Model Profiles of Temperature and Density up to 80 km Based on Extremes at Selected Altitudes

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Vertical profiles of temperature and density have been developed based on 1 and 10% warm and cold temperatures and 1 and 10% high and low densities occurring at the worst (most extreme) locations in the world (except Antarctica) during the most severe month. The profiles, from the surface to 80 km, are based on extremes that occur at 5, 10, 20, 30, and 40 km. For example, one of the temperature profiles that has been developed was based on a 10% warm temperature at an altitude of 20 km, so that it represents meteorological conditions typically associated with this extreme. Ten such warm profiles (five levels by two percentiles) and 10 cold profiles have been constructed from 14 years of rawinsonde and rocketsonde observations. Twenty analogous density profiles also have been developed from extreme densities occurring at the aforementioned altitudes. Thus, a set of realistic vertical profiles of temperature and density associated with extremes at specified levels in the troposphere and stratosphere are available for altitudes up to 80 km.

Introduction

INFORMATION on expected extremes of the thermodynamic properties of the atmosphere are required for the design and operation of systems traversing the atmosphere. Such data are particularly important at altitudes from the surface to approximately 80 km for developing all types of airborne vehicles ranging from helicopters and airplanes to sophisticated aerospace systems.

Cole and Kantor[1,2] provide information on atmospheric structure at 15-deg intervals of latitude from the equator to the pole. However, these were based on limited data above 30 km. Several temperature models of regional extremes have been developed for a few selected locations by Martin.[3-5] They provide temperature profiles based on estimated 1% hot and cold temperatures at pressure levels between 850 mb (1.5 km) and 100 mb (16 km). NASA[6] also presents temperature and density envelopes and extreme profiles up to 90 km, but only at several missile ranges. Other NASA and ISO model atmospheres provide monthly means and day-to-day variability, but not extremes, whereas other range atmospheres that do address extremes are restricted to a few specific geographic locations.

Cole et al.[7] and Kantor[8] address temperature structure at 15°N and 75°N, respectively, but are limited to the altitudes between 25 and 55 km. Reports by Kantor and Cole[9] and Kantor[10,11] contain information on the time and space variations of density in the upper stratosphere and lower mesosphere for time periods up to 72 h and horizontal distances out to nearly 400 km (200 n.mi.). However, these do not directly address low probabilities of occurrence.

For designing aerospace vehicles, vertical thermodynamic properties need to be related in time and space; i.e., values at one altitude must occur at the same time and location as those at other altitudes. Profiles that contain high (or low) extremes at one altitude very well may have low (or high) extremes at another altitude. For example, low density or high density cannot occur simultaneously at any given location through a vertical thickness more than a few kilometers, as shown in Fig. 1.[2,12] In this figure, the density profile associated with a warm winter stratosphere in the region near 60°N displays a 5% density maximum near 30 km and a 5% density minimum near 55 km.

In this paper, vertical profiles of temperature and density have been developed based on 1 and 10% hot and cold temperatures and 1 and 10% high and low densities occurring at specified altitudes during the most severe month at the worst (most extreme) locations for which reliable upper-air data are available. The 1 and 10% hot-temperature or high-density values exceed 99 and 90% of the observations at a specified altitude at the most extreme location, respectively. Conversely, the 1 and 10% cold-temperature or low-density values are exceeded by 99 and 90% of the observations, respectively. These are also referred to as 1 and 10% values (cold-temperature, low-density), and 90 and 99% values (hot-temperature, high-density), as obtained from a plot of the cumulative frequency distribution of all the monthly temperature (or density) observations. The profiles, from the surface to 80 km, are based on extremes that occur at 5, 10, 20, 30, and 40 km. They are more appropriate for design considerations than earlier profiles developed by Cole and Kantor[1,13] because they are global in scope and are based on extremes rather than being limited to mean annual or monthly models. Furthermore, considerably more data above 30 km have become available for use in these new model profiles.

Basic Assumptions and Equations

The atmospheric profiles in this paper are defined by temperature-altitude segments in which vertical gradients of temperature are linear with respect to geopotential altitude. For simplicity, gradient changes occur at "breakpoints" of whole and half kilometers of altitude, and the "breakpoint" temperatures are in whole and half degrees Kelvin. 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-mol), is considered to be constant to 80 km. Dissociation of molecular oxygen begins to take place

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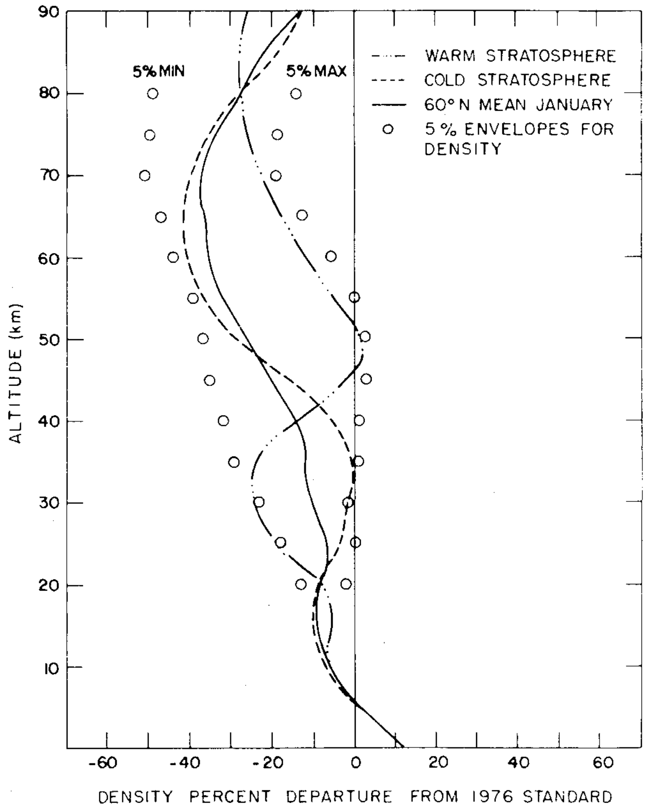

Fig. 1 Density profiles associated with extreme temperatures in the upper stratosphere.

near 80 km, and molecular weight starts descreasing slowly above that altitude.[2,14] Consequently, molecular-scale temperatures T_M and the ambient kinetic temperatures T are identical in this report because $T_M = (M_0/M)T$, and M_0, the sea-level molecular weight, and M, the molecular weight of air at a specific altitude, are equal for altitudes up to 80 km.

Numerical values for the various thermodynamic and physical constants used in computing the tables of temperature and density for these model profiles are the same as those used in the preparation of the *U.S. Standard Atmosphere, 1976,* with two exceptions: 1) surface conditions for the profiles are based on sea-level pressures and temperatures for the appropriate month and location rather than on standard conditions; 2) the accelerations due to gravity at sea level for the specified sites were obtained from the following expression by Lambert[15] in which gravity g (m/s^2) varies with latitude ϕ:

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

The Static Atmosphere and Perfect Gas Law

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

$$\mathrm{d}P = -\rho g\, \mathrm{d}Z \quad (2)$$

which relates air pressure P to density ρ, acceleration due to gravity g, and altitude Z. The perfect gas law relates air pressure to density and temperature as follows:

$$P = \rho^{R^* T_M} / M_0 \quad (3)$$

where R^* is the universal gas constant, 8.31432 J/K (k-mol).

Geopotential

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

$$H = (r_\phi Z / r_\phi + Z)(g_\phi / G) \quad (4)$$

where H is the geopotential altitude in geopotential meters (m′), Z is the geometric altitude in meters, g_ϕ is the sea-level value for acceleration of gravity (m/s^2) at a specific latitude ϕ as given by Lambert's equation, G is the unit geopotential set equal to 9.80665 m^2/s^2 (m′), and r_ϕ is the effective Earth radius in meters given in Sec. IV, Smithsonian Tables.[15] Values of r_ϕ and g_ϕ at the locations selected to develop the model profiles are given in Table 1.

Table 1 Sea-level acceleration due to gravity and effective Earth's radius at locations selected to develop model profiles

Location	Sea-level gravity g, m/s^2	Effective radius r, km
Alert, NWT, Canada (82.5N, 62.3W)	983.119	6377.124
Eureka, NWT, Canada (80.0N, 85.9W)	983.051	6376.562
Thule, Greenland (76.6N, 68.8W)	982.929	6375.544
Barrow, Alaska (71.2N, 156.5W)	982.667	6373.366
Norman Wells, NWT, Canada (65.3N, 126.8W)	982.300	6370.330
Poker Flats, Alaska (65.1N, 147.5W)	982.288	6370.227
Coral Harbor, NWT, Canada (64.2N, 83.4W)	982.224	6369.700
Frobisher Bay, NWT, Canada (63.8N, 68.6W)	982.193	6369.432
Ft. Churchill, Manitoba, Canada (58.8N, 94.1W)	981.808	6366.236
China Lake, California (35.4N, 117.4W)	979.766	6349.314
Point Mugu, California (34.1N, 119.1W)	979.656	6348.407
Truk Island (7.5N, 151.7E)	978.123	6335.711
Majuro, Marshall I. (7.1N, 171.1E)	978.113	6335.626
Pago Pago, Tutuila I. (14.2S, 170.4W)	978.344	6337.537
Antofagasta, Chile (23.4S, 70.2W)	978.848	6341.715
Punta Arenas, Chile (53.1S, 70.6W)	981.338	6362.345

Computational Equations

Vertical distributions of pressure can be obtained from the appropriate vertical temperature structure and associated sea-level pressures, according to the following two forms of the barometric equations:

$$P/P_b = (T_{Mb}/T_{Mb} + Lh)^{(GM_0/R^* L)} \quad (L \neq 0) \quad (5)$$

$$P/P_b = \exp\,(-GM_0 h / R^* T_{Mb}) \quad (L = 0) \quad (6)$$

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 altitude (dT_M/dh); and T_{Mb} and P_b are the respective values of temperature and pressure at altitude H_b. Rewriting Eq. (3) for ρ and ρ_b and combining both with Eqs. (5) and (6) yields the following two computational expressions for density:

$$\rho/\rho_b = (T_{Mb}/T_{Mb} + Lh)^{1+(GM_0/R^*L)} \qquad (L \neq 0) \qquad (7)$$

$$\rho/\rho_b = \exp\left(-GM_0h/R^*T_{Mb}\right) \qquad (L = 0) \qquad (8)$$

Data Base

The data used in this investigation consist primarily of two types of observations: 1) rawinsonde observations from the surface to approximately 25 km, and 2) Meteorological Rocket Network (MRN) observations for altitudes roughly 25-65 km. The total period of record spans 14 years from 1969-1982.

Rawinsondes

Rawinsonde data, provided in National Climatic Data Center (NCDC) Tape Deck 5600 format, consist of 00 and 12 UT observations of temperatures and pressure altitudes for most areas of the world excluding Eurasia, Africa, and Australia. The effect of excluding these regions is discussed later. Although both NCDC TD 5685 and the USAF Environmental Technical Applications Center Data Save (DATSAV) Data Base tapes cover these regions, these data are considered unreliable for analysis of extremes and low probabilities of occurrence of temperature and density. Tape Deck 5600, used for this paper, contains observations from some 130 locations (U.S., Central and South America, and Oceania) for the years 1969-1981 and was used in combination with Canadian rawinsonde tapes, which also contain twice-daily observations from some 40 Canadian-controlled high-latitude stations for the years 1969-1982.

Meteorological Rockets

Meteorological Rocket Network Tape Deck Format 5850 was used for this paper; it provides temperatures and calculated densities at 21 MRN locations for altitudes from approximately 25-65 km for the years 1969-1982. Table 2 lists the number of soundings at the 18 MRN stations for which usable data were available. They lie mostly in the Western Hemisphere and are located between latitudes 77°N and 38°S.

Limitations and Accuracy

Rawinsonde temperature measurement errors vary linearly with altitude from 0.7°K at the surface to 1.5°K at 30 km.[16] Rocketsonde measurement errors, corrected for a warm bias for altitudes between 30 and 65 km,[17] also increase linearly with altitude from about 0.5°K at 25 km to 3°K at 65 km. However, temperature data were not used for altitudes above 60 km because thermistor measurements are subject to additional uncertainties above this level.

Density at a given level in the atmosphere, except near the surface, is dependent upon the integrated temperature profile through a substantial layer of the atmosphere rather than from an observed temperature at a specific altitude. Thus, random observational errors in temperature tend to average out in the integration over the entire layer, minimizing the errors in computed densities. The root-mean-square (rms) errors in densities derived from rawinsonde temperature observations vary from 0.1% at the surface to 1.5% near 30 km. The rms errors in densities derived from rocketsonde temperature measurements have been estimated to vary from 3% at 30 km to 4 or 5% at 60 km.[16]

Data Processing

Several conversions and mathematical and statistical procedures have been used in developing the vertical profiles of temperature and density from rawinsode and rocketsonde observations for the 14-yr period 1969-1982. These are discussed in the following sections.

Table 2 Meteorological rocket network stations, overall period of record 1969-1982

Station	Location	Number of soundings
Thule AFB, Greenland	77N, 69W	896
Poker Flats, Alaska (Ft. Greely)	65N, 147W	861
Ft. Churchill, Manitoba	59N, 94W	1242
Primrose Lake, Alberta	55N, 110W	1076
Shemya, Alaska	53N, 174W	510
Green River, Utah	39N, 110W	3
Wallops Island, Virginia	38N, 76W	1111
El Arenosillo, Spain	37N, 7W	27
Point Mugu, California	34N, 119W	1531
White Sands, New Mexico	32N, 107W	1601
Cape Kennedy, Florida	29N, 81W	1500
Barking Sands, Hawaii	22N, 160W	1318
Antigua, British West Indies	17N, 62W	785
Ft. Sherman, Canal Zone	9N, 80W	919
Kwajalein, Marshall Islands	9N, 168E	1434
Natal, Brazil	6S, 35W	44
Ascension Island	8S, 14W	1181
Mar Chiquita, Argentina	38S, 57W	31

Rawinsondes

Analysis of available rawinsonde data entailed assimilation of as many as 9000 soundings per station (two per day for 13 years). Computer techniques and analyses produced threshold values of 1, 10, 90, and 99% temperatures at 5, 10, and 20 km for the most severe month and location. The resulting threshold temperatures and locations of occurrence are shown in Table 3. The two temperatures, 241 and 235°K, that are listed for the 99% threshold at 20 km are discussed in the next section. These 13 values were used to select sets of soundings that meet or exceed the 1 and 10% hot and cold temperatures at the appropriate location, month, and altitude. The same procedure provided the threshold densities shown in Table 4 and those soundings that meet or exceed the 1 and 10% high and low densities.

The lack of Eurasian, African, and Australasian data in this study resulted in warm extremes that are less severe than expected at 5 and 10 km. Near-Eastern locations, particularly over the Indian subcontinent in summer, undoubtedly would produce warmer 90 and 99% temperatures at these levels. Similarly, winter observations over Siberia would produce somewhat colder 1% temperatures at 5 km. The inclusion of African and Australasian densities also would produce more extreme 90 and 99% densities at 5, 10, and possibly 20 km.

Rocketsondes

A procedure analogous to that used for rawinsondes was used to analyze MRN temperatures and densities at 30 and 40 km. MRN data from the 18 stations listed in Table 2 were used to produce the desired threshold temperatures and densities. Although the period of record, 1969-1982, is approximately the same as that available for the rawinsonde analysis, MRN observations are limited to locations mostly in the Western Hemisphere, and both the number of stations and the number of soundings are an order of magnitude smaller than that for the rawinsondes. Threshold temperatures and densities are shown in Tables 5 and 6, respectively, for 30 and

Table 3 Rawinsonde temperature extremes for the most severe month and location (with paired MRN location)

Percentile, %	Site Rawin-month (MRN)	5 km Temperature, K	Site Rawin-month (MRN)	10 km Temperature, K	Site Rawin-month (MRN)	20 km Temperature, K
1	Eureka-Feb. (Thule)	220	Eureka-March (Thule)	199	Alert-Feb. (Thule)	186
10	Eureka-Feb. (Thule)	224	Alert-Feb. (Thule)	204	Alert-Jan. (Thule)	192
90	Antofagasta-Feb. (Cape Kennedy-Aug.)	276	Majuro-Jan. (Kwajalein)	243	Alert-June (Thule)	234
99	Point Mugu-July (Point Mugu)	279	Pago-Pago-Jan. (Kwajalein-July)	245	Alert-Feb. (Thule)	241 (a)
					Alert-June (Thule)	235 (b)

Table 4 Rawinsonde density extremes for the most severe month and location (with paired MRN location)

Percentile, %	Site Rawin-month (MRN)	5 km Density, kg/m³	Site Rawin-month (MRN)	10 km Density, kg/m³	Site Rawin-month (MRN)	20 km Density, kg/m³
1	Punta Arenes-Jan. (Wallops I. -July)	6.93-1[a]	Coral Habor-Jan. (Churchill)	3.39-1[a]	Coral Harbor-Feb. (Churchill)	6.73-2[a]
10	Point Mugu-Sept. (Point Mugu)	7.04-1	Frobisher Bay-March (Churchill)	3.53-1	Eureka-Feb. (Thule)	7.14-2
90	Barrow-Jan. (Poker Flats)	7.74-1	China Lake-Dec. (Point Mugu)	4.30-1	Truk-Feb. (Kwajalein)	9.71-2
99	Norman Wells-Jan. (Poker Flats)	7.83-1	Point Mugu-Jan. (Point Mugu)	4.33-1	Truk-Feb. (Kwajalein)	9.93-2

[a]Power of ten by which preceding numbers should be multiplied.

Table 5 Rocketsonde temperature extremes for the most severe month and location

Percentile, %	Site/month	30 km Temperature, K	Site/month	40 km Temperature, K
1	Churchill Dec.	189	Thule Jan.	201
10	Thule Dec.	195	Thule Jan.	211
90	Poker Flats June	244	Poker Flats June	273
99	Thule July	254	Poker Flats June	276

Table 6 Rocketsonde density extremes for the most severe month and location

Percentile, %	Site/month	30 km Density, kg/m³	Site/month	40 km Density, kg/m³
1	Thule Jan.	1.22-2[a]	Thule Feb.	2.06-3[a]
10	Thule Jan.	1.24-2	Thule Feb.	2.22-3
90	Poker Flats July	2.04-2	Poker Flats July	4.79-3
99	Thule July	2.06-2	Poker Flats July	4.88-3

[a]Power of ten by which preceding numbers should be multiplied.

40 km at the indicated locations and months of occurrence. Those soundings that meet or exceed the 1 and 10% hot and cold temperatures and high and low densities were selected for final analysis.

Analysis

All soundings that met or exceeded the 40 criteria established for temperature and density as described in Tables 3–6 were carefully analyzed for development of model vertical profiles typical of each of the indicated atmospheric conditions. As noted previously, two 99% temperatures at 20 km are listed for Alert (see Table 3). These values, 241°K in February and 235°K in June, reflect the existence of an atypical high-latitude winder stratosphere known as a "sudden warming." It occurs sufficiently often to produce the more extreme 99% temperature in winter rather than summer. For completeness, an alternate June profile, based on the 235°K threshold, was also derived.

The sea-level pressures used for each profile were derived from analyses of the 40-yr monthly means in the Northern Hemisphere and more than 30 years' data in the Southern Hemisphere. Errors introduced by using monthly mean sea-level pressures normally are insignificant because the defining element for these models is temperature. For example, an unusually large pressure error of 10 mb at sea level (roughly 1%) would remain constant throughout the model and would result in a density error of no more than 1% at any altitude. Exceptions do occur, however, for high-density extremes at low levels. The high-density thresholds at 5 km occur during high-latitude winter under the influence of unusually high surface pressure. Consequently, a surface pressure of 1032 mb was used for the 90 and 99% 5-km density profiles rather than the mean January pressure of 1018.5 mb at Barrow and 1021 mb at Norman Wells.

Rawinsonde Extremes at 5, 10, and 20 Km

Twelve temperature-height profiles representative of atmospheric conditions associated with threshold temperatures at 5, 10, and 20 km were derived for the locations and months shown in Table 3 using the equations and basic assumptions discussed earlier. For the 12 model profiles based on threshold densities, temperatures in the soundings associated with density criteria at 5, 10, and 20 km were used to construct the profiles for the locations and months shown in Table 4. Densities associated with each of these 24 temperature-height profiles were computed from Eqs. (7) and (8).

At altitudes above 25–30 km, concomitant values from the most appropriate MRN stations were employed to extend all 24 profiles to approximately 55 km. The MRN stations used to complement the rawinsonde stations are listed in Tables 3 and 4. They were chosen from the 18 usable MRN sites considering proximity, climate, and specific synoptic situation for the dates in question. MRN observations at the selected locations were matched with the corresponding rawinsonde dates ±1 day. For the overlap region, 20–30 km, greater weight was given to rawinsonde observations below 25 km, and greater weight was given to MRN observations above 25 km, the altitude regions where the respective data are more reliable.

As an example, Fig. 2 shows the profile that was subjectively fitted to the appropriate rawinsonde and MRM temperatures based on the 1% cold temperature threshold at 10 km, 199°K, that occurred in March at Eureka. In the figure, the lower portion of the profile up to approximately 25 km was fitted to three rawinsonde temperature soundings associated with the 1% 10-km cold temperature. The profile was further extended from 25 km to approximately 55 km using the most appropriate MRN data (Thule). Extension of the profile above 55 km is explained later.

Three profiles, based on the 90% threshold temperature at 5 km, the 99% threshold temperature at 10 km, and the 1% threshold density at 5 km, were developed from observations at Southern Hemisphere rawinsonde locations in combination with observations from the most appropriate MRN stations in the Northern Hemisphere. A six-month seasonal adjustment was applied to the MRN data, as indicated in Tables 3 and 4, so that the two data sets comprise a profile in the same season.

Rocketsonde Extremes at 30 and 40 Km

Eight temperature-height profiles typical of conditions associated with the 1, 10, 90, and 99% temperatures at 30 and 40 km were developed for the locations and months shown in Table 5. For the eight additional profiles based on the 1, 10, 90, and 99% densities, temperatures in the soundings associated with the density criteria at 30 and 40 km were used to construct the model proftiles for the locations and months shown in Table 6. Concomitant rawinsonde data for all soundings of interest at the selected stations (Tables 5 and 6) were used to develop continuous profiles upward from sea level. Again, the model profiles were constructed and computed according to the previously discussed assumptions and equations.

Profiles above 55 Km

The 20 model profiles based on 1 and 10% cold temperatures and low densities at the five specified altitudes, 5, 10, 20, 30, and 40 km, are representative of high-latitude winter conditions during which there can be rather wide fluctuations of temperature and density near the mesopause (≈80 km). However, information on the temperature structure above 55 km can be derived from the profile values at 50 km. As a result, the portions of these temperature-height profiles above 55 km were based on estimates obtained from interlevel

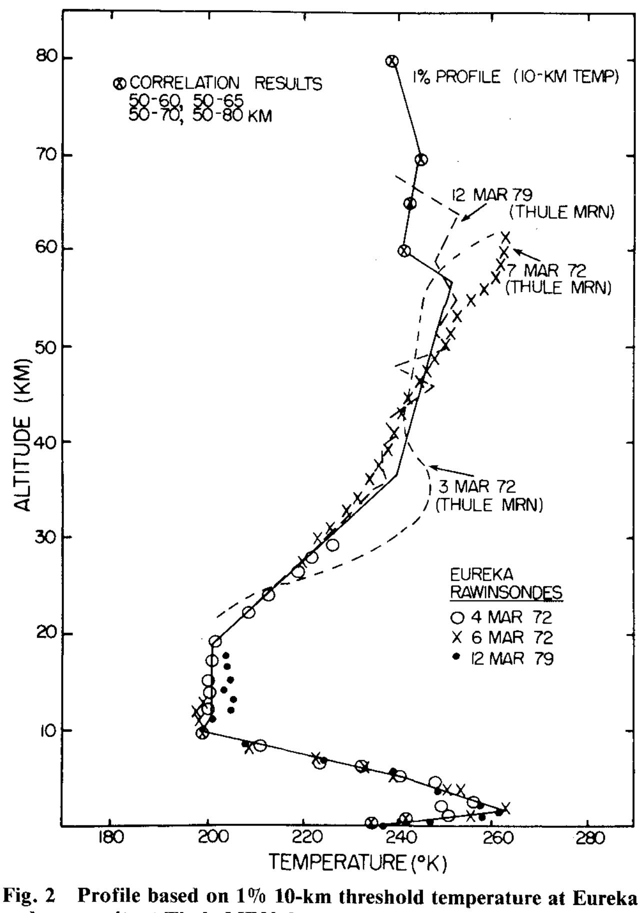

Fig. 2 Profile based on 1% 10-km threshold temperature at Eureka and concomitant Thule MRN data.

Table 7 Interlevel temperature correlations for high-latitude profiles

Alt (km)	40	45	50	55	60	65	70	75	80
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	−0.049	−0.049	0.251	0.446	0.547	1.0

Table 8 Temperature-altitude profiles in geopotential km (from temperature extremes)

Percentile temperatures, %	Sea-level pressure, mb	Breakpoints in geopotential km and temperature, K Alt	K	Alt	K	Alt	K	Alt	K	Alt	K	Alt	K
5 km													
1	1016.0	S. L.	220.15	1.0	236.15	2.5	233.15	5.5	216.65	9.5	212.65	16.0	199.65
		22.0	199.65	34.5	247.15	43.5	269.65	47.0	269.65	59.5	249.65	64.5	230.1
		70.0	230.15	80.0	218.15								
10	1016.0	S. L.	229.65	1.5	238.65	4.5	226.65	8.0	209.15	12.0	209.15	15.5	202.15
		21.0	202.15	33.5	252.15	41.5	264.15	59.0	250.15	65.0	229.15	70.0	220.15
		80.0	219.15										
90	1012.5	S. L.	291.65	1.0	287.15	2.0	291.15	4.0	283.15	16.0	193.15	17.0	193.15
		22.5	215.15	47.5	260.15	54.0	260.15	66.0	212.15	80.0	191.15		
99	1012.5	S. L.	290.15	0.5	288.15	1.0	299.15	5.5	276.65	13.5	212.65	16.0	201.15
		17.0	201.15	20.0	213.15	46.5	266.15	50.0	266.15	55.0	255.15	70.0	204.15
		80.0	191.15										
10 km													
1	1019.5	S. L.	237.15	1.5	262.65	5.0	241.65	10.0	199.15	12.0	201.15	19.0	201.15
		36.5	239.65	56.5	251.65	60.0	241.15	70.0	245.15	80.0	237.15		
10	1016.5	S. L.	246.15	1.5	261.15	5.0	240.15	10.0	203.15	12.0	203.15	22.0	185.15
		31.0	198.65	48.5	279.15	56.0	279.15	65.0	216.15	75.0	203.15	80.0	203.15
90	1011.0	S. L.	300.65	9.0	251.15	15.0	200.15	17.5	186.15	20.0	207.65	47.5	268.15
		53.5	268.15	66.0	230.65	80.0	195.65						
99	1008.0	S. L.	299.15	9.0	254.15	17.0	186.15	18.0	186.15	20.5	208.15	45.5	268.15
		52.5	268.15	72.5	198.15	80.0	198.15						
20 km													
1	1016.5	S. L.	236.65	1.5	253.15	9.0	206.65	12.0	206.65	20.0	186.65	24.0	192.65
		46.5	264.65	55.0	264.65	60.0	253.15	65.0	228.15	80.0	207.15		
10	1015.0	S. L.	240.15	2.0	254.15	4.0	245.15	9.0	208.65	20.0	192.15	24.0	192.15
		34.0	212.15	47.0	264.15	55.0	264.15	60.0	255.15	65.0	229.15	70.0	226.15
		80.0	210.15										
90	1014.5	S. L.	273.15	4.0	253.15	9.0	223.15	11.0	234.15	26.0	234.15	32.0	243.15
		37.0	255.15	47.0	287.15	52.5	287.15	65.0	257.15	80.0	158.15		
99[a]	1016.5	S. L.	228.15	1.0	238.65	2.5	238.65	7.0	216.15	8.5	216.15	16.0	223.65
		21.0	245.15	28.5	230.15	46.0	230.15	54.0	242.15	64.0	235.15	70.0	235.15
		80.0	223.15										
99[b]	1014.5	S. L.	273.15	2.0	268.15	4.0	257.15	10.0	218.15	12.0	233.15	27.0	237.65
		32.0	243.15	37.0	255.15	47.0	287.15	52.5	287.15	65.0	257.15	80.0	158.15
30 km													
1	1012.6	S. L.	241.15	1.0	243.15	3.5	239.15	8.5	220.15	13.0	220.15	20.0	216.65
		25.0	196.65	30.0	190.15	34.0	190.15	39.0	200.15	48.0	258.65	50.0	258.65
		55.0	249.15	70.0	241.65	80.0	217.65						
10	1012.8	S. L.	253.15	1.5	257.65	8.5	212.15	13.0	212.15	25.0	194.15	31.0	194.15
		51.0	258.15	55.0	258.15	62.5	237.15	70.0	241.65	80.0	219.65		
90	1011.7	S. L.	285.15	4.0	163.15	8.0	227.15	9.5	222.65	12.5	228.65	20.0	228.65
		26.0	234.65	46.0	286.65	52.5	286.65	62.5	261.65	80.0	163.65		
99	1011.3	S. L.	279.15	2.0	275.15	10.0	223.15	12.5	227.15	20.0	230.15	31.0	257.65
		46.0	286.15	52.5	286.15	65.0	246.15	80.0	156.15				
40 km													
1	1014.7	S. L.	253.15	1.5	259.15	8.5	213.65	13.0	218.15	42.5	207.15	55.0	254.65
		60.0	240.15	70.0	255.15								
10	1014.7	S. L.	253.15	1.5	259.15	8.5	213.65	12.5	215.65	36.0	200.65	45.0	223.15
		50.0	244.15	55.0	251.15	80.0	226.65						
90	1011.7	S. L.	283.15	9.5	226.15	12.0	228.15	20.0	228.15	47.0	286.65	51.0	286.65
		63.5	264.15	80.0	165.15								
99	1011.7	S. L.	287.15	9.0	224.15	12.0	228.65	19.0	228.65	42.0	284.65	48.5	284.65
		62.5	263.65	80.0	162.15								

[a]Profile for "sudden warming." [b]Alternate profile (see text).

Table 9 Temperature-altitude profiles in geopotential km (from density extremes)

Percentile densities, %	Sea-level pressure, mb	Breakpoints in geopotential km and temperature, K											
		Alt	K	Alt	K	Alt	K	Alt	K	Alt	K	Alt	K
5 km													
1	1002.0	S. L.	281.65	1.0	280.15	3.0	273.15	4.0	280.15	13.0	208.15	17.0	208.15
		34.0	233.65	46.5	271.15	48.5	271.15	80.0	176.65				
10	1012.0	S. L.	289.15	1.0	292.15	4.5	281.65	12.0	215.65	15.0	203.65	18.0	203.65
		21.0	215.65	36.0	236.65	46.0	266.65	49.0	266.65	60.0	244.65	70.0	208.65
		80.0	196.65										
90	1032.0	S. L.	238.15	0.5	250.15	1.5	250.15	8.0	211.15	13.0	218.15	28.0	206.15
		41.5	260.15	45.0	260.15	55.0	249.15	70.0	249.15	80.0	223.15		
99	1032.0	S. L.	251.15	3.0	242.15	5.0	226.15	8.0	221.65	15.0	225.15	31.0	225.15
		41.0	266.15	48.0	266.15	60.0	236.15	70.0	226.15	80.0	202.15		
10 km													
1	1012.0	S. L.	228.15	1.0	232.15	4.0	223.15	6.0	231.15	10.0	233.15	13.5	233.15
		26.0	213.15	38.0	213.15	55.5	248.15	60.5	242.15	70.5	253.15	80.0	243.65
10	1011.0	S. L.	243.15	1.0	246.15	6.0	222.15	11.0	228.15	15.0	228.15	27.0	216.15
		34.0	216.15	48.0	258.15	53.0	258.15	65.0	240.15	80.0	226.65		
90	1020.0	S. L.	289.15	4.0	273.15	12.0	205.15	16.0	205.15	36.0	229.15	47.5	263.65
		51.5	263.65	69.0	225.15	80.0	208.65						
99	1019.5	S. L.	295.15	0.5	297.15	5.5	265.15	12.0	206.65	17.0	204.15	27.0	217.15
		42.0	256.15	50.0	256.15	70.0	218.15	75.0	218.15	80.0	208.15		
20 km													
1	1014.5	S. L.	235.15	1.5	247.15	7.0	208.65	10.0	213.15	15.0	213.15	18.0	223.65
		21.5	251.65	30.5	238.15	43.0	238.15	51.5	255.15	54.0	255.15	64.0	239.15
		70.0	236.15	80.0	226.15								
10	1016.0	S. L.	230.15	1.0	238.15	4.0	229.15	8.0	209.15	12.0	209.15	15.5	202.15
		21.0	202.15	33.5	252.15	41.5	264.15	59.0	250.15	65.0	229.15	70.0	229.15
		80.0	219.15										
90	1011.0	S. L.	301.15	8.0	257.15	17.0	185.15	23.0	212.15	35.5	239.65	45.5	274.65
		50.0	274.65	70.0	218.65	77.0	190.65	80.0	192.15				
99	1011.0	S. L.	301.15	8.0	261.15	17.0	189.15	22.0	213.15	37.0	243.15	45.0	271.15
		49.5	271.15	77.0	188.65	80.0	191.65						
30 km													
1	1014.7	S. L.	248.15	1.0	257.15	9.0	205.15	10.5	205.15	19.5	191.65	27.5	199.65
		42.5	258.15	47.5	262.15	52.0	262.15	60.0	234.15	70.0	227.15	80.0	212.15
10	1014.7	S. L.	247.15	1.0	251.15	8.5	209.15	10.0	209.15	22.0	191.15	27.0	198.15
		42.0	246.15	48.0	261.15	52.5	261.15	60.0	235.65	70.0	228.65	80.0	212.65
90	1010.3	S. L.	292.15	5.0	260.15	10.0	223.15	15.0	230.15	24.5	230.15	31.5	240.65
		46.5	281.15	52.5	281.15	62.5	264.15	80.0	159.15				
99	1011.3	S. L.	282.15	4.0	264.15	10.0	222.15	12.5	231.15	20.0	231.15	31.0	236.65
		46.0	278.65	51.0	283.65	54.5	283.65	61.5	273.15	70.0	230.65	80.0	155.65
40 km													
1	1016.1	S. L.	253.15	2.0	257.15	10.0	201.15	12.5	201.15	20.0	189.15	25.5	189.15
		32.5	199.65	49.0	282.15	51.0	282.15	58.5	267.15	70.5	201.15	80.0	201.15
10	1016.1	S. L.	253.65	2.0	256.65	10.0	208.65	20.0	188.65	25.0	188.65	35.0	215.65
		48.0	280.65	51.0	280.65	61.0	256.65	70.0	202.65	80.0	202.65		
90	1010.3	S. L.	290.15	5.0	260.15	10.0	223.15	15.0	230.15	23.5	230.15	31.0	240.65
		46.0	282.65	50.0	282.65	62.5	265.15	80.0	160.15				
99	1010.3	S. L.	294.15	5.0	261.15	10.0	221.15	15.0	229.15	27.0	235.15	47.0	283.15
		50.5	283.15	63.0	260.65	80.0	158.65						

temperature correlations (Table 7) that were developed from data derived from independent rocket grenade and pressure gauge experiments at Fort Churchill during the winters 1957–1972,[12] along with the model profile temperatures adopted at 50 km. The equation used for these calculations is

$$\hat{T}_2 = \bar{T}_2 + (rS_2/S_1)(T_1 - \bar{T}_1) \tag{9}$$

where $\bar{T}_1$ and $\bar{T}_2$ are the monthly mean temperatures at lower level 1 and upper level 2, 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 two levels, and $\hat{T}_2$ is the estimated temperature at level 2. Estimated temperatures for 60, 65, 70, and 80 km were used to develop the winter profiles above 55 km, as shown in Fig. 2.

The 20 model profiles based on the 1 and 10% hot temperatures and high densities at the same five specified altitudes are generally representative of summer conditions and/or occur at low-latitude locations. During these months (and during all months at low latitudes), the temperature structure in the mesosphere is relatively stable above 60 km. Consequently, these model profiles were extended from 60 to 80 km using the Air Force Reference Atmospheres for the appropriate month and latitude.

Results

The model profiles of temperature and density derived for this paper represent atmospheric conditions associated with 1 and 10% hot and cold temperatures and high and low densities that occur at each of five levels (5, 10, 20, 30, and 40 km). Results are presented in Tables 8 and 9 in the form of temperature-altitude profiles with lapse-rate breakpoints in geopotential kilometers as derived from the threshold temperatures and densities. These values can be used to reconstruct any or all segments of the models between 0 to 80 km using Eqs. 4–8 and the values for r_ϕ and g_ϕ given in Table 1.

Kantor and Tattlman[18] provide additional information on the models and tables of the profiles at 2-km intervals of geometric altitude from the surface to 80 km. These tables include internally consistent hydrostatic profiles of density associated with the temperature profiles and corresponding temperatures associated with the density profiles.

The model profiles represent realistic, hydrostatically consistent representations of the temperature and density structure resulting from the extremes that occur at the indicated altitudes. They are appropriate for the design of vehicles traversing the atmosphere or other considerations for which the total influence of the atmosphere is needed. Each of the profiles should be considered individually to determine which ones are the most appropriate for a given application.

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