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NUCLEAR WAR: PRELIMINARY ESTIMATES OF THE CLIMATIC EFFECTS OF A NUCLEAR EXCHANGE

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ABSTRACT

The smoke rising from burning cities, industrial areas, and forests if such areas are attacked as part of a major nuclear exchange is projected to increase the hemispheric average atmospheric burden of highly absorbent carbonaceous material by 100 to 1000 times. As the smoke spreads from these fires, it would prevent sunlight from reaching the surface, leading to a sharp cooling of land areas over a several day period. Within a few weeks, the thick smoke would spread so as to largely cover the mid-latitudes of the Northern Hemisphere, cooling mid-continental smoke-covered areas by, perhaps, a few tens of degrees Celsius. Cooling of near coastal areas would be substantially less, since oceanic heat capacity would help to buffer temperature changes in such regions.

The solar radiation not being absorbed at the surface would be absorbed by the smoke in the middle troposphere (up to heights of perhaps 10 km). As the smoky layer warms, this heating of the upper troposphere would induce further mixing of the smoke up into the atmosphere, where the smoke could remain even longer than the 10-20 days that normal scavenging now allows. The strong atmospheric stability created by the strongly warmed smoke layer overlying the cooled surface and lower troposphere would tend to reduce precipitation over both the ocean and the land areas, where evaporation would also be reduced due to surface cooling. The precipitation that does occur would likely be shallow and relatively ineffective in scavenging the higher smoke layer. Thus, solar absorption by the smoke and the reduction in scavenging would allow the smoke particles to remain in the

atmosphere for longer times, thereby probably prolonging the darkness and continental cooling for perhaps several months. The net effect of a summertime nuclear exchange would be that summer conditions in mid-latitudes would turn to dark near winter-like conditions, while a wintertime nuclear exchange would lead to somewhat more severe winter conditions. Lower latitude temperatures would become more like those in middle or higher latitudes. The impacts of these climatic perturbations on society and agriculture remain to be evaluated.

Injections of dust and nitrogen dioxide into the stratosphere as a result of a hypothetical nuclear exchange involving large numbers of nuclear explosions having yields greater than about one-half megaton are projected to have an effect on the stratospheric radiation balance about equivalent to that of very large volcanic eruptions (e.g., Krakatoa in 1883 or Tambora in 1816). The climatic cooling of the Northern Hemisphere from such injections could be one to a few degrees Celsius, with variable effects regionally resulting from possible shifts in storm tracks.

The calculations on which these findings are based contain many assumptions, shortcomings and uncertainties that affect many aspects of the estimated response. It seems, nonetheless, quite possible that if a nuclear exchange involves attacks on a very large number of cities and industrial areas, thereby starting fires that generate as much smoke as is suggested by recent studies, substantial cooling could be expected that would last weeks to months over most continental regions of the Northern Hemisphere, but which may have relatively little direct effect on the Southern Hemisphere.

INTRODUCTION

Crutzen and Birks (1982) and Turco et al. (1983) have suggested that a major nuclear exchange in which urban and forest areas are primary targets would lead to extensive fires and massive injections of smoke into the middle troposphere and above. These emissions would be in addition to the nitrogen oxide and dust injections into the atmosphere occurring coincident with the nuclear explosions. A comparison of the mass of material projected to be injected as a result of a major nuclear exchange with that estimated to have resulted from major volcanic eruptions of the last two hundred years is given in Table 1. Estimates of current background loading are also included in the table.

There are substantial uncertainties in the estimates of emissions from both the volcanic eruptions and the nuclear exchange, values for which are highly dependent on the particular exchange scenario. It appears that the expected stratospheric injection of sub-micron size nuclear-induced dust, however, would

Table 1. Mass of Injected Material from a Major Nuclear Exchange Compared to Volcanic Injections and Background (10^{12} g)*

Species for Various Events	Stratosphere	Troposphere
Aerosol (including dust)		
Nuclear Exchange (dust)	118	5000†
Tambora (1815)	hundreds	200000
Krakatoa (1883)	50	20000
Agung (1963)	10-20	4-8000
Mt St Helens (1981)	∿ 0	2000
El Chichon (1982)	10-20	2-4000
Background (Northern Hemisphere)	∿ 1	5-10
Nitrogen Oxides (as N)		
Nuclear Explosions Generated Injection (bomb-created)	∿ 7	∿ 1†
Fire-Generated Injection	0	26†
Background (Northern Hemisphere)	∿ 4	∿ .2
Ozone (as O_3)		
Nuclear Exchange Induced Change	∿ -600	40-100†
Background	∿ 1700	∿ 200
Soot		
Injection by Nuclear-Exchange Induced Fires		
Cities	0	150
Forests	0	57
Annual Forest Fire Injection in U.S.	∿ 0	a few
Background	∿ 0	.1-1

† The climatic effect of NO_2 and dust injections into the troposphere, and the resulting effect on tropospheric ozone, are not treated in this calculation.

* Values are drawn from estimates given by a variety of sources, including Turco et al. (1983), Crutzen (1983), Lamb (1970), Ellsaesser (1975), Turco, et al. (1982), Penner (1983), and our own evaluations. For the nuclear exchange and major volcanoes, tropospheric aerosol lofted is total amount rather than just amount remaining in the atmosphere.

be comparable to injections from major volcanic eruptions that are believed to have led to noticeable (~ 1°C) coolings of surface temperatures over a few year period following the eruption. The nuclear-generated nitrogen oxide injection, which leads to formation of NO_2 (an absorber of solar radiation) and destruction of ozone (an absorber of solar radiation and active infrared gas), also is clearly a major perturbation of background levels.

Of most concern, however, is the very large, nearly instantaneous injection of soot (urban fires are generally assumed to burn to near completion in a few days and forest fires in about a week), which is a strong absorber of solar radiation. We assume that the soot has a log-normal particle size distribution with a mode radius of 0.06 μm and a standard deviation of 2.2. Other radiative characteristics are taken from Turco et al. (1983). Radiative calculations (e.g., Crutzen and Birks, 1982; Turco et al., 1983; Cess, 1983) suggest that the hundred to thousand fold increase in atmospheric soot concentration would prevent sunlight from reaching the surface over those latitudes whereever substantial amounts of the smoke spread. These calculations also assume that the particles do not increase in size with time and will therefore not affect the infrared radiation balance, an assumption that allows for the sharp cooling that is found.

While there are many devastating social and economic impacts of a nuclear exchange, comparison of injections projected to occur from plausible, but admittedly uncertain, scenarios for a nuclear exchange indicate that there is the potential for substantial impacts on the hemispheric, and perhaps global, radiation balance and climate. Better understanding of the potential climatic effects is essential, both so that there is an accurate perception of the post-exchange environment and to indicate that many nations, whether belligerent or bystander, will be affected significantly if a nuclear exchange does occur.

BACKGROUND

The equitable climate of the Earth results from the complex interplay of many energy reservoirs and interactive processes that store and redistribute the incoming solar energy. The composition of the atmosphere and character of the surface determine both how much solar energy is absorbed and is reflected to space and the flux of infrared radiation between the surface, the atmosphere and space. Atmospheric motions move the absorbed energy both vertically and horizontally in order to relieve dynamic and thermal instabilities, through these motions cooling low latitudes and warming high latitudes. Solar absorption at the surface evaporates water (primarily from the ocean), providing water vapor to the atmosphere that reduces infrared emission to space and increases such emission to the surface. Condensation of the water vapor in the atmosphere far from where it was evaporated both balances the net radiative cooling of the atmosphere and cleanses it of particulate matter. The rapid increase of evaporation rate with temperature tends to prevent overheating of the ocean, whereas the ocean's large heat capacity tends to prevent rapid cooling.

These many processes interact to form a climate that has been remarkably stable on time scales of decades (annual average hemispheric temperatures have varied by only about 0.5°C over the last hundred years), but which has been rather unstable on time scales of millenia (e.g., ice sheets a few kilometers thick covered Canada only 18000 years ago when global average ocean surface temperatures were only about 2°C colder than at present). The apparent cause of climate variations on the longer scale have been relatively small latitudinal and seasonal shifts (i.e., several percent) in the solar radiation striking the top of the atmosphere resulting from slight eccentricities in the orbital parameters of the Earth; the relatively large climatic consequences that result occur because of augmentation of the initial causal factors by numerous feedback processes. There is also some evidence that perturbations of the radiation balance resulting from volcanic injections into the stratosphere have been the cause of at least some of the climatic variability over the last hundred years (e.g., Hansen et al., 1981).

Thus, the suggestion that the material injected into the atmosphere from the blasts and fires created by a major nuclear exchange will significantly perturb the solar radiation balance of the atmosphere deserves careful study.

METHODOLOGY

Although qualitative analysis of the climate system can provide important insights, quantitative estimates of possible perturbations to the delicately balanced climate system require the use of numerical models that represent, at least, those aspects of the physics of the climate system that become involved in the response to exchange-generated injections. Given the magnitude and complexity of the potential perturbation, such a model must treat space scales from a few to thousands of kilometers and from hours to months, radiative, dispersive and convective processes acting on and affected by the injected aerosol, and land and ocean surface interactions. There are not, at present, however, verified models formulated to deal with all of these processes and scales simultaneously. In the interest of estimating, rather than fully assessing, potential effects, analyses done to date have resorted to use of available models that involve important simplifications and approximations.

To develop an initial estimate of the effects of the soot on the radiative fluxes and the hemispheric average temperatures, a one-dimensional model has been used to calculate perturbations as a function of altitude. Turco et al. (1983) used an extension of Manabe and Wetherald's (1967) radiative-convective model to study the time-dependent change of radiative fluxes and atmospheric temperatures, assuming there was no land surface heat capacity and that the smoke aerosol was instantaneously spread over the entire Northern Hemisphere. Our preliminary results, described in the next section, are based on a very similar one-dimensional model derived instead from our two-dimensional model (MacCracken et al., 1981), but allowing for a surface heat capacity. These models explicitly calculate the vertical distribution of solar and infrared radiative fluxes, including the effects of prescribed cloudiness; a simplification in our present implementation of the perturbation to the solar radiation, however, will underestimate the effect somewhat at low soot concentrations and therefore may indicate a slightly faster recovery from the cooling than will actually be the case. One-dimensional models can also only represent vertical heat transport with a simple lapse rate limitation and do not consider horizontal transport, the hydrologic cycle, or cloud formation processes. The removal rates for the aerosol must also be prescribed, based, for example, on removal rates in the unperturbed atmosphere. The inability to treat the horizontal distribution of land (with its low, or zero, surface heat capacity) and ocean (with its relatively high surface heat capacity resulting from ocean mixing processes) is an extremely important simplification, since it is likely that air flow from one region to the other will be accelerated by the greatly increased temperature differences between the two surface types and thereby moderate temperature changes over land.

The assumption that the aerosol is instantaneously well-mixed over the Northern Hemisphere is also important since it, in effect, exposes more solar radiation to absorption and scattering by the aerosol than would be the case following a nuclear exchange when thicker smoke exists over more limited regions. For this reason, the one-dimensional approach will overestimate the hemispheric average radiative and climatic impacts.

To address some of these issues, we have applied higher dimensional models. To improve calculation of the dispersal of the smoke, we have developed the GRANTOUR trace species transport model (Walton and MacCracken, 1983) that uses transport and precipitation data from a 3-D general circulation model (Gates and Schlesinger, 1977) to spread the smoke around the globe from source regions and to scavenge the smoke by rain and snow. While this model appears to give reasonable estimates of aerosol lifetimes (and its results for radionuclide lifetimes compare acceptably with observations, refer to Knox (1983)), there are a number of important simplifications and assumptions. Of most importance is the assumption that the presence of the aerosol will not affect the dispersal and scavenging characteristics of the atmosphere, which, given the results to be shown, will almost certainly overestimate removal rates. Our present implementation of GRANTOUR also neglects vertical wind shear in the atmosphere, which will somewhat underestimate spread of the smoke and may overestimate the unevenness (or patchiness) of the smoke.

GRANTOUR will, however, provide approximate estimates of the time for the smoke to spread around the mid-latitudes and to higher and lower latitudes. These estimates have been used to specify the latitudinal and vertical distribution of the smoke (and dust and NO_x injected into the stratosphere) for introduction into our two-dimensional (latitude and vertical) climate model (MacCracken et al., 1981), referred to hereafter as the LSDM. This model provides 10° latitude resolution from pole to pole with nine layers in the vertical extending to about 35 km altitude. Temperature, water vapor, surface pressure, and wind fields are predicted based on approximations to the conservation equations for energy, water vapor, mass and momentum. Cloud cover is calculated diagnostically as a function of relative humidity. The land-ocean distribution at each latitude is represented approximately based on averaging over the appropriate fractions of several surface types, each treated separately in terms of their own energy balance, radiative fluxes, hydrology and surface temperature. While this approximation will provide a better estimate of latitudinal and hemispheric average temperature and hydrologic cycle perturbations than a one dimensional model, the regional distribution and central continental perturbation extremes will not be properly represented.

Aleksandrov (1983) goes a step further than our 2-D approximation in presenting results from a 3-D ocean-atmosphere general circulation model (the atmospheric portion of which is a derivative of the Oregon State University model used to drive GRANTOUR) that includes proper global geography, but his approach is more limited in terms of the detail of its radiative approximation and does not yet treat the time-dependent spread of the smoke. Thus, Aleksandrov's and our results can be viewed as complementary, but recognizing that both approaches still contain many shortcomings.

SPREADING OF THE SMOKE

In order to allow comparison with the climate impacts estimated by Turco et al. (1983), we have assumed that 150 Tg of soot aerosol are injected into the troposphere above the surface boundary layer from urban fires within one day of the nuclear exchange and an additional 57 Tg of soot are injected from forest fires over the seven days following the exchange. If spread evenly over the Northern Hemisphere, this amount of soot would, with the aerosol optical properties that we assume, have a vertical optical depth of more than four about equally divided between absorption and scattering. (For reference, Turco et al. (1983) suggest that heavy overcast conditions have an absorption optical depth of about 1 to 1.5). We, however, arbitrarily assume that the particles are injected in equal amount from four likely target regions centered on the Ohio River basin, the southwestern United States, the Rhine Valley, and Moscow. Following emission, the particles are spread by the winds and scavenged, primarily by precipitation. For the case shown, we will be using, as the meteorological conditions, results from a GCM simulation for January, a period when zonal winds, cyclogenesis and precipitation are all relatively high compared to other seasons; we do not believe, however, that the general characteristics of the results are strongly sensitive to this choice of meteorology. After three days the smoke covers the North Atlantic Ocean and most of the mid-latitude continental regions of the Northern Hemisphere (see Figure 1), but most of the Northern Hemisphere sees no smoke at all even though the hemispheric average optical depth is 3.8. There are large regions where the optical depth is greater than 20, with large horizontal gradients present that might well perturb dynamical and scavenging processes. The patchy nature of the smoke distribution is shown in Figure 2, which indicates the fractional area of the hemisphere having optical depth greater than a given amount at various times following the exchange.

By day 30, normal scavenging processes would reduce the optical depth to about 1 (in agreement with the rate of decrease considered by Turco et al. (1983)). The hemispheric distribution (see Figure 3) still shows extensive patchiness, with a number of small regions having optical depth greater than 5 and a rather large area with an optical depths greater than 1. While GRANTOUR will underestimate dispersion and spreading, unless the intensity of the large scale planetary waves is greatly diminished, the predicted heterogeneous character of the distribution pattern is likely to be generally correct, indicating that particular locations may experience large day-to-day variations in smoke intensity. By day 60 of the simulation (see Figure 4), only a few smoky patches remain that have $\tau > 1$, most occurring at high latitudes because, at lower latitudes, precipitation processes have been able to more effectively cleanse the atmosphere. The hemispheric average optical depth is, however, about 0.5, so after 60 days the smoke is more uniformly spread than at earlier times (see Figure 2).

Because initial studies of the effects of the soot on the radiation balance indicate that the upper troposphere may warm,

Fig. 1. Hemispheric distribution of smoke-induced optical depth 3 days after the hypothetical nuclear exchange (forest fires are assumed to be still burning), assuming precipitation scavenging at non-perturbed wintertime rates. As assumed by Turco et al. (1983), the hemispheric average optical depth is 3.8, but the pattern is not hemispherically homogeneous.

thereby stabilizing the atmosphere and leading to reduced precipitation scavenging of the aerosol, these initial GRANTOUR calculations probably underestimate particle lifetimes. Although it would be desirable to investigate the dependence of particle concentrations on scavenging rates with a coupled model, this has not yet been possible. Therefore, to investigate the effect of reduced scavenging, we have carried out a simulation in which the precipitation rate was arbitrarily multiplied by $e^{-\tau/3}$ where τ is the local optical depth. This dependence is actually somewhat less than indicated by a comparison of observed solar radiation absorbed at the surface and observed precipitation rate (see Figure 5), an analog that should be viewed with caution, but which does generally exhibit the postulated relationship.

Figure 6 shows the hemispheric optical depth distribution 30 days after the hypothetical exchange, assuming damped scavenging

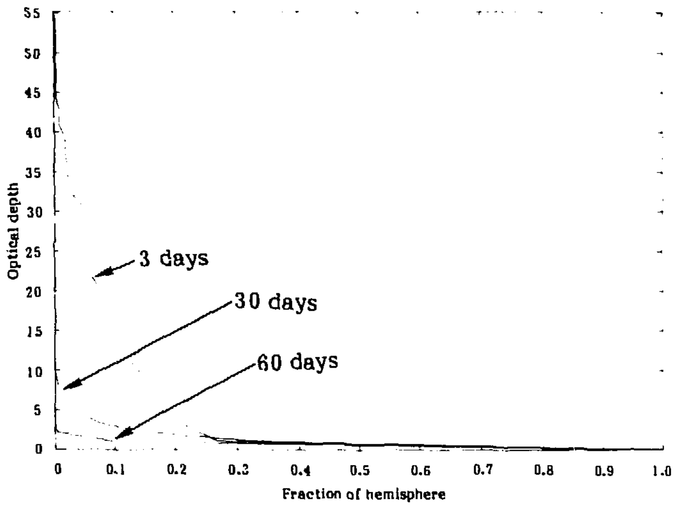

Fig. 2. Fractional area of the Northern Hemisphere experiencing optical depths greater than the value indicated at various times following a nuclear exchange assuming continued precipitation scavenging at non-perturbed wintertime rates.

and wintertime circulation patterns. Compared to the results shown in Figure 3, optical depth remains significantly greater over a large fraction of the hemisphere. Similarly, at day 60, as shown by contrasting Figure 7 to Figure 4, the optical depth remains significantly higher when scavenging is reduced. Note that the aerosol becomes better spread out in these cases (contrast Figure 8 and Figure 2), but that patchiness is still strongly evident.

A comparison of these two cases and of a third case, in which precipitation scavenging was reduced by $e^{-\tau}$, are shown in Figure 9. Quite clearly, if stabilization and a reduction in scavenging rates occur as a result of solar absorption by the soot particles, particle lifetime will increase greatly and prolong any climatic perturbation.

ONE-DIMENSIONAL ESTIMATES OF TEMPERATURE CHANGE

We have used a one-dimensional radiative convective model with an interactive surface to develop an initial estimate of the climatic effects of injections of soot, dust, and nitrogen dioxide and of the resulting reduction in stratospheric ozone.

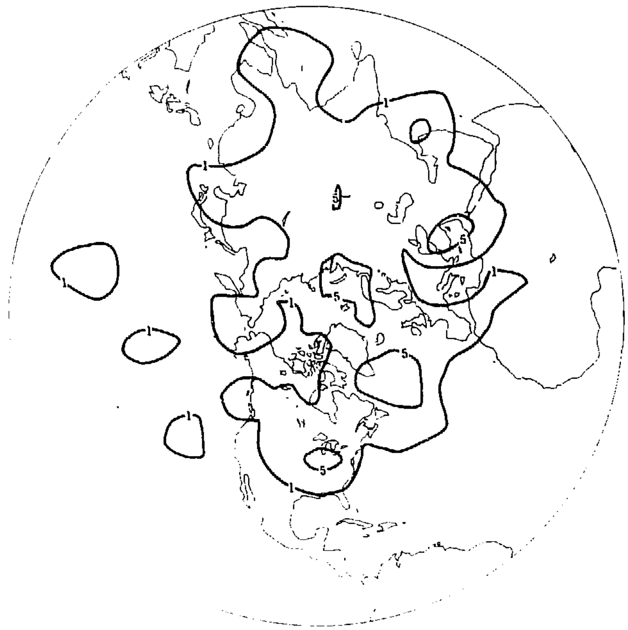

Fig. 3. Hemispheric distribution of smoke-induced optical depth on day 30 following the hypothetical nuclear exchange, assuming precipitation scavenging at non-perturbed wintertime rates. Hemispheric average optical depth is 1.1, but the pattern remains uneven, which is a result of scavenging in individual storm systems.

Smoke concentration as a function of time is based on the hemispheric integral of the GRANTOUR results. A dust injection of 118 Tg and a nitrogen dioxide injection of 8.3 Tg N are also assumed to be spread instantaneously over the Northern Hemisphere stratosphere, with scavenging occurring only very slowly since the stratospheric residence time is assumed to range from 4 1/2 to 8 months, depending on latitude. To account for ozone reduction by nitrogen oxides, the ozone concentration is assumed to be multiplied by $0.3 + 0.7^{-\alpha[NO_2]}$ where the coefficient α is based on results from the LLNL one-dimensional chemical kinetics model (Luther, 1983).

Assuming normal wintertime scavenging rates for the soot, the change in land surface air temperature as a function of time after the exchange is shown in Figure 10. Because we are using a one-dimensional model, these results can only loosely be interpreted in terms of a change in the annual average hemispheric

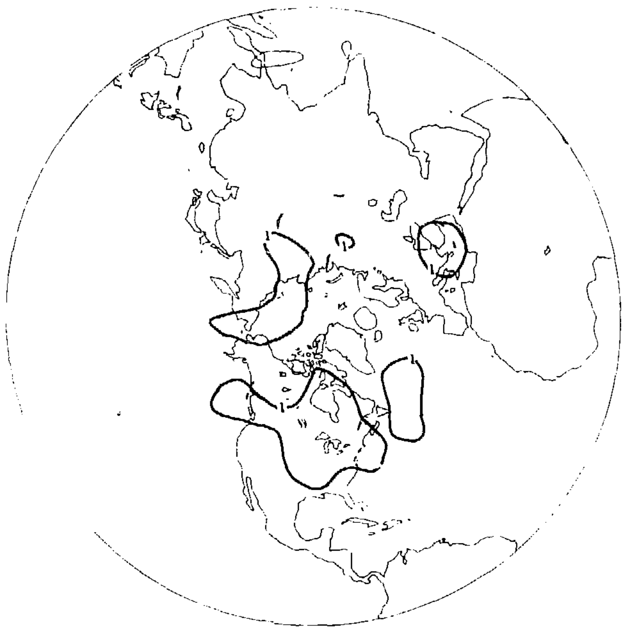

Fig. 4. Hemispheric distribution of smoke-induced optical depth on day 60 following the hypothetical nuclear exchange, assuming precipitation scavenging at non-perturbed wintertime rates. Hemispheric average optical depth is 0.5, with relatively few areas with values greater than 1, indicating greater uniformity of soot concentrations than at earlier times.

land surface temperature as a function of time. The temperature is seen to drop rapidly, decreasing more than 30° C within two weeks (assuming constant, rather than patchy, smoke cover). This cooling time is controlled by the heat capacity of the lower atmosphere, which is low. This result compares quite well with the results of Turco et al. (1983). The relative warming that occurs from two to six weeks after the exchange is primarily a result of the scavenging of the soot from the atmosphere, a process with a time constant of 2 to 3 weeks. The slower recovery of temperature beyond six weeks reflects the effect of the stratospheric injections, which are scavenged from the atmosphere more slowly than the tropospheric soot.

To test the robustness of this predicted perturbation, we have conducted a variety of sensitivity experiments with the one-dimensional model, as listed in Table 2. The second and third

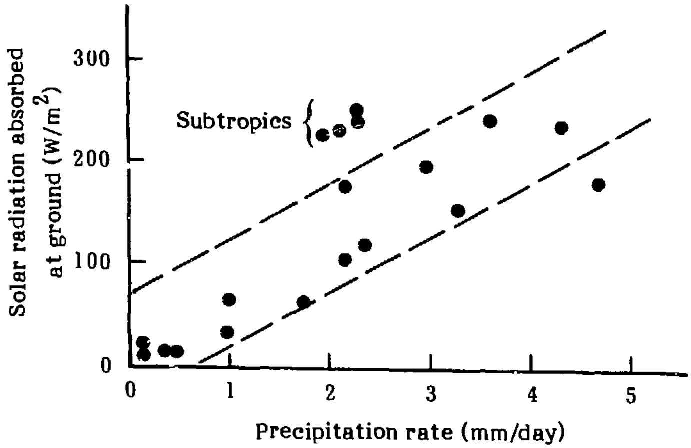

Fig. 5. Relationship of solar radiation absorbed at the surface in our zonal climate model to observed precipitation rate (Jaeger, 1976) as a function of latitude. If the solar radiation scale is converted to optical depth, the linear fit to the data indicates precipitation is roughly proportional to $e^{-\tau/1.3}$.

simulations with the radiative-convective model tested the effect of decreasing scavenging rates, thereby allowing the smoke to remain in the atmosphere longer (see Figure 8). This has the effect of greatly increasing the maximum temperature decrease, and, given the stabilization of the smoke layer that occurs, indicates that mid-continental temperature changes may be very large.

The fourth simulation tested the effect of removing the cloud cover. Such a reduction in cloud cover may result from the warming and subsequent evaporation of the clouds present in the control. The effect of removing cloud cover is to further increase the temperature reduction. This occurs because, without clouds, there will be much less downward emission of infrared radiation from the warm smoky layer toward the cold surface. Because the smoke particles are assumed to be small, the effect of removing the cloud cover is not made up for by the small amount of infrared emission from the particles.

The next simulation tested the dependence of the result on surface heat capacity. In contrast to the case for land, if a high surface heat capacity appropriate for oceanic surface types is used, the temperature reduction is much smaller and much more gradual. Given that the Northern Hemisphere's surface is about half land and half ocean and that the ocean's large heat capacity

Fig. 6. Hemispheric distribution of smoke-induced optical depth on day 30 following the hypothetical nuclear exchange, assuming wintertime precipitation scavenging is reduced by $e^{-\tau/3}$. Hemispheric average optical depth is 4.5, although these levels are typical only at middle and high latitudes.

can somewhat buffer the sharp cooling over land, we can expect that the hemispheric average temperature change will be somewhere between the land and ocean values, probably closer to the latter. We may also speculate that the contrasting changes will substantially perturb atmospheric dynamics, although this effect will be smaller than expected since the land-ocean temperature contrast will exist relatively near the surface and not at mid-tropospheric altitudes.

For the case of no smoke from fires, the dust, NO_2 and O_3 induce a much smaller perturbation over land than the cases with the smoke, and, if averaged over ocean and land, the effect would be even less. The NO_2 and O_3 perturbations only induce a comparatively small change, in part because of a cancellation of radiative effects. These perturbations are roughly comparable to the effects of major volcanic injections of the past few hundred years and are, therefore, within the realm of human experience.

Fig. 7. Hemispheric distribution of smoke-induced optical depth on day 60 following the hypothetical nuclear exchange, assuming wintertime precipitation scavenging is reduced by $e^{-\tau/3}$. Hemispheric average optical depth is 3.0, but these values are exceeded only in middle and high latitudes.

These perturbations will not be further considered here separately from the smoke.

TWO-DIMENSIONAL ESTIMATES OF CLIMATE CHANGE

Instantaneously spreading the injections over the Northern Hemisphere has the effect of exposing many more of the smoke particles to sunlight than would be the case if this assumption were not made. In addition, one-dimensional radiative-convective model results clearly indicate the need to treat both land and ocean surface types. We have attempted to improve treatment of the effects of spreading of the particles and of land-ocean contrast by applying our two-dimensional climate model (LSDM). In the simulation we have conducted, the smoke, dust, and NO_2 injections (and O_3 reduction) are instantaneously spread longitudinally, a process that normally takes days to weeks, but the

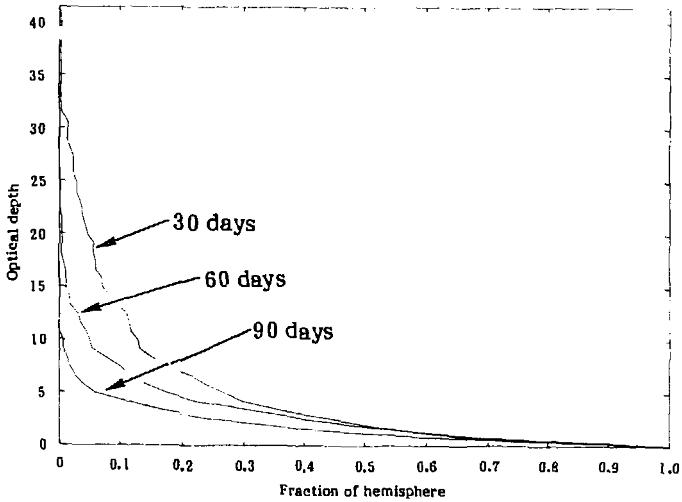

Fig. 8. Fractional area of the Northern Hemisphere experiencing optical depths greater than the value indicated at various times following a nuclear exchange assuming wintertime precipitation scavenging rates are reduced by $e^{-\tau/3}$.

latitudinal spread that takes weeks to months is prescribed based on GRANTOUR results. The LSDM also, as indicated earlier, attempts to schematically account for the land-ocean fractionation at each latitude.

Only very preliminary model results are available from our first two simulations of the hypothetical nuclear exchange. In these simulations we have used the GRANTOUR results that assume, first, normal precipitation scavenging, and second, that scavenging is damped by a factor $e^{-\tau/3}$. In this latter simulation, our LSDM calculations of the radiative fluxes indicate, for example, that after a month there is virtually no solar radiation reaching the lower half of the atmosphere from about 20° N to 70° N - a reduction of about 50-150 W/m^2.

Figure 11 summarizes the hemispheric average land surface temperature changes for the above two cases, and the ocean temperature change for the larger of the two cases. For the case with normal scavenging, we again see that the maximum reduction in land temperature occurs within two weeks, but that it is a much smaller reduction than indicated by the one-dimensional model. This is a result both of the modulation of the temperature change by the ocean and of the reduced effect of the smoke

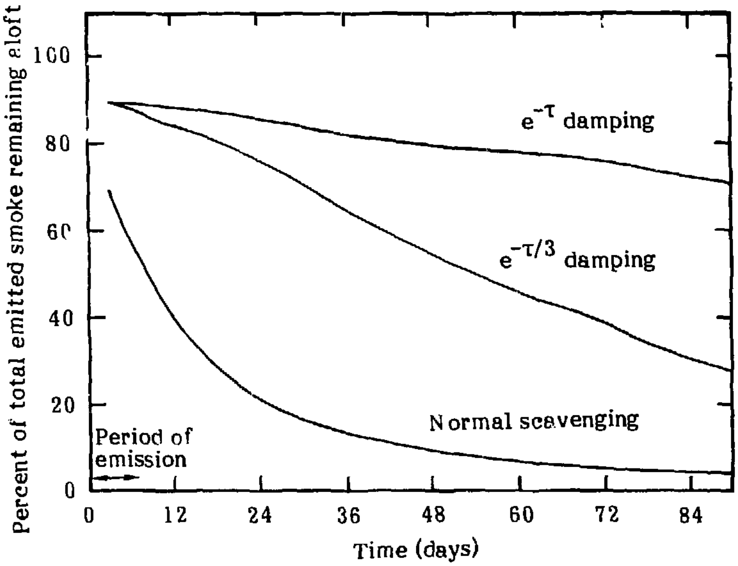

Fig. 9. Fraction of smoke aerosol remaining aloft as a function of time for the cases of normal and damped (two cases) wintertime scavenging rates.

aerosol when latitudinal spread is accounted for. It should be noted, however, that mid-continental temperature reductions and temperature changes under the smoke cloud, which only partly covers the hemisphere, could be substantially larger. Partial recovery of the temperature again occurs over the two to six week interval, with the longer lasting change due to the effects of the stratospheric perturbations.

For the case of damped scavenging, the maximum temperature reduction is only slightly larger than for normal scavenging (and much smaller than the -60° C given by the one-dimensional model for the mid-continental land surface type), but the reduction persists for much longer than is the case for normal scavenging, being still almost as large after three months as is the case for normal scavenging after ten days. Recovery from the maximum temperature reduction is slowed because there is time for the aerosol to spread more uniformly throughout the hemisphere, thereby exposing most of the particles to sunlight, and because the ocean temperature is slowly decreasing and therefore cannot as effectively buffer the land temperature changes.

We have examined the effect of the induced atmospheric stabilization on the precipitation rates predicted by the model for

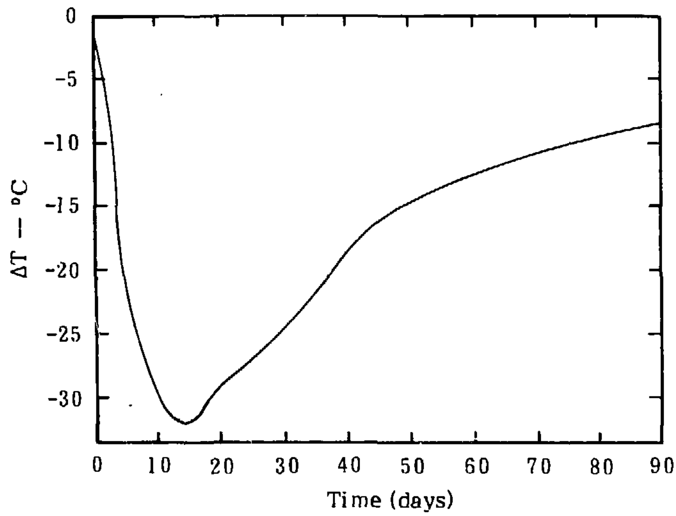

Fig. 10. Land surface air temperature change as a function of the time after the hypothetical nuclear exchange as calculated by one-dimensional radiative-convective model.

the simulation with damped precipitation scavenging. As shown in Figure 12, there is indeed a reduction in the precipitation rate in this case, reaching about 25% over the land and about 20% over the ocean. Although this is not as great as an $e^{-\tau/3}$ dependence would imply (hemispheric average τ at 60 days is about 3), another effect indicated in the model calculations may counterbalance this overestimate. Namely, the model indicates that the precipitation is more shallow in the perturbed case than in the control simulation, thereby reducing the effectiveness of the precipitation in scavenging the smoke. In addition, at the top of the smoke layer, the strong absorption of solar radiation induces a warming that would, if the process were being represented in our simulation, mix the aerosol higher in the atmosphere, thereby further reducing the scavenging effectiveness of the precipitation that does occur.

We have examined the latitudinal pattern of this precipitation change and have found that it is largely a result, at one month after the exchange, of a reduction in the intensity of the precipitation in the tropical convergence zone. This poses further concerns because it is the precipitation in this region that is expected to effectively prevent spread of the smoke to the Southern Hemisphere. This issue will deserve close attention in interactive simulations.

Table 2. Summary of Sensitivity Tests Using a One-Dimensional Radiative-Convective Model

Perturbations Included	Sensitivity Tested	Maximum Temperature Change (°C)	Time of Maximum Temperature Change (days)
Soot, dust, NO_2, O_3	Normal scavenging, land surface	−30	10–20
	Scavenging damped ($e^{-\tau/3}$), land surface	−60	30–60
	Scavenging damped ($e^{-\tau}$), land surface	−70	> 50
	Scavenging damped ($e^{-\tau/3}$), land surface no cloud cover	−80	30–70
	Scavenging damped ($e^{-\tau/3}$), ocean surface	−3	>50
Dust, NO_2, O_3 only	Scavenging damped ($e^{-\tau/3}$), land surface	−7	>60
NO_2, O_3 only	Scavenging damped ($e^{-\tau/3}$), land surface	−1	>60

SUMMARY

Our simulations indicate that significant climatic effects can be expected from the amounts of smoke that have been suggested will be generated from fires started by a major nuclear exchange involving urban and suburban areas adjacent to or surrounding potential military targets. We have not, however, separately evaluated the estimates of these smoke injections, but have instead used the results of other investigators to allow comparison of resulting climatic effects. Because the results are so sensitive to emission amount, research on this issue deserves attention.

We have found that there are several important sensitivities related to calculation of the climatic effects. Those of highest importance include treatment of the spread and height of injection of the smoke, scavenging rates of the soot and of land-ocean differences. The effects of changes in cloud cover are also important.

From these calculations, we can suggest that Northern

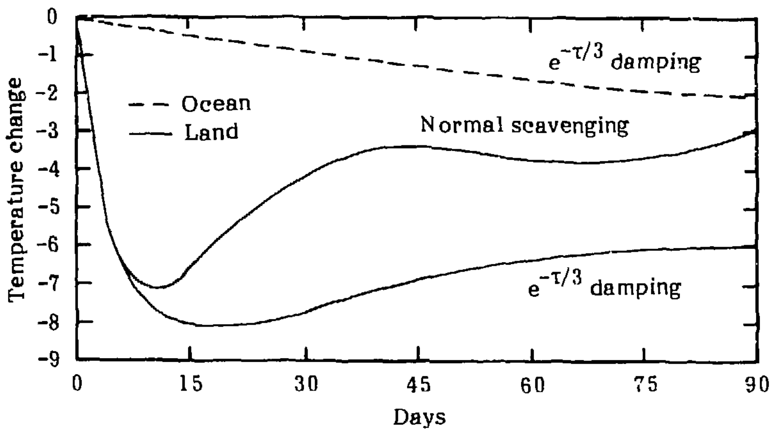

Fig. 11. Reduction in Northern Hemisphere land and ocean temperatures as a function of time following a nuclear exchange, assuming either normal or damped ($e^{-\tau/3}$) wintertime precipitation scavenging rates.

Hemisphere mid-latitude land temperatures will cool rapidly (days to a week) by 10-15° C following injection of the smoke, and that temperature changes will be smaller near the ocean and larger in mid-continental regions. Precipitation rates will decrease, especially in mid-continental regions. This precipitation decrease will occur even over the oceans, largely because of the atmospheric stabilization of the mid-troposphere that shuts off deep convection.

Absolute temperature reductions can be expected to be larger in summer than in winter, both because there is more solar radiation to be affected in summer and because particle lifetimes are longer in summer when mid-latitude precipitation rates are reduced. Note, however that temperatures in mid-continental regions in summer, where the cooling is expected to be largest, are substantially warmer than the hemispheric average temperature, so that the larger cooling starts from a higher base temperature.

Circulation and temperature changes will tend to lengthen smoke lifetimes and increase the vertical and latitudinal spread of the smoke. These effects appear to act to further prolong the perturbation.

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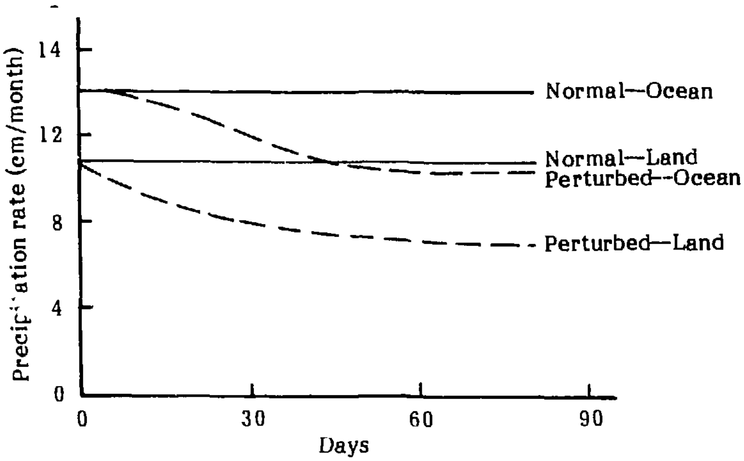

Fig. 12. Changes in Northern hemisphere average precipitation rates over land and ocean for the case of damped ($e^{-\tau/3}$) wintertime precipitation scavenging rates.

Lawrence Gates of Oregon State University has graciously allowed use of their GCM output to drive the GRANTOUR model. The radiative effects of the smoke have been implemented with the help of Robert Cess of the State University of New York at Stony Brook. Others at LLNL, including Fred Luther, Jerry Potter, Jim Ellis and Hugh Ellsaesser have helped with recent improvements and applications of the zonal climate model. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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