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Monthly 90°N Atmospheres and High-Latitude Warm and Cold Winter Stratosphere/Mesosphere

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FOR THE COMMANDER

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A set of 12 mean monthly reference atmospheres, which describes the seasonal changes in the distributions of the thermodynamic properties of the atmosphere, is provided for the North Pole for altitudes up to 55 km. Additional atmospheric models for arctic and subarctic regions are presented to describe the large variations that occur in the vertical distributions of atmospheric temperature, density, and pressure during typical warmings and coolings of the winter stratosphere and mesosphere.

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These atmospheric models are the final portion of a more comprehensive effort to develop up-to-date sets of mean monthly reference atmospheres at 15° intervals of latitude between the Equator and the North Pole. Monthly models to 90 km have already been completed for the Equator and for latitudes 15°, 30°, 45°, 60°, and 75° N.

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1. INTRODUCTION

A set of monthly reference atmospheres, which describes the seasonal changes in the vertical distributions of atmospheric temperature, density, and pressure for altitudes up to 55 km, is provided herein for the North Pole. Additional atmospheric models for arctic and subarctic regions are presented to describe the large variations that occur in the vertical distributions of these parameters during major warmings and coolings of the winter stratosphere and mesosphere. These large-scale fluctuations can be important factors in designing aerospace vehicles that must operate in these regions. Designers of reentry vehicles, for example, can make computer-simulated flights through the density profiles of these special models to determine the effect of major stratospheric and mesospheric warmings on guidance systems and trajectories of proposed reentry vehicles.

These atmospheric models represent the final portion of a more extensive effort to develop up-to-date sets of mean monthly reference atmospheres at 15° intervals of latitude between the Equator and the North Pole. Mean monthly models to 90 km have already been completed for the Equator, 15°, 30°, 45°,

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60°, and 75°N.[1-3] They are intended as replacements for the U.S. Standard Atmosphere Supplements, 1966, which were completed by the Committee on Extension to the Standard Atmosphere (COESA) 12 years ago. Since that time, there has been a substantial increase in the number of observations available for the region between 30 and 90 km.

2. BASIC ASSUMPTIONS AND FORMULAS

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

Numerical values for the various thermodynamic and physical constants used to compute the tables of atmospheric properties for these models (Appendix A) are identical to those used in the preparation of the U.S. Standard Atmosphere, 1976, with two exceptions: surface pressure and temperature, and acceleration due to gravity. Surface conditions 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 was obtained from the following expression by Lambert[4] in which gravity, g, varies

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with latitude ϕ:

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

2.1 The Static Atmosphere and Perfect Gas Law

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

$$dP = -\rho g\, dZ \qquad (2)$$

that 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:

$$P = \frac{\rho R^* T_M}{M_o} \qquad (3)$$

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

2.2 Geopotential

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

$$H = \left(\frac{r_\phi Z}{r_\phi + Z}\right) \frac{g_\phi}{G} \qquad (4)$$

where H is the geopotential altitude in geopotential meters (m'), Z is the geometric altitude, r_ϕ is the effective earth radius, g_ϕ is the sea-level value for acceleration of gravity at a specific latitude ϕ, as given by Lambert's equation,[4] and G is the unit geopotential set equal to $9.80665\ m^2 sec^{-2} (m')^{-1}$.

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:

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

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

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 vertical gradient of molecular-scale temperature with geopotential height (dT_M/dh); and T_{Mb} and P_b are the respective values of temperature and pressure at altitude H_b.

3. DATA

Initial sea-level pressures for each atmosphere were taken from mean monthly sea-level charts for the Northern Hemisphere.[5-7] At the North Pole, monthly temperature-height profiles for altitudes up to 30 km were derived from mean monthly and seasonal maps[7-10] based on radiosonde observations around the Northern Hemisphere and from radiosonde summaries at individual stations in the Arctic. Temperature and height data for altitudes above 30 km were taken from mean monthly constant-pressure and temperature maps for the 5-, 2-, and 0.4-mb levels. These maps were developed from grid-point

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data, which were extracted from a series of weekly constant pressure maps prepared by the National Meteorological Center (NMC) for the years 1964 through 1968, and from January 1972 through June 1974.[11-17] Since no direct observations are available north of 81° latitude, these maps provide the bulk of the information used to develop monthly models at the Pole for altitudes 30 to 55 km. As an example, mean January and July constant-pressure and temperature maps for 0.4 mb are shown in Figures 1 and 2, respectively. During the winter months, there is considerable longitudinal asymmetry in the mean monthly temperature and pressure patterns north of 45° latitude. In summer the circulation patterns are nearly symmetrical about the Pole, so that the mean monthly isotherms and height contours at these altitudes parallel the latitude circles.

The first 55 km of the temperature-height profiles, for the models representing "warm" and "cold" stratospheric conditions, are based on individual radiosonde observations at stations in arctic and subarctic regions, and on Meteorological Rocket Network (MRN) observations[18] from the locations given in the upper part of Table 1. The MRN data were corrected, as suggested by Krumins and Lyons,[19] for altitudes between 30 and 55 km. They were not used for altitudes above 55 km, since thermistor measurements are subject to larger uncertainties at these altitudes. The temperature and density distributions between 55 and 90 km are based on values derived from grenade, pressure gauge,

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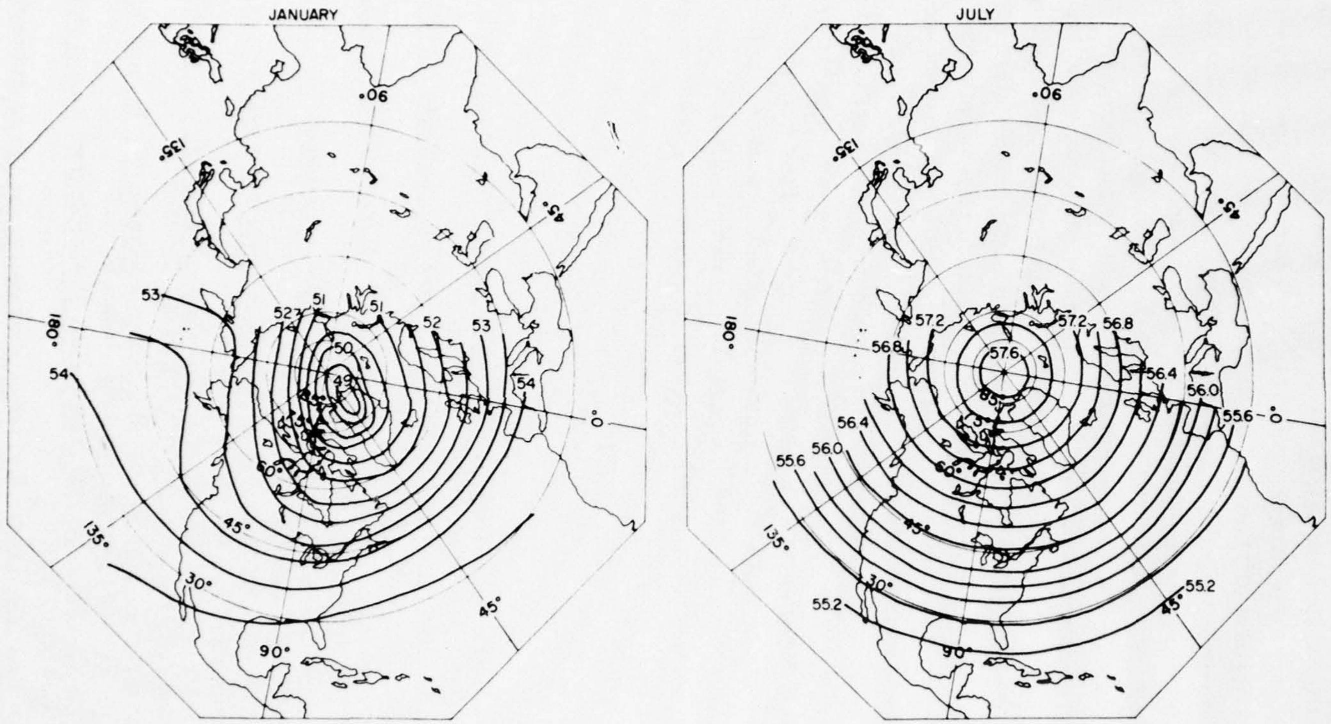

Figure 1. Mean January and July Constant-Pressure Maps (km) for 0.4 mb

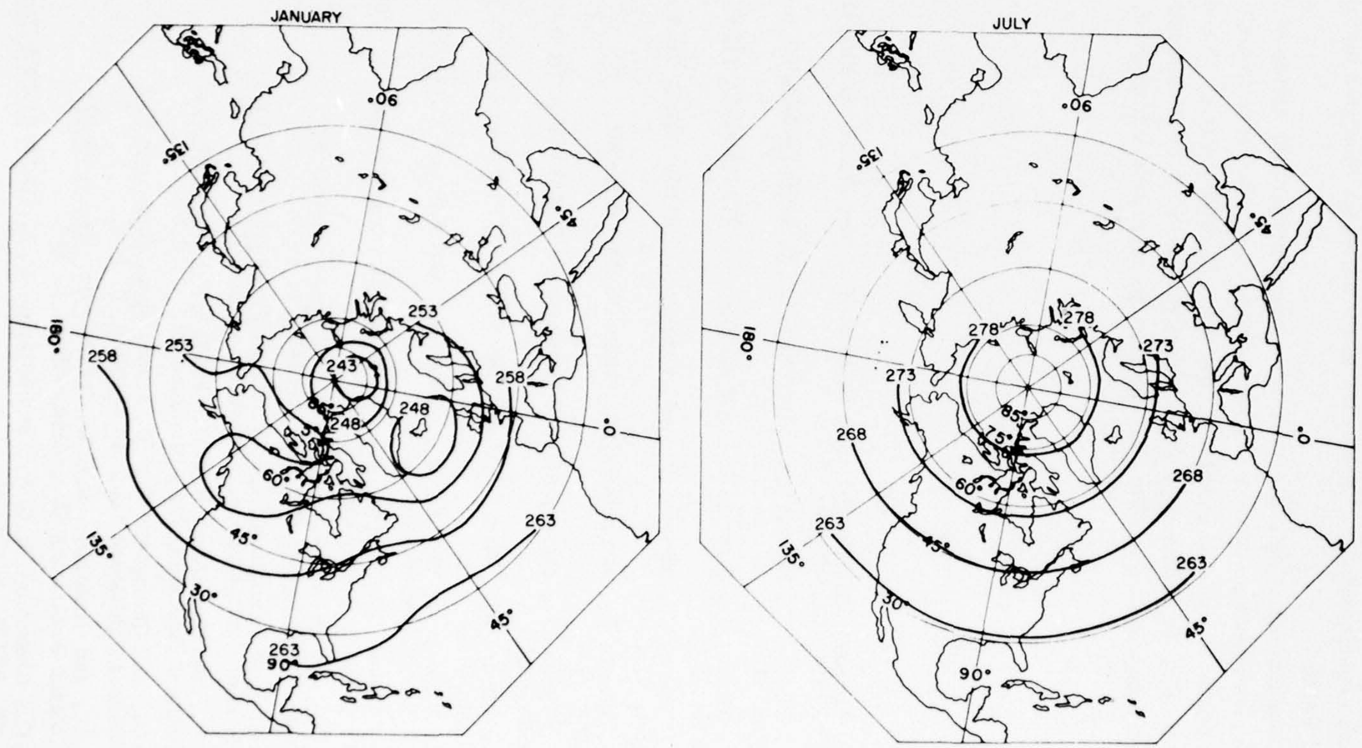

Figure 2. Mean January and July Temperature Maps (°K) for 0.4 mb

and falling sphere experiments[20-34] conducted at the locations indicated on the lower portion of Table 1.

The increasing amount of satellite-derived temperatures in the stratosphere and mesosphere represents an additional data source, which was used in construction of the 1972-1974 weekly synoptic maps for 5, 2, and 0.4 mb. These satellite data will be more widely used in the development of future atmospheric models as the accuracy and reliability of these remote sensors are improved.

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Table 1. Observational Sites

Meteorological Rockets			
Stations	Latitude	Longitude	Period of Record
Wallops Island	38° N	75° W	Jan 1965 - Dec 1976
Volgograd	49° N	44° E	Sept 1965 - Dec 1974
Shemya	53° N	174° E	Jan 1975 - Dec 1976
Primrose Lake	55° N	110° W	Apr 1967 - Dec 1976
West Geirinish	57° N	7° W	Jan 1965 - Jan 1972
Churchill	59° N	94° W	Jan 1965 - Dec 1976
Fort Greely/Poker Flats	64° N	146° W	Jan 1965 - Dec 1976
Thule	77° N	69° W	Jan 1965 - Dec 1976
Heiss Island	81° N	58° E	Nov 1957 - Dec 1974
Experimental Rockets			
Woomera	31° S	137° E	1957 - 1973
Ascension Island	8° S	14° W	1964 - 1965
Natal	6° S	35° W	1966 - 1968
Kourou	5° N	52° W	1971
White Sands	32° N	106° W	1965 - 1971
Wallops Island	38° N	75° W	1961 - 1971
Churchill	59° N	94° W	1957 - 1971
Barrow	71° N	157° W	1965 - 1972

4. 90°N MODELS

A mean monthly temperature-height time cross-section for 90° N, based on data derived from the monthly constant-pressure and temperature maps for levels up to 0.4 mb, is depicted in Figure 3 for altitudes up to 50 km. An annual cycle is obvious at all levels. Near the stratopause (50 km), warmest temperatures occur on or about the summer solstice (21 June), with coldest temperatures in November and December. In the lower stratosphere, coldest temperatures appear in January between 18 and 28 km, with warmest temperatures at this level in June and July. Temperature-height profiles for each of the monthly 90° N

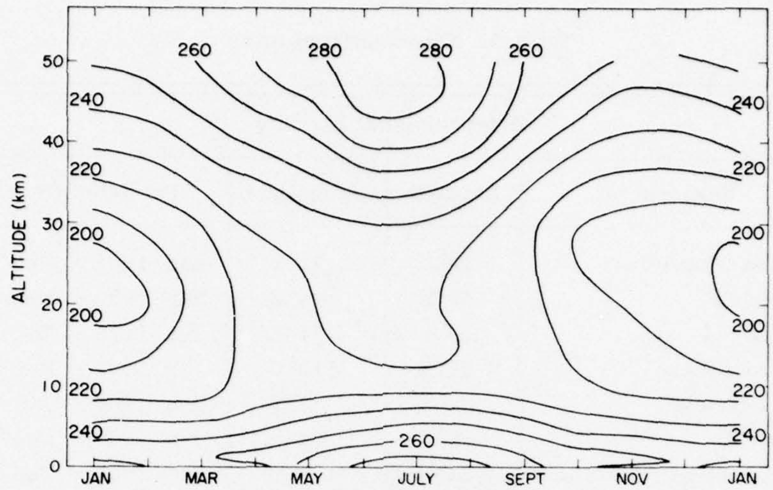


Figure 3. Mean Monthly Temperature-Height Cross-Section for 90° N

models were obtained from this cross-section, and are defined in Table 2. The segmented vertical temperature gradients are linear with geopotential altitude.

Curves representing the estimated seasonal change of monthly temperatures in the upper stratosphere at the North Pole are shown in Figure 4 for 30, 40, and 50 km. Measurements at Heiss Island, the observational site closest to the Pole, are also shown in Figure 4. Although data for Heiss Island are rather sparse, the observed mean monthly values follow the same general pattern as the temperatures for the 90° N monthly models. The differences are similar to those shown on the maps in Figure 2; that is, winter temperatures near Heiss Island are warmer than those at 90° N and summer temperatures are somewhat cooler.

Densities and pressures were computed from the temperature-height profiles that were adopted for each of the monthly atmospheres. Curves based on the computed mean monthly densities are shown in Figure 5 for 30, 40, and 50 km. There is a strong 12-month cycle at all levels, characteristic of high-latitude regions where diurnal, semi-annual, and biennial oscillations are not as significant as at lower latitudes.[3] The maximum densities occur at the end of June or in early July, and minimum values appear in January. Figure 5 also shows monthly densities derived from observations at Heiss Island. The data for Heiss Island, although barely sufficient for analysis, are in rough agreement with the 90° N model densities.

Table 2a. 90°N Temperature-Height Profiles to 55 km

MONTH	SURFACE PRESSURE	BREAKPOINTS IN GEOPOTENTIAL KILOMETERS AND TEMPERATURE (°K)											
	(mb)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)
Jan	1015.0	(0) (28.0)	237.15 196.65	(1.5) (38.0)	247.65 229.65	(2.5) (50.5)	244.15 252.15	(8.5) (55.0)	214.15 252.15	(14.0)	208.65	(20.0)	196.65
Feb	1018.0	(0) (41.0)	240.65 238.65	(1.5) (51.0)	249.65 254.65	(8.5) (55.0)	214.65 254.65	(13.5)	213.15	(20.0)	200.15	(28.5)	208.65
Mar	1020.0	(0) (29.5)	242.15 219.15	(1.5) (41.5)	248.15 249.15	(3.0) (50.5)	243.65 262.65	(8.5) (55.0)	216.15 262.65	(12.0)	219.65	(19.5)	212.15
Apr	1020.5	(0) (47.5)	248.65 270.15	(1.5) (55.0)	254.65 270.15	(8.5)	219.65	(11.5)	224.15	(23.5)	224.15	(33.5)	235.15
May	1020.0	(0) (36.5)	260.65 252.15	(2.0) (48.5)	260.65 276.15	(9.0) (55.0)	222.15 276.15	(11.5)	229.65	(24.0)	229.65	(31.5)	238.65
June	1016.0	(0) (41.0)	272.15 274.65	(2.5) (47.0)	264.15 286.65	(9.0) (55.0)	225.15 286.65	(12.0)	231.15	(24.5)	231.15	(32.0)	243.15
July	1013.0	(0) (32.0)	273.15 243.15	(2.0) (41.0)	271.15 274.65	(4.0) (47.0)	260.15 283.65	(9.0) (55.0)	227.15 283.65	(11.5)	231.15	(24.5)	231.15
Aug	1014.0	(0) (31.5)	273.15 236.15	(1.5) (42.0)	270.15 267.65	(3.0) (47.0)	264.15 277.15	(9.0) (55.0)	225.15 277.15	(14.0)	230.15	(24.0)	227.15
Sept	1016.0	(0) (30.0)	264.15 222.15	(2.0) (38.5)	264.15 239.15	(9.0) (42.5)	222.15 249.15	(11.5) (47.5)	225.15 259.15	(16.0) (55.0)	225.15 259.15	(21.0)	222.15
Oct	1014.0	(0) (38.5)	252.65 227.15	(1.5) (46.5)	257.15 255.15	(8.5) (55.0)	218.65 255.15	(12.0)	222.15	(24.0)	210.15	(30.0)	210.15
Nov	1018.0	(0) (51.5)	245.65 249.15	(1.5) (55.0)	254.65 249.15	(8.5)	216.15	(13.5)	216.15	(23.5)	205.15	(29.5)	205.15
Dec	1013.0	(0) (50.0)	243.15 249.65	(1.5) (55.0)	249.15 249.65	(2.5)	247.15	(8.5)	214.15	(23.5)	203.65	(30.0)	203.65

Table 2b. High-Latitude Temperature-Height Profiles to 90 km for Warm and Cold Winter Stratosphere/Mesosphere

	SURFACE PRESSURE	BREAKPOINTS IN GEOPOTENTIAL KILOMETERS AND TEMPERATURE (°K)											
	(mb)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)
MODEL A (warm)	1014.4	(0) (30.0) (80.0)	257.15 203.65 198.15	(1.0) (40.0) (90.0)	259.15 268.65 198.15	(3.5) (44.0)	251.15 300.65	(8.5) (45.0)	217.15 300.65	(11.0) (55.0)	217.15 245.65	(23.0) (75.0)	193.15 205.65
MODEL B (warm)	1014.4	(0) (30.0) (74.0)	257.15 216.65 201.65	(1.0) (35.0) (84.0)	259.15 245.15 185.65	(3.5) (42.0) (89.0)	251.15 273.15 180.65	(8.5) (44.5)	217.15 280.65	(11.0) (46.5)	217.15 280.65	(23.0) (54.0)	199.15 265.65
MODEL C (warm)	1014.4	(0) (20.0) (90.0)	257.15 196.15 196.65	(1.0) (30.0)	259.15 241.15	(3.5) (36.0)	251.15 280.15	(8.5) (49.0)	217.15 247.65	(11.0) (69.0)	217.15 211.65	(18.0) (84.0)	196.15 196.65
MODEL D (cold)	1014.4	(0) (32.0) (76.0)	257.15 217.15 241.65	(1.0) (38.0) (86.0)	259.15 208.15 225.65	(3.5) (43.0) (89.0)	251.15 217.15 219.65	(8.5) (50.0)	217.15 241.65	(12.5) (56.0)	223.15 256.65	(20.0) (66.0)	223.15 251.65

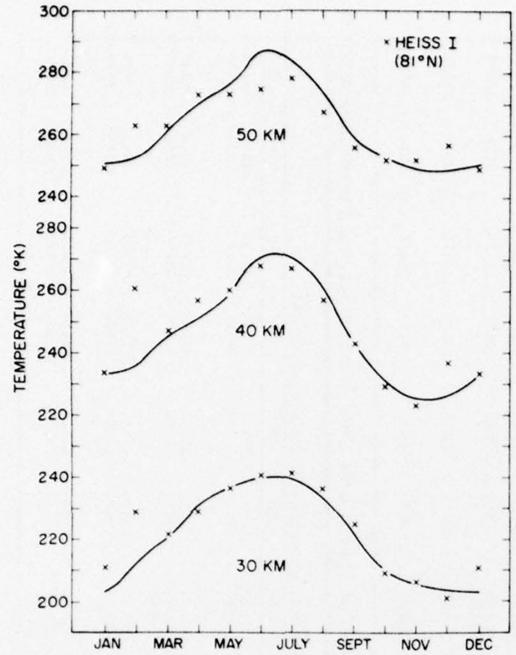


Figure 4. Comparison of Observed Temperatures at Heiss Island (81°N) With Model Temperatures for 90°N

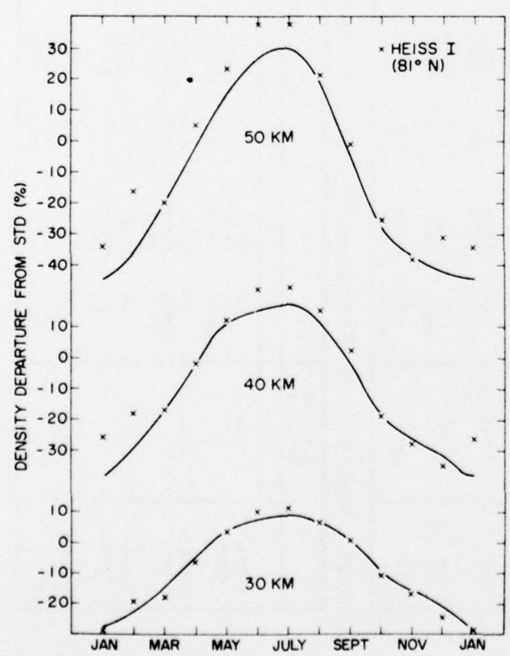


Figure 5. Comparison of Observed Densities at Heiss Island (81°N) With Model Densities for 90°N

5. WARM AND COLD WINTER STRATOSPHERE/MESOSPHERE

In arctic and subarctic regions, sudden warmings and coolings of the winter stratosphere and mesosphere produce large changes in the vertical (and horizontal) structure of the atmosphere. Both the magnitude and altitude of maximum temperature and density fluctuations during major warmings and coolings vary considerably. Some of the largest temperature changes that have been observed occur in the upper stratosphere between 35 and 45 km. The observed 35- to 45-km temperatures have a range of roughly 85K in winter compared with 20K in summer. As a result, mean monthly atmospheric models for the winter months are of limited value for specifying temperatures at these altitudes, since the day-to-day variations in temperature are in some cases as great or greater than the seasonal or latitudinal changes. Although these warmings and coolings occur throughout the arctic and subarctic region, the largest changes generally occur between latitudes 60° and 70°N, and are observed more frequently at some longitudes than at others.

A family of warm and cold atmospheric models, typical of the region between 60° and 70°N, has been prepared to provide an indication of the magnitude of the variations that may occur in the vertical distributions of temperature, density, and pressure in winter, for altitudes up to 90 km. Temperature-height profiles representative of one cold and three warm stratospheric regimes that occur at these latitudes are described in Figure 6 and Table 2b. Again, the segmented vertical temperature gradients, defined in Table 2b, are linear with geopotential altitude. These profiles are based on radiosonde observations plus MRN and experimental observations (grenades, falling spheres and pressure gauges) taken at Fort Greely, Fort Churchill, Point Barrow, and West Geirinish during the past 15 years. Mean January conditions at 60°N were assumed below 9 km, since the temperature-height profiles for this region during the various warmings and coolings are not significantly different from the mean January 60°N atmosphere.

The warm models are defined by the altitude and temperature of the stratopause. The temperature-height profile between 9 and 55 km for Model A (Figure 6), the model with the warmest stratopause, is based on an average of three MRN soundings (in different years) in which the maximum observed stratospheric temperature occurred between 44 and 46 km and was within 2° of 300K. Model B is based on an average of five MRN observations in which the maximum stratospheric temperature also occurred between 44 and 46 km and was within 2° of 280K. Model C is based on two MRN soundings in which a maximum stratospheric temperature of 280K, ±2°, occurred between 34 and 38 km. The frequencies of occurrence of the 35- and 45-km temperatures at

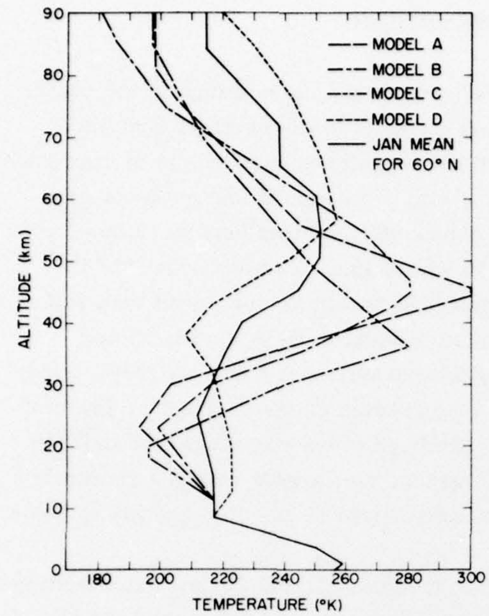


Figure 6. High-Latitude Temperature-Height Profiles

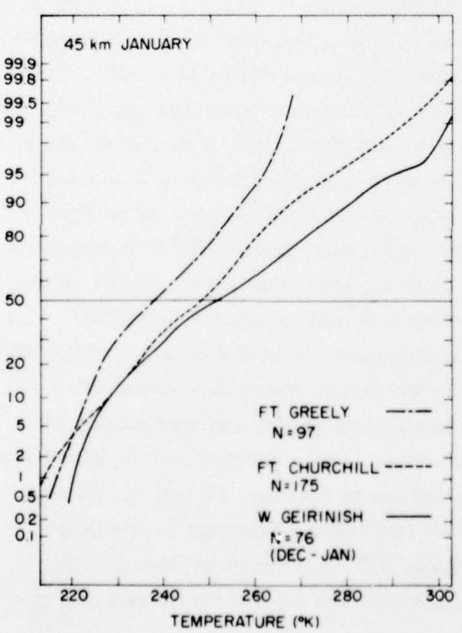
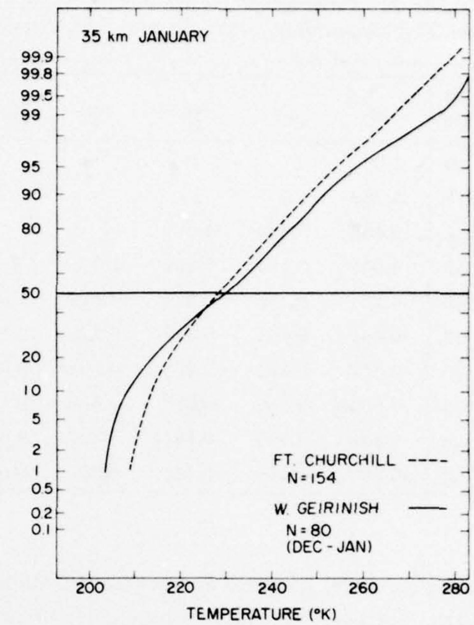


Figure 7. Frequency Distributions of Observed Temperatures in Winter at 45 km

Figure 8. Frequency Distributions of Observed Temperatures in Winter at 35 km



Fort Churchill and West Geirinish in January can be determined from the frequency distributions of the observed 35- and 45-km temperatures, which are plotted on probability paper in Figures 7 and 8. The three warm models could all occur during various stages of one large-scale warming. However, available observations indicate that a temperature of 300K at 45 km is equalled or exceeded 2 percent of the time at West Geirinish and 0.4 percent at Fort Churchill during January, whereas a temperature of 280K at 45 km is equalled or exceeded 10 percent of the time at West Geirinish and 4 percent of the time at Fort Churchill. A temperature of 280K near 36 km is equalled or exceeded 0.6 percent of the time at West Geirinish and 0.1 percent of the time at Fort Churchill.

The cold profile, Model D, is based on an average of five observations in which the temperature at 45 km was within 2° of 223K. Observed data indicate that in January a temperature of 223K or colder occurs at Fort Churchill 6 percent of the time, at West Geirinish 4 percent of the time, and at Fort Greely 9 percent of the time.

The portions of the temperature-height profiles between 55 and 85 km are based on estimates obtained by using the interlevel temperature correlations, Table 3, which were developed from data derived from 27 independent grenade

Table 3. Interlevel Temperature Correlations for High-Latitude Models (based on 27 independent grenade and pressure gauge experiments at Fort Churchill)

Alt (km)	40	45	50	55	60	65	70	75	80	85
40	1.0									
45	0.783	1.0								
50	0.458	0.583	1.0							
55	0.031	0.144	0.509	1.0						
60	-0.234	-0.176	0.325	0.670	1.0					
65	-0.451	-0.404	-0.342	0.272	0.509	1.0				
70	-0.546	-0.421	-0.483	-0.134	-0.082	0.473	1.0			
75	-0.600	-0.560	-0.330	-0.058	0.151	0.209	0.513	1.0		
80	-0.436	-0.497	-0.561	-0.322	-0.049	0.251	0.446	0.547	1.0	
85	-0.630	-0.499	-0.157	-0.323	0.001	0.112	0.419	0.359	0.438	1.0

and pressure gauge experiments conducted at Fort Churchill in the years 1957-1972, between 20 December and 10 February, and the temperatures adopted for 40, 45, and 50 km. There is a strong negative correlation between the temperatures at 40 to 50 km and those at 65 to 85 km, which has been noted in previous studies.[35-37] The equation used for these calculations is:

$$\hat{T}_2 = \overline{T}_2 + \frac{rS_2}{S_1}(T_1 - \overline{T}_1) \quad (7)$$

where S_1 is the standard deviation of the temperature (T_1), S_2 is the standard deviation of the temperature (T_2), r is the correlation coefficient of temperature between the lower level 1 and upper level 2, and $\hat{T}_2$ is the estimated temperature at level 2.

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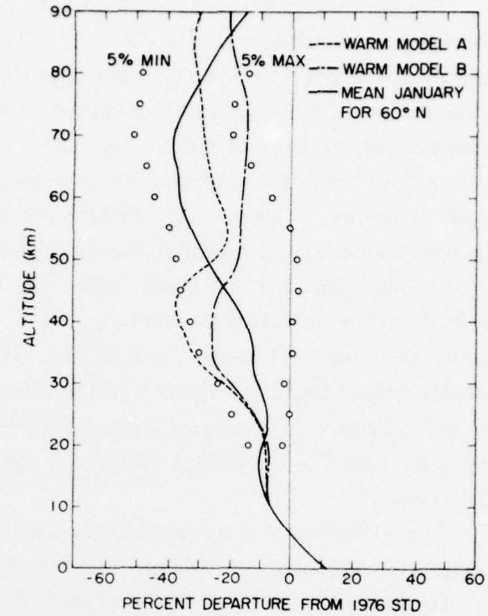

Figure 9a. High-Latitude Density-Height Profiles and 5-Percent Envelope

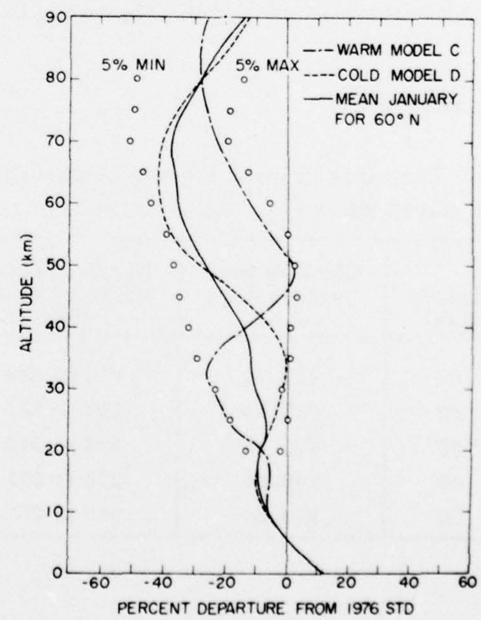

Figure 9b. High-Latitude Density-Height Profiles and 5-Percent Envelope

The density profiles associated with both the warm and cold models are provided along with the mean January 60° N profile in Figures 9a and 9b. The densities are portrayed as percent departures from the 1976 Standard Atmosphere. An envelope of the high and low values of density, which are equalled or surpassed 5 percent of the time at 60° N in January, is also shown. They are envelopes, rather than realistic profiles, since 5-percent values do not occur simultaneously at all altitudes. The density profiles for the warm and cold models illustrate the negative correlations that exist between the densities at various levels in the atmosphere. For example, when the density is much less than the mean monthly value at altitudes between 25 and 40 km (Figure 9b), it is greater than the mean values between 45 and 75 km. In most cases, the departures of density from the monthly mean fall within the 5-percent envelope. However, as shown in Figure 9, the profile for an extreme winter warming or cooling will approach both the 5-percent maximum and 5-percent minimum values at different altitudes.

The altitudes of the maximum density departures from the monthly mean are related to the altitudes of maximum temperature deviations in that the maximum density departures are roughly 10 to 20 km above the maximum temperature deviations. For example, the largest positive density departure for profile C (Figure 9b) occurs near 49 km, whereas the maximum stratospheric temperature, 280K for profile C (Figure 6), is at 36 km. The largest negative density departure for the same profile (Figure 9b) occurs near 33 km, and its minimum stratospheric temperature, 196K (Figure 6), is at 18-20 km.

6. SUMMARY

The range of mean monthly temperatures and densities at altitudes between 10 and 50 km is given below for 90° N:

Altitude (km)	Mean Annual Temperature (°K)	Range of Mean Monthly Temp. (°K)	Mean Annual Density (kg/m^3)	Range of Monthly Density (%)
10	220.54	213 to 229	3.8321×10^{-1}	-9.6 to -4.3
20	217.15	197 to 231	8.2695×10^{-2}	-13.6 to +0.5
30	221.61	203 to 240	1.7095×10^{-2}	-27.3 to +9.2
40	246.26	226 to 271	3.6303×10^{-3}	-37.9 to +17.0
50	263.85	249 to 287	9.2316×10^{-4}	-44.5 to +29.8

Winter warmings and coolings of the high-latitude stratosphere and mesosphere produce large changes in the structure of the atmosphere. In fact, observed temperatures between 35 and 45 km fluctuate by as much as 85K in winter over these regions. As a result of these large-scale disturbances, densities depart from mean January values by as much as 15 percent near 30 km, 28 percent between 50 and 60 km, and 24 percent near 70 km, approaching the 5-percent envelope of observed densities in these arctic and subarctic regions.

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Appendix A

Tables of Thermodynamic Properties

Table A1. 90°N Mean Monthly Thermodynamic Properties

Altitude (km)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
TEMPERATURE (K)													
0.000	237.15	240.65	242.15	248.65	260.65	272.15	273.15	273.15	264.15	252.65	245.65	243.15	254.44
5.000	231.60	232.10	233.60	237.10	244.10	249.09	253.49	251.09	246.09	237.85	235.35	233.35	240.40
10.000	212.64	214.19	217.66	221.91	225.18	227.17	228.76	226.16	223.36	220.16	216.15	213.09	220.54
15.000	206.64	210.14	216.64	224.15	229.65	231.15	231.15	229.84	225.15	219.14	214.49	209.59	220.64
20.000	196.67	200.17	212.49	224.15	229.65	231.15	231.15	228.35	222.75	214.16	209.01	206.10	217.15
25.000	196.65	205.11	215.97	225.76	230.81	231.89	231.89	228.31	222.15	210.15	205.15	203.65	217.29
30.000	203.04	212.09	220.24	231.23	236.77	239.84	239.84	234.27	222.15	210.15	206.02	203.65	221.61
35.000	219.41	224.00	232.64	238.64	247.82	253.29	253.29	247.36	231.94	219.94	215.94	214.91	233.26
40.000	232.98	235.89	245.03	251.03	258.85	270.63	270.63	263.71	242.53	231.71	225.85	226.31	246.26
45.000	241.89	244.73	254.10	263.40	268.75	282.25	280.35	272.45	253.75	246.55	237.40	237.69	256.94
50.000	250.78	252.63	261.51	270.15	276.15	286.65	283.65	274.15	259.15	253.15	249.15	249.05	263.85
55.000	252.15	254.65	262.65	270.15	276.15	286.65	283.65	274.15	259.15	253.15	249.15	249.65	264.28
PRESSURE (mb)													
0.000	1.0150	1.0180	1.0200	1.0205	1.0200	1.0160	1.0130	1.0140	1.0160	1.0140	1.0180	1.0130	1.0164 +3*
5.000	4.9862	5.0201	5.0393	5.1113	5.2214	5.2899	5.3279	5.3097	5.2419	5.1081	5.0834	5.0166	5.1463 +2
10.000	2.2922	2.3132	2.3368	2.3996	2.4922	2.5541	2.5951	2.5688	2.5064	2.3937	2.3600	2.3114	2.4270
15.000	1.0174	1.0387	1.0698	1.1197	1.1831	1.2179	1.2392	1.2176	1.1738	1.1056	1.0709	1.0311	1.1237
20.000	4.3714	4.5276	4.8302	5.2374	5.6355	5.8292	5.9312	5.7897	5.4913	5.0370	4.7910	4.5441	5.1680 +1
25.000	1.8410	1.9560	2.1838	2.4545	2.6884	2.7935	2.8424	2.7439	2.5545	2.2563	2.1027	1.9784	2.3664
30.000	0.7806	0.8642	1.0013	1.1674	1.3003	1.3598	1.3836	1.3168	1.1895	1.0058	0.9192	0.8595	1.0957
35.000	3.4968	3.9711	4.7354	5.6612	6.4438	6.8145	6.9337	6.4907	5.6359	4.5708	4.1151	3.8215	5.2242 0
40.000	1.6590	1.9018	2.3308	2.8353	3.3065	3.5704	3.6329	3.3460	2.7589	2.1556	1.9123	1.7740	2.5986
45.000	0.8141	0.9423	1.1858	1.4696	1.7423	1.9401	1.9709	1.7865	1.3972	1.0630	0.9210	0.8561	1.3407
50.000	0.4104	0.4780	0.6163	0.7836	0.3938	1.0747	1.0855	0.9648	0.7259	0.5437	0.4606	0.4279	0.7093
55.000	2.1032	2.4652	3.2441	4.1997	5.1061	5.9709	5.9937	5.2184	3.7891	2.7947	2.3423	2.1790	3.7839 -1
DENSITY (kg m^{-3})													
0.000	1.4910	1.4736	1.4674	1.4297	1.3632	1.3005	1.2919	1.2932	1.3399	1.3981	1.4436	1.4513	1.3953 +0*
5.000	7.5000	7.5348	7.5150	7.5099	7.4518	7.3981	7.3221	7.3667	7.4203	7.4816	7.5245	7.4892	7.4595 -1
10.000	3.7553	3.7623	3.7401	3.7669	3.8556	3.9168	3.9519	3.9568	3.9092	3.7877	3.8036	3.7788	3.8321
15.000	1.7152	1.7219	1.7203	1.7402	1.7947	1.8355	1.8676	1.8455	1.8163	1.7575	1.7393	1.7139	1.7723
20.000	7.7432	7.8797	7.9188	8.1399	8.5488	8.7853	8.9390	8.8325	8.5878	8.1936	7.9853	7.6805	8.2695 -2
25.000	3.2614	3.3220	3.5225	3.7876	4.0577	4.1965	4.2700	4.1868	4.0059	3.7403	3.5706	3.3843	3.7755
30.000	1.3392	1.4195	1.5838	1.7589	1.9132	1.9751	2.0097	1.9581	1.8653	1.6673	1.5542	1.4702	1.7095
35.000	5.5520	6.1757	7.0908	8.2639	9.0580	9.3722	9.5361	9.1409	8.4647	7.2395	6.6386	6.1943	7.7272 -3
40.000	2.4805	2.8085	3.3137	3.9347	4.4499	4.5959	4.6763	4.4201	3.9628	3.2409	2.9496	2.7307	3.6303
45.000	1.1725	1.3412	1.6258	1.9437	2.2584	2.3945	2.4491	2.2843	1.9182	1.5020	1.3514	1.2547	1.7913
50.000	0.5701	0.6592	0.8209	1.0104	1.1856	1.3061	1.3332	1.2259	0.9758	0.7482	0.6440	0.5986	0.9232
55.000	2.9058	3.3724	4.3028	5.4157	6.4414	7.2566	7.3612	6.6311	5.0936	3.8459	3.2751	3.0407	4.9118 -4

Table A2. High-Latitude Thermodynamic Properties for Warm and Cold Winter Stratosphere/Mesosphere

Altitude (km)	Model A (warm)	Model B (warm)	Model C (warm)	Model D (cold)	Model A (warm)	Model B (warm)	Model C (warm)	Model D (cold)	Model A (warm)	Model B (warm)	Model C (warm)	Model D (cold)
	TEMPERATURE (K)				PRESSURE (mb)				DENSITY (kg m^{-3})			
0.000	257.15	257.15	257.15	257.15	1.0144	1.0144	1.0144	1.0144 +3*	1.3742	1.3742	1.3742	1.3742 +0*
5.000	240.93	240.93	240.93	240.93	5.1610	5.1610	5.1610	5.1610 +2	7.4623	7.4623	7.4623	7.4623 -1
10.000	217.15	217.15	217.15	219.39	2.4192	2.4192	2.4192	2.4221	3.8811	3.8811	3.8811	3.8460
15.000	209.18	211.17	205.19	223.15	1.0910	1.0943	1.0843	1.1252	1.8169	1.8052	1.8409	1.7565
20.000	199.22	203.70	196.15	223.15	4.7425	4.8194	4.6097	5.2503 +1	8.2929	8.2419	8.1870	8.1965 -2
25.000	196.05	203.98	218.35	220.68	1.9899	2.0744	2.0291	2.4425	3.5360	3.5428	3.2373	3.8557
30.000	203.49	216.39	240.68	218.20	0.8515	0.9257	0.9687	1.1278	1.4576	1.4901	1.4021	1.8006
35.000	235.19	244.31	272.69	212.87	3.9263	4.4323	5.0035	5.1529 +0	5.8156	6.3201	6.3920	8.4329 -3
40.000	267.35	264.35	270.64	211.39	2.0018	2.2802	2.7096	2.3060	2.6084	3.0049	3.4878	3.8002
45.000	300.65	280.65	258.29	223.24	1.1094	1.2298	1.4312	1.0568	1.2855	1.5266	1.9303	1.6491
50.000	274.94	274.30	246.43	240.50	6.1836	6.7169	7.3358	5.1080 -1	0.7835	0.8531	1.0370	0.7399
55.000	247.86	263.73	237.57	253.14	3.2469	3.5962	3.6600	2.5842	4.5635	4.7502	5.3669	3.5563 -4
60.000	236.61	248.00	228.72	254.89	1.6197	1.8647	1.7804	1.3391	2.3847	2.6194	2.7118	1.8302
65.000	226.80	232.29	219.88	252.43	7.8530	9.2725	8.4285	6.9130 -2	1.2062	1.3906	1.3353	0.9540
70.000	216.99	216.60	211.32	248.32	3.6917	4.3957	3.8742	3.5440	5.9267	7.0697	6.3867	4.9718 -5
75.000	207.20	201.29	206.42	243.42	1.6780	1.9727	1.7399	1.7953	2.8212	3.4140	2.9362	2.5693
80.000	199.48	193.47	201.54	236.67	7.3779	8.4664	7.6749	8.9645 -3	1.2884	1.5244	1.3266	1.3195
85.000	198.15	185.67	196.66	228.87	3.1829	3.5139	3.3225	4.3803	5.5959	6.5930	5.8855	6.6674 -6
90.000	198.15	180.79	196.65	219.93	1.3742	1.4167	1.4253	2.0879	2.4160	2.7299	2.5250	3.3072

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