FIELD INVESTIGATIONS OF THE WATER VAPOR CONTINUUM ABSORPTION NEAR 10.6 μm

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Some results of field measurements of the water vapor continuum absorption near 10.6 μm are presented. The adjustable parameters of the approximating expression used for calculations of the coefficients of continuum absorption are obtained. The positive temperature dependence of the linear term in the expression for the continuum absorption coefficient was found to be +0.97...+1.05%·deg^{-1} *in the temperature range* 285–308 K, *while the negative temperature dependence of the squared term was* –2.1...–2.4%·deg^{-1}.

The regularities of the continuum absorption of optical radiation by water vapors in the 8–13 μm atmospheric relative transmission window were studied in quite a few experimental works on slant and horizontal paths under field conditions and in laboratory cells.[1–13] The analysis of these papers makes it possible to determine the general behavior of the continuum: nonlinear dependence of the continuum absorption coefficient (α_c) on partial pressure of water vapor (or absolute air humidity) and negative temperature dependence of α_c. At the same time, the continuum absorption coefficients differ markedly. The critical review of the recent representative data on water vapor continuum[14] revealed some factors which caused distortions of the results of measurements of α_c. Among these factors, when measurements are carried out on the real atmospheric paths, are the difficulties associated with correct consideration of the selective absorption by water vapor and atmospheric gases (CO_2, O_3, NH_3, and so on), the presence of aerosol extinction and its dependence on relative air humidity, possible uncertainties in measuring the temperature and watervapor distributions along the path, and the problems with calibration of the instrumentation.

In this paper we separated out the contribution of the water vapor continuum absorption from the total extinction near 10.6 μm based on the results of previous investigations. The input data were optical radiation transmission in 15 sections of the visible and IR ranges which were obtained on 4.63–km measurement path with the help of the system described in Ref. 15 in the arid zone of Kazakhstan in April 1986–October 1987. The spectral sections were selected using interference light filters in combination with cutoff pigmented glass filters centered at wavelengths of 0.44, 0.48, 0.55, 0.63, 0.69, 0.87, 0.94, 1.06, 1.22, 1.6, 2.17, 3.97, 9.2, 10.6, and 11.5 μm. The half–width of the filter bands in the spectral range 0.44–2.17 μm was 0.01–0.02 μm and in the spectral range 3.97–11.5 μm it was 0.15–0.30 μm. The random error in calculating the total extinction coefficients ($\varepsilon(\lambda)$) in the range λ = 0.44...11.5 μm was ~0.005 km^{-1}. The aerosol extinction coefficients ($\alpha_a(\lambda)$) in the range 0.44...3.97 μm were found based on the technique described in Ref. 16. In the spectral ranges 0.44...1.06 μm and 1.06–3.97 μm molecular scattering and molecular absorption by water vapors and atmospheric gases were subtracted, respectively.

The ranges of variability for the meteorological parameters of the atmosphere play an important role in determining the dependence of the water vapor continuum on meteorological parameters of the atmosphere. The ranges of variation of the absolute air humidity from 1 to 19 g/m^3, of temperature from 263 to 308 K, and of relative humidity from 25 to 95% realized in the experiment made it possible to study the α_c dependence on the absolute humidity and air temperature.

Due to insignificant variability of the total atmospheric pressure the dependence of the continuum on this parameter was not studied. The mean value of the total pressure was 0.967 atm. The meteorological visibility range varied from 30 to 200 km.

The total extinction coefficient experimentally measured near 10.6 μm can be represented as a sum

$$\varepsilon = \alpha_c + \alpha_a + \alpha_{sw} + \overline{\alpha}_{sg} + \alpha_0 + \delta ,$$

where α_c is the coefficient of continuum absorption by water vapors, α_a is the aerosol extinction coefficient, α_{sw} is the selective absorption coefficient by water vapor, $\overline{\alpha}_{sg}$ is the mean selective absorption coefficient of atmospheric gases (CO_2, NH_3, O_3, etc.), and α_0 and δ are the systematic and random errors in determining ε. In this expression for ε the variations of $\overline{\alpha}_{sg}$ are included in δ. Strictly speaking, α_{sw} and $\overline{\alpha}_{sg}$ cannot be taken to mean the absorption coefficients for nonmonochromatic radiation. Taking this into account, we now describe the technique for separating out the continuum absorption and for determining the criteria of selection of the spectra $\varepsilon(\lambda)$ used to obtain α_c. The absolute air humidity averaged over the measuring path was determined by the optical method.[17] For this method to be realized, the transmission in the 0.94 μm water vapor absorption band was determined. The optical and meteorological measurements of humidity were performed simultaneously at one end of the path. When the difference between the humidities determined by the optical and meteorological methods exceeded 0.5 g/m^3 in absolute value, the corresponding spectrum $\varepsilon(\lambda)$ was excluded from the subsequent analysis. It enables us to decrease the random rms error in determining the humidity by the optical method down to 0.2 g/m^3.

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To derive the dependence of α_c on the meteorological parameters of the atmosphere we used the spectra of the total extinction coefficients with neutrally spectral behavior of $\alpha_a(\lambda)$ in the range 0.44...0.87 μm. Such a criterion for spectrum selection was chosen due to the possible neglect of the submicron aerosol absorption near 10.6 μm. As is well known,[18] the aerosol submicron fraction has an especially pronounced spectral behavior of the extinction coefficients in the visible range which manifests itself in the decrease of the coefficients with radiation wavelength, while the coarse aerosol fraction has neutrally spectral behavior. Then in the spectra $\varepsilon(\lambda)$ selected against the aforementioned criterion, the extinction coefficient of the submicron aerosol in the range 0.44...0.87 μm does not exceed the random error in determining the total extinction (0.005 km^{-1}), and the absorption coefficient of the submicron aerosol near 10.6 μm (according to the single–parameter model calculation[19]) is 0.001 km^{-1}.

The extinction due to the coarse aerosol fraction was taken into account using the following method. Based on the statistical characteristics of the data arrays of the extinction coefficients in the range 1.06...10.6 μm and the meteorological parameters, we found the empirical models for calculating five aerosol extinction coefficients near 10.6 μm (see Ref. 16)

$$\alpha_{ai}(10.6) \sim K_{0i} + K_{1i}\cdot\alpha_a(\lambda_i) ,$$

where $i = 1, \ldots, 5$, $\alpha_a(\lambda_i)$ are the aerosol extinction coefficients at wavelengths of 1.06, 1.22, 1.6, 2.17, and 3.97 μm, and K_{0i} and K_{1i} are the empirical constants. In the subsequent analysis we retained those spectra of extinction coefficients for which the difference between the maximum and minimum model estimates of aerosol extinction near 10.6 μm did not exceed 0.01 km^{-1}. Then the mean value of aerosol extinction near 10.6 μm was derived from these five coefficients and subtracted from the total extinction. This approach made it possible to exclude the aerosol extinction near 10.6 μm with rms error of 0.003 km^{-1}.

To take into account the selective absorption by water vapors we found the transmission function

$$T_{sw}(10.6) = \int_{\lambda_1}^{\lambda_2} T_{sw}(\lambda)\cdot A(\lambda)\mathrm{d}\lambda \Big/ \int_{\lambda_1}^{\lambda_2} A(\lambda)\,\mathrm{d}\lambda ,$$

where λ is the radiation wavelength, $\lambda_1 = 10.35$ μm, $\lambda_2 = 10.85$ μm, $T_{sw}(\lambda)$ is the spectral transmission of the selective component of water vapor on the 4.63–km path, $A(\lambda)$ is the transmission of the interference filter, $A(\lambda) = 4A_0(\lambda - \lambda_1)$ for $\lambda_1 \le \lambda \le 10.6$ μm and $A(\lambda) = 4A_0(\lambda_2 - \lambda)$ for $10.6 \le \lambda \le \lambda_2$, and A_0 is the transmission of the filter at $\lambda = 10.6$ μm. The value $T_{sw}(\lambda)$ was calculated based on the data given in Ref. 20. The coefficient α_{sw} was found using the formula

$$\alpha_{sw} = \ln T_{sw}(10.6)/L ,$$

where L is the path length.

The mean value of the atmospheric gas absorption coefficient ($\overline{\alpha}_{sg}$) and the systematic error (α_0) were excluded from the total extinction. The accuracy of excluding the value $\overline{\alpha}_{sg} + \alpha_0$ from $\varepsilon(10.6)$ was about 0.005 km^{-1}.

Thus, the use of selection criteria resulted, on the one hand, in reduction of the experimental data array $\varepsilon(\lambda)$ from 298 to 65 spectra and, on the other hand, enabled us to minimize the random error in calculating α_c.

The dependence of the continuum absorption coefficient by water vapor on meteorological parameters of the atmosphere was specified in the form[13]

$$\alpha_c(10.6) = k_1\cdot T^n(1 + k_0 P)a + k_2\cdot\exp(H/T)a^2 , \qquad (1)$$

where α_c is the continuum absorption coefficient in km^{-1}; α is the absolute air humidity in g/m^3; T is the temperature in degrees Kelvin; P is the total pressure in atm; and, k_0, k_1, k_2, n, and H are the adjustable parameters. The parameter k_0 was determined so that the values of the product $k_1\cdot T^n k_0$ in Eq. (1) at $T = 296$ K calculated based on the data given in Ref. 13 and on the results of this paper were equal in magnitude. Such a method for finding k_0 can be explained by the fact that in Ref. 13 a part of the absorption coefficient depending on the total pressure was determined experimentally, while we did not perform such investigations. The remaining parameters in Eq. (1) were determined by the least–squares technique after the continuum absorption coefficients were devided by the absolute air humidity. As a result, the following adjustable parameters were obtained:

$k_0 = 2.05$ atm^{-1}, $k_1 = 4.11\cdot10^{-11}$ $g^{-1}\cdot m^3\cdot K^{-3}\cdot km^{-1}$,

$k_2 = 8.61\cdot10^{-7}$ $g^{-2}\cdot m^6\cdot km^{-1}$, $n = 3$, and $H = 1988$ K.

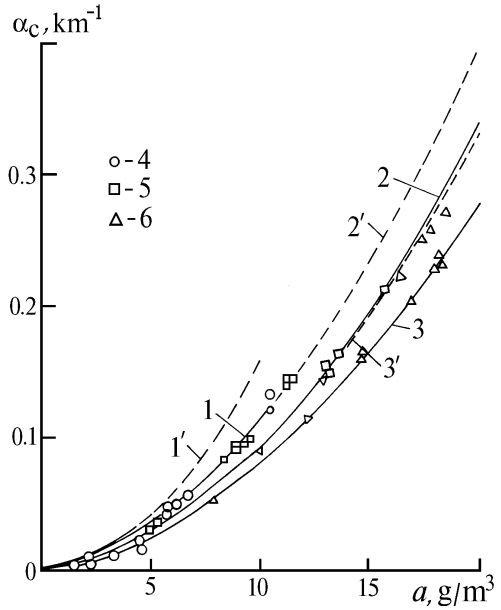

FIG. 1. The coefficients of continuum absorption by water vapors vs absolute air humidity near 10.6 μm at $P = 0.967$ atm: 1, 2, and 3) results of calculation from Eq. (1), 1′, 2′, and 3′) results of calculation according to Ref. 13. For temperature T: 1 and 1′) 285, 2 and 2′) 298, 3 and 3′)308 K, Symbols 4, 5, and 6 are experiment: 4) 263 < T ≤ 285, 5) 285 < T ≤ 298, and 6) 298 < T ≤ 308 K).

The symbols denoted by the numbers *4*, *5*, and *6* in Fig. 1 indicate the experimental values of α_c when the air temperature varied from 263 to 308 K. The solid and dashed curves are calculated from Eq. (1) and according to the data from Ref. 13 for three values of temperature at $P = 0.967$ atm.

It can be seen from the figure that the values of α_c at the temperatures 285–298 and 298–308 K fall well within the corresponding corridors bounded by curves *1–2* and *2–3*. The experimental values obtained at the temperatures 263–308 K are described by formula (1) (with the adjustable parameters obtained in this paper) with a standard deviation of 0.006 km^{-1}; in addition, for $a < 10$ g/m^3 this deviation was 0.004 km^{-1} and for $a > 10$ g/m^3 it was 0.008 km^{-1}. The data given in Ref. 13 inadequately describe our field values of α_c. Thus 90% of its values at 285–298 and 298–308 K do not fall within the coridors bounded by the curves *1′* and *2′* and *2′* and *3′*. The difference between the calculations according to Ref. 13 and the experimental values of α_c in the temperature intervals 263–285, 285–298, and 298–308 K reaches 0.02, 0.04, and 0.05 km^{-1}, respectively.

The first (linear) term in Eq. (1) corresponds to the absorption associated with the H_2O–N_2 molecule interaction and the second (quadratic) term – to H_2O–H_2O interaction (see Ref. 21). It is of interest to compare the temperature dependences of the two parts of the continuum absorption with the data of Ref. 13. The results of this intercomparison are listed in Table I.

TABLE I. Temperature dependence of the two parts of continuum absorption (% · deg^{-1}) near 10.6 μm.

Data	H_2O–N_2			H_2O–H_2O		
	Temperature, K					
	285	300	308	285	300	308
Eq. (1)	+1.05	+1.00	+0.97	–2.4	–2.2	–2.1
Ref. 13	+0.53	+0.50	+0.49	–2.5	–2.3	–2.2

It can be seen from the table that the temperature dependence of the linear term is nearly 0.5%·deg^{-1} larger and of the quadratic term is 0.1%·deg^{-1} smaller in absolute value than that obtained in Ref. 13. The total temperature dependence of the continuum from Eq. (1) and Ref. 13 for the range of relative air humidity (r) 25–95% and for three values of absolute humidity is given in Table II. The absolute value of the temperature dependence in both these cases increases with relative humidity and for the aforementioned conditions from Eq. (1) it reaches –0.7...–1.6%·deg^{-1} which is 0.3–0.4%·deg^{-1} smaller than that obtained in Ref. 13.

TABLE II. Total temperature dependence of the continuum (%·deg^{-1}) near 10.6 μm.

Data	r, %			
	25	55	75	95
	$a = 5$ g/m^3			
Eq. (1)	–0.7	–1.2	–1.4	–1.5
Ref. 13	–1.1	–1.6	–1.7	–1.8
	$a = 10$ g/m^3			
Eq. (1)	–0.9	–1.3	–1.5	–1.6
Ref. 13	–1.3	–1.6	–1.8	–1.9
	$a = 20$ g/m^3			
Eq. (1)	–1.0	–1.4	–1.5	–1.6
Ref. 13	–1.3	–1.7	–1.8	–1.9

To compare the contributions of the linear and quadratic terms of Eq. (1) with the results available elsewhere we represent the continuum absorption coefficient in the simplified form

$$\alpha_c = k_3(T, P)a + k_4(T)\,a^2.$$

Listed in Table III are the values of k_3 and k_4 available elsewhere near 10.6 μm at $P = 1$ atm and three temperatures. Our results for the parameter k_3 are in good agreement, with those from Refs. 7 and 13 and differ markedly from the data obtained in Refs. 5 and 12. The parameter k_4 agrees well only with the data obtained in Ref. 5. The results published elsewhere give larger values for k_4. The last column of Table III shows the values of α_c calculated for $a = 10$ g/m^3 from where it can be seen that the calculations based on Eq. (1) give smaller values of the absorption coefficients compared to the results available elsewhere. The values α_c calculated using Eq. (1) are in the best agreement with the results given in Ref. 13.

TABLE III.

Data	k_3, $km^{-1}\cdot g^{-1}\cdot m^3$	k_4, $km^{-1}\cdot g^{-2}\cdot m^6$	α_c, km^{-1}
	$T = 283$ K		
Eq. (1)	0.0028	0.00097	0.125
Ref. 12	0.0014	0.00181	0.195
Ref. 13	0.0031	0.00121	0.152
	$T = 296$ K		
Eq. (1)	0.0033	0.00071	0.104
Ref. 7	0.0033	0.00091	0.124
Ref. 13	0.0033	0.00088	0.121
	$T = 300$ K		
Eq. (1)	0.0034	0.00065	0.099
Ref. 5	0.0055	0.00066	0.121
Ref. 12	0.0018	0.00117	0.135
Ref. 13	0.0034	0.00080	0.114

Table IV lists the results of calculation of the continuum absorption coefficients based on the data given in Ref. 13 and formula (1) for four values of relative humidity and three values of absolute air humidity. It follows from the table that the difference between the results of Ref. 13 and Eq. (1) increases with relative and absolute air humidities. This difference reaches 0.07 km^{-1} for $a = 20$ g/m^3 ($r = 95\%$).

TABLE IV. Continuum absorption coefficients (km^{-1}) *near* 10.6 μm.

Data	r, %			
	25	45	75	95
	$a = 5$ g/m^3			
Eq. (1)	0.034	0.037	0.041	0.043
Ref. 13	0.039	0.044	0.050	0.053
	$a = 12$ g/m^3			
Eq. (1)	0.119	0.133	0.151	0.160
Ref. 13	0.133	0.155	0.180	0.193
	$a = 20$ g/m^3			
Eq. (1)	0.249	0.284	0.325	0.347
Ref. 13	0.276	0.328	0.386	0.417

In conclusion we formulate the principal results.

1. The adjustable parameters of the approximating expression used to calculate the continuum absorption coefficients near 10.6–μm range have been obtained.

2. The general negative temperature dependence of the continuum has been determined which is $-0.7\ldots-1.6\%\cdot\text{deg}^{-1}$ in the range of relative air humidities 25–95%.

3. The positive temperature dependence of the linear term of the continuum absorption coefficient being $+0.97\ldots+1.05\%\cdot\text{deg}^{-1}$ in the temperature range 285–308 K and the negative temperature dependence of the quadratic term being $-2.1\ldots-2.4\%\cdot\text{deg}^{-1}$ have been obtained.

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