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Monthly Midlatitude Atmospheres, Surface to 90 km

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23 June 1976

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FOR THE COMMANDER:

John Howard

Chief Scientist

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Sets of mean monthly Reference Atmospheres that reflect the seasonal changes in the vertical distributions of temperature, pressure, and density at altitudes up to 90 km are presented for latitudes 30°N and 45°N. Estimates of the magnitude of the diurnal, day-to-day, and spatial variability of temperature and density are included for altitudes above 20 km. Special attention is given to the distribution of atmospheric density since density is the atmospheric property of most concern to aerospace designers and engineers.

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This report is part of a comprehensive effort to develop sets of mean monthly atmospheric models, surface to 90 km, for 15° intervals of latitude from pole to equator. The research is being performed to help satisfy the many requests that have been received from Air Force engineers and designers for information on the time and space variability of atmospheric density and temperature at altitudes up to 90 km.

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Monthly Midlatitude Atmospheres, Surface to 90 km

1. INTRODUCTION

Sets of mean monthly Reference Atmospheres that reflect the seasonal changes in the vertical distributions of temperature, pressure, and density at altitudes up to 90 km are presented for latitudes 30°N and 45°N. Estimates of the magnitude of the diurnal, day-to-day, and spatial variability of temperature and density are included for altitudes above 20 km.

This report is part of a comprehensive effort to develop sets of mean monthly model atmospheres, surface to 90 km, for 15° intervals of latitude from pole to equator. Models for 0° and 15°N were published in 1975.[1] The work is being performed to help satisfy the many requests that have been received from Air Force engineers and designers for information on the time and space variability of atmospheric density since this is the atmospheric property of most concern to aerospace designers and engineers.

Most of the rocket observations on which these models are based were taken over or near North America. Consequently, at altitudes above 30 km, the models are biased toward conditions between longitudes 70°W and 160°W in the Northern Hemisphere. However, summaries of temperature data regressed from satellite radiances for the years 1971 to 1974[2] show that longitudinal variations in the mean

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(Received for publication 22 June 1976)

1. Cole, A.E., and Kantor, A.J. (1975) Tropical Atmospheres, 0 to 90 km, AFCRL-TR-75-0527.
2. Labitzke, K. (1976) The Use of Single Channel Radiances for the Regression of Temperatures at Discrete Pressure Levels in the Upper Stratosphere, presented at the XIVth Plenary Meeting of COSPAR, June 1976.

monthly temperatures near 40 km are relatively small south of 45°N. Larger longitudinal variations occur north of 45°N, particularly in winter.

These models along with those for other latitudes will be submitted to the U.S. Committee for the Extension of the Standard Atmosphere (COESA) for consideration as part of the new set of Reference Atmospheres that COESA plans to publish as a replacement for the U.S. Standard Atmosphere Supplements, 1966.

2. BASIC ASSUMPTION AND FORMULAS

The defining parameter for each of the monthly atmospheres is molecular scale temperature presented with linear gradients in geopotential height. It is assumed that the air is dry, is in hydrostatic equilibrium and behaves like a perfect gas. The molecular weight of air is assumed to be constant, 28.9644 Kg $(\text{k-mol})^{-1}$, to 90 km. Actually, dissociation of molecular oxygen begins to take place near 80 km, and molecular weight starts decreasing slowly at that altitude. Consequently, the molecular scale temperatures (T_M) that are given in Appendix A for levels above 80 km are slightly (but not significantly) larger than the ambient kinetic temperature (T), as $T_M = (M_o/M)\,T$, where M_o is the sea-level molecular weight and M is the molecular weight of the air at a specific altitude.

The numerical values for the various thermodynamic and physical constants used in the computations of the tables (Appendix A) of the atmospheric properties for the mean monthly midlatitude atmospheres are the same as those used in the preparation of the U.S. Standard Atmosphere, 1976, with two exceptions. Surface conditions for the 30°N and 45°N atmospheres are based on mean monthly sea-level values of pressure and temperature for the appropriate latitude rather than on standard conditions. The acceleration due to gravity at sea level for 30° latitude was obtained from the following expression by Lambert[3] in which gravity g varies with latitude ϕ.

$$g_\phi = 9.780356\,(1 + 0.0052885\sin^2\phi - 0.0000059\sin^2\phi)\,. \qquad (1)$$

The value for sea-level gravity from Lambert's formula for 30° latitude is 9.79324 m/sec^{-2}. For 45°N the value of acceleration due to gravity is taken as 9.80665 m/sec^{-2}. This value has been adopted for Standard Atmospheres (ICAO, U.S. Standard and ISO Standard) which theoretically represent mean annual conditions at 45°N. It differs slightly from 980.616 m/sec^{-2}, the value obtained from Lambert's formula for 45°N.

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[3] List, R.J., ed (1968) Smithsonian Meteorological Tables, Smithsonian Inst. Press, Washington, D.C.

2.1 The Static Atmosphere and Perfect Gas Law

The air is assumed to be in hydrostatic equilibrium and to satisfy the differential equation

$$dP = -\rho \, g dZ \, , \tag{2}$$

which relates air pressure P, to density ρ, acceleration of free fall g and height Z. The perfect gas law relates air pressure to density and temperature as follows:

$$P = \frac{\rho R^{*} T_M}{M_o} \, , \tag{3}$$

where R^{*} is the universal gas constant, 8.31432×10^3 joules K^{-1} $(\text{k-mol})^{-1}$.

2.2 Geopotential

The relationship between geopotential and geometric altitude is the same as that used for the U.S. Standard Atmosphere Supplements, 1966:

$$H = \left(\frac{r_\phi Z}{r_\phi + Z}\right) \left(\frac{g_\phi}{9.80665}\right) \, , \tag{4}$$

where H is the geopotential and Z the geometric altitude, r_ϕ and g_ϕ are the effective earth radius and sea level value for acceleration of gravity at a specific latitude ϕ, as given by Lambert's equation.[3]

2.3 Pressure

Vertical distributions of pressure were computed from appropriate temperature-height profiles and associated mean monthly surface pressures, according to the following barometric equations:

$$\frac{P}{P_b} = \left(\frac{T_{Mb}}{T_{Mb} + Lh}\right)^{\frac{g_o M_o}{R^{*} L}} \quad (L \neq 0) \, , \tag{5}$$

$$\frac{P}{P_b} = \exp\left(\frac{-g_o M_o h}{R^{*} T_{Mb}}\right) \quad (L = 0) \, , \tag{6}$$

where $h = H - H_b$; H_b is the geopotential altitude at the base of a particular layer characterized by a specific value of L which is the gradient of temperature with geopotential height; T_{Mb} and P_b are the respective values of temperature and pressure at altitude H_b; and M_o, g_o and R^* are respectively the mean molecular weight of air, acceleration due to gravity at sea level, and the universal gas constant.

3. DATA

The initial pressures (sea level values for each atmosphere) were obtained from monthly normal sea level charts of the Northern Hemisphere.[4,5] Mean monthly temperature-height profiles for altitudes up to 30 km where obtained for latitudes 30°N and 45°N by giving equal weight to observed and interpolated radiosonde temperatures[6-10] for each 10 degrees of longitude.

There has been a substantial increase in the number of available meteorological and experimental rocket observations since the U.S. Standard Atmosphere Supplements, 1966, were prepared. Although a few new launch sites have been established, most of the measurements have been taken over or near the North American continent. Meteorological Rocket Network (MRN) observations[11] which provide data between 30 and 50 km are taken on a routine basis from locations given in Table 1. A relatively large number of observations are available for each month at each location. Instrumentation used in obtaining these data consisted of parachute-borne telemetering sets with temperature sensing elements (bead thermistors). The observed temperatures for altitudes up to 50 km were

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[4] U.S. Weather Bureau (1952) Normal Weather Charts for the Northern Hemisphere, USWB Tech Paper No. 21.

[5] Lahey, J.F., Bryson, R.A., and Wahl, E.W. (1958) Atlas of Five-day Normal Sea Level Pressure Charts for Northern Hemisphere, Scientific Report No. 7, Contract AF19(604)-992, Univ. Wisconsin Press.

[6] Goldie, N., Moore, J.G., and Austin, A.A. (1960) Upper Air Temperature over the World, Geophys. Memoirs, No. 101, Meteorological Office, London.

[7] Egdon, R.A. (1970) Average Temperature, Contour Height and Winds at 50 Millibars over the Northern Hemisphere, Geophys. Memoirs No. 112, Meteorological Office, London.

[8] Berry, F.A., Bollay, E., and Beers, N.R. (1945) Handbook of Meteorology, McGraw-Hill Book Co., Inc.

[9] Taljaard, J.J., Van Loon, H., Crutcher, H.L., and Jenne, R.L. (1969) Climate of the Upper Air, Southern Hemisphere, Vol. 1 Temperature, Dew Point and Height at Selected Pressure Levels EDS, ESSA.

[10] Crutcher, H., and Meserve, J.M. (1970) Selected Level Heights, Temperatures and Dew Points for the Northern Hemisphere, NAVAIR 50-1C-52, Commander, Naval Weather Service.

[11] World Data Center A (1965-1975) Data Report Meteorological Rocket Network Firings, Ashville, N.C.

corrected as suggested by Krumins and Lyons.[12] MRN data were not used for altitudes above 50 km due to the uncertainty in the temperature corrections above 50 km.

Table 1. Observational Sites

Meteorological Rockets Stations	Latitude	Period of Record
Ascension I.	8°S	Jan 1964 - Dec 1972
Fort Sherman	9°N	Dec 1966 - Dec 1972
Antigua	17°N	Jan 1965 - Dec 1972
Barking Sands	22°N	Dec 1966 - Dec 1972
Cape Kennedy	28°N	Jan 1964 - Dec 1972
White Sands	32°N	Jan 1965 - Dec 1972
Point Mugu	34°N	Jan 1965 - Dec 1972
Wallops I.	38°N	Jan 1965 - Dec 1972
Primrose Lake	55°N	Apr 1967 - Dec 1972
Fort Churchill	59°N	Jan 1965 - Dec 1972
Experimental Rockets		
Woomera	31°S	1957 - 1973
Ascension I.	8°S	1964 - 1965
Natal	6°S	1966 - 1968
Kourou	5°N	1971
Guam	13°N	1958
White Sands	32°N	1965 - 1971
Wallops I.	38°N	1961 - 1971
Fort Churchill	59°N	1957 - 1971
Point Barrow	71°N	1965 - 1972

Temperature and density distributions for altitudes from 50 to 90 km are based on grenade, pressure-gage and falling-sphere experiments[13-27] taken at the locations listed in Table 1. The quantity of available data decreases rapidly with height above 50 km. The two locations with the largest number of observations at these altitudes are Wallops Island, Virginia (38°N) and Ft. Churchill, Manitoba (59°N). Even at these locations, data for a given month and altitude vary from a few to several dozen observations. The unequal distribution of observations by month and time of day, as well as by location, makes it difficult to derive accurate estimates of monthly, day-to-day and diurnal variations of temperature and density at altitudes between 55 and 90 km.

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*Because of the large number of references mentioned in the above text, refer to pages 25 and 26 for References 12-27.

A series of constant pressure maps prepared at weekly intervals by the Upper Air Branch of the National Meteorological Center, for 5.0-, 2.0- and 0.4-mb surfaces[28-32] provides a useful source for estimating the magnitude of the longitudinal variations in the structure of the upper stratosphere and lower mesosphere. The maps are based on rocketsonde observations, hydrostatic build-up techniques from the 5- and 10-mb levels, and the thermal wind equation. The analysis covers the North American continent and adjacent areas, extending eastward to the British Isles and westward to approximately 160°W longitude. Recently, attempts have been made to extend the analysis over the entire globe with the use of satellite radiance measurements. However, since accuracy of the satellite data is not known, these data were not used in this study.

4. ANALYSIS

Mean monthly pressure-height maps were developed for 5.0-, 2.0-, and 0.4-mb from grid-point data taken from the weekly maps prepared by the National Meteorological Center.[28-32] In winter there is considerable longitudinal asymmetry in the mean monthly circulation patterns north of 45° latitude. In summer, the mean monthly isotherms and pressure-height contours at these levels parallel the latitude circles such that the circulation patterns are symmetrical about the pole.

Monthly median values of temperature and density were derived at 5-km intervals of altitude between 30 and 90 km from meteorological and experimental rocket observations taken at the locations given in Table 1. Bi-monthly running medians were used for levels and locations where data for one or more months were missing.

The median monthly temperatures and densities for each location and level were subjected to harmonic analysis for semi-annual and annual cycles. The analyses smoothed the data and gave regression equations of the form

$$Y = \overline{Y} + A_1 \sin(X + \phi_1) + A_2 \sin(2X + \phi_2) . \qquad (7)$$

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[28] Staff, Upper Air Branch, NMC (1967) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1964, ESSA TR WB-2.

[29] Staff, Upper Air Branch, NMC (1967) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1965, ESSA TR WB-3.

[30] Staff, Upper Air Branch, NMC (1969) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1966, ESSA TR WB-9.

[31] Staff, Upper Air Branch, NMC (1970) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1967, ESSA TR WB-12.

[32] Staff, Upper Air Branch, NMC (1971) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1968, NOAA TR NWS-14.

where A is amplitude, Y is either density or temperature, $\overline{Y}$ is the mean annual value, x = iz, z = 360° period, and i = 0, 1, 2, ... 11 where 0 represents 15 January, 1 represents 15 February, etc.

Curves representing the sum of the first two harmonics of the temperature oscillations for altitudes between 25 and 80 km are shown in Figure 1 for Wallops Island and White Sands. Curves for altitudes up to 50 km are based on MRN observations; those for altitudes 60 to 80 km are based on experimental observations.

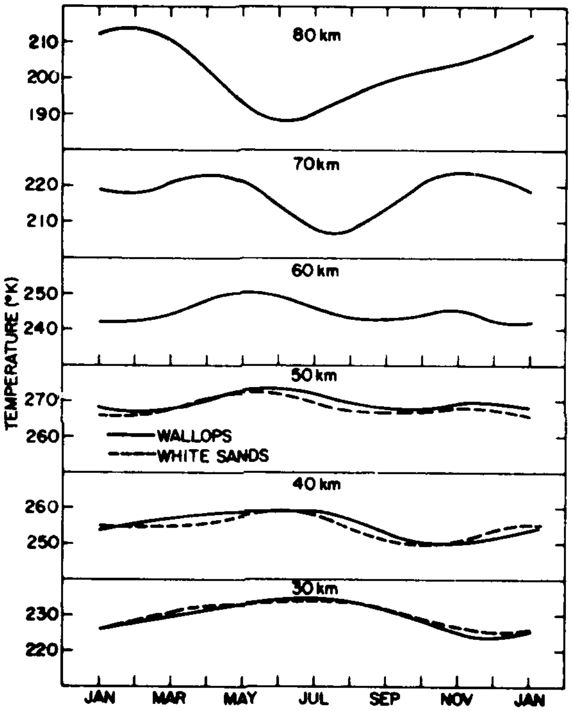

Figure 1. Sum of the First Two Harmonics of the Annual Temperature Distribution at Wallops Island (solid line) and White Sands (dashed line)

Monthly temperatures from the individual harmonic curves and the mean monthly maps for 5.0-, 2.0-, and 0.4-mb were plotted vs latitude. Estimates of the mean monthly temperature-height profiles for altitudes from 30 to 50 km at 30°N and 45°N were obtained by fitting latitudinal temperature curves to these data.

The temperature plots for altitudes above 50 km, extend from 8°S to 71°N. Third degree polynominal curves were fitted to the temperatures for four data points (Ascension/Natal, Wallops Island, Churchill, and Barrow) to obtain estimates of the latitudinal temperature variations at altitudes between 55 and 90 km. Curves for January and July temperatures at 75 km are shown in Figure 2. During the summer months, when longitudinal and latitudinal temperature variations are small, the polynomial curves appear to provide reasonable estimates of the temperature at 15° intervals of latitude between the equator and pole. However, during the Northern Hemisphere winter the longitudinal and latitudinal temperature variations are large and the curves do not appear to provide realistic estimates.

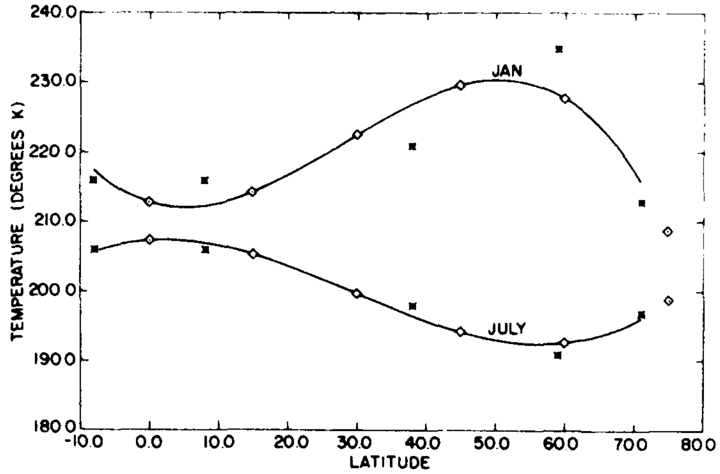

Figure 2. Latitudinal Distributions of Mean Monthly 75-km Temperatures for January and July. The solid curve is a 3-deg polynominal fit to the observed data (asterisks). Diamonds are polynominal values for 15-deg intervals of latitude

Fourth and fifth degree polynominal fits provided even poorer estimates. Consequently, data for the 3-degree polynominal curves were only used for the months May through August and linear interpolations were used for the remaining months.

Median monthly temperatures at 1-km intervals between 45 and 55 km and 75 and 85 km were analyzed at the locations in Table 1 to obtain realistic estimates of the variations in height and thickness of the isothermal layers associated with the stratopause and mesopause, respectively. Time cross-sections of the adopted temperatures for 30°N and 45°N are shown in Figures 3 and 4 for altitudes between 45 and 90 km.

The temperature-height profiles adopted for each of the monthly atmospheres at 30°N and 45°N are defined in Table 2. The vertical temperature gradients between breakpoints are linear with geopotential altitude.

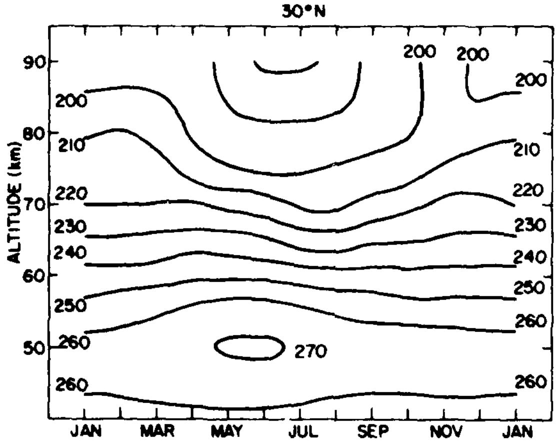

Figure 3. Mean Monthly Temperature-Height Cross-Section for 30°N

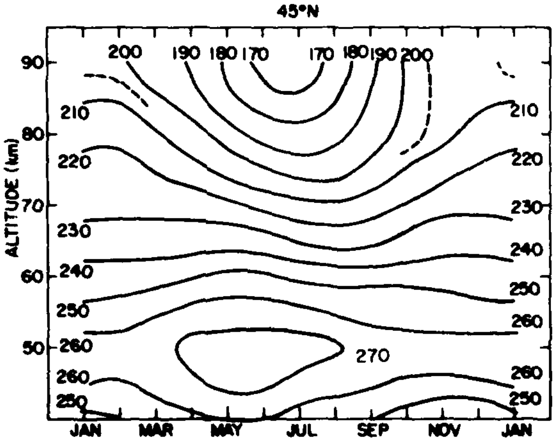

Figure 4. Mean Monthly Temperature-Height Cross-Section for 45°N

Table 2a. 30°N Temperature-Height Profiles to 90 KM

MONTH	SURFACE PRESSURE (MB)	BREAK-POINTS IN KILOMETERS (GEOPOTENTIAL) AND TEMPERATURE (°K)					
JAN	1019.1	(Sfc)287.15 (30.5)230.15 (74.0)218.15	(2.0)281.15 (35.5)241.65 (89.0)191.15	(12.0)216.15 (45.5)265.65	(17.0)203.15 (50.0)265.65	(18.0)203.15 (55.0)252.65	(25.5)221.15 (70.0)218.15
FEB	1018.2	(Sfc)286.65 (40.0)255.15 (89.5)192.15	(4.0)270.65 (45.0)266.65	(12.0)218.65 (49.5)266.65	(17.0)204.15 (54.5)253.65	(18.0)204.15 (69.5)219.15	(26.0)220.15 (74.5)219.15
MAR	1017.1	(Sfc)289.15 (39.0)254.15 (83.0)202.15	(4.0)269.15 (44.0)264.65 (89.0)196.15	(12.0)217.15 (47.0)267.65	(17.0)206.15 (50.5)267.65	(18.0)206.15 (55.5)256.65	(24.0)218.15 (68.0)221.65
APR	1015.9	(Sfc)292.15 (32.0)239.15 (76.0)200.65	(5.0)267.15 (42.0)261.15 (90.0)193.65	(12.0)218.15 (47.0)269.15	(17.0)206.15 (51.0)269.15	(18.0)206.15 (56.0)257.65	(22.0)216.15 (66.0)229.65
MAY	1013.9	(Sfc)295.15 (44.5)267.15 (89.0)188.65	(5.0)271.15 (47.0)270.65	(12.0)218.65 (50.0)270.65	(16.0)204.65 (55.0)263.65	(17.0)204.65 (75.0)197.65	(37.0)250.65 (84.0)188.65
JUNE	1012.9	(Sfc)298.65 (36.0)247.65 (72.5)202.15	(1.0)292.65 (40.0)257.65 (88.5)178.15	(5.0)272.65 (45.0)268.65 (90.0)178.15	(12.0)220.15 (47.5)271.15	(15.0)203.65 (50.5)271.15	(16.0)203.65 (54.5)265.15
JULY	1012.9	(Sfc)301.15 (42.0)262.15	(1.0)293.65 (47.0)269.15	(6.0)266.15 (50.0)269.15	(15.0)203.15 (55.0)263.15	(16.0)203.15 (70.0)206.15	(36.0)247.15 (90.0)176.15
AUG	1012.7	(Sfc)298.65 (42.0)258.65 (89.0)182.15	(1.0)292.15 (47.0)267.65	(5.5)269.65 (50.0)267.65	(15.5)203.65 (55.0)258.15	(16.5)203.65 (69.0)209.15	(22.0)214.65 (87.0)182.15
SEP	1013.9	(Sfc)296.65 (22.0)217.65 (60.0)244.65	(1.0)290.15 (34.5)240.15 (71.0)206.15	(5.0)272.15 (44.5)263.15 (83.0)194.15	(12.0)219.65 (47.0)266.65 (89.0)194.15	(16.0)203.65 (50.0)266.65	(17.0)203.65 (55.0)256.65
OCT	1016.9	(Sfc)293.65 (34.5)238.65 (79.0)199.65	(5.0)268.65 (45.5)266.15 (89.0)199.65	(12.0)219.65 (47.0)267.65	(16.0)203.65 (50.0)267.65	(17.0)203.65 (55.0)253.65	(22.0)216.15 (75.0)201.65
NOV	1018.6	(Sfc)289.15 (34.5)237.65 (79.0)201.15	(4.0)273.15 (44.5)265.65 (89.0)201.15	(12.0)217.15 (47.0)269.15	(17.0)203.15 (50.0)269.15	(18.0)203.15 (55.0)253.15	(22.0)215.15 (65.0)229.15
DEC	1019.6	(Sfc)286.15 (30.0)227.65 (74.0)217.65	(2.0)280.15 (36.0)242.65 (83.0)199.65	(12.0)217.15 (46.0)266.65 (89.0)199.65	(17.0)203.65 (50.0)266.65	(18.0)203.65 (60.0)242.65	(22.0)215.65 (70.0)221.65

Table 2b. 45°N Temperature-Height Profiles to 90 KM

MONTH	SURFACE PRESSURE (MB)	BREAKPOINTS IN KILOMETERS (GEOPOTENTIAL) AND TEMPERATURE (°K)								
JAN	1016.6	(Sfc)272.15	(3.0)261.65		(10.0)219.65		(19.0)215.15	(27.0)215.15		(34.5)231.65
		(44.5)261.65	(47.5)264.65		(50.5)264.65		(54.5)252.65	(69.5)225.65		(74.0)225.65
		(80.0)213.65	(90.0)201.65							
FEB	1016.5	(Sfc)273.15	(3.0)262.65		(10.0)217.15		(22.5)217.15	(30.0)224.65		(35.0)235.65
		(40.0)250.65	(47.5)264.15		(50.5)264.15		(55.5)253.15	(69.5)225.15		(74.5)225.15
		(89.5)199.65								
MAR	1016.1	(Sfc)274.15	(3.0)265.15		(11.0)217.15		(22.0)217.15	(27.5)222.65		(35.0)239.15
		(42.5)261.65	(47.5)268.15		(50.5)268.15		(55.5)256.15	(64.5)233.65		(79.5)209.65
		(87.0)194.65	(89.0)194.65							
APR	1015.9	(Sfc)279.15	(3.0)270.15		(11.0)218.15		(22.5)218.15	(29.5)228.65		(35.5)243.65
		(40.5)258.65	(47.0)271.65		(50.5)271.65		(65.5)232.65	(79.5)204.65		(85.5)189.65
		(89.0)189.65								
MAY	1014.0	(Sfc)284.65	(3.0)274.15		(11.0)218.15		(20.0)218.15	(27.0)225.15	(37.0)253.15	(44.5)272.65
		(47.0)274.65	(50.5)274.65	(55.5)262.65	(68.0)227.65		(74.0)206.65	(85.0)179.15		(89.0)179.15
JUN	1013.0	(Sfc)288.15	(2.5)279.15		(12.5)216.15		(17.0)216.15	(27.0)227.15		(35.0)247.15
		(42.0)268.15	(47.5)275.15		(50.5)275.15		(60.5)248.15	(75.5)195.65		(85.5)167.65
		(89.0)167.65								
JUL	1013.5	(Sfc)294.15	(2.0)285.15		(16.0)261.15		(13.0)215.65	(17.0)215.65	(22.0)221.65	(27.0)227.15
		(47.0)273.15	(51.5)273.15	(54.5)264.15	(74.5)194.15		(87.0)164.15	(89.0)164.15		
AUG	1014.1	(Sfc)292.15	(2.5)282.15		(12.5)215.15		(17.0)215.15	(24.5)224.15		(34.5)240.15
		(46.5)270.15	(51.0)270.15	(59.0)246.15	(74.0)195.15			(89.0)172.65		
SEP	1016.3	(Sfc)288.15	(2.5)278.15		(12.5)215.15		(17.5)215.15	(27.5)225.15		(36.0)242.15
		(46.0)266.15	(48.0)268.15		(50.5)268.15	(55.5)255.15	(72.5)204.15	(87.5)187.65		(89.0)187.65
OCT	1017.5	(Sfc)284.15	(3.0)269.15		(12.0)215.15		(20.0)215.15	(31.0)226.15		(41.0)247.15
		(44.0)257.65	(48.0)267.65		(51.0)267.65	(56.0)254.15	(62.0)236.15	(79.0)202.15		(89.0)202.15
NOV	1018.6	(Sfc)278.15	(3.0)266.15		(11.0)218.15		(16.0)214.65	(20.0)214.65		(30.0)221.65
		(35.0)229.65	(41.0)244.65		(46.0)262.65		(48.5)265.65	(51.5)265.65	(56.5)253.15	(61.5)239.15
		(71.5)225.15	(76.5)207.15		(90.0)207.15					
DEC	1017.9	(Sfc)273.15	(3.0)264.15		(10.0)218.65		(15.0)216.15	(28.0)216.15		(35.0)230.15
		(41.0)245.15	(46.0)259.65		(48.5)264.15		(51.5)264.15	(54.5)253.65		(69.5)228.15
		(74.5)222.15	(81.5)208.15		(89.0)208.15					

5. DISCUSSION

Vertical profiles of the phases (times of maximum) and amplitudes of the annual and semi-annual oscillations in temperature and density are shown for Wallops Island (30 to 90 km), White Sands and Point Mugu (30 to 50 km) and Woomera, Australia (55 to 80 km) in Figures 5 and 6. The outstanding feature in the vertical profiles of the annual temperature cycles (Figure 5a) is the abrupt change in phase between 60 and 65 km. At altitudes below 60 km, maximum temperatures occur in May or June, and at altitudes above 65 km the maximum occur between mid-December and mid-February. Similar changes in the phase of the annual temperature cycle occur at all latitudes between the pole and equator.[33] However, the height at which the change in phase occurs, increases with latitude from 35 km in the Tropics, to 60 or 65 km at midlatitudes and 75 km in the Arctic. The observed amplitude of the annual component at midlatitudes decreases from roughly 4°C at 35 km to 2°C at 60 km; it then increases with altitude becoming 12 to 14°C between 75 and 90 km.

The first maximum of the semi-annual temperature oscillation in Figure 5b occurs in May and November at 70 km and is propagated downward and upward, reaching 30 km in September and March and 90 km in October and April. The amplitude increases from 1°C at 30 km to 2°C at 50 km, 4°C at 80 km and 8°C at 90 km.

The annual density oscillation in Figure 6a is propagated downward from the mesopause. Maximum densities occur in late June at 80 km, early July at 45 km and late July or early August at 30 km. Amplitudes increase with altitude from 4 percent of the annual mean at 30 km to 16 percent at 70 km and then decrease with altitude to roughly 12 percent at 80 km.

The semi-annual density oscillations in Figure 6b, are also propagated downward from the mesopause. Maximum densities occur in November and May at 80 km and March and September at 30 km. Amplitudes are relatively small, 0.5 percent of the annual mean at 30 km increasing with height to 2.0 percent at 50 km and then remaining more-or-less constant with height up to 80 km.

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[33] Cole, A.E., and Kantor, A.J. (1974) Periodic Oscillations in the Stratosphere and Mesosphere, AFCRL-TR-0504.

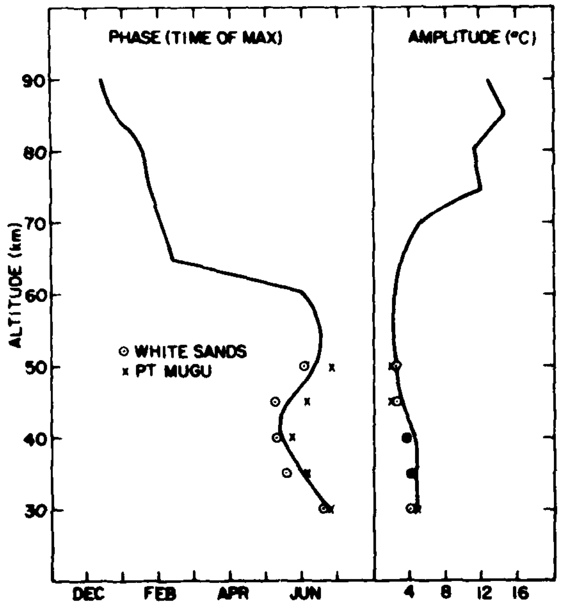

Figure 5a. Vertical Profile of the Phase (time of maximum) and Amplitude of the Annual Temperature Oscillation

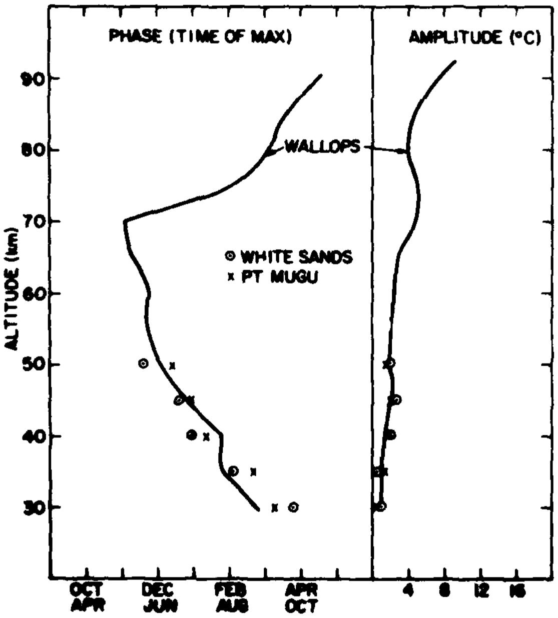

Figure 5b. Vertical Profile of the Phase (time of maximum) and Amplitude of the Semi-annual Temperature Oscillation

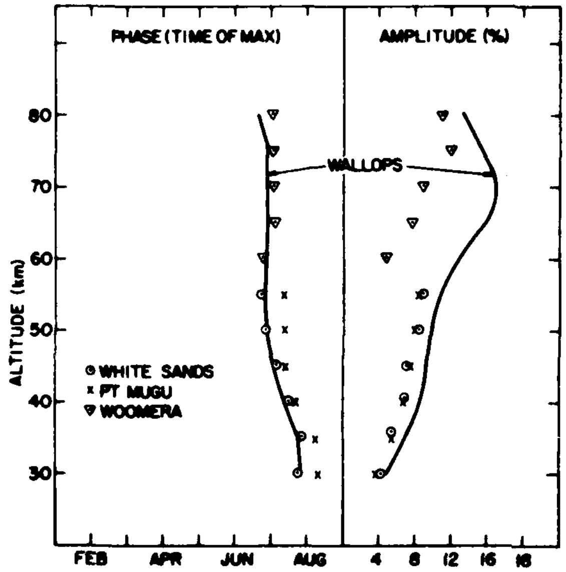

Figure 6a. Vertical Profile of the Phase (time of maximum) and Amplitude of the Annual Density Oscillation

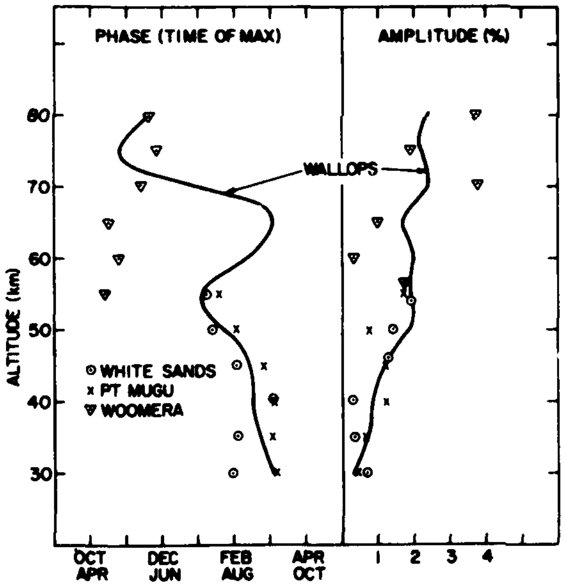

Figure 6b. Vertical Profile of the Phase (time of maximum) and Amplitude of the Semi-annual Density Oscillation

6. COMPARISON OF OBSERVED AND MODEL DENSITIES

Densities computed from the temperature-height profiles adopted for the monthly atmospheres for 30°N and 45°N are compared in Figure 7 with the harmonically smoothed values observed at Wallops Island (38°N). The model densities for 45°N are higher in summer and lower in winter than those at 30°N. During April and September the model densities for 30° and 45° latitude and the observed values for Wallops Island are nearly the same. During the remaining months the observed values at most levels fall between the model densities for 30°N and 45°N. Data from the constant pressure maps which extend from 10°W to 160°W, indicate that during the winter months at 45°N longitudinal variations in mean monthly densities of 5 to 6 percent and 10 to 12 percent occur at altitudes from 12 to 28 km and 30 to 60 km, respectively. In other months the variations are smaller.

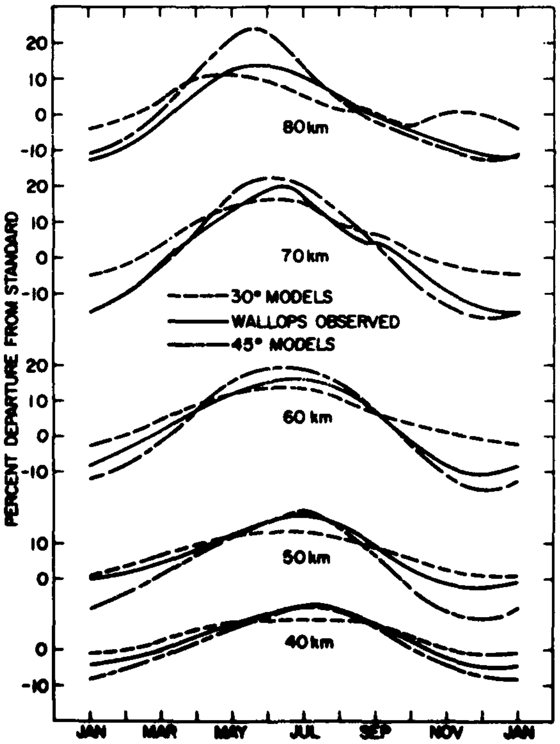

Figure 7. Comparison of Observed Mean Monthly Densities at Wallops Island With Densities for Monthly Models at 30°N and 45°N

7. DIURNAL VARIABILITY OF DENSITY

During the equinox of 19 and 20 March 1974, eleven meteorological rockets, (Loki Datasonde Systems) were launched within a 24-hr period at Wallops Island. The launchings were part of an experiment initiated by NASA[34] to examine the diurnal variations in the structure of the upper stratosphere and lower mesosphere. Corrections to the observed temperature data were applied following the recommendations of Krumins and Lyons.[12] Densities computed from the corrected temperature profile for 30, 40, and 50 km, were subjected to harmonic analysis (Figure 8) for diurnal and semi-diurnal cycles. The combined amplitudes of the diurnal and semi-diurnal oscillations are approximately 1.2, 2.4, and 1.5 percent of the daily means at 30, 40, and 50 km, respectively. The variation of 1.5 percent in density at 50 km is approximately one-third of that observed at the same altitude at Ascension (8°S) with Arcasonde 1A instrumentation and at Kourou (5°N) with grenades. These latitudinal differences are in agreement with theory which predicts larger amplitudes in diurnal variations near the equator.

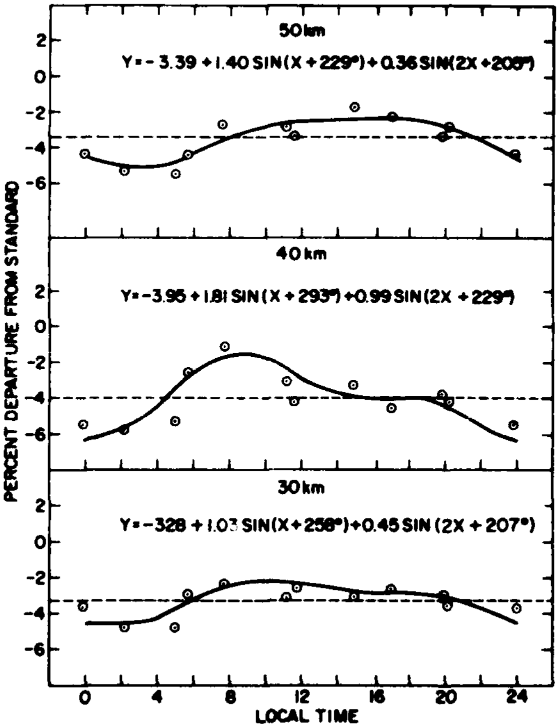

Figure 8. Sum of the First Two Harmonics of the Daily Density Distribution Observed at Wallops Island on 19-20 March 1974. Circles are Observations

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[34] Schmidlin, F.J., Yamasaki, Y., Motta, A., and Brynsztein, S. (1975) Diurnal Experiment Data Report, March 19-20, 1974, NASA SP-3095.

8. DAY-TO-DAY VARIABILITY OF DENSITY

Estimates of the standard deviations of the day-to-day variations in temperature and density about the monthly means at altitudes between 20 and 80 km are given in Table 3 for the mid-season months at Wallops Island. These are the rms errors one would expect if mean monthly conditions were used as a prediction of actual conditions. The values at levels below 50 km are considered to be more reliable than those for the higher levels where estimates are based on relatively few observations. Variability generally increases with altitude and is smallest for both temperature and density at most levels in July.

Table 3. Standard Deviations of Observed Temperatures and Densities Around the Monthly Means at Wallops Island, 38°N

Altitude (km)	Temperature (°C)			
	Jan	Apr	July	Oct
20	3.7	3.0	2.6	2.8
25	3.7	3.6	2.6	3.5
30	4.2	5.0	2.7	4.5
35	6.9	4.3	2.9	5.5
40	8.4	5.0	3.3	5.6
45	8.0	5.3	3.9	7.5
50	4.1	5.2	3.6	6.8
60	8.5	6.0	6.1	6.0
70	9.8	9.0	9.2	6.7
80	18.1	12.2	12.1	8.5
	Density (% of Monthly Mean)			
20	2.6	2.2	1.6	1.9
25	2.1	1.5	1.4	2.0
30	2.3	2.1	1.7	2.2
35	2.8	3.4	2.1	2.6
40	3.4	5.1	2.8	4.2
45	4.3	5.2	3.3	4.9
50	4.5	5.4	3.7	6.0
60	6.0	6.3	6.0	3.2
70	8.0	5.0	7.0	4.3
80	9.0	7.7	7.2	6.2

9. SPATIAL VARIABILITY OF DENSITY

The mean monthly latitudinal density gradients between 15°N and 60°N are shown in Table 4 for altitudes 40 to 80 km. Densities at these levels decrease toward the pole in January and toward the equator in July. The mean monthly gradients at most levels are largest in January with the maximum gradients occurring near 70 km. There are relatively large day-to-day variations around the mean monthly gradients at a particular level and location due to changes in the daily synoptic conditions

Table 4. Mean Monthly Latitudinal Density Gradients, Percent Change in Density per Degree of Latitude in the Direction of the Pole, for Various Latitude Bands

Altitude (km)	15° to 30°N	30° to 45°N	45° to 60°N
		January	
40	-0.2	-0.5	-0.5
50	-0.3	-0.6	-1.3
60	-0.5	-0.7	-1.7
70	-0.8	-0.7	-1.8
80	-0.8	-0.5	-1.7
		April	
40	+0.2	-0.3	-0.2
50	+0.1	-0.3	-0.4
60	-0.1	-0.2	-0.3
70	-0.2	-0.2	-0.4
80	+0.4	-0.1	-0.3
		July	
40	+0.1	+0.2	+0.2
50	+0.2	+0.4	+0.4
60	+0.2	+0.6	+0.4
70	+0.3	+0.6	+0.8
80	+0.7	+0.8	+1.4
		October	
40	-0.1	-0.3	-0.2
50	-0.4	-0.6	-0.4
60	-0.6	-0.6	-0.7
70	-0.7	-0.5	-0.8
80	-0.1	-0.2	-0.7

Estimates of density gradients equalled or exceeded 1 percent of the time in January and July at altitudes between 40 and 80 km are presented in Table 5 for the region between 30°N and 45°N. These estimates are based on the standard deviations of day-to-day variations in density at Wallops Island (Table 3); the mean seasonal density gradients between 30°N and 45°N (Table 4); and the assumption that the correlation coefficients between densities at two points at the same altitude 600 and 1200 nautical miles apart are 0.5 and 0.0, respectively. This decay in the correlation coefficients with horizontal distance is based on the extrapolation of data obtained from: (1) a study of spatial correlation of radiosonde temperatures, pressures, and densities at levels up to 16 km over the North Atlantic and Europe,[35] and (2) estimates of the wave lengths of migratory disturbances between 30 km and 55 km determined from sets of constant pressure maps prepared from rocketsonde data and satellite radiance measurements for levels up to 50 km.[28-32]

Table 5. Density Gradients, Percent Change per Degree of Latitude, Which are Equalled or Exceeded 1 Percent of the Time at Altitudes Between 40 km and 80 km and Latitudes 30°N to 45°N

Altitude (km)	January	July
40	1.3%	1.0%
50	1.7%	1.3%
60	2.1%	2.0%
70	2.6%	2.2%
80	2.6%	2.7%

10. FINDINGS

1. The ranges of mean monthly temperatures and densities at altitudes between 10 km and 90 km are given below for 30°N and 45°N:

	30°N		45°N	
Altitude (km)	Mean Annual Temp. (K)	Range of Mean Monthly Temp. (K)	Mean Annual Temp. (K)	Range of Mean Monthly Temp. (K)
10	233	229 to 240	226	217 to 235
20	210	208 to 212	217	215 to 219
30	231	227 to 234	228	220 to 234
40	254	251 to 257	251	242 to 260
50	268	266 to 271	269	264 to 275
60	245	242 to 249	246	243 to 252
70	217	209 to 223	222	211 to 229
80	201	193 to 211	202	183 to 217
90	192	178 to 201	191	164 to 208

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35. Bertoni, E.A., and Lund, I.A. (1964) Winter Space Correlations of Pressure, Temperature, and Density to 16 km, AFCRL-64-1020.

Altitude (km)	30°N Mean Annual Density (kg m^{-3})	 Range % of Mean Monthly Density	45°N Mean Annual Density (kg m^{-3})	 Range % of Mean Monthly Density
10	4.1816×10^{-1}	-0.7 to +0.8	4.1183×10^{-1}	-1.3 to +1.2
20	9.3875×10^{-2}	-2.4 to +3.6	8.9751×10^{-2}	-4.5 to +5.1
30	1.8436×10^{-2}	-3.7 to +3.4	1.8500×10^{-2}	-5.2 to +6.2
40	4.1722×10^{-3}	-5.2 to +4.2	4.0473×10^{-3}	-9.5 to +10.5
50	1.1031×10^{-3}	-6.1 to +5.4	1.0573×10^{-3}	-14.0 to +13.2
60	3.2877×10^{-4}	-7.8 to +7.1	3.1601×10^{-4}	-16.9 to +16.7
70	8.7289×10^{-5}	-9.9 to +9.8	8.3932×10^{-5}	-18.4 to +20.7
80	1.8970×10^{-5}	-6.8 to +7.9	1.8898×10^{-5}	-13.7 to +18.9
90	3.6276×10^{-6}	-7.6 to +7.3	3.5888×10^{-6}	-8.7 to +12.7

2. The standard deviations of the day-to-day variations of temperature and density around the January means at altitudes between 20 km and 80 km are given below for Wallops Island (38°N):

Altitude (km)	Standard Deviations Temp (°C)	 Density (%)
20	3.7	2.6
30	4.2	2.3
40	8.4	3.4
50	4.1	4.5
60	8.5	6.0
70	9.8	8.0
80	19.1	9.0

3. Between 30° and 45° latitude the amplitudes of the diurnal density oscillation appear to be 1 to 3 percent for levels between 30 and 50 km.

4. An analysis of available data indicates that the density gradients (percent change per degree of latitude) which are equalled or exceeded 1 percent of the time at altitudes between 40 km and 80 km range from 1.0 to 2.7 percent depending on altitude and time of year.

5. Additional observations are required to determine more accurately the magnitude of the diurnal oscillations of temperature and density between 50 km and 90 km.

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Appendix A

Thermodynamic Properties of the Midlatitude Atmospheres

Table A1. Mean Monthly Thermodynamic Properties at 30°N

Altitude (km)	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Annual	
TEMPERATURE (K)														
0.000	287.15	286.65	289.15	292.15	295.15	298.65	301.15	298.65	296.65	293.65	289.15	286.15	292.86	
5.000	261.72	264.22	262.72	267.20	271.20	272.70	271.70	272.20	272.19	268.70	266.22	261.31	267.67	
10 000	229.34	231.84	230.34	232.35	233.87	235.37	238.35	240.14	234.87	233.85	231.35	229.93	233.47	
15.000	208.49	210.11	210.67	211.08	208.34	203.95	203.54	207.31	207.87	207.87	208.90	209.20	208.11	
20.000	207.73	207.97	209 97	210.92	211.34	212.25	211.75	210.47	211.79	210.92	208.88	209.38	210.28	
25.000	219.63	217.88	220.23	222.74	222.74	223.15	222.65	220.95	222.81	221.31	220.31	219.95	221.20	
30.000	228.92	229.69	232.11	234.13	234.13	234.05	233.55	231.85	231.72	230.22	229.22	227.37	231.41	
35.000	239.94	242.05	243.97	245.22	245.49	244.92	244.42	242.72	240.74	239.30	238.37	239.55	242.22	
40.000	251.71	254.38	255.61	256.07	256.57	256.88	256.38	253.57	252.09	251.63	252.19	251.51	254.05	
45.000	263.54	265.78	265.27	265.34	267.32	267.81	265.82	263.37	263.32	263.95	265.82	263.34	265.06	
50.000	265.65	266.54	267.65	269.15	270.65	271.15	269.15	267.65	266.65	267.65	269.15	266.65	268.14	
55 000	254.07	253.77	258.95	261.20	264.41	265.22	263.80	259.19	257.74	255.18	254.90	255.96	258.70	
60.000	242.62	242.48	245.85	248.25	249.27	248.15	246.59	242.90	246.19	242.32	242.69	244.19	245.12	
65.000	231.36	231.21	232.14	234.54	233.11	231.01	227.98	225.76	229.76	229.59	230.94	233.71	230.92	
70.000	220.12	219.97	220.16	220.53	216.98	213.90	209.41	208.93	212.65	216.88	220.86	223.45	216.99	
75.000	218.10	219.15	213.82	206.38	200.87	199.86	200 11	201.61	203.12	204.19	211.10	217.60	207.99	
80.000	209.33	211.23	207.48	199.20	193.75	192.55	192.80	194.30	198.25	199 70	201.35	207.85	200.65	
85.000	200.57	202.47	201.38	196.76	188.88	185.25	185.50	187.00	194.15	199.65	201.15	199.65	195.20	
90.000	191.83	193.73	196.53	194.34	188.65	178.15	178.22	182.15	194.15	199.65	201.15	199.65	191.52	
PRESSURE (mb)														
0.000	1.0191	1.0182	1.0171	1.0159	1.0139	1.0129	1.0129	1.0127	1.0139	1.0169	1.0186	1.0196	1.0160	+3*
5.000	5.4994	5.4942	5.4888	5.5207	5.5517	5.5707	5.5742	5.5643	5.5571	5.5441	5.5262	5.4921	5.5320	+2
10.000	2.7470	2.7637	2.7494	2.7901	2.8264	2.8475	2.8618	2.8636	2.8367	2.8135	2.7853	2.7443	2.8024	
15.000	1.2528	1.2705	1.2601	1.2834	1.2986	1.3065	1.3242	1.3381	1.3058	1.2942	1.2749	1.2553	1.2887	
20.000	5.4791	5.5787	5.5704	5.6791	5.7217	5.7570	5.8235	5.8770	5.7415	5.6849	5.5825	5.5070	5.6669	+1
25.000	2.4795	2.5176	2.5328	2.6010	2.6213	2.6438	2.6696	2.6784	2.6386	2.5998	2.5416	2.5096	2.5861	
30.000	1.1670	1.1814	1.1989	1.2404	1.2501	1.2615	1.2717	1.2689	1.2536	1.2291	1.1976	1.1781	1.2248	
35.000	5.6761	5.7737	5.8978	6.1325	6.1818	6.2323	6.2736	6.2278	6.1326	5.9853	5.8139	5.7138	6.0034	+0
40.000	2.8584	2.9270	3.0036	3.1296	3.1586	3.1814	3.1982	3.1568	3.0937	3.0113	2.9235	2.8756	3.0431	
45.000	1.4871	1.5323	1.5748	1.6423	1.6612	1.6749	1.6812	1.6469	1.6100	1.5672	1.5265	1.4953	1.5916	
50.000	7.8958	8.1583	8.3939	8.7773	8.9118	8.9942	8.9876	8.7682	8.5564	6.3510	8.1603	7.9530	8.4923	-1
55.000	4.1447	4.2799	4.4469	4.6746	4.7627	4.8174	4.7909	4.6415	4.5162	4.4009	4.3074	4.1893	4.4977	
60.000	2.1105	2.1784	2.2909	2.4229	2.4831	2.5078	2.4883	2.3832	2.3231	2.2435	2.1953	2.1436	2.3142	
65.000	1.0418	1.0749	1.1375	1.2115	1.2407	1.2472	1.2291	1.1668	1.1510	1.1040	1.0831	1.0641	1.1460	
70.000	4.9711	5.1262	5.4229	5.8149	5.9056	5.8851	5.7247	5.4068	5.4079	5.2237	5.1686	5.1241	5.4318	-2
75.000	2.3160	2.3954	2.5146	2.6617	2.6575	2.6168	2.5271	2.3994	2.4109	2.3654	2.3879	2.4024	2.4712	
80.000	1.0626	1.1064	1.1407	1.1643	1.1384	1.1200	1.0827	1.0347	1.0517	1.0336	1.0650	1.0982	1.0915	
85.000	4.7216	4.9532	5.0567	5.0284	4.7748	4.6452	4.4961	4.3263	4.5010	4.4956	4.6607	4.8440	4.7086	-3
90.000	2.0260	2.1428	2.1956	2.1519	1.9809	1.8623	1.8048	1.7532	1.9144	1.9577	2.0422	2.1094	1.9951	
DENSITY (kg m^{-3})														
0.000	1.2363	1.2374	1.2254	1.2113	1.1967	1.1815	1.1717	1.1812	1.1906	1.2063	1.2272	1.2412	1.2089	+0*
5.000	7.3201	7.2440	7.2781	7.1976	7.1314	7.1163	7.1469	7.1212	7.1121	7.1879	7.2313	7.3217	7.2007	-1
10.000	4.1727	4.1529	4.1583	4.1832	4.2102	4.2145	4.1827	4.1542	4.2076	4.1912	4.1940	4.1578	4.1816	
15.000	2.0933	2.1066	2.0837	2.1181	2.1713	2.2316	2.2665	2.2485	2.1883	2.1689	2.1260	2.0904	2.1578	
20.000	9.1885	9.3448	9.2420	9.3798	9.4314	9.4489	9.5807	9.7276	9.4437	9.3893	9.3105	9.1626	9.3875	-2
25.000	3.9329	4.0254	4.0065	4.0679	4.0997	4.1272	4.1768	4.2229	4.1255	4.0924	4.0190	3.9749	4.0726	
30.000	1.7760	1.7918	1.7994	1.8456	1.8600	1.8777	1.8969	1.9066	1.8847	1.8599	1.8201	1.8051	1.8436	
35.000	8.2408	8.3097	8.4214	8.7119	8.7722	8.8646	8.9415	8.9385	8.8740	8.7132	8.4965	8.3094	8.6328	-3
40.000	3.9559	4.0084	4.0935	4.2575	4.2885	4.3144	4.3456	4.3368	4.2751	4.1689	4.0383	3.9829	4.1722	
45.000	1.9657	2.0084	2.0682	2.1562	2.1649	2.1787	2.2033	2.1784	2.1300	2.0684	2.0005	1.9780	2.0917	
50.000	1.0354	1.0662	1.0925	1.1360	1.1470	1.1555	1.1632	1.1412	1.1178	1.0869	1.0562	1.0390	1.1031	
55.000	5.6830	5.8753	5.9824	6.2344	6.2749	6.3276	6.3267	6.2385	6.1041	6.0079	5.8869	5.7017	6.0536	-4
60.000	3.0303	3.1297	3.2462	3.4001	3.4702	3.5207	3.5152	3.4181	3.2872	3.2253	3.1512	3.0581	3.2877	
65.000	1.5687	1.6195	1.7070	1.7995	1.8542	1.8808	1.8781	1.8005	1.7451	1.6751	1.6338	1.5860	1.7290	
70.000	7.8672	8.1182	8.5806	9.1854	9.4816	9.5846	9.5234	9.0149	8.8592	8.3906	8.1523	7.9887	8.7289	-5
75.000	3.6992	3.8079	4.0969	4.4928	4.6088	4.5612	4.3993	4.1460	4.1349	4.0355	3.9406	3.8461	4.1474	
80.000	1.7683	1.8247	1.9153	2.0362	2.0469	2.0263	1.9564	1.8551	1.8480	1.8032	1.8425	1.8406	1.8970	
85.000	8.2006	8.5222	8.7473	8.9025	8.8062	8.7352	8.4433	8.0593	8.0763	7.8443	8.0718	8.4523	8.4051	-6
90.000	3.6793	3.8531	3.8919	3.8574	3.6581	3.6418	3.5279	3.3531	3.4351	3.4160	3.5369	3.6807	3.6276	

*Power of 10 by which preceding numbers should be multiplied.

Table A2. Mean Monthly Thermodynamic Properties at 45°N

Altitude (km)	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Annual	
TEMPERATURE (K)														
0.000	272.15	273.15	274.15	279.15	284.65	288.15	294.15	292.15	288.15	284.15	278.15	273.15	281.78	
5.000	249.67	249.67	253.17	257.17	260.17	263.42	267.17	265.42	262.42	257.17	254.17	251.17	257.56	
10.000	219.74	217.25	223.24	224.75	225.26	231.99	235.25	232.00	230.99	227.24	224.24	218.75	225.89	
15.000	217.16	217.15	217.15	218.15	218.15	216.15	215.65	215.15	215.15	215.15	215.37	216.16	216.38	
20.000	215.15	217.15	217.15	218.15	218.15	219.38	219.17	218.67	217.58	215.15	214.65	216.15	217.21	
25.000	215.15	219.55	220.05	221.75	223.05	224.84	224.84	224.79	222.55	220.05	218.08	216.15	220.90	
30.000	221.44	224.50	227.84	229.54	233.15	234.29	233.72	232.72	229.86	225.00	221.55	219.86	227.79	
35.000	232.57	235.22	238.72	241.92	247.01	246.67	245.10	240.92	239.76	234.14	229.34	229.76	238.43	
40.000	247.40	249.90	253.40	256.40	260.30	260.45	256.47	253.27	251.15	244.52	241.52	242.02	251.40	
45.000	261.83	259.08	264.48	267.01	272.79	271.20	267.82	265.60	262.99	259.35	257.91	255.83	263.82	
50.000	264.65	264.15	268.15	271.65	274.65	275.15	273.15	270.15	268.15	267.65	265.65	264.15	268.94	
55.000	252.59	255.28	258.48	261.98	264.98	264.27	264.05	259.56	257.67	258.12	258.08	253.60	259.06	
60.000	243.76	245.27	246.30	249.01	251.62	251.01	246.86	244.65	243.33	243.83	244.92	245.25	246.32	
65.000	234.93	235.46	234.04	235.77	237.89	234.70	229.70	227.98	228.62	231.46	235.17	236.91	233.55	
70.000	226.12	225.67	226.07	225.17	223.31	217.56	212.56	211.34	213.93	221.67	228.31	228.59	221.69	
75.000	225.39	225.15	218.24	215.39	206.33	200.46	195.46	194.96	202.36	211.89	215.69	222.60	211.16	
80.000	215.63	217.49	210.44	205.63	194.13	185.83	183.33	187.64	196.99	202.15	207.15	213.13	201.63	
85.000	208.99	209.20	200.89	193.70	181.95	172.19	171.64	180.33	191.63	202.15	207.15	208.15	194.00	
90.000	203.15	200.93	194.65	189.65	179.15	176.65	164.15	173.03	187.65	202.15	207.15	208.15	190.54	
PRESSURE (mb)														
0.000	1.0166	1.0165	1.0161	1.0159	1.0140	1.0130	1.0135	1.0141	1.0163	1.0175	1.0186	1.0179	1.0158	+3*
5.000	5.3027	5.3125	5.3402	5.4004	5.4429	5.4736	5.5251	5.5155	5.4821	5.4205	5.3773	5.3338	5.4106	+2
10.000	2.5629	2.5573	2.6088	2.6596	2.6939	2.7485	2.8026	2.7769	2.7451	2.6797	2.6349	2.5796	2.6708	
15.000	1.1760	1.1681	1.1943	1.2221	1.2381	1.2684	1.2995	1.2781	1.2624	1.2257	1.2057	1.1794	1.2265	
20.000	5.3555	5.3424	5.4622	5.6094	5.6828	5.8002	5.9336	5.8251	5.7442	5.5654	5.4660	5.3746	5.5968	+1
25.000	2.4346	2.4514	2.5087	2.5857	2.6338	2.7026	2.7643	2.7099	2.6576	2.5522	2.4956	2.4522	2.5790	
30.000	1.1153	1.1433	1.1746	1.2200	1.2489	1.2887	1.3175	1.2925	1.2544	1.1923	1.1550	1.1230	1.2104	
35.000	5.2931	5.4769	5.6897	5.9540	6.1746	6.3792	6.5013	6.3264	6.1050	5.6993	5.4544	5.2930	5.8622	+0
40.000	2.6188	2.7295	2.8638	3.0220	3.1742	3.2772	3.3159	3.1944	3.0670	2.8147	2.6616	2.5868	2.9438	
45.000	1.3512	1.4079	1.4974	1.5881	1.6870	1.7417	1.7431	1.6679	1.5918	1.4400	1.3530	1.3134	1.5319	
50.000	7.1403	7.4191	7.9744	8.5260	9.1324	9.4243	9.3866	8.9287	8.4713	7.6277	7.1426	6.8970	8.1725	-1
55.000	3.7381	3.8923	4.2212	4.5509	4.9087	5.0655	5.0414	4.7508	4.4806	4.0381	3.7731	3.6215	4.3402	
60.000	1.9013	1.9905	2.1714	2.3604	2.5644	2.6410	2.6135	2.4421	2.2939	2.0700	1.9370	1.8482	2.2361	
65.000	0.9442	0.9915	1.0809	1.1825	1.2933	1.3259	1.2936	1.2017	1.1277	1.0209	0.9616	0.9225	1.1122	
70.000	4.5705	4.7997	5.2233	5.7172	6.2671	6.3265	6.0699	5.6105	5.2947	4.8795	4.6723	4.4967	5.3273	-2
75.000	2.1806	2.2863	2.4631	2.6787	2.8788	2.8445	2.6761	2.4639	2.3637	2.2583	2.2117	2.1445	2.4542	
80.000	1.0237	1.0773	1.1314	1.2131	1.2516	1.1975	1.1083	1.0305	1.0255	1.0091	0.9968	0.9980	1.0886	
85.000	4.6681	4.9370	5.0373	5.2714	5.1630	4.7231	4.3373	4.1695	4.3538	4.4293	4.4628	4.5072	4.6716	-3
90.000	2.0837	2.1949	2.1632	2.2011	2.0450	1.7602	1.5985	1.6273	1.8080	1.9465	2.0005	2.0282	1.9548	
DENSITY (kg m^{-3})														
0.000	1.3013	1.2964	1.2911	1.2678	1.2409	1.2246	1.2003	1.2092	1.2286	1.2474	1.2757	1.2982	1.2568	+0*
5.000	7.3988	7.4125	7.3481	7.3153	7.2679	7.2387	7.2042	7.2390	7.2775	7.3427	7.3701	7.3978	7.3914	-1
10.000	4.0631	4.1007	4.0711	4.1224	4.1662	4.1272	4.1502	4.1697	4.1399	4.1081	4.0934	4.1081	4.1183	
15.000	1.8865	1.8740	1.9160	1.9516	1.9771	2.0443	2.0994	2.0695	2.0440	1.9847	1.9503	1.9007	1.9748	
20.000	8.6716	8.5707	8.7629	8.9578	9.0750	9.2105	9.4313	9.2800	9.1969	9.0114	8.8711	8.6623	8.9751	-2
25.000	3.9421	3.8897	3.9716	4.0621	4.1135	4.1874	4.2831	4.1997	4.1601	4.0404	3.9865	3.9522	4.0657	
30.000	1.7546	1.7740	1.7961	1.8516	1.8661	1.9162	1.9638	1.9347	1.9011	1.8460	1.8161	1.7793	1.8500	
35.000	7.9284	8.1112	8.3028	8.5738	8.7082	9.0092	9.2402	9.1480	8.8703	8.4795	8.2851	8.0252	8.5568	-3
40.000	3.6876	3.8051	3.9371	4.1059	4.2482	4.3835	4.5040	4.3937	4.2542	4.0101	3.8391	3.7235	4.0743	
45.000	1.7978	1.8931	1.9722	2.0720	2.1543	2.2372	2.2673	2.1876	2.1086	1.9342	1.8275	1.7885	2.0200	
50.000	0.9399	0.9784	1.0360	1.0933	1.1583	1.1932	1.1971	1.1513	1.1005	0.9928	0.9367	0.9096	1.0573	
55.000	5.1554	5.3115	5.6892	6.0516	6.4534	6.6774	6.6512	6.3761	6.0576	5.4499	5.0931	4.9749	5.8284	-4
60.000	2.7172	2.8272	3.0713	3.3023	3.5505	3.6652	3.6881	3.4774	3.2841	2.9575	2.7551	2.6253	3.1601	
65.000	1.4001	1.4668	1.6089	1.7472	1.8939	1.9680	1.9619	1.8363	1.7184	1.5365	1.4244	1.3565	1.6599	
70.000	0.7041	0.7409	0.8049	0.8845	0.9776	1.0130	0.9948	0.9248	0.8622	0.7668	0.7129	0.6853	0.8393	
75.000	3.3703	3.5375	3.9315	4.3323	4.8605	4.9433	4.7696	4.4026	4.0692	3.7128	3.5721	3.3561	4.0715	-5
80.000	1.6538	1.7257	1.8730	2.0551	2.2461	2.2448	2.1061	1.9133	1.8136	1.7391	1.6763	1.6312	1.8898	
85.000	7.7812	8.2210	8.7352	9.4805	9.8850	9.5555	8.8031	8.0547	7.9148	7.6330	7.5052	7.5435	8.4260	-6
90.000	3.5731	3.8054	3.8715	4.0433	3.9767	3.6577	3.3925	3.2763	3.3565	3.3544	3.3643	3.3945	3.5888	

*Power of 10 by which preceding numbers should be multiplied.