NUCLEAR WAR: ILLUSTRATIVE EFFECTS OF ATMOSPHERIC SMOKE AND DUST UPON SOLAR RADIATION

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Abstract. It has recently been suggested that following a nuclear exchange there might be a significant reduction in surface temperature over land areas, due to the impact upon the radiation budget of the surface-atmosphere system of smoke produced by fires and of dust injected into the stratosphere by ground bursts. The present study addresses several aspects of this possible radiative perturbation, such as the unusual nature of the climate response to the perturbation, a description of differences which are inherent within existing model studies, an evaluation of radiative transfer assumptions which have been employed in existing model studies, and illustrative latitudinal and diurnal variability of the smoke-dust impact upon solar radiation.

1. Introduction

Recently four studies have appeared which consider the climate impact of a large-scale nuclear war (Turco *et al.*, 1983; MacCracken, 1983; Aleksandrov and Stenchikov, 1983; Covey *et al.*, 1984). These studies followed an earlier suggestion by Crutzen and Birks (1982) that fires resulting from a nuclear exchange could produce large quantities of atmospheric smoke, thus significantly reducing the amount of solar radiation reaching the earth's surface.

Turco *et al.* (1983) subsequently pointed out that, in addition to smoke, ground bursts in the vicinity of missile silos could inject substantial quantities of dust directly into the stratosphere. They then employed a one-dimensional radiative-convective climate model to estimate, for a number of different scenarios, that the ground temperature for mid-continental regions might be significantly suppressed, by perhaps several tens of degrees Celsius, for a period of several months following the exchange. Comparable results were obtained in the three other studies. MacCracken (1983) employed both a one-dimensional radiative-convective model and a two-dimensional statistical-dynamical model. The remaining two investigations utilized general circulation models; an annual-average model by Aleksandrov and Stenchikov (1983) [see also Thompson *et al.* (1984)], and a seasonal model with fixed sea-surface temperature by Covey *et al.* (1984) who showed changes in atmospheric circulation for winter, spring and summer simulations, but presented surface temperatures only for the summer.

Because of the significantly different nature of the models, as well as their differing smoke-dust solar forcing as will be illustrated in following sections, a comparison of the model results would not be particularly meaningful. But it is important to understand why, in somewhat differing manners, the models all produced strong surface cooling, even though in three of the models the smoke-dust addition produced increased solar absorp-

Climatic Change 7 (1985), 237–251. 0165–0009/85.15.

tion by the surface-atmosphere system. One intent of the present paper is to provide such an understanding.

A second and primary purpose of this paper is to study one aspect of the climate forcing; the impact of atmospheric smoke and dust upon the absorption of solar radiation by the surface-atmosphere system. This includes an appraisal of radiative transfer approximations which have been utilized in certain of the climate impact studies, in addition to illustrating the smoke-dust impact upon both latitudinal and diurmal variability of the solar radiation budget of the surface atmosphere system.

2. Climate Response to a Forcing

As a prelude to understanding nuclear-war induced climate change as predicted by the current model efforts, it is instructive to subdivide climate change into a two-stage process. The first stage pertains to the direct (or initial) radiative forcing which induces the change, such as infrared radiative forcing due to an increase in atmospheric CO_2, or solar radiative forcing resulting from a change of the solar constant, to cite two often studied examples. The second stage is the climate response to that forcing, and it is here that climate feedback processes play a role. As discussed by Dickinson (1982), for example, the change in global-mean surface temperature, as induced by a radiative forcing G, may be expressed by

$$\Delta T_s = \frac{G}{\lambda} \tag{1}$$

where λ is a responsive function which incorporates relevant feedback processes.

What is germane to the present discussion is the radiative forcing G, which refers to the net radiative forcing of the surface-troposphere system. In other words, and as summarized by Potter and Cess (1984), it is not the direct radiative forcing of either the surface or the troposphere which is important, but rather the forcing of the surface-troposphere system. This is due to the fact, at least within the models which have been used to arrive at this conclusion, that small-scale convective mixing within the troposphere essentially couples the surface and troposphere so that they act as a single thermodynamic system. But the restriction here is to small radiative perturbations.

Quite a different conclusion applies to the nuclear war studies, and this is due mainly to the large magnitude of the smoke-dust radiative forcing. To illustrate this, it is convenient to first consider the general circulation model results of Covey *et al.* (1984), for which the sea surface temperature was held fixed, since the large heat capacity of the oceans would preclude their changing significantly over the 20 day simulation which was considered.

Covey *et al.* (1984) included only smoke and assumed that this was purely absorbing at solar wavelengths and had a negligible infrared opacity. In a later section it will be shown that their neglect of scattering of solar radiation by smoke is reasonable, while except possibly for very large optical depths the infrared opacity of smoke is unimportant (J. T. Kiehl, private communication). Smoke was uniformly distributed between the altitudes of 1 and 10 km and latitudes 30° N to 70° N. Note that the smoke vertical distribution was such that it was totally contained within what was initially the model's convective troposphere. Moreover, the presence of the purely absorbing smoke *increased* absorption of solar radiation by the model's surface-troposphere system, such that if our prior discussion were still applicable, there should have been warming of the model's surface (actually land surfaces).

But what instead happened was that solar absorption by smoke produced strong warming of the atmosphere with a corresponding substantial reduction in solar radiation reaching the surface. This in turn increased the static stability of what had been the convective troposphere to such an extent that small-scale convective activity ceased within that region, thus convectively decoupling the atmosphere and surface with the result that the surface was nearly in radiative equilibrium (sensible and latent heat transports still occur, but at greatly reduced levels). Since convective processes cool the surface, this elimination of convective mixing would, by itself, lead to surface warming. But the reduction of solar radiation reaching the surface, as a consequence of atmospheric absorption, is only partially compensated by enhanced downward infrared emission from the hotter atmosphere, since a significant part of the solar radiation absorbed by the atmosphere is lost through subsequent infrared emission to space. Thus, since the elimination of convective mixing means that the surface temperature is governed by radiative processes, then the corresponding reduction in net radiation absorbed by the surface leads to the cooling of land surfaces.

This illustrates that for the nuclear-war climate studies the surface-atmosphere system responds in a dramatically different fashion than for conventional climate model studies, due in part to the magnitude of the solar radiation perturbation. In this respect, it is interesting to speculate how the model would respond to more modest smoke optical depths. Clearly there should be some threshold optical depth below which tropospheric convective mixing is not curtailed (this would certainly be regionally dependent), with the result that for smaller optical depths there would be warming rather than cooling of land surfaces. In a broader sense, such a threshold optical depth should be strongly dependent upon the vertical smoke distribution and the amount of highly scattering dust injected into the stratosphere.

This point is important with respect to issues raised at the recent SCOPE/ENUWAR Workshop on the 'Climatic Consequences of a Nuclear War and their Influence on the Biosphere' (Leningrad, U.S.S.R., 14–18 May 1984), at which it was suggested that current scenarios overestimate the number of weapons detonated and the number of cities hit, and that it is important to study the nonlinear nature of the climatic response as a function of smoke/dust optical depth for optical depths less than those in current scenarios.

The remaining three nuclear war studies (Turco *et al.*, 1983; MacCracken, 1983; Aleksandrov and Stenchikov, 1983) all incorporate the added complexity of smoke/dust injection into the stratosphere, a region where small-scale convection does not exist within the models. Thus the presence of either smoke or dust within the stratosphere will lead to a net loss of energy by the surface-atmosphere system. Backscattering by particulates will of course cause direct loss of solar energy, while roughly half of the particulate solar absorption will be lost through stratospheric upward reemission at infrared wavelengths. In the study by Turco *et al.* (1983) smoke due to firestorms was initially mixed with stratospheric dust, with subsequent further smoke injection due to diffusive transport. The strong initial surface cooling produced by this model was essentially due to the same mechanism as just described for the Covey *et al.* model, but probably modified to some extent by the presence of stratospheric smoke and dust. As the time-dependence of the model proceeded, during which the smoke/dust optical depths decreased while the center-of-mass of the reduced smoke loading moved to progressively higher altitudes, the cold lower atmosphere reestablished convective coupling with the surface. But atmospheric solar absorption within the region overlying the reestablished surface-troposphere system, with subsequent partial infrared reemission to space, resulted in reduced net radiation absorbed by this system, so that significant surface cooling was still maintained even after the reestablishment of lower-atmosphere convective mixing.

The model study by MacCracken (1983) also appears to be physically analogous to the Covey *et al.* (1984) results, although in contrast to Turco *et al.* (1983) he did not mix smoke with the stratospheric dust in his model. Thus backscattering by dust resulted in reduced solar absorption by the surface-atmosphere system, in contrast to the Turco *et al.* (1983) model, for which absorption by stratospheric smoke counteracted backscattering by dust, leading to increased solar absorption by the surface-atmosphere system. To put it another way, the planetary albedo was reduced in the Turco *et al.* (1983) model, but it increased in MacCracken's model.

Although the two-level general circulation model study by Aleksandrov and Stenchikov (1983) appeared to produce initial cooling over land areas which was roughly comparable to the general circulation model study of Covey *et al.* (1984), the mechanism appears to be somewhat different. As discussed in more detail in Section 4, Aleksandrov and Stenchikov placed *purely absorbing* dust above the model's two layers, and they assumed that half the solar absorption within this 'third layer' was reemitted downward as infrared radiation. In their initial 30 day simulation, the dust absorption optical depth was sufficiently large so that most of the solar radiation was absorbed *before* it reached the levels of the model within which prognostic variables are calculated. This rendered their incorporation of lower-altitude smoke rather redundant. In short, what occurred is that the energy supplied to the model layers was reduced by a factor of two and appeared as infrared rather than solar radiation. It is not clear that this is physically comparable to the general circulation model study by Covey *et al.* (1984).

Obviously the existing model studies concerning the climatic impact of nuclear war incorporate somewhat different solar radiation forcing by atmospheric smoke and dust. The intent of the remainder of this paper is to examine further issues associated with this direct solar forcing.

3. Smoke-Dust Solar Radiation Model

For present illustrative purposes the solar radiation properties of smoke and dust are taken from existing Mie theory calculations. Atmospheric smoke is assumed to be represented by the urban aerosol model of Shettle and Fenn (1979), which has a single scattering albedo of 0.70 at a wavelength of 0.55 μm, a value close to the National Academy of Sciences (1984) smoke model. But there nevertheless is uncertainty in this value, and thus sensitivity results will also be presented. For dust the World Meteorological Organization (1983) water-soluble aerosol is utilized, since its refractive indices are coincidently nearly identical to those for mid-latitude soil (see WMO, 1983, Table 2.5). This has a 0.55 μm single scattering albedo of 0.96, compared with the National Academy of Sciences (1984) suggested value of 0.98.

Three smoke-dust scenarios are employed, and these are described as follows, with the smoke optical depth for the total atmospheric column being the same for all cases.

- Case I: The dust is above 250 mb and the smoke below 250 mb, with the dust optical depth taken to be one-third that of the smoke.
- Case II: The same as in Case I, but with no dust.
- Case III: The same dust as in Case I, but with one-third of the smoke optical depth above 250 mb and two-thirds below 250 mb.

With a smoke optical depth of 3, Case I corresponds to the smoke and dust optical depths of the initial zero-time baseline scenario of Turco *et al.* (1983). But, as previously discussed, some smoke is mixed with stratospheric dust in their model, and this is the motivation for Case III. Case II is chosen to allow, through comparison with Cases I and III, an appraisal of the relative roles of smoke and dust.

The treatment of absorption and scattering by atmospheric smoke and dust utilizes the delta-Eddington approximation with combination of layers as discussed by Coakley *et al.* (1983), but with some minor modifications as described in the Appendix. This model accounts for the wavelength dependence of smoke-dust optical properties, the interaction with Rayleigh scattering, and crudely incorporates the interactive effects of absorption by atmospheric gases.

For present purposes attention is restricted to cloud-free conditions, since the impact of large quantities of atmospheric particulates upon cloud optical properties is not known. Moreover, cloud structure will certainly be altered as, in fact, shown by the general circulation model study of Covey *et al.* (1984).

4. Spherical Averages

For illustrative purposes, spherically-averaged solar radiation, reflected at the top of the atmosphere and incident at the surface, will first be considered. Letting $Q(\mu)$ denote the flux of solar energy, where μ is the cosine of the solar zenith angle, the spherical-averaged solar flux, $\bar{Q}$, is

$$\bar{Q} = \tfrac{1}{2} \int_0^1 Q(\mu)\, \mathrm{d}\mu. \tag{2}$$

Except for a minor nonlinear interaction due to latitudinal variability of surface albedo, Equation (2) essentially denotes a global-diurnal average or, alternatively, on an annual basis a hemispherical-diurnal average. In the following section, pertaining to diurnal, lati-

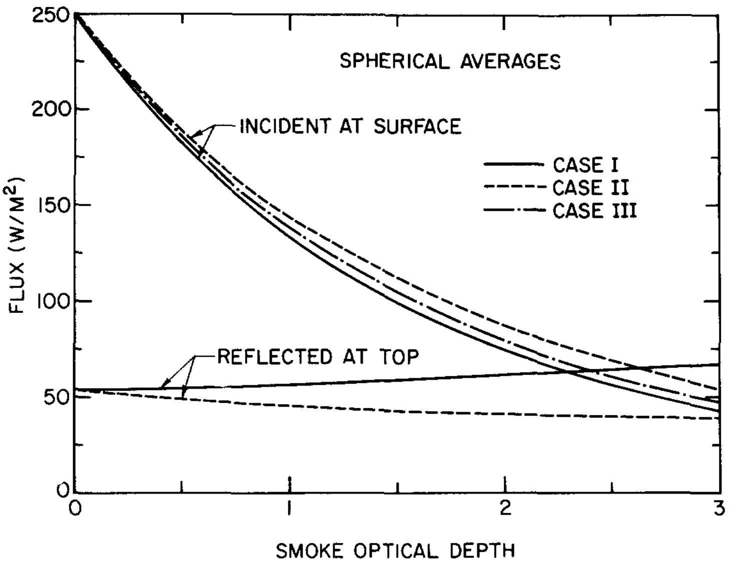

Fig. 1. Spherically-averaged fluxes, reflected at the top of the atmosphere and incident at the surface, as a function of smoke optical depth. Cases II and III are virtually identical for the reflected radiation at the top, and thus only Case II is shown.

tudinal and seasonal variability, Robock's (1980) surface albedos are utilized, and to be consistent with this, his hemispherical-mean NH albedo of 0.134 is presently employed.

Spherical averages of reflected solar radiation at the top of the atmosphere, and that incident at the surface, are illustrated in Figure 1 for the three smoke-dust vertical partitionings as described in the prior section. These comparisons are shown as a function of smoke optical depth, since this is the same for the three cases, but recall that Cases I and III additionally incorporate dust with an optical depth of one-third that of the smoke.

Consider first the results for the top of the atmosphere. The inclusion of both smoke and dust (Case I) causes an increase in reflected radiation at the top of the atmosphere, resulting in net cooling of the surface-atmosphere system due to the highly scattering dust overlying the smoke. When the dust is removed (Case II), the smoke reverses this, thus producing net warming of the surface-atmosphere system. Case III is virtually identical to Case II, and for this reason it is not separately shown in Figure 2. Recall that in this instance one-third of the smoke is mixed with the dust, and this mixing essentially negates the increase in reflected radiation (Case I) due to the dust.

With regard to solar radiation incident upon the surface, there is little difference between the three cases. Case II allows the most incident energy, since it does not include attenuation by dust. Because Cases II and III are so similar, no further consideration will be given to Case III.

At this point it is necessary to clarify differences between Figure 1 and the results of Turco *et al.* (1983), whose baseline results for the period just after the exchange, corresponding closely to Case I, indicate roughly 10 W m^{-2} of solar radiation incident upon the surface. This number is considerably lower than the approximately 40 W m^{-2} from Figure

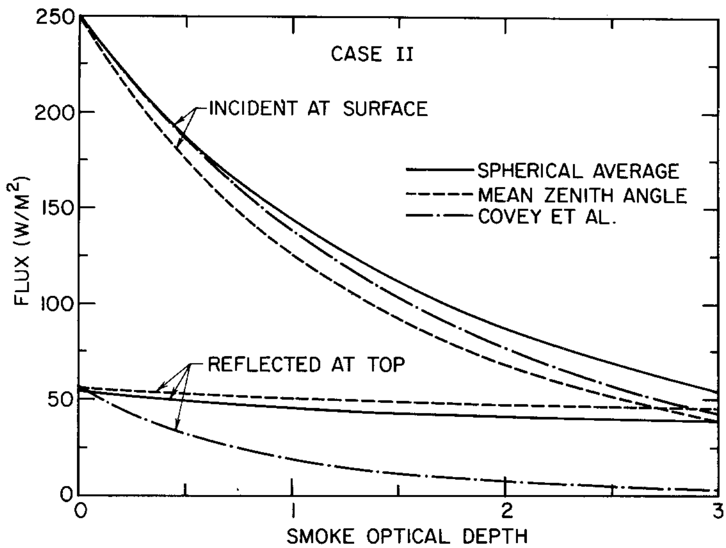

Fig. 2. Comparison of radiative transfer approximations for Case II.

1, but part of the difference is due to Turco *et al.* (1983) employing a mean solar zenith angle of 60° rather than performing a spherical average. For a 60° solar zenith angle, the present 40 W m^{-2} is reduced to 30 W m^{-2} (see Figure 3). Further, the result of Turco *et al.* (1983) more closely coincides with a smoke single scattering albedo of 0.5, as opposed to the present value of 0.7, and when this change is made the present 30 W m^{-2} is further reduced to 15 W m^{-2}. The small remaining difference is probably attributable to the fact that there are no clouds in the present model, while Turco *et al.* (1983) incorporate a fixed cloud with 50% coverage. Thus the two solar radiation models seem to be in quite good agreement.

A somewhat different solar radiation model has been employed by Covey *et al.* (1983) in their general circulation model study. They considered only smoke (Case II), and they assumed it to be purely absorbing with the smoke optical depth being the absorption optical depth. In addition to neglecting scattering by the smoke, they also assumed the absorption optical depth to be independent of wavelength. To appraise the validity of their simplifications, these modifications were made in the present model. In addition, the inclusion of Rayleigh scattering, as discussed in the Appendix, was modified to more closely mimic the manner in which it is incorporated within the general circulation model formulation of Covey *et al.* (1983) for which Rayleigh scattering effectively acts at the surface.

In Figure 2 the complete version of the present model is compared with the modified version incoporating the Covey *et al.* (1983) simplifications. Covey *et al.* (1983) also utilized latitudinal mean zenith angles rather than a diurnal average which, on a hemispherical basis, corresponds to employing a 60° mean zenith angle. Thus the present model is shown for this case as well as for the spherical average (i.e., a hemispherical-diurnal average). The results shown in Figure 2 illustrate that the use of the mean zenith

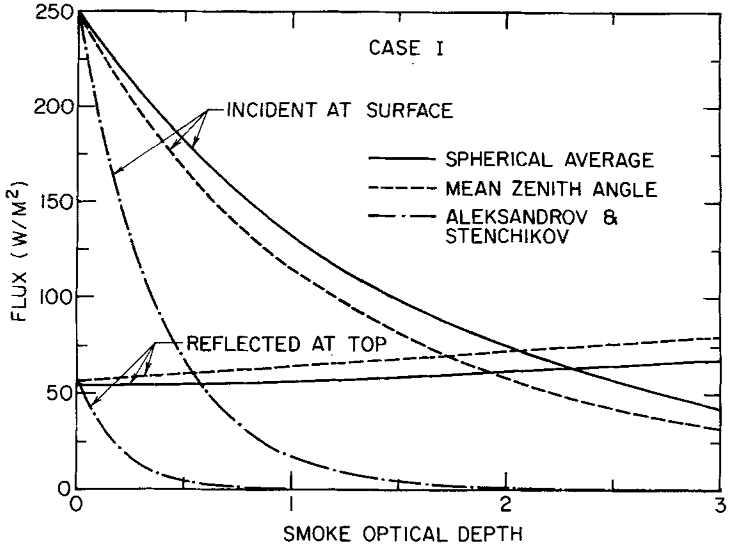

Fig. 3. Comparison of radiative transfer approximations for Case I.

angle underestimates the incident solar flux at the surface, an intuitively obvious conclusion, since diurnally there is proportionally more energy passing through the smoke for small zenith angles, when the insolation is greatest, than for large zenith angles. But with reference to the Covey *et al.* (1984) approximation, this error is partially compensated by their no-scattering approximation, which allows more solar radiation to reach the surface.

Realistically, of course, the fine points of how one treats radiative transfer in smoke would have little impact upon the specific application considered by Covey *et al.* (1984), since they assumed an absorption optical depth of 3 (which translates to a smoke optical depth of 10 for the present smoke model), for which virtually no solar radiation reaches the surface irrespective of how one models the phenomenon. The present comparison is solely for the purpose of delineating the various assumptions for more modest smoke loadings which, as previously discussed, may be germane if current estimates of smoke optical depth prove to be too large and, if not, would certainly be applicable in time-dependent scenarios (e.g. Turco *et al.*, 1983) in which the optical depth ultimately decreases with time. The reason that Covey *et al.* (1984) use a much larger smoke optical depth than Turco *et al.* (1983) is due to their placing the smoke only over a portion of the Northern Hemisphere (30° N–70° N).

With reference to the comparisons of Figure 2 concerning reflected solar radiation at the top of the atmosphere, the use of a mean zenith angle is quite applicable, while the Covey *et al.* (1984) approximation overestimates atmospheric solar absorption (i.e., underestimates reflected energy). Again this is probably not important in their specific application, for which the increased solar absorption would occur fairly high in the atmosphere, with most thus being emitted to space as infrared radiation. But if, for modest optical depths, convective mixing were to play a role, then it is the surface-troposphere perturbation, rather than the surface perturbation, which dominates, and under such a condition the Covey *et al.* (1984) approximation might not be as applicable.

Considerably different conclusions apply to the solar radiation model utilized by Aleksandrov and Stenchikov (1983), who considered both smoke and dust (Case I). As did Covey *et al.* (1984), Aleksandrov and Stenchikov employed, within their general circulation model, latitudinal mean zenith angles, although an annual-mean model was used. They also ignored scattering (by both smoke *and dust*), but unlike Covey *et al.* (1984) they assumed the optical depth to be the total extinction optical depth rather than the absorption optical depth. In effect, this amounts to treating scattering as if it were absorption. A comparison showing the consequences of their assumptions is shown in Figure 3, with these assumptions significantly underestimating solar radiation both incident upon the surface and reflected at the top of the atmosphere.

In their study, Aleksandrov and Stenchikov employed a smoke-dust optical depth of 6 for the first 30 days, 3.5 for the next 70 days, and 0.5 for the following 260 days, essentially a step-function approximation to an earlier version of the Turco *et al.* (1983) baseline case with the dust optical depth being one-fifth that of smoke. As in the prior discussion concerning the results of Covey *et al.* (1984), the large errors shown in Figure 3 would probably be of little significance for the optical depth of 6, and possibly might only be marginally significant for 3.5, although the caveats discussed in Section 2 still apply. But a seemingly interesting conclusion of Aleksandrov and Stenchikov pertained to their 260 day simulation with a smoke-dust optical depth of only 0.5, which surprisingly produced a zonally-averaged temperature inversion northward of 12° N, which coincides with where the smoke-dust was located within their model. This then implied that the model's atmospheric static stability reacted strongly to even a modest perturbation as induced by the optical depth of 0.5. But with retrospect, that perturbation was rather large. Within the context of the comparisons of Figure 3, for an optical depth of 0.5, the approximations of Aleksandrov and Stenchikov produce a reduction in incident solar flux reaching the surface of 158 W m^{-2}, and an increase in absorbed solar radiation by the atmosphere of 183 W m^{-2}, whereas the present spherical-average results, with both dust and smoke scattering included, give respective values of 57 W m^{-2} and 51 W m^{-2}.

Note also from Figure 3 that the assumption of a mean zenith angle overestimates the perturbation of reflected solar radiation at the top of the atmosphere by nearly a factor of 2.

5. Latitudinal-Diurnal Variability

The next aspect of this paper is to consider latitudinal and diurnal variability of the smoke-dust solar forcing. To accomplish this, the smoke-dust radiation model was coupled with a standard orbit calculation (e.g., Sellers, 1965), employing seasonal-latitudinal surface albedos from Robock (1980), and in the following all results refer either to diurnal averages or to noon. The use of a latitudinal-mean zenith angle, as employed by MacCracken (1983), Aleksandrov and Stenchikov (1983), and Covey *et al.* (1984), in contrast to a diurnal average, will produce latitudinal errors similar to those shown in Figures 2 and 3 for the comparisons of mean-zenith-angle results with spherical-average results.

For the sake of brevity, results are shown only for the month of April (actually 15 April), and for purely illustrative purposes only the Northern Hemisphere is considered with the totally simplistic assumption that the smoke and dust optical depths are independent of both longitude and latitude. The following results refer to 10° latitude zones, with the calculations performed at the midpoints of the zones.

In Figure 4 the diurnally-averaged reflected radiation at the top of the atmosphere is shown for Case I and Case II, both having a smoke optical depth of 3, in addition to that for the control (or prewar) climate. For the control climate the reflected radiation at the top of the atmosphere increases with latitude, despite a latitudinal decrease in insolation (e.g., the insolation is 432 W m^{-2} at 5° N and 228 W m^{-2} at 85° N). This is due to a latitudinal increase in surface albedo, which becomes very pronounced at high latitudes as a consequence of snow and ice. The presence of smoke and dust replaces surface reflection as the dominant process by atmospheric absorption and scattering, and Cases I and III produce results which are essentially independent of latitude. For both cases this translates to a change in the difference in equator-to-pole solar absorption by the surface-atmosphere system of roughly 100 W m^{-2} , a result which may have implications concerning large-scale atmospheric motions.

Note that for Case I, which has dust overlying the smoke, the reflected radiation is increased at low and midlatitudes, but decreased at high latitudes. When area weighting is taken into account, the net hemispheric effect is to increase reflected radiation at the top of the atmosphere, consistent with the spherical average shown in Figure 1. For Case II (no dust), both latitudinal and net effects yield a reduction in reflected radiation, again consistent with Figure 1.

Comparable results are shown in Figure 5 for the flux of solar radiation which is inci-

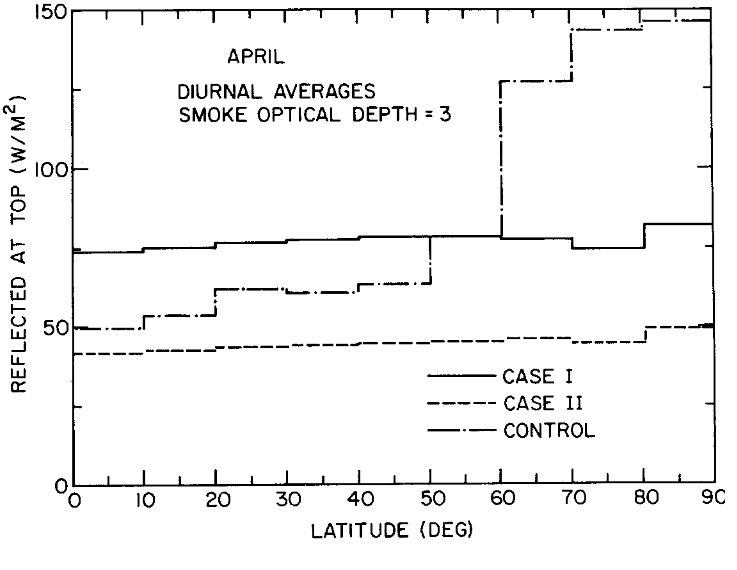

Fig. 4. Diurnally-averaged reflected radiation at the top of the atmosphere for the month of April, a smoke optical depth of 3, and as a function of latitude.

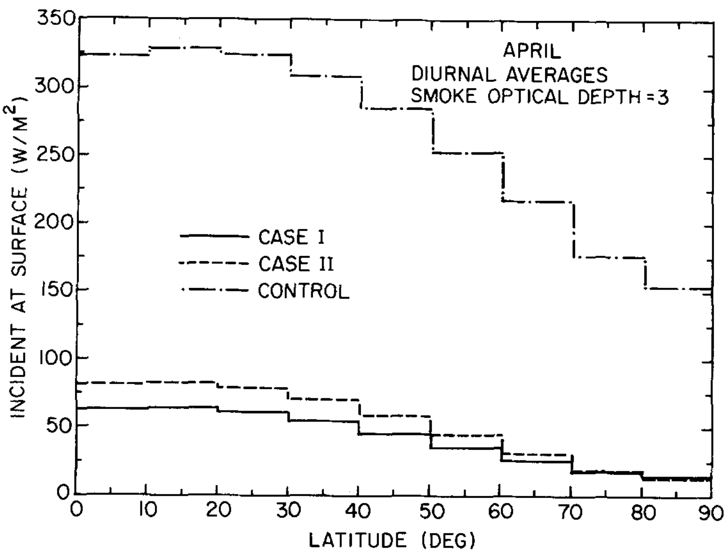

Fig. 5. Diurnally-averaged incident radiation at the surface for the month of April, a smoke optical depth of 3, and as a function of latitude.

dent upon the surface. As in Figure 1, Case I gives the smallest incident flux due to the additional presence of dust. With reference to Figures 2 and 3, the tropics receive twice the diurnally-averaged incident solar radiation as would be predicted employing a global model with a 60° mean zenith angle (see Figures 2 and 3).

Figure 6 is the same as Figure 5, except that here the results are for noon so as to illustrate the amplitude of the diurnal cycle. Note that there is a relatively large amount of noontime solar radiation reaching the surface; below 40° N this is roughly one-quarter of the control value for Case I, and one-third for Case II. This then indicates that, despite the large smoke-dust optical depths, there is still substantial diurnal variability in solar radiation reaching the surface.

It must, of course, be emphasized that uncertainties associated with this type of modeling are enormous. In addition to many other aspects, the present smoke optical depth, as well as the single scattering albedo of 0.7 for smoke, can only be regarded as illustrative choices. With respect to the single scattering albedo, Turco *et al.* (1983) employed a value of about 0.5, while the National Academy of Sciences (1984) value is closer to 0.7.

For purposes of a sensitivity study, both diurnal average and noon results are shown in Figure 7 for Case II, a smoke optical depth of 1.5, and smoke single scattering albedos of 0.6, 0.7 and 0.8. Comparison with Figures 5 and 6 shows that, as would be anticipated, the reduced smoke optical depth more than doubles the incident solar radiation at the surface, and also more than doubles the amplitude of the diurnal cycle.

The rather substantial diurnal variability in solar radiation reaching the surface, as illustrated in Figures 6 and 7, raises a point concerning the elimination of lower-atmosphere convective mixing as discussed in Sections I and II. None of the existing model studies has employed a diurnal cycle, and the point is whether the inclusion of diurnal variability

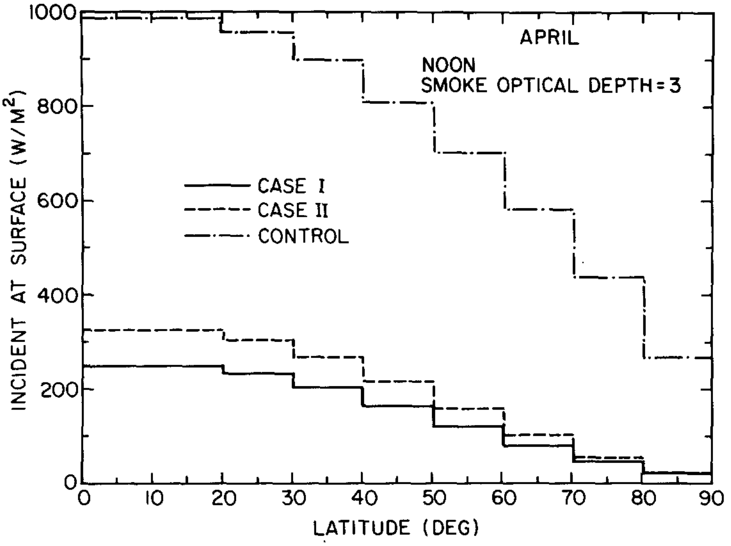

Fig. 6. Noontime incident solar radiation at the surface for the month of April, a smoke optical depth of 3, and as a function of latitude.

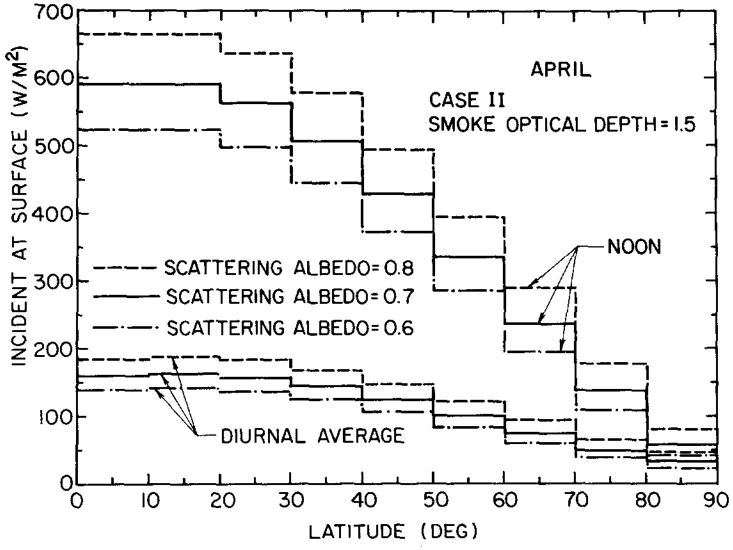

Fig. 7. Incident radiation at the surface, both diurnally averaged and noontime, for the month of April, a smoke optical depth of 1.5, smoke single scattering albedos of 0.6, 0.7, and 0.8, and as a function of latitude.

might, with possible restriction to moderate latitudes and/or modest optical depths, induce convective mixing over land areas during midday, resulting in a lesser cooling response over such areas as a consequence of periodic short-term convective coupling between atmosphere and surface. In particular, with reference to modest optical depths, the incorporation of the diurnal cycle might impact the previously discussed nonlinear response of the climate system to smoke/dust optical depth.

6. Concluding Remarks

It is important to reemphasize that the type of climate response associated with existing nuclear-war climate studies is unique with respect to our experience with climate models, since past investigations, such as those pertaining to increasing levels of atmospheric CO_2, involve very modest climate perturbations for which the conventional surface-troposphere structure is not altered. This raises the question as to the validity of existing climate models when the models are forced into a mode of strong atmospheric static stability. Because of this, and because of different climate forcing employed in existing model studies as discussed in Section 2, it would seem prudent to define a 'standard experiment' by which models could conveniently be intercompared. For this purpose a particularly simple forcing would be that of purely absorbing smoke as employed by Covey *et al.* (1984). The advantages here are threefold:

- For models which do not have incorporated within them a detailed smoke-dust solar radiation prescription, it is relatively easy to include purely absorbing smoke within the existing solar radiation routine.
- Conversely, models which treat atmospheric smoke and dust in a detailed fashion may easily be degraded to the case of purely absorbing smoke.
- Finally, purely absorbing smoke embodies the important aspect of the forcing; i.e., direct solar heating of the atmosphere and cooling of the surface.

The importance of examining threshold smoke/dust optical depths and the nonlinear climate response to smoke/dust forcing, consistent with previously discussed issues raised at the SCOPE/ENUWAR Workshop, is also emphasized.

Acknowledgements

The results presented herein were reported, in somewhat of an evolutionary fashion, at the Conference of the Long-Term Global Atmospheric and Climatic Consequences of Nuclear War (Cambridge, Mass., 22–23 April, 1983), the Third International Seminar on Nuclear War (Erice, Sicily, 19–23 August, 1983), and the Study Session on the Potential Climatic Effects of Nuclear Explosions (National Academy of Sciences, 2 March, 1984). I thank Dr V. Ramanathan for suggesting numerous improvements to an earlier version of this manuscript, and I further benefited from useful suggestions by Drs T. P. Ackerman, F. M. Luther, M. C. MacCracken, and S. L. Thompson. This work was supported by the National Science Foundation through Grant No. ATM8212791.

Appendix. Atmospheric Solar Radiation Model

As discussed in the text, the atmospheric solar radiation model utilizes the delta-Eddington approximation with combination of layers as formulated by Coakley *et al.* (1983), but with minor modifications. Their Equations (B19) and (B20) are employed for combining layers, and since a typographical error occurred, the corrected equations are given below. Letting $R(\mu)$ and $T(\mu)$ denote, respectively, the monochromatic reflectivity and transmissivity of the total atmospheric column, where μ is the cosine of the solar zenith angle, then

$$R(\mu) = R_1(\mu) + \bar{T}_1 \left\{ R_2(\mu) \exp(-\tau_1^*/\mu) + \bar{R}_2 [T_1(\mu) - \exp(-\tau_1^*/\mu)] \right\} (1 - \bar{R}_1 \bar{R}_2)^{-1}, \quad \text{(A1)}$$

and

$$T(\mu) = T_2(\mu) \exp(-\tau_1^*/\mu) + \bar{T}_2 \left\{ [T_1(\mu) - \exp(-\tau_1^*/\mu)] + \bar{R}_1 R_2(\mu) \exp(-\tau_1^*/\mu) \right\} (1 - \bar{R}_1 \bar{R}_2)^{-1}.$$

The overbar denotes a reflectivity or transmissivity for diffuse incident radiation, the subscripts 1 and 2 refer, respectively, to the upper layer (above 250 mb) and the lower layer (below 250 mb), while

$$\tau^* = (1 - \omega f)\tau, \quad \text{(A3)}$$

where τ is the monochromatic optical depth, ω is the monochromatic single scattering albedo and, as discussed by Coakley *et al.* (1983), f is related to the coefficient of the second Legendre polynomial for a scattering phase function represented by a series of Legendre polynomials. For Rayleigh scattering this yields $f = 0.2$, while for smoke and dust f will presently be related to the asymmetry factor g through expansion of a Henyey-Greenstein phase function, such that $f = g^2$.

In each of the two layers it is assumed that smoke and dust are uniformly mixed within the atmospheric layer. In combining smoke/dust and Rayleigh scattering within each layer, the single scattering albedo and the asymmetry factor are evaluated from the component quantities employing

$$\omega = \frac{\Sigma \tau_i \omega_i}{\Sigma \tau_i} \quad \text{(A4)}$$

and

$$g = \frac{\Sigma \tau_i \omega_i g_i}{\Sigma \tau_i \omega_i}. \quad \text{(A5)}$$

The subscript i denotes a specific component, with $\omega_i = 1$ and $g_i = 0$ for Rayleigh scattering. The rationale for Equations (A4) and (A5) is discussed by Cess (1983), with Eqution (A5) being analogous to his expression for the backscattered fraction, since for the asymmetry factors used herein there is a near linear relationship between g and the backscattered fraction.

Interaction with atmospheric water vapor is crudely incorporated as in Coakley *et al.* (1983), except that the fraction of incident solar flux over which particulate effects are assumed to occur has been increased from 0.698 to 0.798 so as to produce a more realistic control simulation.

As in Coakley *et al.* (1983), the monochromatic planar albedo of the surface-atmosphere system, $\alpha(\mu)$, is given by

$$\alpha(\mu) = R(\mu) + \frac{\alpha_s \bar{T} T(\mu)}{1 - \alpha_s \bar{R}}, \quad \text{(A6)}$$

while the fraction of insolation which is incident upon the surface, $D(\mu)$, is

$$D(\mu) = \frac{T(\mu)}{1 - \alpha_s \bar{R}}, \tag{A7}$$

where α_s is the surface albedo. In evaluating these expressions, $R(\mu)$ and $T(\mu)$ are determined from Equations (A1) and (A2), within which the layer quantities $R_j(\mu)$ and $T_j(\mu)$ are given by Equations (B1) through (B10) of Coakley *et al.* (1983), while their equations (B12) through (B15) describe R and $\bar{T}$. Further, $\bar{R}$ and $\bar{T}$, as appear within Equations (A6) and (A7), were evaluated from their Equations (B21) and (B22) of Caokley *et al.* (1983), but with the layer subscripts reversed for $\bar{R}$, since this refers to upward diffuse radiation which has been reflected by the underlying surface.

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(Received 25 June, 1984; in revised form 22 October, 1984)