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ESTIMATION OF GROUND TEMPERATURE FROM GFCR RADIOMETRIC SIGNAL

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S. K. Gupta

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Progress Report

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Under
Research Grant NSG 1282
February 1977 - May 1977
Dr. Henry G. Reichle, Technical Monitor
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Norfolk, Virginia 23508

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FOREWORD

This report constitutes a part of the work done on the research project entitled "Determination of Atmospheric Pollutants from Infrared Radiation Measurements." The work was supported by the NASA-Langley Research Center (Atmospheric Systems Branch of the Atmospheric Environmental Sciences Division) through Grant NSG 1282. The grant was monitored by Dr. Henry G. Reichle, Jr.

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ESTIMATION OF GROUND TEMPERATURE FROM GFCR RADIOMETRIC SIGNAL

by

S. K. Gupta and S. N. Tiwari
School of Engineering
Old Dominion University
Norfolk, Virginia 23508

SUMMARY

A simple procedure has been developed which demonstrates the feasibility of estimating actual surface temperature from the effective brightness temperature which can be conveniently measured by a radiometer from remote sensing platforms. Atmospheric corrections to the effective brightness temperature are computed corresponding to the "base model" atmosphere and several modifications of this caused by deviations of the various atmospheric or surface parameters from their base model values. Simple analytical relations have been established between the deviations of these parameters and the additional temperature corrections required to compensate for them. Effects of simultaneous variation of several parameters have also been examined. Use of these analytical relations, instead of radiative transfer calculations, results in tremendous savings in data reduction costs.

1. INTRODUCTION

Determination of the concentrations of various atmospheric pollutants such as carbon monoxide, methane, ammonia, and sulfur dioxide is of great importance because of their considerable effect on various natural processes affecting human health, environment and meteorology [1]*. The feasibility of measurement of such pollutants from analysis of the upwelling infrared radiation observed by passive remote sensing instruments is well established [2]. Several such instruments working on the principle of spectral correlation have been developed in recent years and have been demonstrated to possess the ability of remotely measuring concentrations of trace gases in the atmosphere from airborne or space platforms [3,4].

Analysis of the data obtained from such instruments requires prior knowledge of various parameters of the atmosphere and the underlying surface. The atmospheric parameters, such as pressure, temperature and humidity profiles, can be obtained either from additional instruments mounted aboard the carrier itself or from other independent sources (e.g., radiosondes). The surface parameters, namely, the emittance and temperature cannot be obtained from any such source. Any meaningful physical contact measurement of the surface parameters is not feasible because of the vast areas covered in remote sensing experiments and large spatial variations of the quantities involved. Reliable estimates of surface emittance, however, can be obtained from approximate knowledge of the texture and composition of a surface. This is possible because extensive tabulations relating basic characteristics of the surfaces to their emittance values are available in the literature [5].

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*Numbers inside the parentheses indicate references.

This leaves surface temperature as the important unknown parameter to be determined.

The work presented in this report is relevant to an ongoing project at the Langley Research Center aimed at measuring the concentration of carbon monoxide in the troposphere. The instrument presently employed for this purpose is a gas-filter correlation radiometer which operates in the CO fundamental band region around 4.66 μ (2070-2220 cm^{-1}). The instrument measures, in addition to other signals, the total upwelling radiance in the above spectral region. Since this is a single channel and non-dispersive instrument, the differential absorption technique [6,7] cannot be applied in the present case for surface temperature retrieval. The interference from the spectra of other atmospheric species such as H_2O, CO_2, and N_2O in the frequency range of interest further complicates the application of this technique. This passive remote sensing instrument is flown frequently on an aircraft and operates in nadir viewing mode. A simple procedure developed for retrieving surface temperature from upwelling radiance measurements made by this instrument involves line-by-line radiative transfer calculations for every set of atmospheric conditions [8]. The cost of data reduction (on routine basis over extended periods of time) using such schemes tend to be extremely high.

The purpose of the present work is to develop a procedure for inferring the actual surface temperature from the radiometrically measured effective brightness temperature (EBT) by applying appropriate atmospheric correction. It is intended, in particular, to achieve this objective by establishing simple analytical relations between the deviations of the various atmospheric and surface parameters from their "base model" values and the additional atmospheric corrections to EBT required to compensate for them. This eliminates the need of performing detailed radiative transfer calculations for every set of atmospheric conditions and thereby results in a drastic cost reduction.

2. BASIC FORMULATION

The integrated upwelling radiance from a homogeneous non-scattering atmosphere can be expressed as [2,9]

$$E = \int_{\omega_1}^{\omega_2} [E_G(\omega) + E_R(\omega)] \, d\omega \tag{2.1}$$

where ω_1 and ω_2 represent the frequency limits of the observed spectral region. In this equation, $E_G(\omega)$ represents the thermal radiation emitted by the underlying surface and the atmosphere. It is given by the relation

$$E_G(\omega) = \varepsilon(\omega) \, B(\omega, T_s) \, \tau(\omega, 0) + \int_0^h B(\omega, T(z)) \, [d\tau(\omega,z)/dz] \, dz \tag{2.2}$$

where $\varepsilon(\omega)$ is the surface emittance, $B(\omega, T)$ is the Planck's blackbody function, T_s is the surface temperature, $T(z)$ is the temperature at the altitude z, and $\tau(\omega,z)$ is the monochromatic transmittance of the atmosphere. The first term on the right hand side of this equation represents the radiation from the surface while the second term is the radiation from the atmosphere. The contribution from sunlight reflected from the surface becomes significant at shorter wavelengths. This contribution is represented by $E_R(\omega)$ and can be expressed as

$$E_R(\omega) = (1/\pi)[1-\varepsilon(\omega)] \cos\theta \, H_s(\omega) \, [\tau(\omega)]^{\zeta} \tag{2.3}$$

where θ is the sun zenith angle and $\zeta = 1 + f(\theta)$. Function $f(\theta) = \mathrm{Sec}\,\theta$ for $0 \leq \theta \leq 60°$ and equals $\mathrm{Ch}\,(\theta)$ for $\theta > 60°$, with $\mathrm{Ch}(\theta)$ denoting the Chapman function. $H_s(\omega)$ is the sun irradiance at the top of the atmosphere.

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For the spectral range between ω_1 and ω_2, it is possible to define an equivalent temperature such that

$$\int_{\omega_1}^{\omega_2} B(\omega,T_e)\ d\omega = \int_{\omega_1}^{\omega_2} [E_G(\omega) + E_R(\omega)]\ d\omega \tag{2.4}$$

where T_e denotes the effective brightness temperature (EBT) of the underlying surface. A combination of equations (2.1) and (2.4) results in

$$E = \int_{\omega_1}^{\omega_2} B(\omega,T_e)\ d\omega \tag{2.5}$$

A simple inversion of equation (2.5) for radiometrically measured values of E would yield T_e for any given altitude and a set of surface and atmospheric conditions. Inversion of equation (2.1) on the other hand, would involve detailed radiative transfer calculations to obtain the actual surface temperature T_s. Furthermore, the accuracy requirements of the problem necessitate the use of line-by-line method of transmittance computation [10].

The need to perform line-by-line radiative transfer calculations for every set of surface and atmospheric conditions may be eliminated by performing some model calculations and establishing relations between T_s, T_e and the input (surface and atmospheric) parameters. To accomplish this, a correction term ΔT_o (referred to as the "base correction") is defined as

$$\Delta T_o = T_s - T_e \tag{2.6}$$

For this relation T_e is obtained from equation (2.5). Since, radiometrically measured value of E is not available at present, it is calculated from equation (2.1) corresponding to an actual surface temperature T_s and the "base model" atmosphere. If, however, one (or more) of the input parameters x undergoes a change Δx relative to base model value, a different value of EBT (say, T_e') would be obtained. The modified correction may be expressed as

$$\Delta T = T_s - T_e' \tag{2.7}$$

It can also be expressed as

$$\Delta T = \Delta T_o + \Delta T_x \tag{2.8}$$

where ΔT_x may be called the "additional correction" caused by the deviation Δx .

Gupta and Tiwari [8] studied in detail the effect of uncertainties in various input parameters on the retrieved value of surface temperature. For all the parameters considered, their results indicate the existence of simple functional relationships between Δx and ΔT_x . For most cases, therefore, these relationships may be expressed by polynomials as

$$\Delta T_x = \sum_{n=o}^{N} a_n (\Delta x)^n \tag{2.9}$$

In this relation, the first two or three terms should adequately represent the additional correction ΔT_x for the expected range of the deviation Δx . The coefficients a_n can be obtained by polynomial regression of the results obtained from the model calculations. Future computations of ΔT_x can then be made from a_n and Δx . The base correction ΔT_o , can also be obtained from one model calculation and then ΔT can be evaluated for any set of input parameters without performing radiative transfer calculations.

When more than one input parameters undergo simultaneous deviations, the combined additional correction, to be denoted by ΔT_{xc} , may be represented as a function of the individual additional corrections. For example,

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if Δx and Δy represent deviations of two input parameters x and y, respectively, then the combined additional correction may be expressed as

$$\Delta Txc = f(\Delta Tx, \Delta Ty) \tag{2.10}$$

where ΔTx and ΔTy represent the individual additional corrections caused by the deviations Δx and Δy separately. Additional model calculations may be performed to examine the nature of the above function for different sets of parameters. Results of such model calculations are discussed in Sec. 5.

3. DATA SOURCES AND COMPUTATION PROCEDURE

Spectral lines from the appropriate bands of CO_2, H_2O and N_2O which interfere with the CO fundamental band were considered in the evaluation of transmittance and the total upwelling radiance. The values of the line parameters were taken from the SAI compilation [11]. It was observed that the line parameters from the AFCRL compilation [12] yielded essentially the same results. Calculations were made for the base model atmosphere as well as for several modifications of each of the input parameters. The "base model atmosphere" is essentially the U.S. Standard Atmosphere (1962) [13] along with a standard Gutnick water vapor profile. The uniformly mixed concentrations of CO_2, N_2O and CO were assumed to be 320, 0.27 and 0.20 ppmV, respectively. Solar irradiance values at the top of the atmosphere were also obtained from the SAI compilation [11].

The non-homogeneous atmosphere up to 17,500 ft. was divided into ten layers. Pressure, temperature and water vapor concentration for these layers are given in Table 3.1. The altitudes at the layer boundaries are listed in the first column of the table. Data in the next three columns represent the averages for layers between the altitudes in the first column appearing just below and above the values. Attenuation of the solar radiation through the entire atmosphere (up to 17,500 ft.) was taken into consideration in computing the reflected solar component of the total upwelling radiance.

Integrated upwelling radiance was obtained from equation (2.1) by performing line-by-line radiative transfer calculations as outlined in [14]. Effective brightness temperature T_e was then obtained by inversion of equation (2.5) using quadratic interpolation. In this illustrative study, calculations were made for seven different values of the input surface temperature T_s (between 290 and 320 °K) but only for one altitude of 10,500 ft. Results discussed in this report refer to this particular altitude, but results for any other altitude can be obtained similarly. As far as possible, realistic ranges of the various input parameters were chosen for the present work. For all values of Δx , an agreement of better than 0.1 °K was required between the computed value of additional correction ΔT_x (see Eq. (2.8)) and that obtained from regression coefficients a_n (Eq. (2.9)).

Table 3.1

Base model atmosphere

Altitude (ft)	Pressure (mm Hg)	Temperature (°K)	Water Vapor Conc. (10^3 ppmV)
0			
	763.16	287.66	7.626
500			
	742.65	286.17	7.240
1,500			
	716.03	284.19	6.726
2,500			
	677.55	281.22	5.972
4,500			
	628.87	277.26	5.100
6,500			
	583.07	273.30	4.222
8,500			
	540.03	269.34	3.338
10,500			
	499.59	265.38	2.669
12,500			
	461.66	261.42	2.074
14,500			
	417.57	256.48	1.493
17,500			

4. ANALYSIS AND DISCUSSION OF MODEL CALCULATIONS:

VARIATION OF SINGLE PARAMETERS

Model calculations have been performed and analyzed for deviations of a single parameter at a time and also for simultaneous variation of more than one parameter. Results obtained for the variation of single parameters are discussed in this section. Discussion of results obtained for simultaneous variation of more than one parameter is covered in Section 5. The atmospheric corrections obtained using the base model (called the base corrections) for the seven values of T_s are given below in Table 4.1, and also shown in Fig. 4.1. Effects of the deviations of the individual input parameters on the atmospheric correction are discussed in the following subsections.

Table 4.1

Base atmospheric correction as a function of input surface temperature

Input Surface Temperature T_S(°K)	Base Atmospheric Correction ΔT_o(°K)
290	-2.97
295	-4.07
300	-5.03
305	-5.90
310	-6.74
315	-7.46
320	-8.18

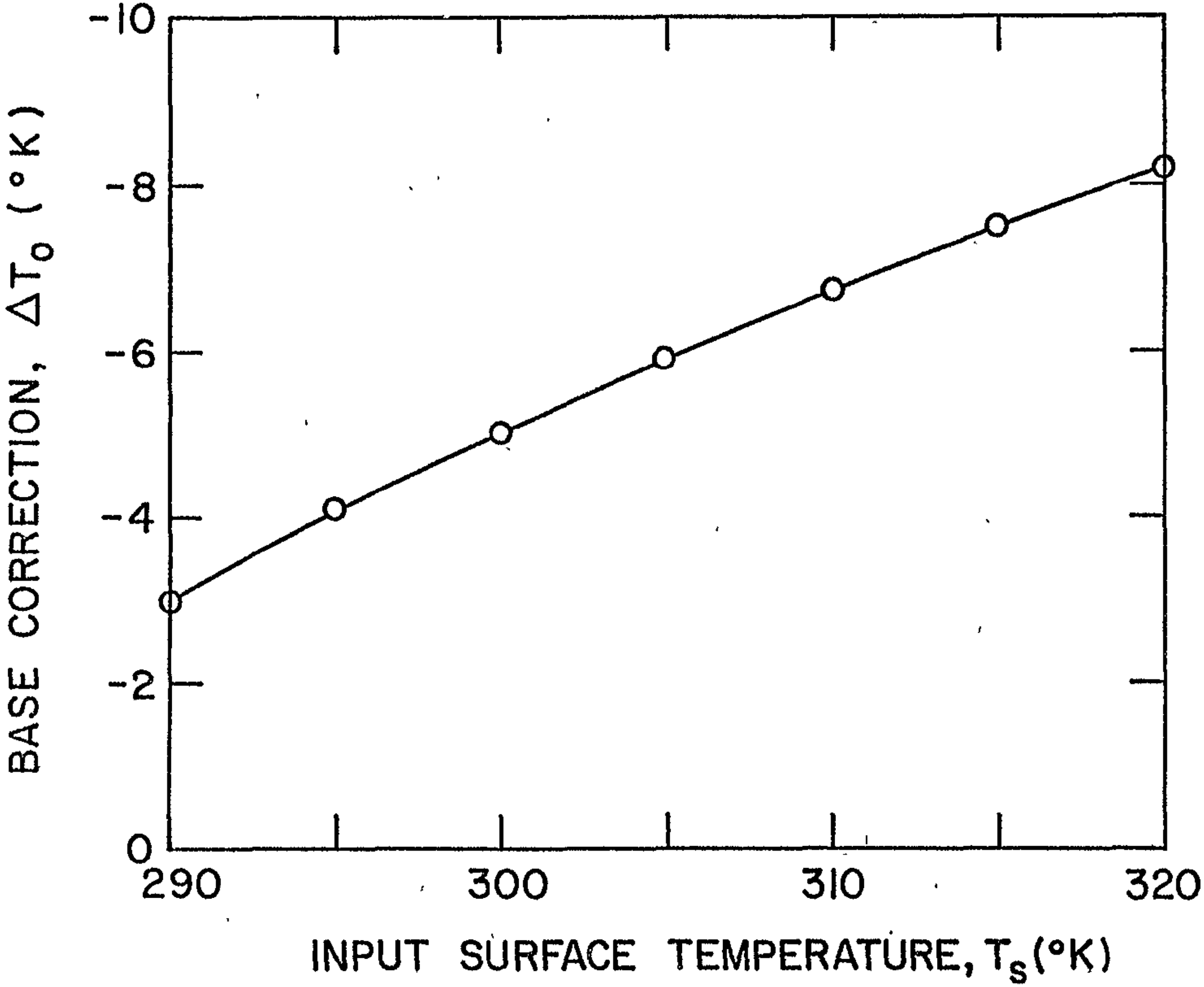

Figure 4.1. Base atmospheric correction as a function of input surface temperature, T_s,

4.1 Water Vapor Distribution

Since water vapor is an important and highly variable constituent of the troposphere, its variation in the atmosphere was considered in two ways, (i) increasing or decreasing water vapor concentration as multiples of standard Gutnick profile in all layers, and (ii) increasing concentration in some layers while decreasing in others so that the total water vapor burden of the atmosphere remains constant.

Computations of additional correction to EBT were made for six multiples of the water vapor profile, namely, 0.0, 0.25, 0.50, 1.5, 2.0 and 3.0 in addition to the standard, for each of the seven values of the surface temperature mentioned earlier. Results for T_s = 300 °K were chosen for graphical illustration and these are shown in Fig. 4.2. Δx represents the deviation of the multiple water vapor profile from its standard value while the solid circles represent the computed additional corrections ΔT_x for each case. Solid line represents the best least-squares straight line fit to the data. However, differences much greater than the prescribed 0.1 °K were observed between the circles and the straight line and, therefore, a search for a better representation was continued. After several trials, it was found that these results can be represented adequately by two quadratic expressions, one for water vapor burdens below the standard (Δx between -1 and 0) and the other for water vapor burdens above the standard (Δx between 0 and 2). Computed values of ΔT_x and those obtained from these quadratic expressions agreed within 0.1 °K with each other. Coefficients for the quadratic fit, a_0, a_1 and a_2 were obtained for both ranges of Δx for all seven values of the surface temperature and the results are presented in Table 4.2. It can be seen from Fig. 4.2 that both quadratic segments of the

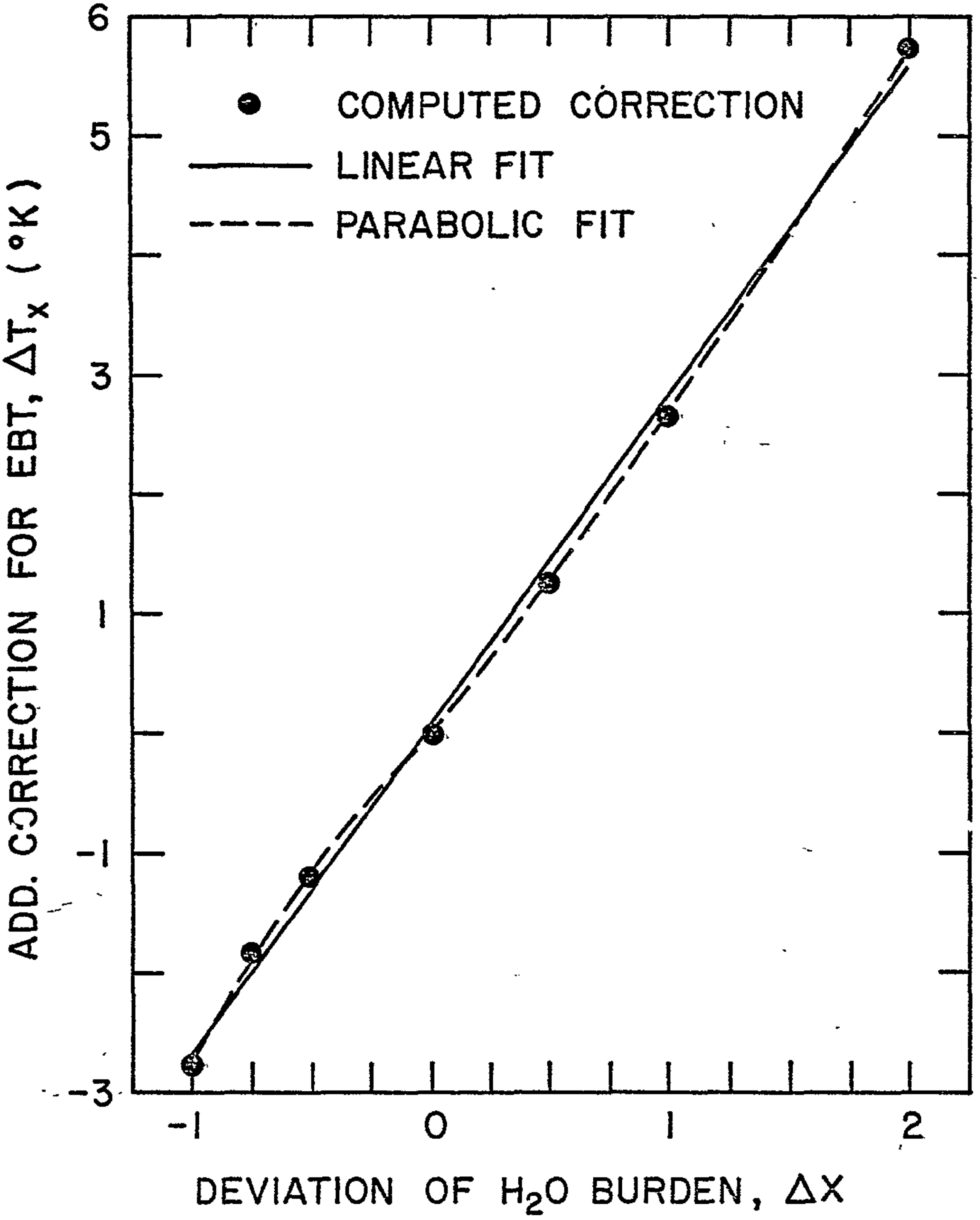

Figure 4.2. Additional correction for EBT as a function of the deviation of water vapor burden.

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curve pass through the(0,0) point on the graph and, therefore, the coefficients a_o in all cases are insignificant. On the other hand, Table 4.2 shows that the significant coefficients a_1 and a_2 are both dependent of the input surface temperature T_s. Figures 4.3 and 4.4 show the variations of the coefficients a_1 and a_2, respectively, for both ranges of Δx. Since these coefficients depend on the end result, namely, the actual surface temperature T_s, an iterative method has been developed to determine the appropriate values of a_1 and a_2. Details of this iterative procedure are discussed later in this section.

Table 4.2

Regression coefficients for the analysis of water vapor multiple profiles.

Input Surface Temp. (°K)	Δx(-1 to 0)			Δx(0 to 2)		
	a_o	a_1	a_2	a_o	a_1	a_2
290	0.0031	-1.0658	0.5018	0.0011	-1.3771	-0.1018
295	0.0045	-1.4709	0.6909	0.0000	-1.9000	-0.1600
300	0.0069	-1.8742	0.8582	0.0016	-2.4756	-0.1927
305	0.0078	-2.1924	0.9964	0.0022	-29142	-0.2836
310	0.0092	-2.5896	1.1236	0.0008	-3.3172	-0.3536
315	0.0106	-2.8547	1.2327	0.0044	-3.7984	-0.3873
320	0.0112	-3.1616	1.3636	0.0008	-4.0728	-0.5064

Figure 4.5 shows the standard water vapor profile (solid line) and four modifications of this profile (dashed lines marked 1, 2, 3 and 4, respectively). These modifications are obtained by arbitrarily shifting

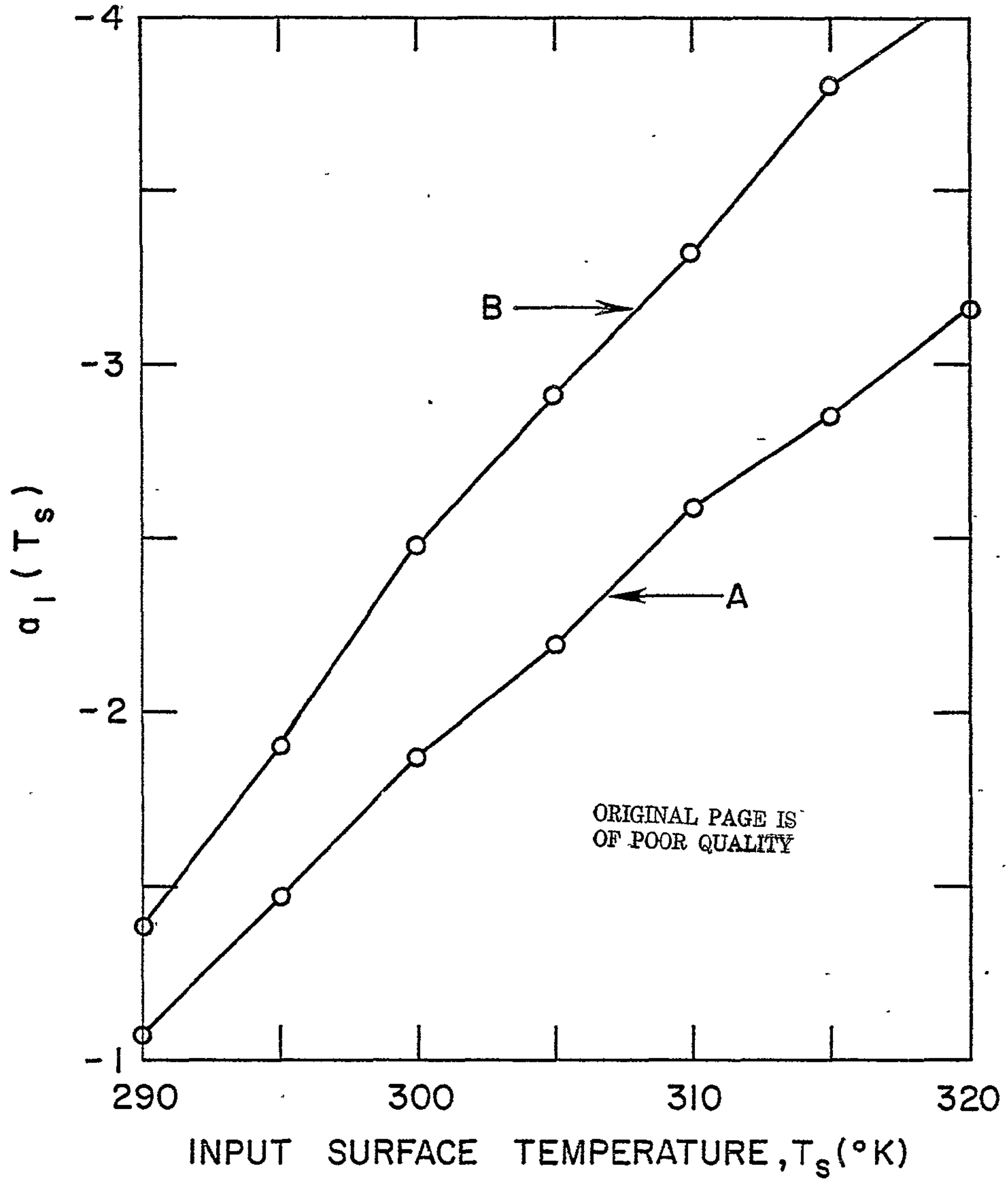

Figure 4.3. Regression coefficients a_1 as a function of the input surface temperature, T_s, for the two ranges of water burden. A - for Δx(-1 to 0); B - for Δx(0 to 2).

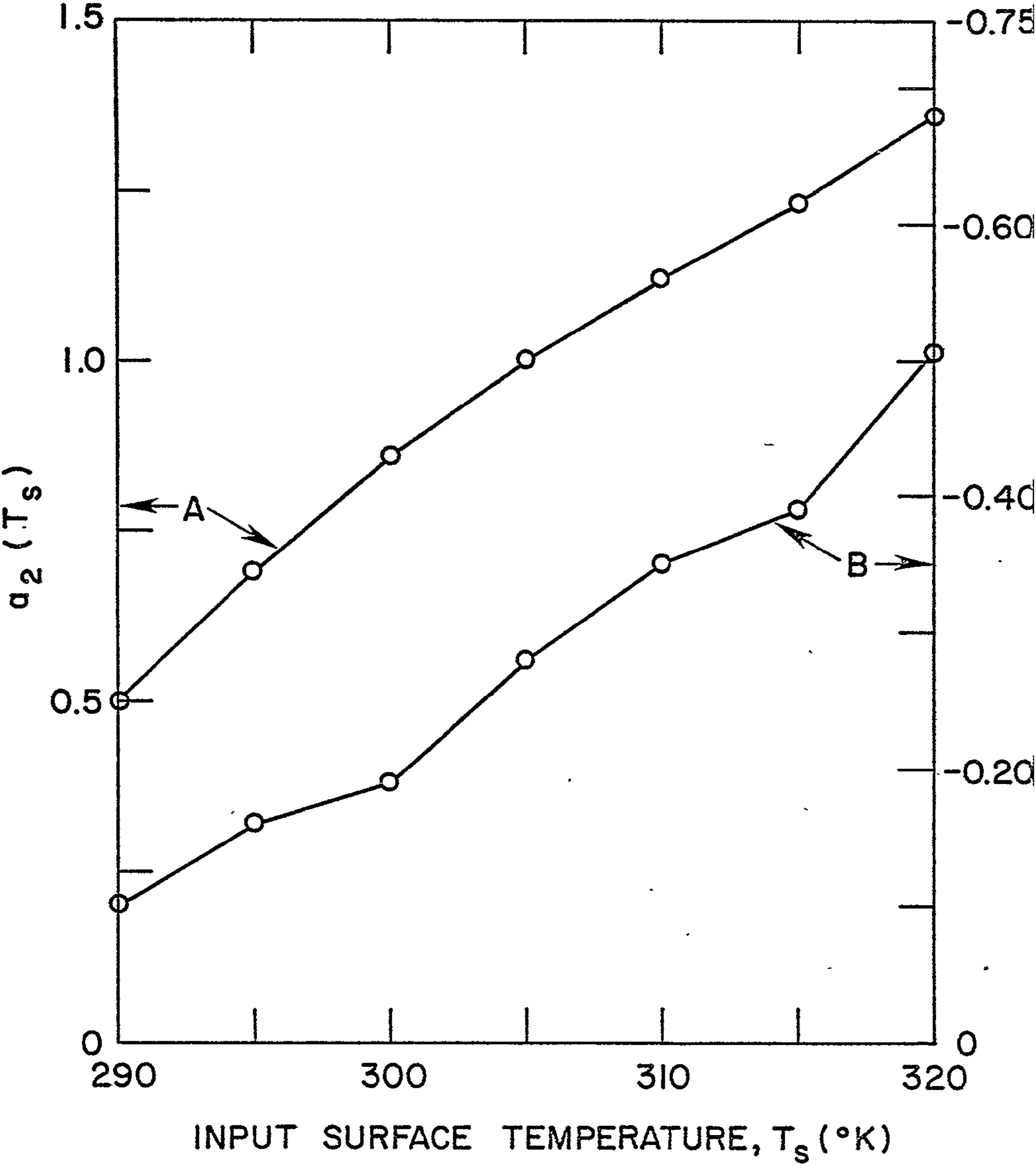

Figure 4.4. Regression coefficient a_2 as a function of the input surface temperature, T_s, for the two ranges of water vapor burden. A - for $\Delta x(-1$ to $0)$; B - for $\Delta x(0$ to $2)$. Ordinate scale on the right refers to the data set B.

certain amounts of water vapor from the lower layers to the upper ones and vice versa in such a manner that the total water vapor burden, up to 10,500 ft., remains unaltered. For convenience of computation in this redistribution, the water vapor distribution is expressed in cm-atm/kft. Modification 1 is obtained by decreasing the burden in layers 1, 2 and 3 by 10 cm-atm/kft each and compensating for it by increasing the burden in layers 5, 6 and 7 by 2.5, 5 and 5 cm-atm/kft, respectively. The burden in layer 4 is kept unchanged. Other modifications are obtained similarly but with different magnitudes. Table 4.3 shows the standard and modified water vapor distributions for the seven layers of the atmosphere from surface up to 10,5000 ft.

Table 4.3

Standard and modified water vapor distribution in the lower seven layers.

Layer No.	Water Vapor Burden (cm-atm)				
	Standard	Mod. 1	Mod. 2	Mod. 3	Mod. 4
1	87.68	82.68	77.68	92.68	97.68
2	162.86	152.86	146.86	172.86	178.86
3	146.89	136.89	130.89	156.89	162.89
4	249.43	249.43	249.43	249.43	249.43
5	200.53	205.54	2.0.54	195.54	190.54
6	156.15	166.16	172.16	146.16	140.16
7	116.02	126.02	132.02	106.02	100.02

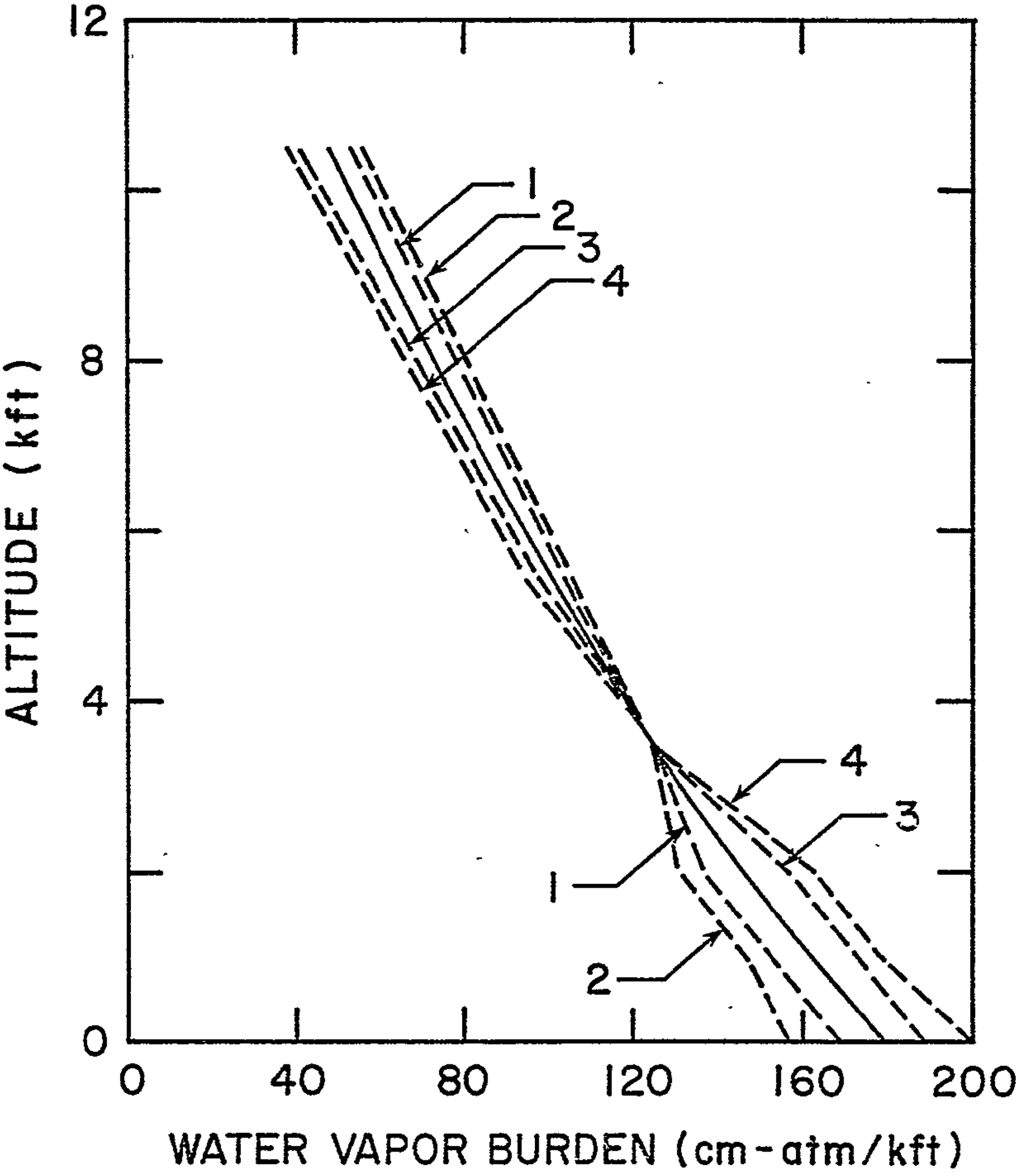

Figure 4.5. Standard water vapor profile and its four modifications.

Retrieved values of effective brightness temperature for the standard and modified water vapor profiles for different values of T_s are given in Table 4.4. It can be seen that the retrieved EBT for the standard and the modified profiles do not differ by more than 0.04 °K, which is well within the acceptable difference of 0.1 °K. This indicates that within given limits, redistribution of water vapor in the atmosphere does not affect the EBT significantly.

Table 4.4

Effect of redistribution of water vapor on retrieved EBT.

Input Surface Temp. (°K)	Retrieved EBT (°K)				
	Standard	Mod. 1	Mod. 2	Mod. 3	Mod. 4
290	287.26	287.24	287.22	287.28	287.30
295	291.25	291.23	291.22	291.26	291.27
300	295.37	295.36	295.36	295.38	295.39
305	299.56	299.56	299.56	299.57	299.57
310	303.81	303.81	303.81	303.81	303.81
315	308.15	308.15	308.16	308.14	308.14
320	312.48	312.49	312.50	312.47	312.47

4.2 Surface Emittance

Integrated upwelling radiance and EBT were evaluated for several values of surface emittance between 1.00 and 0.70 for all values of input surface temperature, T_s . Since reflected solar radiation makes significant contribution to the total upwelling radiance in the daytime (for this spectral region), it was included in one set of calculations. Another set of calculations was performed with the solar reflected component excluded from consideration for application to nighttime conditions.

Results obtained for an input surface temperature $T_s = 300°K$ have been chosen again for graphical illustration. Figure 4.6 shows the results for daytime condition for the deviation of surface emittance, $\Delta\varepsilon$, from its standard value, which was unity. Value of ε was varied up to 0.7 and it can be seen that over the present range of variation of ε , the relation between $\Delta\varepsilon$ and the corresponding additional correction ΔT_ε can be represented adequately by a straight line. However, results obtained for higher values of T_s could only be represented satisfactorily by a quadratic expression and, therefore, in the interest of uniformity, quadratic representation was used for the entire range of T_s values.

Figure 4.7 shows the results obtained for the nighttime condition (solar reflected component excluded) for $T_s = 300°K$. The same range of ε values was considered in this case as in the previous one. Computed values of additional correction, ΔT_ε are represented by the solid circles and the solid line represents the best linear fit to the data. In this case, differences greater than 0.1°K were observed between computed values of ΔT_ε and those obtained from the linear representation and, therefore, a higher order fit was attempted. The dashed line represents the least-squares quadratic fit to the data. Since this is found to be satisfactory, the same was done for representing the data for all other values of T_s also.

The coefficients of quadratic regression, namely, a_o , a_1 and a_2 for all values of T_s for the daytime (IR=1) as well as nighttime (IR=0) conditions are given in Table 4.5. Note that IR=1 refers to the daytime condition when the reflected solar component is included. IR=0 refers to the

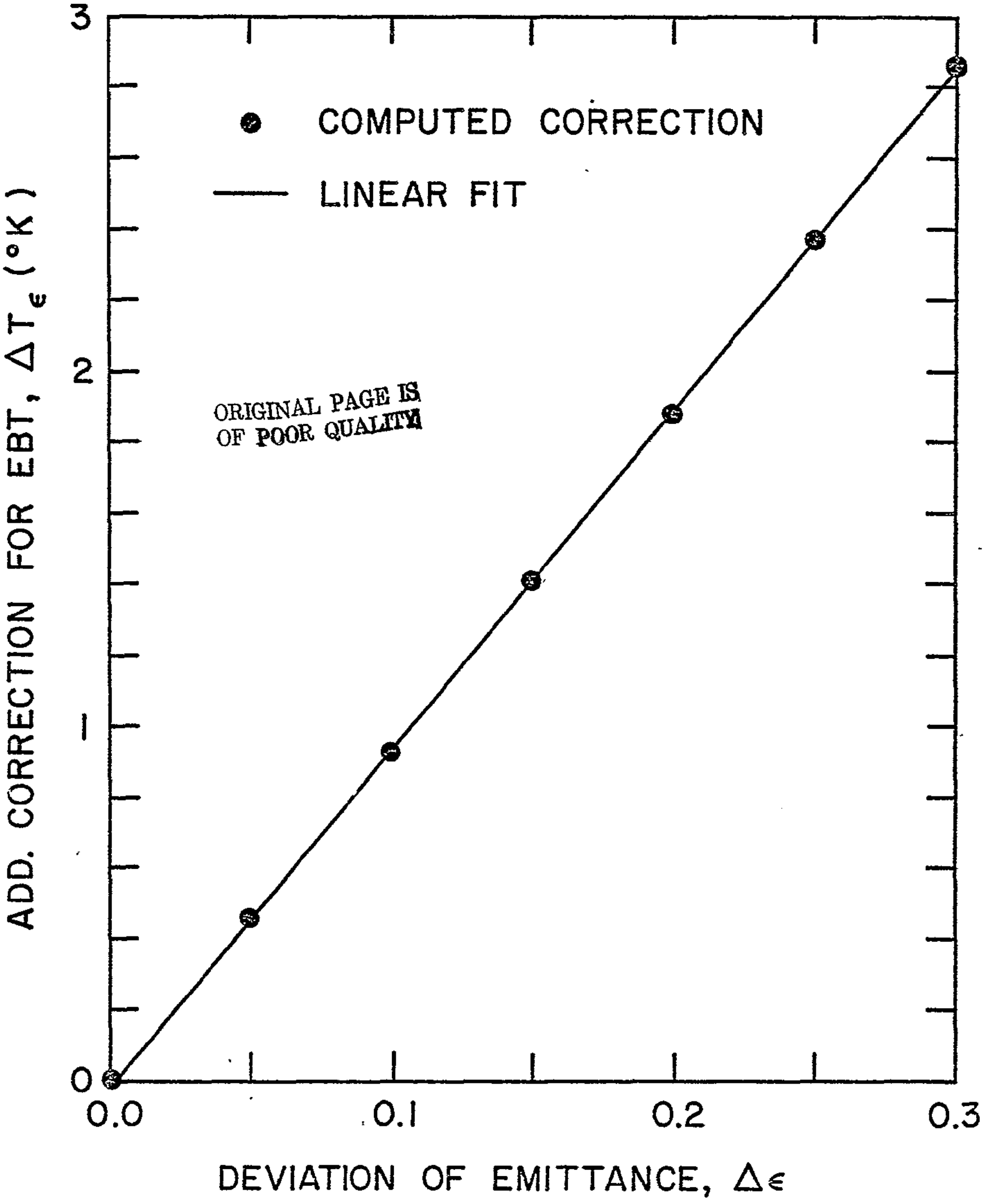

Figure 4.6. Additional correction for EBT as a function of the deviation of surface emittance for daytime condition (IR = 1) and T_s = 300 °K.

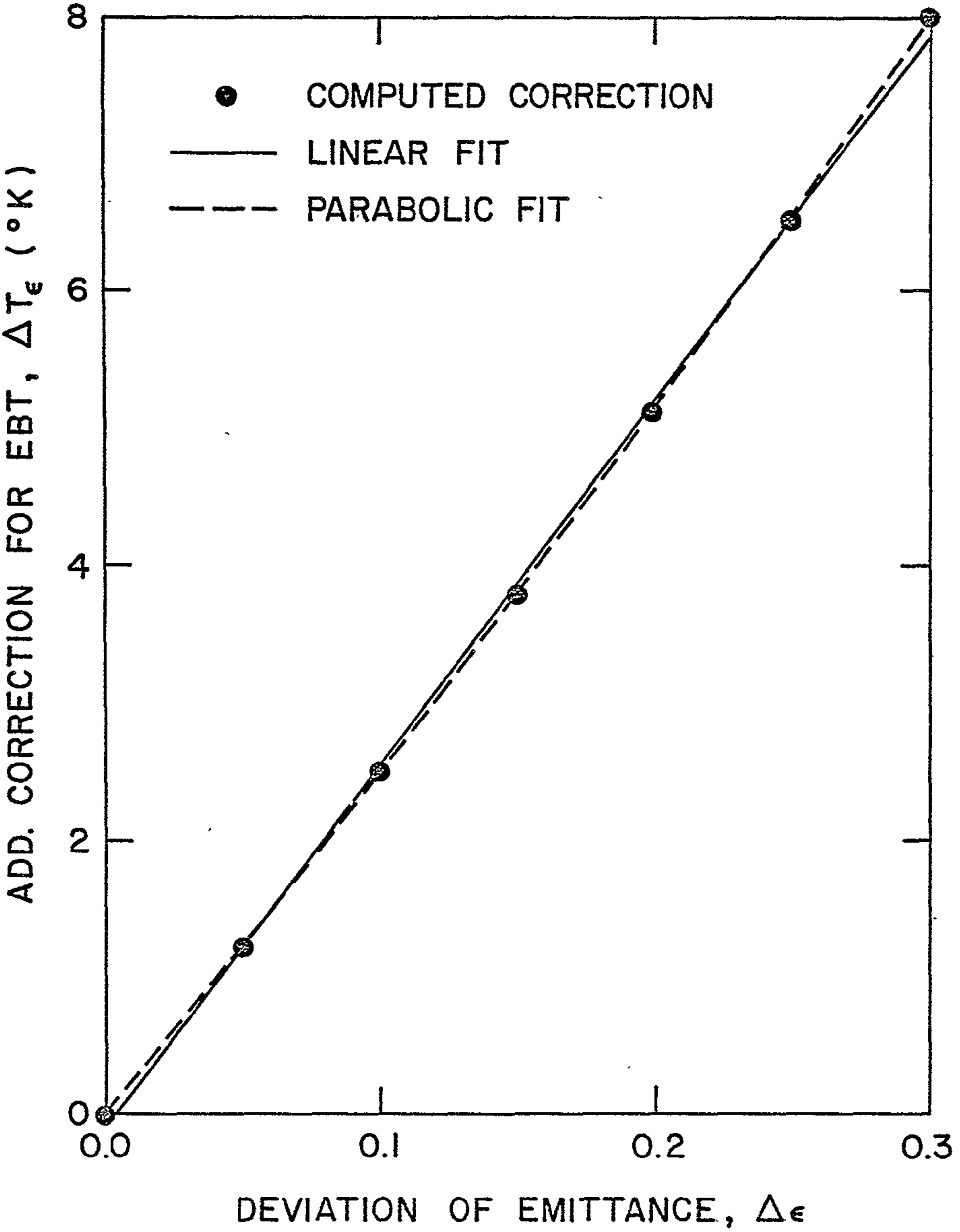

Figure 4.7. Additional correction for EBT as a function of the deviation of surface emittance for nighttime condition (IR = 0) and T_s = 300 °K.

nighttime condition when solar reflected component is not included in the total upwelling radiance. Since the curves in both Figures 4.6 and 4.7 go through the origin, it is evident that the coefficients a_o in both cases are insignificant.

Table 4.5

Regression coefficients of surface emittance variation study.

Input Surface Temp. (°K)	IR=1			IR=0		
	a_0	a_1	a_2	a_0	a_1	a_2
290	0.0000	2.6000	0.0000	0.0021	21.1357	8.1429
295	0.0017	5.9143	0.4762	0.0048	21.8357	10.8095
300	-0.0010	9.2071	1.0952	0.0064	23.7143	9.4286
305	0.0024	11.9429	2.4762	0.0024	24.8929	11.1905
310	0.0005	14.6143	2.9524	0.0112	25.6929	12.8095
315	-0.0005	17.1786	4.3333	0.0036	27.4429	12.0000
320	0.0060	19.0357	6.3333	0.0090	28.0071	14.8095

It can be seen that the significant regression coefficients a_1 and a_2, for both cases (IR=1 and 0), are dependent on the input surface temperature T_s. Variation of these coefficients with T_s is shown in Figures 4.8-4.11. It is evident from these figures that with the exception of a_1 for IR=1, it is not feasible to represent these coefficients with simple analytical functions in terms of T_s. Also, since T_s is the required end result of the computation, an iterative method (to be discussed later) will be used to obtain the appropriate values of a_1 and a_2.

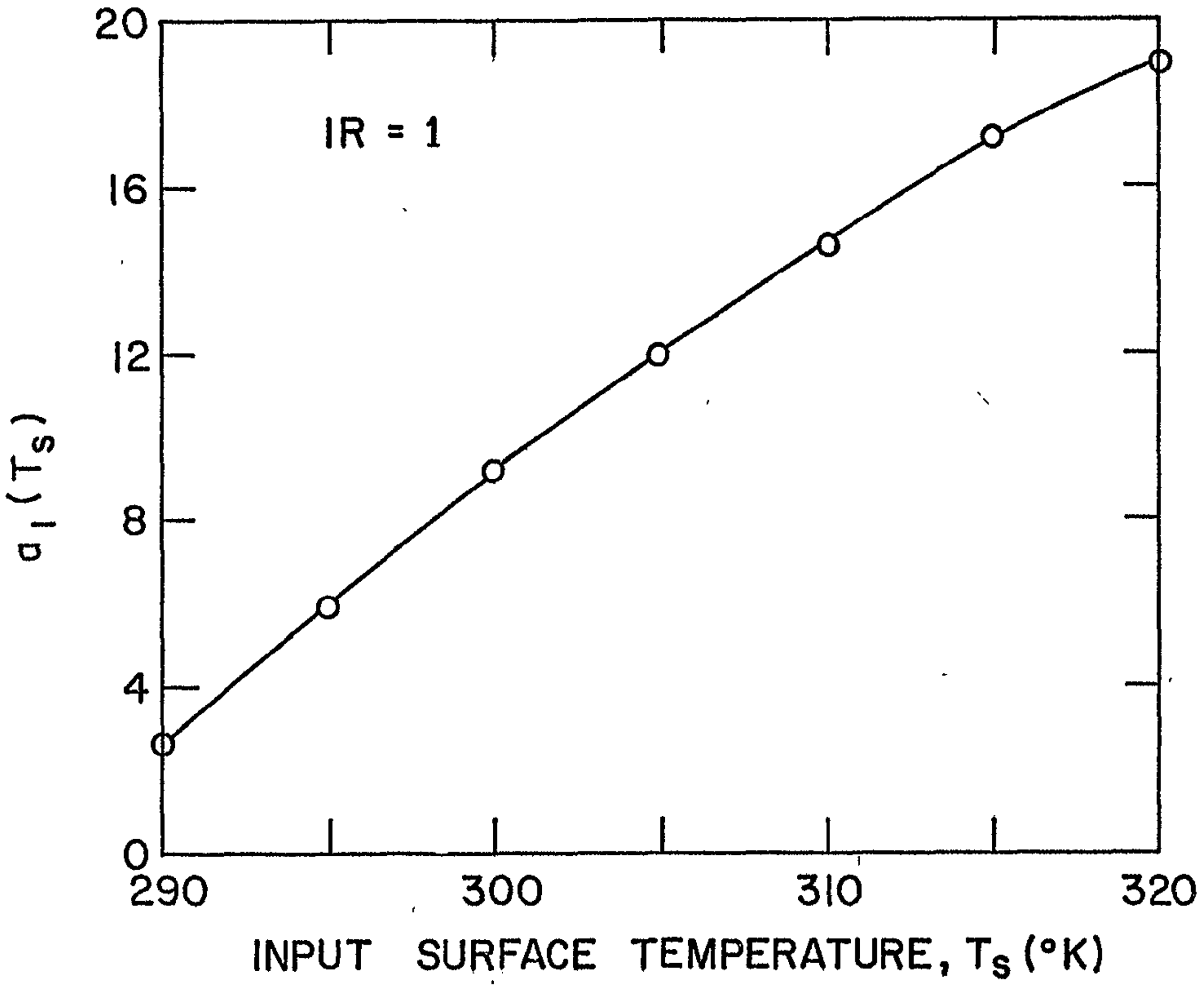

Figure 4.8. Regression coefficient a_1 as a function of input surface temperature, T_s, for daytime condition (IR = 1).

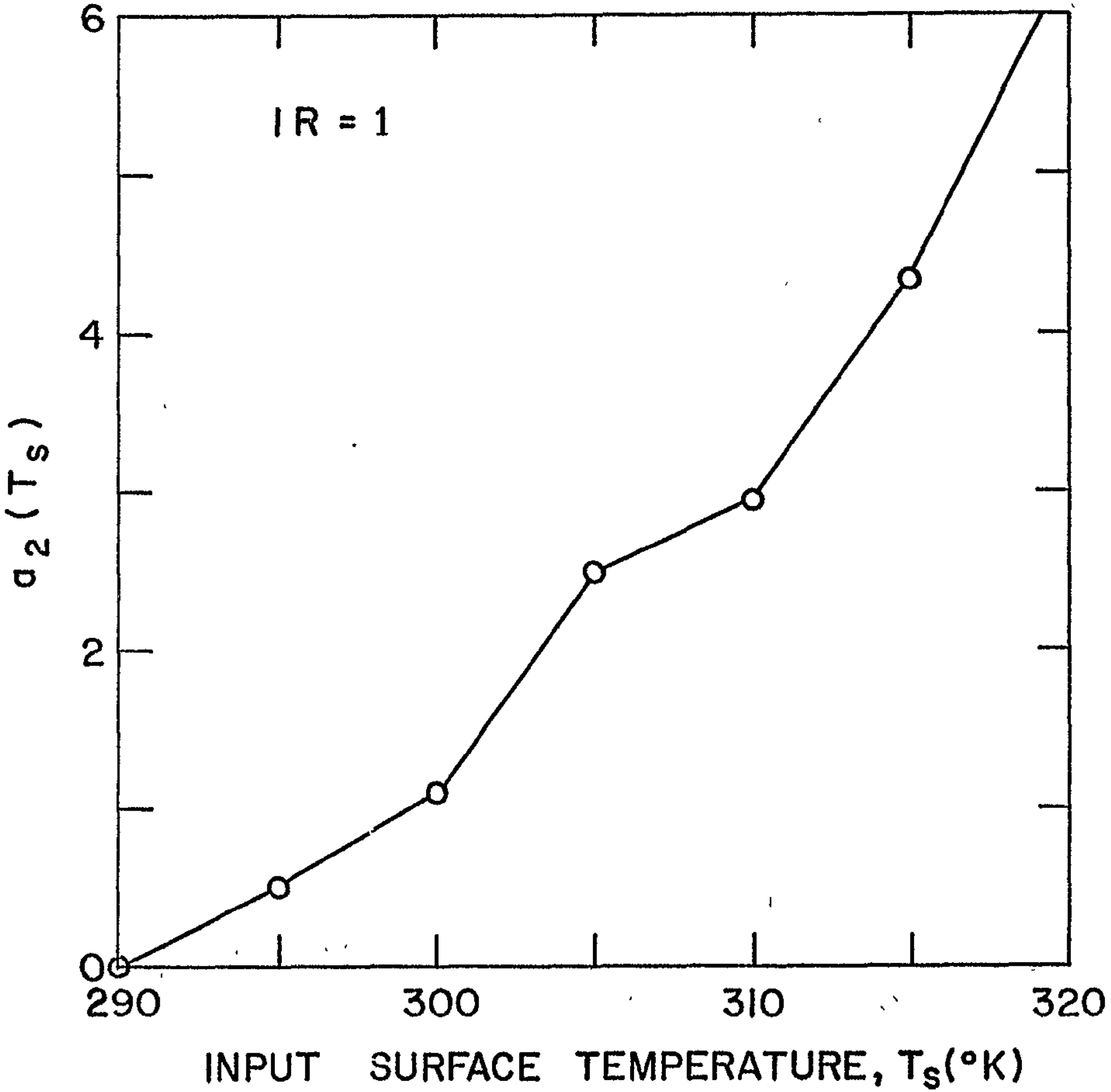

Figure 4.9. Regression coefficient a_2 as a function of input surface temperature, T_s, for daytime condition (IR = 1).

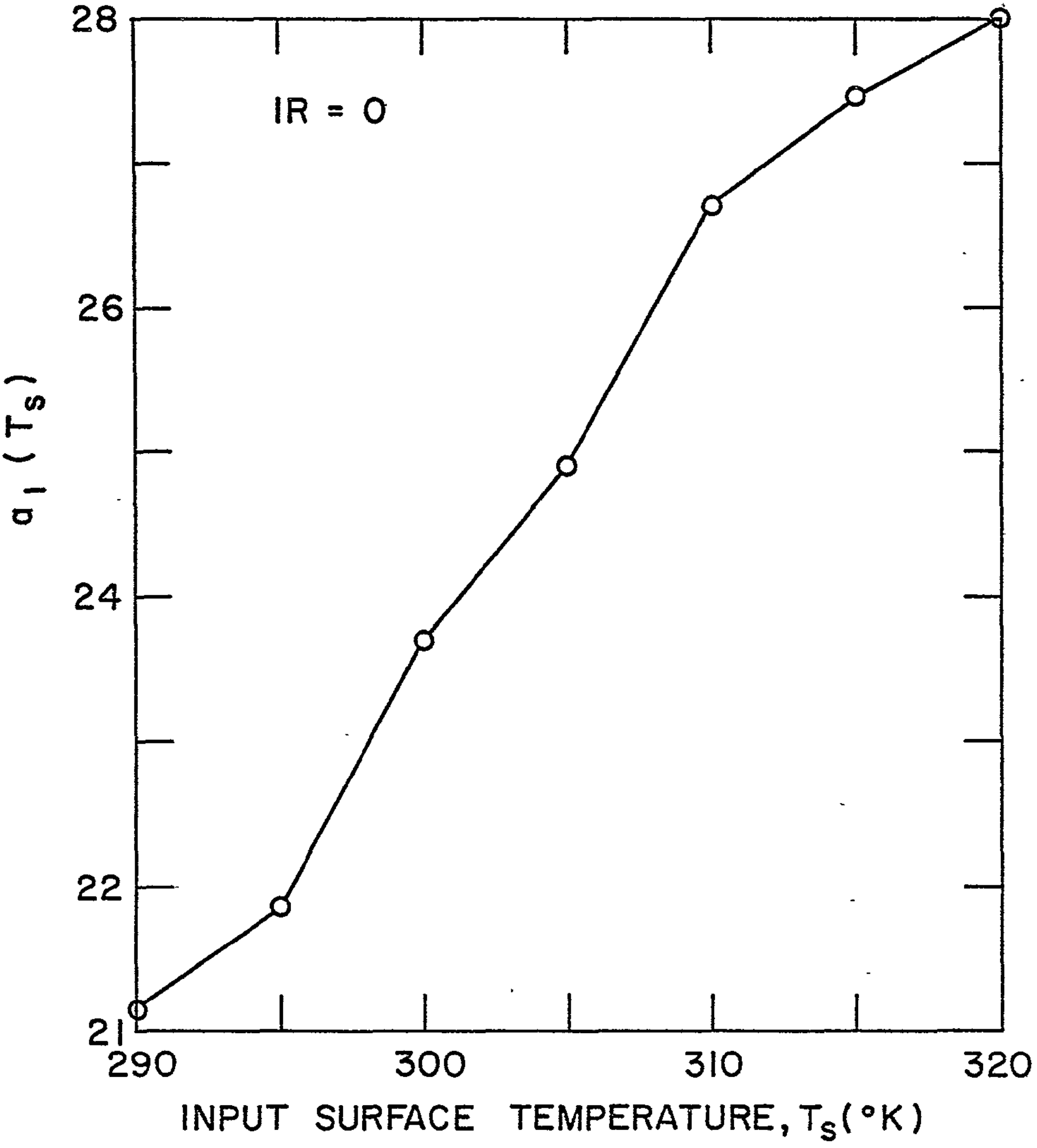

Figure 4.10. Regression coefficient a_1 as a function of input surface temperature, T_s, for nighttime condition (IR = 0).

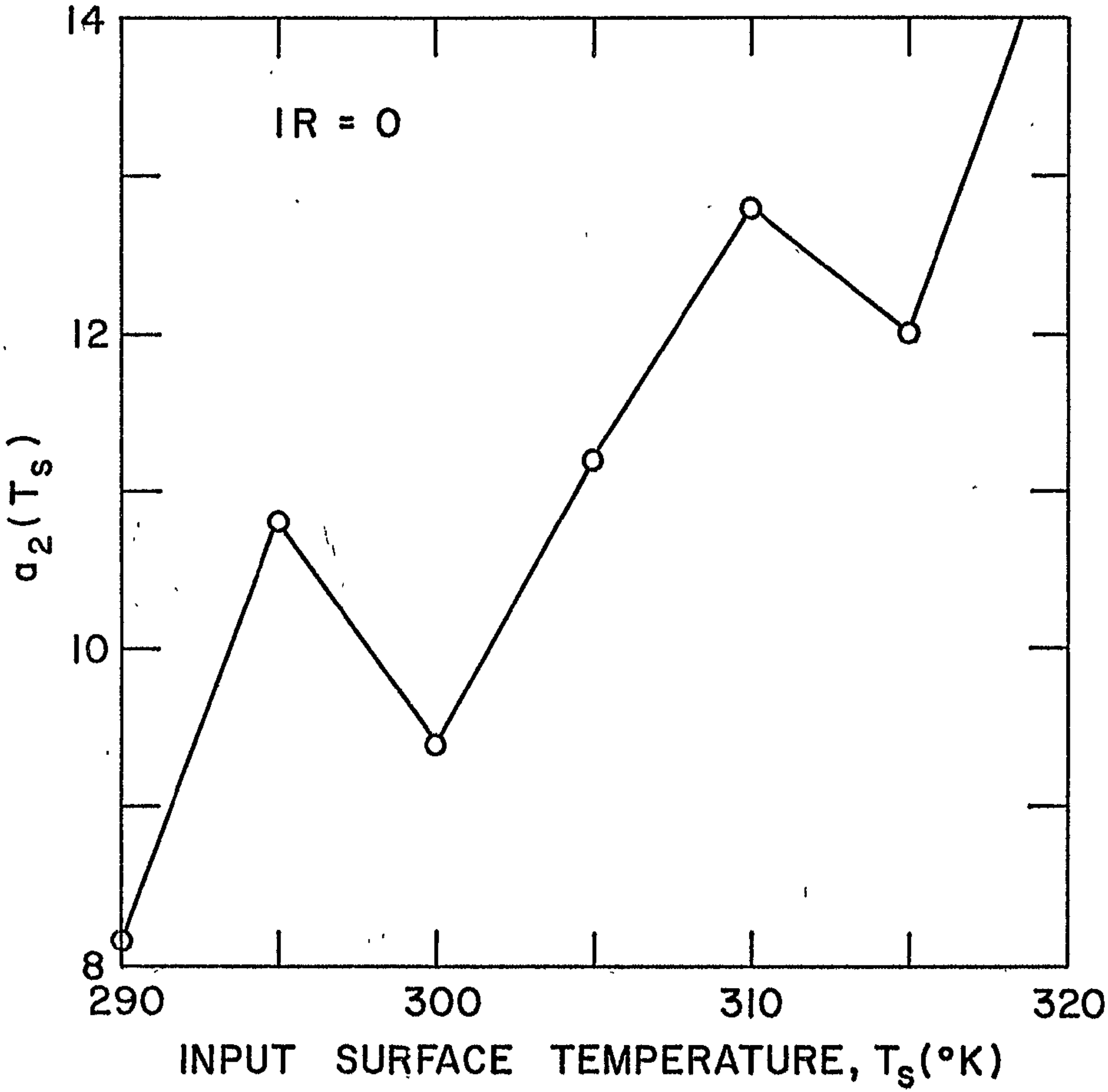

Figure 4.11. Regression coefficient a_2 as a function of input surface temperature, T_s, for nighttime condition (IR = 0).

4.3 CO Concentration

Earlier studies [8] indicate that the deviation of CO concentration in the atmosphere has a significant effect on EBT, although the magnitude of the additional correction in this case is much smaller than for the water vapor deviations. Two variations of CO concentration (0.1 and 0.3 ppmV), in addition to the base model value of 0.2 ppmV, were examined in the present work. Results obtained for T_s = 300 °K are shown in Fig. 4.12. The solid circles represent the computed additional correction to EBT and the solid line the least-squares linear fit to the data. It is found that the straight line adequately represents these results as well as those for other values of T_s . Table 4.6 lists the retrieved values of EBT for all values of T_s under different conditions and the coefficients of linear regression a_o and a_1 .

Table 4.6

Effect of variation of CO concentration
in the atmosphere on EBT.

Input Surface Temp. (°K)	EBT for CO=0.2 ppmV	CO = 0.1 ppmV		CO = 0.3 ppmV		a_o	a_1
		EBT	ΔT_x	EBT	ΔT_x		
290	287.03	287.17	0.14	286.90	-0.13	0.0033	-1.35
295	290.93	291.12	0.19	290.77	-0.16	0.0100	-1.75
300	294.97	295.20	0.23	294.77	-0.20	0.0100	-2.15
305	299.10	299.37	0.27	298.87	-0.23	0.0133	-2.50
310	303.26	303.57	0.31	303.01	-0.25	0.0200	-2.80
315	307.54	307.88	0.34	307.26	-0.28	0.0200	-3.10
320	311.82	312.19	0.37	311.51	-0.31	0.0200	-3.40

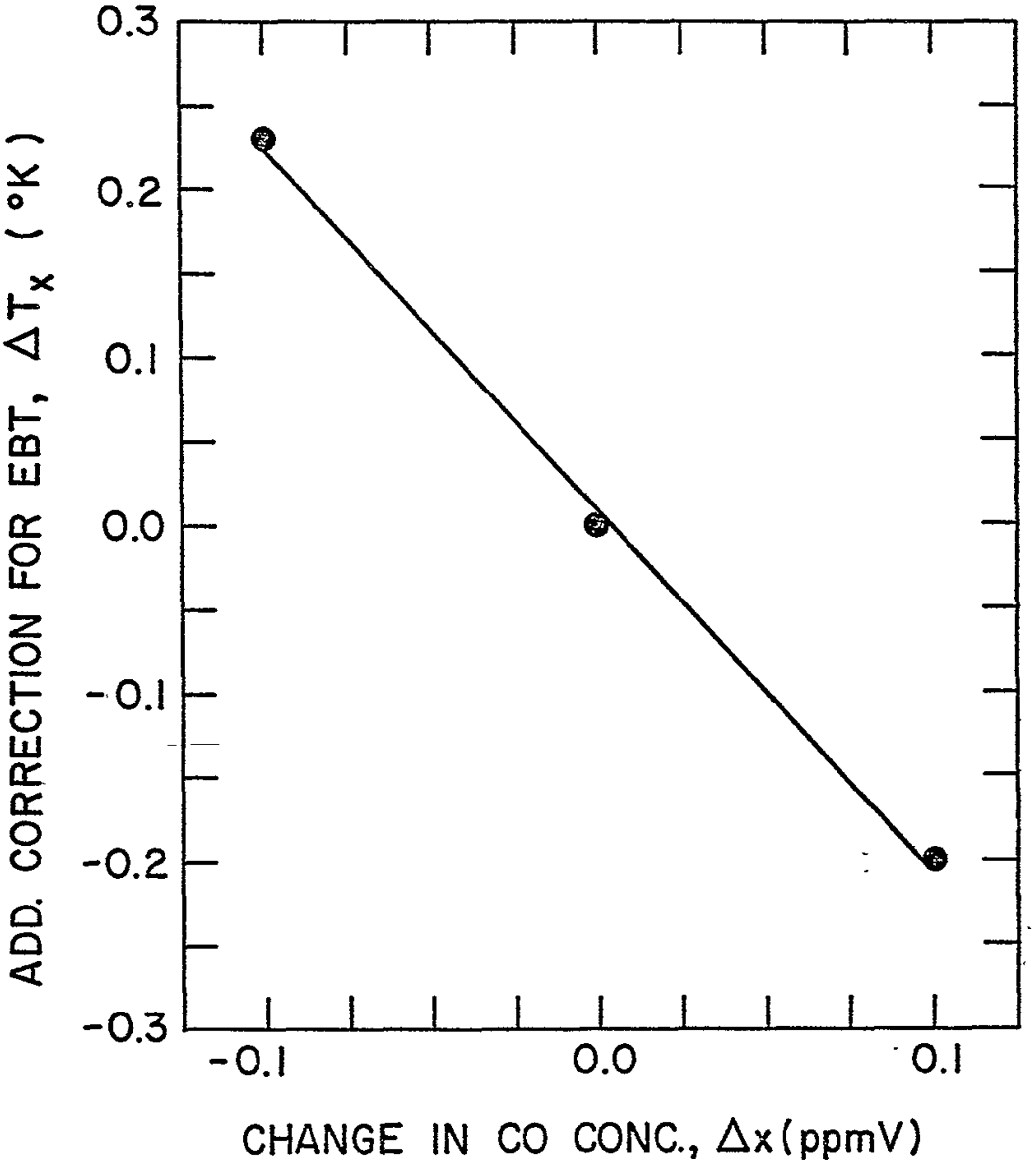

Figure 4.12. Additional correction for EBT as a function of the deviation of atmospheric CO concentration.

Again, because of the line going through the origin, the coefficients a_o are insignificant. Also, since a_1 is dependent on T_s, the iterative procedure is used to obtain the appropriate value of a_1. Figure 4.13 shows the variation of a_1 as a function of T_s.

4.4 Atmospheric Temperature Profile

Atmospheric temperature distribution is expected to have a significant effect on the upwelling radiance and hence on the EBT. This effect was examined numerically by adopting two additional atmospheric temperature profiles. Since the temperature gradient in the troposphere is relatively constant, profiles with fixed biases of +2°K and -2°K relative to the standard, are considered realistic. Results of this computation for an input surface temperature (T_s) of 300°K are shown in Figure 4.14 where solid circles represent the computed values of ΔT_x and the line represents the least-squares linear fit to the data. It is obvious again that these data and those for other values of T_s can be represented adequately by straight lines. Retrieved values of EBT for all values of T_s with different temperature profiles and the coefficients of linear regression, a_o and a_1 are listed in Table 4.7. Here again, the coefficients a_o are not significant and a_1, as a function of T_s, is shown in Figure 4.15. Appropriate values of a_1 are obtained from the iterative procedure mentioned earlier.

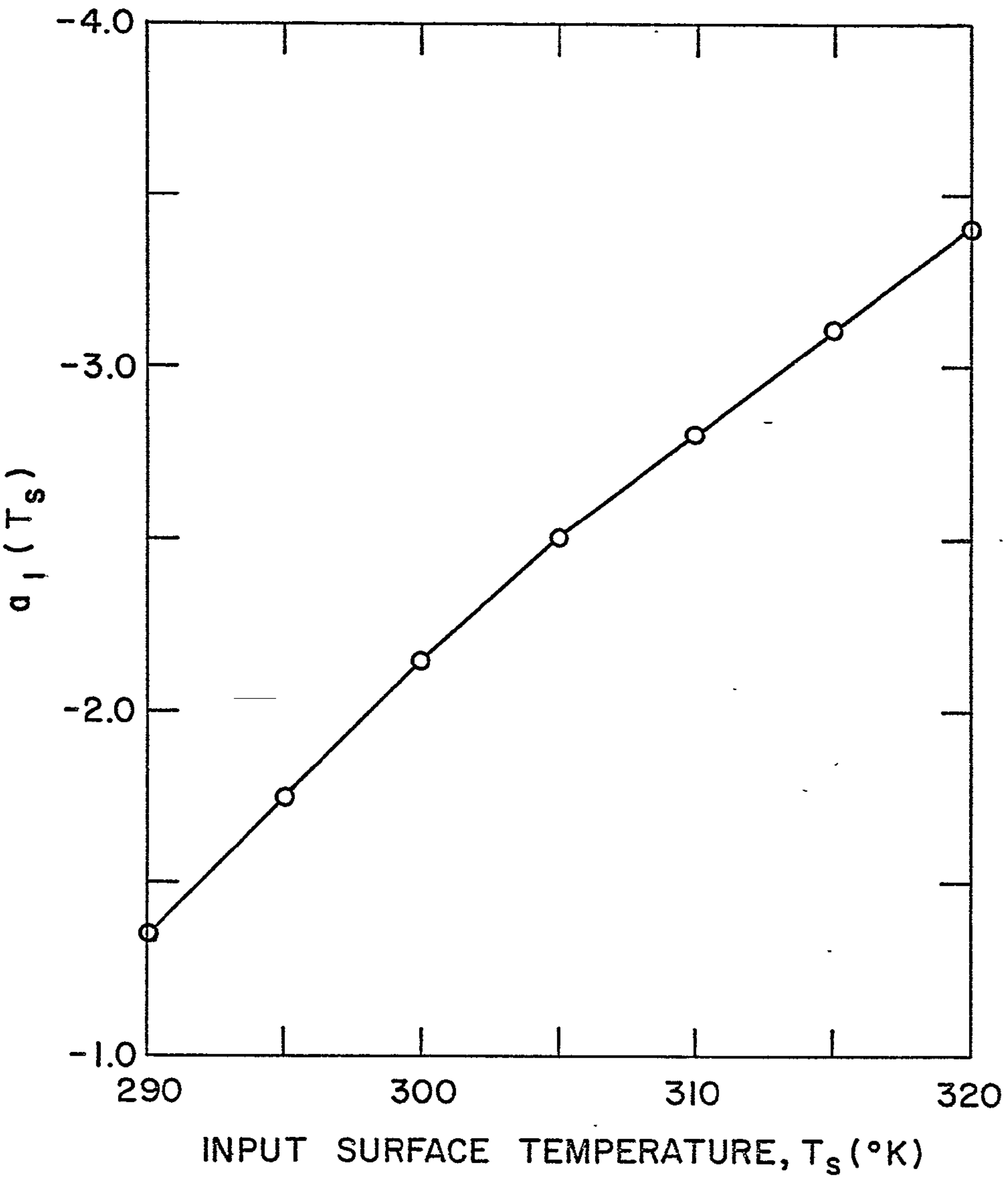

Figure 4.13. Regression coefficient a_1 as a function of input surface temperature, T_s, for the CO concentration deviations.

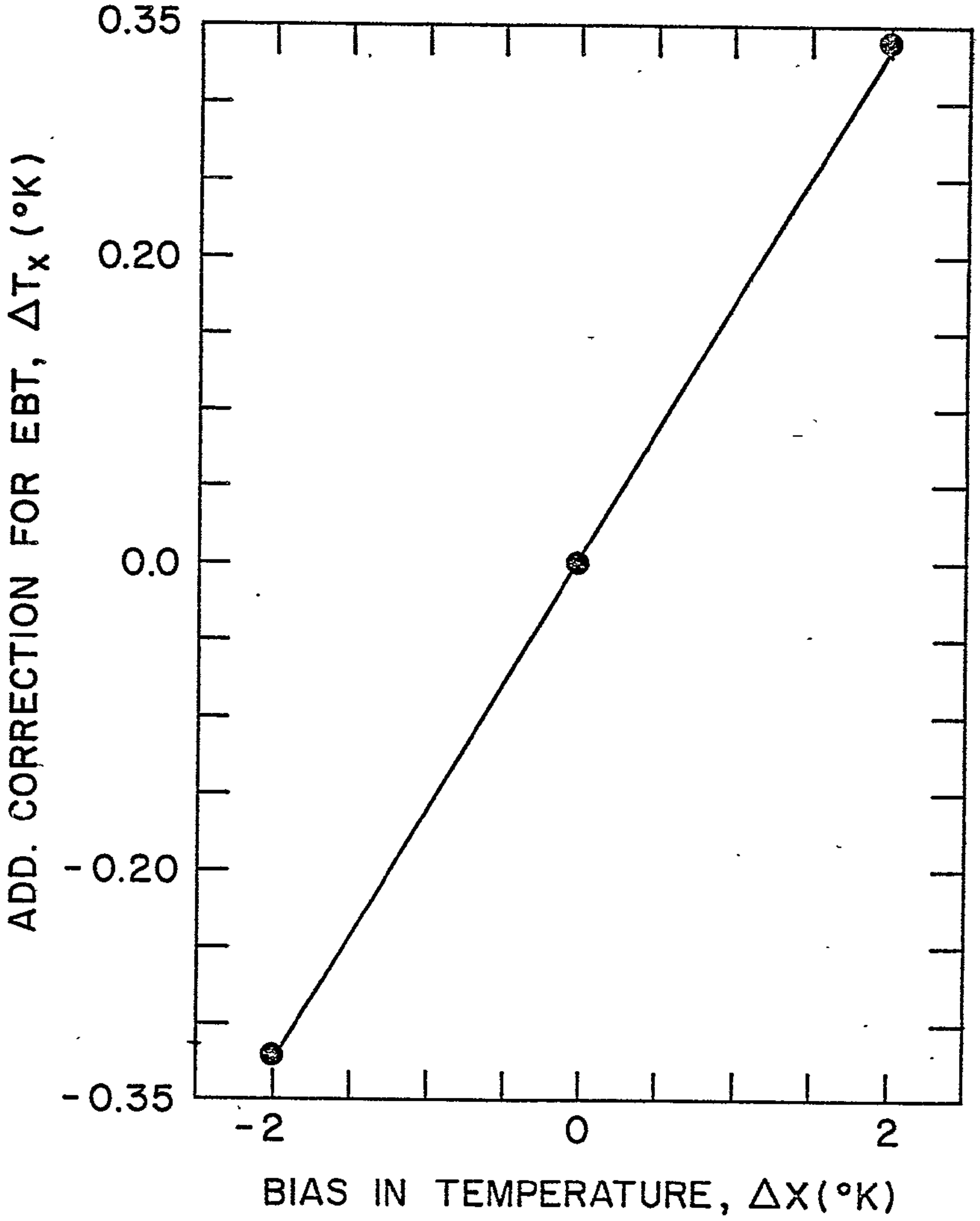

Figure 4.14. Additional correction for EBT as a function of the biases in the atmospheric temperature profile.

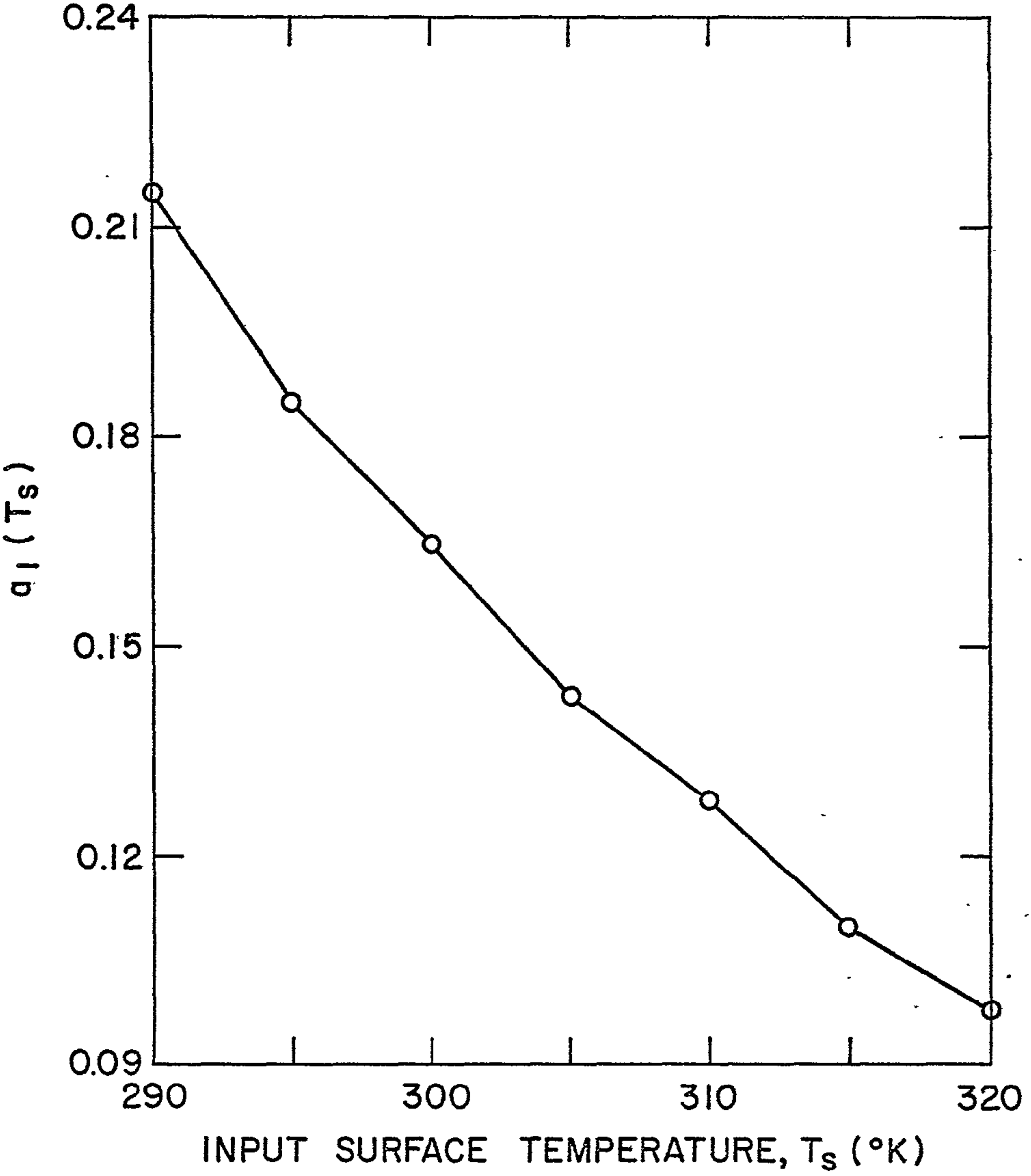

Figure 4.15. Regression coefficient a_1 as a function of input surface temperature, T_s, for the atmospheric temperature profile biases.

Table 4.7

Effect of deviation of atmospheric temperature profile on EBT. (T stands for the standard temperature profile and T' for the modified profile.)

Input Surface Temp. (°K)	EBT with Standard Profile	T' = T + 2		T' = T - 2		a_o	a_1
		EBT	ΔT_x	EBT	ΔT_x		
290	287.03	287.47	0.44	286.61	-0.42	0.0067	0.215
295	290.93	291.31	0.38	290.57	-0.36	0.0067	0.185
300	294.97	295.31	0.34	294.65	-0.32	0.0067	0.165
305	299.10	299.39	0.29	298.82	-0.28	0.0033	0.143
310	303.26	303.53	0.27	303.02	-0.24	0.0100	0.128
315	307.54	307.77	0.23	307.33	-0.21	0.0067	0.110
320	311.82	312.02	0.20	311.63	-0.19	0.0033	0.098

4.5 Altitude of Observation

In actual flight experiments, it may not be possible to fly exactly at the same altitude every time for which the model calculations are made. Since upwelling radiance (and hence EBT) depends on the altitude of observation, computations were made to determine the variation of the additional EBT correction with the altitude of observation. EBT obtained for altitudes 500 ft. below and above the standard altitude of 10,500 ft. are listed in Table 4.8 for all values of T_s . An inspection of the data in this table shows that the additional corrections ΔT_x for each value of T_s can be represented by a straight line. All values of a_o are found to be zero in this case and values of a_1 listed in the table. Figure 4.16 shows a_1 as a function of the input surface temperature T_s .

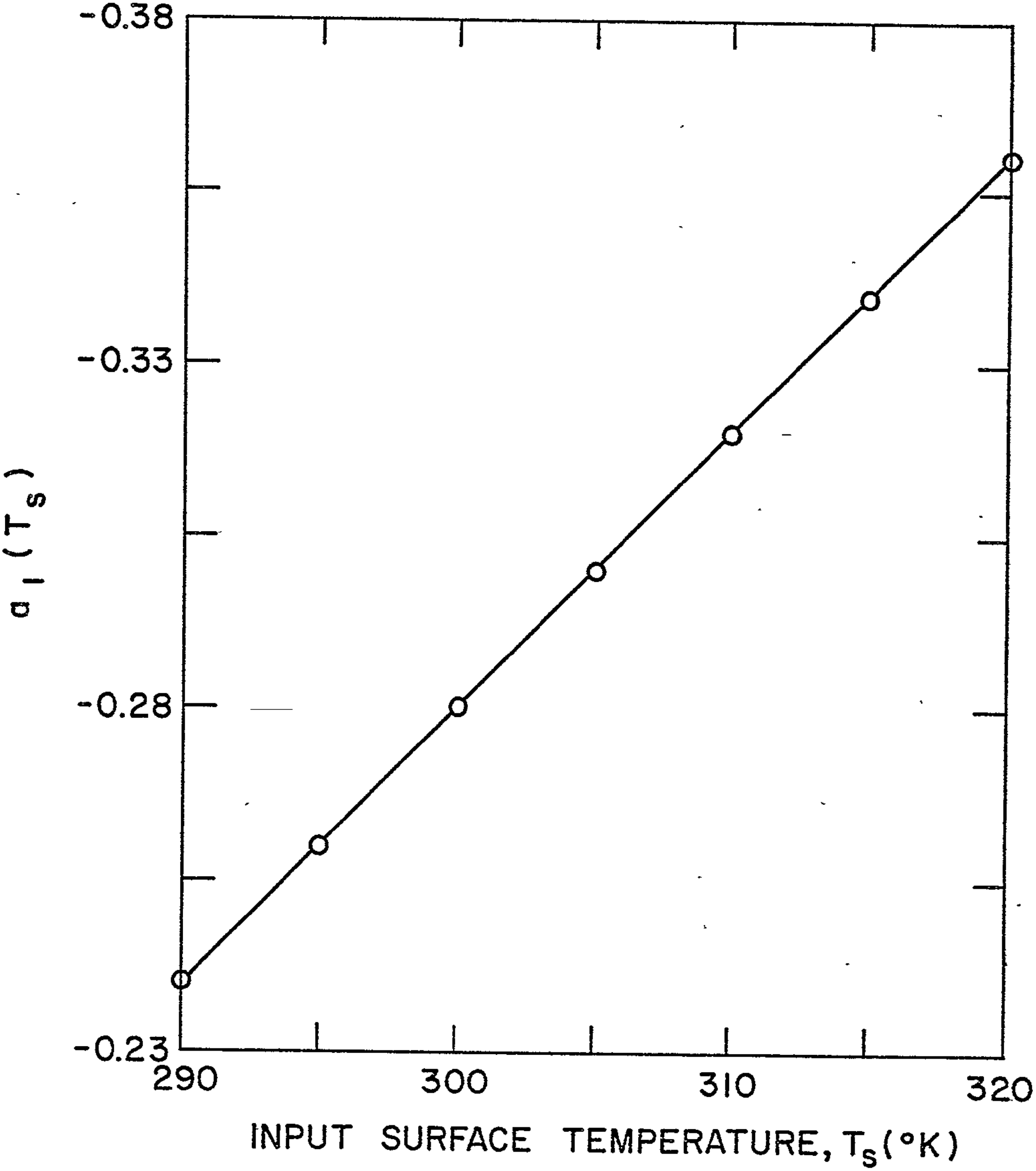

Figure 4.16. Regression coefficient a_1 as a function of input surface temperature, T_s, for the deviations of the altitude of observation.

Table 4.8

Effect of deviation of the altitude of observation on EBT.

Input Surface Temp.(°K)	EBT from 10,500 ft.	From 11,000 ft.		From 10,000 ft.		a_1
		EBT	ΔT_x	EBT	ΔT.	
290	287.03	286.91	-0.12	287.15	0.12	-0.24
295	290.93	290.80	-0.13	291.06	0.13	-0.26
300	294.97	294.83	-0.14	295.11	0.14	-0.28
305	299.10	298.95	-0.15	299.25	0.15	-0.30
310	303.26	303.11	-0.15	303.43	0.17	-0.32
315	307.54	307.37	-0.17	307.71	0.17	-0.34
320	311.82	311.64	-0.18	312.00	0.18	-0.36

4.6 CO_2 and N_2O Concentration

In the troposphere, concentrations of CO_2 and N_2O are well known and are highly stable. However, small variations from one geographic location to another are possible due to local perturbations. Values of EBT were obtained for CO_2 concentrations of 300 and 350 ppmV in addition to the standard value of 320 ppmV. The values of N_2O concentration considered in addition to the standard value of 0.27 ppmV were 0.25 and 0.30 ppmV. Additional EBT corrections obtained for all values of T_s for CO_2 and N_2O deviations are presented in Tables 4.9 and 4.10, respectively. An inspection of these tables shows that ΔT_x is approximately linearly dependent on the deviation of the input parameter in all cases. However, the magnitudes of ΔT_x in these cases were smaller than or close to 0.1°K. Therefore, no regression analysis was performed.

Table 4.9

Effect of deviation of CO_2 concentration in the atmosphere on EBT.

Input Surface Temp.(°K)	EBT with CO_2 = 320 ppmV	CO_2 = 300 ppmV		CO_2 = 350 ppmV	
		EBT	ΔT_x	EBT	ΔT_x
290	287.03	287.06	0.03	286.98	-0.05
295	290.93	290.97	0.04	290.87	-0.06
300	294.97	295.01	0.04	294.90	-0.07
305	299.10	299.15	0.05	299.02	-0.08
310	303.26	303.32	0.06	303.18	-0.08
315	307.54	307.61	0.07	307.44	-0.10
320	311.82	311.89	0.07	311.71	-0.11

Table 4.10

Effect of deviation of N_2O concentration in the atmosphere on EBT.

Input Surface Temp.(°K)	EBT with N_2O = 0.27 ppmV	N_2O = 0.25 ppmV		N_2O = 0.30 ppmV	
290	287.03	287.05	0.02	287.00	-0.03
295	290.93	290.95	0.02	290.89	-0.04
300	294.97	295.00	0.03	294.92	-0.05
305	299.10	299.13	0.03	299.04	-0.06
310	303.26	303.31	0.05	303.20	-0.06
315	307.54	307.58	0.04	307.47	-0.07
320	311.82	311.87	0.05	311.75	-0.07

5. ANALYSIS AND DISCUSSION OF MODEL CALCULATIONS: SIMULTANEOUS VARIATION OF PARAMETERS

Deviation of only a single parameter from their base model values, as considered in the previous section, represents a rather idealized situation for the real atmosphere where more than one parameter may undergo deviations at the same time. In this preliminary study, we have tried to examine some cases where two of the input parameters undergo deviations simultaneously. It is evident from the discussion in section 4 that the important parameters affecting the effective brightness temperature are water vapor concentration, surface emittance, CO concentration and the atmospheric temperature profile. Several combinations of the deviations of these parameters have been examined in this section. It is intended to establish relationships between the combined additional correction ΔT_{xc} and the individual additional corrections ΔT_x caused by separate variations of the two parameters.

5.1 Carbon Monoxide - Water Vapor Variations

The first case considered in this study was that of water vapor = 1.5 x standard, and carbon monoxide = 0.3 ppmV. Results of the model calculations for this particular case are presented in Table 5.1. As shown in the last column, the differences between the linear sum of the individual additional corrections ΔT_x and ΔT_y and the combined additional correction ΔT_{xc} , for the entire range of T_s is no greater than 0.02°K.

Table 5.1

Simultaneous variation of parameters

(H_2O = 1.5 x Standard - CO = 0.3 ppmV)

Input Surface Temp. (°K)	EBT with base model (°K)	EBT with this model (°K)	ΔT_{xc}	ΔT_x for H_2O=1.5x standard	ΔT_y for CO=0.30 ppmV	$\Delta T_x+\Delta T_y$	Diff.
290	287.03	286.20	-0.83	-0.71	-0.13	-0.84	0.01
295	290.93	289.79	-1.14	-0.99	-0.16	-1.15	0.01
300	294.97	293.51	-1.46	-1.28	-0.20	-1.48	0.02
305	299.10	297.37	-1.73	-1.52	-0.23	-1.75	0.02
310	303.26	301.27	-1.99	-1.75	-0.25	-2.00	0.01
315	307.54	305.29	-2.25	-1.98	-0.28	-2.26	0.01
320	311.82	309.37	-2.45	-2.16	-0.31	-2.47	0.02

A similar computation was made for another case, namely, water vapor = 2 x standard, and carbon monoxide = 0.1 ppmV, and the results indicate again that the combined additional correction ΔT_{xc} is approximately equal to the sum of the individual additional corrections ΔT_x and ΔT_y . It can be inferred from these results that the combined additional correction can be represented as a linear combination of the individual additional corrections when the parameters undergoing deviations are the concentrations of the various constituents. The relationship in such cases can be represented mathematically as

$$\Delta T_{xc} = \Delta T_x + \Delta T_y \qquad (5.1)$$

5.2 Surface Emittance - Carbon Monoxide Variations

Another case examined for this study was that of, surface emittance = 0.90 (IR=0), and carbon monoxide = 0.1 ppmV. Table 5.2 shows the results of the model calculations obtained for this case. It is apparent from the last column of the table that the differences between the combined additional correction ΔT_{xc} and the sum of the individual additional corrections are very small. This indicates that a linear combination relation similar to equation (5.1) will be applicable in this case also.

Table 5.2

Simultaneous variation of parameters
(Surface emittance = 0.90 (IR=0), CO = 0.1 ppmV)

Input Surface Temp. (°K)	EBT with base model (°K)	EBT with this model (°K)	ΔT_{xc}	ΔT_x for ε=0.90 (IR=0)	ΔT_y for CO=0.1 ppmV	$\Delta T_x+\Delta T_y$	Diff.
290	287.03	284.95	-2.08	-2.20	0.14	-2.06	0.02
295	290.93	288.80	-2.3	-2.30	0.19	-2.11	0.02
300	294.97	292.70	-2.27	-2.48	0.23	-2.25	0.02
305	299.10	296.75	-2.35	-2.60	0.27	-2.33	0.02
310	303.26	300.82	-2.44	-2.72	0.31	-2.41	0.03
315	307.54	304.99	-2.55	-2.87	0.34	-2.53	0.02
320	311.82	309.21	-2.61	-2.96	0.37	-2.59	0.02

5.3 Surface Emittance - Water Vapor Variations

Another similar case examined here is that for surface emittance = 0.90 (IR=1), and water vapor = 0.5 x standard. The results of model calculation obtained for this particular case are presented in Table 5.3. In this case also, the differences between the combined additional correction and the linear sum of the individual additional corrections are either less than 0.10°K or only slightly greater than that and so are still acceptable. In this case also, therefore, a linear combination relation, similar to (5.1), would be applicable.

Two more combinations of surface emittance - water vapor

Table 5.3

Simultaneous variation of parameters
Surface emittance = 0.90 (IR=1),
Water vapor = 0.5 x standard

Input Surface Temp. (°K)	EBT with base model (°K)	EBT with this model (°K)	ΔT_{xc}	ΔT_x for ε = 0.90 (IR=1)	ΔT_x for H_2O=0.5 x standard	$\Delta T_x+\Delta T_y$	Diff.
290	287.03	287.57	+0.54	-0.26	0.68	0.42	-0.12
295	290.93	291.35	+0.42	-0.60	0.94	0.34	-0.08
300	294.97	295.29	+0.32	-0.93	1.20	0.27	-0.05
305	299.10	299.32	+0.22	-1.22	1.40	0.18	-0.04
310	303.26	303.41	+0.16	-1.49	1.64	0.15	-0.01
315	307.54	307.60	+0.06	-1.76	1.81	0.05	-0.01
320	311.82	311.81	-0.01	-1.98	2.00	0.02	+0.03

variations were examined in addition to the one discussed above. They are: (i) surface emittance = 0.80 (IR=0), and water vapor = 0.5 x standard, (ii) surface emittance = 0.80 (IR=1), and water vapor = 0.5 x standard. Results of the model calculations for the case (i) are presented in Table 5.4. The differences listed in the last column are consistently much larger than 0.10°K. Large differences are observed for case (ii) also for most values of the surface temperature T_s . It is apparent from the analysis of these results that large deviations of surface emittance present a difficult problem in the estimation of surface temperature.

Table 5.4

Simultaneous variation of parameters

(Surface emittance = 0.80 (IR=0),
Water vapor = 0.5 x standard).

Input Surface Temp. (°K)	EBT with base model (°K)	EBT with this model (°K)	ΔT_{xc}	ΔT_x for $\varepsilon = 0.80$ (IR=0)	ΔT_y for H_2O=0.5 x Standard	$\Delta T_x+\Delta T_y$	Diff.
290	287.03	282.81	-4.22	-4.55	0.87	-3.87	-0.35
295	290.93	286.75	-4.18	-4.80	0.94	-3.86	-0.32
300	294.97	290.72	-4.25	-5.12	1.20	-3.92	-0.33
305	299.10	294.80	-4.30	-5.43	1.40	-4.03	-0.27
310	303.26	298.95	-4.31	-5.65	1.64	-4.01	-0.30
315	307.54	303.11	-4.43	-5.97	1.81	-4.16	-0.27
320	311.82	307.36	-4.46	-6.20	2.00	-4.20	-0.26

5.4 Water Vapor - Temperature Profile Variations

Initial analysis of two simultaneous variation cases showed that when deviation of the concentration of a certain constituent is accompanied with a constant bias in the vertical temperature profile, the resulting combined additional correction cannot be represented by a linear sum as in (5.1). This is mainly so because, in addition to the changed concentration of the constituent affecting the radiation, increased or decreased temperature in the atmosphere also affects the emission rates. Table 5.5 shows the results of model calculations for the two cases mentioned above which are: (i) water vapor = 2 x standard, temperature bias = +2°K, and (ii) water vapor = 2 x standard, temperature bias = -2°K. Columns 4 and 7 of Table 5.5 list the combined additional corrections obtained in these cases, while 5 and 8 list the differences between ΔT_{xc} and $\Sigma\Delta T_x$ for the two cases. These differences (columns 5 and 8) which average -0.25 and +0.25°K, respectively, are signigicantly larger than 0.10°K but their temperature dependence is weak at best and, therefore, will be ignored. These results suggest, however, that a detailed study be made of the simultaneous variation of the water vapor burden and the atmospheric temperature profile in order to establish a precise relationship between the individual and combined additional corrections. Model calculations were made for 1.5 and 2.0 times the standard water vapor burden and temperature profiles with biases of +1, +2, +3 and +4°K. Important results of these calculations are shown in Table 5.6. The numbers in the first two columns Δx and Δy represent the deviations of the two parameters (water vapor burden and atmospheric temperature, respectively). The third column, $\Delta T'$ represents differences between ΔT_{xc} and $\Sigma\Delta T_x$ averaged for the entire range of the input surface temperature. A parameter a' is defined as

$$a' = \Delta T'/(\Delta x \; \Delta y) \tag{5.2}$$

and is found to be approximately constant. The combined additional correction can, therefore, be represented as

$$\Delta T_{xc} = \Delta T_x + \Delta T_y + a'\Delta x \; \Delta y \tag{5.3}$$

Table 5.5

Simultaneous variation of parameters, retrieved EBT for 2 x standard water vapor and temperature profiles with constant biases of +2°K and -2°K.

Input Surface Temp.(°K)	EBT with base model(°K)	Temp. Bias = +2°K			Temp. Bias = -2°K		
		EBT (°K)	ΔT_{xc}	Diff.	EBT (°K)	ΔT_{xc}	Diff.
290	287.03	286.27	-0.76	-0.28	284.85	-2.18	0.28
295	290.93	289.52	-1.41	-0.27	288.25	-2.68	0.26
300	294.97	292.90	-2.07	-0.26	291.72	-3.25	0.26
305	299.10	296.46	-2.64	-0.27	295.37	-3.73	0.25
310	303.26	300.09	-3.17	-0.23	299.10	-4.16	0.25
315	307.54	303.82	-3.72	-0.24	302.90	-4.64	0.24
320	311.82	307.67	-4.15	-0.23	306.82	-5.00	0.23

Table 5.6

Simultaneous variation of parameters. Study of water vapor burden - temperature profile deviations.

Deviation of water vapor Δx	Deviation of temp.profile Δy	Diff. $\Delta T' = \Sigma\Delta T_x - \Delta T_{xc}$	$a' = \frac{\Delta T'}{\Delta x \, \Delta y}$
0.5	1.0	-0.06	-0.12
0.5	2.0	-0.12	-0.12
0.5	3.0	-0.17	-0.11
0.5	4.0	-0.23	-0.12
1.0	1.0	-0.13	-0.13
1.0	2.0	-0.25	-0.13
1.0	3.0	-0.38	-0.13
1.0	4.0	-0.51	-0.13

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6. EVALUATION OF SURFACE TEMPERATURE

As discussed in section 2, the total atmospheric correction can be determined by combining the base correction (Table 4.1) and the additional correction caused by the deviations of the various input parameters from their base model values. The additional corrections are calculated from the regression coefficients tabulated for the various cases in section 4.

6.1 Iterative Method for Coefficients.

It is evident from the results presented in section 4 that the coefficients a_1 and a_2 in subsections 4.1 and 4.2, and a_1 in subsections 4.3-4.5, as well as the base correction ΔT_o, are all dependent on the input surface temperature. Since the input surface temperature, T_s, is the desired end result of the entire computation, an iterative procedure has been developed to arrive at the appropriate values of the atmospheric correction. Values of the base correction and the coefficients referring to $T_s = 300°K$ are chosen as their initial estimates.

For cases involving deviaiton of a single parameter, total correction is computed by combining the initial estimate of the base correction and the additional correction computed from the initial estimates of the coefficients a_n, using appropriate form of equation (2.9). The total correction, combined with the measured value of EBT yields the first estimate of the actual surface temperature, say T_{s1}. Values of the temperature dependent base correction and the coefficients a_n are now obtained corresponding to T_{s1}. Since it was not found possible to represent the variation of all the coefficients a_n with T_s by simple analytical functions, it was decided to obtain the values of the coefficients corresponding to T_{s1} by linear interpolation between the tabulated values. The base correction, ΔT_o, corresponding to T_{s1} is also obtained by linear interpolation. Total correction is obtained corresponding to T_{s1} using the above information and the second estimate T_{s2} is obtained by combining it with EBT. The process continues till the successive estimates of T_s become consistent within 0.01°K

For cases involving simultaneous variation of two parameters, the additional correction is evaluated in a single step for both parameters [equation (5.1)] using all the relevant coefficients. Total correction is obtained in the same manner as described earlier and the iteration continues till the successive estimates of T_s are consistent within 0.01°K. As has been shown in section 5, for cases involving deviations of vertical temperature profile and water vapor concentration, equation (5.3) is used to evaluate the additional correction.

A computer program named ITERATE has been developed to accomplish the evaluation of T_s . The program uses an appropriate expression for computing the additional correction depending on whether none, one or two parameters have undergone deviations. Also, if the vertical temperature profile and water vapor concentration undergo deviations simultaneously, it uses equation (5.3) to compute additional correction. The program performs up to a maximum of ten iterations and if the result does not converge as desired, it reports the last estimate and indicates the non-convergence. A listing of this program is reproduced in Appendix B.

6.2 Sample Calculations with ITERATE

Several sample calculations have been made with program ITERATE to examine its usefulness in real situations. Since the real measurement data were not available at present, values of the measured EBT (T_e') and the corresponding values of the deviations of the input parameters Δx etc. obtained from some of the model calculations performed with program SURFACE were used in the present work. Most of the sample cases examined in this subsection involved deviations of two parameters, since the one parameter cases are relatively simple and present no problems. Results from some of these sample calculations are discussed below.

The first two sample cases involve deviations of the concentrations of certain constituents and the details are as follows. (1) T_e' (measured EBT) = 287.37°K, water vapor = 0.5 x standard, CO = 0.3 ppmV, and T_s(Retrieved Surface Temp.) = 305.06°K. (2) T_e' = 289.05°K, water vapor = 2 x standard, CO = 0.1 ppmV, and T_s = 295.01°K. For both these cases, the additional correction was evaluated using equation (5.1) and the retrieved surface temperature T_s is found to be within 0.10°K of the input surface temperature. The third sample case involves deviations of water vapor concentration and atmospheric temperature distribution, I.e., (3) T_e' = 300.09°K, water vapor = 2 x standard, T'(z) = (T(z) + 2) °K, and T_s = 309.99°K. As mentioned in section 5, equation (5.3) is used in this case for the evaluation of additional correction. The value of T_s obtained here agrees with the input value to better than 0.10°K.

The next two samples involve deviations of surface emittance. These are, (4) T_e' = 304.99°K, ε = 0.90 (IR=0), CO = 0.1 ppmV, and T_s = 314.71°K, and (5) T_e' = 311.81°K, ε = 0.90 (IR=1), water vapor = 0.5 x standard, and T_s = 319.89°K. In both of these cases, the differences between the retrieved surface temperature and the input surface temperature are larger than 0.10°K. these results are indicative of the difficulty mentioned in section 5 regarding agreement between the retrieved and input surface temperatures for cases involving deviations of surface emittance.

7. CONCLUSIONS

The present study shows that it is possible to represent the difference between the actual surface temperature (T_s) and the effective brightness temperature (T_e'), as measured remotely by a radiometer by simple analytical relations in terms of the magnitudes of various atmospheric and surface parameters. This difference, defined as the total correction consists of two parts; (i) base correction, which is the difference between T_s and T_e' due to the presence of the atmosphere with the parameters having their base model values, and (ii) additional correction, caused by the deviations of the parameters from their base model values. It was concluded, on the basis of the model calculations contained in section 4, that the additional correction can be represented by a simple linear or quadratic relation in terms of the deviation of the involved parameter from its base model value. In cases where two parameters undergo simultaneous deviations, the combined additional correction can be obtained from a simple (linear or otherwise) combination of the individual additional corrections. It is concluded that with the availability of precise information on pressure, temperature and humidity profiles, the actual surface temperature can be estimated with high degree of accuracy without having to perform radiative transfer calculations. The cumulative errors of computation, in most cases, do not exceed 0.1°K. For cases involving large deviations of surface emittance, cumulative errors as large as 0.3-0.4°K are encountered.

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APPENDIX A1

EXPLANATION OF SYMBOLS USED IN THE COMPUTER PROGRAM "SURFACE" AND ITS SUBROUTINES

AC	Array of monochromatic absorption coefficients within one interval.
ACB, ACE & ACM	Absorption coefficients due to wing contributions at the boundaries and the center of an interval.
AL	Array of half-widths of individual lines.
ALFT, ALKM	Altitudes of observation in feet and kilometers respectively.
ALX	Width of a narrow subinterval near line center.
AVN	Averaged upwelling radiance from the two beam paths of the instrument.
AVN1, AVN2	Total upwelling radiance inside and outside the instrument respectively.
AW	Water vapor continuum absorption coefficient for a given layer.
BVN	Averaged upwelling radiance for the in-atmosphere condition.
BVN1, BVN2	Total upwelling radiance inside and outside the instrument for the no-atmosphere condition.
CLEN	Length of the instrument gas cell.
COMP, COMQ	Atmospheric upwelling radiance outside and inside the instrument respectively.
CPTR	Pressure path length for the instrument gas cell.
DEL	Width of an interval (1 cm^{-1}).
DLIM	Width of the region from which the direct contribution is obtained.
EL	Array of the energies of the lower states for individual lines.
EMI	Surface emittance.
FACT	Factor used for obtaining line-intensities corresponding to the temperature of each layer.

FGR	Gradients used in computing the filter function for each interval from the tabulated values.
FIL	Array of filter function values for all intervals.
FR	Array of frequencies for individual lines.
FRB	Frequencies at the boundaries of the intervals.
FRC	Frequencies at the centers of the intervals.
FRE	Frequencies of all lines within one interval.
FRG	Frequencies of all locations where absorption coefficients are evaluated within one interval.
FRL, FRU	Lower and upper frequency boundaries of the entire frequency range.
FRS	Frequencies at the subinterval boundaries within an interval.
FRT	Tabulated values of the filter function.
GR	Gradients used in computing solar irradiances at the top of the atmosphere in each interval.
HL	Computed value of the solar irradiance at the top of the atmosphere in each interval.
HS	Tabulated values of solar irradiances at the top of the atmosphere at a few prequencies.
ID	Integers identifying the molecule of origin of each line.
IER	Error parameter from the interpolation subroutine.
IG	Total number of frequency locations at which transmittance computation is made, within an interval.
IN1, IN2, IN3, IN4	Indices for the gases H_2O vapor, CO_2, N_2O and CO respectively. 1 indicates presence of the gas, 0, the absence.
IR	Index, IR=0 means reflected solar radiation not included in radiance calculation, IR=1 means, it is included.
JT	Number of surface temperature values TEMX.
LE	Total number of lines of all molecules in the entire frequency range.
LLH	Number of altitudes of observation.

LX	Number of layers for an altitude of observation.
MP	Number of lines in an interval.
NG	Number of interacting gases considered present in the atmosphere.
NG1, NG2, NG3, NG4	Identifying integers for the absorbing gases being considered.
NGX	Identifying integer for a particular gas, being transmitted to the subroutine SMITH.
NQ	Number of subintervals in an interval.
NT	Number of surface temperature values TEMS.
PART	A lumped constant taking account of the variation of vibrational and rotational partition functions.
PCB, PHB	Planck functions for the cold and hot calibration black bodies, respectively.
PCEL	Total pressure in the instrument gas cell.
PL	Optical thickness from the ground to the sensor including the as cell.
PLK	Planck functions for the atmospheric layers.
PNTP	Pressure at NTP (750 mm Hg).
PPCL	Partial pressure of CO in the gas cell.
PREC	Average pressure in the atmospheric layers.
PSK	Planck functions for the surface at different temperatures.
PW	Partial pressure of water vapor in each atmospheric layer.
PXK	Planck functions corresponding to the temperature array TEMX.
QV	Concentrations of different gases (in ppmV) in each layer.
RAD	Total upwelling radiance across the gas cell.
RCOM1, RCOM2	Reflected solar components of total radiance in front of and across the instrument.
RDNC	Total upwelling radiance in front of the gas cell.
RP	Array of exponents which account for the temperature dependence of the rotational partition functions.

SI	Array of intensities for individual lines.
SL1, SL2	Slopes between the interval boundaries and center for computing wing contribution.
APTR	Pressure path lengths for all layers and all gases.
TA	Balance parameter of the instrument.
TCEL	Temperature of the gas cell of the instrument.
TCB, THB	Temperatures of the cold and hot calibration black bodies.
THC	Thicknesses of the layers (in km).
TEMC	Temperatures of the atmospheric layers.
TEMR	Reference temperatures for line parameters of the various gases.
TEMS	Array of surface temperatures for which the total upwelling radiance AVN are computed.
TEMX	Array of surface temperatures for which the upwelling radiances BVN are computed for the no-atmosphere condition.
TEMY	Retrieved value of the EBT.
TNTP	Temperature for NTP condition (273°K)
TP	Total optical thickness for the solar radiation from the top of the atmosphere to the instrument via ground reflection.
TR	Monochromatic transmittance at each of the frequencies FRG.
TRA	Averaged transmittance for an interval excluding the instrument gas cell.
TRC	Averaged transmittance for an interval including the instrument gas cell.
TRS	Averaged transmittance for an interval in subroutine TRANS.
TWC	Reference temperature for the water vapor continuum absorption coefficient.
VPF	Factor accounting for the temperature dependence of the vibrational partition functions.
WF	Frequencies at which the filter function is tabulated.
WIDF	Factor used to convert line half-widths from reference values to those appropriate for each layer.

WL1, WL2	Weighting factors used in the Gauss-Legendre quadrature formula.
WLIM	Width of the regions from which the wing contribution is obtained.
WN	Frequencies at which the solar irradiances at the top of the atmosphere are tabulated.
XA	Array of independent variables used by the interpolation routine IUNI.
XL1, XL2	Abscissa values used in the Gauss-Legendre quadrature formula.
YA	Array of dependent variables used by the interpolation routine IUNI.
ZEN	Sun zenith angle.

APPENDIX A2

EXPLANATION OF SYMBOLS USED IN PROGRAM "ITERATE"

A	Two-dimensional array of base atmospheric correction and relevant regression coefficients a_1 and a_2.
AC	Estimates of additional correction.
AONE	Array of regression coefficients a_1 for all parameters and all values of T_s.
ASTM	Estimate of actual surface temperature.
ASTN	Next estimate of actual surface temperature.
ATWO	Array of regression coefficients a_2 for all parameters and all values of T_s.
AX	Estimates of the base correction and relevant regression coefficients returned by the interpolation routine.
BAC	Array of base atmospheric corrections for all values of T_s.
BC	Estimates of the value of base atmospheric correction.
DX	Deviation of the first input parameter from its base model value.
DY	Deviation of the second input parameter from its base model value.
DZ	Array of deviations of the relevant parameters from their base model values.
EBT	Radiometrically measured effective brightness temperature.
ICON	Integar indicating convergence of the surface temperature from the interpolation routine.
IER	Error parameter returned by the interpolation routine.
IN	Identifying integers for the input parameter which have undergone deviations.
PT	Coefficient for the product term in equation (5.3).
SURTEMP	Final value of the retrieved surface temperature.
TEMS	Array of the input surface temperature values.
TC	Total atmospheric correction.

APPENDIX B1

COMPUTER PROGRAM "SURFACE"

```
      PROGRAM SURFACE(INPUT,OUTPUT)
      INTEGER X,Y,G,T
      DIMENSION ALFT(10),ALKM(10),THC(10),PREC(10),TEMC(10),LX(10),
     /QV(10,4),TEMR(5),SPTR(10,4),VPF(10,4),RP(5),HL(150),FRT(31),
     /WF(31),FGR(30),FIL(150),AVN1(9,10),AVN2(9,10),TEMS(9),PLK(10),
     /FRE(100),PL(400),OD(400),TP(400),PSK(9),TRA(11),TRC(11),RDNC(9),
     /RAD(9),AVN(9,10),XA(3),YA(3),IER(10,10),AW(10),PW(10),TEMX(10),
     /BVN1(10),BVN2(10),PXK(10),BVN(10),TEMY(10,10),HS(5),WN(5),GR(5)
      COMMON/ABSORB/FR(1320),SI(1320),EL(1320),AL(1320),ID(1320),
     /FRG(400),AC(400),FRB(151),FRC(150),WIDF(11,4),FACT(11,4),
     /PART(11,4),DLIM,WLIM,DELA,NGX,LE,IG,PI
      COMMON/TRANE/FRS(101),TR(400),WL1,WL2,NQ,DEL
      READ 10, EMI,ZEN,AWC,TWC
      READ 11, NG,LE,NT,JT,LLH,IR
      READ 12, (ALFT(LL),LL=1,LLH)
      READ 10, FRL,FRU,DEL,PNTP,PCEL,PPCL,CLEN
      READ 10, TNTP,TCEL,THB,TCB
      READ 10, DLIM,WLIM,ALX
      READ 10, (PREC(L),L=1,10)
      READ 10, (TEMC(L),L=1,10)
      READ 10, (TEMS(T),T=1,NT)
      READ 10, (TEMX(J),J=1,JT)
      READ 10, (TEMR(G),G=1,NG)
      READ 13, (THC(L),L=1,10)
      READ 13, (FRT(M),M=1,31)
      READ 13, ((VPF(L,G),L=1,10),G=1,NG)
      READ 14, XL1,XL2,WL1,WL2
      READ 15, ((QV(L,G),L=1,10),G=1,NG)
      READ 10, (RP(G),G=1,NG)
      READ 11, IN1,IN2,IN3,IN4
      READ 11, NG1,NG2,NG3,NG4
      READ 16, (WN(N),N=1,5),(HS(N),N=1,5)
      READ 18, (FR(X),SI(X),EL(X),AL(X),ID(X),X=1,LE)
   10 FORMAT(10F8.2)
   11 FORMAT(16I5)
   12 FORMAT(10F8.0)
   13 FORMAT(10F8.4)
   14 FORMAT(8F10.6)
   15 FORMAT(5E16.3)
   16 FORMAT(5F10.2/5E12.3)
   18 FORMAT(2(F10.3,E12.4,F10.3,F5.3,I3))
C   DETERMINES THE NUMBER OF LAYERS FOR EACH ALTITUDE OF OBSERVATION
      DO 100 LL=1,LLH
      ALKM(LL)=ALFT(LL)*3.048E-04+0.05
```

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```
      L=0
      STHC=0.
  101 L=L+1
      STHC=STHC+THC(L)
      ALR=ALKM(LL)-STHC
      IF (ALR.LT.0) GO TO 100
      LX(LL)=L
      GO TO 101
  100 CONTINUE
      PI=3.14159
C   EVALUATES PARTIAL PRESSURE OF WATER VAPOR AND CHANGES THE UNITS
C   OF WATER VAPOR CONCENTRATION SO THAT THE PATH LENGTH COMES
C   OUT IN PRECIPITABLE CENTIMETERS
      DO 102 L=1,10
      PW(L)=1.3158E-09*QV(L,1)*PREC(L)
  102 QV(L,1)=8.032E-04*QV(L,1)
      CONST=0.1*TNTP/PNTP
C   COMPUTES PRESSURE PATH LENGTHS FOR VARIOUS CONSTITUENTS AND LAYERS
      DO 103 L=1,10
      PTR=CONST*PREC(L)*THC(L)/TEMC(L)
      DO 103 G=1,NG
      SPTR(L,G)=PTR*QV(L,G)
      FACT(L,G)=1.439*(TEMC(L)-TEMR(G))/(TEMC(L)*TEMR(G))
      WIDF(L,G)=(SQRT(TEMR(G)/TEMC(L)))*PREC(L)/PNTP
  103 PART(L,G)=VPF(L,G)*(TEMR(G)/TEMC(L))**RP(G)
      DELA=0.5*DEL
      RK=(FRU-FRL)/DEL+0.1
      KR=RK
C   COMPUTES FREQUENCIES AT INTERVAL BOUNDARIES AND CENTERS
      FRB(1)=FRL
      DO 104 K=1,KR
      FRC(K)=FRB(K)+DELA
  104 FRB(K+1)=FRB(K)+DEL
      ALY=2.*ALX
      ZEN=COS(ZEN/57.29578)
      CONS=18.*6.625*1.E-07
      CNST=6.625*0.3/1.38
      WF(1)=FRL
C   GENERATES THE FREQUENCY GRID WHERE THE INSTRUMENT FILTER
C   FUNCTION IS TABULATED AND COMPUTES SLOPES OF FILTER FUNCTION
      DO 105 M=1,30
      WF(M+1)=WF(M)+5.
  105 FGR(M)=(FRT(M+1)-FRT(M))/(WF(M+1)-WF(M))
C   COMPUTES THE VALUE OF FILTER FUNCTION FOR EACH INTERVAL
```

```
      DO 106 K=1,KR
      M=0
  107 M=M+1
      IF (FRC(K).LT.WF(M)) GO TO 106
      IF (FRC(K).GE.WF(M+1)) GO TO 107
      FIL(K)=FRT(M)+FGR(M)*(FRC(K)-WF(M))
  106 CONTINUE
C   COMPUTES SLOPES FOR CALCULATION OF THE SOLAR IRRADIANCE AT
C   THE TOP OF THE ATMOSPHERE
      DO 173 N=1,4
  173 GR(N)=(HS(N+1)-HS(N))/(WN(N+1)-WN(N))
C   EVALUATES SOLAR IRRADIANCE AT THE TOP OF THE ATMOSPHERE
C   IN EACH INTERVAL
      DO 174 K=1,KR
      N=0
  175 N=N+1
      IF (FRC(K).LT.WN(N)) GO TO 174
      IF (FRC(K).GE.WN(N+1)) GO TO 175
      HL(K)=HS(N)+GR(N)*(FRC(K)-WN(N))
      HL(K)=HL(K)*DEL
  174 CONTINUE
      TANN=0.
      TADD=0.
      DO 108 LL=1,LLH
      DO 108 T=1,NT
      AVN1(T,LL)=0.
  108 AVN2(T,LL)=0.
      DO 179 J=1,JT
      BVN1(J)=0.
  179 BVN2(J)=0.
      VPC=1.
      G=4
      L=11
C   COMPUTES PRESSURE PATH LENGTH FOR THE INSTRUMENT GAS CELL
      CPTR=PPCL*TNTP*CLEN/(PNTP*TCEL)
      FACT(L,G)=1.439*(TCEL-TEMR(G))/(TEMR(G)*TCEL)
      WIDF(L,G)=(SQRT(TEMR(G)/TCEL))*PCEL/PNTP
      PART(L,G)=VPC*(TEMR(G)/TCEL)**RP(G)
      Y=0
C   THE TOTAL OPERATION OF TRANSMITTANCE AND RADIANCE COMPUTATION
C   IS PERFORMED FOR ONE INTERVAL AT A TIME. THE LOOP BELOW
C   GOES OVER ALL THE INTERVALS
      DO 109 K=1,KR
      M=0
```

```
      MP=M
  111 IF (Y.GE.LE) GO TO 110
      Y=Y+1
C   DETERMINES WHICH AND HOW MANY LINES LIE IN AN INTERVAL
      IF (FR(Y).LT.FRB(K)) GO TO 111
      IF (FR(Y).GE.FRB(K+1)) GO TO 112
      M=M+1
      FRE(M)=FR(Y)
      MP=M
      GO TO 111
  112 Y=Y-1
  110 CONTINUE
C   DIVIDES THE INTERVAL INTO A SUITABLE NUMBER OF SUBINTERVALS
C   DEPENDING ON THE NUMBER OF LINES IN THE INTERVAL
      N=1
      FRS(N)=FRB(K)
      IF (MP.LE.0) GO TO 113
      DO 114 M=1,MP
      DIF=FRE(M)-FRS(N)
      IF (DIF.LE.ALX) GO TO 115
      IF (DIF.LE.ALY) GO TO 116
      FRS(N+1)=FRE(M)-ALY
      FRS(N+2)=FRE(M)-ALX
      FRS(N+3)=FRE(M)
      N=N+3
      GO TO 117
  116 FRS(N+1)=FRE(M)-ALX
      FRS(N+2)=FRE(M)
      N=N+2
      GO TO 117
  115 FRS(N+1)=FRE(M)
      N=N+1
  117 IF (M.EQ.MP) GO TO 118
      DIF=FRE(M+1)-FRS(N)
      IF (DIF.LE.ALX) GO TO 114
      IF (DIF.GT.ALY) GO TO 119
      FRS(N+1)=FRE(M)+ALX
      N=N+1
      GO TO 114
  119 FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRE(M)+ALY
      N=N+2
  114 CONTINUE
  118 DIF=FRB(K+1)-FRE(M)
```

```
      IF (DIF.LE.ALX) GO TO 113
      IF (DIF.LE.ALY) GO TO 120
      FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRE(M)+ALY
      FRS(N+3)=FRB(K+1)
      NP=N+3
      GO TO 121
  120 FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRB(K+1)
      NP=N+2
      GO TO 121
  113 FRS(N+1)=FRB(K+1)
      NP=N+1
  121 NQ=NP-1
C   CREATES FOUR FREQUENCY LOCATIONS IN EACH SUBINTERVAL
C   FOR GAUSS-LEGENDRE QUADRATURE
      DO 122 N=1,NQ
      I=4*(N-1)+1
      VAR=0.5*(FRS(N+1)-FRS(N))
      CON=0.5*(FRS(N+1)+FRS(N))
      FRG(I)=CON-VAR*XL1
      FRG(I+1)=CON-VAR*XL2
      FRG(I+2)=CON+VAR*XL2
  122 FRG(I+3)=CON+VAR*XL1
      IG=4*NQ
C   INITIALIZES TOTAL OPTICAL THICKNESS AT ALL FREQUENCIES
C   WITHIN THE INTERVAL
      DO 124 I=1,IG
  124 TP(I)=0.
C   DETERMINES IF THE REFLECTED SOLAR RADIATION IS TO BE
C   INCLUDED IN THE COMPUTATION OF TOTAL UPWELLING RADIANCE.
C   IF SO, COMPUTES TRANSMITTANCE THROUGH ALL TEN LAYERS
      IF (IR.EQ.0) GO TO 123
      DO 125 L=1,10
      IF (IN1.LE.0) GO TO 126
C   IF WATER VAPOR IS PRESENT, IT COMPUTES OPTICAL THICKNESS
C   AT THAT FREQUENCY DUE TO WATER VAPOR
      AW(L)=AWC*(1.-0.02*(TEMC(L)-TWC))*PW(L)
      G=1
      NGX=NG1
      CALL SMITH(G,L,K)
      DO 127 I=1,IG
  127 TP(I)=TP(I)+SPTR(L,G)*(AC(I)+AW(L))
C   IF CARBON DIOXIDE IS PRESENT, ITS OPTICAL THICKNESS IS COMPUTED
```

```
  126 IF (IN2.LE.0) GO TO 128
      G=2
      NGX=NG2
      CALL SMITH(G,L,K)
      DO 129 I=1,IG
  129 TP(I)=TP(I)+SPTR(L,G)*AC(I)
C    IF NITROUS OXIDE IS PRESENT, ITS OPTICAL THICKNESS IS COMPUTED
  128 IF (IN3.LE.0) GO TO 130
      G=3
      NGX=NG3
      CALL SMITH(G,L,K)
      DO 131 I=1,IG
  131 TP(I)=TP(I)+SPTR(L,G)*AC(I)
C    IF CARBON MONOXIDE IS PRESENT, ITS OPTICAL THICKNESS IS COMPUTED
  130 IF (IN4.LE.0) GO TO 125
      G=4
      NGX=NG4
      CALL SMITH(G,L,K)
      DO 132 I=1,IG
  132 TP(I)=TP(I)+SPTR(L,G)*AC(I)
  125 CONTINUE
      DO 138 I=1,IG
  138 TP(I)=TP(I)/ZEN
  123 CONTINUE
C    COMPUTES PLANCK FUNCTIONS FOR THE SURFACE AND ATMOSPHERIC LAYERS
      PNUM=DEL*CONS*FRC(K)*FRC(K)*FRC(K)*1.E-07
      EEX=CNST*FRC(K)
      DO 133 T=1,NT
  133 PSK(T)=PNUM/(EXP(EEX/TEMS(T))-1.)
      DO 134 L=1,10
  134 PLK(L)=PNUM/(EXP(EEX/TEMC(L))-1.)
      DO 137 J=1,JT
  137 PXK(J)=PNUM/(EXP(EEX/TEMX(J))-1.)
      PHB=PNUM/(EXP(EEX/THB)-1.)
      PCB=PNUM/(EXP(EEX/TCB)-1.)
      TAD=(PHB-PCB)*FIL(K)
C   INITIALIZES OPTICAL THICKNESS FROM SENSOR TO THE
C   GROUND THROUGH AS WELL AS OUTSIDE THE GAS CELL
      DO 109 LL=1,LLH
      DO 135 I=1,IG
      PL(I)=0.
  135 OD(I)=0.
      NGX=NG4
      G=4
```

```
      L=11
      CALL SMITH(G,L,K)
      DO 136 I=1,IG
      OD(I)=OD(I)+CPTR*AC(I)
  136 TR(I)=EXP(-OD(I))
      LA=LX(LL)
      LB=LA+1
      CALL TRANS(TRS)
      TAM=TAD*TRS
      TRC(LB)=TRS
      TRA(LB)=1.
      TANN=TANN+TAM
      TADD=TADD+TAD
C   COMPUTES OPTICAL THICKNESS FROM SENSOR TO THE GROUND
C   THROUGH AS WELL AS OUTSIDE THE GAS CELL
      DO 139 M=1,LA
      L=LA+1-M
      AW(L)=AWC*(1.-0.02*(TEMC(L)-TWC))*PW(L)
      IF (IN1.LE.0) GO TO 140
      G=1
      NGX=NG1
      CALL SMITH(G,L,K)
      DO 141 I=1,IG
      PROD=SPTR(L,G)*(AC(I)+AW(L))
      PL(I)=PL(I)+PROD
  141 OD(I)=OD(I)+PROD
  140 IF (IN2.LE.0) GO TO 142
      G=2
      NGX=NG2
      CALL SMITH(G,L,K)
      DO 143 I=1,IG
      PROD=SPTR(L,G)*AC(I)
      PL(I)=PL(I)+PROD
  143 OD(I)=OD(I)+PROD
  142 IF (IN3.LE.0) GO TO 144
      G=3
      NGX=NG3
      CALL SMITH(G,L,K)
      DO 145 I=1,IG
      PROD=SPTR(L,G)*AC(I)
      PL(I)=PL(I)+PROD
  145 OD(I)=OD(I)+PROD
  144 IF (IN4.LE.0) GO TO 146
      G=4
```

```
      NGX=NG4
      CALL SMITH(G,L,K)
      DO 147 I=1,IG
      PROD=SPTR(L,G)*AC(I)
      PL(I)=PL(I)+PROD
  147 OD(I)=OD(I)+PROD
  146 CONTINUE
C  COMPUTES TRANSMITTANCE FROM SENSOR TO THE GROUND
C  OUTSIDE THE GAS CELL
      DO 148 I=1,IG
      IF (PL(I).GT.675.) GO TO 149
      TR(I)=EXP(-PL(I))
      GO TO 148
  149 TR(I)=0.
  148 CONTINUE
      CALL TRANS(TRS)
      TRA(L)=TRS
C  COMPUTES TRANSMITTANCE FROM SENSOR TO THE GROUND
C  THROUGH THE GAS CELL
      DO 151 I=1,IG
      IF (OD(I).GT.675.) GO TO 152
      TR(I)=EXP(-OD(I))
      GO TO 151
  152 TR(I)=0.
  151 CONTINUE
      CALL TRANS(TRS)
      TRC(L)=TRS
  139 CONTINUE
C  IF REFLECTED SOLAR RADIATION IS TO BE TAKEN INTO
C  CONSIDERATION,IT COMBINES THE OPTICAL THICKNESS FOR ALL
C  TEN LAYERS WITH THE OPTICAL THICKNESS FROM SENSOR TO THE GROUND
      IF (IR.EQ.0) GO TO 154
      DO 155 I=1,IG
      TP(I)=TP(I)+PL(I)
      IF (TP(I).GT.675.) GO TO 169
      TR(I)=EXP(-TP(I))
      GO TO 155
  169 TR(I)=0.
  155 CONTINUE
      CALL TRANS(TRO)
      DO 157 I=1,IG
      TP(I)=TP(I)+OD(I)-PL(I)
      IF (TP(I).GT.675.) GO TO 170
      TR(I)=EXP(-TP(I))
```

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      GO TO 157
  170 TR(I)=0.
  157 CONTINUE
      CALL TRANS(TRT)
      DO 178 I=1,IG
  178 TP(I)=TP(I)-OD(I)
      GO TO 159
  154 TRO=0.
      TRT=0.
  159 CONTINUE
C  COMPUTES THE REFLECTED SOLAR COMPONENT AND COMBINES IT
C  WITH THE ATMOSPHERIC RADIATION
      RCOM1=(1.-EMI)*DEL*ZEN*HL(K)*TRO
      RCOM2=(1.-EMI)*DEL*ZEN*HL(K)*TRT
      COMP=0.
      COMQ=0.
      DO 160 L=1,LA
      COMP=COMP+PLK(L)*(TRA(L+1)-TRA(L))
  160 COMQ=COMQ+PLK(L)*(TRC(L+1)-TRC(L))
C  COMBINES SURFACE RADIATION WITH THE PREVIOUS SUM AND
C  EVALUATES RADIANCE OUTSIDE THE CELL AND THROUGH IT
      DO 161 T=1,NT
      PROD=EMI*PSK(T)
      RDNC(T)=RCOM1+COMP+PROD*TRA(1)
  161 RAD(T)=RCOM2+COMQ+PROD*TRC(1)
C  EVALUATES THE TOTAL UPWELLING RADIANCE AS SEEN BY THE
C  DETECTORS_THROUGH THE TWO PATHS
      DO 162 T=1,NT
      AVN1(T,LL)=AVN1(T,LL)+RAD(T)*FIL(K)
  162 AVN2(T,LL)=AVN2(T,LL)+RDNC(T)*FIL(K)
C  EVALUATES TOTAL UPWELLING RADIANCE FOR A SET OF SURFACE
C  TEMPERATURES IN ABSENCE OF ANY ATMOSPHERE
      DO 163 J=1,JT
      BVN1(J)=BVN1(J)+PXK(J)*TRC(LB)*FIL(K)
  163 BVN2(J)=BVN2(J)+PXK(J)*FIL(K)
  109 CONTINUE
C  EVALUATES THE BALANCE PARAMETERS
      TA=TANN/TADD
C  COMPUTES THE AVERAGED UPWELLING RADIANCE AS
C  MEASURED BY THE INSTRUMENT
      DO 164 LL=1,LLH
      DO 164 T=1,NT
  164 AVN(T,LL)=0.5*(AVN1(T,LL)+AVN2(T,LL)*TA)
C  COMPUTES AVERAGED UPWELLING RADIANCE FOR THE NO-ATMOSPHERE
```

```
C   CONDITION. THIS TABLE OF BVN IS USED TO OBTAIN THE EBT
C   CORRESPONDING TO THE UPWELLING RADIANCES AVN
      DO 180 J=1,JT
  180 BVN(J)=0.5*(BVN1(J)+BVN2(J)*TA)
      NMAX=3
      NN=3
      NTAB=1
      IORDER=2
C   COMPUTES THE VALUES OF EBT CORRESPONDING TO THE RADIANCES
C   AVN BY QUADRATIC INTERPOLATION BETWEEN TABULATED VALUES OF BVN
      DO 165 LL=1,LLH
      DO 165 T=1,NT
      J=-1
  166 IF ((J+2).GE.JT) GO TO 171
      J=J+2
      IF (AVN(T,LL).LT.BVN(J)) GO TO 172
      IF (AVN(T,LL).GE.BVN(J+2)) GO TO 166
      XO=AVN(T,LL)
      DO 167 N=1,NN
      XA(N)=BVN(J+N-1)
  167 YA(N)=TEMX(J+N-1)
      IPT=-1
      CALL IUNI(NMAX,NN,XA,NTAB,YA,IORDER,XO,YO,IPT,IERR)
      TEMY(T,LL)=YO
      IER(T,LL)=IERR
      GO TO 165
  171 TEMY(T,LL)=0.
      IER(T,LL)=9
      GO TO 165
  172 TEMY(T,LL)=0.
      IER(T,LL)=-9
  165 CONTINUE
      PRINT 60, TA,CPTR
      DO 168 LL=1,LLH
      PRINT 61, (TEMS(T),AVN(T,LL),T=1,NT)
      PRINT 62, (TEMY(T,LL),IER(T,LL),T=1,NT)
  168 CONTINUE
      PRINT 61, (TEMX(J),BVN(J),J=1,JT)
   60 FORMAT(1H1////(2F15.5))
   61 FORMAT(1H1////(F15.2,E20.5,//))
   62 FORMAT(1H1////(F20.2,I10,//))
      STOP
      END
```

```
      SUBROUTINE SMITH(G,L,K)
      INTEGER X,G
      COMMON/ABSORB/FR(1320),SI(1320),EL(1320),AL(1320),ID(1320),
     /FRG(400),AC(400),FRB(151),FRC(150),WIDF(11,4),FACT(11,4),
     /PART(11,4),DLIM,WLIM,DELA,NGX,LE,IG,PI
C  INITIALIZES ABSORPTION COEFFICIENTS AT ALL FREQUENCIES WITHIN
C  AN INTERVAL AND ALSO AT INTERVAL CENTER AND BOUNDARIES
      ACB=0.
      ACM=0.
      ACE=0.
      DO 300 I=1,IG
  300 AC(I)=0.
      DO 301 X=1,LE
C  DETERMINES IF THE LINE BELONGS TO THE MOLECULE UNDER
C  CONSIDERATION. IF NOT,IT SKIPS THAT LINE
      IF (NGX.NE.ID(X)) GO TO 301
      DIF =ABS(FR(X)-FRC(K))
      IF (DIF.GT.WLIM) GO TO 301
      SIA=SI(X)*PART(L,G)*EXP(EL(X)*FACT(L,G))
      ALB=AL(X)*WIDF(L,G)
      IF (DIF.GT.DLIM) GO TO 302
C  COMPUTES THE DIRECT CONTRIBUTION AT ALL FREQUENCIES FROM
C  LINES LYING WITHIN DLIM OF THE INTERVAL CENTER
      DO 303 I=1,IG
      FD=FR(X)-FRG(I)
      DEN=PI*(FD*FD+ALB*ALB)
  303 AC(I)=AC(I)+SIA*ALB/DEN
      GO TO 301
C  COMPUTES WING CONTRIBUTION AT INTERVAL CENTER AND BOUNDARIES
C  DUE TO LINES LYING BETWEEN DLIM AND WLIM ON BOTH SIDES
  302 FB =FR(X)-FRB(K)
      FM =FR(X)-FRC(K)
      FE =FR(X)-FRB(K+1)
      PNUM=SIA*ALB
      ACB=ACB+PNUM/(PI*FB*FB)
      ACM=ACM+PNUM/(PI*FM*FM)
      ACE=ACE+PNUM/(PI*FE*FE)
  301 CONTINUE
C  COMPUTES SLOPES FOR CALCULATION OF WING CONTRIBUTION
      SL1 =(ACM-ACB)/(FRC(K)-FRB(K))
      SL2 =(ACE-ACM)/(FRB(K+1)-FRC(K))
C  ADDS DIRECT AND WING CONTRIBUTIONS
      DO 304 I=1,IG
      DIF=(FRG(I)-FRB(K))
```

```
      IF (DIF.GE.DELA) GO TO 305
      AC(I)=AC(I)+ACB+SL1*DIF
      GO TO 304
  305 AC(I)=AC(I)+ACM+SL2*(DIF-DELA)
  304 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TRANS(TRS)
      COMMON/TRANE/FRS(101),TR(400).WL1,WL2,NQ,DEL
      TRS=0.
C   COMPUTES AVERAGED TRANSMITTANCE OVER AN INTERVAL FROM
C   MONOCHROMATIC TRANSMITTANCES AT A LARGE NUMBER OF
C   FREQUENCIES USING GAUSS-LEGENDRE QUADRATURE FORMULA
      DO 400 N=1,NQ
      I=4*(N-1)+1
      VAR=0.5*(FRS(N+1)-FRS(N))
      SUM1=TR(I)+TR(I+3)
      SUM2=TR(I+1)+TR(I+2)
      SUM=WL1*SUM1+WL2*SUM2
  400 TRS=TRS+SUM*VAR/DEL
      RETURN
      END
```

APPENDIX B2

COMPUTER PROGRAM "ITERATE"

```
      PROGRAM ITERATE(INPUT,OUTPUT)
      DIMENSION DZ(7),IN(2),A(7,5),AONE(7,7),ATWO(7,7),AX(5),
     /IER(10),TEMS(7),BAC(7)
      READ 10, ((AONE(I,J),I=1,7),J=1,7),((ATWO(I,J),I=1,7),J=1,7)
      READ 12, (TEMS(I),I=1,7)
      READ 11, (BAC(I),I=1,7)
      READ 11, (DZ(J),J=1,7)
      READ 13, EBT
   10 FORMAT(7F10.4)
   11 FORMAT(7F10.2)
   12 FORMAT(7F10.0)
   13 FORMAT(F10.2)
      ICON=1
      PT=0.124
C  PUTS BASE CORRECTION ARRAY BAC IN THE ARRAY A
C  TO BE USED BY THE INTERPOLATION ROUTINE
      DO 111 I=1,7
  111 A(I,1)=BAC(I)
      DO 113 L=1,10
  113 IER(L)=9
      N=0
C  IDENTIFIES WHICH PARAMETERS HAVE UNDERGONE DEVIATIONS
C  AND PUTS APPROPRIATE REGRESSION COEFFICIENTS IN THE ARRAY A
      DO 100 J=1,7
      IF (DZ(J).EQ.0) GO TO 100
      N=N+1
      IN(N)=J
      IF (N.GE.2) GO TO 101
      DX=DZ(J)
      DO 102 I=1,7
      A(I,2)=AONE(I,J)
  102 A(I,3)=ATWO(I,J)
      GO TO 100
  101 DY=DZ(J)
      DO 103 I=1,7
      A(I,4)=AONE(I,J)
  103 A(I,5)=ATWO(I,J)
  100 CONTINUE
      ASTM=300.
      NMAX=7
      NN=7
      IORDER=1
      IT=0
      AX(1)=A(3,1)
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C  DETERMINES HOW MANY PARAMETERS HAVE UNDERGONE DEVIATIONS,
C  IF NONE,IT JUST COMPUTES THE BASE CORRECTION
      IF (N.GE.1) GO TO 104
      NTAB0=1
  106 IT=IT+1
      BC=AX(1)
      TC=BC
C  COMPUTES FIRST ESTIMATE OF THE ACTUAL SURFACE TEMPERATURE
      ASTN=EBT-TC
      DIF=ABS(ASTN-ASTM)
C  CHECKS THE DIFFERENCE BETWEEN SUCCESSIVE ESTIMATES OF
C  THE ACTUAL SURFACE TEMPERATURE
      IF (DIF.LE.0.01) GO TO 105
      ASTM=ASTN
      IPT=-1
C  CALLS THE SUBROUTINE TO INTERPOLATE THE VALUES OF
C  BASE CORRECTION AND THE REGRESSION COEFFICIENTS
      CALL IUNI(NMAX,NN,TEMS,NTAB0,A,IORDER,ASTN,AX,IPT,IERR)
      IER(IT)=IERR
C  CHECKS THE NUMBER OF ITERATIONS
      IF (IT.GE.10) GO TO 112
      GO TO 106
C  DETERMINES IF THE NUMBER OF PARAMETERS WHICH HAVE UNDERGONE
C  DEVIATIONS IS ONE OR TWO
  104 IF (N.GT.1) GO TO 107
      AX(2)=A(3,2)
      AX(3)=A(3,3)
      NTAB1=3
  108 IT=IT+1
      BC=AX(1)
      AC=AX(2)*DX+AX(3)*DX*DX
      TC=BC+AC
      ASTN=EBT-TC
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 105
      ASTM=ASTN
      IPT=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB1,A,IORDER,ASTN,AX,IPT,IERR)
      IER(IT)=IERR
      IF (IT.GE.10) GO TO 112
      GO TO 108
C  INITIALIZES REGRESSION COEFFICIENTS FOR TWO PARAMETER CASES
  107 NTAB2=5
      AX(2)=A(3,2)
```

```
      AX(3)=A(3,3)
      AX(4)=A(3,4)
      AX(5)=A(3,5)
C  DETERMINES IF THE TWO PARAMETERS ARE WATER VAPOR CONCENTRA-
C  TION AND THE VERTICAL TEMPERATURE PROFILE. IF SO,IT USES
C  EQUATION (5.3) TO COMPUTE ADDITIONAL CORRECTION
      IF (IN(2).NE.6) GO TO 109
      IF (IN(1).GT.2) GO TO 109
  110 IT=IT+1
      BC=AX(1)
      AC=AX(2)*DX+AX(3)*DX*DX+AX(4)*DY+AX(5)*DY*DY+PT*DX*DY
      TC=BC+AC
      ASTN=EBT-TC
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 105
      ASTM=ASTN
      IPT=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB2,A,IORDER,ASTN,AX,IPT,IERR)
      IER(IT)=IERR
      IF (IT.GE.10) GO TO 112
      GO TO 110
C  FOR ALL OTHER COMBINATIONS,USES EQUATION (5-1) TO
C  COMPUTE ADDITIONAL CORRECTION
  109 IT=IT+1
      BC=AX(1)
      AC=AX(2)*DX+AX(3)*DX*DX+AX(4)*DY+AX(5)*DY*DY
      TC=BC+AC
      ASTN=EBT-TC
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 105
      ASTM=ASTN
      IPT=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB2,A,IORDER,ASTN,AX,IPT,IERR)
      IER(IT)=IERR
      IF (IT.GE.10) GO TO 112
      GO TO 109
C  IF THE RESULT DOES NOT CONVERGE AS DESIRED IN TEN ITERATIONS
C  IT PUTS THE CONVERGENCE INDICATOR ICON=0
  112 ICON=0
  105 SURTEMP=ASTN
      PRINT 60, SURTEMP
      PRINT 61, ICON,(IER(L),L=1,10)
      PRINT 62, DIF
   60 FORMAT(F20.2)
   61 FORMAT(I15,5X,10I10)
   62 FORMAT(F20.3)
      STOP
      END
```