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1.0   2.8   2.5
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

NASA TM X- *70786*

A MID-LATITUDE OZONE MODEL
FOR THE
U.S. STANDARD ATMOSPHERE, 1975
(Summary)

ARLIN J. KRUEGER
RAYMOND A. MINZNER

SEPTEMBER 1974
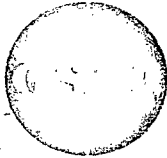
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

4.
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ABSTRACT

A mid-latitude, northern-hemisphere model of the daytime ozone distribution in the troposphere, stratosphere, and lower mesosphere has been constructed. Data from rocket soundings in the latitude range 45°N ±15°, results of balloon soundings at latitudes from 41 to 47°N, and latitude gradients from satellite ozone observations have been combined to produce estimates of the annual mean ozone concentration and its variability at heights to 72km for an effective latitude of 45°N. This model is a revision, for heights above 26km, of the tentative Mid-Latitude Ozone Model, included in the U.S. Standard Atmosphere Supplements, 1966.

A MID-LATITUDE OZONE MODEL FOR THE

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(Summary)

A mid-latitude, northern-hemisphere model of the ozone distribution in the tropo-
sphere, stratosphere, and lower mesosphere has been constructed (Krueger and
Minzner, 1974). Data from rocket soundings in the latitude range 45°N ±15°,
results from satellite ozone observations, and the results of balloon soundings
at latitudes from 41 to 47°N have been merged to produce estimates of the annual-
mean, ozone concentration and its variability at heights to 72 km. This model is
a revision, for heights above 26 km, of the tentative Mid-Latitude Ozone Model,
included in the U.S. Standard Atmosphere Supplements, 1966 (U.S. Committee
on Extension to the Standard Atmosphere, 1966), hereafter referred to as the
1966 Supplements. Such a revision is justified by the greater number of rocket
soundings presently available, compared to the number available in 1966, as well
as by the newly acquired ozone data from the Backscatter Ultraviolet (BUV) ex-
periment on the Nimbus 4 satellite, (Heath, et al., 1973).

For heights below 27 km, the herein described ozone model is essentially un-
changed from that of the 1966 Supplements. This portion of the model was com-
puted from the mean mass-density values (in $kg\,m^{-3}$) and their standard deviations,
as given in the 1966 Supplements. These data were originally obtained from the
systematic program of weekly ozonesonde ascents made throughout the year

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1963 at: Seattle, Washington; Fort Collins, Colorado; Madison, Wisconsin; and Bedford, Massachusetts (Hering and Borden, 1964). Because of the location of these stations, the average of annual-mean profiles computed for each of these stations, after first averaging individual sounding data over 2-km vertical intervals, is considered here to represent a 45° average for the United States. Approximately 150 balloon ozonesonde ascents were used in the determination of this mean ozone profile.

For heights above 27 km, the ozone model was computed from a set of column densities of ozone, a quantity usually obtained from optical observations, and frequently expressed in units of centimeters of ozone, at standard temperature and pressure (STP), per unit vertical distance. In abbreviated form these units are expressed as atm-cm/km. The column density represents the amount of ozone per vertical kilometer column, at any height, reduced to STP conditions. The thickness of the resulting layer of pure ozone is then the measure of the column density. For example, a column density of 0.01 atm-cm/km corresponds to 2.14148×10^{-4} kg/m$^2 \cdot$km, or to 2.14148×10^{-7} kg/m^3. The height integral of the column density, called the total ozone and expressed in atm-cm (or m-atm-cm, the Dobson unit), is also a commonly used measure of ozone.

The column densities of this model for heights above 32 km were determined from 12 daytime and 5 twilight rocket measurements of the ozone distribution (15 over North America and 2 over Japan), while the values for the height region

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from 28 to 32km represent a composite of both rocket and balloon data. Latitude gradients, for correction of the mean rocket data, have been derived from the global BUV satellite data. These satellite data have not been used directly in the model because of height-resolution considerations. Such data will, however, be very valuable for extension of this model to other latitudes, and to establish variabilities for supplementary models.

The 17 rocket soundings used to develop the model comprise a subset selected from the 31 daytime and 6 twilight rocket soundings obtained through 1972 at sites between 30°N and 60°N. Seventeen soundings were chosen from the 37 soundings using a set of selection criteria established to allow computation of realistic mean values and standard deviations. These criteria include traceable absolute accuracy (either inherent in the technique or established by comparison with an absolute instrument), and a height resolution of 2km or better. Soundings influenced by abnormal geophysical conditions or showing significant biases from the statistical distribution of the majority of the soundings were rejected.

The rocket model is based on tabular data furnished or published by Hilsenrath (1972); Krueger (1974); Ogawa (1972); Smith (1969); Craig (1965), after Johnson, et al. (1952); Weeks, et al. (1972); and Weeks and Smith (1968). The techniques have been described elsewhere by Hilsenrath, et al. (1969); Krueger and McBride (1968); and Nagata, et al. (1971). Ten of the selected soundings were made

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at Wallops Island, Virginia (38°N, 75°W); two are from Fort Churchill, Manitoba (59°N, 94°W); two are from Uchinoura, Japan (31°N, 131°E); and one sounding has come from each of the following: Point Mugu, California (34°N, 119°W); Primrose Lake, Alberta (55°N, 110°W); and White Sands Missile Range, New Mexico (32°N, 107°W). Fourteen of the soundings were made during the years 1968-1970, the others in 1972, 1966, and 1949.

The mean latitude of these rocket soundings is 38°N. The latitudinal gradient derived from the satellite data provided the means for adjusting the rocket model in the height region of 26 to 40km to an effective latitude of 45°N. The greatest adjustment (-15%) was applied at 28 to 30km. The adjusted rocket model merges cleanly with the balloon data defining the 1966 model. In the region of overlap, 28 to 34km, the mean values of these two data sets have been used. The differences between these two data sets, however, are all less than 5 percent at corresponding heights.

The data for the combined model come principally from the North American continent. The balloon observations were taken in the 51° longitude band between Seattle, Washington and Bedford, Massachusetts, and all but two of the rocket soundings (those at Uchinoura, Japan) were made in the United States and Canada. The two Japanese Soundings did not differ significantly from those over North America. On the basis of this limited evidence, the model above 30km is tentatively taken to represent mean mid-latitude conditions around the northern hemisphere. Additional data will be needed to verify this assumption.

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The amount of information about secular changes is very limited. Near the tropopause, large inter-annual changes would be expected because of the dominant effects of meteorological transport processes on the ozone distribution. At altitudes above 35 km, changes might be expected due to variations in the solar spectrum during the solar cycle. The quantity of ozone data is far from adequate to establish such trends. It should be noted that the present Model, for heights above 30 km, is weighted towards the solar maximum conditions which existed in the late 1960's.

Table 1 defines the mid-latitude ozone model in height increments of 2 kilometers. The ozone mass densities ρ_3, which are the basis for the lower portion of the model ($<$27 km), and the ozone column densities ϵ_3, which are the basic data for the upper portion of the model ($>$27 km) have both been transformed into a common continuous profile of ozone number densities n_3, with corresponding standard deviations σ. These transformations were accomplished using equations and values of physical constants given in the appendix. The values of N, R*, and V_0 are those given by Mechtly (1973), and are consistent with an atomic weight scale based on $C^{12} = 12.0000$ (Taylor et al., 1969). The values of M_3 and M, based on the same atomic weight scale, are taken from the U.S. Standard Atmosphere, 1962 (U.S. Committee on the Extension to the Standard Atmosphere, 1962). The values of σ for heights below 27 km were transformed from the standard deviations of ρ_3 given in the 1966 Supplements.

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Table 1
Mid-Latitude Ozone Model

Geometric Height Z, m	Geopotential Height H, m'	Number Density			Column Density atm-cm/km c_3	Mass Density kg/m³ ρ_3	Partial Pressure mb p_3	Mass Mixing Ratio kg/kg r_3
		m⁻³ n_3	Variability m⁻¹ σ	Percent Variability 100 σ/n_3				
2000	1999	6.8 (+17)	3.8 (+17)	56	2.5 (-3)	5.4 (-8)	2.6 (-5)	5.4 (-8)
4000	3997	5.8	2.9	50	2.1	4.6	2.1	5.6
6000	5994	5.7	3.0	53	2.1	4.5	1.9	6.8
8000	7990	6.5	5.9	90	2.4	5.2	2.1	9.9
10000	9984	1.13 (+18)	1.23 (+18)	109	4.2	9.0	3.5	2.18 (-7)
12000	11977	2.02	1.58	78	7.5	1.61 (-7)	6.0	5.16
14000	13969	2.35	1.48	63	8.7	1.87	7.0	8.21
16000	15960	2.95	1.42	48	1.10 (-2)	2.35	8.0	1.41 (-6)
18000	17949	4.04	1.23	30	1.50	3.22	1.21 (-4)	2.65
20000	19937	4.77	0.98	21	1.77	3.80	1.43	4.27
22000	21924	4.86	0.82	17	1.81	3.87	1.47	6.0
24000	23910	4.54	0.61	14	1.69	3.62	1.38	7.77
26000	25894	4.03	0.55	14	1.49	3.21	1.24	9.39
28000	27877	3.24	0.45	14	1.20	2.57	1.00	1.02 (-5)
30000	29859	2.52	0.33	13	9.38 (-3)	2.01	7.88 (-5)	1.09
32000	31840	2.03	0.34	17	7.55	1.62	6.40	1.19
34000	33819	1.58	0.27	17	5.88	1.26	5.10	1.27
36000	35737	1.22	0.17	14	4.54	9.72 (-8)	4.03	1.34
38000	37774	8.73 (+17)	1.10 (+17)	13	3.25	6.96	2.95	1.30
40000	39750	6.07	0.79	13	2.26	4.84	2.10	1.21
42000	41724	3.98	0.44	11	1.48	3.17	1.40	1.06
44000	43698	2.74	0.49	18	1.02	2.18	9.89 (-6)	9.67 (-6)
46000	45669	1.69	0.36	21	6.29 (-4)	1.35	6.23	7.86
48000	47640	1.03	0.17	17	3.83	8.20 (-9)	3.85	6.23
50000	49610	6.64 (+16)	1.10 (+16)	17	2.47	5.29	2.48	5.15
52000	51578	3.84	0.7	18	1.43	3.06	1.43	3.8
54000	53545	2.55	0.68	27	9.49 (-5)	2.03	9.28 (-7)	3.18
56000	55511	1.61	0.37	32	6.00	1.28	5.74	2.58
58000	57476	1.12	0.29	26	4.17	8.93 (-10)	3.90	2.25
60000	59439	7.33 (+15)	2.5 (+15)	34	2.73	5.85	2.50	1.88
62000	61401	4.81	1.8	38	1.79	3.83	1.60	1.59
64000	63362	3.17	1.2	38	1.18	2.52	1.03	1.36
66000	65322	1.72	0.66	38	6.4 (-6)	1.37	5.5 (-8)	9.6 (-7)
68000	67280	7.5 (+14)	5.1 (+14)	68	2.8	6.0 (-11)	2.4	5.5
70000	69238	5.4	3.1	57	2.0	4.3	1.6	5.1
72000	71194	2.2	1.7	77	8.2 (-7)	1.8	6.5 (-9)	2.8
74000	73148	1.7	0.9	53	6.3	1.3	4.9	2.9
Total Ozone Amount = 0.345 atm-cm								

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The percent-variability column represents 100 times the value of σ divided by n_3. The values in the remaining columns, i.e., the values of ϵ_3 below 27 km, the value of ρ_3 above 27 km, and the entire range of values for ozone partial pressure p_3 and for ozone mass mixing ratio r_3 (or, equivalently, density mixing ratio) were computed from the appropriate basic data sets in accordance with equations and constants given in the appendix. The computations of p_3 and r_3 require, respectively, the additional values of temperature T_S and air mass density ρ_S which are consistent with the 1974 U.S. Standard (U.S. Committee on Extension to the Standard Atmosphere, 1974), and were obtained from Kantor and Cole (1974). It should be noted that pressure mixing ratio (or equivalently volume mixing ratio r_j) may be computed by multiplying values of r_3 by 0.603448, the ratio of the molecular weight of air to that of ozone. Values of this quantity are not given in Table 1.

The total ozone content of this model, 0.345 atm-cm, is about five percent more than that obtained with the global network of Dobson spectrophotometers for 45°N (London, 1963). This is indicative of some longitudinal variation in the ozone densities in the lower stratosphere. The total ozone value of 0.345 atm-cm is equivalent to 7.39×10^{-3} kg/m^2, or 9.27×10^{22} molecules/m^2.

The height profile of number density for this mid-latitude ozone model is shown in Figure 1. The ozone density reaches a maximum at a height of about 22 km, and, between 38 and 70 km, decreases nearly exponentially by three orders of magnitude in accordance with a mean scale height of about 4.6 km. In the height
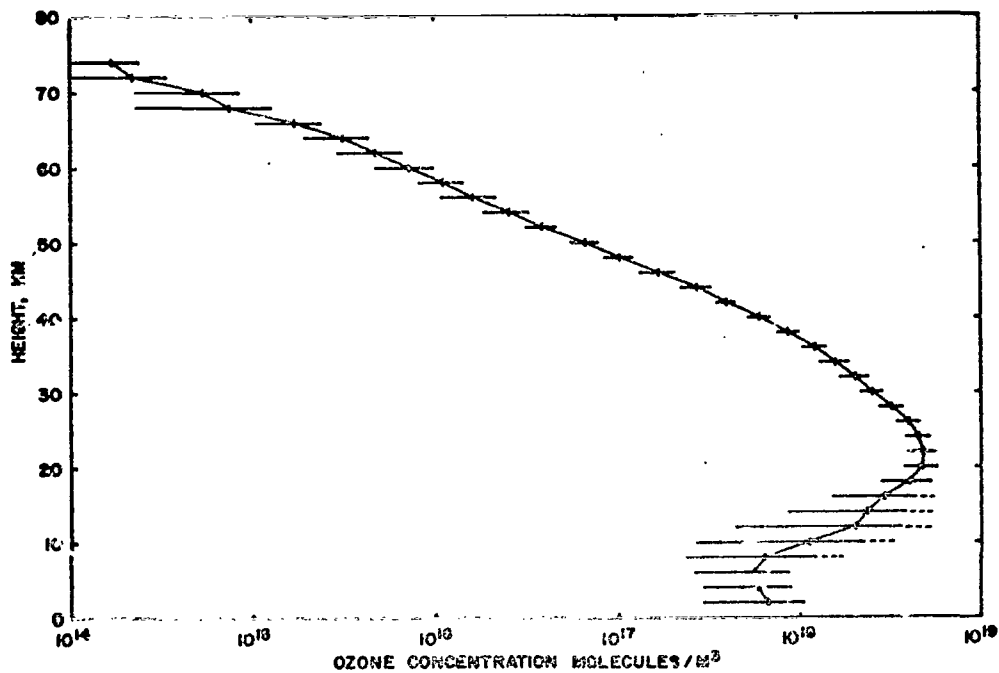
Figure 1. Mid-Latitude Ozone Model Density vs Height

region 22 to 75km, the number density decreases by more than four orders of
magnitude. The variability is shown at successive levels, with bars represent-
ing plus and minus one standard deviation. The dashed bars indicate uncertainty
in the statistical distribution of data at 8 to 16km.

Because of the large range of ozone densities, it is frequently convenient to use
the ratio of ozone density to air density (i.e., mixing ratio) as shown in Figure
2. The greatest mixing ratios, approximately 1.5×10^{-5} kg/kg (15 μgm/gm),
occur at about 35km. Above and below this maximum, the values tend to fall
off nearly symmetrically, decreasing by about 50% at 23 and 48km. It is
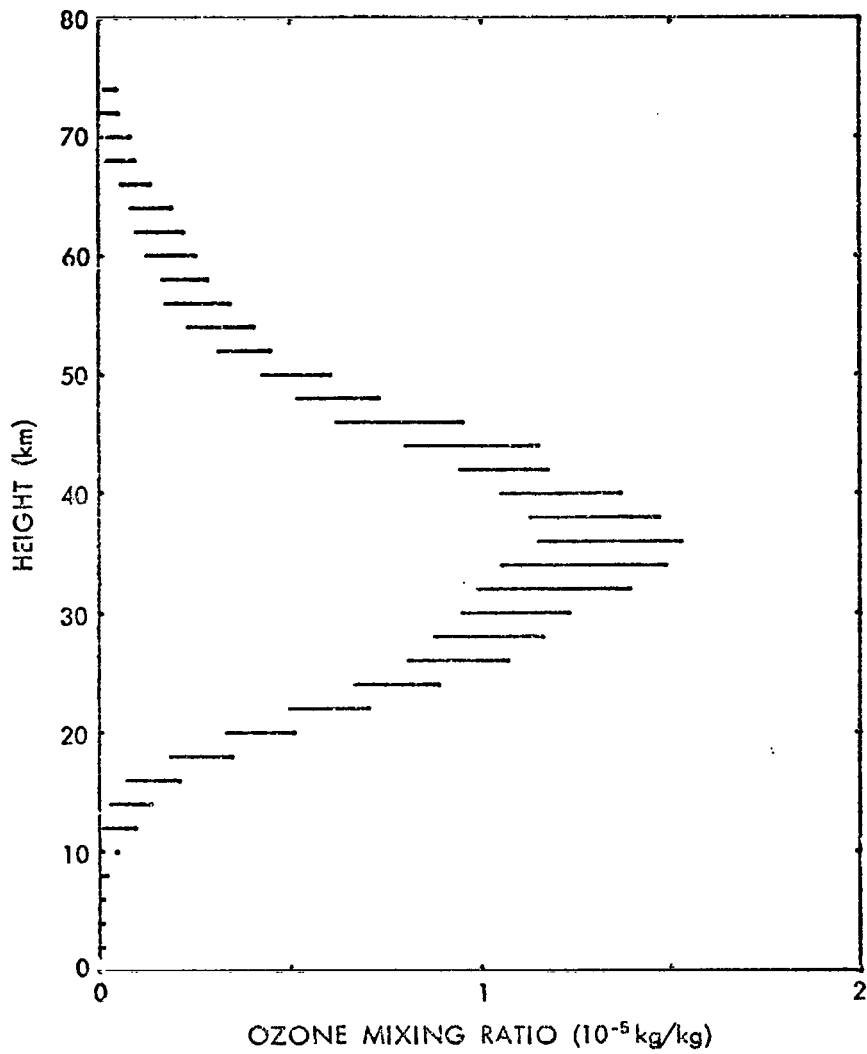
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Figure 2. Mixing Ratio vs Height from Mid-Latitude Ozone Model

important to note that the height of the mixing-ratio maximum occurs about 15 km higher than the density maximum. The range of mixing ratios shown at each height level correspond to plus and minus one sigma value.

The tabulated standard deviations of the data, upon which this Mid-Latitude Ozone Model is based, show apparent percentage variabilities ranging from near 10% to greater than 100%. The tropospheric variability derived from balloon ozone-sondes is of the order of 50%. At heights from 8 to 16 km, the variability (also from balloon data) is found, to increase significantly, reaching a maximum in excess of 100% at 10 km.

This large variability is due both to large-scale mixing processes in the atmosphere, and to changes in tropopause height with latitude. Tropospheric ozone profiles tend toward a constant mixing ratio (leading to a decrease of ozone density with height), while in the lower stratosphere the mixing ratio (and density) increases rapidly with height. The mid-latitude ozone-height profiles may contain elements of a low-latitude profile, with a minimum near 16 km (approximately 100 mb), and elements of a high-latitude profile, with a minimum at a height of about 10 km (approximately 250 mb). This situation is the result of transport to mid-latitudes of high-latitude tropospheric and lower stratospheric air, with its high-latitude ozone signature. Thus, one or more secondary ozone maxima, of the type shown in Figure 3 may result. This figure shows results of simultaneous ozone and temperature soundings at Boulder, Colorado on January 13, 1964
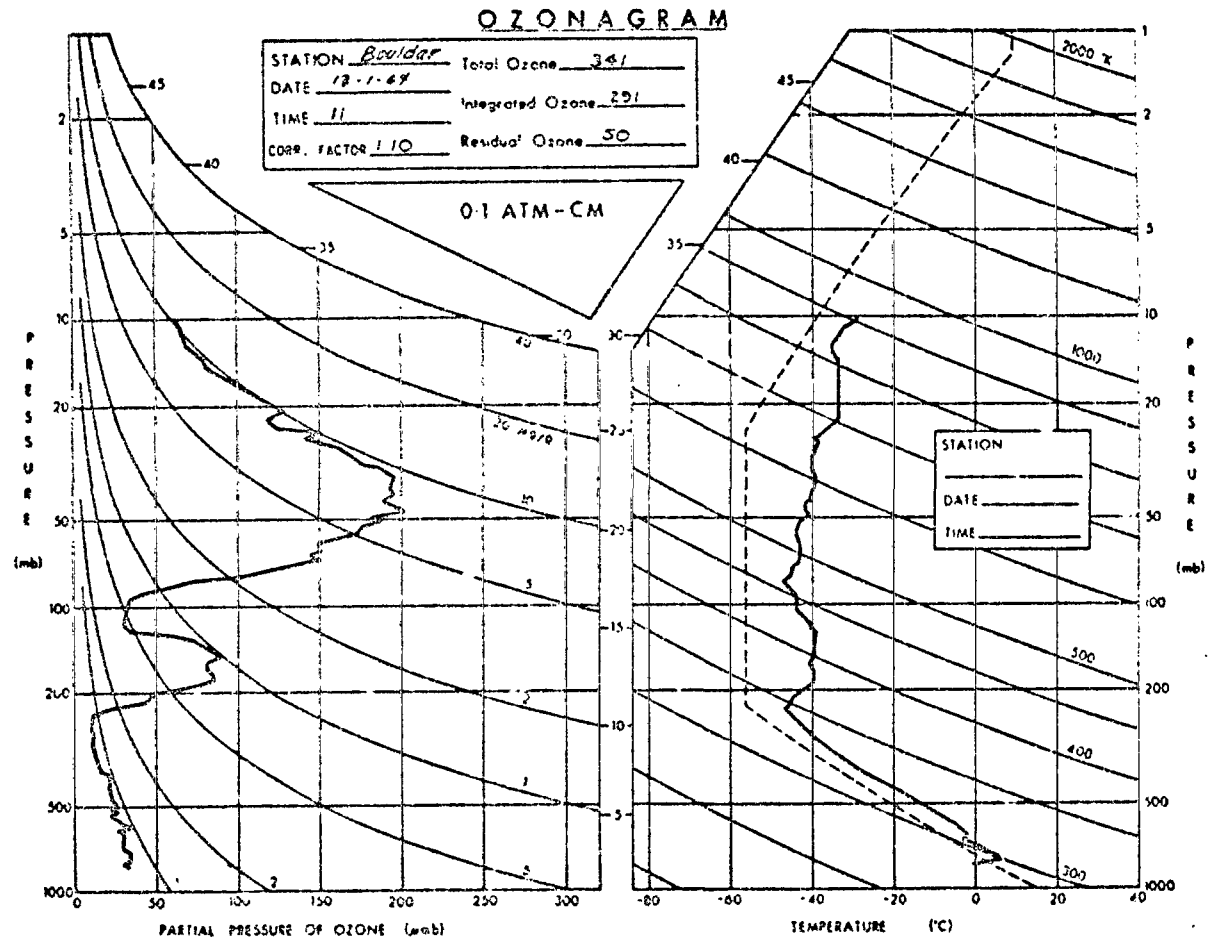
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Figure 3. A Measured Temperature-Height Profile and a Simultaneously Measured
Ozone-Height Profile Showing both a Primary and a Secondary Maximum

(Dutsch, 1966). Here a distinct secondary maximum is found near 150 mb (13 km), under the primary maximum at 80 mb (22 km). Such secondary maxima, found most frequently in the winter and spring, are the cause of the large variability in the Mid-Latitude Ozone Model at heights from 8 to 16 km.

Above the 22-km ozone maximum, the variability decreases to 14 percent in the balloon data, and is approximately 15 percent in the rocket data up to 52 km. The variabilities assessed from the satellite data are near 11 percent between 30 and 52 km, a value lower than that for the rocket model. This situation may be due in part to the greater smoothing of the ozone profile associated with the satellite technique. This difference may also be due to the fact that the satellite data represent the results of a single instrument, while the rocket model is derived from a multiplicity of instruments flown by several experimenters.

Between 52 and 66 km, the percentage variability in the rocket model increases to approximately 35%, and is greater than 50% at 68 to 74 km. These increases are due to the addition at these heights of twilight data which exhibit a much greater variability than that existing in daytime data. Diurnal changes, which would lead to a higher apparent variability, have been predicted from theory at altitudes above 55 km. Therefore, the reliability of the Model is considerably degraded at these altitudes.

The ozone densities and variabilities in this Mid-Latitude Ozone Model are consistent with the knowledge and the state of the art of ozone measurement techniques of 1974. The densities are derived principally from instruments with known absolute accuracy, and are thus believed to be definitive. The variabilities are based on a relatively small data set and therefore need refinement. Clearly, a need exists for further models which include seasonal, latitudinal, and secular dependences. These extensions of the Model will depend on systematic in-situ, rocket and balloon soundings coordinated with continued satellite monitoring.

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Derived Quantity	Basic Quantity	
	Mass Density ρ_3	Column Density ϵ_3
Number Density n_3 (molecules) m^{-3}	$\dfrac{N_A}{M_3} \cdot \rho_3$ $1.25467 \times 10^{25} \cdot \rho_3$	$10^{-5} \cdot \dfrac{N_A}{V_0} \cdot \epsilon_3$ $2.68684 \times 10^{20} \cdot \epsilon_3$
Column Density ϵ_3 atm-cm km^{-1}	$10^5 \cdot \dfrac{V_0}{M_3} \cdot \rho_3$ $4.66968 \times 10^4 \cdot \rho_3$	ϵ_3
Mass Density ρ_3 kg m^{-3}	ρ_3	$10^{-5} \cdot \dfrac{M_3}{V_0} \cdot \epsilon_3$ $2.14148 \times 10^{-5} \cdot \epsilon_3$
Partial Pressure p_3 $N\ m^{-2}$ _ _ _ _ _ _ _ mb	$\dfrac{R^*}{M_3} \cdot T_s \cdot \rho_3$ $1.73222 \times 10^2 \cdot T_s \cdot \rho_3$ _ _ _ _ _ _ _ $1.73222 \cdot T_s \cdot \rho_3$	$10^{-5} \cdot \dfrac{R^*}{V_0} \cdot T_s \cdot \epsilon_3$ $3.70951 \times 10^{-3} \cdot T_s \cdot \epsilon_3$ _ _ _ _ _ _ _ $3.70951 \times 10^{-5} \cdot T_s \cdot \epsilon_3$
Mass Mixing Ratio r_3 dimensionless	$\dfrac{\rho_3}{\rho_s}$	$10^{-5} \dfrac{M_3 \cdot \epsilon_3}{V_0 \cdot \rho_s}$ $2.14148 \times 10^{-5} \cdot \epsilon_3/\rho_s$
Volume Mixing Ratio r_3' dimensionless	$\dfrac{\rho_3 \cdot M}{\rho_s \cdot M_3}$ $6.03448 \times 10^{-1} \cdot \rho_3/\rho_s$	$10^{-5} \cdot \dfrac{M \cdot \epsilon_3}{V_0 \cdot \rho_s}$ $1.29227 \times 10^{-5} \cdot \epsilon_3/\rho_s$

Avogadro's Number $N_A = 6.022169 \times 10^{26}$ (molecules) $kmol^{-1}$
Universal gas constant $R^* = 8.31434 \times 10^3\ N\ m\ K^{-1}\ kmol^{-1}$
Volume of ideal gas at STP $V_0 = 22.4136\ m^3/kmol$
Molecular weight of O_3 $M_3 = 47.9982\ kg/kmol$
Molecular weight of air $M = 28.964\,\ kg/kmol$
Temperature of the U.S. Standard Atmosphere T_s K (at height Z)
Density of the U.S. Standard Atmosphere ρ_s kg/m^3 (at height Z)
$1.0\ N\ m^{-2} = 0.01$ mb