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Instituut voor Cultuurtechniek en Waterhuishouding
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INFLUENCE OF ATMOSPHERE ON THERMAL INFRARED RADIATION

ir. G.J.A. Nieuwenhuis

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1. INTRODUCTION

Infrared pictures taken from air planes or satallites play an important role in the study of the earth surface. In the case of Infra Red Line Scanning (IRLS) the 'windows' in the atmosphere (3-5 μm and 8-14 μm) are used. But even under clear sky conditions the atmosphere in the 'windows' is not completely transparent for infrared radiation.

The atmosphere does not cause only a shift of the level of the surface temperatures, but it causes also a smoothing of the temperature differences at the surface. So information about the influence of the atmosphere on thermal infrared radiation is very important.

To calculate atmospheric corrections under clear sky conditions different models are available. In this paper a NASA-model as developed by RANGASWAMY and SUBBARAYUDU (1978) for the 10.5 -12.5 μm wave length band is tested for meteorological conditionsin the Netherlands. The model needs information about temperature, pressure and humidity at different levels in the atmosphere (PTH profiles). As different scanners measure in the 8-14 μm wave length band the NASA model has been adjusted for application in this band.

Also a simplified model of BECKER (1978) has been tested. In this model it is supposed, that atmospheric attenuation in the 8-14 μm wave length band is proportional to the amount of water vapour in the atmosphere.

PTH-profiles are not always available. It is, however, possible to eliminate the atmospheric parameters in BECKER's model, if the radiation emitted by the surface is measured in two different wave length bands of the electromagnetic spectrum.

2. THEORY

2.1. Thermal emission of a natural body

The radiance emitted by a black body depends on the temperature of the body and the wave length. The radiance is given by the formula of Planck:

$$R_b^1(\nu,T) = \frac{c_1.\nu^5}{\exp(c_2\nu/T) - 1} \quad (W.m^{-2}.sr^{-1}.\mu^{-1}) \qquad (2.1)$$

where

$c_1 = 1.185 \cdot 10^8 \quad W.m^{-2}.\mu^{-4}$

$c_2 = 1.439 \cdot 10^4 \quad \mu.K$

T = the temperature (K)

$\nu = \lambda^{-1}$ = frequency (μ^{-1})

λ = wave length (μ)

Per unit of frequency interval the radiance is equal to:

$$R_b(\nu,T) = \frac{c_1\nu^3}{\exp(c_2\nu/T) - 1} \quad (W.m^{-2}.sr^{-1}) \qquad (2.2)$$

Studying the influence of the atmosphere the surface is regarded as a black body. As this is actually not the case the radiation of the surface is equal to:

$$R_s = \varepsilon(\nu)\, R_s(\nu,T_s) + (1-\varepsilon(\nu)).R_a(\nu,T_a) \quad W.m^{-2}.sr^{-1} \qquad (2.3)$$

where R_s is the radiance of the surface per unit of frequency interval, R_a is the radiance at the surface from the atmosphere ($W.m^{-2}.sr^{-1}$), T_s and T_a are the temperature of the surface and the atmosphere respectively (K), and $\varepsilon(\nu)$ is the emission coefficient of the surface. An equivalent black body temperature of the surface can be calculated from the inversion of Planck's formula:

$$T_{bs} = \frac{c_2\nu}{\ln(c_1\nu^3/R_s + 1)} \quad (K) \qquad (2.4)$$

2.2. Transmittance of radiation in the atmosphere

In the atmosphere radiance is scattered and absorbed. By these processes an extinction of the surface infrared radiation occurs in the atmosphere.

Depending on the relation between wave length and particle size of the scattering medium, scattering can be divided in (e.g. FARROW, 1975):

- Scattering by particles with small dimensions with respect to the wave length of the radiance: Rayleigh-scattering. According to the Rayléigh scattering theory the scattering coefficient β is strongly wave length dependent. The relation is:

$$\beta \sim \lambda^{-4} \tag{2.5}$$

- Scattering by particles with dimensions comparable to the wave length: Mie-scattering. Wave length dependence is then less than for Rayleigh scattering. Mie scattering depends on shape and size of the particles. In the atmosphere Mie-scattering is mainly caused by droplets. The problem is that the shape and size of droplets fluctuate very much with time. If the amount of particles causing Mie-scattering is too high conditions are too bad to perform IRLS flight. The visibility has to be more than 5 km (BECKER, 1977).
- Scattering by particles with dimensions much larger than the wave length. In this case scattering is independent of the wave length of the radiance.

Under clear sky conditions the extinction of thermal infrared radiation is mainly caused by absorption of discrete amounts of energy by molecules. In this case also extinction of radiation is strongly wave length dependent.

BEKCER (1977) divided the molecules in the atmosphere in two categories:

- Molecules present in a given proportion: N_2, O_2, CO_2 etc.
- Molecules present in proportions that fluctuate with time: mainly H_2O.

Absorption by ozonemolecules, concentrated in a layer between 10 to 30 km above the surface, is neglected. In case of measurements by satellites the wave length from 10.5 - 12.5 μm is usually applied, while absorption by ozone is concentrated at a wave length of 9,6 μm. With air planes is usually flown lower than 10 km, by which ozone absorption can be neglected.

If the atmosphere is divided into layers and each layer is regarded as a uniformly absorbing medium the transmission of monochromatic radiation obeys an exponential law:

$$\tau(\nu) = \exp(-k(\nu)x) \qquad (2.6)$$

where x is the optical path length ($g.cm^{-2}$) and $k(\nu)$ is the mass absorption coefficient ($cm^2.g^{-1}$).

For absorption by different molecules $k(\nu)$ is equal to the sum of the absorption coefficients of the different molecules:

$$k(\nu) = k_{H_2O}(\nu) + k_{CO_2}(\nu) + \dots \quad (cm^2.g^{-1}) \qquad (2.7)$$

The transmission coefficient is then equal to the product of the transmission coefficients of the various molecules:

$$\tau(\nu) = \tau_{H_2O}(\nu) \cdot \tau_{CO_2}(\nu) \;\dots\dots \qquad (2.8)$$

Transmission in the 8-14 μm wave length band is, however, mainly determined by the amount of water vapour.

3. ATMOSPHERIC MODELS

3.1. The RADTRA model developed by RANGASWAMY and SUBBARAYUDU (1978)

The RADTRA-model estimates the attenuation of the atmosphere in the 10.5 - 12.5 μm wave length band. The attenuation of infrared radiation by the atmosphere can be estimated by solving the equation of radiative transfer.

If only absorption by molecules is regarded, attenuation of radiation can be described by Beer's law:

$$dR(\nu) = - R(\nu)\ k(\nu,z).\rho.dz \qquad (W.m^{-2}.sr^{-1}) \qquad (3.1)$$

where ρdz is defined as the optical thickness, ρ is the density ($g.cm^{-3}$) of the absorbing gas and z is the distance (m).

The transmission of radiation emitted by the soil surface is described by:

$$R_s(\nu,h) = R_s(\nu,T_s).\tau(\nu,h) \qquad (W.m^{-2}.sr^{-1}) \qquad (3.2)$$

where $R_s(\nu,T_s)$ is the total radiation emitted by the soil surface if the emission coefficient of the surface is set equal to 1 and $\tau(\nu,h)$ is the transmission coefficient of the airlayer of thickness h above the soil surface. This coefficient is found by integrating eq. (3.1):

$$\tau(\nu,h) = e^{-\int_o^h k(\nu,z)\rho dz} \qquad (3.3)$$

Radiance emitted by the atmosphere is extinguished by the layer above the emitting level. The contribution of the atmosphere is:

$$R_a(\nu,h) = \int_{z=o}^{h} k(\nu,z)\ R_a(\nu,T_a,z)\ \exp(-\int_{z^1=z}^{h} k(\nu,z^1)\ \rho dz^1)\ \rho dz \qquad (W.m^{-2}.sr^{-1}) \qquad (3.4)$$

The general solution of the transfer equation is then:

$$R(\nu,h) = R_s(\nu,h) + R_a(\nu,h) \qquad (W.m^{-2}.sr^{-1}) \qquad (3.5)$$

The atmospheric attenuation in the 10.5 - 12.5 μm wave length band can be calculated with the eq. (3.2), (3.3), (3.4) and (3.5) assuming, that radiation is monochromatic at a representative wave length within the called band.

Calculations are performed by dividing the atmosphere in different layers and taking mean values for the mass absorption coefficient and the meteorological variables for each layer. The radiance at the top of layer n is equal to the sum of the transmitted radiance of layer (n-1) and the emitted radiance of layer n:

$$R(\nu,n) = R(\nu,n-1).\exp(-k_n x_n) + R_a(\nu,n)(1-\exp(-k_n x_n) \qquad (W.m^{-2}.sr^{-1}) \qquad (3.6)$$

The radiance emitted by layer n is calculated by substituting a mean air temperature of layer n in Planck's equation.

As the atmospheric attenuation in the 10.5 - 12.5 μm wave length band is mainly caused by water vapour molecules the optical path length x_n is:

$$x_n = \rho_v.\Delta h \qquad (g.cm^{-2}) \qquad (3.7)$$

where ρ_v is water vapour density ($g.cm^{-3}$) and Δh is thickness of layer n (m).

According to BIGNELL (1970), the constant k_n of eq. (3.6) can be described as:

$$k_n = f_1(T).k_1(\frac{P_n}{1000}) + f_2(T).k_2 \frac{e_n}{1000} \qquad (g^{-1}.cm^2) \qquad (3.8)$$

where

$f_1(T) = 1 - 0,005\ (303-T_n)$

$f_2(T) = 1 + 0,02\ (303-T_n)$

T_n = mean air temperature of layer n (K)

e_n = mean partial pressure of water vapour of layer n (mbar)

P_n = mean pressure of layer n (mbar)

$k_1 = 0,10 \quad (g^{-1} \ cm^2)$
$k_2 = 3,2 \quad (g^{-1} \ cm^2)$

If the angle between direction of observation and the vertical is θ, the optical pathlength x_n must be divided by cos (θ). With this method upward radiation is calculated at each height above the surface. With eq. (2.4) an equivalent black body temperature $T_{bs}(h,\theta)$ is calculated. The difference of this temperature and the surface temperature T_{bs} is the correction for the attenuation of thermal infrared radiation by the atmosphere.

$$\Delta T = T_{bs}(h,\theta) - T_{bs} \qquad (K) \qquad (3.9)$$

3.2. Adjustments of the RADTRA-model for application in the 8-14 µm wave length band

Fig. 1 shows, that transmission for water vapour is wave length dependent and that the mean transmission coefficient for the 10.5 - 12.5 µm wave length band is higher than for the 8-14 µm wave length band.

For each wave length interval a mean value should be calculated. Then attenuation of radiance per wave length interval can be calculated from the eqs. (3.2) to (3.5).

Atmospheric attenuation has been calculated taking 11 µm as a representative wave length and taking a weighting mean for the transmission coefficient in the 8-14 µm wave length band.

The radiance emitted by the surface is wave length dependent. As a wave length interval is more important when the radiance emitted in this interval is higher, the transmission coefficient has been calculated mean proportional to the radiance per interval.

For the calculation of the transmission coefficient of a wave length interval the model of ALTSHULER (ANDING et al., 1971) has been applied. This model is based on the melecular band absorption theory (ANDING, 1967).

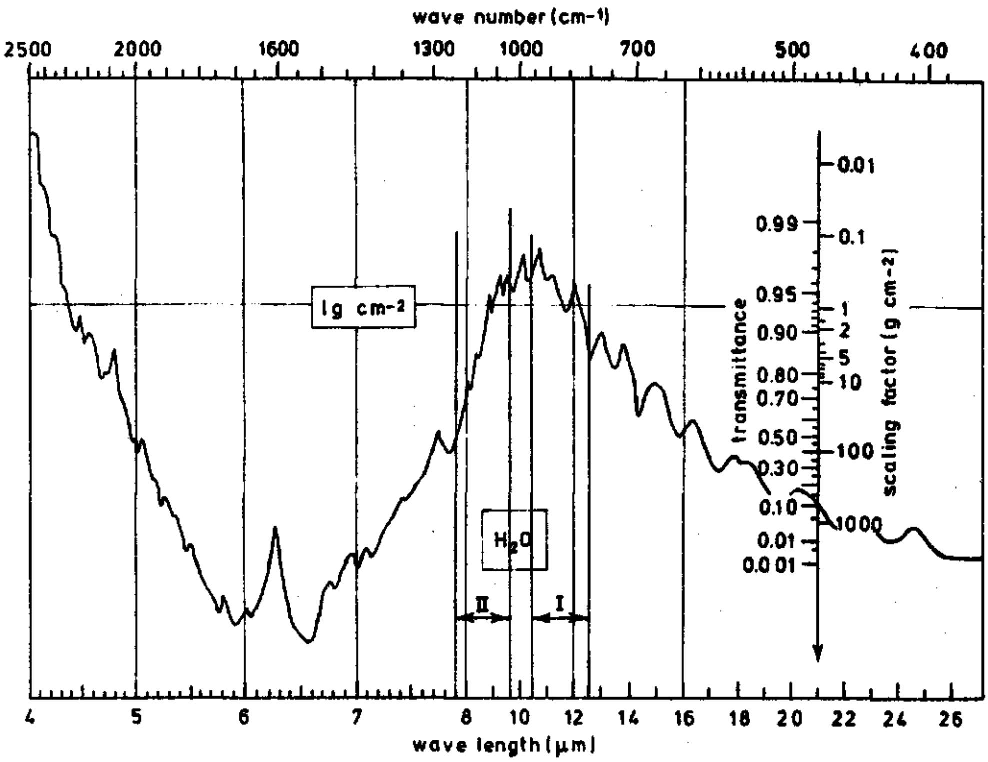

Fig. 1. Transmission depending on the wave length and the amount of water vapour (W) taken from Mc. CLATCHEY et al. (after BECKER, 1978)

If only water vapour absorption is considered the transmission for a resolution element ($\Delta\lambda$) is given by:

$$\tau(\Delta\lambda) = \exp - (W^*.K(\Delta\lambda))^{\frac{1}{2}} \qquad (3.10)$$

Table 1 shows the spectral absorption coefficient $K(\Delta\lambda)$ (cm^{-1}) The 8-14 μm wave length interval has been divided into 12 intervals.

The mean values $\bar{K}(\Delta\lambda)$ as calculated from table 1 are shown in table 2.

In eq. (3.9) W^* is the equivalent optical depth (cm) of liquid water at standard temperature and pressure. For a layer of thickness h this optical depth is equal to:

$$W^* = \int_0^h \rho_v \left(\frac{P}{P_o}\right)^2 \left(\frac{T_o}{T_a}\right)^{1.5} dz \qquad (cm) \qquad (3.11)$$

Table 1. Spectral absorption coefficients for water vapour (after ANDING et al., 1971)

Wavelength (μm)	K(Δλ) (cm^{-1})	Wavelength (μm)	K(Δλ) (cm^{-1})	Wavelength (μm)	K(Δλ) (cm^{-1})
7.737	2.00E 00	10.070	2.65E-03	13.400	4.95E-02
7.797	1.74E 00	10.190	1.98E-03	13.440	5.14E-02
7.859	1.56E 00	10.290	1.86E-03	13.480	5.33E-02
7.921	1.77E 00	10.440	1.90E-03	13.510	5.47E-02
7.984	1.54E 00	10.550	2.00E-03	13.550	5.66E-02
8.048	8.30E-01	10.900	2.50E-03	13.590	5.85E-02
8.114	4.36E-01	11.500	4.52E-03	13.620	6.10E-02
8.180	2.41E-01	11.670	5.33E-03	13.660	6.52E-02
8.247	1.42E-01	11.790	6.23E-03	13.700	6.95E-02
8.316	8.30E-02	11.900	7.15E-03	13.740	7.38E-02
8.386	5.46E-02	12.050	8.17E-03	13.770	7.72E-02
8.457	4.67E-02	12.200	1.01E-02	13.810	8.19E-02
8.529	4.19E-02	12.350	1.28E-02	13.850	8.66E-02
8.602	3.89E-02	12.500	1.71E-02	13.890	8.82E-02
8.677	3.67E-02	12.530	1.81E-02	13.950	9.07E-02
8.753	3.49E-02	12.560	1.92E-02	13.990	9.24E-02
8.830	3.32E-02	12.590	2.00E-02	14.030	9.58E-02
8.909	3.12E-02	12.630	2.05E-02	14.060	9.89E-02
8.989	2.93E-02	12.660	2.15E-02	14.100	1.03E-01
9.070	2.73E-02	12.690	2.25E-02	14.140	1.07E-01
9.130	2.60E-02	12.720	2.34E-02	14.180	1.11E-01
9.220	2.35E-02	12.760	2.46E-02	14.220	1.17E-01
9.310	2.10E-02	12.790	2.50E-02	14.270	1.26E-01
9.335	1.90E-02	12.820	2.55E-02	14.310	1.33E-01
9.398	1.49E-02	12.850	2.60E-02	14.350	1.41E-01
9.463	1.18E-02	12.890	2.69E-02	14.390	1.48E-01
9.494	1.05E-02	12.920	2.76E-02	14.430	1.54E-01
9.526	9.00E-03	12.950	2.83E-02	14.470	1.59E-01
9.590	7.20E-03	12.990	2.92E-02	14.510	1.64E-01
9.652	6.20E-03	13.020	3.01E-02	14.560	1.70E-01
9.713	5.20E-03	13.050	3.12E-02	14.600	1.75E-01
9.773	4.40E-03	13.090	3.26E-02	14.640	1.86E-01
9.834	3.75E-03	13.120	3.39E-02	14.680	1.98E-01
9.893	3.35E-03	13.160	3.58E-02	14.730	2.12E-01
9.953	2.95E-03	13.190	3.71E-02	14.770	2.23E-01
		13.230	3.95E-02	14.810	2.34E-01
		13.260	4.14E-02	14.860	2.44E-01
		13.300	4.37E-02	14.900	2.52E-01
		13.330	4.54E-02	14.950	2.63E-01
		13.370	4.78E-02	14.990	2.72E-01

where: P_o = standard pressure at sea level (P_o = 1013 mbar)

T_o = standard absolute temperature at sea level (T_o = 288,15 K)

P = atmospheric pressure (mbar)

T_a = atmospheric temperature (K)

Table 2. Mean spectral absorption coefficients ($\bar{K}(\Delta\lambda)$) depending on the wave length interval ($\Delta\lambda$) calculated from table 1

$\Delta\lambda$	$\bar{K}(\Delta\lambda)$
8.0 - 8.5	0.262
8.5 - 9.0	0.035
9.0 - 9.5	0.019
9.5 - 10.0	0.005
10.0 - 10.5	0.002
10.5 - 11.0	0.002
11.0 - 11.5	0.003
11.5 - 12.0	0.006
12.0 - 12.5	0.012
12.5 - 13.0	0.025
13.0 - 13.5	0.041
13.5 - 14.0	0.073

Except for applying weighting factors per wave length interval for the radiation intensity, also weighting factors for the properties of the scanner should be introduced. Because of the properties of the filter the wave length bands in the middle of the 8-14 μm wave length interval are probably more important than the other ones (SHAW and IRBE,1972). As no data about the filter of the used scanner are available this effect is not taken into account.

The transmission coefficient in the 12.5 - 14.0 μm wave length interval is strongly influenced by the absorption of radiation by CO_2 molecules. So in this interval transmission in the atmosphere is determined both by H_2O molecules and CO_2 molecules. This effect, however, is omitted as well, because of the uncertainties in the operations of the filter.

3.3. The model of BECKER

In this model it is assumed, that at atmospheric attenuation in the 8-14 μm band is caused by water vapour molecules only. Applying linear expansion of Planck's formula, BECKER (1978) has derived that:

$$T_{bs}(h,\theta) = T_{bs} + \frac{AW(h)}{\cos} \quad (\Theta(h) - T_{bs}) + \delta \qquad (K) \qquad (3.12)$$

where

- h = altitude (m)
- θ = angle of observation
- T_{bs} = black body temperature of the surface (K)
- $W(h)$ = total water content of the atmosphere over the column of length h ($g.cm^{-2}$)
- A = constant characteristic of the atmosphere ($cm^2.g^{-1}$)
- δ = correction, which can be neglected to first order
- $\Theta(h)$ = an effective atmospheric temperature (K)

The effective atmospheric temperature is defined as:

$$\Theta(h) = \sum_{n=1}^{N} W_n T_n \Big/ \sum_{n=1}^{N} W_n \qquad (K) \qquad (3.13)$$

According to a first order approximation the temperature correction for atmospheric attenuation is:

$$\Delta T = T_{bs}(h,\theta) - T_{bs} = \frac{AW(h)}{\cos\theta} \quad (\Theta(h) - T_{bs}) \qquad (K) \qquad (3.14)$$

Results obtained with this model have been compared with the RADTRA-model. The factor A has been calculated assuming that for a surface temperature equal to the temperature of the lower atmosphere, the corrections as calculated by both models are the same at the top of the atmosphere.

In both of the mentioned models information about the PTH profiles in the atmosphere is necessary. In eq. (3.14), however W(h) and Θ(h) can be eliminated by measuring the radiation temperatures of the soil surface in two different wave length bands.

These are:

$$T_1(h,\theta) = T_{bs} + \frac{A_1 W(h)}{\cos\theta}(\Theta(h) - T_{bs}) \qquad (K) \qquad (3.15)$$

$$T_2(h,\theta) = T_{bs} + \frac{A_2 W(h)}{\cos\theta}(\Theta(h) - T_{bs}) \qquad (K) \qquad (3.16)$$

The radiation temperature of the soil surface T_{bs} is found by combining the eqs. (3.15) and (3.16):

$$T_{bs} = \frac{T_1(h,\theta) + T_2(h,\theta)}{2} + (T_1(h,\theta) + T_2(h,\theta))\ \bar{A} \qquad (K) \qquad (3.17)$$

where:

$$\bar{A} = \frac{A_1 + A_2}{2(A_2 - A_1)}$$

Calculations with eq. (3.17) are only accurate, if the difference in atmospheric transmission in the two wave length bands is large enough.

4. RESULTS

The influence of the atmosphere on thermal infrared radiation has been studied for an 'ideal' day to perform an Infra Red Line Scanning (IRLS) flight. This is a day, upon which the amount of water vapour in the atmosphere is very low. As an 'ideal' day June 8, 1976 has been chosen. The meteorological data of this date are shown in table 3. From which data corrections for the influence of the atmosphere have been calculated.

Table 3. Meteorological data of June 8, 1976

h(m)	P(mbar)	T(K)	e(mbar)
174	1,001	298,2	12.2
619	951	292.7	9.4
1,080	901	288.4	8.7
1,560	851	284.7	6.3
2,060	801	281.6	3.3
2,980	716	278.2	3.0
4,180	616	268.8	1.0
5,550	516	260.6	0.5
6,740	441	253.2	0.4

Fig. 2 shows some results obtained with the RADTRA-model. From this figure it is evident, that even for ideal Netherlands weather conditions the influence of the atmosphere cannot be neglected.

In 1978 an IRLS-flight has been performed under clear sky conditions at July 31. Moreover this flight coincided with a passing over of the Heat Capacity Mapping Mission (HCMM) satellite. The meteorological conditions at midday are shown in table 4.

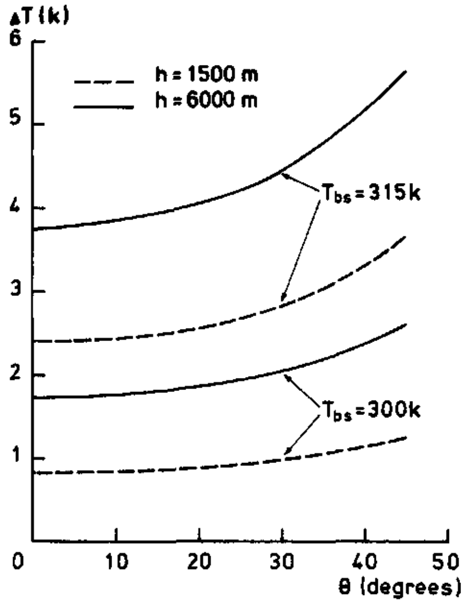

Fig. 2. Atmospheric temperature corrections (ΔT) depending on observation angle (θ) as calculated with the RADTRA-model for June 8, 1976

Table 4. Meteorological data of July 31, 1978

h(m)	P(mbar)	T(K)	e(mbar)
88	1,003	300.8	16.2
539	953	298.1	14.8
1,010	903	294.9	10.7
1,500	853	289.9	9.8
2,010	803	285.4	8.4
3,230	693	277.4	2.9
4,470	593	267.1	1.6
5,890	493	258.7	0.3
6,690	443	252.0	0.2

Fig. 3 shows temperature corrections for the influence of the atmosphere ΔT depending on the height above the soil surface as calculated with the RADTRA and BECKER's model. From the corrections

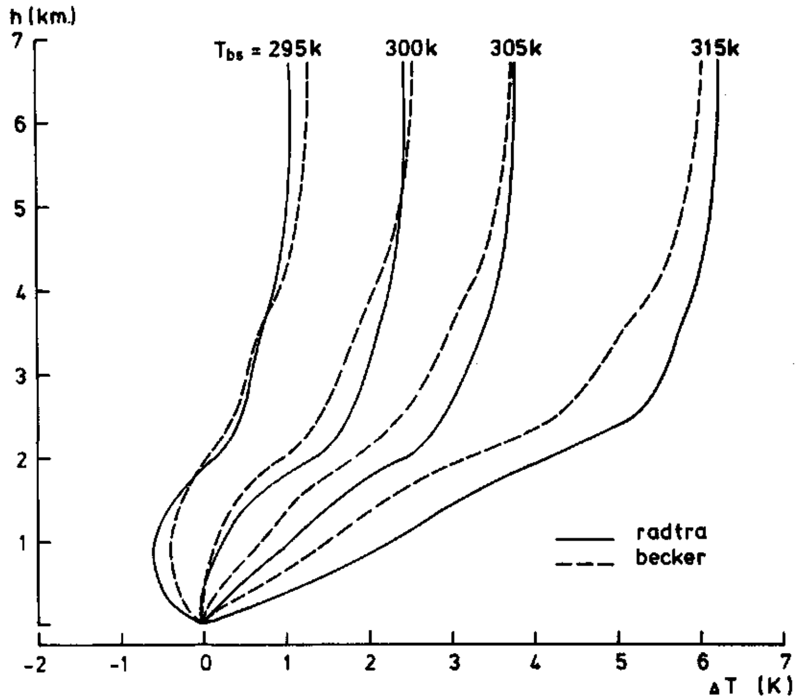

Fig. 3. Atmospheric temperature corrections (ΔT) depending on height (h) above the earth surface for differenct surface temperatures as calculated both with the RADTRA-model and BEKCER's model for July 31, 1978. The observation angle θ is zero

at 6700 m height as calculated with the RADTRA model, the constant A in BECKER's model has been derived. This constant A is found to be equal to 0.09 $cm^2.g^{-1}$.

From fig. 3 can be concluded, that for surface temperatures which are about equal to the temperature of the lower atmosphere (± 300 K), the models agree very well. With an increase of the surface temperature the agreement is less.

BECKER has tested his model against water temperatures of the river Rhine. This means that he checked his model only for relatively low surface temperatures.

For the meteorological conditions of July 31, 1978 the influence of the atmosphere above a height of 4.5 km is negligible. Fig. 4 shows for both models the dependence on the observation angle θ. For flights performed at low altitudes the influence of the observation angle is only important for high surface temperatures. With an increase of the altitude the influence of the observation angle increases. So for flights performed at high altitudes as well as for satellite measurements the influence of the observation angle may not be neglected. This also holds true for low surface temperatures.

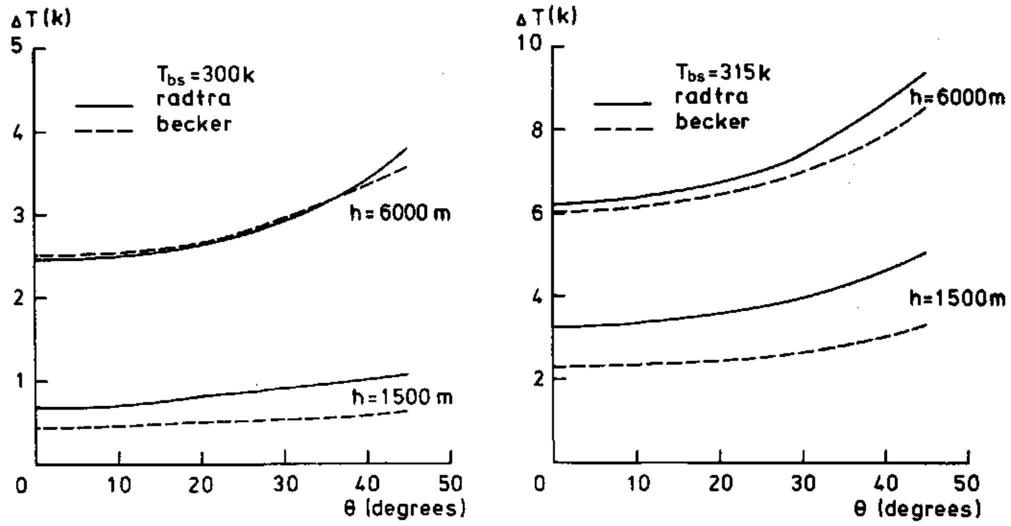

Fig. 4. Atmospheric temperature corrections (ΔT) depending on observation angle (θ) as calculated both with RADTRA-model and BECKER's model for July 31, 1978 for surface temperature T_{bs}= 300K (fig. 4A) and for T_{bs}= 315K (fig. 4B)

Mean atmospheric transmission coefficients for the 10.5-12.5 μm wavelength band have been calculated according to the method of BIGNELL (eq. 4.8) and ALTSHULER (eq. 4.10). RANGASWAMY and SUBBARAYUDU apply in their model k_2 = 3.2 $g^{-1} cm^2$ (BURCH, 1970). BIGNELL (1970), however, gives a value of 10 $g^{-1} cm^2$ for k_2 (fig. 5). With the model of ALTSHULER also mean transmission coefficients for the 8-14 μm wave length band have been calculated. Table 5 shows some results.

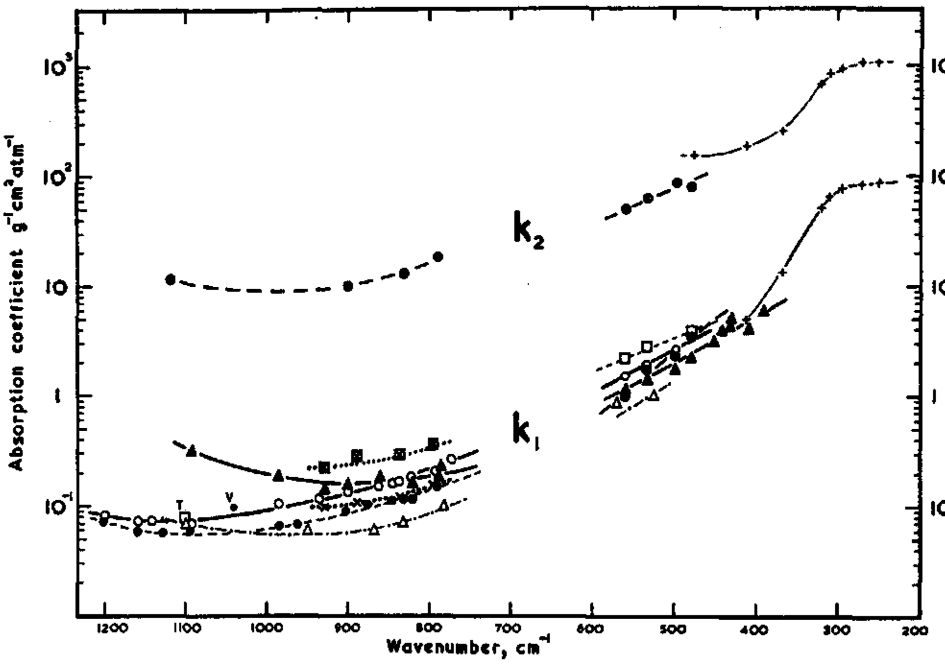

Fig. 5. Mass absorption coefficients k1 and k2 as a function of wave number (after BIGNELL, 1970)

The influence of the atmosphere has been calculated with the different formula's for the transmission coefficient. The results are presented in figs. 6A and B. Even small differences in transmissivity cause considerable differences in the atmospheric temperature corrections. So it is extremely important to calculate the transmissivity of the atmosphere very accurately.

Finally fig. 7 presents the atmospheric corrections for July 31, 1978 both in the 10.5 - 12.5 µm and 8 - 14 µm wave length band. Even for IRLS flights at low altitudes the influence of the atmosphere is not negligible. The correction in the 8 - 14 µm band is much larger than in the 10.5 - 12.5 µm band.

Table 5. Mean transmission coefficients for the 10.5 - 12.5 µm wave length interval according to BIGNELL (formula 3.8) with k_2 is 3.2 and 10.0 $g^{-1}cm^2$ respectively and according to ALTSHULER (formula 3.10). With the method of ALTSHULER also mean transmission coefficients for the 8 - 14 µm wave length interval have been calculated.

h(m)	Mean transmission coefficients for $\theta = 0^o$			
	BIGNELL (10.5-12.5 µm)		ALTSHULER	
	$k_2 = 3.2$	$k_2 = 10.0$	10.5-12.5 µm	8-14 µm
88	.942	.898	.959	.916
540	.986	.976	.980	.958
1,012	.997	.995	.989	.976
1,502	.982	.964	.979	.956
1,910	.993	.987	.985	.968
2,662	.992	.989	.984	.966
3,533	.996	.994	.988	.975
4,481	.998	.998	.992	.982
5,531	1.000	1.000	.996	.991
6,710	1.000	1.000	.997	.993

h(m)	Mean transmission coefficients for $\theta = 45^o$			
	BIGNELL (10.5-12.5 µm)		ALTSHULER	
	$k_2 = 3.2$	$k_2 = 10.0$	10.5-12.5 µm	8-14 µm
88	.906	.821	.951	.901
540	.978	.957	.976	.950
1,012	.995	.992	.987	.972
1,502	.969	.933	.975	.948
1,910	.988	.977	.982	.962
2,662	.988	.981	.981	.960
3,533	.994	.991	.986	.970
4,481	.997	.996	.990	.978
5,531	.999	.999	.996	.990
6,710	1.000	1.000	.996	.992

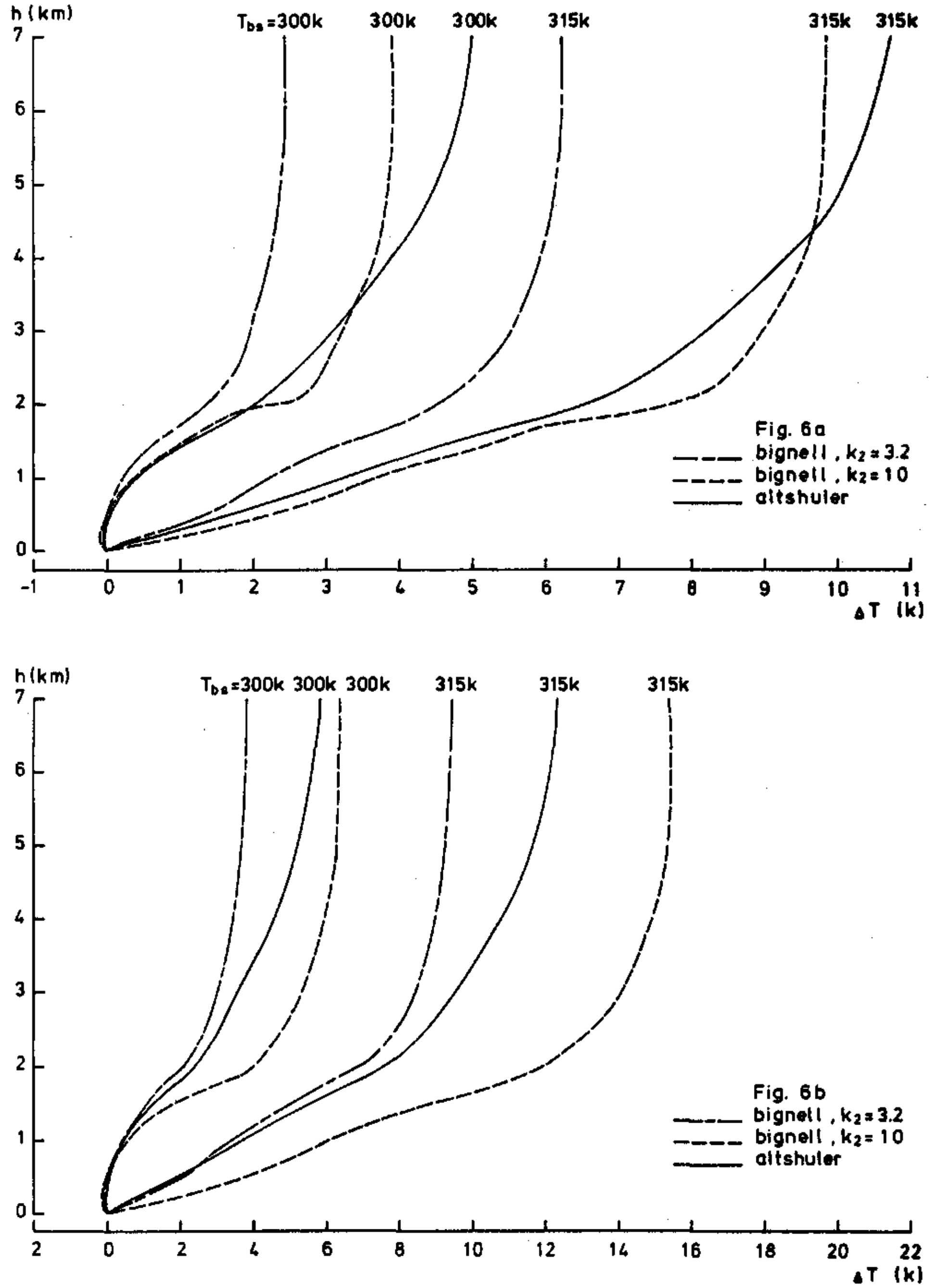

Fig. 6. Atmospheric temperature corrections (Δt) on July 31, 1978 as calculated with the RADTRA-model for two surface temperatures (T_{bs}) and for observation angle $\theta = 0^{o}$ (fig. 6A) and for $\theta = 45^{o}$ (fig. 6B). Transmission of the atmosphere is calculated according to BIGNELL (eq. 4.8) with k_2 is 3.2 and 10.0 $g^{-1}.cm^{2}$ respectively and according to ALTSHULER (eq. 4.10)

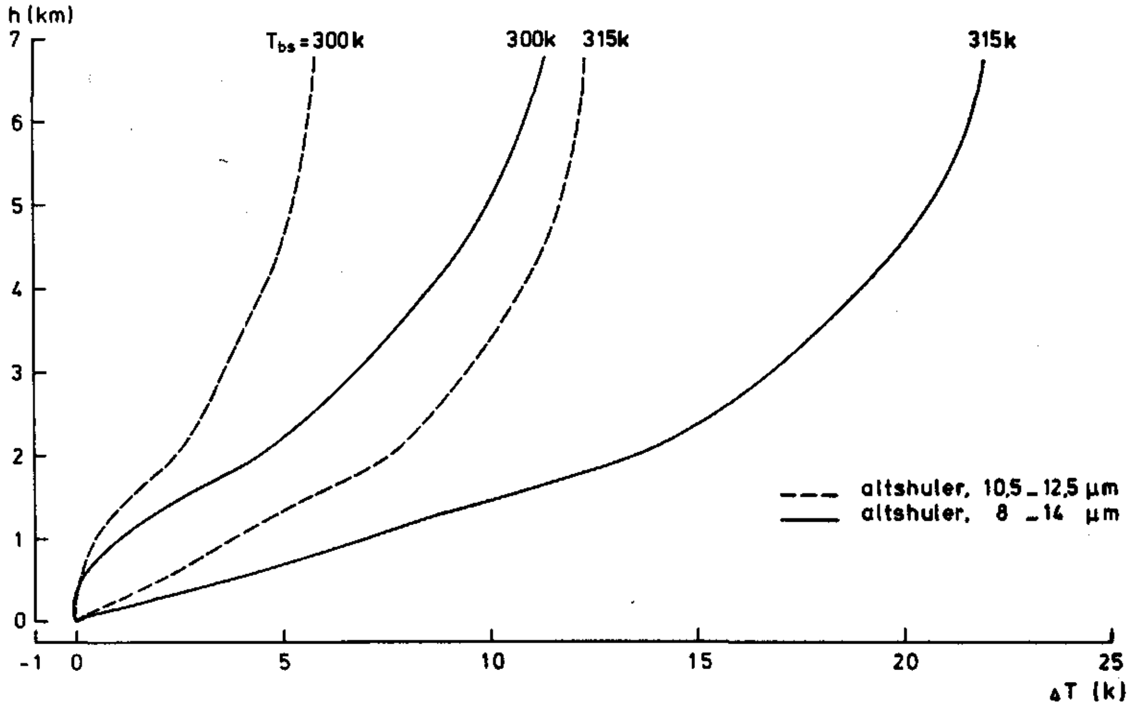

Fig. 7. Atmospheric temperature corrections (ΔT) depending on height (h) for two surface temperatures (T_{bs}) and an observation angle (θ) of 45° as calculated with the RADTRA-model for July 31, 1978. Mean transmission coefficients have been calculated according to the method of ALTSHULER for the 10.5 - 12.5 µm and the 8-14 µm wave length band respectively

5. SUMMARY

Crop radiation temperatures as determined by scanners from air planes or satellites are more and more used in regional hydrological models (JACKSON et al., 1977 and SOER, 1977). Large errors, however, may be introduced when neglecting the influence of the atmosphere on thermal infrared radiation. Even under clear sky conditions atmospheric corrections may amount to several degrees Kelvin. Moreover the atmosphere causes a smoothing of temperature differences at the surface.

Most atmospheric models are based on calculation of the transmission coefficient of the atmosphere in any wave length band from profiles of pressure, temperature and humidity (PTH-profiles). It is evident, however, that these models are very sensitive for errors in the transmission coefficient. Therefore the model of BECKER is preferred. In this model the influence of the atmosphere is taken linearly proportional to the amount of water vapour in the atmosphere. It is possible, however, that, when the surface temperature is high in relation to the temperature of the lower atmosphere, with BEKCER's model atmospheric corrections are underestimated. Further study on this subject is necessary.

As an input into the models PTH-profiles are required. Often these models are not known. With BEKCER's model, these data can be eliminated if the radiation emitted by the surface is measured in two different wave length bands.

Insight in atmospheric processes can be obtained by applying simulations with models. For a reliable calibration of radiation temperatures measured with scanners from a certain height above the surface, such models are, however, not sufficient. Reference measurements in the field are indispensable. As the atmosphere smoothes surface temperature differences which occur, measurements of both relatively low- and relatively high reference surface temperatures are required.

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LIST OF USED SYMBOLS

Symbol	Description	Units
A	constant characteristic of the atmosphere	$cm^2.g^{-1}$
β	scattering coefficient	
c_1	constant in formula of Planck (=1.185.10^8)	$W.m^{-2}.\mu^{-4}$
c_2	constant in formula of Planck (=1.439.10^4)	μ.K.
δ	correction term	
e	partial pressure of water vapour	mbar
ε	emission coefficient	
Θ	effective atmospheric temperature	K
θ	angle between the direction of observation and the vertical	
h	height above the earth surface	m
K	spectral absorption coefficient	cm^{-1}
k	massabsorption coefficient	$cm^2.g^{-1}$
k_1	constant in formula of Bignell (=0.10)	$cm^2.g^{-1}$
k_2	constant in formula of Bignell (=3.2 or 10)	$cm^2.g^{-1}$
λ	wavelength	μ
n	indicates number of layers in the atmosphere	
ν	wave number or frequency of the electro-magnetic radiation (= λ^{-1})	μ^{-1}
P	atmospheric pressure	mbar
P_o	standard pressure at sea level (= 1013)	mbar
R	radiation per unit of frequency interval	$W.m^{-2}.sr^{-1}$
R_b^1	blackbody radiation	$W.m^{-2}.sr^{-1}.\mu^{-1}$
R_b	blackbody radiation per unit of frequency interval	$W.m^{-2}.sr^{-1}$
R_a	radiance emitted by the atmosphere	$W.m^{-2}.sr^{-1}$
R_s	radiance emitted by the soil surface	$W.m^{-2}.sr^{-1}$
ρ	density	$g.cm^{-3}$
ρ_v	water vapour density	$g.cm^{-3}$
T	temperature	K
T_o	standard absolute temperature at sea level (= 288.15)	K

Symbol	Description	Units
T_{bs}	black body temperature of the surface	K
T_a	atmospheric temperature	K
T_s	surface temperature	K
τ	transmission coefficient	
W	total water content of the atmosphere over a certain column length	$g.\ cm^{-2}$
W*	equivalent optical depth	cm
x	optical path length	$g.cm^{-2}$