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Satellite and Correlative Measurements of Stratospheric Ozone: Comparison of Measurements Made By SAGE, ECC Balloons, Chemiluminescent, and Optical Rocketsondes

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The validity of ozone profile data from the satellite sensor SAGE was tested in a series of correlative experiments conducted at five fixed sites between 6°S and 65°N during 1979–1980. The intercomparisons included data taken with electrochemical ozone (ECC) balloonsondes and chemiluminescent and optical rocketsondes. The average mean difference for 17 separate comparisons between the SAGE and ECC balloonsonde observations over the altitudes 18–28 km was 9.3% with a standard deviation of 2.8%. Excluding comparisons separated by greater than 500 km reduces the average mean difference to 8.9% and the standard deviation to 2.1%. The average mean difference between SAGE and three optical rocketsonde observations over the altitudes 25–50 km was 11% and between SAGE and two chemiluminescent rocketsondes over the altitudes 20–60 km it was 13.5%. Considering the differences in vertical resolution, experimental errors, and ozone time and space gradients, the agreement between SAGE-derived ozone profiles and these correlative measurements is considered very good. In addition, isopleths of ozone mixing ratio versus latitude and altitude are in good agreement with previously published results.

Introduction

A comprehensive series of correlative experiments was conducted during 1979–1980 at five fixed sites between 6°S and 65°N to test the validity of ozone profile data from the satellite sensor SAGE (Stratospheric Aerosol and Gas Experiment). Table 1 lists the sensors employed. A similar series of correlative measurements was conducted from European stations during the same time period, and those results have been reported by *Reiter et al.* [1982]. The purpose of this paper is to present the SAGE and correlative sensor ozone data and demonstrate that the satellite data are validated by these "ground-truth" comparisons.

SAGE Data and Uncertainties

The Stratospheric Aerosol and Gas Experiment was launched February 18, 1979, on the Applications Explorer Mission-2 (AEM-2) satellite of NASA. The satellite instrument successfully operated until November 18, 1981, making over 13,000 ozone profile measurements during that time. The instrument utilizes the technique of solar occultation to measure limb path atmospheric extinction, which is mathematically inverted to yield vertical profiles of various atmospheric constituents in the latitude range from about 72°S to 72°N.

The experiment is such that shortly before each sunrise and sunset encountered by the satellite, the SAGE instrument is enabled and searches for the sun in azimuth. When the sun is nulled to within ±1 arc min, a scan mirror is activated to locate the sun in elevation. The mirror then scans up and down across the face of the sun, reversing itself each time a sun limb crossing occurs. The instantaneous field of view is 0.5 arc min, which yields a better than 1 km vertical resolution on the earth's horizon. A complete description of this experiment can be found in *McCormick et al.* [1979]. The solar radiance in each of four spectral channels is measured by a photodiode detector, digitized, recorded, and telemetered to earth. This information is subsequently inverted to generate various output products including an extinction profile for each measurement. The ozone spectral channel is centered at 0.60 μm in the middle of the Chappuis absorption band. Details of the inversion technique are given in *Chu and McCormick* [1979].

The retrieved ozone profile is ozone extinction from cloud tops to approximately 50 km. Ozone number densities are obtained from these extinction values by using the relationship

$$\beta_0(Z) = N_0(Z) \cdot \sigma_0(\lambda)$$

where $\beta_0(Z)$ is the retrieved ozone extinction at altitude Z; $N_0(Z)$ is the ozone number density at Z; and, $\sigma_0(\lambda)$ is the ozone absorption cross section as a function of wavelength, λ, integrated over the spectral band pass of the SAGE spectrometer. The cross section for ozone in the Chappuis absorption band has been measured in the laboratory by *Penny* [1979] as a function of temperatures and pressures representative of the stratosphere.

Since the SAGE satellite orbital period is approximately 1.5 hours, there are about 30 sampling opportunities per day (15 sunrises and 15 sunsets) with each successive sunrise or sunset event separated by 24° in longitude around a latitude circle. Figure 1 illustrates the latitudinal coverage of SAGE during the first year of operation. Note that the SAGE measurements were restricted to sunset measurements only after July 1979. This was necessitated because of spacecraft power system deficiencies. Each profile derived by SAGE describes an average of the extinction coefficient within the spherical atmospheric shells intersected by the limb path between SAGE and the sun. For a shell of thickness 1 km, this limb path at the earth tangent location is about 200 km.

Correlative Measurements

Correlative measurements presented in this paper were performed at locations and times within 800 km and ±9 hours of

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TABLE 1. Ozone Sensors Used in SAGE Correlative Measurements

Sensor	Data Height, km	Platform	Investigator
SAGE	cloud tops to 50	AEM-2 satellite	M. P. McCormick et al.
ECC Sonde	0–30	balloon	Field Measurements Support Office, WFF, GSFC
Chemical Rocketsonde	15–70	rocket-parachute descent	E. Hilsenrath
Optical Rocketsonde	15–60	rocket-parachute descent	A. J. Krueger

TABLE 2. SAGE Measurement Error Estimates

	Estimated Errors
Ozone Profile	
Systematic Errors	
Ozone absorption cross section	1.5%
Instrument calibration	2.0%
Rayleigh cross section	0.5%
Aerosol optical properties	
$Z < 25$ km	4.0%
$Z \geq 25$ km	<1.0%
Altitude Determination	0.25 km
Random Errors	
Noise (measurement and inversion)	
tropopause to 35 km	5–10%
35 to 50 km	20–40%
Total Ozone	
Systematic Errors	
Trend determination not affected	
Absorption cross section	1.5%
Instrument calibration	2.0%
Trend determination affected	
Temperature dependent absorption cross section change	< 0.05%
Long-term instrument calibration drifts	1.0%/year
Change in stratospheric aerosol optical property	0.2%
Random Errors	
Noise (measurement and inversion)	1.0%
Tropospheric ozone	1.0%

the SAGE observation. Specifically, they were conducted at Palestine, Texas; Wallops Island, Virginia; Primrose Lake, Canada; Poker Flat, Alaska; Natal, Brazil; and a number of European locations [*Reiter et al.*, 1982]. Table 2 enumerates the random and systematic errors associated with SAGE measurements. A variety of different correlative sensors were employed which included electrochemical ozone balloonsondes and chemiluminescent and optical rocketsondes. The method of operation and associated measurement errors are given below.

Electrochemical ozone balloonsondes. The Electrochemical Concentration Cell (ECC) balloon-borne ozonesonde is a lightweight, compact, and relatively inexpensive instrument developed for routinely measuring the vertical distribution of atmospheric ozone. It is electronically coupled to a standard NOAA radiosonde and thus also provides atmospheric pressure and temperature. The operating height range is typically from the ground to approximately 30 km. The calibration data for this system are obtained from the ozonesonde's preflight calibration process and the radiosonde's preflight baseline checks. The accuracy of the ECC ozonesonde is currently estimated to be within 10–12% (1 sigma) [*Komhyr and Harris*, 1971]. Recent studies (A. L. Torres, private communication, 1979) show that near 10 mbar and above, errors can exceed 20% because of uncertainty in the pressure (height) measurement.

Chemiluminescent ozone rocketsondes. The chemiluminescent ozonesonde is a rocket-launched payload ejected at apogee that measures the ozone distribution between 70 and 15 km as the sonde descends through the atmosphere on a parachute. Accurate position data are obtained through radar tracking. A description of the measurement principle and a recent assessment of the accuracy of the chemiluminescent rocketsonde are contained in *Hilsenrath and Kirschner* [1980]. An error analysis indicates precisions of about 6.4% below 60 km where this value is calculated for each flight. Absolute errors that result in a bias are more difficult to assess. Examples of absolute errors are uncertainty of the sonde calibration, undetected ozone losses, and nonlinearities in the measurement. The absolute error for the chemiluminescent

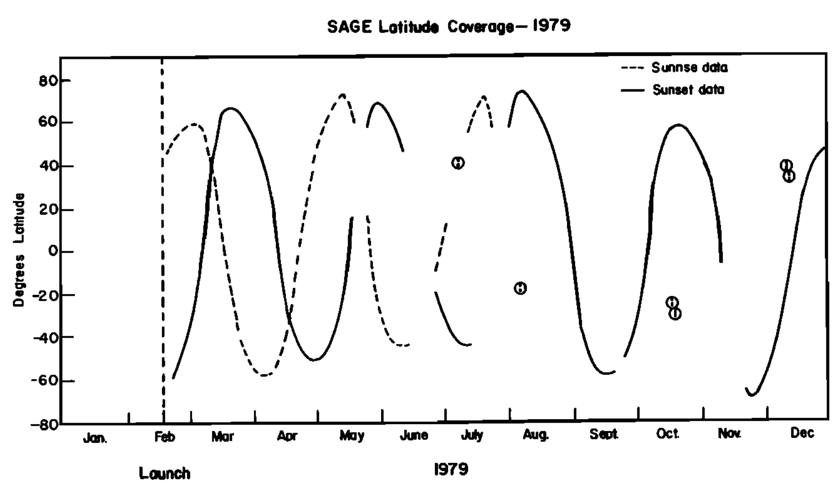

Fig. 1. The latitude location of SAGE measurements for 1979. Satellite sunrise measurements are given by dashed lines and by a circle for a small number of measurements. Sunset data are given by the solid lines.

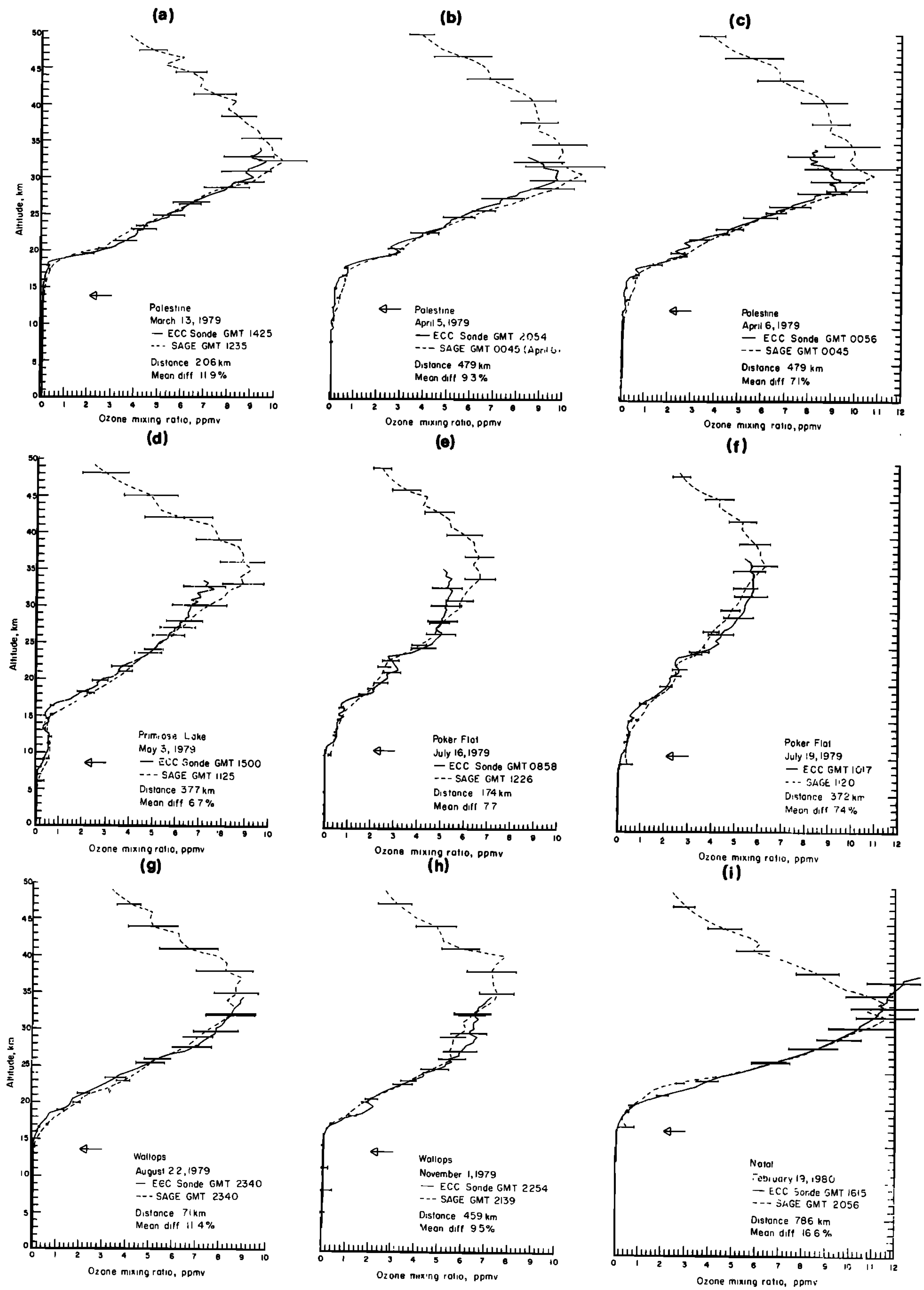

Fig. 2. Comparisons of SAGE-derived and ECC sonde-derived ozone volume mixing ratio profiles. The locations of the balloon launch is given with the date of comparison. The times listed are for balloon launch and SAGE 20 km measurement. The measurement distance given corresponds to this time. Also listed is the average of the absolute mean differences in the measurements over the altitudes 18–28 km.

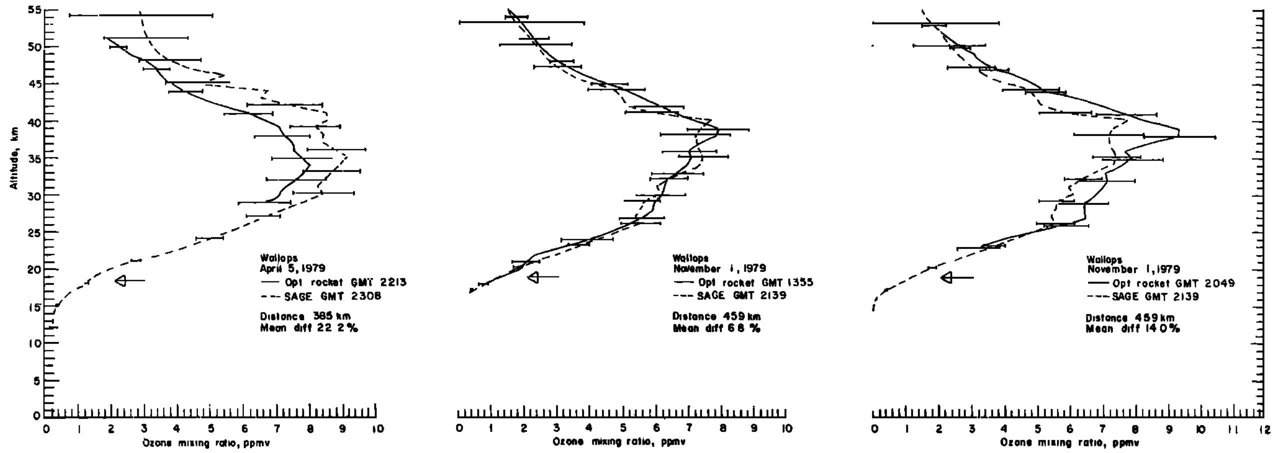

Fig. 3. Comparisons of SAGE-derived and optical rocket-derived ozone volume mixing ratio profiles. The location of the rocket launch is given with the date of comparison. The times listed are for rocket launch and SAGE 20 km measurement. The measurement distance given corresponds to this time. Also given is the average of the absolute mean differences in the measurements over the altitudes 29–50 km in the first left-hand comparison and 25–50 km in the other two comparisons.

ozonesonde has been estimated to be 12% [*Hilsenrath and Kirschner*, 1980]. Combining precision and absolute error, the measurement error between 20 and 60 km is about 13.5%.

Optical rocket ozonesonde. Similarly, the optical ozonesonde is a rocket-launched payload that provides ozone profiles between 70 and 15 km. The sensor provides an absolute measurement based on known values of the ozone absorption coefficients during daylight hours. The sensor is a four-channel filter-wheel ultraviolet photometer. The precision of the measurement is estimated to be 5% or better between 25 and 50 km. The system accuracy is significantly dependent on two factors: (1) the error of the ozone absorption coefficient and (2) the changes in the UV filter characteristics after calibration. The accuracy is believed to be better than 10%, giving a combined measurement error between 25 and 50 km of about 12%. [*Krueger*, 1973].

Validation Comparisons

The SAGE ozone correlative experiments that were conducted during the first year of operation (1979–1980) consisted of 17 ECC balloon comparisons, three optical ozonesonde rocket comparisons, and two chemiluminescent ozone rocketsonde comparisons. A composite of nine SAGE-ECC balloon comparisons is illustrated in Figure 2, plotted as ozone mixing ratio in parts per million by volume. In the profiles illustrated, the SAGE measurement is shown by a dashed line and the ECC sounding by a solid line. The error bars represent the 1 sigma uncertainty in the data for each sensor as described

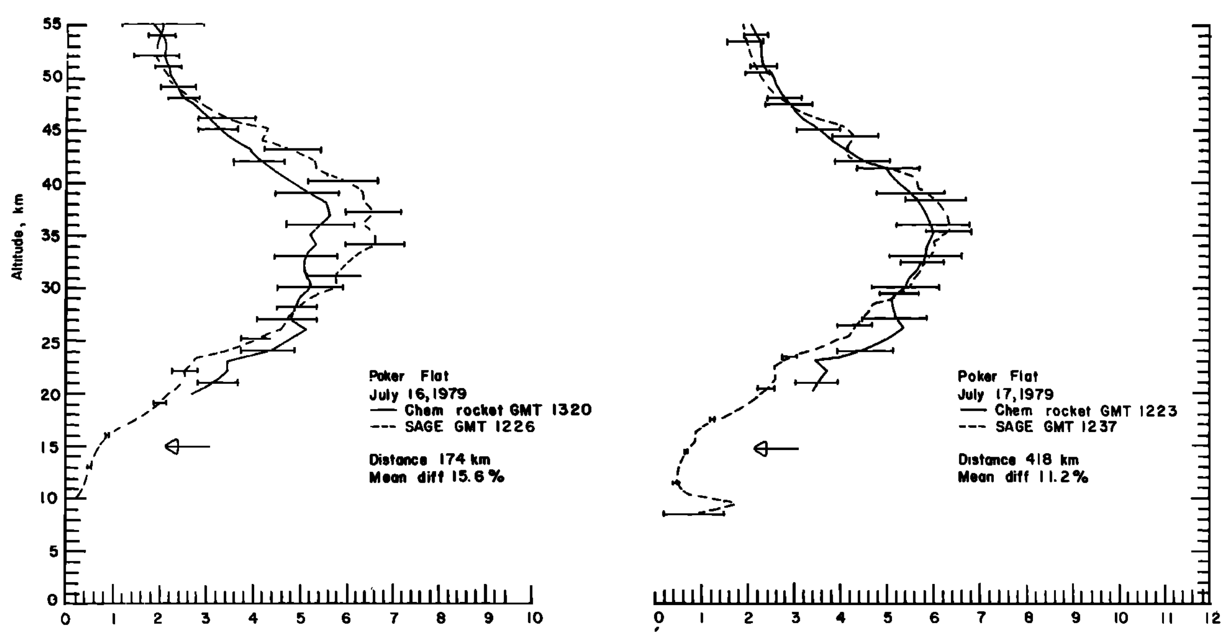

Fig. 4. As in Figure 3 except for chemiluminescent rocketsondes compared with nearly simultaneous SAGE measurements over the altitudes 20–60 km.

TABLE 3. SAGE Ozone Comparisons

Location	Latitude, Longitude, deg.	Date	Time, UT	Sensor	Distance, km	Time of SAGE Observation, UT	Height, km	Mean Difference, %
Palestine	32N, 96W	March 13, 1979	0904	ECC balloon	206	1235	18–28	13
Palestine	32N, 96W	March 13, 1979	1425	ECC balloon	206	1235	18–28	12
Palestine	32N, 96W	April 5, 1979	2054	ECC balloon	479	2445	18–28	9
Wallops	38N, 75W	April 5, 1979	2009	ECC balloon	385	2308	18–28	11
Wallops	38N, 75W	April 5, 1979	2213	optical rocket	385	2308	29–50	22
Wallops	38N, 75W	April 5, 1979	2423	ECC balloon	385	2308	18–28	7
Palestine	32N, 96W	April 6, 1979	0056	ECC balloon	479	0045	18–28	7
Palestine	32N, 96W	April 6, 1979	0613	ECC balloon	479	0045	18–28	8
Primrose Lake	55N, 110W	May 3, 1979	1500	ECC balloon	377	1125	18–28	7
Poker Flat	65N, 147W	July 16, 1979	0858	ECC balloon	174	1226	18–28	8
Poker Flat	65N, 147W	July 16, 1979	1320	chemical rocket	174	1226	20–60	16
Poker Flat	65N, 147W	July 16, 1979	1616	ECC balloon	174	1226	18–28	10
Poker Flat	65N, 147W	July 17, 1979	1223	chemical rocket	418	1237	20–60	11
Poker Flat	65N, 147W	July 17, 1979	1434	ECC balloon	418	1237	18–28	6
Poker Flat	65N, 147W	July 19, 1979	1017	ECC balloon	372	1120	18–28	7
Poker Flat	65N, 147W	July 19, 1979	1310	ECC balloon	372	1120	18–28	8
Wallops	38N, 75W	Aug. 22, 1979	1504	ECC balloon	71	2340	18–28	8
Wallops	38N, 75W	Aug. 22, 1979	2314	ECC balloon	71	2340	18–28	11
Wallops	38N, 75W	Nov. 1, 1979	1355	optical rocket	459	2139	25–50	7
Wallops	38N, 75W	Nov. 1, 1979	2049	optical rocket	459	2139	25–50	14
Wallops	38N, 75W	Nov. 1, 1979	2254	ECC balloon	459	2139	18–28	10
Natal	6S, 35W	Feb. 19, 1980	1615	ECC balloon	786	2056	18–28	17

above. For each profile the height of the local tropopause for that date is indicated by a horizontal arrow. The comparisons with the retrieved SAGE profile are quite reasonable. The falloff of the ozonesonde near 30 km in Figures 2*a* to 2*e* is probably due to pump inefficiencies and pressure altitude uncertainties and is characteristic of many ozonesonde soundings at these altitudes. Everywhere else above the tropopause, the ozone soundings are in good agreement with the SAGE results and within the measurement error bars. The effect of horizontal and vertical integration by SAGE is evident when compared to the fine-scale vertical structure of the ECC soundings and these differences are typical of limb measurement comparisons. The balloon device samples the air as it rises, while SAGE integrates its signal over the earth's limb between the satellite and the sun. As was mentioned above, the effective stratospheric path length for SAGE measurements is about 200 km. Over these distances the tropopause and, therefore, the tops of clouds (cirrus and subvisible cirrus) can be variable and may affect the measured extinction. In addition, clouds, on occasion, have been seen to penetrate the local tropopause making comparisons near the tropopause (typically within 1 km) difficult for satellite limb measurements.

The ozone rocket sounding data that were utilized for the SAGE comparisons incorporate the following criteria (particularly for the optical rocketsondes) in their data retrievals. These are that the estimated overburden at apogee be within 6% of the total ozone derived from the Dobson observations made on the same day and that the ozone values derived from a pair of UV filters at a particular altitude should agree within 7%. A comparison between SAGE and three optical ozonesonde rocket soundings is illustrated in Figure 3. As before, the SAGE data are plotted as a dashed line and the optical sonde data as a solid line, and the error bars are the 1 sigma uncertainty in the sensor measurement. The comparisons are reasonable, with the sensor error bars generally overlapping with each other from 25 to 50 km. The two soundings on November 1, 1979, were part of the International Rocket Ozone Intercomparison at Wallops Island, Virginia. The two chemiluminescent ozone rocket comparisons are shown in Figure 4, plotted in the same manner as described above. The agreement is likewise reasonable.

A mean difference has been calculated for each profile comparison at several atmospheric levels common to each sounding. This mean difference is the average of the absolute difference between the soundings at each level, divided by the average value at that level. Thus,

$$M = \frac{1}{N} \sum_{i=1}^{N} \frac{|R_i - r_i|}{(R_i + r_i)/2)}$$

where M is the mean difference for the N, R_i, and r_i ozone mixing ratios for SAGE and the comparison profile, respectively. The results of these comparisons are summarized in Table 3. Given in the table are the correlative measurement location, date, time, type of comparison sensor, the SAGE measurement time, distance in kilometers between the two

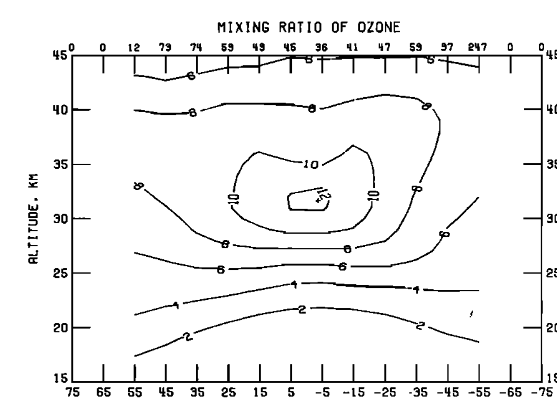

Fig. 5. Zonal average of SAGE-derived ozone volume mixing ratio profiles for April 1979. The approximately 900 SAGE sunrise and sunset profiles were averaged over the month in 10° latitude bins. The number of profiles in each bin is indicated on the top axis.

observations, and the mean difference of each profile comparison over the height range specified. The average mean difference over all comparisons is 10.4%. Allowing for the differences in measurement techniques, differences in vertical resolution, and time and space gradients, this agreement is very encouraging and is representative of all SAGE ozone comparisons.

Global Distribution of SAGE Ozone Data

In Figure 5 the latitudinal distribution of the retrieved SAGE ozone mixing ratios for a month is illustrated. The data were collected in April 1979 between latitudes 55°S and 55°N and represent about 900 individual profiles averaged into 10° latitude bands. Maximum values (12 ppmv) are observed over the tropics with a slight lifting trend in the contours toward higher latitudes. These isopleths are in general agreement with other data collections such as the surveys compiled by *Dutsch* [1978]. These data have been analyzed for the total stratospheric ozone column content. Comparisons of these data with BUV-4 total ozone [*Hilsenrath and Schlesinger*, 1979] and with total ozone values reported from the Dobson network (WODC reports) show similar behavior with season and latitude.

Conclusion

This paper has shown that the SAGE ozone profile data are in good agreement with the results obtained from 22 correlative measurement data sets including both ECC balloonsondes and rocket ozonesondes. In addition, the global distribution of SAGE data is in agreement with previous published results.

The SAGE ozone measurements are generating a highly detailed vertical picture of the global stratospheric ozone distribution which will be very useful in a number of stratospheric photochemical and dynamical studies. The SAGE data are being archived at the National Space Sciences Data Center in Greenbelt, Maryland, and at the World Ozone Data Centre in Toronto, Ontario.

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