Rocketsonde Temperature Variability at High-Latitude Canadian Stations[1]

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ABSTRACT

Rocketsonde temperature measurements made with the Arcasonde-1A payload at Fort Churchill and Primrose Lake, Canada, have been corrected for the effects of aerodynamic heating, time lag, radio frequency heating, longwave radiation and, in particular, solar radiation. In spite of some inherent difficulties in adequately correcting for these factors, particularly at higher altitudes, reasonably good sets of corrected data were obtained and then analyzed for periodicities in the temperature wave. A series of measurements made at Fort Churchill in September 1966 spanning 72 hours at 4 h intervals, was used to investigate diurnal temperature variations. Diurnal temperature ranges were found to be 1.7 K, 3.0 K, 3.3 K, 6.3 K, 5.3 K, 9.3 K, 7.3 K and 8.6 K at 25, 30, 35, 40, 45, 50, 55 and 60 km respectively. The times of maximum temperature were found to be, *with respect to local noon*, 2 h before at 25 km, noon at 30 km, 2 h after at 35 km, 4 h after at 40 km, 3 h after at 45 km, 2–4 h after at 50–60 km. There was evidence of semi-diurnal variations at 25, 30, 35, 45 and 60 km.

Four years of data at Fort Churchill and two years at Primrose Lake were used to investigate annual and shorter-period variations. The maximum in the annual cycle occurred in June in the 25–55 km region at both stations and up to 63 km at Fort Churchill. The annual temperature ranges were of similar magnitudes at both stations, increasing from 10 K at 25 km to about 35 K at 45 km and decreasing thereafter to about 25 K at 55 km and about 20 K at 60 km (at Fort Churchill). There was some evidence of semi-annual variations at 25 km over the two stations with a subsidiary maximum in January in addition to the main one in June. The range of the semi-annual variation was about 5 K at that altitude.

1. Introduction

Within the past ten years, several studies of wind and temperature oscillations have been carried out both theoretically (e.g., Lindzen, 1966, 1967) and experimentally (Miers, 1965; Beyers and Miers, 1965; Beyers *et al.*, 1966; Reed *et al.*, 1966, 1969; Finger and Wolf, 1967; Hoxit and Henry, 1973; etc.). Although there has been reasonable agreement between theory and experimental observations in the case of the amplitudes and phases of the wind oscillations, the same has not been the case for temperature oscillations. For instance, for equinoctial conditions at 30° latitude, Lindzen (1967) obtained values of about 0.5 K at 30 km, 1.6 K at 40 km, 1.3 K at 50 km, 1.5 K at 60 km, etc. for the amplitudes of the diurnal temperature oscillations. Johnson (1953), Pressman (1955), and Leovy (1964) calculated maximum diurnal amplitudes of about 2–2.5 K near the stratopause. On the other hand, observed values for similar locations and times generally have been in the range of 3–4 K at 30 km, 5 K at 40 km, 10 K at 50 km, and 9–20 K in the 55–60 km region (Beyers and Miers, 1965; Beyers *et al.*, 1966; Finger and Wolf, 1967; Reed *et al.*, 1969, Hoxit and Henry, 1973; etc.). There have been similar discrepancies in the phases of the oscillations as well, particularly in the middle and upper stratosphere and in the lower mesosphere (i.e., in the region just above and below the stratopause). The reasons for these are not yet clear but may be connected with the difficulty of separating synoptic and other non-solar related short-term temperature variations from the solar diurnal oscillations especially when the data are from observations over a short period of time (Hoxit and Henry, 1973). The difficulty of adequately correcting for the solar radiation effects may also be an important factor.

Longer-term temperature oscillations (semi-annual, annual, biennial) have also received considerable attention in the literature. Annual variations at all locations and biennial oscillations in the equatorial stratospheric regions are well-known phenomena. Recently, some evidence of semi-annual variations at northern mid-latitudes in the 40–55 km region has been reported, with the maxima occurring in May–June and December, and the minima in February–March and September–October (Hoxit and Henry, 1973).

In this paper, rocketsonde temperature measurements made with the Arcasonde-1A sensor at two high-latitude Canadian stations, Fort Churchill (58.7°N, 93.8°W) and Primrose Lake (54.8°N, 110.1°W), are corrected according to a scheme described previously (Ezemenari, 1972) and are then analyzed for periodicities in the temperature wave. Data from a series of flights at Fort Churchill

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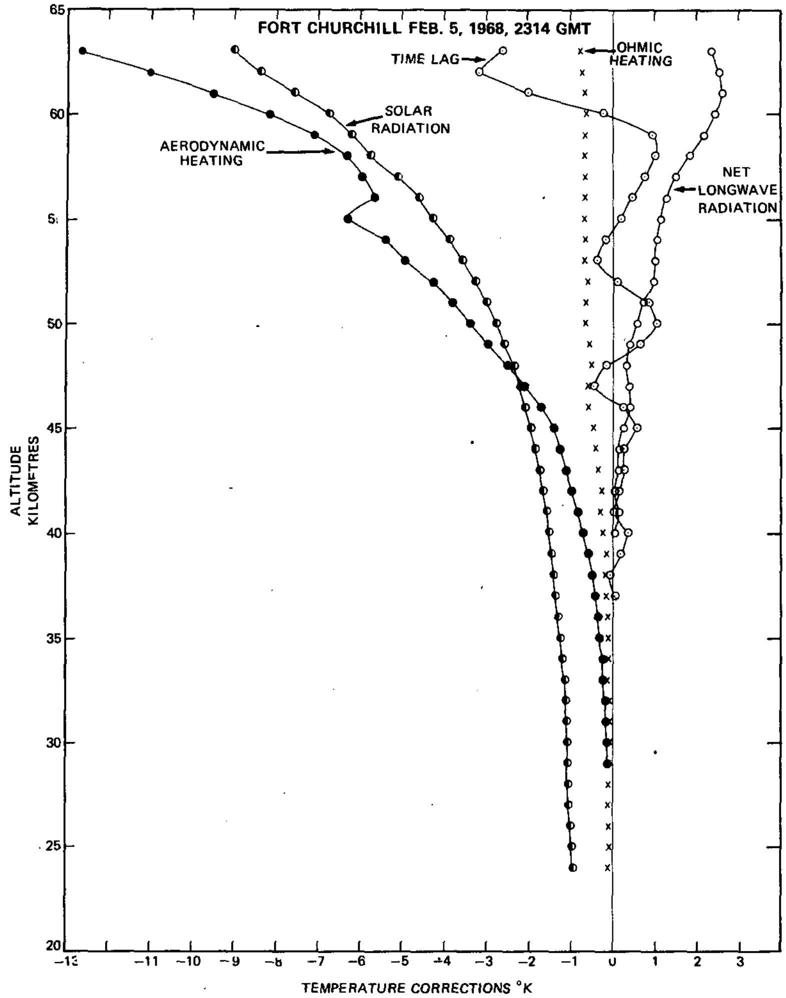

FIG. 1. Calculated temperature corrections for the Arcasonde-1A flight at Fort Churchill on 5 February 1968 at 2314 GMT.

starting at 2300 local time on 6 September 1966 and continuing every four hours until 2300 local time on 9 September 1966, are used to study the diurnal variations. The longer period oscillations have also been studied using four years of data (May 1964 to April 1968) at Fort Churchill, and two years of data (December 1967 to November 1969) at Primrose Lake.

TABLE 1. Calculated temperature corrections (K) for the flight of 5 February 1968, 2314 GMT, at Fort Churchill.

Altitude (km)	Aerodynamic heating	Solar radiation	Time lag	Ohmic heating	Net long wave radiation	Total
63	−12.7	−8.9	−2.6	−0.8	2.4	−22.6
60	− 8.1	−6.8	−0.2	−0.7	2.5	−13.3
55	− 6.3	−4.3	0.2	−0.7	1.1	−10.0
50	− 3.4	−2.8	1.0	−0.6	0.6	− 5.2
45	− 1.3	−2.0	0.7	−0.5	0.3	− 2.8
40	− 0.8	−1.5	0.4	−0.2	0.1	− 2.0
35	− 0.3	−1.3	0	−0.1	0	− 1.7
30	− 0.1	−1.1	0	−0.1	0	− 1.3
25	0	−1.0	0	−0.1	0	− 1.1

The main objective of this work is to correct each temperature observation very carefully for the effects of aerodynamic heating, time lag, radio frequency heating, longwave radiation and, in particular, solar radiation, before using it for any analysis. It is hoped that, with such data, the diurnal and other effects will be more satisfactorily determined.

The symbols used in the text of the paper are defined in the Appendix.

2. Temperature corrections

The temperature correction is given by (Ezemenari, 1972)

$$(T_t - T_e) = 1/h_s[\dot{H}_{\mathrm{aero}} - \dot{H}_{\mathrm{lag}} + \dot{H}_{\mathrm{sr}} + \dot{H}_{\mathrm{oh}} + \dot{H}_{\mathrm{lwr}}],$$

where $\dot{H}_{\mathrm{aero}}$, $\dot{H}_{\mathrm{lag}}$, $\dot{H}_{\mathrm{sr}}$, $\dot{H}_{\mathrm{oh}}$, $\dot{H}_{\mathrm{lwr}}$ are, respectively, the power contributions due to aerodynamic heating, time lag, solar radiation, electrical and electromagnetic power dissipation, and longwave radiation. The contributions of each type of correction to the total applicable correction for the flight of 2314 GMT 5 February 1968 at Fort Churchill are shown in Table 1 and plotted in Fig. 1. Solar radiation correction is probably the most important one because it is significant at practically all levels. Aerodynamic and time lag corrections are substantial at the higher levels only. Longwave radiation cooling is significant in the region of the stratopause temperature maximum and is expected to decrease in the mesosphere when the temperature again decreases. However, since the net longwave radiation has a negative sign at mesospheric levels when the solar radiation effect is positive, the overall effect becomes more and more positive. Proper account must be taken of these facts before radiation effects can be adequately corrected for in the data.

Because of the importance of radiation corrections, the scheme used for the data sets analyzed in this paper is described in a little more detail in the following section.

a. Radiation corrections

Accurate calculation of the solar radiation term

$$1/h_s[J_s(\alpha_s A_p + 2K_l\beta\alpha_{fs}A_{fp}/LS_f)]$$

is difficult for several reasons. In the first place, widely varying values have been measured for the shortwave absorptivity, α_s, of the 10 mil Al-coated thermistor. Drews (1966) reported 0.072, Thompson (1966) a value of 0.15, and Morrissey (personal communication) 0.12 (the value used here). Similarly, both Drews (1966) and Hyson (1968) reported 0.06 for the shortwave absorptivity, α_{fs}, of the mylar film while Morrissey obtained a value of 0.12 which is used here. Secondly, the values given for the fraction of the surface area of the bead exposed to solar radiation, A_p, has also varied from 1.608×10^{-7} m^2 by Drews (1966), to 8.04×10^{-8} m^2 by Hyson (1968), to 8.83×10^{-8} m^2 (used here) by Thompson and Keily (1967). Finally, the value of the solar radiation flux, J_s, depends on the directional reflection of the earth's surface features and clouds, which are very difficult to determine accurately. In this study, J_s was calculated from the formula

$$J_s = 1394(1 + r\cos\theta_0),$$

where a solar constant of 1394 J m^{-2} s^{-1} has been used.

The determination of the longwave radiation cooling from the term

$$1/h_s\{\sigma[(\alpha_l A_t + 2K_l\beta\alpha_{fl}A_{fr}/LS_f) \times (0.050T_{be}^4 + 0.06T_{ai}^4 + 0.44T_{ae}^4) - T_t^4(\epsilon_l A_t + 2K_l\beta\epsilon_{fl}A_{fr}/LS_f)]\}$$

is no more precise than that of the solar radiation effect. The absorptivities α_l, α_{fl} and emissivities ϵ_l, ϵ_{fl} for

Table 2. Temperature corrections for solar radiation effects (to be subtracted). Units are K: (a) Fort Churchill, (b) Primrose Lake.

	1966			1967			1968	
(a) Altitude (km)	Apr. 15 1903 GMT	Jul. 3 1953 GMT	Aug. 7 1831 GMT	Jan. 31 2200 GMT	Feb. 1 1430 GMT	Oct. 13 2335 GMT	Jan. 4 2000 GMT	Feb. 5 2314 GMT
63	7.3	5.8				5.9	7.1	8.9
60	5.6	4.0	4.8			4.2	5.3	6.8
55	3.5	2.6	3.0	4.3	4.3	3.0	3.7	4.3
50	2.3	1.9	2.1	2.9	2.7	2.1	2.5	2.8
45	1.7	1.4	1.7	2.0	1.9	1.5	1.9	2.0
40	1.4	1.1	1.3	1.5	1.5	1.2	1.6	1.5
35	1.2	1.0	1.1	1.3	1.2	1.1	1.4	1.3
30	1.0	1.0	1.0	1.1	1.1	1.0	1.2	1.1
25	0.9	0.8	0.9			0.9	1.0	1.0

	1968			1970
(b) Altitude (km)	Apr. 5 1807 GMT	Jul. 19 1732 GMT	Oct. 9 1829 GMT	Jan. 21 1800 GMT
63	7.4	4.5	4.6	
60	5.6	3.6	3.7	5.8
55	3.5	2.4	2.5	3.9
50	2.3	1.7	1.8	2.6
45	1.6	1.3	1.4	1.9
40	1.3	1.1	1.2	1.5
35	1.1	1.0	1.1	1.3
30	1.0	0.9	1.0	1.1
25	0.9	0.8	0.9	1.0

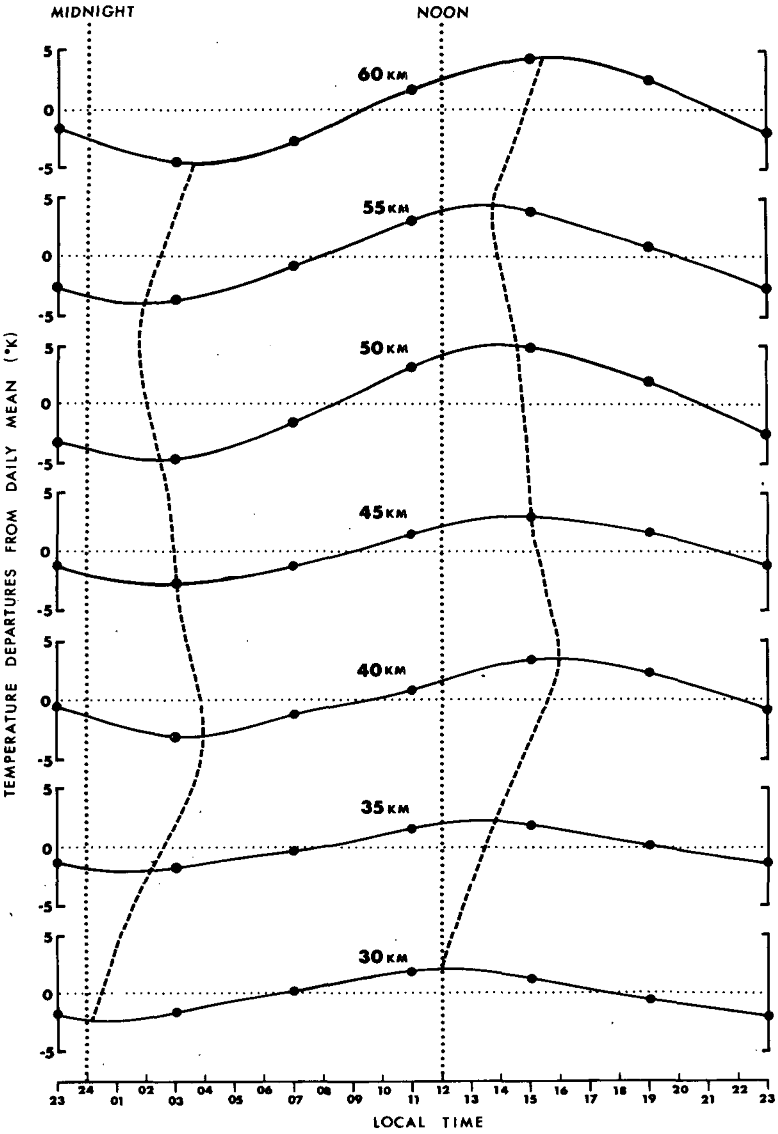

FIG. 2. Temperature departures from daily mean as a function of time (hours) for different altitudes, showing the diurnal variations. The dashed lines indicate the continuity of the times of maximum and minimum temperatures. Fort Churchill, 6–9 September 1966.

longwave radiation are not precisely known, nor are the environmental temperatures T_{be}, T_{ai} and T_{ae} which had to be estimated from altitude-dependent linear relationships given by Wagner (1964) on the basis of the work of Aagard (1960). Thus, the computed corrections for radiation effects are the best estimates obtainable under these limitations. Table 2 shows some typical values of the temperature corrections to be made for solar radiation effects.

3. Results and discussion

a. Diurnal variations

Two-kilometer layer running averages were computed using the corrected temperatures from the series of flights of 6 September 1966, 2300 local time to 9 September 1966, 2300 local time. From these, 4 h averages spanning a period of 24 hours were computed for each level. The results are presented in Table 3. Since measurements were made every four hours, there were six data points on each 24 h curve, and harmonic analysis of the data showed that the first three harmonics accounted for 83% of the total variance.

The calculated amplitude and phase angles of each harmonic were then used to derive the temperature wave corresponding to that particular harmonic. The results for the diurnal temperature wave (i.e., the first harmonic) are plotted in Fig. 2 for the 30 km to 60 km region in terms of the temperature departures from the daily mean temperature. (The 25 km results were too

TABLE 3. Two-kilometer-layer running mean temperatures (K), Fort Churchill: (a) 6, 7, 8, 9 September 1966; (b) averages of (a). Times are local. Values in parentheses are extrapolated.

(a) Altitude (km)	Sept. 6	Sept. 7						Sept. 8						Sept. 9					
	2300	0300	0700	1100	1500	1900	2300	0300	0700	1100	1500	1900	2300	0300	0700	1100	1500	1900	2300
60		262	268	250	271	270	(256)	246	267	258	255	263	255	256	253	272	263	257	258
55		259	259	262	264	266	259	255	260	262	267	263	261	254	269	267	265	261	261
50		261	269	265	270	267	263	261	267	272	272	267	261	259	262	268	271	271	267
45	263	261	267	261	271	263	265	260	266	261	268	269	260	260	268	266	269	266	266
40	253	250	255	252	257	257	254	252	256	252	260	256	253	249	251	254	259	256	254
35	243	242	249	242	250	245	246	246	244	242	247	247	241	239	242	243	248	246	239
30	230	232	235	233	239	235	(235)	(235)	234	232	235	231	230	229	230	234	233	229	228
25	225	225	227	225	227	223	(223)	(224)	225	222	224	223	224	221	225	223	224	221	221

(b) Altitude (km)	2300	0300	0700	1100	1500	1900
60	256	255	263	260	263	269
55	260	256	263	264	265	263
50	264	260	266	268	271	268
45	264	260	267	263	269	266
40	254	250	254	253	259	256
35	242	242	244	242	248	242
30	231	232	233	233	236	231
25	223	223	226	223	225	223

small to be plotted on the scale used but have, nevertheless, been included in the discussions.)

In the stratopause region near 45–50 km, the maximum of the diurnal temperature wave occurs some 2½ to 3 h after local noon; the minimum 2½ to 3 h after midnight. In the upper stratosphere, the time of maximum temperature is about 4 h after local noon; the minimum 4 h after midnight. In the lower stratosphere the time of maximum temperature is much earlier, occurring about 2 h after local noon at 35 km, practically at noon in the 30 km region, and some 2 h before noon at 25 km.

In the mesosphere, the times of maximum temperatures are from 1½ h (at 55 km) to about 3½ h (at 60 km) after local noon; minimum temperatures occurred 1½ h to 3½ h after midnight at 55 km and 60 km respectively. These observations are illustrated in Fig. 2.

The temperature ranges over a 24 h period were also determined for each harmonic. These are presented in Table 4 for all three harmonics and plotted in Fig. 3 for the diurnal temperatures. The computed diurnal temperature ranges were 1.7 K, 3.0 K, 3.3 K, 6.3 K, 5.3 K, 9.3 K, 7.3 K and 8.6 K at 25, 30, 35, 40, 45, 50, 55 and 60 km respectively. The error bars represent the 95% confidence interval computed from the measured temperature data on the assumption that they are normally distributed. Lindzen's (1967) theoretical calculations based on thermal tidal theory, and those of Leovy (1964) resulting from photochemical-radiative equilibrium considerations, and the experimental results of Hoxit and Henry (1973) are also plotted on Fig. 3 for comparison. Also shown in Table 4 are the percentage contributions to the total variance, σ_H^2/σ^2, of each of the three harmonics, where σ^2 is the total

TABLE 4. Harmonic components of the 24 h temperatures showing fractional contributions to the total variance (σ_H^2/σ^2), and the maximum 24 h temperature change at Fort Churchill, September 1966.

		Number of the harmonic					
		$n=1$ (Diurnal)		$n=2$ (Semi-diurnal)		$n=3$ (Ter-diurnal)	
Altitude (km)	95% confidence interval (K)*	σ_H^2/σ^2	Range (K)	σ_H^2/σ^2	Range (K)	σ_H^2/σ^2	Range (K)
60	±4.2	36%	8.6	47%	8.0	0	0.6
55	±2.6	67%	7.3	10%	2.5	6%	1.7
50	±3.0	76%	9.3	3%	1.5	5%	1.7
45	±2.6	35%	5.3	15%	3.0	33%	3.7
40	±2.4	59%	6.3	4%	1.5	20%	2.7
35	±1.9	27%	3.3	27%	3.0	30%	2.7
30	±1.5	45%	3.0	26%	2.0	13%	1.3
25	±1.4	22%	1.7	22%	1.5	39%	1.7

* The 95% confidence interval was computed from the measured temperature data, which were assumed to be normally distributed. It serves to show which harmonic components are significant at the given altitude.

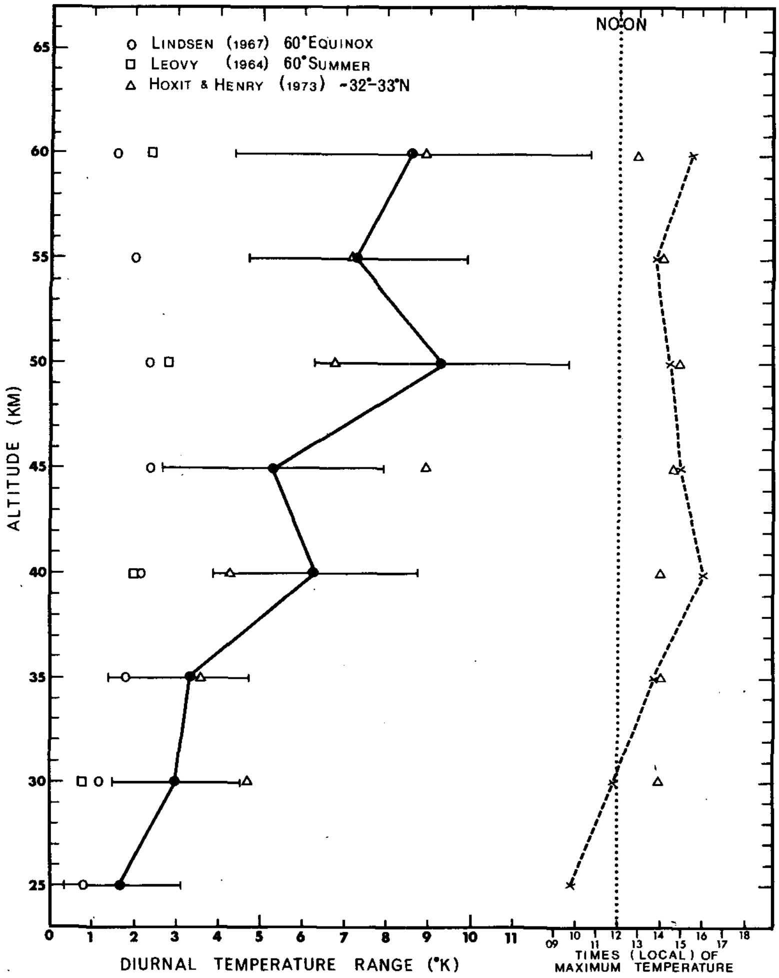

FIG. 3. Diurnal temperature range at Fort Churchill, 6–9 September 1966. The experimental results of Hoxit and Henry (1973) and the theoretical results of Lindzen (1967) and Leovy (1964) are plotted for comparison. Times of maximum temperatures at each altitude are shown on the right.

variance and σ_H^2 is the harmonic variance defined as

$$\sigma_H^2 = C_i^2/2 \text{ for all but the last harmonic,}$$
$$= C_i^2 \text{ for the last harmonic,}$$

and C_i is the amplitude of the ith harmonic. On the basis of the calculated fractional contributions of each harmonic to the total variance, and the size of the temperature range with respect to the 95% confidence band, there would seem to be significant semi-diurnal temperature variations in the mesosphere around 60 km and in the lower stratosphere (25 km to 35 km), and even ter-diurnal (period ≈ 8 h) variations in the stratosphere (25 km to 45 km). These latter observations are, of course, tentative owing to the smallness of the sample size, but would seem to deserve further investigations.

In summary, Table 5 shows the calculated diurnal temperature ranges compared with the experimental results of Beyers and Miers (1965) and Hoxit and Henry (1973), and with the theoretical calculations of Lindzen (1967) and Leovy (1964). Clearly, there is no agreement between theory and observations. The theoretical results of Lindzen (1967) and Leovy (1964) appear to show reasonable agreement between them particularly in the 30–50 km region. There is no agreement whatsoever between the observational results of Beyers and Miers (1965) and either the present results or those of Hoxit and Henry (1973) even though the work of Beyers and Miers and of Hoxit and Henry cover the same general geographical area. Beyers and Miers report their results as maximum 24 h temperature changes which would include non-diurnal heating. Further, they estimate for some of their soundings a diurnal temperature range of at least 15–20°C between 55 and 60 km decreasing to near 5°C at 30 km (Beyers and Miers, 1965). Hoxit and Henry (1973), on the other hand, report a diurnal temperature range of 4.7 K at 30 km, but 7–9 K between 55 and 60 km. There

Table 5. Values of the diurnal temperature ranges from various sources. Units are K. Errors quoted for present results represent the 95% confidence band.

Altitude (km)	Present results Churchill, 58.7°N 6–9 Sep. 1966	Beyers and Miers (1965) White Sands, 32.5°N 7–8 Feb. 1964	Hoxit and Henry (1973) ~32–33°N	Lindzen (1967) Equinox 60°	Leovy (1964) 60°	
					Summer	Winter
60	8.6±4.2		8.9	1.6	2.4	2.5
55	7.3±2.6	22.0*	7.2	2.0		
50	9.3±3.0	20.0*	6.8	2.4	2.8	3.0
45	5.3±2.6	15.0*	8.9	2.4		
40	6.3±2.4	10.0*	4.3	2.2	2.0	1.5
35	3.3±1.9	9.0*	3.6	1.8		
30	3.0±1.5	7.0*	4.7	1.2	0.8	0.4
25	1.7±1.4			0.8		

* The authors report these as maximum 24 h temperature changes.

Table 6. Monthly average temperatures (K) and, in parentheses, the number of observations averaged: (a) Fort Churchill, (b) Primrose Lake.

(a) Altitude (km)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
63	252 (4)	265 (10)	265 (9)	269 (10)	271 (9)	269 (7)	264 (2)	269 (9)	263 (9)	269 (5)	265 (4)	272 (10)
60	246 (9)	253 (13)	266 (19)	262 (15)	273 (14)	271 (14)	271 (11)	269 (21)	260 (21)	257 (13)	257 (8)	261 (13)
55	253 (27)	260 (23)	262 (35)	268 (24)	274 (16)	275 (23)	275 (20)	272 (31)	262 (30)	255 (40)	249 (14)	255 (29)
50	251 (37)	261 (27)	263 (41)	271 (25)	277 (17)	280 (26)	279 (24)	275 (39)	265 (30)	255 (41)	251 (19)	248 (39)
45	248 (39)	253 (27)	260 (42)	267 (25)	275 (17)	276 (28)	276 (26)	272 (41)	265 (31)	248 (43)	243 (21)	237 (44)
40	241 (39)	238 (28)	247 (42)	252 (26)	262 (17)	265 (30)	263 (26)	259 (41)	253 (31)	235 (43)	232 (23)	224 (44)
35	233 (40)	225 (28)	232 (42)	236 (26)	246 (17)	250 (29)	250 (26)	246 (41)	241 (31)	226 (43)	221 (23)	216 (44)
30	222 (39)	220 (26)	223 (39)	225 (23)	233 (17)	238 (27)	238 (26)	235 (40)	232 (29)	220 (43)	215 (22)	216 (38)
25	220 (35)	220 (24)	220 (36)	222 (23)	226 (15)	229 (25)	229 (23)	227 (40)	223 (30)	218 (43)	216 (16)	221 (32)
(b)												
63	261 (1)	267 (5)	240 (3)	252 (6)	253 (14)	255 (8)	248 (2)	246 (10)	247 (4)	258 (4)	270 (1)	277 (1)
60	268 (2)	254 (10)	252 (5)	258 (7)	260 (18)	260 (11)	256 (2)	253 (13)	253 (7)	250 (5)	257 (2)	254 (2)
55	246 (2)	252 (12)	258 (8)	265 (10)	269 (18)	271 (13)	269 (2)	264 (16)	257 (7)	254 (9)	253 (5)	246 (3)
50	241 (4)	254 (12)	258 (9)	269 (13)	275 (18)	278 (13)	274 (5)	270 (18)	266 (11)	256 (9)	256 (5)	250 (4)
45	233 (9)	248 (12)	254 (9)	264 (13)	273 (19)	275 (13)	271 (7)	267 (18)	262 (12)	251 (10)	245 (5)	250 (4)
40	226 (12)	235 (12)	246 (9)	252 (13)	262 (19)	264 (13)	260 (9)	256 (18)	252 (13)	238 (10)	230 (6)	237 (4)
35	218 (12)	225 (12)	238 (8)	236 (12)	247 (19)	249 (13)	247 (9)	243 (18)	240 (14)	228 (11)	221 (6)	228 (4)
30	218 (12)	218 (12)	230 (8)	225 (12)	233 (19)	237 (13)	236 (9)	235 (18)	229 (14)	224 (11)	217 (6)	222 (4)
25	217 (12)	217 (12)	223 (8)	220 (12)	225 (19)	226 (13)	229 (9)	227 (18)	221 (14)	216 (11)	217 (6)	218 (4)

is, thus, agreement between the two results at 30 km. In the 55–60 km altitude regions, however, the results of Beyers and Miers exceed those of Hoxit and Henry by 50–100%. There is no doubt that this discrepancy is associated with the effects of non-diurnal heating. Hoxit and Henry took careful steps to remove these heating errors from their results while Beyers and Miers acknowledged the presence of non-diurnal heating

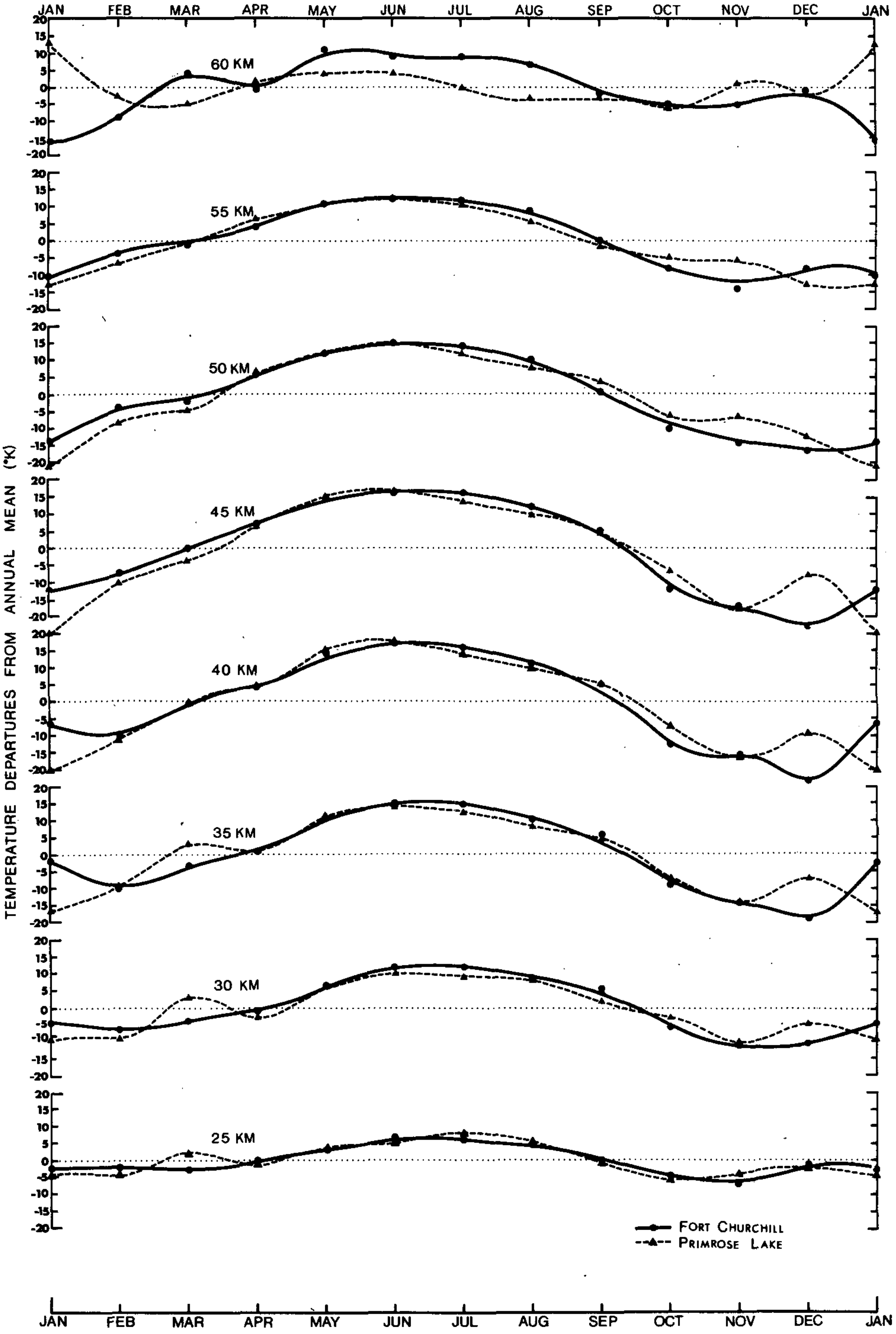

FIG. 4. Temperature departures from annual mean (K) as a function of time (months) for different altitudes for Fort Churchill and Primrose Lake. The position shown for each month is the *end* of the month.

TABLE 7. Harmonic components of the annual temperature waves at Fort Churchill and Primrose Lake. σ_H^2/σ^2 is the fractional contribution to the total variance.

Altitude (km)	95% Confidence interval (K)*	Number of the harmonic, *n* *n* = 1 (Annual) σ_H^2/σ^2	Range (K)	*n* = 2 (Semi-annual) σ_H^2/σ^2	Range (K)	*n* = 3 (Quarterly) σ_H^2/σ^2	Range (K)	*n* = 4 (Termly) σ_H^2/σ^2	Range (K)	*n* = 5 (Bi-monthly) σ_H^2/σ^2	Range (K)
Fort Churchill											
63	±3.0	12	5.0	22	6.5	6	2.6	12	4.0	14	5.5
60	±4.6	66	18.7	3	4.0	7	5.0	8	5.5	7	4.9
55	±5.3	86	24.4	3	4.1	1	1.7	0	1.0	1	2.7
50	±6.6	90	31.3	1	3.3	0	0.7	1	2.0	0	1.6
45	±7.8	88	36.6	2	5.8	1	3.0	0	1.3	0	2.2
40	±7.7	84	35.0	2	5.6	2	4.6	0	0.4	2	4.8
35	±6.6	78	28.6	5	6.5	3	5.7	0	1.7	2	4.5
30	±4.8	80	20.5	7	6.0	2	3.7	1	1.6	0	0.8
25	±2.4	70	10.0	17	5.0	2	1.4	1	1.1	1	1.0
Primrose Lake											
63	±6.2	44	20.5	30	16.5	0	1.7	3	4.3	7	7.9
60	±2.7	12	4.7	30	7.3	15	10.0	8	3.3	18	5.7
55	±5.0	88	23.4	1	3.0	1	2.7	0	1.5	0	1.1
50	±6.5	85	29.1	2	4.7	0	2.0	2	3.8	2	4.1
45	±7.3	83	32.7	1	4.3	0	2.3	3	5.4	3	5.9
40	±7.4	86	33.8	0	1.6	1	2.6	3	5.8	1	4.2
35	±6.1	82	27.2	0	0.4	0	1.6	7	6.6	3	4.8
30	±4.1	78	17.8	1	2.2	0	1.0	6	3.8	6	5.0
25	±2.6	72	10.8	8	3.7	5	2.0	2	1.5	2	1.8

Altitude (km)	(Bi-monthly) σ_H^2/σ^2	Range (K)
Fort Churchill		
63	27	5.5
60	0	0
55	1	1.7
50	0	0.7
45	1	2.4
40	2	4.2
35	3	4.0
30	1	1.5
25	0	0.5
Primrose Lake		
63	8	6.0
60	9	2.9
55	0	0
50	0	1.1
45	1	2.9
40	0	1.0
35	0	0.4
30	0	0.4
25	2	1.3

* The 95% confidence interval was computed from the measured temperature data which were assumed to be normally distributed. It serves to show if the computed temperature ranges are significant.

which they were not able to isolate from their results. This is further borne out by the fact that there was agreement at 30 km but not at the higher altitudes where, as was explained in Section 2 (and illustrated in Fig. 1) the heating effects, particularly those associated with radiation, are much more severe. The times of occurrence of the maximum temperatures were found, in both studies, to be within one hour of 1400 h local time suggesting, perhaps, that there might have been excellent agreement but for the non-diurnal heating effects.

Still on the subject of agreement among experimental observations, it is interesting to note the excellent agreement in the magnitude of the diurnal temperature range between the present results and those of Hoxit and Henry (1973) particularly above the stratopause (50–60 km), in spite of latitudinal differences. Even the times of occurrence of the maximum temperatures agree quite well at 35, 45, 50 and 55 km but differ notably at 60 km where Hoxit and Henry report 1300 h local time while present results show 1500–1600 h local time, and at 30 km where the times were 1400 and 1200 h local times, respectively. Thus, it would appear that experimental observations of the diurnal temperature oscillations could show more consistent agreement among themselves once the non-diurnal heating effects are better determined and anticipated. Nevertheless, the question of why experimental observations differ so substantially from theoretical calculations remains unresolved.

The observed temperature variations clearly represent the local temperature changes, and it would appear that they may be due to factors other than the diurnal range especially at the higher altitudes. Among the factors that could cause the additional variations are, of course, the effects of direct, reflected and scattered solar radiation and longwave radiation on the thermistor beads. These have been corrected for although, as pointed out earlier, one cannot say for certain that these corrections are adequate at all altitudes. Beyers and Miers (1965) also mention the effect of the finite response time of the thermistor sensor which could mean that, after deployment at a much higher payload temperature at around 75 to 65 km, the thermistor would more closely measure a warmer than a colder stratopause temperature value as it cooled to ambient temperatures near 50 km. These thermal lag effects were also corrected for here and should not introduce any significant uncertainties especially in the stratosphere. Adiabatic warming caused by sinking motions (Hoxit and Henry, 1973) and heating due to energy dissipation of gravity waves by eddy processes at the higher altitudes, are other factors which could affect the diurnal range in a manner that is not known precisely. Obviously, more experimental observations with adequate corrections for radiation errors (in particular) are needed before the exact nature of the diurnal variations can be determined.

b. *Longer-period variations*

The corrected Arcasonde-1A temperatures measured at Fort Churchill from May 1964 to April 1968, and at Primrose Lake from December 1967 to November 1969 were lumped together and averaged by month. 2 km layer running averages were then computed and the results shown in Table 6 including, in parentheses, the number of observations averaged. The curves were subjected to harmonic analysis, the 6 harmonics computed accounting for 92% of the total variance. The results are plotted in Fig. 4 in terms of the temperature departures from the annual mean for each level, as a function of time (in months). Further, the annual temperature ranges at each height were computed, together with the times of maximum temperature, as shown in Fig. 5 and Table 7. Also shown in Table 7 are the temperature ranges of each of the six harmonics used, their fractional contributions to the total variance, σ_H^2/σ^2, and the 95% confidence band which may be used to verify if the computed ranges are statistically significant. The following observations may be made from these results.

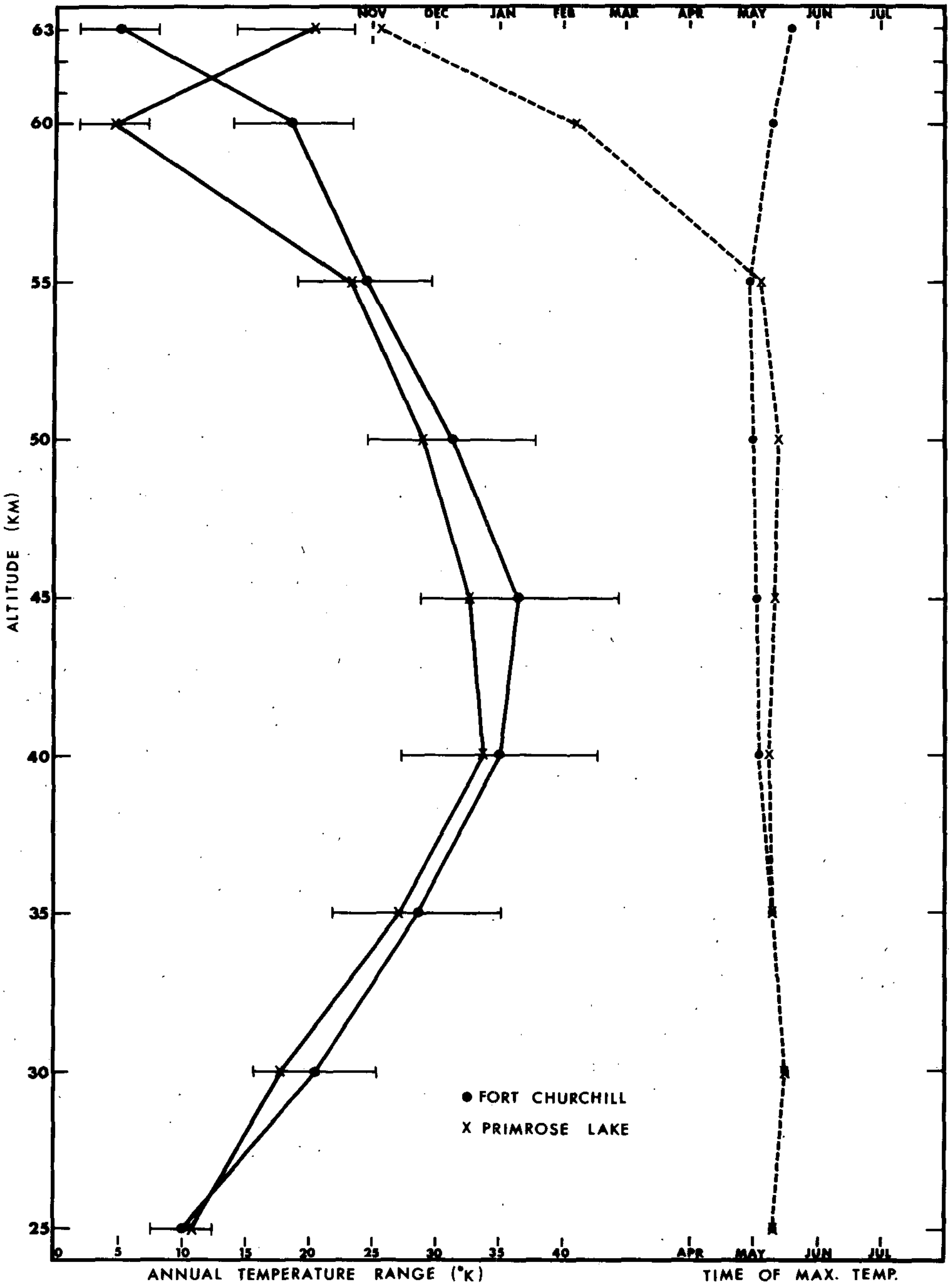

FIG. 5. Annual temperature ranges at Fort Churchill and Primrose Lake for different altitudes. The times of maximum temperatures at each altitude are shown on the right. The position shown for each month is the *end* of the month.

At both stations, the annual cycle is clearly predominant at all altitudes with the temperature maxima occurring in June (in month 6, where 1 January was taken as time $t=0$) throughout the stratosphere and the lower mesosphere (to 55 km). Above the 55 km level, while the maxima continue to occur in June at Fort Churchill, they now appear to occur much earlier over Primrose Lake—during March at 60 km and even as early as December at 63 km. It should be noted that the data for Primrose Lake cover only two years and the observation of peaks in the temperature wave in March at 60 km and December at 63 km may be due to some synoptic conditions, such as stratospheric warming events, which may be occurring at these times in one or the other of the years. Such occurrences would distort the observed temperature waves and may explain what seems to be significant semi-annual variations at Primrose Lake in the 60–63 km region, and even an approximately bi-monthly fluctuation at the same altitudes (See Table 7). Also, there seem to be indications of semi-annual variations at 25 km over the two stations with subsidiary peaks in December–January. This may be compared with the report by Hoxit and Henry (1973) of some evidence of a semi-annual variation in the 32–33°N latitude band for the 40–55 km levels with maxima in May–June and in December.

The computed annual temperature ranges and the times of maximum temperatures at both stations are summarized in Fig. 5. The error bars are the 95% confidence band for the Fort Churchill data (except at 60 and 63 km where they are also plotted for the Primrose Lake data). Clearly, the annual temperature ranges are the same at the two stations between 25 and 55 km, increasing from about 10 K at 25 km to a maximum of about 35 K at 45 km and thereafter decreasing to about 25 K at 55 km. Above this altitude, little reliance should be placed on the Primrose Lake results because of the small sample size while the Fort Churchill results would seem to indicate the correct size of the annual temperature range at 60 km (i.e., about 20 K), although the results for 63 km should be regarded as mostly qualitative, again because of the relatively small sample size.

4. Concluding remarks

A series of Arcasonde-1A rocketsonde temperature measurements at Fort Churchill, Canada, spanning 72 hours at 4 h intervals, was corrected for aerodynamic, time lag, radio frequency, and solar (and longwave) radiation heating (and cooling) effects and analyzed for the diurnal variations in temperature.

In the stratopause region (45–50 km), maximum diurnal temperatures occurred about 3 h after local noon, and minimum temperatures some 3 h after midnight.

In the upper stratosphere, maxima occurred about 4 h after local noon, and minima 4 h after midnight. In the lower stratosphere maxima occurred much earlier, about 2 h after local noon at 35 km, at noon at 30 km and 2 h before noon at 25 km. Correspondingly, the minima occurred respectively 2 h after midnight, at midnight, and 2 h before midnight at 35, 30, and 25 km.

In the mesosphere, maxima occurred from 2 h (at 55 km) to about 4 h after local noon; minima from 2 h to 4 h after midnight.

The computed diurnal ranges were 1.7 K at 25 km, 3.0 K at 30 km, 3.3 K at 35 km, 6.3 K at 40 km, 5.3 K at 45 km, 9.3 K at 50 km, 7.3 K at 55 km, and 8.6 K at 60 km.

These results agreed well with the experimental results of Hoxit and Henry (1973) but disagreed significantly with the theoretical results of Leovy (1964) and Lindzen (1967).

There was some evidence of semi-diurnal variations at 25, 30, 35, 45 and 60 km, with the semi-diurnal ranges being 1.5 K at 25 km, 2.0 K at 30 km, 3.0 K at 35 km and 45 km, and 8.0 K at 60 km. The maxima occurred at 0530 and 1730 h local time at 25 km; 0300 and 1500 h at 30 km; 0330 and 1530 h at 35 km; 0600 and 1800 h at 45 km; 0700 and 1900 at 60 km.

There would even appear to be ter-diurnal variations (period 8 h) at 25 km, 35 km, 40 km and 45 km.

Four years of data at Fort Churchill and two years at Primrose Lake were also used to investigate some longer-term variations. The annual cycle was found to be quite predominant at all latitudes with the temperature maxima occurring in June throughout the stratosphere and the lower mesosphere (to 55 km) at both stations and up to the 63 km height at Fort Churchill. Above 55 km at Primrose Lake the maxima seemed to occur much earlier—in March at 60 km and in December at 63 km. The annual temperature ranges were found, at both stations, to be about 10 K at 25 km, 20 K at 30 km, 28 K at 35 km, 35 K at 40 and 45 km, 30 K at 50 km, and 25 K at 55 km. Above this height the results are largely inconclusive for Primrose Lake but would seem to indicate a range of about 20 K at 60 km at Fort Churchill.

There was evidence of semi-annual variations at 25 km over the two stations with a subsidiary maximum in January, and range about 5 K.

APPENDIX

List of Symbols

A_{fp}	effective area of the mylar film exposed to solar radiation $=7.27\times10^{-4}$ m^2
A_{fr}	effective area of the mylar film for long-wave radiation $=7.27\times10^{-4}$ m^2
A_p	effective area of the thermistor exposed to solar radiation $=8.83\times10^{-8}$ m^2
A_t	surface area of the thermistor $=3.217\times10^{-7}$ m^2
h_s	convective heat transfer coefficient for the thermistor-mylar film system [J s^{-1} K^{-1}]

J_s	solar radiation flux [J m^2 s^{-1}]
K_l	thermal conductivity of the lead wires $= 69.5$ J m^{-1} s^{-1} K^{-1}
L	length of lead wires $= 1.6 \times 10^{-3}$ m
S_f	dissipation factor of the mylar film [J s^{-1} K^{-1}]
T_{ae}	temperature of the environment above the sensor (K)
T_{ai}	temperature of the instrument above the sensor (K)
T_{be}	temperature of the environment below the sensor (K)
T_e	temperature of the free atmospheric environment (K)
T_t	temperature measured by the thermistor (K)
α_{fl}	longwave absorptivity of the mylar film $= 0.4$
α_{fs}	shortwave absorptivity of the mylar film $= 0.12$
α_l	longwave absorptivity of the thermistor $= 2.2 \times 10^{-2}$
α_s	shortwave absorptivity of the thermistor $= 0.12$
β	cross-sectional area of the lead wires $= 1.013 \times 10^{-9}$ m^2
ϵ_{fl}	longwave emissivity of the mylar film $= 0.4$
ϵ_l	longwave emissivity of the thermistor $= 2.2 \times 10^{-2}$
σ	Stefan-Boltzman constant $= 5.726 \times 10^{-8}$ J m^{-2} s^{-1} K^{-4}
r	average directional reflection of earth surface features and clouds $= 0.3$
θ_0	sun's zenith angle $= \cos^{-1} (\cos\phi \cos\delta \cos t + \sin\phi \sin\delta)$
ϕ	latitude angle (°)
δ	solar declination angle (°)
t	local hour angle (°)

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