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RADIATION INFLUENCES ON A WHITE-COATED THERMISTOR TEMPERATURE SENSOR IN A RADIOSONDE

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ABSTRACT

An assessment of the spurious temperature variation of conventional Australian radio-sonde is made using heat transfer theory. The results are applied to the observed diurnal and semi-diurnal variation of temperatures over Melbourne between 0 and 30 km.

INTRODUCTION

One of the major sources of error in the direct observational determination of temperature in the atmosphere is the effect of solar and terrestrial radiation on the temperature measuring element. As indirect sounding techniques appear to be capable of determining point temperatures in the troposphere and lower stratosphere with errors in general between 1°C and 3°C (Smith, 1969), an up-to-date assessment of the radiation error in conventional radio-sondes is required for comparison. Aspects of such an assessment for the higher levels have already appeared in the literature (Lindzen, 1967; Beyers and Miers, 1967); these cast some doubt on the accuracy of current techniques of instrumental analysis of errors.

The diurnal nature of the radiation error and the difficulties involved in its adequate estimation make the observational determination of tidal oscillations particularly prone to error. However, Harris *et al* (1962), by using a linear form of equations of motion for frictionless flow, used wind components to obtain estimates of the tidal oscillations of pressure independent of temperature measurements. As these were in general agreement with estimates of the effect on temperature of the direct solar heating of the ozone layer (Pressman, 1955), the difference between these determinations and those based on direct temperature measurement were inferred to be due entirely to the diurnal error in radio-sonde temperature observations. No direct estimate of instrumental error due to radiation was made for comparison. Also, in order to obtain sufficiently frequent observation for adequate sampling, it was necessary to combine data for two different periods each of approximately one year. During one period six hourly observations were made at one set of scheduled times; during the second period the scheduled times were displaced by three hours.

More recently Tucker (1971) has analysed a set of three-hourly soundings extending up to 30 km over a 28-day period in September and October 1966. Following Harris *et al* (1962) he has obtained independent wind and temperature based estimates of both diurnal and semi-diurnal variations of pressure (and temperature). Owing to the importance of comparing instrument analysis estimates of radiation error with inferred errors from independent wind and temperature tidal determinations, a complementary study was made of the spurious temperature variation due to radiation on the thermistor used for these observations. The results are reported below.

After making a quantitative assessment of the various physical phenomena involved in the heat balance of the ascending thermistor, the effects of radiation on the temperature recorded by the instrument were estimated as a function of height. Corrections due to solar radiation were then applied to the average temperature for the 28 days of the observational experiment at each observing time of the day and at each level. The eight corrected observations for each level were re-analysed to obtain the corrected amplitude and phase of the diurnal and semi-diurnal wave of temperatures.

An alternative method of obtaining the diurnal and semi-diurnal temperature waves is to analyse each 24-hour and 12-hour period independently, average the individual cosine and sine harmonic coefficients, and obtain the amplitude and phase for the whole period from these mean harmonic coefficients. The amplitudes for the diurnal and semi-diurnal temperature waves calculated by each method are shown in Fig 1. Because the results are similar (phases were also compared), it was considered unnecessary to compute the radiation correction for each individual observation.

HEAT TRANSFER EQUATION

The thermistor (temperature T) is not generally in thermal equilibrium with the immediate environment (temperature T_e). Solar radiation reaches the thermistor directly, by scattering from the atmosphere, and by reflection from ground, clouds and radiosonde instrument. Long-wave radiation is emitted by the environment, the thermistor and other parts of the radiosonde. Conduction of heat along the leads supporting the thermistor is considered negligible.

For unit length of the thermistor, the heat transfer equation is

$$\begin{aligned} C\frac{dT}{dt} &= H + Q \\ &= q(T_e - T) + Q_s + Q_L \qquad \ldots .1 \end{aligned}$$

where C is the heat capacity per unit length, $\frac{dT}{dt}$ is the time rate of change of temperature, H is the net rate of heat transfer by forced convection, and Q is the net rate of heat transfer by radiation. H is expressed in terms of the heat transfer coefficient q and the difference between environment and thermistor temperatures. Q is effectively the sum of the net rate of heat transferred by short-wave radiation Q_s, and by long-wave radiation Q_L.

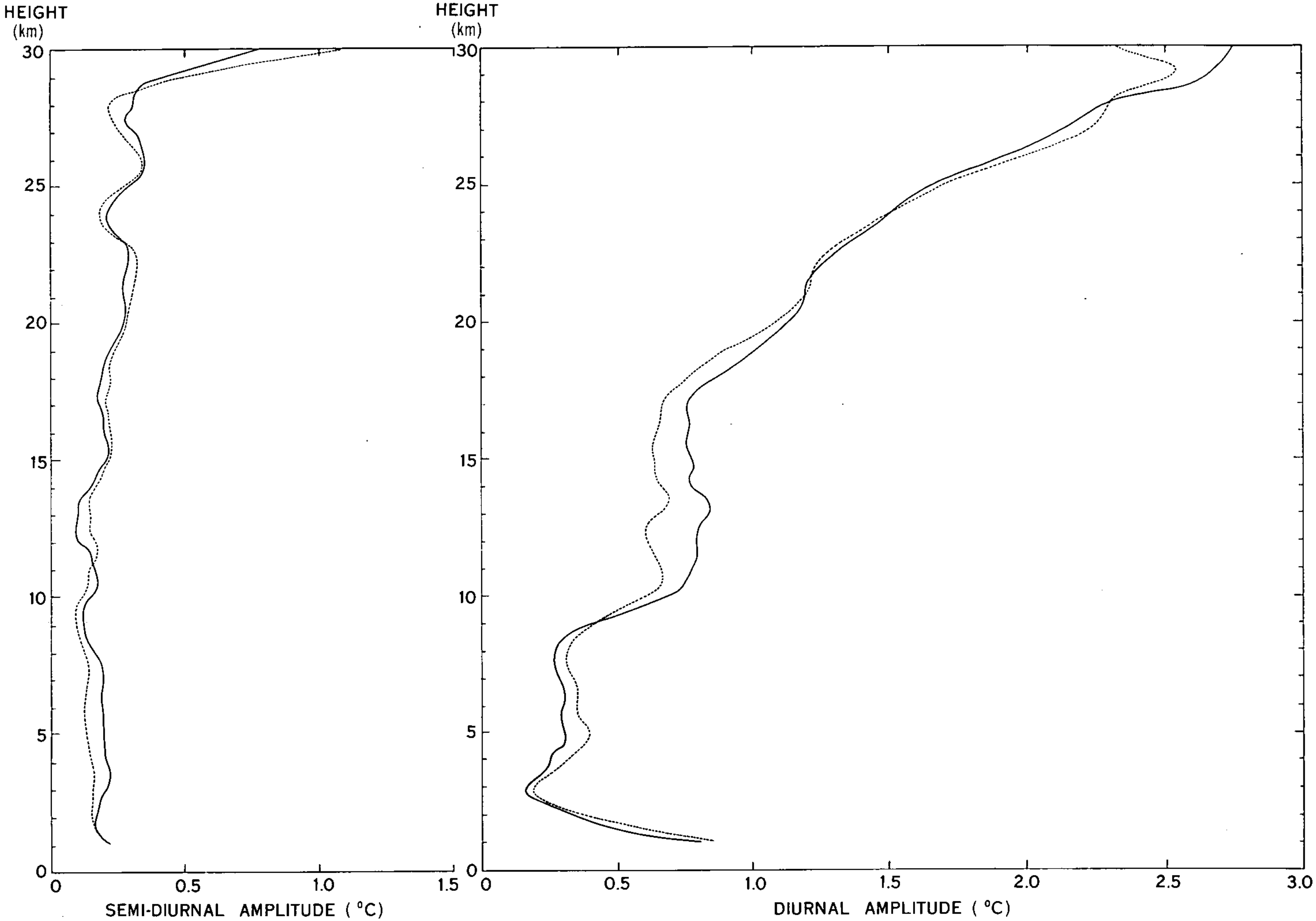

Fig. 1 Amplitude of observed diurnal and semi-diurnal temperature waves. The solid line is derived from an analysis of each 24-hour period. The dotted line is derived from a single analysis of the average temperatures of the 28-day period.

On rearrangement, eq 1 becomes

$$T - T_e = \frac{Q_s}{q} + \frac{Q_L}{q} - \lambda \frac{dT}{dt} \qquad \ldots.2$$

where $\lambda = \frac{C}{q}$, the lag coefficient or time constant of the thermistor. By evaluating the terms in this equation, an estimate of the difference between instrumental and ambient temperature may be obtained.

EVALUATION OF TERMS IN HEAT TRANSFER EQUATION

The heat transfer coefficient q may be obtained empirically from the relation (Scrase, 1954)

$$q = Nu\ k\ \frac{S}{d}$$

$$Nu = 0.32 + 0.43\ Re^{0.52} \quad \text{for } 10^{-1} < Re < 10^{3} \qquad \ldots.3$$

where Nu is the Nusselt number, k the thermal conductivity of air, S the area exposed to convective heat transfer, and d (0.127 cm) the diameter of the cylindrical thermistor. The Reynolds number Re is given by $\frac{V\rho d}{\mu}$ where V is the rate of air flow, ρ the air density, and μ the dynamic viscosity of the air. V is the balloon ascent rate and was calculated over a 1 km depth, centred on the level concerned. To eliminate irregular effects when the balloon is near bursting point, the mean time taken to reach any level was calculated for only those balloons which reached a level at least 2 km higher.

For unit length of the thermistor, $S = \pi d$, eq 3 becomes

$$q = \pi\ k\ Nu$$

The United States standard atmosphere for middle latitudes (spring) was used for values of k and $\frac{\rho}{\mu}$. These are included in Table 1 with Re, Nu, q and the balloon ascent rate, w'.

When the thermistor is in a horizontal plane and makes an arbitrary angle β with a line fixed in this plane (Fig 2), the absorption of solar radiation per unit length of the cylinder is given by

$$Q_s = e_1\ d\ J\ \sin\gamma$$

where γ is the angle between the incident solar rays and the thermistor (γ is a function of β and the sun's zenith distance ζ), and e_1 is the short-wave absorptivity of the thermistor. J represents the solar radiation flux suitably modified for atmospheric absorption and diffuse radiation. It is assumed that the sonde itself neither enhances (by reflection) nor decreases (by shading) the solar radiation intercepted by the thermistor. The declination of the sun is taken as $6^{\circ}48'$S, the mean value for the duration of the serial soundings.

Table 1 Heat Transfer Parameters

Values of w' (balloon ascent rate), μ/ρ (ratio of dynamic viscosity of air to its density), Re (Reynolds number) Nu (Nusselt number), k (thermal conductivity of air) and q (heat transfer coefficient) as a function of height.

Height km	w' m min^{-1}	μ/ρ cm^{2} s^{-1}	Re	Nu	k 10^{-5} cal cm^{-1}/ s^{-1} ^{o}C^{-1}	q 10^{-5} cal cm^{-1}/ s^{-1} ^{o}C^{-1}
0	290	0.15	420	10.3	6.05	195
5	300	0.22	287	8.5	5.43	144.7
10	290	0.35	174	6.6	4.79	99.5
15	305	0.68	95	4.9	4.66	71.9
20	340	1.61	45	3.4	4.66	50.2
25	375	3.72	22	2.5	4.76	36.9
30	400	8.20	10	1.7	4.86	26.6

The thermistor can take up any orientation. If we make the assumption that it revolves in a horizontal plane at a constant rate, all orientations are presented to the sun for similar times. Further it may be assumed that this rate of rotation i sufficiently rapid to enable the use of an integrated orientation to determine the intensity of incident solar radiation.

In Fig 2, the line SO represents the rays from the sun in the vertical plane XOZ, and the line TO represents the line of axis of the thermistor in the horizontal plane XOY. For a fixed ζ, it requires a mean value $\overline{E}$ of sin γ when β rotates through 360^{o}.

Now γ is the angle between the lines OS and OT which for the coordinate system shown, have direction cosines ($\sin\zeta$, 0, $\cos\zeta$) and ($\sin\beta$, $\cos\beta$, 0) respectively. Since $\cos\gamma = \sin\beta\sin\zeta$ then

$$\overline{E} = \frac{4\int_{o}^{\frac{\pi}{2}} \sin\gamma \, d\beta}{2\pi} = \frac{2}{\pi}\int_{o}^{\frac{\pi}{2}} \sqrt{1-\sin^2\beta\sin^2\zeta}\; d\beta$$

Values for the elliptic integral for given values of ζ were taken from tables published by Abramowitz and Stegun (1965).

For the loss of intensity due to atmospheric absorption and scattering, a graph constructed by Vaisala (1948) was used. For a given solar elevation and height of sonde, this graph gives values of the intensity of solar radiation as a fraction F of the intensity J_s at the top of the atmosphere. Values of F are presented for various altitudes in Table 2; $\overline{E}$ for various solar elevations is also given.

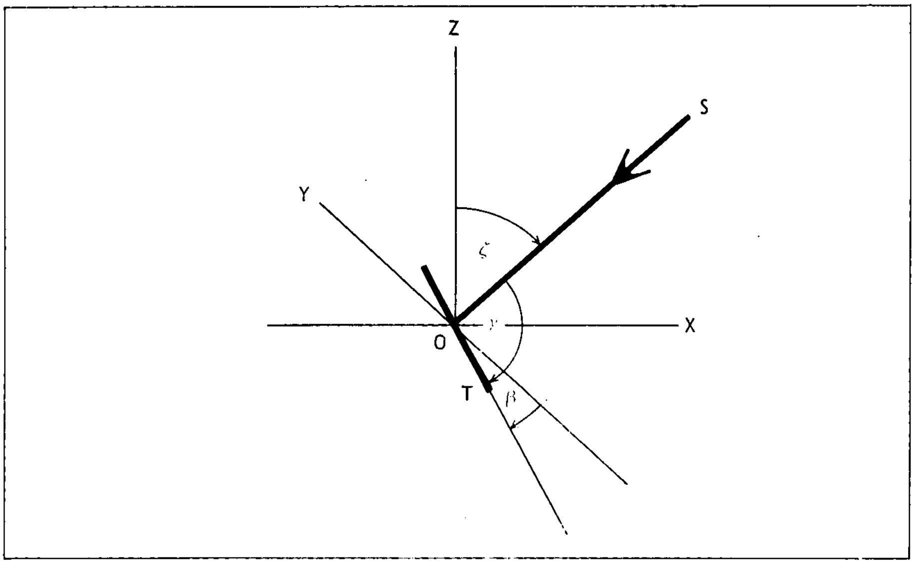

Fig 2 Orientation of thermistor in relation to the principal coordinate axes and the solar elevation. SO represents the solar beam, and TO the thermistor orientation. β is the angle the thermistor makes with an arbitrary line in the XY plane, ζ is the sun's zenith distance, and γ is the angle between the incident solar rays and the thermistor.

Table 2 Values of $\bar{E}$ (integrated value of sin γ when β rotates through 360°) and F (fraction of solar radiation intensity).

$\bar{E}$	Solar Elevation \ Height	F						
		30 km	25 km	20 km	15 km	10 km	5 km	Surface
.64	-5	.35	.20	.07				
.64	-4	.60	.50	.30	.12			
.64	-3	.78	.65	.52	.32	.15		
.64	-2	.87	.79	.62	.50	.33	.10	
.64	-1	.92	.86	.77	.62	.44	.22	
.64	0	.95	.91	.83	.71	.54	.33	.09
.64	5	.99	.97	.94	.89	.79	.60	.37
.66	10	1.00	.98	.96	.93	.87	.67	.51
.71	20	1.00	.99	.98	.96	.92	.80	.65
.77	30	1.00	.99	.98	.97	.94	.84	.71
.83	40	1.00	.99	.99	.98	.95	.86	.76
.93	60	1.00	1.00	.99	.98	.96	.89	.79
1.00	90	1.00	1.00	.99	.98	.97	.90	.80

Following Wagner (1964), the intensity was subsequently increased by 35 percent to take account of atmospheric and terrestrial reflection and scattering which reaches the thermistor as diffuse radiation. (Wagner (1961) increases the solar flux by only 25 percent at all levels. In view of an overall value of the earth's albedo of about 0.5, a 35 percent increase seems more than reasonable but it is obviously a coarse estimate).

Specifications for the radio-sonde thermistor include an absorptivity e_1 of less than 0.11 for the solar spectrum. In normal production control tests, conducted by the radio-sonde manufacturer (for 29 thermistors), the absorptivity under a tungsten lamp varied from 0.03 to 0.09 with a mean of 0.06. However, no reliable values for e_1 under normal working conditions is available. To avoid under-estimation of the absorptivity, it was thought better to choose a value in the high part of the range. The value of e_1 is critical, for if the absorptivity was as high as about 0.2 of the whole observed daytime variation would be instrumental in origin, but this seems unlikely. A value of $e_1 = 0.08$ is taken for the following calculations.

Thus for a given solar elevation and height of sonde, the mean intensity of solar radiation is $F(1.35)\,J_s$ at an effective area (unit length) $\bar{E}\,d$, giving a mean rate of heat transfer by solar radiation.

$$Q_s = e_1 \bar{E}\, F\, (1.35)\, J_s\, d$$

Taking $J_s = 0.032$ cal cm^{-2} s^{-1}, the short-wave radiation effect $\frac{Q_s}{q}$ is represented as a function of height for various solar elevations in Fig 3.

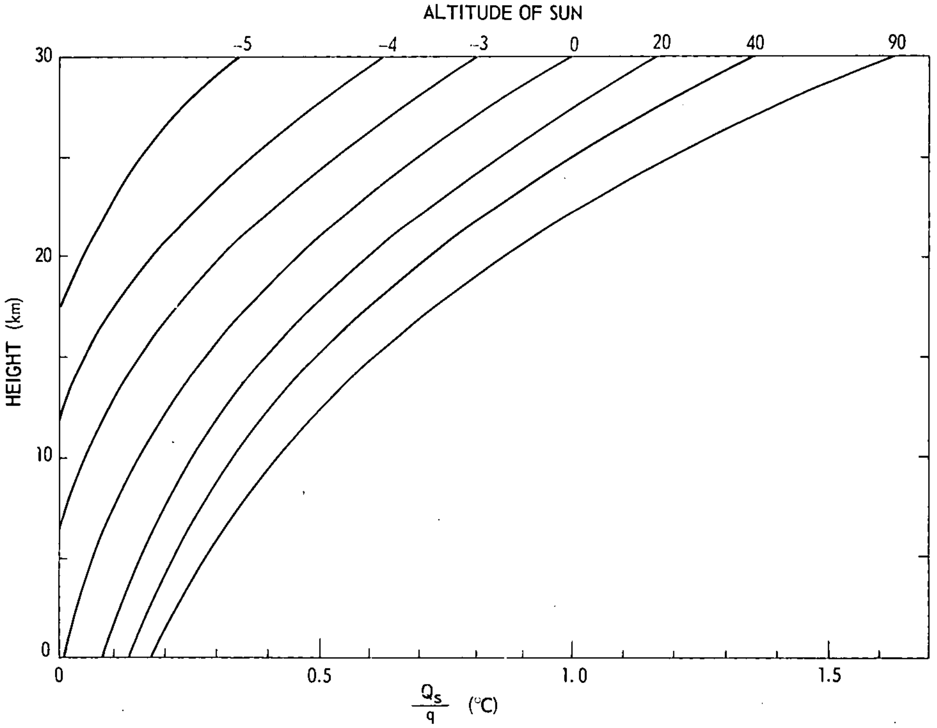

Fig 3 Increase in thermistor temperature due to short-wave (solar) radiation, with a thermistor absorptivity of 0.08.

To determine the intensity of infrared radiation at the thermistor, Wagner (1964) makes use of the effective blackbody radiation temperatures, T_a and T_b of the environment above and below the thermistor. Thus,

$$Q_L = e_2 \quad \sigma\pi d\,(a_1 T_b{}^4 + a_2 T_a{}^4 + a_3 T_i{}^4 - T^4) \qquad \ldots 5$$

where e_2 is the long-wave absorptivity of the thermistor, σ is Stefan's constant, a_1, a_2, a_3 are fractions of the area subtended by the various emmitters, T_i is the effective blackbody radiation temperature of the instrument package and, as before, T is the temperature of the thermistor. The thermistor is taken to be a perfect blackbody, *ie* $e_2 = 1.0$. For the serial sounding experiment, values of $a_1 = 0.32$, $a_2 = 0.46$, $a_3 = 0.22$ were obtained from measurements of the radiosonde, and T_i and T were taken to be the same as the mean temperature at a particular level. The method of determining the effective values of T_a and T_b is somewhat obscure - references originate with Badgley (1957). In this study, in the absence of a more satisfactory method of determination, Badgley's values of $T-T_a$ and T_b-T were applied at corresponding levels.

When these estimates are inserted in eq 5, it is found that when the sonde is higher than about 15 km the thermistor emits more radiation than it absorbs (*cf* Badgley, 1957) and the term $\frac{Q_L}{q}$ has a value of about -1.0°C at 25 km and about -1.5°C at 30 km.

A spurious diurnal temperature variation probably arises from long-wave as well as short-wave radiation because each of T_b, T_a, T_i and T will be higher in daytime than at night. However, it is difficult to estimate the magnitude of the change in T_b and T_i from night to day, although T_i in particular could conceivably be the source of a significant diurnal variation. The overall spurious variation due to changes in the long-wave radiation field is probably a small residue from various counteracting effects, but cannot be reliably estimated.

The final term in the heat transfer eq 2 is the lag error $-\lambda\frac{dT}{dt}$. The lag coefficient for the Australian radio-sonde has been determined experimentally by Moncur (1969) and the derivative can be estimated from the mean temperature lapse rate, $\frac{\partial}{\partial z}T_e$, and the balloon ascent rate w'. The results are shown in Table 3 where it is assumed that $\frac{dT}{dt} = w' \frac{\partial}{\partial z} T_e$.

It is seen that the lag errors are quite small and that above the tropopause they are of opposite sign to the solar radiation error. A small spurious diurnal variation from lag errors would be present because, for daytime soundings, radiational heating, as well as changes of air temperature, will determine $\frac{dT}{dt}$. However, this variation is negligible compared with that caused by the dominant term $\frac{Q_s}{q}$ of the heat transfer eq 2.

Table 3 Time constants and lag errors

Height (km)	lag λ (s)	lapse rate $\frac{\partial}{\partial z} T_e$ ($^{\circ}$C km^{-1})	ascent rate w' (m min^{-1})	lag error $-w'\lambda \frac{\partial}{\partial z} T_e$ ($^{\circ}$C)
0	2.3	-6	290	+.07
5	3.1	-6	300	+.09
10	4.4	-6	290	+.13
20	8.9	+1	340	-.05
25	12.2	+1	375	-.08
30	16.7	+1	400	-.11

COMBINED HEAT TRANSFER TERMS

The heat gain by the thermistor due to short-wave radiation input, together with heat loss due to long-wave radiation and the effects of lag have been derived above. The results suggest that in the higher levels during the day, the radiosonde temperatures approximate the ambient temperatures, whereas at night the instrumental temperatures are cooler than ambient. Table 4 gives values at 25 and 30 km when the altitude of the sun is 60°.

Table 4 Combined heat transfer terms - Altitude of sun 60°

	25 km		30 km	
	day ($^{\circ}$C)	night ($^{\circ}$C)	day ($^{\circ}$C)	night ($^{\circ}$C)
$\frac{Q_s}{q}$	1.1	0	1.5	0
$\frac{Q_L}{q}$	-1.0	-1.0	-1.5	-1.5
$-\lambda \frac{dT}{dt}$	-0.1	-0.1	-0.1	-0.1
$T - T_e$	0.0	-1.1	-0.1	-1.6

APPLICATION TO OBSERVED TEMPERATURE WAVE

Referring to eq 2; $\lambda\frac{dT}{dt}$ produced negligible instrumental diurnal variation: $\frac{Q_L}{q}$ which generally is negative at higher levels, provides a virtually unknown instrumental diurnal variation but it is not likely to be large: $\frac{Q_s}{q}$, the solar radiation effect, is the major cause of spurious diurnal variation.

The average observed temperature at each observing time was obtained for the whole period of the serial soundings, at every 5 km level. The amplitude and phase of both the diurnal and semi-diurnal wave at each level were extracted from the average temperatures using the method outlined by Conrad and Pollak (1950).

The sun's altitude was calculated for the time when the sonde reached a particular level and the term $\frac{Q_s}{q}$ was subtracted from the observed mean daytime T values. These modified values, together with the observed night-time means were re-analysed to obtain amplitude and phases of the diurnal and semi-diurnal components of the temperature variation.

Table 5 lists the results before and after subtraction of the estimated solar radiation effect from the mean daytime observations. The reduction in amplitude is quite substantial at higher levels but the phase is little changed.

CONCLUSION

The results shown in Table 5 indicate the diurnal temperature amplitude to be about 0.2°C at mid-troposphere levels, increasing to about 0.5°C in the lower stratosphere, with a rise to 1.5°C at 30 km. The time of maximum appears to be early afternoon at all levels, the earliest time occurring in the stratosphere.

In the assessment of instrumental error, the estimate of short-wave absorptivity in particular, as well as the increase in intensity due to reflector and scattering need better estimation. Also, although less important than direct solar radiation estimates, the assumptions made about long-wave absorptivity and the effective blackbody radiation temperatures of the atmosphere need improved evaluation. This points to the need for a detailed reconsideration of the effect of the whole spectrum of radiation on a white thermistor temperature sensor at higher levels. However the errors likely to arise from uncertainties in the above factors appear to be relatively small since the total estimated error amounts to only about 1.6°C at 30 km (Table 4).

Table 5 Amplitudes and phases of temperature variation before and after subtraction of the solar radiation term $\frac{Q_s}{q}$ from the observed daytime values.

Height (km)	Uncorrected for Solar Radiation				Corrected for Solar Radiation			
	Diurnal		Semi-Diurnal		Diurnal		Semi-Diurnal	
	Amplitude (°C)	Time of Maximum (Local Time)	Amplitude (°C)	Time of Maximum (Local Time)	Amplitude (°C)	Time of Maximum (Local Time)	Amplitude (°C)	Time of Maximum (Local Time)
Surface	4.0	1409	.8	1159	3.9	1412	.8	1158
5	.3	1305	.1	1043	.2	1425	.1	1023
10	.6	1317	.1	1318	.4	1412	.1	1359
15	.6	1042	.3	1346	.3	0933	.3	1401
20	1.2	1226	.2	1149	.7	1248	.2	1136
25	1.7	1245	.4	1136	1.1	1313	.3	1127
30	2.4	1226	1.2	1302	1.5	1235	1.1	1307

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REFERENCES

Badgley, F.I. 1957. Response of radiosonde thermistors. *Rev. Sci. Inst. 28*, 1079-1084.

Beyers, N.J. and Miers, M.T. 1967. Diurnal temperature change in the atmosphere between 30 and 60 km over White Sands Missile Range. *J. atmos. Sci., 22*, 262-266.

Conrad, V and Pollak, L.W. 1950. *Methods in Climatology.* 2nd Ed. Cambridge, Mass., Harvard University Press, 459. pp.

Harris, M.F., Finger, F.G. and Teweles, S. 1962. Diurnal variation of wind pressure and temperature in the troposphere and stratosphere over the Azores. *J. atmos. Sci., 19*, 136-149.

Lindzen, R.S. 1967. On the consistency of the thermistor measurements of upper air temperatures. *J. atmos. Sci., 24*, 317-318.

Moncur, R.L. 1969. Response of the thermistor used in the Australian radiosonde. *Aust. Met. Mag., 17*, 215-227.

Pressman, J. 1955. Diurnal Temperature Variations in the Middle Atmosphere. *Bull.Amer.Met.Soc., 36*, 220-223.

Scrase, F.J. 1954. Radiation and lag errors of the meteorological office radiosonde and the diurnal variation of upper air temperature. *Quart.J.Roy.Met.Soc., 80*, 565-578.

Smith, W.L. 1969. Statistical estimation of the atmosphere's geopotential height distribution from satellite radiation measurements. *ESSA Tech. Rep., NESC 48.*

Tucker, G.B. 1972. Diurnal and semi-diurnal variations of temperature, pressure and winds over Melbourne (38°S) (To be published in Quart J.R. Met. Soc.)

Vaisala, V. 1948. Solar radiation intensity at the ascending radiosonde. *Geophysica, Helsinki, 3*, 39-55.

Wagner, N.K. 1961. Theoretical time constant and radiation error of a rocketsonde thermistor. *J. Meteor, 18*, 606-614.

Wagner, N.K. 1964. Theoretical accuracy of a meteorological rocketsonde thermistor. *J. appl. Met., 3*, 461-469.