ABSTRACT

Calculated values of atmospheric turbidity were computed to measure spectrally-integrated aerosol optical depth for cloudless and near cloudless days for Alice Springs, Australia and Albuquerque, New Mexico. Changes in turbidity over diurnal, seasonal and annual periods were analyzed for both arid sites. Results indicate that turbidity rarely exceeded 0.1 for either site and that the annual average value for both sites was approximately 0.05. This is in contrast to studies of turbidity in the Sahara, where background values averaging 0.5 and higher have been observed. Concerns have been raised about possible detrimental effects on global climate as a result of a high concentration of atmospheric aerosol caused by high turbidity in arid regions. The low values reported here tend to dispute the comparatively high values on which these concerns are based.

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Effect of aerosols on radiation attenuation in arid environments

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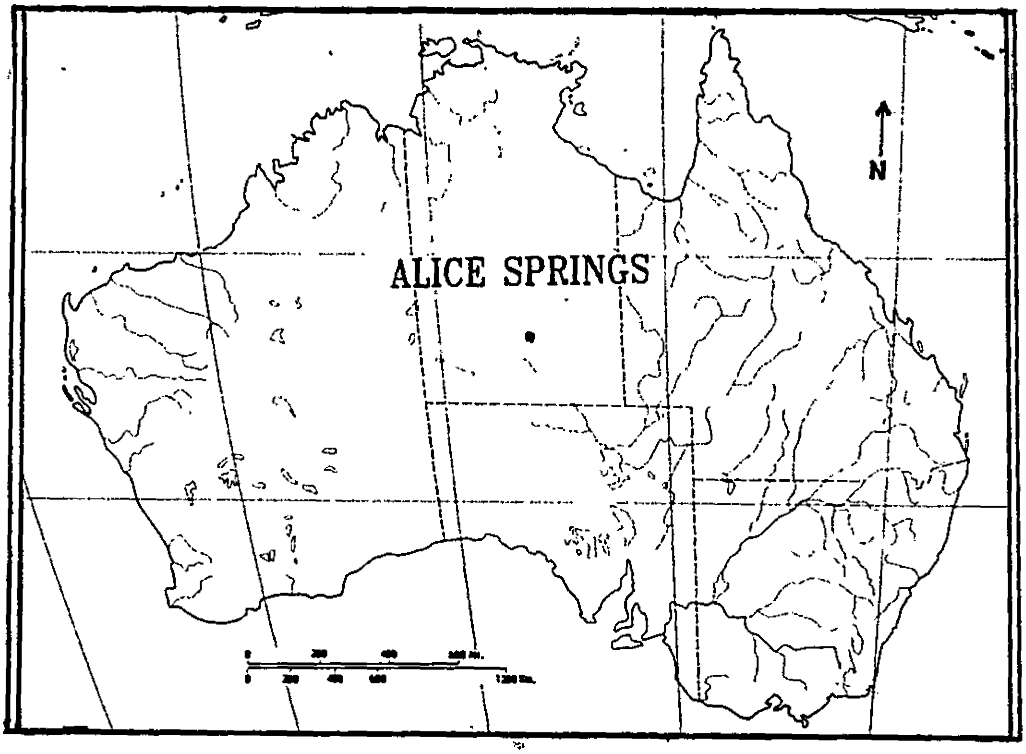
Chapter 1. INTRODUCTION

The main objective of this study is to test the claim that the presence of aerosol particles in the atmosphere over arid environments has a significant effect on the attenuation of solar radiation reaching the Earth's surface. The effect that desert aerosol has on the radiation budget of the earth-atmospheric system is what prompted interest in this research. The absorption and scattering of solar radiation as a result of an increase in desert aerosol has been linked to surface temperature changes (Rasool and Schneider, 1971). In addition to this, according to d'Almeida (1987), "desert aerosol or mineral dust is the most prominent and widespread natural aerosol". However, previous studies that have been concerned with assessing the effect of aerosols over deserts have yielded many different results. Some have stated that aerosols play a significant role in the measured attenuation of incoming solar radiation over deserts while others have found that aerosols have little effect on solar radiation. The author has attempted to provide some evidence in support of the latter conclusion.

The available data were measured at two sites which represent desert and arid conditions (Figure 1). Alice Springs, Australia (with diurnal data from 1980-82) is situated within a tropical to subtropical latitude which experiences desert-like conditions. The second site is Albuquerque, New Mexico (with diurnal data from 1978-80) which is considered to be a partly desert, partly urban city. For both sites, only clear sky or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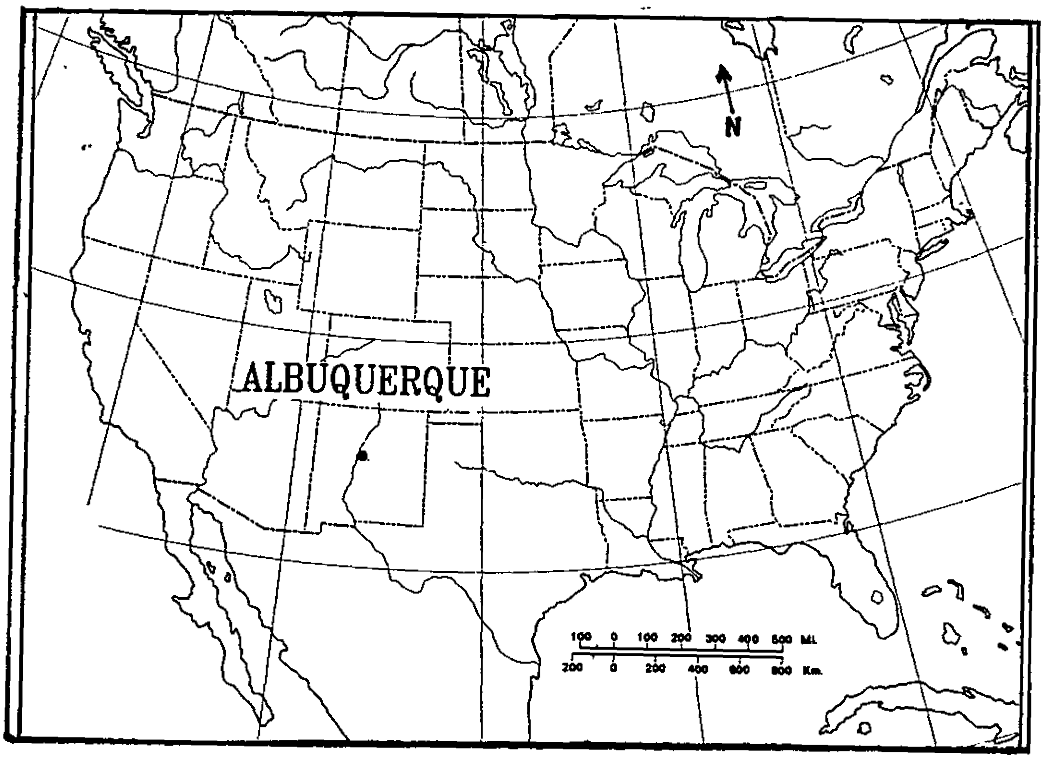
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Figure 1.

near cloudless sky data have been considered since cloud covered regions tend to produce "noise" in the data due to the attenuation effect of the clouds.

The bulk of this study is based on values of aerosol optical depth calculated for each site from astronomical, meteorological and radiative variables (as discussed in Chapter 3). By obtaining mean values of optical depth with acceptable error terms and analyzing the patterns that these data exhibit over set time periods, the overall effect that aerosol has on the attenuation of radiation over arid environments is assessed.

Chapter 2. LITERATURE REVIEW

The aerosol attenuation coefficient (τa) is a measure of the degree to which aerosol attenuates solar radiation and, as a result, it provides the basis for this study. Unsworth and Monteith (1972) developed the theoretical background for the coefficient using the Bouguer-Lambert Law which is defined by Uboegbulam and Davies (1983) as

$$I(\lambda) = Io(\lambda) \exp\{-[\tau r(\lambda) + \tau o(\lambda) + \tau w(\lambda) + \tau a(\lambda)]m\} \qquad (1)$$

where $I(\lambda)$ is the spectral flux density of direct beam solar radiation following atmospheric attenuation, $Io(\lambda)$ is the flux density of solar radiation incident at the top of the atmosphere, m is the optical air mass and $\tau r(\lambda)$, $\tau o(\lambda)$, $\tau w(\lambda)$ and $\tau a(\lambda)$ are the spectral optical depths for Raleigh scatter, ozone absorption, water vapor absorption and aerosol attenuation respectively. For simplicity, each value collected for this paper is averaged over the entire spectrum of solar radiation rather than considered for individual wavelengths as illustrated above. Equation (1) can be rewritten as

$$\tau a = -[\ln(I/Io^*)]/m \qquad (2)$$

where

$$Io^* = Io \exp\{-(\tau r + \tau o + \tau w)m\} \qquad (3)$$

Unsworth and Monteith (1972) applied this theoretical process in an analysis of aerosol attenuation of the solar beam measured during cloudless days at sites in Great Britain. They assumed that the optical depth data collected at each site sufficiently represented one of three environments, these being "isolated", "rural" or "urban". They found that the attenuation values in urban sites were larger relative to rural sites and that the attenuation for rural sites exceeded that found at isolated sites and concluded that the differences were due in part to a general decrease in smoke and industrial and natural pollution from urban to isolated sites. However, the most significant conclusion from their study was their claim that changes in air mass type, rather than changes in the amount of aerosol produced from local sources, were mostly responsible for major changes in aerosol attenuation. This suggestion must certainly be taken into account during an analysis of attenuation over desert-like environments.

Uboegbulam and Davies (1983) used the Bouguer-Lambert Law and the Unsworth and Monteith (1972) aerosol attenuation coefficient to calculate the turbidity (τa) from hourly cloudless sky data for sites in central and eastern Canada. Many of the variables used in their study coincide with those used in the method developed for this paper, the most prominent of which is the examination of the observed effects of aerosol on radiation over a long-term time interval. They discovered that aerosol attenuation decreased over the 1968-78 period and attribute the change to a decrease in overall turbidity following the advent of the Canadian Clean Air Act in 1971.

d'Almeida (1987) studied aerosol optical depth from 1979-82 at three sampling stations spaced evenly across north-western Africa. He specifically chose the locations of his sites to be in arid regions that produced optimum amounts of dust. Each site was apparently far enough away from prime source areas of dust to allow aerosol enough time and space to become well-mixed in the atmospheric column before measurement took place. Among his attenuation results, as described in Chapter 5, he found that the particle size of desert dust ranges considerably from 0.02 to up to 100 μm and that aerosol mass concentration can vary by more than three orders of magnitude. He concludes that this high variation can have a significant effect on optical depth. In addition to this, experiments carried out over a two year period at four additional sites in north Africa revealed a substantial, apparently natural, seasonal variability in aerosol optical depth. However, an unusual increase was observed during the summer and winter of 1982, a phenomenon that Jaenicke and d'Almeida (1983) believe is a direct result of the El Chichon volcanic eruption in Mexico in April 1982. This observation will be considered when data from 1982 at Alice Springs is analyzed.

The results of d'Almeida (1987) were accepted by Cess and Vulis (1989), who used his aerosol optical depth values in an attempt to create a desert aerosol model. Their main objective was the examination of directional planetary albedo for clear-sky desert conditions and, in the process of doing this, they took into account the optical properties of aerosol as described by d'Almeida (1987).

The effect of aerosols on the radiative budget of the earth-atmospheric system, particularly over extensive lengths of time, have been theorized to be at least partially responsible for periods of drought and desertification. Fouquart et al (1987) analyzed size distributions of dust and spectral optical thicknesses of aerosols over the Sahara desert and the Sahelian regions bordering the desert. Among other conclusions, they discovered that the common occurrence of a "dry haze" of aerosol was a direct result of an increase in intermediate size particles (with a radius approximately equal to 0.5 μm) while larger and smaller size particles remained relatively constant. As a result, intermediate size particles are considered to be the most important aerosol contributor to radiation attenuation. It is interesting to note that this particle size is quite similar to that adopted by Cess and Vulis (1989) from d'Almeida's (1987) observations (0.55 μm). If the results of Fouquart et al (1987) are considered to be acceptable, the analysis of Cess and Vulis (1989) will be based on a higher-than-average amount of desert aerosol. This has been taken into account in Chapter 5 of this paper since discrepancies have been found between the attenuation values observed by d'Almeida and those calculated for Alice Springs and Albuquerque.

Chapter 3. METHODOLOGY

In order to reach the primary research objective, that is, the measure of attenuation due to aerosols, diurnally measured values of the variables listed in Table 1 were obtained from both desert sites over the specified three year periods for use in equations designed for this purpose. The final result involves the derivation of the Unsworth and Monteith (1972) aerosol attenuation coefficient τa, which is actually a spectrally weighted aerosol optical depth. As mentioned in Chapter 2, it is defined using the Bouguer-Lambert Law which is used to calculate the attenuation of direct beam solar radiation by the atmosphere. Averaged over the spectrum, this law is as follows:

$$I = Io \exp\{-[\tau r + \tau o + \tau w + \tau a)m\} \quad (4)$$

where I is the flux density of direct beam solar radiation received at the surface, Io is the flux density of the same radiation incident at the top of the atmosphere, m is the optical air mass and τr, τo, τw, and τa are optical depth values for Raleigh scattering, ozone absorption, water vapor absorption and attenuation due to aerosol respectively (Uboegbulam and Davies, 1983). This is based on Beer's Law such that

$$I{\downarrow}z = I{\downarrow}o \exp(-\tau m) \quad (5)$$

Table 1. Variables used for the Calculation of τa

Date:	year, month, day
Time:	hour of day, solar time
Radiative Data:	global irradiance (Wm^{-2}) diffuse-sky irradiance (Wm^{-2}) direct solar beam radiation (Wm^{-2})
Meteorological data:	dew point temperature (°C)
Miscellaneous data:	station identification

where $I\downarrow z$ is the value of direct beam radiation received at depth z into the atmosphere, $I\downarrow o$ is the direct beam radiation value incident at the top of the atmosphere and a is the extinction coefficient. If equation (4) is rearranged with

$$Io^* = Io \exp\{-[\tau r + \tau o + \tau w]m\} \quad (6)$$

then

$$I = Io^* \exp\{-\tau am\} \quad (7)$$

resulting in

$$\tau a = -m^{-1} \ln(I/Io^*) \quad (8)$$

The optical air mass m, also called the "path length", is the ratio of the distances of the zenith path to the slant path used by the direct solar beam. Its calculation requires the equation

$$m = \frac{1}{\cos z} \quad (9)$$

where z is the solar zenith angle. The value of z defines the angle between the direct solar beam and the local zenith direction such that

$$\cos z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h \qquad (10)$$

where ϕ is the latitude of each of the two sites, Alice Springs (24 °S) and Albuquerque (35 °N), δ is the solar declination defining the angle between the direct solar beam and the equatorial plane and h is the hour angle which is calculated using

$$h = 15\ (12\text{-LAT}) \qquad (11)$$

where LAT is the local apparent time which considers midnight to be the zero hour and local apparent noon as the twelfth hour. The local apparent time is determined from the equation of time (the difference between apparent solar time and mean solar time) which, along with solar declination, is calculated using the computer algorithm "astro", based on Michalsky (1988).

The value of the optical air mass is more acceptable when the zenith angle is low than when it is high. When the sun is overhead and the zenith angle is zero degrees (causing the optical air mass to equal 1), the direct solar beam passes through less atmosphere than when the sun is on the horizon (and the zenith angle approaches 90°). Essentially, the more atmosphere the beam comes in contact with, the greater the correction factor (for refraction and other effects) will be for the optical air mass. Since no attempt at correcting for this phenomenon has been made, values of aerosol attenuation at and around solar noon of each day have been given greater weight than those values calculated for other times of the day.

The flux density of direct beam solar radiation received at the surface (I) from equation (8) is expressed as a residual from

$$I = G - D \tag{12}$$

where G is the global irradiance and D is the diffuse-sky irradiance, both of which are measured at each site.

The calculation of the flux density of direct beam solar radiation incident at the top of the atmosphere (Io*) involves the calculation

$$Io^* = S(RV^2)(\tau o \tau r - Awv) \tag{13}$$

where S is the value of the solar constant (corrected using the radius vector RV) and Awv is the absorption of solar radiation due to water vapor.

The correction for the solar constant takes into account the eccentricity of the Earth's orbit. For this purpose, the algorithm "astro" was used to calculate the radius vector, a variable which represents the ratio of the mean annual Sun-Earth distance (R*) to the actual time-dependent Sun-Earth distance (R') such that

$$RV = \frac{R*}{R'} \qquad (14)$$

The uncorrected solar constant value S from equation (13) was considered to be 1376 Wm^{-2} (Davies et al, 1988).

The calculation of the absorption of solar radiation as a result of water vapor considered the dew-point temperatures measured at each site. These measurements assisted in empirically determining the amount of ozone (Uo) and the amount of water vapor (Uwv) present in the atmospheric column. Coupled with the calculation of the transmission of ozone absorption (τo) and Raleigh scatter (τr), the optical air mass and the corrected solar constant, absorption due to water vapor was calculated following Davies et al (1988).

By directly taking into account equations (9), (12) and (13), the aerosol attenuation value is calculated as shown in equation (8). This process was used for all cloudless sky and near cloudless sky data collected from both sites. The final τa values represent an aerosol optical depth component for each hour of every day that measurements were provided.

Unfortunately, about 8% of the τa values were negative. Since a negative aerosol optical depth is impossible considering that aerosol does not exist above the top of the atmosphere, the inconsistency of these values is most likely due to either measurement or calculation error. Through examination of the calculations involved in computing aerosol attenuation, it was concluded that the source of error must be in the original data collected at each site. This conclusion is strongly supported when taking into account the fact that virtually all of the erroneous τa values were a result of measurements taken during the early (usually before 9:00 a.m.) or latter (usually beyond 3:00 p.m.) parts of the day, a situation which almost certainly points to the error as being a result of high solar zenith angles (as described earlier). To avoid further error, the entire set of radiative values measured at each solar hour where τa was negative was deleted from the data set. However, as a result of this, the months of January 1981, June 1981 and January 1982 for Alice Springs have only five, one and six total values, respectively, remaining following the deletion. Since no confidence can be placed in a monthly average τa represented by such a small number of values, these three months have been omitted from figure 3(b). To maintain consistency, however, these twelve values were included in the calculation of the mean annual τa values.

The remaining data sets of positive, hourly values of aerosol attenuation for both sites are the only data sets examined and taken into consideration in the discussion and analysis of the results of this paper.

Chapter 4. ANALYSIS OF RESULTS

Plots of optical depth against solar time reveal few surprises. The diurnal, seasonal and annual trends behave largely as would be expected in that changes in attenuation of radiation by aerosol is an indirect response to changes in atmospheric convection that take place over time. The analysis of the results will involve the description of these patterns as exhibited by Alice Springs and Albuquerque. A comparison of the two sites and the few unusual trends seen in the data will be described in greater detail throughout the analysis.

4.1 - Diurnal and Seasonal Variation

The general diurnal variation of aerosol attenuation of radiation in arid environments would not be expected to change significantly from that found in Figure 2. This simple curve reveals a gradual increase in optical depth from mid-morning to about noon followed by an equally gradual decrease to late afternoon, a pattern that closely resembles the peak-and-ebb diurnal intensity of solar radiation. This trend is similar for both Alice Springs and Albuquerque.

The link between a change in the intensity of solar radiation and a change in aerosol optical depth involves a change in atmospheric turbidity. For both sites, turbidity would be expected to be a direct result of convection caused by solar heating of the desert surface. The convective cycle would act to

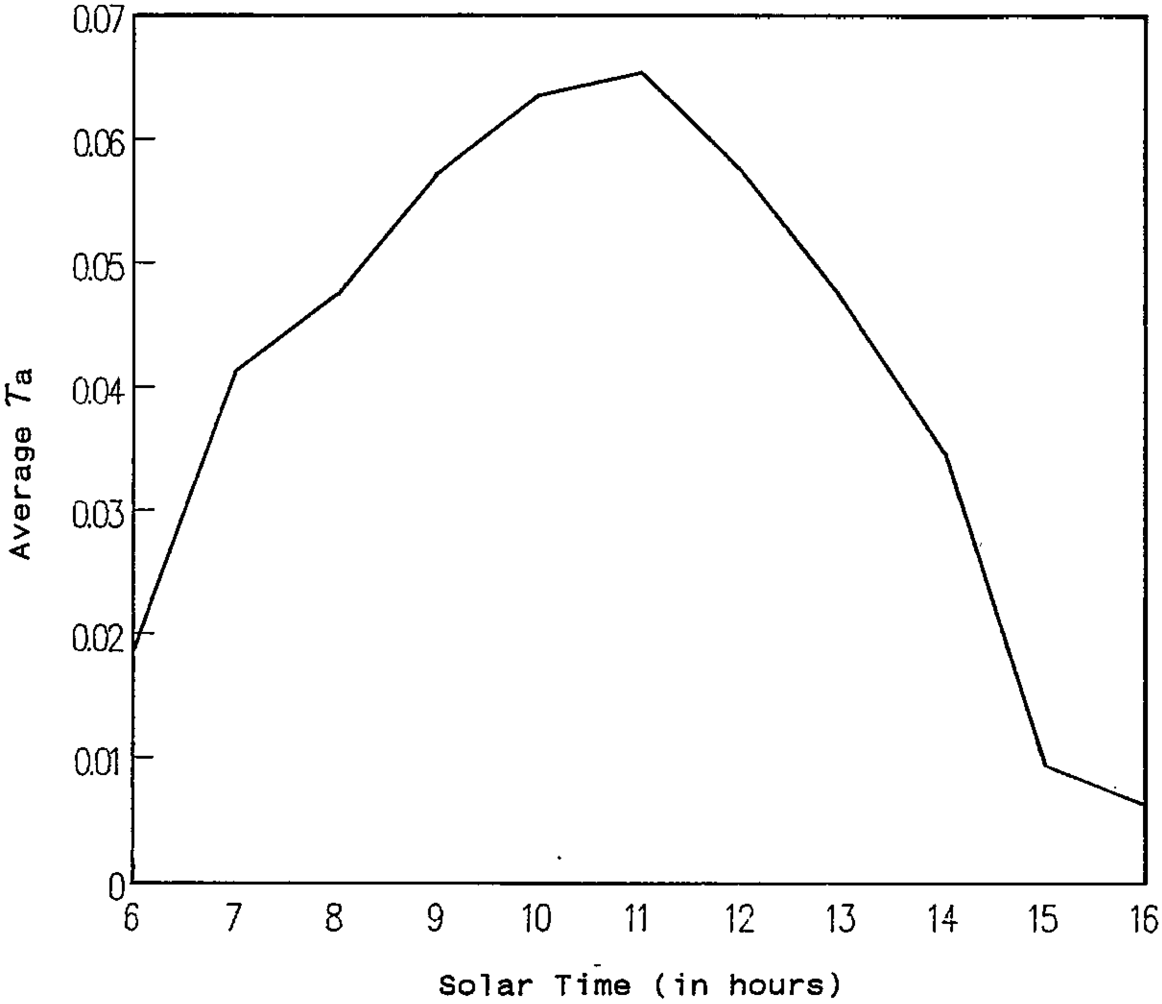

Figure 2. The diurnal variation of τa for Alice Springs, January 7,1980.

suspend aerosols in the atmospheric column and, as a result, create an aerosol optical depth. However, since convection is dependant on surface temperature, which is dependant on the intensity of solar radiation, the optical depth of aerosols increases with an increase in solar radiation. Of course, the amount of aerosol carried into the atmosphere not only depends on the degree of convection but on the availability of aerosol as well.

In addition to the variation of optical depth with time, a variation in the diurnal peak-to-minimum difference in optical depth can be seen on a seasonal basis for both Alice Springs and Albuquerque. In general, for both sites, the difference between the average diurnal peak optical depth and the recorded daily minimum optical depth is higher in the summer (where it often exceeds 0.05) than in the winter (where it averages about 0.03). This is probably due to a higher diurnal variation of convection in the summer than in the winter.

4.2 - Annual Variation

The annual variation of aerosol optical depths for both sites, based on monthly averages, reveals a general pattern of peaks in the summer and minimum values in the winter (Figures 3(a) and (b)). The standard error of the mean calculated for both plots is relatively small, indicating that the given pattern is sufficiently accurate. The annual variation is indicative of

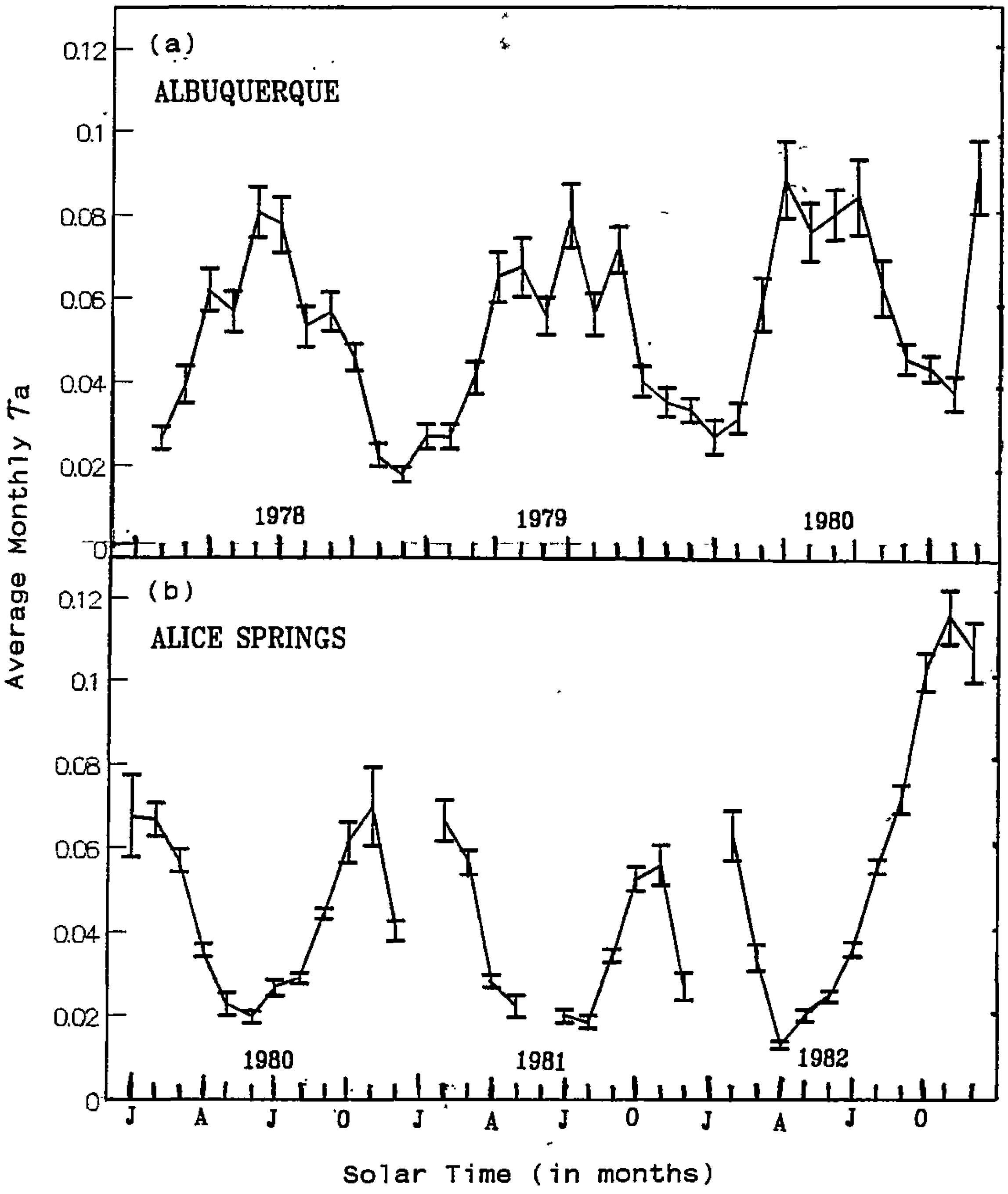

Figure 3. The annual variation of mean monthly τa for (a) Albuquerque, New Mexico and (b) Alice Springs, Australia. The bars indicate the standard error of the mean.

the control of aerosol optical depth by convection, a process which varies with the annual cycle of solar radiation. In other words, an increase in solar intensity as that experienced in the summer would tend to increase the height and rate of ascent at which a parcel of air rises into the atmosphere. The resulting convectional process would force an increase in the amount of natural aerosol picked up by the winds. This increase in aerosol would seem to provide the degree of radiation attenuation measured for the summer months. For the winter months, the dampening of convection due to the decrease in solar intensity would result in a decrease in the amount of aerosol carried into the atmosphere and a decrease in the resulting radiation attenuation. Of course, the close correlation between this process and the obvious evidence observed from Figures 3(a) and (b) would seem to indicate that urban aerosol sources for the two sites, Albuquerque in particular, do not significantly affect the annual variation.

Over the three year period in Alice Springs from 1980 to 1982, τa reached an average peak of close to 0.07 and an average minimum of less than 0.02, resulting in an average annual variation of about 0.05. For the period 1978-80 in Albuquerque, these values were virtually similar at 0.08, 0.03 and 0.05 respectively. This obvious similarity is further demonstrated when considering that the overall mean optical depth for Alice Springs and Albuquerque, calculated for the entire three year period associated with each site, is 0.046 and 0.054

respectively, revealing a difference of less than 0.01. As a result of these figures, it would seem that the degree to which aerosol attenuates radiation is virtually identical for the two sites. The reason for the slightly higher value for Albuquerque is probably due to the addition of a minor amount of urban aerosols.

Unsworth and Monteith (1972) suggest that the average aerosol optical depth value for many parts of Britain is probably about 0.2. It appears that, since the mean annual optical depth value for Alice Springs (about 0.05) is significantly less than this, the atmospheric turbidity and/or availability of aerosol is proportionally smaller for desert areas in Australia when compared to European rural/urban regions.

Since the mean annual optical depth value for Albuquerque is compatible with that observed for Alice Springs, it would seem that the conditions surrounding the behavior of turbidity are relatively similar for both sites. This would seem to indicate that the local urban input of industrial aerosols into the atmosphere over Albuquerque has little effect when coupled with the atmospheric turbidity in the area.

However, since no measurements of either turbidity or the availability of aerosol were available for either site for this study, no claim as to their extent can be seriously considered until further research is conducted.

Chapter 5. DISCUSSION OF RESULTS

I will begin by considering the unusual increase in aerosol optical depth during the last half of 1982 at Alice Springs. The remaining part of the chapter will be devoted to the analysis of literature which deals with the pattern of aerosol attenuation effects over time.

As can be seen from figure 3(b), the normal annual trend of optical depth for Alice Springs involves a decrease to a minimum of about 0.02 in the winter months and an increase to a peak of about 0.07 in the summer months. This pattern was followed quite closely throughout 1980 and 1981. However, the trend was broken in the final three or four months of 1982 when attenuation due to aerosol exceeded the normal peak value and continued to rise to as high as 0.115 by November of that year. According to the data analyzed for this paper, this value is almost twice as high as the value expected for that time of year.

d'Almeida (1987) noticed a similar trend in his study of turbidity in Assekrem, Algeria. He observed an increase of average optical depth of about 0.25 during the summer and winter months of 1982, with the trend of high values continuing until February 1983. He is convinced that the phenomenon is a direct result of the dust cloud formed by the eruption of the El Chichon volcano in April 1982, an event that is believed to have sent dust propagating around the Earth. His argument seems to be supported by the results of his study with Jaenicke (1983) in which they found that both ozone and average aerosol optical depth increased following the eruption, with the latter increasing by about 0.1. There can be little doubt that the unusual pattern of attenuation observed for the last half of 1982 at Alice Springs is due to an increase in aerosol particles from the El Chichon eruption.

Other results of d'Almeida (1987), from his work with data collected at a number of sites in the Sahara desert, reveal unusually high values of optical depth when compared to those measured in this study. He stresses that realistic background values of optical depth for an assumed homogenous dust layer in the Sahara are about 0.4 to 0.5. He supports this by showing that annual values for most of the sampling sites average about 0.5. These are a full magnitude greater than the average attenuation found at Alice Springs and Albuquerque, both of which have wind carrying dust and sandstorm amounts as well as background aerosol factored into their optical depth values. In contrast, the wind carrying dust and sandstorm concentrations described by d'Almeida are 1.6 to 2.5 and 2.8 to 3.5 respectively. Regardless, the results of d'Almeida were accepted by Cess and Vulis (1989) who assumed an optical depth value of 0.5 for their desert aerosol model.

It would seem that the reason for the discrepancy between these two sets of results is most likely due to the location of the sampling sites chosen by d'Almeida. He specifically chose to study arid regions in which optimum amounts of dust are produced and positioned his sites so that they were far enough away from prime sources of aerosol to allow the particles to become well mixed in the atmosphere before he collected his measurements. In addition to this, of all of the tropical arid zones, the Sahara and its bordering regions are considered to be the most efficient producers of aerosol (Fouquart et al, 1987). By taking these factors into consideration, it would seem that d'Almeida's analysis of radiative properties in the Sahara probably does not represent desert aerosol in general as he suggests.

This conclusion is strongly supported when considering the results of Fouquart et al (1987), who studied the occurrence of "dry hazes" of desert aerosol, which are apparently a frequent feature in the Saharan regions. They observed that aerosol optical depth tended to increase from 0.2 on apparently clear days to as high as 1.5 during hazy periods. Since d'Almeida's (1987) measurements are compatible with this latter value, his results are most likely based on atmospheric conditions which have a relatively high aerosol concentration. In addition to this, Fouquart et al (1987) also observe that the common size of dust within the "dry hazes" is about 0.5 μm in diameter. It should be noted that the optical depth value adopted by Cess and Vulis (1989) for their desert aerosol model is produced by particles of a similar diameter (0.055 μm) to the "dry hazes", a property which would seem to cause their results to be based on higher-than-average aerosol concentrations.

The apparent consequences for high aerosol attenuation is the increase in drought and desertification in surrounding regions. Fouquart et al (1987) describe the conclusions of Prospero et al (1972) who noticed a correlation between an unusually high frequency of dust hazes and an intense period of drought in Sahelian regions. However, considering that the degree of aerosol attenuation at Alice Springs and Albuquerque is an order of magnitude lower than those values dealt with in other studies, it is highly unlikely that enough aerosol is present at any one time in the atmosphere at either site to produce such detrimental climatic effects.

Chapter 6. Conclusions

The optical depth of aerosols which are present over the arid sites of Alice Springs, Australia and Albuquerque, New Mexico is much lower than that observed for other desert regions of the world. Seemingly intensive analyses of the desert aerosols of the Sahara by other authors have yielded measurements of optical depth that are more than a magnitude higher than those reported in this paper. This discrepancy is apparently due to the fact that the sites chosen for the Saharan studies are in regions that seem to demonstrate higher-than-average aerosol productivity. Regardless, the results of the research conducted for this paper tend to show that aerosols have little or no significant effect on radiation attenuation over arid environments.

The high values of aerosol attenuation reported from the Saharan studies have created concerns that desert aerosols could have a significant effect on the radiation budget of the earth-atmospheric system. This would apparently be the case if these values are indicative of an average desert environment. However, since the average annual values of aerosol attenuation calculated for the arid sites considered in this paper are much lower than the Saharan values, there seems to be little cause for concern of a serious environmental impact as a result. Of course, there is an obvious need for further research into this area, with special attention given to the horizontal transport of desert aerosol and the resulting effect on climate over surrounding non-desert areas.

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