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SOME OBSERVATIONS ON THE THERMAL BEHAVIOR OF THE MESOSPHERE

by

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ABSTRACT

Temperature and wind soundings of the stratosphere and mesosphere using the acoustic grenade technique were made over Barrow, Alaska (71N) during the arctic winter night and during the summer. The winter mesosphere temperatures were generally warmer than at any other location and season and were variable from day to day. Temperatures oscillated with height in wave-like fashion at magnitudes up to 30 to 40C between 70 and 90 km. These wave-like structures were found to exist also in the winter mesosphere at Churchill (59N) and Wallops Island (38N). However, the magnitude of the oscillations decreased with latitude to a value of 20 to 25C at Wallops. Conversely, variability in summer seemed to decrease with increasing latitude and the wavelike structure was suppressed entirely at Barrow. Temperature variations in summer at Barrow were less than 10C from sounding to sounding at any given altitude from 40 to 85 km. Extremely low mesopause temperatures ranging from 130 to 140K near 85 km were observed in all of these soundings. One of the Barrow soundings, conducted during a noctilucent cloud display, when compared with a sounding conducted in the confirmed absence of noctilucent clouds, failed to show any significant temperature difference at the cloud level.

Simultaneous grenade soundings conducted from Wallops, Churchill and Barrow during 1965 indicate that a stratospheric warming which occurred over Barrow in late January-early February can be explained in terms of the circulation features at 50 km. Ridging of the Aleutian anticyclone over Alaska, combined with the splitting and/or migration of the polar vortex center to a location southwest of Churchill, resulted in a 20 to 25C increase in the Barrow temperatures from 40 to 50 km during the eight day period between soundings (27 January

Turn over

to 4 February). The third set of soundings made on 8 February shows that the original circulation pattern was restored with the polar vortex again centered north of the arctic circle and the Aleutian anticyclone centered south of Alaska. The resulting circulation returned the Barrow temperature profile to its original value of 27 January and was accompanied by a weakening of the pressure gradient over North America which changed the strong northwesterly winds above Barrow to light and variable up to 70 km.

One set of grenade soundings at Wallops in November 1964, and four sets of pitot tube soundings at Ascension Island in April 1964 and May 1965, and aboard ship in March and April 1965, were conducted each within one diurnal cycle. Wallops temperature variations observed at 45 km indicate a tendency toward a higher temperature near midnight than near local noon. This variation, a total of 15C at 45 km, increases with altitude to above 20C at 75 km. The phase of the cycle changes considerably also, and at 70 km the maximum occurs at local sunset and the minimum occurs near local sunrise. Results from the pitot tube soundings indicate higher temperatures at night than in daytime at the stratopause, a rapidly changing phase of maximum temperature with height and an increasing amplitude of the variations with height.

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INTRODUCTION

The experiments reported here are part of a continuing program of rocket soundings in the upper stratosphere and mesosphere conducted by the Goddard Space Flight Center since 1960. Launch sites ranged from several sites in North America (Alaska, Canada and Virginia) to the South Atlantic (Ascension Island 8S) and to a series of ship locations in the eastern South Pacific Ocean between the equator and 60S. Whenever possible, soundings were made simultaneously from several sites to permit a synoptic analysis of wind and pressure fields over the North American continent, especially during mid-winter 1965. Earlier results of this program (1960-64) relating primarily to seasonal and geographical variations of the temperature structure and circulation patterns were discussed by Nordberg et al (1965); in this paper, data resulting from recent soundings (1964-65) are presented. These soundings were specifically devoted to several definitive objectives involving a number of phenomena peculiar to the stratosphere and mesosphere. These objectives were: the observation of the temperature structure in noctilucent clouds; observations of stratospheric warmings and their associated circulation features; exploration of the wavelike temperature profiles in the mesosphere in winter and their relation to gravity waves; and the confirmation of diurnal temperature variations near the stratopause predicted by tidal theory.

METHOD OF OBSERVATIONS

Two rocket-borne techniques have been utilized to measure temperature, pressure, density and winds; the grenade experiment in which the velocities of sound waves generated by a series of high explosive charges detonated as the rocket ascends are measured and related to the absolute temperature and the winds in the atmosphere (Nordberg and Smith, 1964); and the pitot-static tube experiment, in which total and static pressure measurements made with radioactive ionization pressure gauges as the rocket ascends are related to the ambient density and ambient pressure (Horvath et al, 1962).

In the grenade experiment, the pressure profile is obtained by integrating the measured temperature profile upward from a balloonsonde reference pressure using the hydrostatic equation. The density profile is then computed from temperature and pressure data using the perfect gas law. In the pitot-static tube experiment, the temperature profile is obtained by differentiating the measured pressure profile with a form of the hydrostatic equation up to altitudes of about 75 km. Above 50 km altitude, the measured density profile is integrated with a form of the hydrostatic equation to produce a temperature profile also. These two methods for deriving the temperature profile are independent of each other and serve as a check in the overlapping 50 to 75 km region. Temperature in the overlap region may also be determined from the measured pressure and density profiles if the ideal gas law is applied to the measured data.

Observations from Ascension Island (8S); Barrow, Alaska (71N); Churchill, Canada (59N); Wallops Island, Virginia (38N) as well as from the shipboard expedition (equator and 60S) are included in the analysis. A total of 51 rocket grenade experiments and 11 pitot-static tube experiments are discussed. The majority of these soundings were made in 1964 and 1965, but earlier results (1962-63) are included in portions of the discussion. A complete summary of the experiments discussed is given in Table I and tabulated results are presented in Smith et al, (1964), (1966a) and (1966b).

DISCUSSION OF RESULTS

a. Noctilucent Clouds

During the summer of 1965, four grenade soundings were conducted at Pt. Barrow, Alaska, during and immediately after an intense display of noctilucent clouds. An experienced observer flew north from Fairbanks each night to verify the presence or absence of noctilucent clouds over Barrow. The first sounding on 7 August 1965, at 0113 Alaska Standard Time (AST) was directed into the vicinity of a noctilucent cloud display. This sounding was followed by three others, all within a 48 hour period. Two of these soundings (7 August 0939 AST and 7 August 1815 AST) took place in full daylight so that the presence of noctilucent clouds could not be established. The fourth (9 August 0010 AST) occurred in twilight and noctilucent clouds were definitely not present. The results of all four soundings are given in Figure 1. Minimum temperatures of 130 to 140K were observed at the mesopause near 85 km in all four cases. The sounding made with no noctilucent clouds present on 9 August shows essentially the same temperature structure throughout the mesosphere as the noctilucent cloud sounding. The steep, uniform temperature lapse rate from the stratopause to the mesopause and the extremely cold mesopause are common to all four soundings and are rather typical of the high latitude summertime temperature structure (Nordberg et al, 1965). Equally low mesopause temperatures have been observed by Witt et al (1965) in two soundings at Kronogard, Sweden (66N) during July 1963.

Table I

Location, date and time of meteorological sounding rocket experiments included in this report

Location	Date	(GMT)	Experiment
Ascension Island	15 April 1964	0122	pitot
	15 April 1964	1556	pitot
	23 May 1965	0202	pitot
	23 May 1965	1400	pitot
Barrow	27 January 1965	2132	grenade
	4 February 1965	0445	grenade
	8 February 1965	2215	grenade
	7 August 1965	1113	grenade
	7 August 1965	1939	grenade
	8 August 1965	0415	grenade
	9 August 1965	1010	grenade
Churchill	4 December 1962	0705	grenade
	6 December 1962	0543	grenade
	20 February 1963	2334	grenade
	28 February 1963	2148	grenade
	9 March 1963	0001	grenade
	29 January 1964	0417	grenade
	5 February 1964	0040	grenade
	13 February 1964	0430	grenade
	8 August 1964	0400	grenade
	12 August 1964	0215	grenade
	18 August 1964	0115	grenade
	27 January 1965	2223	grenade
	4 February 1965	1735	grenade
	8 February 1965	2300	grenade
	7 August 1965	1200	grenade
	7 August 1965	1945	grenade
	8 August 1965	0400	grenade
	8 August 1965	1003	grenade
Shipboard			
equator, 84°W	8 March 1965	1748	pitot
1°S, 84°W	9 March 1965	0626	pitot
60°S, 78°W	13 April 1965	0405	pitot

Location	Date	(GMT)	Experiment
Shipboard (Continued)			
60°S, 78°W	13 April 1965	1600	pitot
Wallops Island	6 June 1962	2348	pitot
	8 June 1962	0153	grenade
	1 December 1962	2034	pitot
	1 December 1962	2125	grenade
	6 December 1962	0532	grenade
	20 February 1963	2347	grenade
	28 February 1963	2211	grenade
	7 December 1963	1311	grenade
	7 December 1963	1343	pitot
	24 January 1964	0016	grenade
	29 January 1964	0411	grenade
	4 February 1964	0146	grenade
	5 February 1964	0320	grenade
	13 February 1964	0430	grenade
	7 August 1964	0100	grenade
	12 August 1964	0149	grenade
	16 August 1964	0315	grenade
	18 August 1964	0125	grenade
	5 November 1964	1700	grenade
	6 November 1964	0002	grenade
	6 November 1964	0520	grenade
	6 November 1964	1000	grenade
	27 January 1965	2224	grenade
	4 February 1965	0510	grenade
	8 February 1965	2253	grenade
	23 July 1965	1705	grenade
	7 August 1965	2003	grenade
	8 August 1965	0340	grenade
	8 August 1965	1015	grenade

The complete absence of any significant temperature variations in the four soundings at Pt. Barrow is not surprising since the stratosphere and mesosphere were exposed to almost continuous sunlight at Barrow during early August and the solar elevation angle at 50 km at this latitude varies only from 30° at noon to 6° at midnight.

Noctilucent clouds are generally believed to consist of ice coated extra-terrestrial dust particles which scatter incoming sunlight (Hesstvedt, 1961, 1962; Paton, 1964; Charlson, 1965). These dust particles are thought to grow to sufficient size to cause scattering by serving as nuclei for the condensation of terrestrial water vapor. The diameter of the particles becomes sufficiently large only if they fall through a region saturated with water vapor. The extremely cold temperatures observed in the mesopause in summer at high latitudes, as described above, provide for such a region between 80 and 90 km, if one extrapolates upward into the mesosphere the water vapor mixing ratios found at the tropopause. The rocket grenade observations thus demonstrate that the temperatures of 130 to 150°K, consistently observed at high latitudes in summer, are a necessary but not sufficient condition for the existence of noctilucent clouds.

b. Wavelike Temperature Structure in the Mesosphere

Very much in contrast to the summer soundings discussed above, winter soundings at Pt. Barrow show not only a relatively warm mesosphere as previously reported (Nordberg et al, 1965) but also a consistent pattern of periodically reversing vertical temperature gradients throughout the mesosphere. Three soundings were conducted in January and February 1965. Temperature profiles are shown in Figure 2. The difference between the steep and uniform lapse rates in the summer mesosphere and the oscillating lapse rates in the winter mesosphere is remarkable. The height between temperature maxima or minima in successive oscillations ranges generally around 15 km. The peak to peak magnitude of each temperature oscillation ranges from 30 to 40 C. By comparison, the summer temperatures (Figure 1) fluctuate by no more than 6C about the average lapse rate in the mesosphere. The phase of the wintertime oscillations obviously varies from day to day, as may be seen in Figure 2 a-c. Thus one might consider the temperature structure of the high latitude mesosphere as being disturbed by a vertically propagating wave with a peak to peak amplitude of 30 to 40C and a vertical wavelength of about 15 km. Unfortunately, the three soundings at Pt. Barrow are far too few and were separated too much in time to permit any reasonable deduction regarding the propagation velocity of these waves. However, considering the soundings conducted at other sites, one may recognize a pronounced latitudinal as well as seasonal pattern in their occurrence. In winter, the oscillations occur at all high latitude and mid-latitude sites (Pt. Barrow, Churchill, and Wallops Island) but become more pronounced and increase in amplitude poleward. Conversely, in summer the remarkably steep and uniform temperature lapse rates prevail generally at all sites but departures from this constant lapse rate become more frequent at lower latitudes. This is illustrated in Figures 3 and 4. During the winters 1962-1965, the waves were quite pronounced at Churchill (Figure 3 a through c) with wavelengths again ranging from 10 to 20 km but the average peak to peak amplitudes of about 30C are somewhat smaller than at Pt. Barrow (Figure 2).

Summer profiles at Churchill shown in Figure 3d and e for 1964 and 1965 do not exhibit any wave structure between 55 and 80 km and the deviation from an average lapse rate in these summer profiles is generally less than 7C. These results are in substantial agreement with earlier soundings made at Churchill during IGY (Stroud et al, 1961). During the winters 1962 through 1965 (Figure 4a, b, c), the situation at Wallops Island was qualitatively the same as at higher latitudes but the average peak to peak amplitude of the wintertime waves at Wallops was about 20 to 25C which is 5 to 10C smaller than at Churchill and up to 20C smaller than at Pt. Barrow. In summer at Wallops Island, there still is no evidencc of any organized wave structure (Figure 4d and e) but the largest deviations from the average summertime lapse rate, about 10C, occur here.

Thus, although the nature of these waves remains unknown, one can deduce from their seasonal and geographical variations that they are strongly suppressed in a typical high latitude summertime regime; namely, strong temperature lapse rate, very cold mesopause, and an inferred upward motion. The waves are most prominent in the typical high latitude winter regime: small temperature difference between mesopause and stratopause, relatively warm mesosphere and an inferred downward motion.

The winds in the winter mesosphere above Barrow, shown in Figure 5, have a westerly component as expected, but exhibit a stronger northerly component than might be expected from the polar vortex concept of the circulation. These winds result from the influence of the Aleutian anticyclone which displaces the vortex from the northern Pacific Ocean to an altitude of 70 km. The summer winds are generally light northeasterlies up to an altitude of about 70 km. In both summer and winter, the winds above 75 km result from more complex and less understood driving forces than the semi-permanent pressure patterns which govern the winds below 70 km.

In view of the above observations and in view of Hines' (1965) suggestion that reversible adiabatic heating may occur above 80 km due to the propagation of internal gravity waves, the possibility that such waves exist below 80 km was examined. It was believed to be worthwhile to search independently for the presence of internal gravity waves using temperature data rather than wind data. Such a search was based on results from the pitot-static tube soundings because they permit finer vertical resolution of the temperature structure. Three temperature profiles were obtained at Wallops Island from pitot-static tube soundings. They are shown in Figure 6. A wavelike temperature structure is again evident in the two December soundings, while the June sounding shows a relatively smooth lapse rate. A comparison of a grenade and a pitot-static tube sounding made within one-half hour of each other is also shown in Figure 6. The good agreement between the two soundings confirms that the observation of the wavelike structure is independent of the observation technique. For the 7 December 1963 pitot tube sounding, both pressure and density were measured simultaneously from 55 to 80 km. Using the ideal gas law the temperature was obtained and, along with percent density deviation from the 1962 U.S. Standard Atmosphere, was plotted vs. altitude in Figure 7. Temperature and density oscillations should be 180° out of phase for a steady state equilibrium situation and exactly in phase for oscillations produced by adiabatic compression.

In Figure 7 the temperature oscillations are seen to be 180° out of phase with the density oscillations indicating that the atmosphere is in hydrostatic equilibrium. One might expect a departure from hydrostatic equilibrium if internal gravity waves were producing the temperature oscillations; however, the precise relationship between the phases of density and temperature oscillations induced by internal gravity waves is not clear.

Thermally induced atmospheric tides could perhaps have produced the observed oscillations, and the mechanism by which this could be achieved has been delineated by Lindzen (1966). In any case, it does not appear that the temperature structure can be explained on the basis of radiative equilibrium alone, and it will probably be necessary to seek an explanation in terms of dynamic motions of the upper stratosphere and mesosphere.

c. A Stratospheric Warming and Its Associated Circulation Features

Temperature profiles resulting from the three Barrow soundings in January and February 1965 (Figure 2) indicate that a stratospheric warming occurred during the time between 27 January and 4 February between 40 and 50 km altitude. On 4 February, temperatures in that region were 20 to 25C higher than 8 days earlier or 4 days later. The winds did not change direction significantly from the first sounding to the second, but did decrease in speed (Figure 5). On 8 February, however, there was a complete change in the flow to light and variable winds up to 70 km.

The nature of these changes observed above Barrow is more clearly understood if one attempts to draw synoptic maps for the time period under consideration. Such maps, showing isobars and wind vectors at the 50 km level, are presented in Figures 8, 9 and 10. These maps were constructed with data resulting from nearly simultaneous grenade soundings at Pt. Barrow, Churchill, and Wallops Island and from Meteorological Rocket Network wind measurements including those made in the British Isles (Data Reports of the MRN, 1965). MRN winds and the winds and pressures computed from Barrow and Churchill grenade soundings were combined with the geostrophic assumption to produce these anslyses.

The cause for the stratospheric warming, evident in the Pt. Barrow temperature profiles, becomes apparent from these maps. In the first map, (Figure 8) the polar vortex dominated the circulation over the entire North American continent. The vortex was centered just to the south of Thule, Greenland, and a trough extended southwestward across the Hudson Bay and the northwestern portion of the United States. The edge of the Aleutian anticyclone can be seen to give Barrow a relatively high pressure for its latitude and a more northerly component of flow than might otherwise be expected.

In the second map (Figure 9), the low pressure system had filled somewhat and either split and/or migrated so that a vortex centered southwest of Churchill dominated the continental circulation. A trough extended southwestward from the center of the vortex across the continent to the Pacific Coast. Churchill had a southwesterly wind, a 180° reversal from the previous map. Winds to the west of the trough had become lighter as the Aleutian high pressure system spread eastward and northward. Barrow had a large pressure increase amounting to about 12 percent over the 8 day period. This ridging over the Alaskan Peninsula is believed to be responsible for the warming in the 40 to 50 km region over Barrow. The circulation was such that the flow at Barrow on 27 January originated from within the polar vortex, whereas on 4 February Barrow was under the influence of the warmer anticyclone air mass. The rocket data do not permit one to determine whether the trough seen in each of the two maps is actually the same. If it is the same trough, it moved at an average speed of less than 5 km per hour for the time which had elapsed between soundings. Such movement is not unusual for planetary (Rossby) waves.

The 8 February map (Figure 10) shows the vortex restored to its polar position and centered east of Greenland and north of the Scandinavian Peninsula although the exact position is speculative because of insufficient data. The pressure gradient over North America had weakened considerably by 8 February, resulting in lighter winds at all points on the map. The Aleutian anticyclone had retreated from Alaska leaving Barrow under the influence of the vortex once again. These changes were reflected in the Barrow temperature which was 20 to 25C colder on 8 February than it was four days earlier. Two shallow troughs appear on the 8 February analysis, but their relationship to the troughs on the previous maps is not clear.

It appears that the polar vortex and the Aleutian anticyclone are permanent features of the northern hemisphere winter circulation at 50 km. The vortex generally dominates the winter circulation in the lower mesosphere over the North Atlantic and the anticyclone controls the flow over the North Pacific and Alaska. If it were not for the presence of the anticyclone, Barrow would have a prevailing westerly wind. Instead the anticyclone introduces an easterly or northerly component into the winds observed over Barrow at 50 km (Figure 5).

d. Diurnal Temperature Variations

Studies of diurnal temperature variations were conducted by Beyers and Miers (1965) at White Sands with rocket sondes carrying thermistors as sensing elements. These studies show a maximum temperature at the stratopause near local noon and a minimum temperature near local midnight. Data from pitot tube probes and grenade experiments conducted primarily at Wallops Island and in the southern hemisphere (Table I) show higher stratopause temperatures near local midnight than near local noon. In the southern hemisphere four pairs of pitot tube soundings were conducted from sites near the equator and at 60S. In each pair one sounding was launched near local midnight and the other near local noon. Day-night temperature differences for each pair of soundings are shown as a function of height in Figure 11. At 45 km, the nighttime temperatures are 8 to 15C warmer than the daytime temperatures, and at 50 km they are 1 to 15C warmer.

The observed noon-midnight temperature differences (ΔT) change sign several times in the altitude range from 40-100 km indicating that the phase of the diurnal temperature oscillation varies markedly with altitude. The magnitude of ΔT increases with altitude implying that the amplitude of the diurnal temperature variation becomes greater at higher altitudes. These results are in qualitative agreement with the theoretical model of the diurnal tidal variation developed by Lindzen (1966). However, such phase changes were not observed in the studies reported by Beyers and Miers (1965).

Four grenade soundings were conducted during a 17 hour period from Wallops Island in early November 1964. A time-temperature variation cross section was made from the results of these soundings in the following way: temperature profiles of the four soundings were averaged to produce a mean temperature profile for the time period; the average temperature was subtracted from each individual temperature profile and the resulting differences in temperature (deviations from the mean temperature) were analyzed (Figure 12). The results indicate several interesting features: the most outstanding is the warming which occurs from 2000 to 2400 hours in the region between 30 and 60 km altitude and the abrupt cooling which follows in the same altitude region from approximately 0100 to 0500 hours. The total range of the temperature variation is a maximum of about 17C at 42 km and 15C at 52 km. These variations which occur at the level of maximum ozone heating, obviously do not follow the solar input cycle in this case. Instead, the maximum temperature occurs at midnight and the minimum near 0500. More intense variations, centered at about 1800 and 0500 hours, respectively, are observed in the 70 to 80 km altitude region. The total temperature variation at 75 km is 20C, while the maximum temperature occurs near local sunset and a minimum temperature near local sunrise.

The discrepancies between diurnal temperature variations described above and the thermistor rocket sonde results reported by Byers and Miers (1965) have led us to further investigation. Since the thermistor rocket sonde and grenade-pitot tube sounding diurnal studies were not conducted simultaneously, it is difficult to decide whether the obvious discrepancy in the results is due to geographic variations or is inherent in the techniques. To this end temperature measurements from eight grenade soundings were compared to temperature measurements from thermistor rocket sondes (Arcasonde 1A) each of which accompanied a grenade sounding within an hour. Six of the soundings were launched in daylight and two were launched at night. All were made at Churchill during 1964 and 1965. Typical results of these comparisons are shown in Figure 13. The Arcasonde soundings agree best with grenade temperatures at 40 km. Above 40 km the daytime Arcasonde profiles consistently indicate higher temperatures than the grenade data and the differences increase with increasing altitude. At nighttime the temperature profiles are in much better agreement and no substantial differences are observed up to the stratopause.

In Figure 14, the average temperature differences as a function of altitude for the 6 day and 2 night sounding comparisons are plotted. The nighttime curve shows good agreement from 40 to 60 km and the maximum average difference is only 2C at 50 km. The best agreement for the daytime situation is at 40 km where the average temperature difference is 4C while at 60 km, it reaches a maximum of 21C.

There is a strong suggestion that the observed discrepancy between the two techniques is caused by solar radiation affecting the Arcasonde thermistors used in this comparison. Finger and Woolf (1966) reached similar conclusions in analyzing results from a series of 14 Hasp and 2 Arcasonde 1A soundings which were launched during a 39 hour period in September 1965 at Wallops Island and showed rapid changes in the observed temperature profile near sunset and sunrise (approximately 6C from 40 to 50 km) as well as a discrepancy between the measured temperature and the temperature as computed from the winds. Thus, there is considerable doubt that the disagreement between the diurnal temperature variations observed with rocket sonde thermistors and the pitot tube-grenade techniques is entirely due to geographic variations.

CONCLUSIONS

A temperature profile measured at Barrow in August 1965 during a noctilucent cloud display was not significantly different from a profile observed in the absence of noctilucent clouds almost 48 hours later. These data, combined with similar results from Sweden (1963) indicate that mesopause temperatures below 150 K are a necessary but not sufficient condition for the existence of noctilucent clouds.

Wavelike structures are prominent in the mesosphere temperature profiles at high latitude sites but exist only in wintertime and their amplitude of oscillation increases with increasing latitude. Conversely, these variations appear to be completely suppressed under the typical high latitude summertime regime which is characterized by very low mesopause temperatures, a steep uniform temperature lapse rate, and an inferred upward motion.

A stratospheric warming observed over Barrow in mid-winter 1965 can be explained in terms of the circulation features at 50 km altitude. A southward migration of the polar vortex combined with the building of the Aleutian anticyclone over the Alaskan Peninsula was seen to bring warmer air to Barrow during an eight day period, and reestablishment of the polar position of the vortex restored the colder flow to Barrow 4 days later.

The amplitude of the diurnal temperature variation in the upper stratosphere at the equator and at higher latitudes in the northern and southern hemisphere totals 8 to 15C. Contrary to rocket sonde thermistor results, the phase of this variation is such that higher temperatures are found near local midnight than near local noon.

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FIGURE CAPTIONS

Figure 1 - Summer 1965 temperature profiles above Barrow (71N) measured with the rocket grenade technique.

Figure 2 - Winter 1965 temperature profiles above Barrow measured with the rocket grenade technique. Wavelengths of oscillations are indicated.

Figure 3 - Summary of winter and summer temperature profiles for the years 1962 through 1965 at Churchill (59N) measured with the rocket grenade technique.

Figure 4 - Summary of winter and summer temperature profiles for the years 1962 through 1965 at Wallops Island (38N) measured with the rocket grenade technique.

Figure 5 - Winter and summer wind profiles above Barrow measured with the rocket grenade technique.

Figure 6 - Temperature profiles above Wallops Island measured with the pitot-tube technique and the grenade technique.

Figure 7 - Temperature and density profiles obtained from the pitot-tube technique at Wallops Island. The density profile was measured directly and plotted as percent deviation from the 1962 Standard Atmosphere; the temperature profile was determined from the density and the directly measured pressure profiles.

Figure 8 - Pressure pattern at 50 km altitude on 27 January 1965 as determined from rocket grenade technique measurements and MRN winds.

Figure 9 - Pressure pattern at 50 km altitude on 4 February 1965.

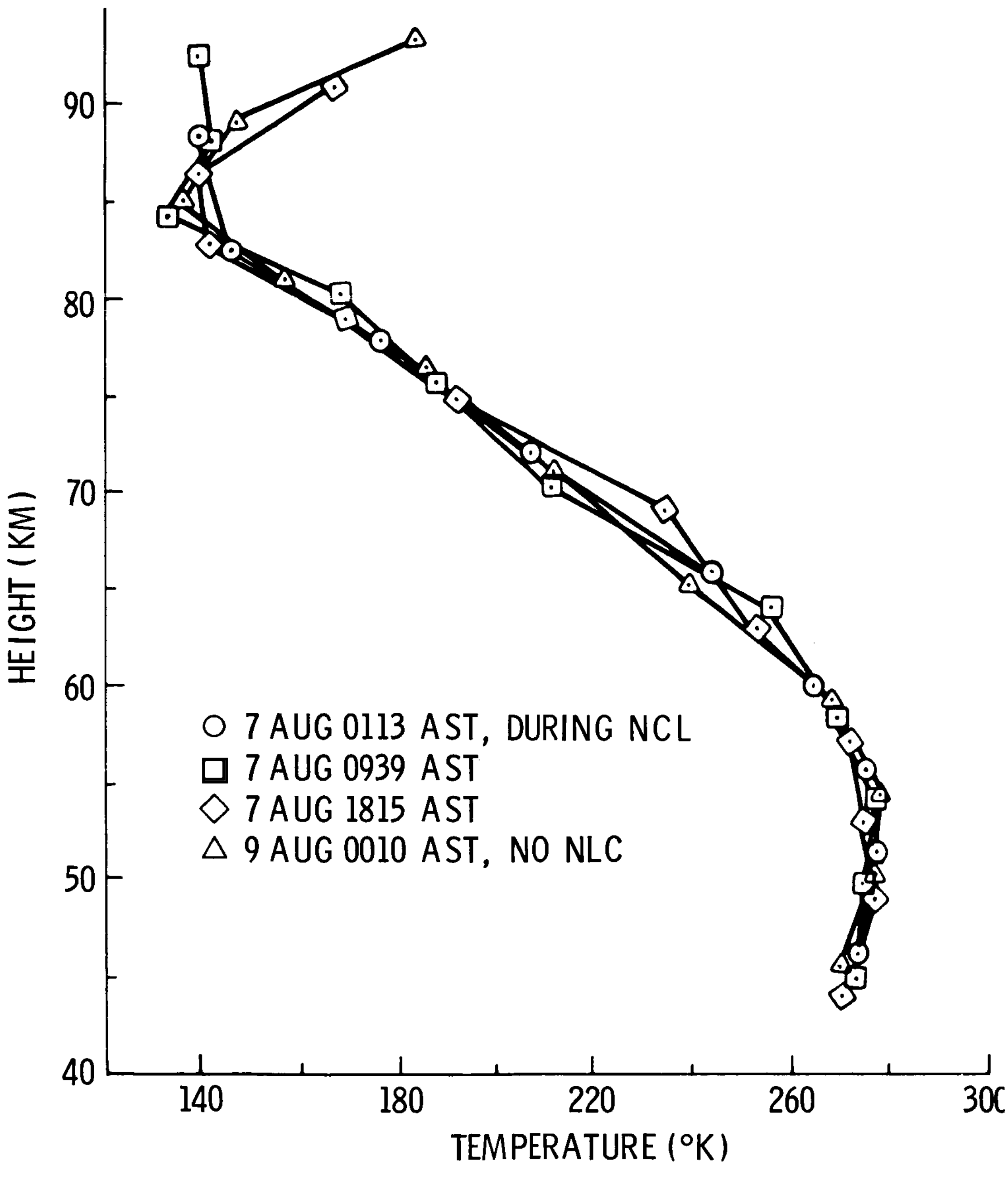
Figure 10 - Pressure pattern at 50 km altitude on 8 February 1965.

Figure 11 - Daytime temperature minus nighttime temperature (ΔT) vs. altitude for four pairs of day-night pitot tube soundings at the equator (ship launched), Ascension Island (8S) and 60S (ship launched).

Figure 12 - Temperature variation (differences from mean temperature) with altitude for 5-6 November 1964 above Wallops Island as determined from four rocket grenade measurements.

Figure 13 - Typical Arcasonde-grenade temperature profile comparisons for four days at Churchill during 1964 and 1965.

Figure 14 - Average temperature differences (Arcas temperature minus the grenade temperature) vs. altitude. Curves are based on averages of six day and two night comparisons conducted at Churchill during 1964 and 1965.



90
80
70
60
50
40
HEIGHT (KM)
140
180
220
260
300
TEMPERATURE (°K)
○ 7 AUG 0113 AST, DURING NCL
□ 7 AUG 0939 AST
◇ 7 AUG 1815 AST
△ 9 AUG 0010 AST, NO NLC

Figure 1

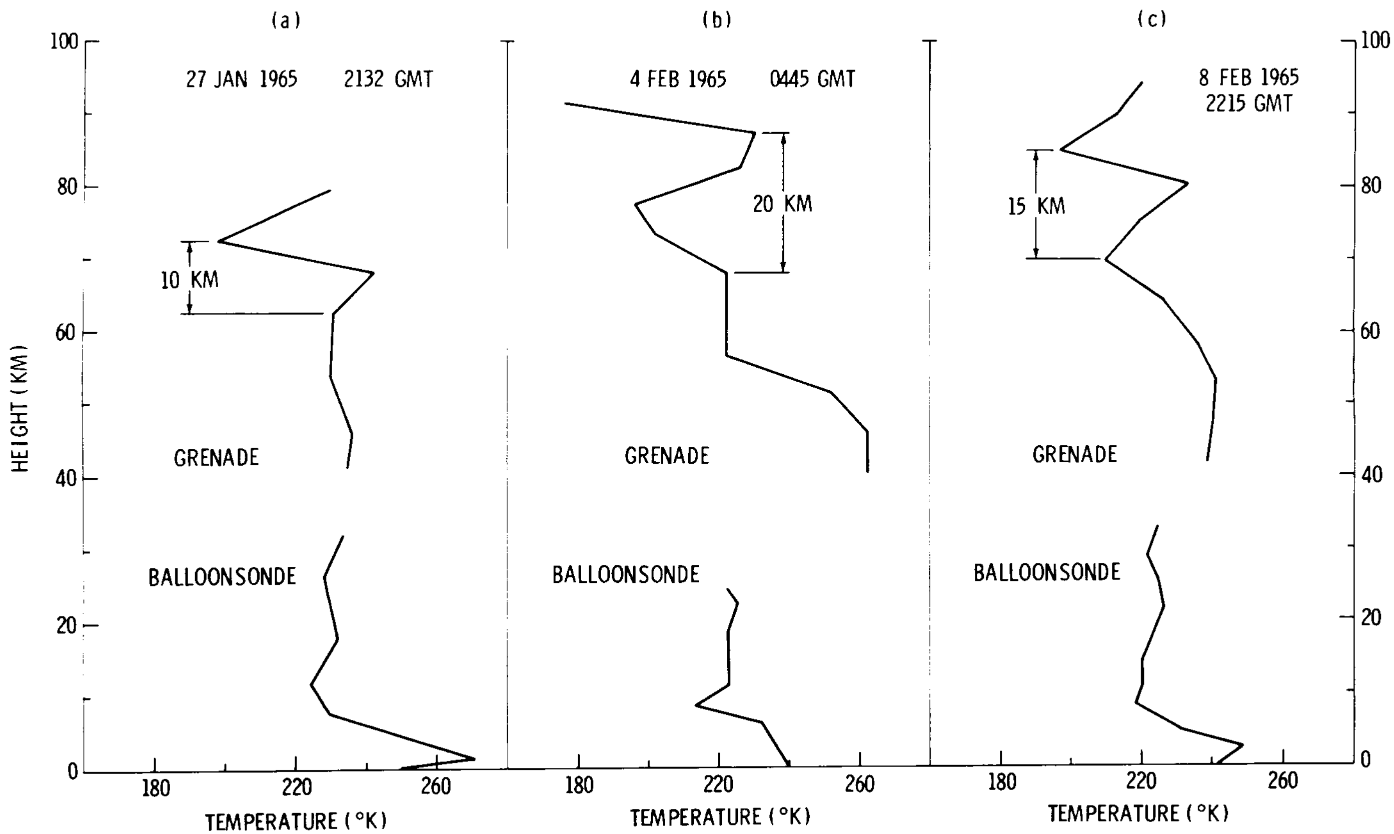

(a)
(b)
(c)
27 JAN 1965 2132 GMT
4 FEB 1965 0445 GMT
8 FEB 1965
2215 GMT
10 KM
20 KM
15 KM
GRENADE
GRENADE
GRENADE
BALLOONSONDE
BALLOONSONDE
BALLOONSONDE
HEIGHT (KM)
100
80
60
40
20
0
180
220
260
TEMPERATURE (°K)
TEMPERATURE (°K)
TEMPERATURE (°K)

Figure 2

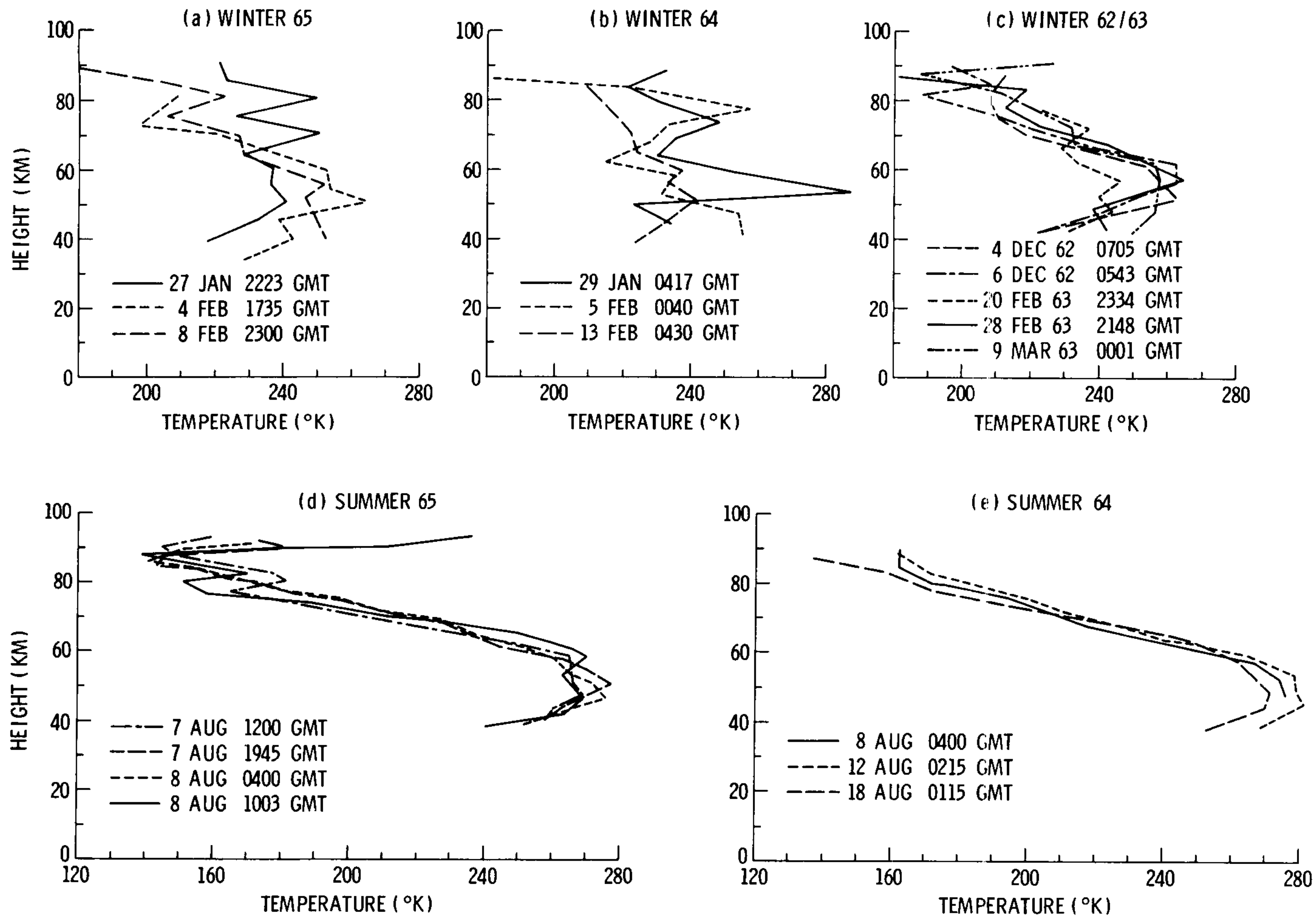

(a) WINTER 65
HEIGHT (KM)
TEMPERATURE (°K)
27 JAN 2223 GMT
4 FEB 1735 GMT
8 FEB 2300 GMT
(b) WINTER 64
TEMPERATURE (°K)
29 JAN 0417 GMT
5 FEB 0040 GMT
13 FEB 0430 GMT
(c) WINTER 62/63
TEMPERATURE (°K)
4 DEC 62 0705 GMT
6 DEC 62 0543 GMT
20 FEB 63 2334 GMT
28 FEB 63 2148 GMT
9 MAR 63 0001 GMT
(d) SUMMER 65
HEIGHT (KM)
TEMPERATURE (°K)
7 AUG 1200 GMT
7 AUG 1945 GMT
8 AUG 0400 GMT
8 AUG 1003 GMT
(e) SUMMER 64
TEMPERATURE (°K)
8 AUG 0400 GMT
12 AUG 0215 GMT
18 AUG 0115 GMT

Figure 3

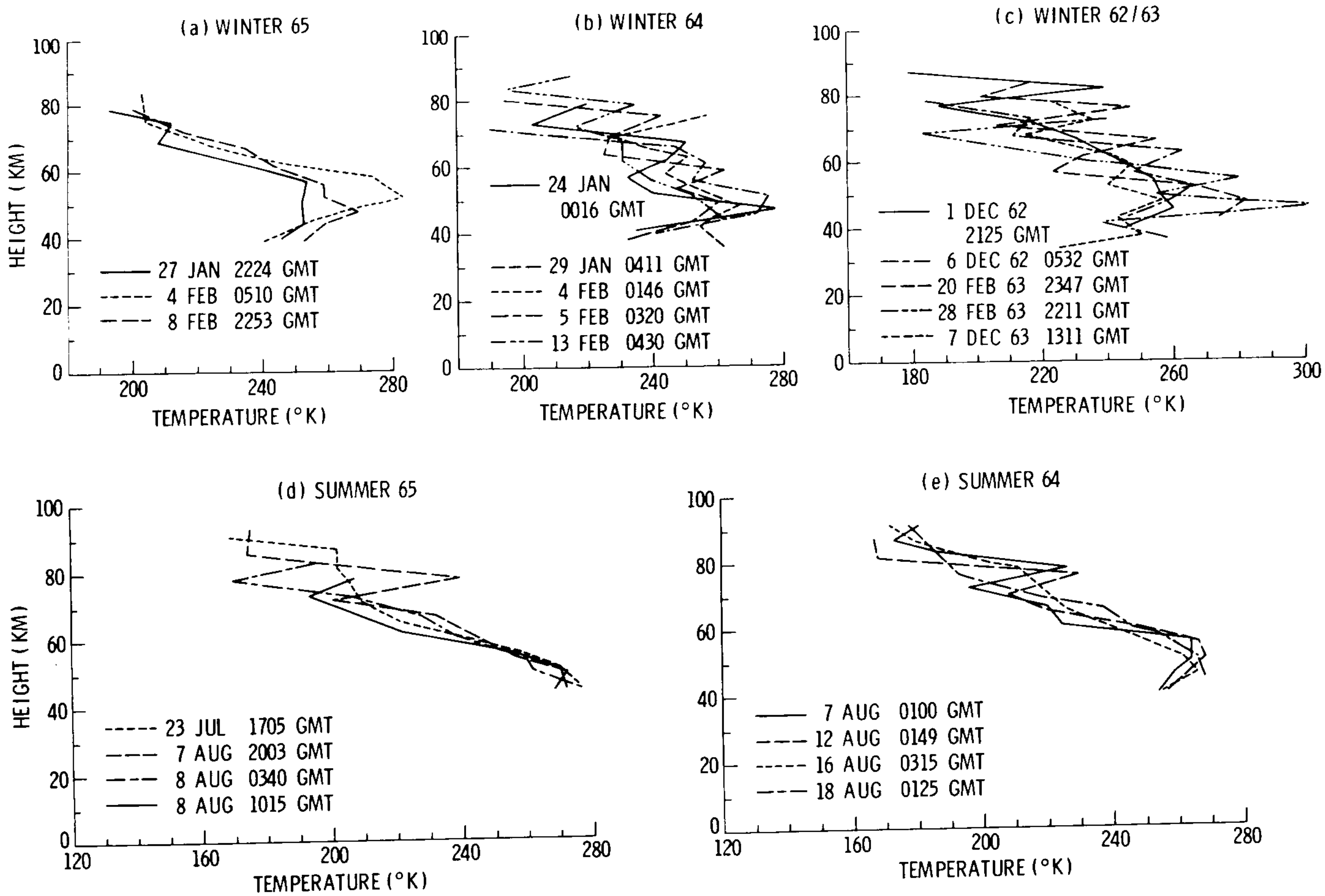

(a) WINTER 65
HEIGHT (KM)
TEMPERATURE (°K)
27 JAN 2224 GMT
4 FEB 0510 GMT
8 FEB 2253 GMT
(b) WINTER 64
TEMPERATURE (°K)
24 JAN 0016 GMT
29 JAN 0411 GMT
4 FEB 0146 GMT
5 FEB 0320 GMT
13 FEB 0430 GMT
(c) WINTER 62/63
TEMPERATURE (°K)
1 DEC 62 2125 GMT
6 DEC 62 0532 GMT
20 FEB 63 2347 GMT
28 FEB 63 2211 GMT
7 DEC 63 1311 GMT
(d) SUMMER 65
HEIGHT (KM)
TEMPERATURE (°K)
23 JUL 1705 GMT
7 AUG 2003 GMT
8 AUG 0340 GMT
8 AUG 1015 GMT
(e) SUMMER 64
TEMPERATURE (°K)
7 AUG 0100 GMT
12 AUG 0149 GMT
16 AUG 0315 GMT
18 AUG 0125 GMT

Figure 4

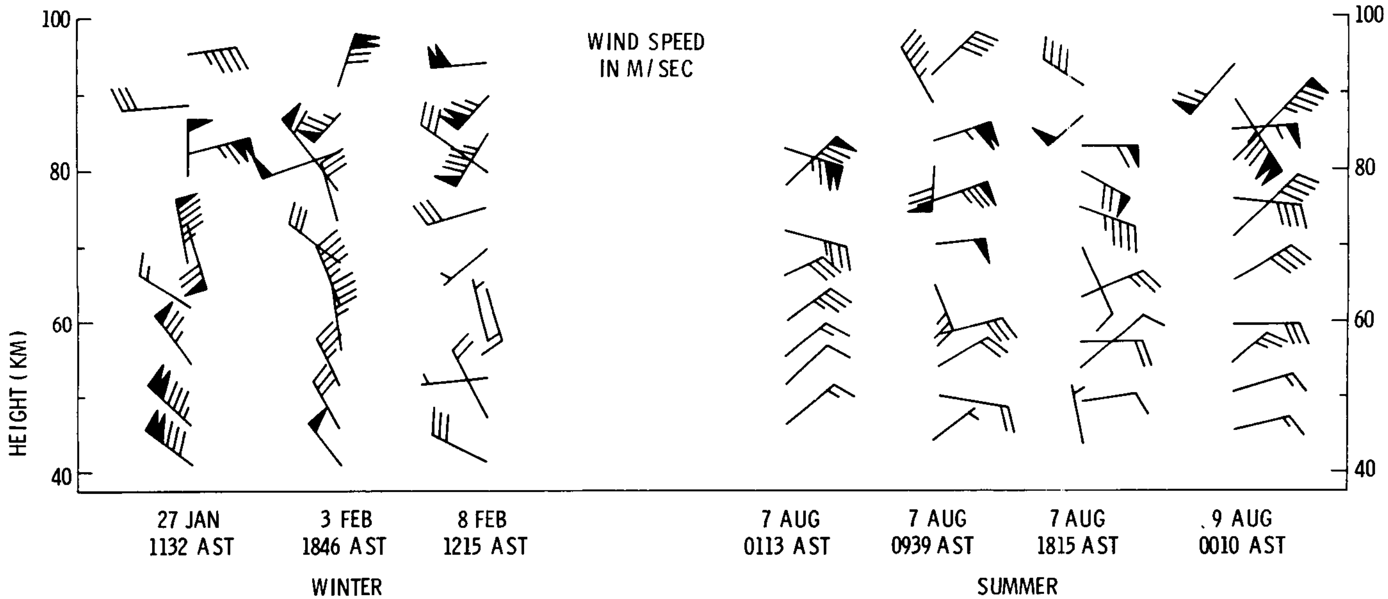
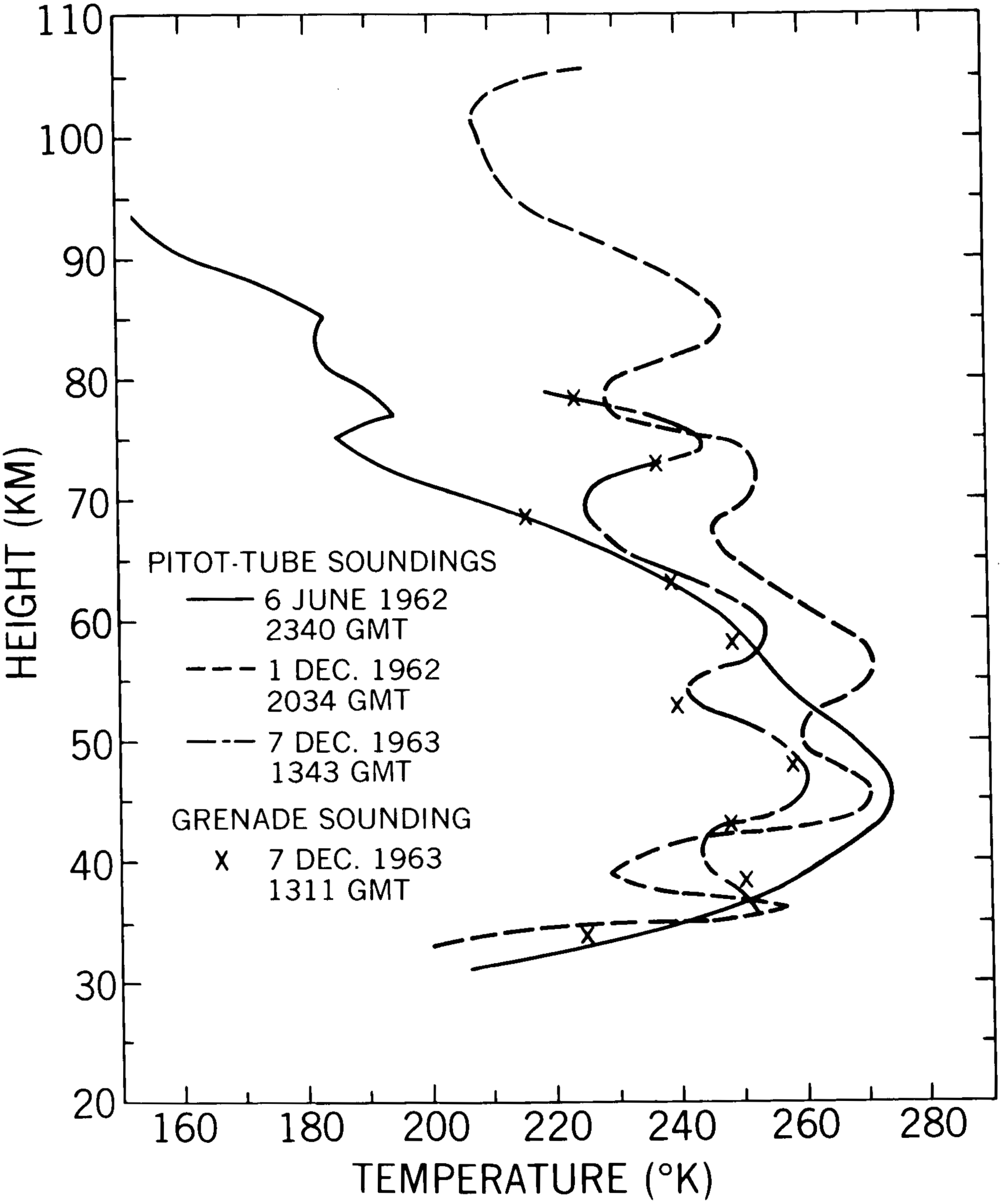

WIND SPEED
IN M/SEC
HEIGHT (KM)
100
80
60
40
27 JAN
1132 AST
3 FEB
1846 AST
8 FEB
1215 AST
7 AUG
0113 AST
7 AUG
0939 AST
7 AUG
1815 AST
9 AUG
0010 AST
WINTER
SUMMER

Figure 5



110
100
90
80
70
60
50
40
30
20
HEIGHT (KM)
PITOT-TUBE SOUNDINGS
6 JUNE 1962
2340 GMT
1 DEC. 1962
2034 GMT
7 DEC. 1963
1343 GMT
GRENADE SOUNDING
X 7 DEC. 1963
1311 GMT
160
180
200
220
240
260
280
TEMPERATURE (°K)

Figure 6

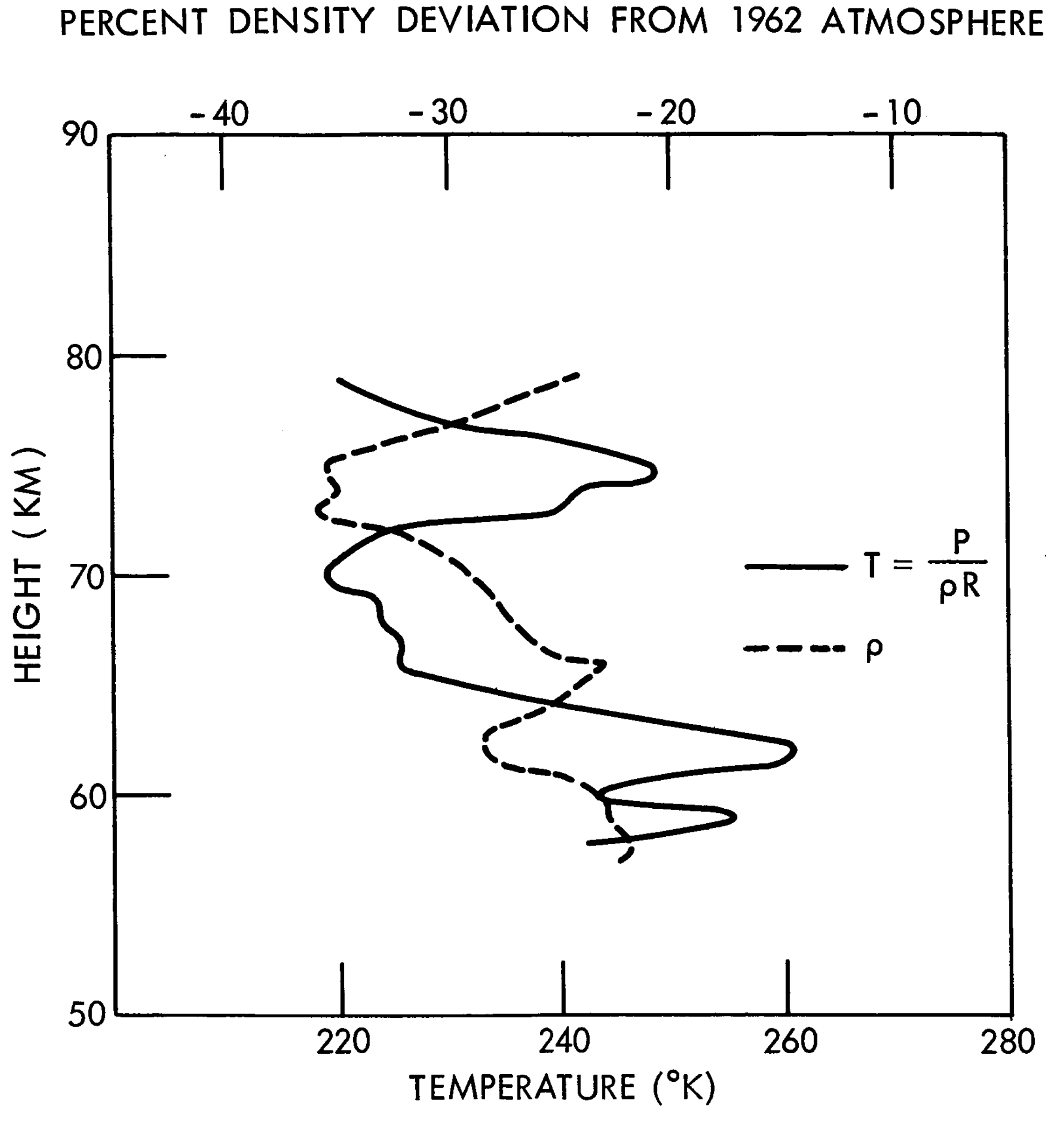

PERCENT DENSITY DEVIATION FROM 1962 ATMOSPHERE
-40
-30
-20
-10
90
80
70
60
50
HEIGHT (KM)
$T = \frac{P}{\rho R}$
ρ
220
240
260
280
TEMPERATURE (°K)

Figure 7

50 KM
27 JAN 65
ISOBARS IN MB.

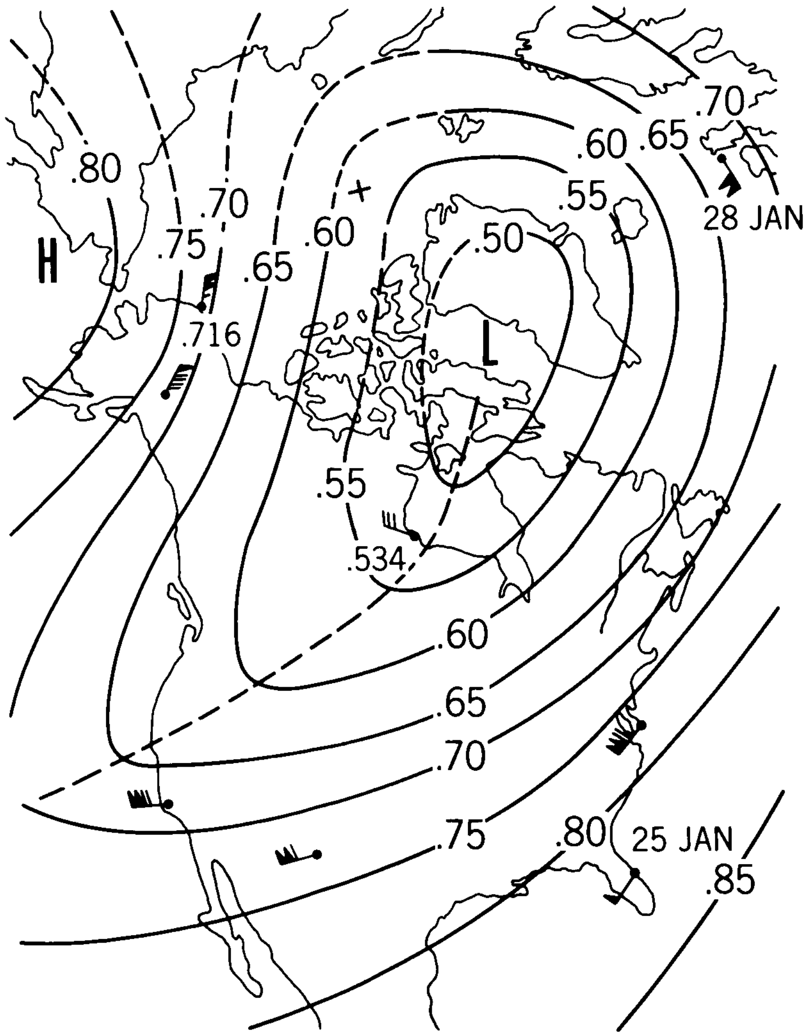
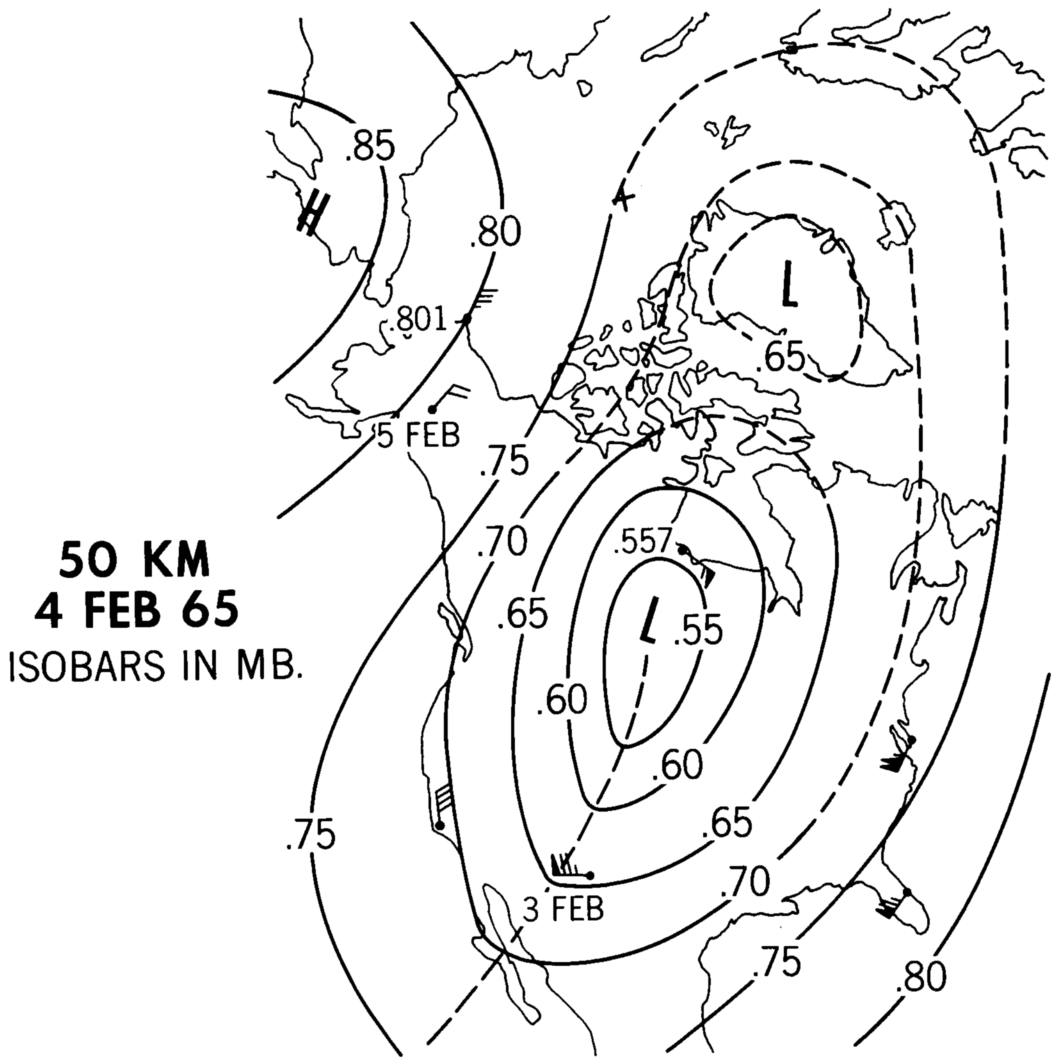


Figure 8



50 KM
4 FEB 65
ISOBARS IN MB.
.85
.80
.801
5 FEB
.75
.70
.65
.60
.557
L
.55
.60
.65
.70
3 FEB
.75
.80
L
.65
.75

Figure 9

50 KM
8 FEB 65
ISOBARS IN MB.

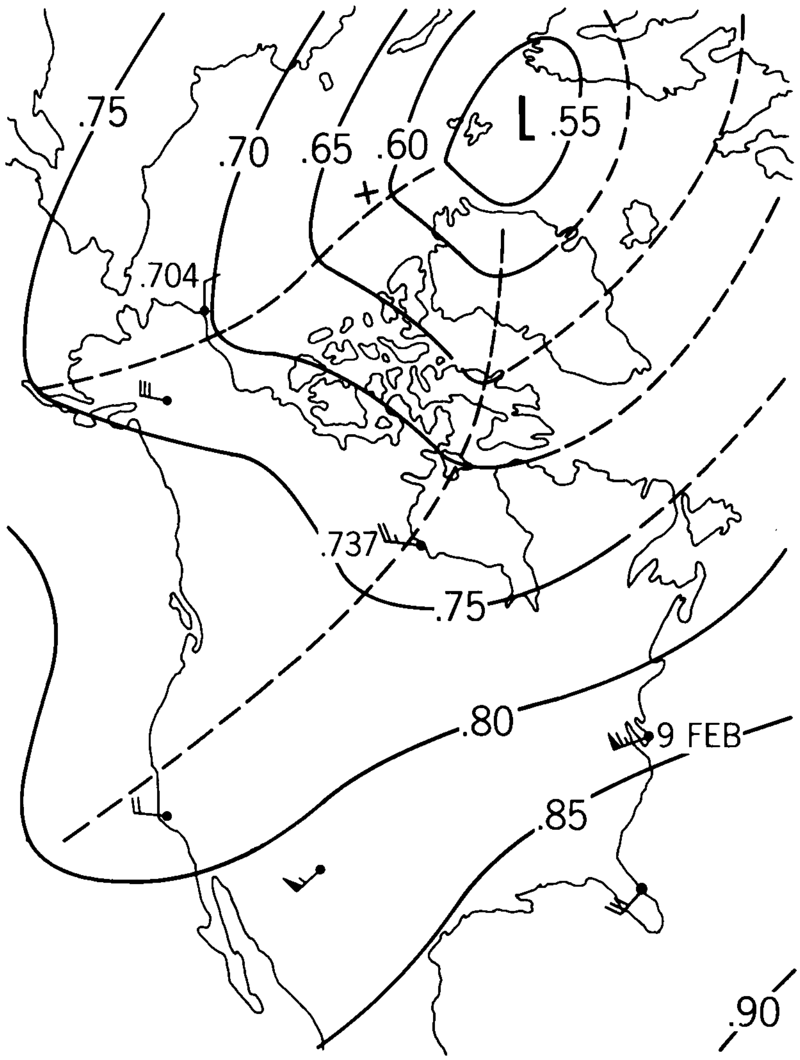


Figure 10

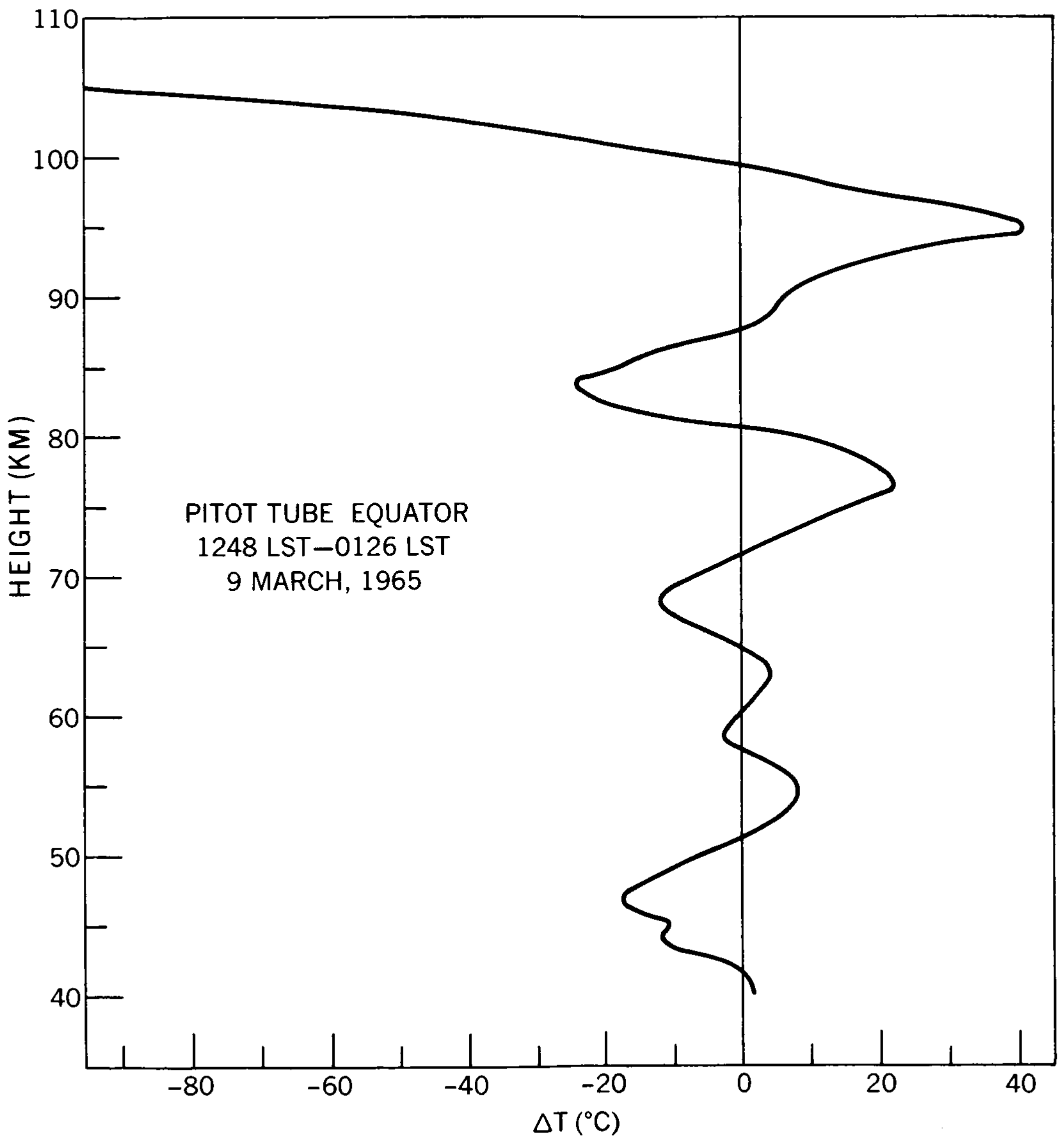
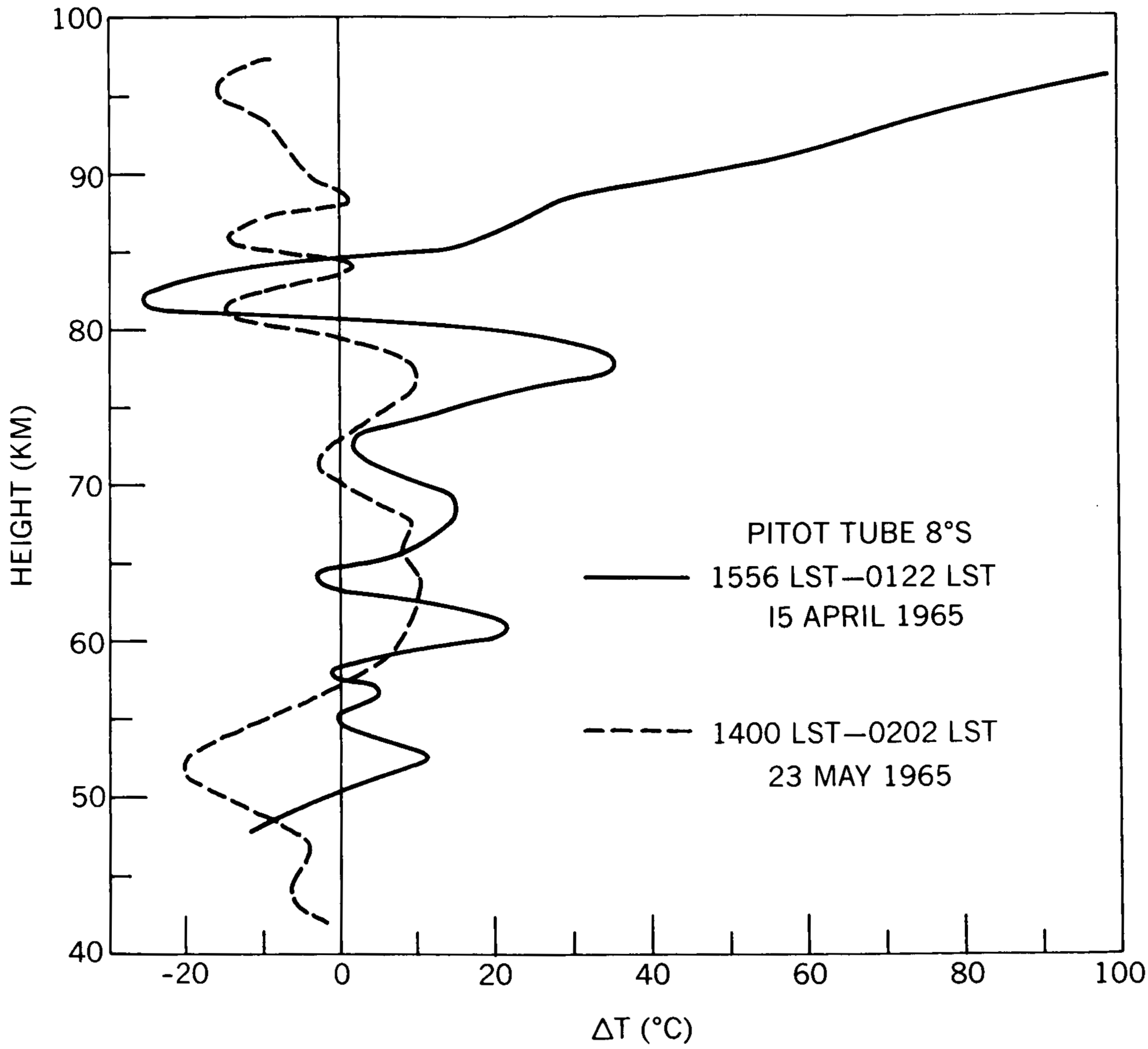
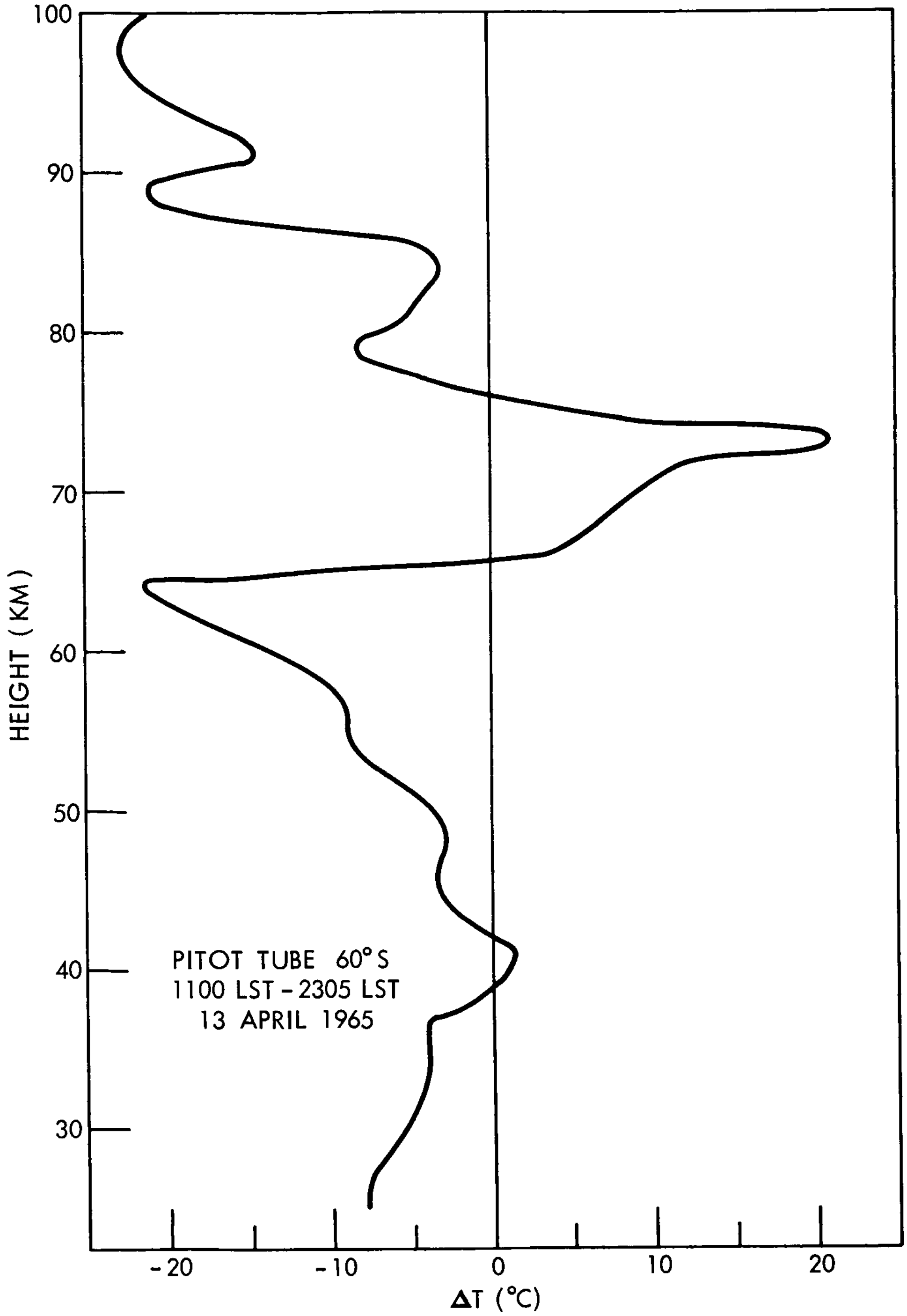

110
100
90
80
70
60
50
40
HEIGHT (KM)
PITOT TUBE EQUATOR
1248 LST—0126 LST
9 MARCH, 1965
-80
-60
-40
-20
0
20
40
ΔT (°C)

Figure 11a



100
90
80
70
60
50
40
HEIGHT (KM)
-20
0
20
40
60
80
100
ΔT (°C)
PITOT TUBE 8°S
1556 LST—0122 LST
15 APRIL 1965
1400 LST—0202 LST
23 MAY 1965

Figure 11b



100
90
80
70
60
50
40
30
HEIGHT (KM)
PITOT TUBE 60° S
1100 LST - 2305 LST
13 APRIL 1965
- 20
- 10
0
10
20
ΔT (°C)

Figure 11c

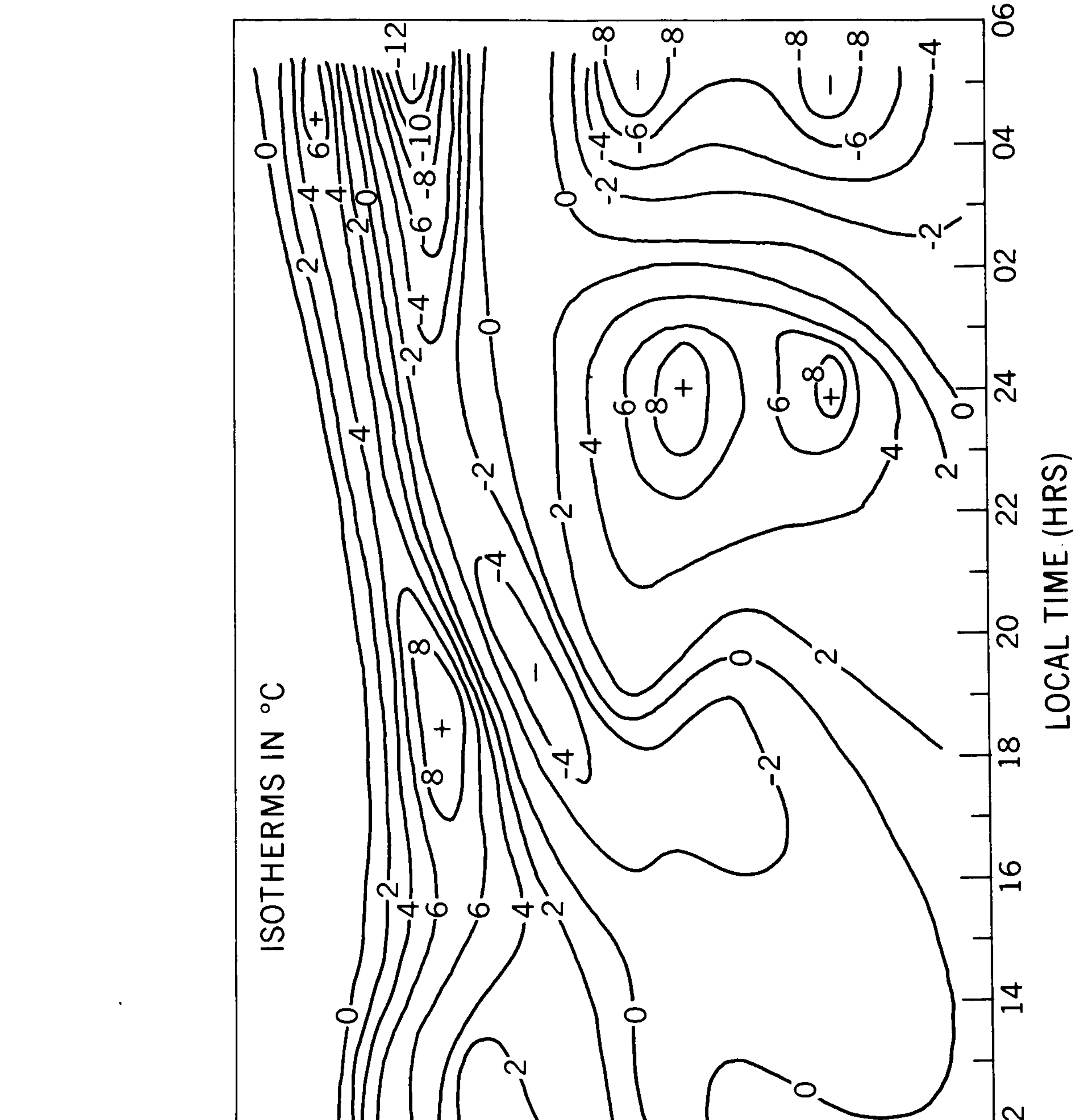

ISOTHERMS IN °C
HEIGHT (KM)
LOCAL TIME (HRS)
90
80
70
60
50
40
30
12
14
16
18
20
22
24
02
04
06

Figure 12

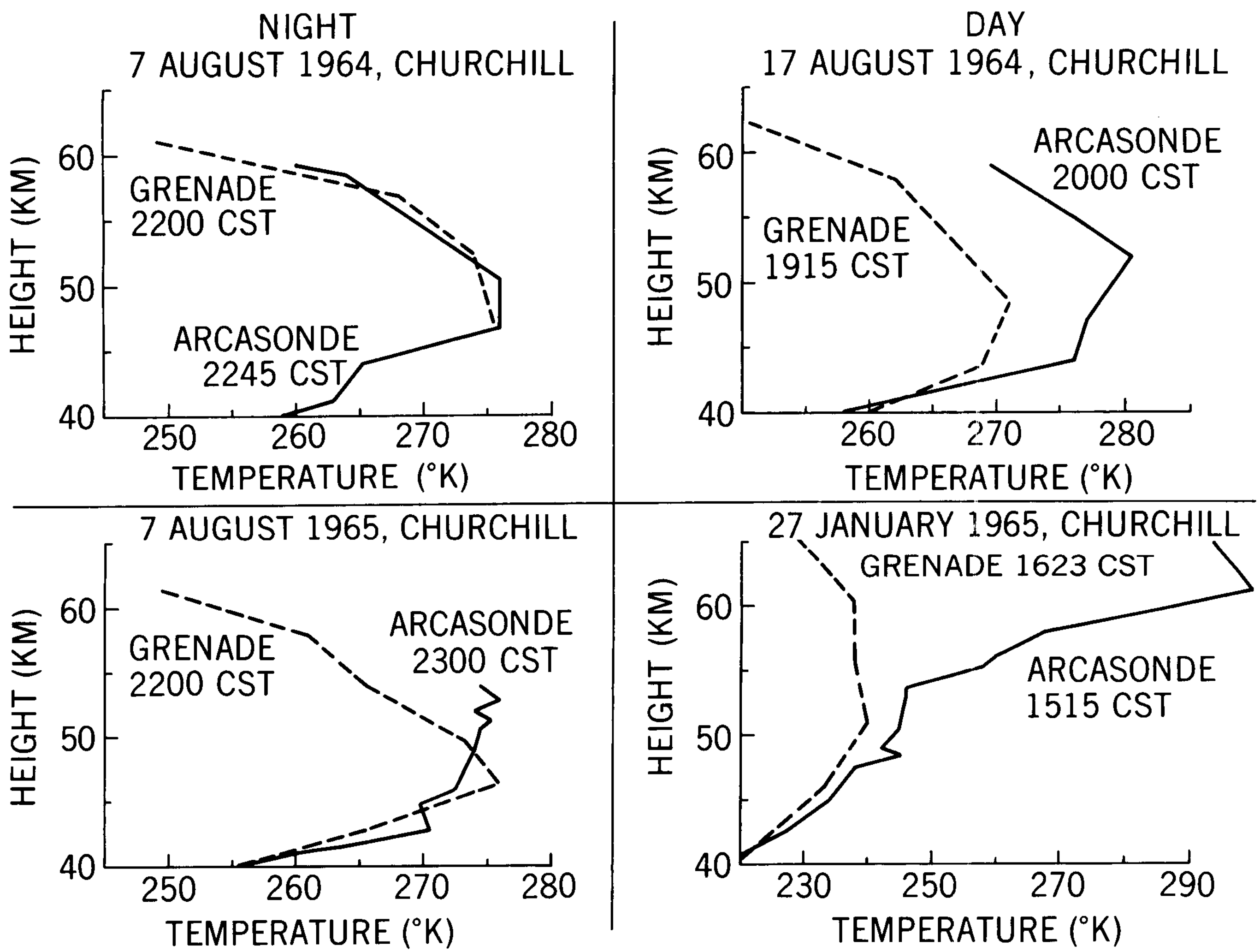

NIGHT
7 AUGUST 1964, CHURCHILL
HEIGHT (KM)
60
50
40
GRENADE
2200 CST
ARCASONDE
2245 CST
250
260
270
280
TEMPERATURE (°K)
DAY
17 AUGUST 1964, CHURCHILL
HEIGHT (KM)
60
50
40
GRENADE
1915 CST
ARCASONDE
2000 CST
260
270
280
TEMPERATURE (°K)
7 AUGUST 1965, CHURCHILL
HEIGHT (KM)
60
50
40
GRENADE
2200 CST
ARCASONDE
2300 CST
250
260
270
280
TEMPERATURE (°K)
27 JANUARY 1965, CHURCHILL
GRENADE 1623 CST
HEIGHT (KM)
60
50
40
ARCASONDE
1515 CST
230
250
270
290
TEMPERATURE (°K)

Figure 13

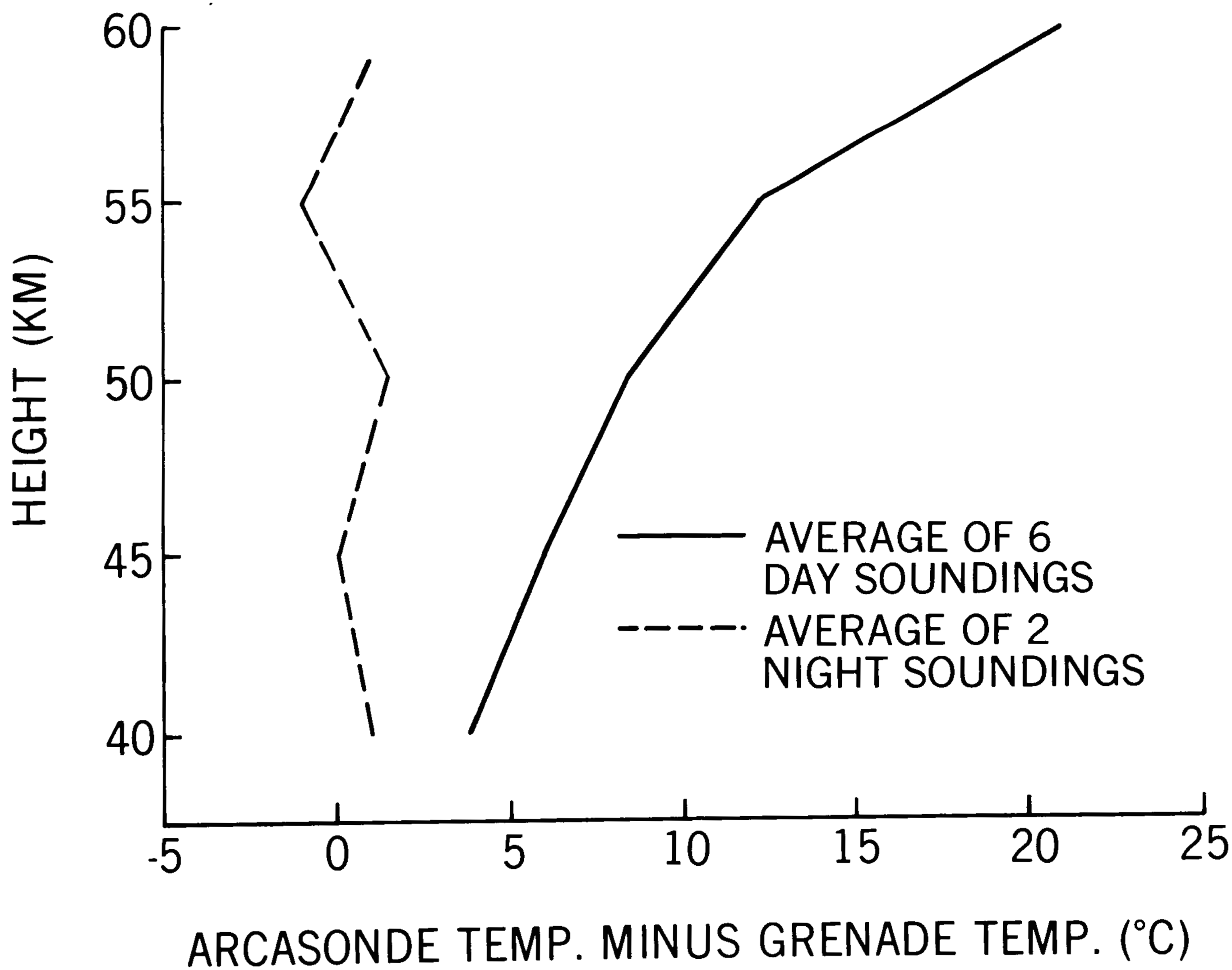

HEIGHT (KM)
60
55
50
45
40
-5
0
5
10
15
20
25
ARCASONDE TEMP. MINUS GRENADE TEMP. (°C)
AVERAGE OF 6
DAY SOUNDINGS
AVERAGE OF 2
NIGHT SOUNDINGS

Figure 14