.	0.8	8.67(18)	0.6
8	376.	0.6	253.	0.6	1.08(19)	0.6
6	489.	0.5	266.	0.5	1.33(19)	0.5
4	629.	0.4	277.	0.4	1.65(19)	0.4
2	801.	0.3	287.	0.6	2.02(19)	0.5

Read 1.76(16) as 1.76 × 10^{16}.

[a] The percentages represent one relative standard deviation. For altitudes below 43 km the relative standard errors of the means can be obtained by dividing the percentages by the square root of 7; for altitudes above 43 km by dividing by the square root of 6 (see text for details).

number density maximum [*Barnes et al.*, 1986]. This increased difference between instruments reflects a fundamental limit in measurements based on ozone column content, which shows little change in the lower stratosphere and the troposphere. From the ground to 20 km there is less than a 20% contribution to total ozone overburden, giving insufficient information to obtain ozone density profiles in the lower stratosphere and the troposphere. This limitation also applies to remote ozone measurements from satellites.

As shown in Figure 2, the relative standard deviations from the set of ROCOZ-A measurements at Natal average 3.8%, with an increase of more than a factor of 3 below 22 km. We believe that less than half of this is caused by increased instrument-to-instrument repeatability [*Barnes et al.*, 1986]. The bulk of the increase is attributed to lower stratospheric variability. The ozone number density values from the ECC ozonesondes also show an increased relative standard deviation below 22 km.

Ozone number density is calculated from the standard data product for the ECC (ozone partial pressure), using the temperatures from the standard meteorological radiosonde. The measured rms repeatability of temperatures from the radiosonde is 0.5°K [*Schmidlin et al.*, 1982], and the relative precision of ECC ozone partial pressure measurements is 5–6% at pressures from 200 to 30 mbar [*Barnes et al.*, 1985]. At 22 and 24 km (see Table 2) the variability of the ozone values from the ECCs is 6%, equal to the previously measured repeatability of the instrument. At 20 km and below the ozone variability from the ECC measurements is much greater than the repeatability of the ECCs and is due primarily to atmospheric changes.

Perhaps the best estimate of atmospheric ozone variability in this measurement set comes from a comparison of the standard deviations for the data with the measured repeatability from ROCOZ-A radiometer [*Barnes et al.*, 1986]. these calculations reveal the variability of stratospheric ozone (in terms of number density) from 22 to 52 km for this measurement period. At one standard deviation this variability averages 2% or less.

For ROCOZ-A measurements, mixing ratio is calculated by direct division of ozone density by total density. It is also possible to obtain equivalent ozone mixing ratios from the slope of overburden with respect to pressure. For ECC measurements, mixing ratio is calculated by dividing ozone partial pressures by the pressure measurements from the meteorological radiosonde. For the Natal data set presented here the standard deviations for the ozone mixing ratios (Figure 3) are equivalent to those for the ozone number densities, reflecting the same increase in variability below 22 km.

Temperature measurements from the Super-Loki data-

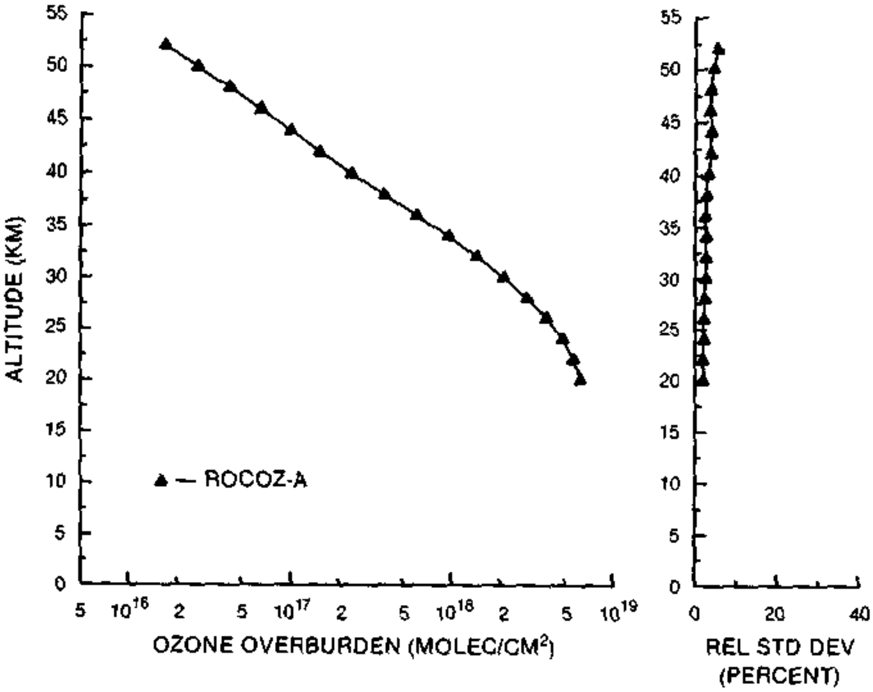

Fig. 1. Means and relative standard deviations (1σ) for ozone overburdens from the measurement series. Standard errors of the means are about 40% of the values presented here.

sondes and the meteorological radiosondes both show an average relative standard deviation of 1% in the stratosphere (Figure 4). This is about twice the measured repeatability for temperature measurements from the datasonde [*Miller and Schmidlin*, 1971; *Schmidlin*, 1981] and perhaps 4 times the repeatability of radiosonde temperatures [*Schmidlin et al.*, 1982]. In the troposphere the temperature variability is significantly less, but it is still more than 2–3 times the measured repeatability of radiosonde temperature measurements.

The variability of atmospheric pressures in the data set is somewhat more difficult to sort out, since the instrumental repeatability of the stratospheric pressure measurements is difficult to determine. The balloons that carry the meteorological radiosondes (along with the ECC ozonesondes) were not radar

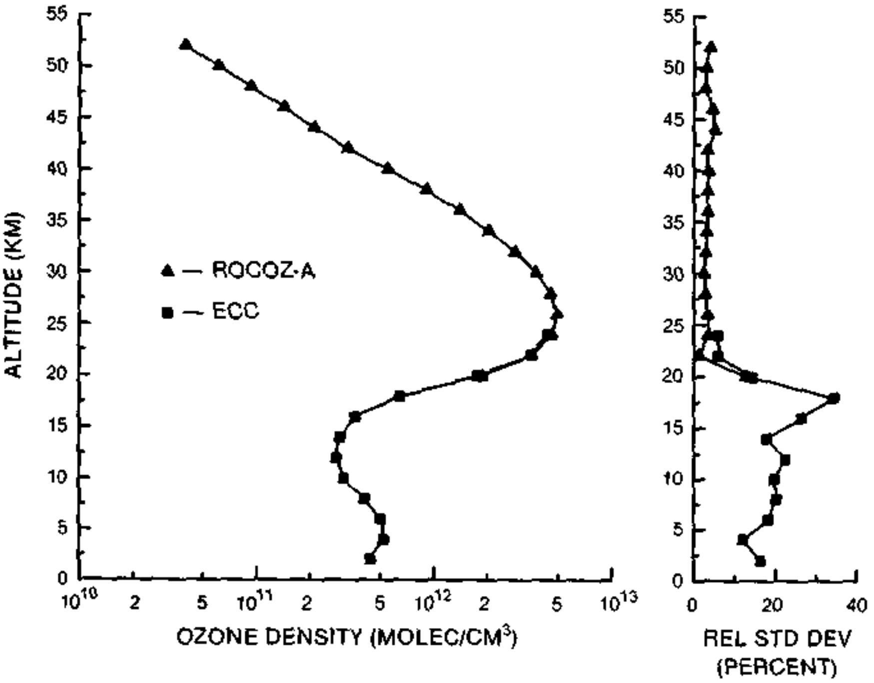

Fig. 2. Means and relative standard deviations (1σ) for ozone number densities from the measurement series. Standard errors of the means are about 40% of the values presented here.

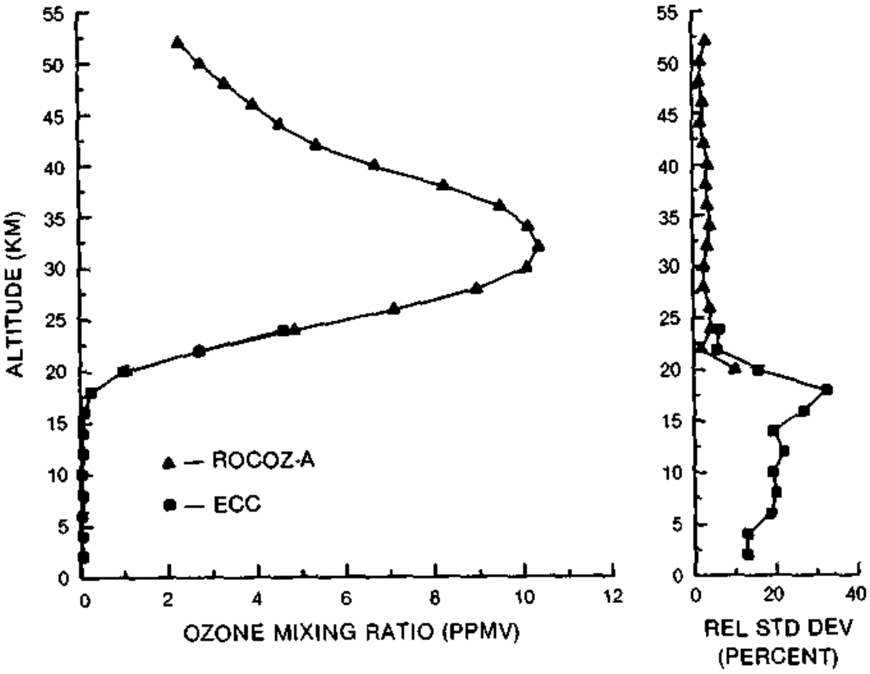

Fig. 3. Means and relative standard deviations (1σ) for ozone mixing ratios from the measurement series. Standard errors of the means are about 40% of the values presented here.

tracked during this measurement series. In this regard the balloon data correspond to the vest majority of profiles in the World Meteorological Organization (WMO) ozonesonde data set. The altitudes for the balloon measurements were calculated with the hypsometric equation, using the radiosonde temperatures and pressures. As a result, measurement errors from the radiosondes convert into mispositioning of the data in the vertical direction, either as altitude or as pressure.

At 20 km the rms repeatability of the radiosonde pressures amounts to 2% of the measured pressure [*Schmidlin et al.*, 1982], along with a 200-m variability in the altitudes calculated from the hypsometric equation [*Parsons et al.*, 1984]. In addition, *Parsons et al.* [1984] found no overall bias in the calculated altitudes below 30 km. We assume that there is only a negligible error in the radiosonde and the ECC altitudes in Tables 2 and 3, since these altitudes are the mean values from seven individual profiles.

For the datasondes, pressures are calculated from the C

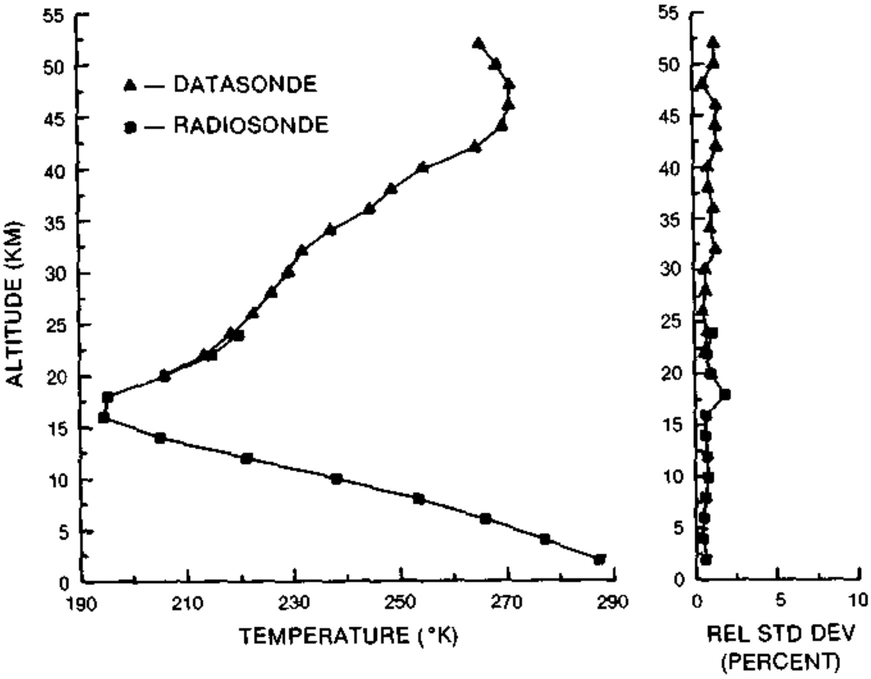

Fig. 4. Means and relative standard deviations (1σ) for temperatures from the measurement series. Standard errors of the means are about 40% of the values presented here.

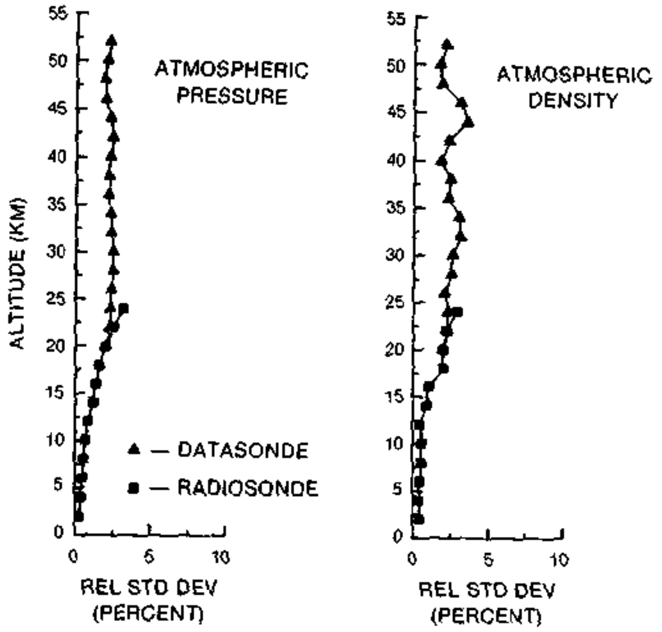

Fig. 5. Relative standard deviations (1σ) for atmospheric pressures and densities from the measurement series. Standard errors of the means are about 40% of the values presented here.

band radar altitudes and the datasonde temperatures, using the hypsometric equation and the initial tie-on pressures from the meteorological radiosondes. For an individual datasonde flight the tie-on pressure is treated as a bias, since it provides the lower limit for an integrated quantity. However, the radiosonde pressure sensors do not show an overall systematic error for substantial sets of measurements [*Schmidlin et al.*, 1982; *Parsons et al.*, 1984]. As a result, we assume that the average of the tie-on pressures for the seven data sondes in this measurement series is better than 1%.

The repeatability of the datasonde-derived pressures is nearly constant from 20 to 52 km (Figure 5), reflecting the instrumental repeatability of the radiosonde tie-on pressures. For this reason, we assume that the variability of the stratospheric pressures in this data set is substantially less than the 2–2.5% values in Table 3, probably duplicating the stratospheric temperature variability of about 1%. In a similar manner it can be shown that the variability in the stratospheric density values (Table 3) is also primarily due to the instrument-to-instrument repeatability of the aneroid pressure sensors in the meteorological radiosondes.

In summary, we find the equatorial stratosphere (and lower mesosphere) to have shown exceptionally low variability during the 3 weeks of this measurement campaign. From 22 to 52 km, ozone number density and mixing ratio show a relative standard deviation of 2% or less. For pressure and temperature the variability is approximately 1%. In this altitude region the greatest portion of the standard deviations in Tables 2 and 3 is caused by the instrument-to-instrument repeatability of the ROCOZ-A ozonesondes and of the aneroid pressure sensors in the meteorological radiosondes.

COMPARISONS WITH OTHER EQUATORIAL OZONE PROFILES

Published equatorial ozone measurements at altitudes above the operating range of meteorological balloons are very limited. *Krueger* [1973] has reported three equatorial ozone soundings with an older, ARCAS version [*Krueger and McBride*, 1968*a*, *b*] of the current ROCOZ-A ozonesonde. Two of the ARCAS profiles were made at 9°N during November 1970, and the third was made earlier at 4°N, in March 1965. The two November flights were launched 1 week apart at Fort Sherman, Panama. Over the possible range of comparison (20–46 km) the absolute value of the differences between the two flights averaged 18%, with differences at altitudes of 42–46 km greater than 30%. The ozone profiles from the two flights crossed at 28 km, with the measurements from the first flight giving lower ozone amounts below this altitude. Although different in latitude and season, the variability in the Forth Sherman measurements is considerably larger than that in the Natal data set presented here.

The March 1965 shipboard launch [*Krueger*, 1973] yielded values significantly different from the Fort Sherman profiles and from the Natal data set presented here. Ozone values from the shipboard launch vary from 50% greater than the Fort Sherman profiles at 32 km to a factor of 2 smaller than Fort Sherman at 22 km. At 32 km the March 1965 flight gave the largest ozone number densities for the 21-flight data set [*Krueger*, 1973] and the smallest ozone densities at 20 and 24 km.

For the ARCAS ozonesonde an anomalous absorption of 290–305 nm solar flux was found at altitudes near 50 km [*Krueger*, 1969, 1973]. This absorption was inferred from signal changes in the ARCAS instruments that were inconsistent with ozone absorption [*Krueger*, 1969]. Normal measurements from the ARCAS ozonesonde were restored by shifting the wavelength of the affected channel to a UV region less subject to spectral bias by the absorption. The absorption was thought to be caused by a metastable state of molecular oxygen [*Krueger*, 1969].

As part of an instrument improvement program, the ROCOZ-A filter wavelengths were set to give optimum overlaps between the four radiometer channels [*Holland et al.*, 1985], placing the center wavelengths of the new filters at 267, 290, 301, and 309 nm, respectively. To date, we have found no evidence of anomalous absorption of solar flux at altitudes near 50 km for wavelengths between 290 and 305 nm (see Figures 2 and 3 of *Barnes et al.* [1986]). In general, we have found difficulty in establishing continuity between the performance specifications for the ROCOZ-A radiometer [*Barnes et al.*, 1986] and those for previous versions of the instrument.

Hilsenrath and Dunn [1979] have produced averaged sets of equatorial ozone soundings during their production of reference profiles for backscattered ultraviolet data. Their compilations are presented as ozone partial pressures at standard atmospheric pressures levels. As mentioned previously, these are the fundamental data outputs for balloon-borne ozonesondes, which comprise the largest portion of their data base. One of their profiles gives the average values from several rocket flights at low latitudes (within 30° of the equator) and at pressures from 40 to 0.3 mbar. The type and number of instruments in this averaged rocket profile are not described. Ozone partial pressure is most certainly not the fundamental ozone measurement for the rocket-borne instruments in the profile, and the conversion to partial pressure requires the use of additional atmospheric measurements. In addition, *Hilsenrath and Dunn* [1979] show no error bars for their compilation. For these reasons, we refer to the low-latitude profiles

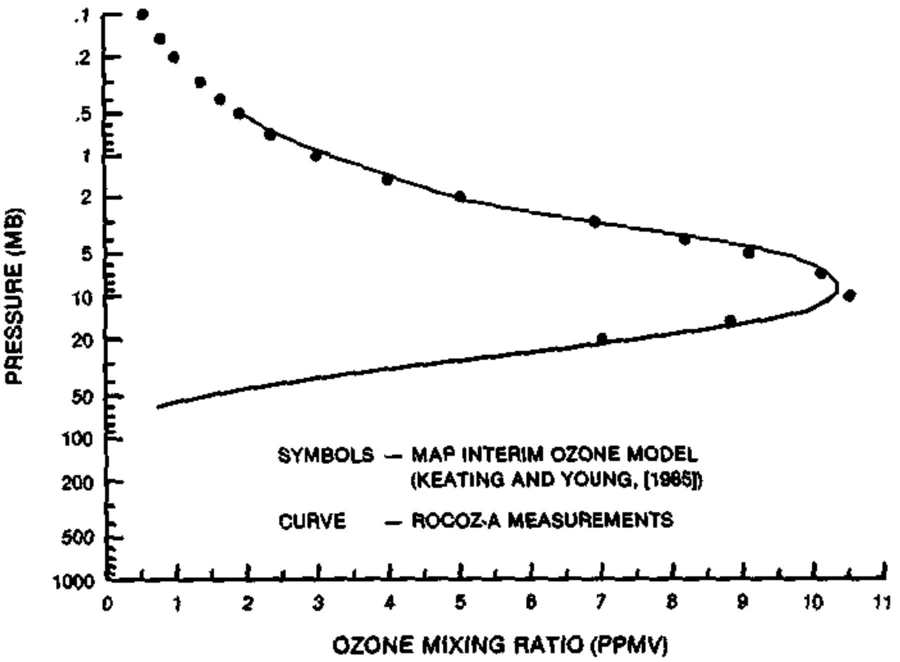

Fig. 6. A comparison of the ROCOZ-A measurements with the Middle Atmosphere Program interim ozone model. The MAP model is based on measurements from five satellites. See text for details.

of *Hilsenrath and Dunn* [1979] as a general climatology that we use only as a rough estimate.

The comparison with *Hilsenrath and Dunn* [1979] is relatively good, with ROCOZ-A values averaging 5% lower than the climatology over the pressure range from 40 to 0.7 mbar. The results of the comparison take the form of a step function, with near-perfect agreement over pressures from 40 to 5 mbar and with an average 11% difference from 3 to 0.7 mbar. We present this comparison with caution, since we feel that it can show no more than the general reasonableness of the two data sets.

There is a change in slope for the ozone profiles in Figures 2 and 3 at about 42 km. Using ROCOZ-A alone, we cannot fully demonstrate whether or not this change is an instrumental artifact. However, coincident SAGE II satellite ozone measurements (M. P. McCormick, NASA Langley Research Center, private communication, 1986) also reveal this change in slope.

The ozone profiles from Natal can also be compared with the Middle Atmosphere Program (MAP) interim reference model [*Keating and Young*, 1985]. This model is based on measurements from five satellites, using data collected from 1978 through 1983. It is presented in the form of ozone mixing ratios at reference atmospheric pressure levels from 20 to 0.03 mbar, above the altitude range of the ECC data presented here. These units, again, are not the fundamental ozone measurements from ROCOZ-A. In addition, the zonally averaged mean values in the MAP model come from data collected several years before this Natal measurement series, which, of course, was made at a single latitude and longitude. Again, we feel that the MAP model can be used only as a rough estimate.

The comparison with the MAP model is made at 11 pressure levels from 20 to 0.7 mbar for the month of April [*Keating and Young*, 1985]. Since Natal is located at 5.9°S, the comparison is made with the mean of the equatorial and the 10°S latitude bands from the model. For the 11 pressure levels of the comparison, the Natal measurement series averages 2% higher than the MAP model, with a 3% standard deviation (Figure 6). The MAP model also confirms the presence of the slope change in ozone mixing ratio near 42 km that is shown in Figure 3.

In the troposphere and lower stratosphere the results of this Natal measurement series can also be compared with the analysis of seasonal variations of ozone at Natal by *Logan and Kirchhoff* [1986]. Their analysis was made of 84 ECC soundings at Natal between November 1978 and April 1984, supplementing previous, smaller ECC data sets [*Kirchhoff et al.*, 1981, 1983], and permitting a study of the seasonal behavior of ozone. The analysis of *Logan and Kirchhoff* [1986] concentrates on the troposphere at seven pressure levels from 1000 to 125 mbar. At these levels the ECC values from the current measurement series average 3% higher than the climatology of *Logan and Kirchhoff* [1986] for the month of April. The standard deviation for the seven comparisons is 16%. *Logan and Kirchhoff* [1986] also show stratospheric ozone readings for five pressure levels from 70 to 15 mbar. For these levels the current ECC values are larger by 1%, with an 11% standard deviation. In conclusion, we find no inconsistency between the current measurement series and previous ECC measurements at Natal.

Finally, the pressure and temperature results from the current measurement series at Natal can be compared with the MAP middle atmosphere reference model [*Barnett and Corney*, 1985]. It is based both on satellite data and on previous climatologies. The model is presented in two forms, with pressure and geometric altitude as two vertical references. For simplicity we chose to compare with data that used geometric altitude for reference. Comparison is made with the mean of the equatorial and 10°S zonal bands for the model in the month of April. From 20 to 50 km the datasonde temperatures average 2°K lower than the model, with a 3° standard deviation. However, this comparison shows a significant difference of 6° at 35 and 40 km, with near perfect agreement at the other altitudes. At present, we have insufficient information to determine if a general systematic difference exists between datasonde and satellite temperature measurements in this altitude region. From 5 to 20 km the meteorological radiosonde temperatures average 0.5° lower than the model, with a 1° standard deviation. Pressure results show comparable differences.

ESTIMATES OF OZONE PROFILE ACCURACIES

The accuracy estimates for ROCOZ-A come from an internal, unpublished error analysis. This analysis is based on the estimated errors in the effective ozone absorption coefficients used to convert the radiometer readings into ozone profiles, plus the differences between the ozone values at altitudes where two ROCOZ-A channels give simultaneous readings [*Barnes et al.*, 1986]. We are in the process of constructing a laboratory flight simulator based on long path length photometry [*DeMore and Patapoff*, 1976; *Barnes*, 1982] to measure the accuracy of ROCOZ-A ozone readings. Publication of a detailed error analysis for ROCOZ-A will follow the conclusion of these experiments. It will complete the primary characterization of the ROCOZ-A ozonesonde.

We estimate the accuracy of ozone overburdens and ozone number densities from ROCOZ-A to be 5–7%. With the addition of auxiliary pressure and temperature measurements, these error estimates expand to 6–8% for ozone mixing ratio.

Comparison With Concurrent ECC Ozonesonde Measurements

There is some evidence to suggest that ROCOZ-A ozone measurements may be of the order of 5–10% too high. For the three overlapping altitudes in this data set, ROCOZ-A ozone number densities average 5% larger than those values from the ECCs, with a 3% standard deviation. This intercomparison was made for seven sets of instruments. Nineteen unpublished ROCOZ-A/ECC intercomparisons have also been made at Wallops Island, Virginia for altitudes from 20 to 24 km. These comparisons show ROCOZ-A to read 4% higher than the ECCs, with a 7% standard deviation. The quality of these comparisons is limited by the 6% precision of ECC ozonesonde readings [*Barnes et al.*, 1985].

Laboratory measurements of the accuracy of 12 ECC ozonesondes [*Barnes*, 1982; *Barnes et al.*, 1985] show these ECCs to read 7% higher than the laboratory simulator at a pressure of 50 mbar (with a standard deviation of the mean of 2%). The estimated accuracy limit for the reference readings from the ECC flight simulator is 3% [*Barnes*, 1982]. An assumption of the batch-to-batch consistency of the ECCs from the manufacturer must be made in order to extrapolate the 1982 laboratory results to the 1985 Natal measurements.

In addition, preflight checks against Dasibi UV spectrometers show the Natal ECCs to average 4% lower than ECCs flow at Wallops Island [*Logan and Kirchoff*, 1986] and 4% lower than the 12 ECCs that form the accuracy estimates in the work by *Barnes et al.* [1985]. It should be noted that the ECCs flown in this measurement campaign were supplied, prepared, and launched in a manner that is identical to those of *Logan and Kirchhoff* [1986]. As noted above, in the lower stratosphere, ECCs from this measurement campaign average 1% higher than the Natal climatology for April in the work by *Logan and Kirchhoff* [1986].

There is an intrinsic problem with ECC intercomparisons. The instrument was designed for synoptic ozone measurements. Over time, improved accuracy and precision have been required of ECCs, along with ozone-measuring instruments in general. At present, it seems evident that differences between manufacturing lots of ECCs and differences between measuring stations may be of the order of 5%. A fully automated flight simulator for ECCs is under construction at NASA's Wallops Flight Facility to examine a large number of ECCs. This should allow for improved estimates of the quality of ECC ozone measurements. In addition, individual flight simulations of all ECCs before launch may improve the quality of ECC measurements themselves. Still, evidence from ECC intercomparisons suggests that ROCOZ-A ozone measurements may be of the order of 5–10% too high, at least at altitudes below 25 km.

Comparison With Other Concurrent Balloon-Borne Ozone Measurements

ROCOZ-A ozone measurements have also been compared with those from an in situ UV absorption photometer during the BOIC campaign [*Hilsenrath et al.*, 1986]. In a single comparison, ROCOZ-A measured 5–10% higher than the in situ photometer for atmospheric pressures from 50 to 4 mbar. In a subsequent balloon flight, a ROCOZ-A ozonesonde was compared with the same in situ photometer and with a mass spectrometer from the University of Minnesota [*Anderson and Mauersberger*, 1981]. A description of this intercomparison is in preparation for publication. However, preliminary results show ROCOZ-A to read higher than the in situ photometer by 5–10% and lower than the mass spectrometer by about 4%. These comparisons were made over the range of atmospheric pressures from 6 to 2 mbar, which is in the middle-altitude range for ROCZ-A measurements. There is cause for concern in this intercomparison, since the in situ photometer and the mass spectrometer are both considered to be absolute standards. Instrument comparisons on large balloons may never give consistent results at better than the 3–5% level. This is particularly true for comparisons with ROCOZ-A, which is designed to collect information during a 30-min parachute descent, rather than on several-hour-long balloon flights.

CONCLUDING REMARKS

The ozone, pressure, and temperature profiles from this data set are in reasonable agreement with satellite climatology in the stratosphere and with previous ECC ozonesonde climatology in the troposphere. Satellite measurements also confirm an ozone slope change at 42 km. In addition, we have been able to separate atmospheric ozone variability from the instrument-to-instrument repeatability of the ozone sensors.

We have found 2% or less variability in stratospheric and lower mesospheric ozone during the 3 weeks of this measurement campaign at Natal. Low variability at a single location for this period implies a comparable uniformity for ozone profiles over a large area around the measurement site. Limb Infrared Monitor of the Stratosphere (LIMS) satellite measurements of stratospheric temperature and ozone at 4°S for the period of April 1–5, 1979, show longitudinal deviations about the zonal mean that duplicate the variations presented here during March and April of 1985 (E. Remsberg, NASA Langley Research Center, private communication, 1986). In addition, tropical SBUV ozone measurements in 1979 [*Frederick et al.*, 1984; *McPeters et al.*, 1984] show equally small longitudinal variations about the zonal ozone means in the upper stratosphere throughout the year. Finally, the ultraviolet spectrometer on SME showed less than 4% variability in tropical ozone measurements at pressures from 0.5 to 0.9 mbar during March and April of 1982 [*Rusch et al.*, 1984]. This information supports the possibility that annual periods of stratospheric ozone stability occur in the region around Natal (and in the equatorial region in general) during the southern hemisphere autumn.

Model calculations [*Herman*, 1979; *Allen et al.*, 1984] predict a diurnal cycle for mesospheric and upper stratospheric ozone, with greater ozone amounts at night. At 52 km the ozone column content measurements presented here show a slight dependence on solar zenith angle. The two ozone column measurements with solar zenith angles near 20° average 4% lower than the mean value for the remaining, high solar zenith angle measurements. This difference is in the same direction as the model predictions. However, the difference cannot be considered statistically significant, since it is less than twice the measured, 1σ repeatability for ROCOZ-A [*Barnes et al.*, 1986] and contains only four measurements in one sample and two measurements in the other. The measurements presented here do not have the combination of precision and sample size to test the model predictions of a diurnal cycle in upper stratospheric ozone.

The low variability during the measurement series described here should improve the quality of satellite intercomparisons with this data set. The SME, NOAA 9, and Nimbus 7 satellites all make daily overpasses near Natal, albeit at different local times. If stratospheric uniformity exists over a sufficiently large area, then it is possible to compare the average profiles presented here with the mean values of 15 or more satellite measurements. In other words, regional uniformity would remove the requirement for exact concurrence of the satellite and local ozone measurements and allow the comparison of a larger set of profiles, improving the precision of the satellite intercomparisons.

In addition, an overall intercomparison of ozone measurements among the four NASA and NOAA satellites may well be possible without the need for zonally averaged means. The assembly of ozone, pressure, and temperature measurements presented here also allows an examination of the expansion of differences that occur as satellite ozone measurements are converted from fundamental to derived quantities. For example, SAGE II uses the National Weather Service gridded analysis to provide the temperatures and pressures to convert ozone densities into mixing ratios (L. R. McMaster, NASA Langley Research Center, private communication, 1986). Nimbus 7 SBUV data, on the other hand, are presented without auxiliary pressure and temperature measurements, requiring the use of standard reference atmospheres for conversion of mixing ratios into ozone densities [*McPeters et al.*, 1984]. The Natal data set presented here can handle these different ozone units directly. In addition, the stability of stratospheric ozone at Natal will allow a check of the measurement-to-measurement repeatability of the ozone profiles from each of the satellites.

Finally, this data set can form the basis for more than a consistency check of satellite ozone measurements. The small atmospheric variability at Natal should provide an opportunity for high-quality intercomparisons of measured and modeled ozone concentrations in the equatorial stratosphere and lower mesosphere. Such an overall intercomparison is exceptionally enticing, since model results are typically 30–50% lower than measured ozone concentrations at altitudes above 35 km [*Watson et al.*, 1986].

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