Aerosols and Climate

Abstract. *To determine the effects of atmospheric aerosols on the radiative heating of the earth-atmosphere system, the radiative transfer equation is solved analytically in the two-stream approximation. It is found that the sign of the heating is independent of optical thickness of an aerosol layer and the amount of heating approaches a finite limit with increasing thickness of a layer. Limitations of the two-stream approximation are discussed.*

In recent years considerable attention has been devoted to the role of atmospheric aerosols in the thermal state of the earth-atmosphere system. These investigations have been motivated by the possibility that there is a connection between observed climatic trends and a general buildup of atmospheric aerosols in large geographical areas. This increase in the amount of aerosols has been attributed to human activities.

The present aerosol concentration over urban areas in the United States is approximately three times the average concentration over nonurban sites (*1*). Electrical conductivity measurements over the oceans (*2*) imply that the aerosol content of the atmosphere may have doubled over the North Atlantic during the last six decades (but changed little over the South Pacific). At the present state of technology we have to expect the concentration of atmospheric particles to grow over large regions of the earth, at least for several coming decades.

It has been suggested (*3*) that the observed decrease in the mean temperature over the northern hemisphere (*4, 5*) may be connected with an increase in the amount of aerosol pollutants in the atmosphere. The aerosols attenuate the solar radiation which reaches the earth's surface by backscattering and absorbing fractions of the incident radiation. It has been estimated (*6*) that a 2 percent decrease in the amount of solar energy reaching the earth might be sufficient to trigger an ice age. Therefore, an understanding of the interaction of solar radiation with aerosols is essential for determining the effects of man's activity on climate.

The absorption of solar radiation by an aerosol layer increases the radiative heating of the atmosphere, while the backscattering decreases the total amount of energy available to the earth-atmosphere system. In this report we determine the conditions under which an additional aerosol layer will cause heating or cooling of the earth-atmosphere system, calculate the amount of heating by using a two-stream approximation, and discuss the limitations of this approximation. Some of these problems have already been investigated by other authors and, as will be pointed out, several incorrect results and conclusions have been published.

Let a be the albedo of the earth-atmosphere system (the fraction of the incident radiative flux which is reflected by the system) and let us investigate how the albedo will be affected by the addition of a plane-parallel aerosol layer of optical thickness τ_1. Since we do not want to limit ourselves to optically thin aerosol layers, we must solve the radiative transfer equation, which for the case of a plane-parallel purely scattering aerosol layer has the form

$$\mu \frac{dI(\mu,\tau)}{d\tau} = I(\mu,\tau) - \frac{1}{2}\int_{-1}^{1} p(\mu,\mu')I(\mu',\tau)d\mu' \quad (1)$$

where $I(\mu,\tau)$ is the specific intensity at optical depth τ and direction $\theta = \arccos \mu$ with respect to the normal of the layer's surface; and $p(\mu,\mu')$ is an appropriate phase function. To determine the albedo R' of the total system consisting of the earth-atmosphere system and an additional aerosol layer, we have to determine the total upward flux leaving the top of the aerosol layer.

The radiative transfer equation, Eq. 1, is an integro-differential equation which in general cannot be solved analytically. Therefore, to determine the effect of an aerosol layer on the total albedo we have either to solve the radiative transfer equation numerically or to use some approximation which would allow us to obtain an analytic solution.

In the two-stream approximation it is assumed that the intensity is isotropic over the upper hemisphere ($\mu > 0$) with the value $I_+(\tau)$ and over the lower hemisphere ($\mu < 0$) with the corresponding value $I_-(\tau)$. Consequently, the radiative transfer equation can be transformed into a set of two coupled first order differential equations

$$\frac{1}{2}\frac{dI_+(\tau)}{d\tau} = I_+(\tau) - (1-\beta)\omega I_+(\tau) - \beta\omega I_-(\tau) \quad (2)$$

$$-\frac{1}{2}\frac{dI_-(\tau)}{d\tau} = I_-(\tau) - (1-\beta)\omega I_-(\tau) - \beta\omega I_+(\tau) \quad (3)$$

where ω is the single scattering albedo (the fraction of radiation which is scattered), so that $(1-\omega)$ is the fraction of radiation which is absorbed, and $\omega\beta$ is the fraction of the radiation scattered into the backward hemisphere (*7*). The solution of the set of Eqs. 2 and 3 satisfying the appropriate boundary conditions, that I_0 is the incident flux

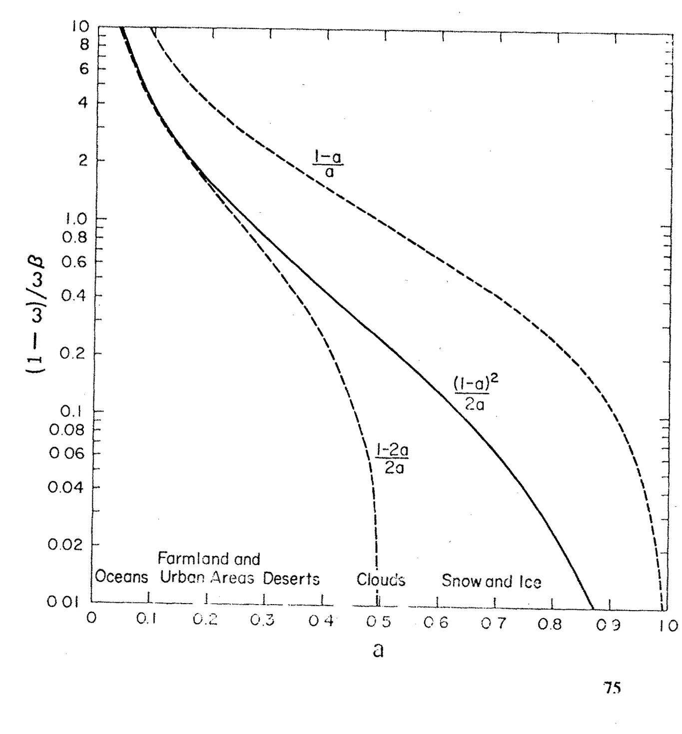

Fig. 1. The critical ratio, $(1-\omega)/\omega\beta$, of the absorption cross section to the average backscattering cross section of the aerosol is equal to $(1-a)^2/2a$ in the two-stream approximation, where a is the albedo of the underlying earth-atmosphere system.

at the top of the layer and $I_R = aI_-(\tau_1)$ is the incident flux at the bottom of the layer resulting from the reflections between the earth-atmosphere system and the aerosol layer, can be written in the form

$$I_-(\tau) = \frac{K_-[I_R K_+ - I_0 K_- \exp(-\tau_1\alpha)]\exp(\tau\alpha) - K_+[I_R K_- - I_0 K_+ \exp(\tau_1\alpha)]\exp(-\tau\alpha)}{K_+^2\exp(\tau_1\alpha) - K_-^2\exp(-\tau_1\alpha)} \quad (4)$$

$$I_+(\tau) = \frac{K_+[I_R K_+ - I_0 K_- \exp(-\tau_1\alpha)]\exp(\tau\alpha) - K_-[I_R K_- - I_0 K_+ \exp(\tau_1\alpha)]\exp(-\tau\alpha)}{K_+^2\exp(\tau_1\alpha) - K_-^2\exp(-\tau_1\alpha)} \quad (5)$$

where $K_\pm = \alpha \pm 2(1-\omega)$ and $\alpha = 2[(1-\omega)\ (1-\omega+2\beta\omega)]^{1/2}$.

By definition, the albedo R' of a combined system is determined by the relation $I_+(0) = R'I_0$. The heating caused by the addition of the aerosol layer is $a - R'$ and it is given by

$$a - R' = \frac{2a(1-\omega) - (1-a)^2\omega\beta}{(1-\omega) + (1-a)\omega\beta + \alpha/2\tanh(\alpha\tau_1)} \quad (6)$$

The sign of Eq. 6 determines whether an aerosol layer will heat or cool the earth-atmosphere system. Since the denominator is always positive, heating occurs if $(1-\omega)/\beta\omega > (1-a)^2/2a$. Therefore, the critical ratio of absorption cross section to average backscattering cross section of the aerosol particles is given by

$$\frac{1-\omega}{\omega\beta} = \frac{(1-a)^2}{2a} \quad (7)$$

We want to emphasize that the ratio, Eq. 7, has been derived for an arbitrary thickness of aerosol layer by using the two-stream approximation. The same relation can be derived for optically thin layers without using the two-stream approximation. In fact, using an approximation which is valid for thin layers, Mitchell (*8*) derived Eq. 7. Other authors (*9*) obtained different values for the critical ratio $(1-\omega)/\beta\omega$ in the limit of optically thin layers—namely $(1-a)/a$ and $(1-2a)/2a$—because they neglected some of the terms proportional to the first power of optical thickness in their derivations.

In Fig. 1 the critical aerosol ratio $(1-\omega)/\beta\omega$ is plotted against the albedo a. The same type of aerosol will have different effects over surfaces with different albedos. For example, most types of aerosols will cool the atmosphere over the unclouded oceans and heat the atmosphere over snow and ice.

Figure 2 shows how the cooling or heating of the earth-atmosphere system proceeds with increasing optical thickness τ of the aerosol layer in the two-stream approximation. The rate of change of the heating or cooling with the optical depth of the aerosol layer is largest for small optical thickness, where the heating or cooling grows approximately linearly with optical depth. With increasing optical thickness the curves level off and finally approach a finite limit. This behavior can be understood from Eq. 6. Since the optical thickness of an aerosol layer enters only in the argument of the hyperbolic tangent, and since the limit of tanh $(\alpha\tau) = 1$ for $\tau \to \infty$, it follows from Eq. 6 that the amount of heating or cooling of the earth-atmosphere system has to approach a definite limit with increasing thickness of the aerosol layer. Although the numerical results obtained by Rasool and Schneider (*10*) with the two-stream approximation agree with our results, they stated incorrectly that the rate of cooling is augmented with increasing aerosol content.

A question which arises at this point is, to what extent do our results depend on the use of the two-stream approximation? First, the two-stream approximation is adequate for optically thin aerosol layers. For thin layers the two-stream approximation reduces to the single scattering approximation. Since single scattering is dominant in a thin aerosol layer, the two-stream results become accurate in this limit. However, numerical solutions to the transfer equation reveal that the accuracy of the two-stream approximation decreases rapidly with increasing optical thickness. At optical depths of several units, the two-stream results may be off by a factor of 2 in the fractional change of the system's albedo, $(a - R')/a$, depending on the size distribution of aerosol particles and consequently on the phase function used. Nevertheless, the qualitative feature of the two-stream approximation, that the heating or cooling curves approach finite limits with increasing τ, remains.

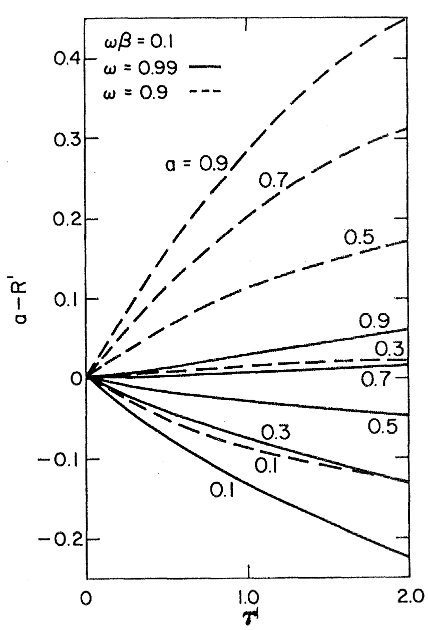

Fig. 2. Two-stream results for the amount of heating $a - R'$ as a function of the optical depth τ of the aerosol layer for several values of the albedo a of the underlying system. The solid curve is for a single scattering albedo $\omega = 0.99$, and the dashed curve is for $\omega = 0.9$. Both curves represent the heating due to an aerosol, which backscatters the fraction of radiation $\omega\beta = 0.1$ at each scattering.

In the two-stream approximation, the heating condition given by Eq. 7 is independent of optical depth. However, from the numerical solutions of the equation of radiative transfer we find generally that if the effect of an optically thin aerosol layer is to heat the earth-atmosphere system, then the same type of aerosol in a layer of an arbitrary thickness will always heat the earth-atmosphere system. Unfortunately, similar statements cannot be made for the case of cooling. Thus, it is possible for an aerosol which causes slight cooling in a thin layer to cause heating as the depth of the layer increases.

Finally, this form of the two-stream approximation is applicable only to globally averaged conditions. It does not include the dependence of the heating on the solar zenith angle which is necessary for the study of regional heating effects.

The fact that the two-stream approximation provides quantitatively reliable results only for thin aerosol layers does not limit its usefulness in studies of climate. Since even a very thin aerosol layer may cause a 2 to 5 percent change in the planetary albedo, which is sufficient for dramatic climatic changes (*4, 6*), the use of the two-stream approximation for determining the sensitivity of the global climate to an aerosol concentration is justified.

Unfortunately, measurements of aerosol parameters on a global scale are not complete. Consequently, we cannot claim conclusively that the buildup of aerosols due to man's activity is responsible for the present cooling trend. Knowing that the smaller aerosols have longer lifetimes in the atmosphere and assuming that the atmospheric aerosols are only weakly absorbing, we can only guess that small values of $(1 - \omega)/\omega\beta$ would be favored and that generally cooling would be expected. Also, the present data on climatic trends do not offer any clues to the effect of aerosols (*5*). We hope that the present gaps in our knowledge will be shortened in the near future by measurements of the aerosol parameters. In fact, someday their effect may be measured directly when the changes in the albedo of the earth-atmosphere system are remotely monitored by satellites (*11*).

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7. Since $I_+(\tau)$ and $I_-(\tau)$ are assumed to be isotropic over the upward and downward hemispheres, respectively, integrating Eq. 1 over μ gives Eqs. 2 and 3 with

$$\beta\omega = \frac{1}{2}\int_0^1 d\mu \int_0^1 d\mu' p(\mu, -\mu')$$

Thus $\beta\omega$ is proportional to the average backscattering cross section of the aerosol.
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Intestinal Lactase Activity in the Suckling Rat: Influence of Hypophysectomy and Thyroidectomy

Abstract. *Intestinal lactase activity, which is high in the infant rat intestine but falls to a low level by the end of the third week, fails to decline in animals hypophysectomized at the age of 6 days. Treating these animals with thyroxine lowers lactase activity to the control level at 24 days, but cortisone is only partly effective. Thyroidectomy at 6 days also results in persistence of high lactase activity; thyroxine again is more effective than cortisone in reducing activity. The thyroid gland appears to play a previously unsuspected role in intestinal maturation.*

The intestines of infant mammals are rich in a neutral β-galactosidase (lactase) that is abundant at birth but generally falls to a low level at about the time of weaning (*1*). In mice and rats, lactase activity begins its decline during the second week, reaching the low adult level in the fourth week (*2–5*). This pattern is the reciprocal of the patterns of increase of maltase activity, which is low in murine rodents during the first 2 weeks, and of sucrase, which is absent (*3, 5–7*). Sucrase and maltase activity may be elicited or enhanced precociously by administration of glucocorticoids (*5–7*), but such treatment does not bring about a premature depression of lactase activity (*6, 8*). Evidently the aspect of intestinal maturation that entails the decrease of lactase is controlled by some mechanism other than (or in addition to) the pituitary-adrenal system. This other mechanism is apparently not the loss of substrate when the young no longer consume milk; although the onset of lactase decline may be postponed by a few days in nurslings forced to subsist solely on maternal milk (*9*), attempts to stave off the decrease of the enzyme by supplying substrate orally or intraperitoneally have generally been unsuccessful (*2, 4, 10*).

Although the adenohypophysis influences the maintenance of the adult intestine (*11*) and promotes the growth of the infant intestine (*12*), little is known about the influence of this gland on the specific maturational events that occur in the mouse and rat intestine during the third postnatal week. In studies now under way in our laboratory, we have observed that the hypophysis influences lactase activity at least in part by way of the thyroid gland.

In these experiments we used NLR rats bred in our laboratory. At 6 days of age or later the infants were hypophysectomized under cold anesthesia by the parapharyngeal approach, as described by Walker *et al.* (*13*). Each operation was completed in less than 10 minutes. Litters of ten were used, of which six were hypophysectomized, two were subjected to the same operation with the exception of removal of the gland, and the others remained intact. They were killed at 20, 24, or 28 days of age, at which times the heads and the tracheas with adherent thyroids were fixed in Bouin's fluid for histological examination. Of 257 rats hypophysectomized at 6 days of age, 151 survived to 20, 24, or 28 days of age (when they were killed); 84 of these were found to be completely free of pituitary fragments.

A 5-cm jejunal segment, taken midway along the length of the small intestine, was used for lactase assay. The content was removed by gentle pressure. The piece was weighed, stored in $0.15M$ NaCl at $-24°C$, and subsequently homogenized in $0.15M$ NaCl in a Ten Broeck grinder. Lactase activity of total homogenates was determined by Dahlqvist's technique (*14*). The substrate mixture consisted of $0.3M$ lactose (Sigma) in $0.1M$ maleate buffer at pH 6.0 (*2, 3*). One-tenth of a milliliter of homogenate (2.5 mg/ml) was added to 0.1 ml of substrate mixture and incubated for 60 minutes at 37.5°C; the reaction was then stopped by adding 2 ml of tris-glucose oxidase reagent (Worthington Biochemical Corporation). Protein was determined by the Lowry technique (*15*). Sucrase and maltase activity were also assayed in all homogenates (*16*). Activity is reported in units that represent micromoles of substrate hydrolyzed per milligram of protein per hour. Results were evaluated statistically by Student's t-test.

In rats hypophysectomized at 6 days of age, lactase activity at 20 days is as high as in intact animals at 6 days (Fig. 1A). Thereafter activity declines somewhat, but at 28 days of age is still higher than in 2-week-old infants. The experimental animals reported in Fig. 1A are those in which histological examination of the base of the skull showed that the operation was complete; in those in which fragments of anterior pituitary were found, lactase activities were lower than in the complete cases, but significantly above those of intact controls. At 24 days the mean value for sham-operated animals was identical to that for intact