Humidity effects on the radiative properties of a hazy atmosphere in the visible spectrum

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ABSTRACT

The present investigation deals with the humidity effect on the radiative properties of a strongly polluted atmosphere in the visible spectrum. For three relative humidity distributions covering the tropospheric humidity range from 30–70 %, the local albedo, the absorption and transmission of the atmosphere are obtained. Corresponding global quantities are calculated also to speculate on possible climatic effects. Additionally, radiative heating rates are calculated for the entire atmosphere, but it is found that within the humidity range of the adopted distribution, the humidity effect is entirely negligible. Most significantly influenced by the humidity are local and global albedo and transmission of the atmosphere.

1. Introduction

In recent years much effort has been devoted to the study of aerosol effects upon the radiative heat budget of the atmosphere. By known methods it is possible to determine such important quantities as radiative heating rates, local and global albedos, atmospheric transmission and absorption values by specifying the particle distribution function and the index of refraction. Usually, the effect of the humidity of the atmosphere upon the radiative properties of the aerosol is simply disregarded, which causes some doubt on the accuracy of previous computations.

The goal of the present paper is to examine the humidity influence upon the radiative properties of a strongly polluted atmosphere within the tropospheric humidity range from 30–70%. For this purpose, the visible spectrum is selected, since here the index of refraction is reasonably well known. Moreover, interpretation of results for this spectral region is made easy, due to the absence of water vapor absorption bands.

Three model atmospheres are constructed representing rather humid and dry air, as well as a more or less normal mid-latitude moisture distribution. The haze particle distribution follows the fourth power law of Junge (1963). Ground particle density is so selected as to give a surface visibility of 5 km for a relative humidity of 50% decreasing in time. The relative change with height of the particle density follows the distribution curve of hazy air given by McClatchey et al. (1972). The strongest decrease in particle number occurs within the lower 5 km where the particle density decreases exponentially by two orders of magnitude. The particle concentration remains roughly constant to a height of 18 km and then decreases strongly with height. The height distribution of molecular density is from the same source also.

For the three relative humidity distributions heating rates, the transmission, albedo and absorption of the atmosphere are determined using a uniform ground albedo of 15%. A latitude of 45 degrees north and mid-February are selected for this study.

2. Humidity effects on extinction parameters

The radiative transfer calculations require the specification of the extinction and absorption parameters of the atmosphere. These quantities can be determined only if the index of refraction of the aerosol and the particle size distribution are known. It is assumed that the aerosol particles are spherical and homogeneous in composition, and that the shape of the particle distribution function is not altered by the humidity effects. For these circumstances Hänel (1970) has derived a relationship which expresses the particle radius r in the humid air in terms of the particle radius of the aerosol in completely dry air. If ϱ_0 and ϱ_w represent the density of the dry substance and of water, respectively, and if $\bar{\mu}$ stands for the mass increase coefficient and f for relative humidity, then

$$\left(\frac{r}{r_0}\right)^{-3} = \left(1 + \frac{\varrho_0}{\varrho_w}\bar{\mu}\frac{f}{1-f}\right)^{-1} \tag{1}$$

Hänel (1968) has also given some interpolation formulas which relate the real part n and the imaginary part k of the complex index of refraction of aerosols in humid and dry air. If, as before, the suffix zero stands for dry condition, then

$$n(f) = n_w + (n_0 - n_w)\left(\frac{r}{r_0}\right)^{-3}$$

$$k(f) = k_w + (k_0 - k_w)\left(\frac{r}{r_0}\right)^{-3} \tag{2}$$

For the dry substance (Hänel, 1972) and the selected wave-length of 0.55 μm the index of refraction is 1.55–0.048 i.

The above formulas are then used to obtain the extinction and absorption coefficients according to

$$\beta_i = \pi \int n(r)\, r^2 Q_i(r)\, dr \quad i = 1, 2, 3 \tag{3}$$

where $n(r)$ represents the particle distribution function and Q the efficency factor. Indices 1, 2, and 3 represent extinction, absorption and scattering, respectively. The quantity Q depends directly on eq. (2) and $n(r)$ on eq. (1).

The humidity effect on the air molecules is sufficiently small to be disregarded. The phase function of the aerosol depends also on the humidity distribution. This effect, however, is found to be reasonably small (Welch & Zdunkowski, 1975) and has been ignored also.

It should also be noted that the β-coefficients are not uniquely determined through specification of the distribution function, the index of refraction and the humidity. There exists also some hysteresis effect of the humidity. For example, a sample of aerosol contains more moisture when the relative humidity is decreasing in time. This effect reflects in the β-coefficients and is properly accounted for. The humidity effects on the β-coefficients are calculated by means of the formulas listed above. Hänel (private communication) kindly provided interpolation tables (to be published soon) which permitted the calculation of the β-coefficients as function of the relative humidity.

3. Radiation computations and results

The radiation transfer program for the calculation of fluxes in the hazy atmosphere is based upon the discrete-ordinate method (Liou, 1973) with further applications to inhomogeneous atmospheres (Liou, 1975). The inhomogeneous hazy atmosphere is subdivided into 10 layers within which the aerosol atmosphere is considered to be homogeneous with respect to the single scattering albedo and phase function. These two parameters and the optical depth include effects of both aerosols and molecules.

The local albedo, absorption and transmission denoting the solar flux reflected, absorbed and transmitted in the aerosol atmosphere may be defined, respectively, as follows:

$$\left.\begin{aligned} R(\mu_0) &= F^{\uparrow}(\infty)/\mu_0 f_{\Delta\lambda} \\ A(\mu_0) &= [F_N(\infty) - F_N(0)]/\mu_0 f_{\Delta\lambda} \\ T(\mu_0) &= F^{\downarrow}(0)/\mu_0 f_{\Delta\lambda} \end{aligned}\right\} \tag{4}$$

where $f_{\Delta\lambda}$ represents the parallel solar flux arriving in a small spectral interval at the top of the atmosphere, $F^{\uparrow}(\infty)$ the reflected solar flux at the top of the atmosphere, $F^{\downarrow}(0)$ the total transmitted solar flux at the earth's surface, F_N the total net flux, and μ_0 refers to the cosine of the solar zenith angle θ_0. The quantity μ_0 is determined from a wellknown equation of mathematical astronomy, which relates the declination angle δ, the hour angle h and the zenith angle θ_0 of the sun with the latitudinal angle ϕ of the earth. The relationship

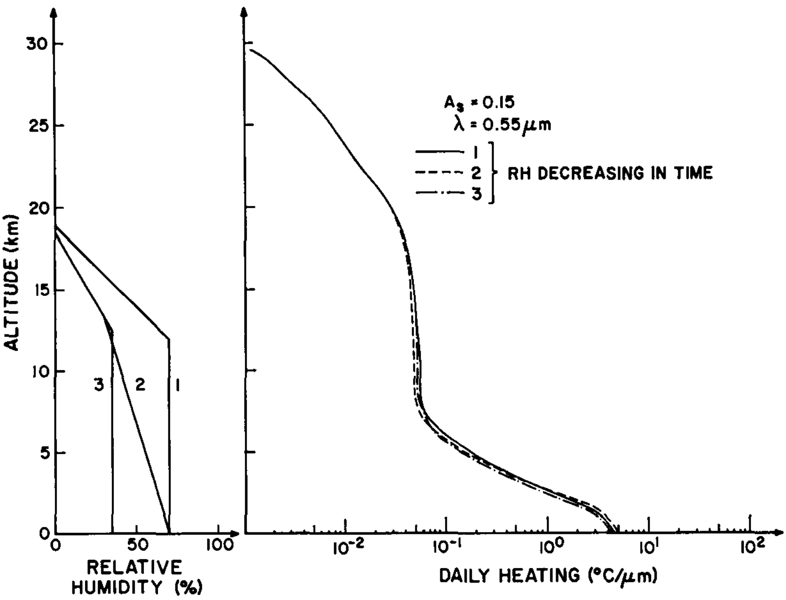

Fig. 1. Humidity profiles and daily heating as function of height.

can be expressed as

$$\mu_0 = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h \qquad (5)$$

The daily heating, assuming complete symmetry in time, is given by

$$\Delta\theta = 2\int_{\text{sunrise}}^{\text{noon}} \left(\frac{\partial\theta}{\partial t}\right) dt (°c/\mu m) \qquad (6)$$

where the temperature change is related to the divergence of the net flux by means of

$$\frac{\partial\theta}{\partial t} = -\frac{1}{\varrho C_p}\frac{\partial F_N}{\partial z} \qquad (7)$$

The quantities ϱ and C_p stand for the density and specific heat at constant pressure of the moist air, respectively.

Three humidity distributions are employed in the present study. These are shown in Fig. 1 together with the daily heating of the atmosphere for a surface albedo of 15%. A latitude of 45° north and mid-February are selected for this study, which results in a 10-hour day. The noon solar zenith angle is approximately 60°. Distributions 1 and 3 represent, respectively, rather humid and dry atmospheres, while the distribution 2 is probably more frequently encountered. In all three cases it is assumed that the relative humidity was decreasing in time to the present value. Inspection of the daily heating for the wavelength of 0.55 μm shows that the humidity effect is rather small. For relative humidity increasing in time to the present values, the results of the daily heating are so similar that they are not presented. Note that the solar flux at 0.55 μm is about 0.2 joules sec^{-1} cm^{-1} μm^{-1}. Largest heating takes place at the earth's surface where the aerosol concentration has a maximum value. The solar heating decreases with height in a way similar to the decreasing concentration of aerosols in the atmosphere.

Fig. 2 shows the effects of the humidity on the local radiation parameters. The left-hand side of the figure denotes the results for the relative humidity decreasing in time. The humidity effect is found insignificant for the absorption. On the other hand, however, the local transmission of the atmosphere shows substantial variations caused by the humidity. Maximum differences of nearly 9% occur at the solar noon when the transmission is largest. Near sunrise time the transmission differences amount to only about 2%. With respect to the local albedo, we find that an increase of the relative humidity increases its values for all

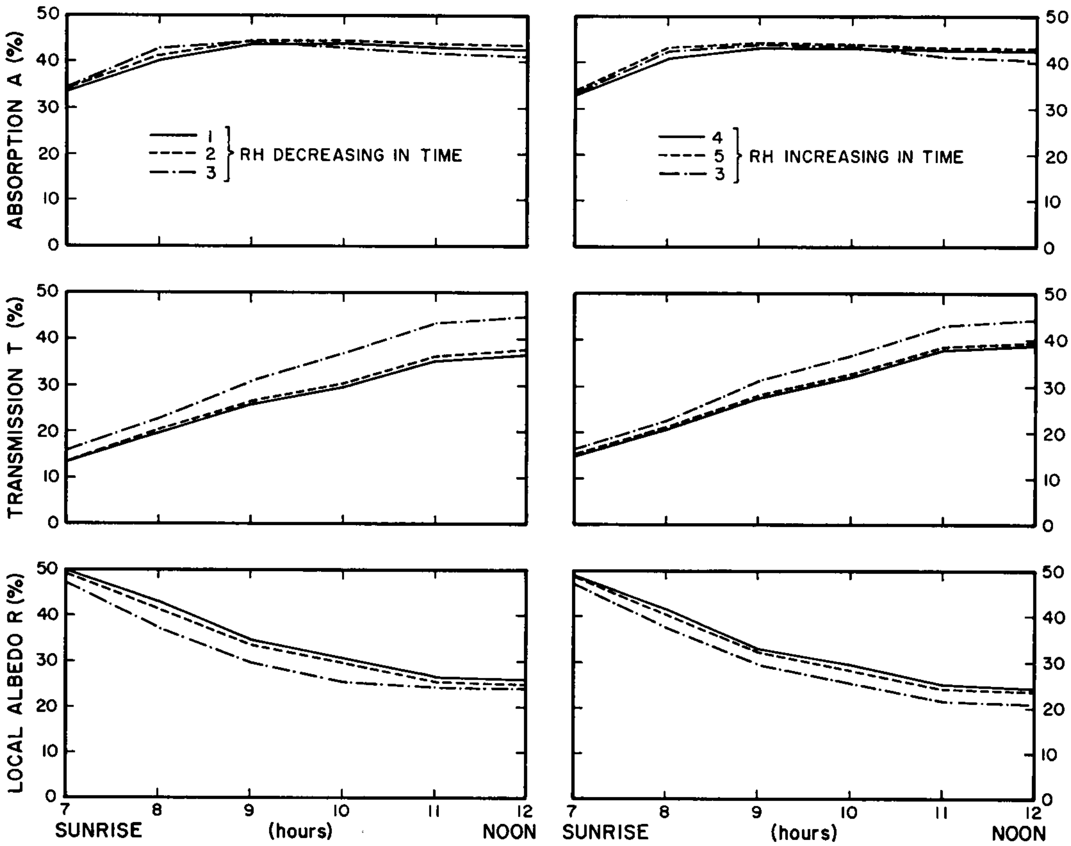

Fig. 2. Local attenuation parameters as function of the time of the day.

solar zenith angles. It is most strongly influenced at 9 a.m., at which time a difference of about 5% is obtained, owing to the variation of the humidity distribution from a dry to a humid condition. At the solar noon the local albedo is about 26% for the humid case. The right-hand side of Fig. 2 gives the corresponding results for the relative humidity decreasing in time. The shapes of curves for the radiation parameters are fairly similar to those presented on the left-hand side. Overall, humidity effects are about the same as for the case of decreasing relative humidity, but the magnitude decreases somewhat.

Table 1. *Global albedo, transmission and absorption*

	Case				
	1	2	3	4	5
$\bar{R}$	8.32 %	8.08 %	6.96 %	7.94 %	7.74 %
$\bar{T}$	6.98 %	7.20 %	8.54 %	7.52 %	7.64 %
$\bar{A}$	10.74 %	10.84 %	10.68 %	10.68 %	10.02 %

Of particular interest to the study of possible aerosol effects on climatic changes are global values of the albedo, absorption and transmission. These are obtained by integrating the local values defined in eq. (4), assuming complete symmetry in time, over all solar zenith angles that occur on a particular day. Thus, the global albedo $\bar{R}$, the global absorption $\bar{A}$, and the global transmission $\bar{T}$ are given, respectively, by

$$\left.\begin{matrix}\bar{R}\\ \bar{A}\\ \bar{T}\end{matrix}\right\} = 2\int_0^{\mu_0(\max)} \left\{\begin{matrix}R(\mu_0)\\ A(\mu_0)\\ T(\mu_0)\end{matrix}\right\} \mu_0\, d\mu_0 \quad (8)$$

It will be noticed that the global attenuation parameters are defined in such a way that at the time of the equinoxes ($\mu_0(\max) = 1$) for the hypothetical case $R(\mu_0) = 1$ the global albedo $\bar{R}$ becomes unity also. Similar statements also hold for $A(\mu_0) = 1$ and $T(\mu_0) = 1$.

Results of these parameters are shown in Table 1. In Table 1, cases 1 and 2 are for humidity distributions 1 and 2, respectively, when the relative humidity is decreasing in time. Cases 4 and 5 denote again humidity distributions 1 and 2, respectively, but for the relative humidity increasing in time. Case 3 is for the dry atmosphere which varies insignificantly with time. The humidity effect on the global absorption appears to be unimportant as can be understood from the two top graphs in Fig. 2. However, for the global transmission and reflection the differences due to various humidity distributions are quite significant. This is best indicated by the transmission and reflection ratios (values in case 1 divided by those in case 3) of 0.8 and 1.2, respectively.

4. Concluding remarks

Of greatest interest are the global attenuation quantities which express a possible impact on climatic changes induced by air pollution. It was shown that the humidity effects on the global albedo and the transmission are quite significant. More complete future investigations dealing with the computation of global quantities and related parameters should no longer ignore the humidity effect on the index of refraction and the particle size distribution. The inclusion of the humidity effect should alter present estimates of the impact of heavily polluted atmospheres on climatic changes.

The humidity effect on the global attenuation quantities is particularly prominent and important in the visible part of the solar spectrum which contains nearly one-half of the entire solar energy. It is estimated that the humidity modification in the visible spectral region represents an upper bound for the entire solar spectrum. Although the attenuation coefficients for single scattering in the infrared part may be significantly altered, their impact on the global and local attenuation parameters will probably be small. This is due to the fact that in the infrared regions the attenuation is mostly controlled by the numerous water vapor absorption bands.

Apparently Grassl (1973) is the first investigator to include the relative humidity effect on the refractive index and on particle growth of aerosol particles. He finds by approximate calculations in which scattering effects are disregarded that the humidity effect upon the radiation regime of the boundary layer in the atmospheric window region from 8–13 microns can be quite substantial.

A fairly complete analysis dealing with the humidity effect on the attenuation parameters of aerosol particles (covering the wavelength region from 0.29–100 microns) will be reported in the near future by one of the present authors (Welch & Zdunkowski). The complete radiative transfer mechanism is used to show that the humidity effect on the attenuation coefficients of aerosol particles for boundary layer calculations should no longer be disregarded which is in harmony with Grassl's findings.

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ВЛИЯНИЕ ВЛАЖНОСТИ НА РАДИАЦИОННЫЕ СВОЙСТВА ЗАМУТНЕННОЙ АТМОСФЕРЫ В ВИДИМОЙ ОБЛАСТИ СПЕКТРА

В настоящем исследовании рассматривается влияние влажности на радиационные свойства сильно замутненной атмосферы в видимой области спектра. Для трех распределений относительной влажности, покрывающих интервал влажности в тропосфере от 30 до 70 %, получены локальные значения альбедо, поглощение и пропускание атмосферы. Вычислены также соответствующие глобальные величины для оценки возможных климатических эффектов. Дополнительно вычислены скорости радиационного нагревания всей атмосферы, однако, найдено, что в пределах интервала принятых распределений влиянием влажности можно полностью пренебречь. Наиболее значительное влияние влажности испытывают значения локального и глобального альбедо и пропускание атмосферы.