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# THE EFFECTS OF INTERACTIVE TRANSPORT AND SCAVENGING OF SMOKE ON THE CALCULATED TEMPERATURE CHANGE RESULTING FROM LARGE AMOUNTS OF SMOKE

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ABSTRACT

Several theoretical studies with numerical models have shown that substantial land-surface cooling can occur if very large amounts ($\sim 100 \times 10^{12} = 100$ Tg) of highly absorbing sooty-particles are injected high into the troposphere and spread instantaneously around the hemisphere (Turco et al., 1983; Covey et al. 1984; MacCracken, 1983). A preliminary step beyond these initial calculations has been made by interactively coupling the two-layer, three-dimensional Oregon State University general circulation model (GCM) to the three-dimensional GRANTOUR trace species model developed at the Lawrence Livermore National Laboratory. The GCM simulation includes treatment of tropospheric dynamics and thermodynamics and the effect of soot on solar radiation. The GRANTOUR simulation includes treatment of particle transport and scavenging by precipitation, although no satisfactory verification of the scavenging algorithm has yet been possible. We have considered the climatic effects of 150 Tg (i.e.. the 100 Mt urban war scenario from Turco et al., 1983) and of 15 Tg of smoke from urban fires over North America and Eurasia. Starting with a perpetual July atmospheric situation, calculation of the climatic effects as 150 Tg of smoke are spread slowly by the winds, rather than instantaneously dispersed as in previous calculations, leads to some regions of greater cooling under the denser parts of the smoke plumes and some regions of less severe cooling where smoke arrival is delayed. As for the previous calculations, mid-latitude decreases of land surface air temperature for the 150 Tg injection are greater than 15°C after a few weeks. For a 15 Tg injection, however, cooling of more than several degrees centigrade only occurs in limited regions under the dense smoke plumes present in the first few weeks after the injection.

## INTRODUCTION

There are several important requirements for the onset of "nuclear winter"; essentially all must occur. It is important to have a large injection of relatively highly absorbing smoke over a short period and to have the injection high in the troposphere. If the smoke is only injected in the lower atmosphere, the effect will be much less and the scavenging will be relatively rapid. If all of these conditions are met, a significant cooling (commonly called a "nuclear winter") could occur.

Many simplifications and limitations have been present in the models that have been used to date to calculate potential climatic effects. Cess et al. (1984) have mentioned assumptions concerning height and amount of injection, cloud feedback effects, the role of scattering and the diurnal cycle of radiation and there are several more that are important. One important assumption is certainly the failure to treat moving smoke, another is not coupling calculation of the scavenging of aerosols to the perturbed atmospheric conditions. Most previous calculations have also included poor treatment of solar radiation, as Cess et al. (1984) described. There has not yet been consideration of infrared effects by any of the multi-dimensional modeling groups, although it has not been demonstrated that this might be important. All models are treating early time phenomena and mesoscale effects very poorly. Thus, there is a lot to do to further improve the model representations of the physical effects of smoke on the atmosphere.

## MODEL DESCRIPTION

Our studies attempt to address a few of the identified shortcomings. We have done this by intercoupling two models. One is the Oregon State University (OSU) general circulation model (Gates and Schlesinger, 1977; Schlesinger and Gates, 1980), which Cess et al. (1984) have also been using. The second is called GRANTOUR, which is basically a transport and microphysics model for the smoke. Scavenging of the smoke is included, but microphysics, dry deposition, and homogeneous and heterogeneous coagulation are not yet included. Thus, we are moving the smoke with the wind and scavenging the smoke with the calculated precipitation. The smoke concentration is then used to perturb the solar radiation in the climate model. We start with smoke in particular locations and a particular day's meteorology and then calculate smoke movement and atmospheric perturbations for a month. This calculation, it should be remembered, is simply one preliminary test case; much remains to be done.

While we are treating some processes not previously treated, there are still many limitations. Development of more accurate scavenging algorithms is probably the most important problem in conducting these global scale simulations. The models do calculate the precipitation fields approximately correctly, but it is not easy to relate water removal to smoke removal. The height distribution of rainfall, for example, is not yet adequately treated in our calculation. The major difficulty in calculating the scavenging of the aerosol, however is that there is not any good case to compare against, at least on a global scale. The only global scale particulate pollutants that have been measured are radionuclides from past nuclear tests, but their removal rate and concentration in the atmosphere are basically controlled by the rate of transport from the stratosphere to the troposphere and not by the scavenging rate; that isn't the case for the smoke. In our model we attempt to relate the scavenging rate to the lifetime of water vapor; that is not necessarily a very good way to represent this process, but it is the only approach that can now be easily implemented. Another assumption that we make is that aerosol properties are constant in time, an assumption that may overestimate optical depth up to about 50% over the first 30 days, based on calculations reported by Penner (1984).

As reported by Cess et al. (1984), the version of the OSU/GCM that we are using makes several assumptions. The model divides the troposphere into two layers and does not treat the stratosphere. The version we are using prescribes sea surface temperatures and solar declination angle at their July values. This perpetual July simulation gives conditions somewhat warmer over land than observed for July (as might be expected if July conditions persisted in the real world).* This extended period with July solar radiation does tend to dry out the continents, which results in less precipitation over the continents than would occur in a normal July.

The GRANTOUR model was described briefly in the paper here last year (MacCracken, 1983). At that time, GRANTOUR was a two-dimensional model (Walton and MacCracken, 1984); that is, it just moved parcels around on trajectories vertically-averaged through the troposphere. Since last year, the model has been converted into a three-dimensional version that divides the troposphere into about 10,000 equal volume parcels that are then moved by the winds being calculated by the general circulation model. These parcels are moved by the three-dimensional wind field and experience precipitation if that is occurring at the nearest grid cell in the general circulation model. These parcels are, however, very large; our resolution is not adequate to treat scales less than hundreds of kilometers. We treat two classes of smoke particle, one having a diameter less than one micron and one larger than one micron. The two particle size ranges are scavenged at different rates by the precipitation, with the larger particles being scavenged at a rate about four times as high as the smaller particles. Coagulation (e.g., transfer of mass from one size bin to the other) and dry deposition are not yet being treated. The two particle sizes also contribute separately to the total optical depth, with the smaller particles having an extinction cross section of 6.7 $m^2/g$ and the larger particles having an extinction cross section of 2.6 $m^2/g$. These specific extinction coefficients, which are appropriate for the Turco et al. (1983) size distribution for urban smoke, are held constant in time.

## MODEL SIMULATIONS

The control simulation is for a perpetual July situation, as described by Cess et al. (1984). We have carried out four smoke simulations, two with smoke being moved by the winds and scavenged by the calculated precipitation (referred to as interactive calculations) and two simulations with the smoke spread uniformly around the hemisphere and held fixed in time and space (referred to as "uniform-smoke" calculations). The two uniform-smoke calculations have been done in order to help isolate the effect of treating the movement of smoke. The primary interactive smoke calculation postulates an injection of 150 Tg of smoke, which is equivalent to the urban fire emissions injected by Turco et al. (1983) in both their 100 Mt urban war scenario and the urban component of their 5000 Mt baseline simulation, which also included 75 Tg of forest fire smoke. We omitted the forest fire contribution because forest fire aerosol tends to be less absorbing than urban smoke and

* Note added in proof: We have also found a few small errors in the new solar radiation calculation that caused an underestimation of atmospheric absorption and allowed too much solar energy to reach the surface. Correcting these errors leads to a slightly cooler control case, but does not significantly affect the perturbation results reported in this paper.

to be injected at lower altitudes; such smoke should therefore have a more limited climatic effect than urban smoke. The second interactive calculation assumes an injection of 15 Tg of urban smoke. The smoke is injected assuming an equal mixing ratio of smoke from the surface to 11 km. This leads to 50% of the smoke being injected above the middle of the troposphere (600 mb), which is about equivalent to Turco et al. (1983), who assume equal density injection from 1 to only 7 km (about 47% above 600 mb, excluding their assumed stratospheric contribution from firestorms).

The primary uniform-smoke calculation has been described by Cess et al. (1984). This case assumes an extinction optical depth of three from 3–90°, linearly decreasing to zero at 2°N, for a Northern Hemisphere average optical depth of 2.4; this value is about equal to the average optical depth over the first 30 days for our 150 Tg interactive case. The second uniform-smoke case reduces the first case by a factor of 10. We have also studied two additional cases to better determine the effect of interactive transport of the smoke on the spreading rate of the smoke. In the first of these cases we transport the smoke with the winds and scavenge the smoke with the precipitation from the control simulation, and in the second case we use the winds and precipitation from the uniform-smoke simulation having average optical depth of 2.4.

To date, we have been focusing on analysis of only certain aspects of the simulations. Our focus has been primarily on the pattern of smoke spreading, the removal rate, and the resulting changes in surface temperature. We have not yet looked at changes in circulation, cloud amount, precipitation or other climatic variables.

## SMOKE CIRCULATION

Figure 1a shows the smoke distribution after day one for the interactive baseline case of 150 Tg injection. Smoke was initially injected equally in four regions centered over the western and eastern U.S., Europe, and western Asia. Note that this distribution of injected smoke does not represent any real scenario but simply the places where major smoke emissions may occur. After only one day of smoke spread, the maximum optical depths are very large. Because wind speeds are relatively low in this July case, early time optical depths over Europe and Asia are as large as 50. Over North America there has been somewhat more dispersion, but the optical depth still reaches values of about 20. Just as for the urban smoke case in the Turco et al. (1983) calculations, the hemispheric average optical depth is about three; however, in our calculation the patchy nature of the smoke is quite evident.

By day five in this particular simulation, easterlies have carried smoke emitted over the United States southwest and toward the equator. Smoke from eastern North America was also carried across the Atlantic, and Eurasian smoke was swept eastward toward the Pacific. The hemispheric average optical depth does not decrease much over the first five days, but the maximum optical depth has dropped to less than 20.

By day 10, the smoke has spread out over a much larger area (see Figure 1b). There is still some patchiness. We believe that the model may actually be underestimating the patchiness because of how we now are calculating the scavenging. The grid size in the GCM is 4 by 5°. When there is rain in a grid cell, the model assumes that it rains over the entire grid. That is not how this process actually occurs; rain tends to occur in relatively

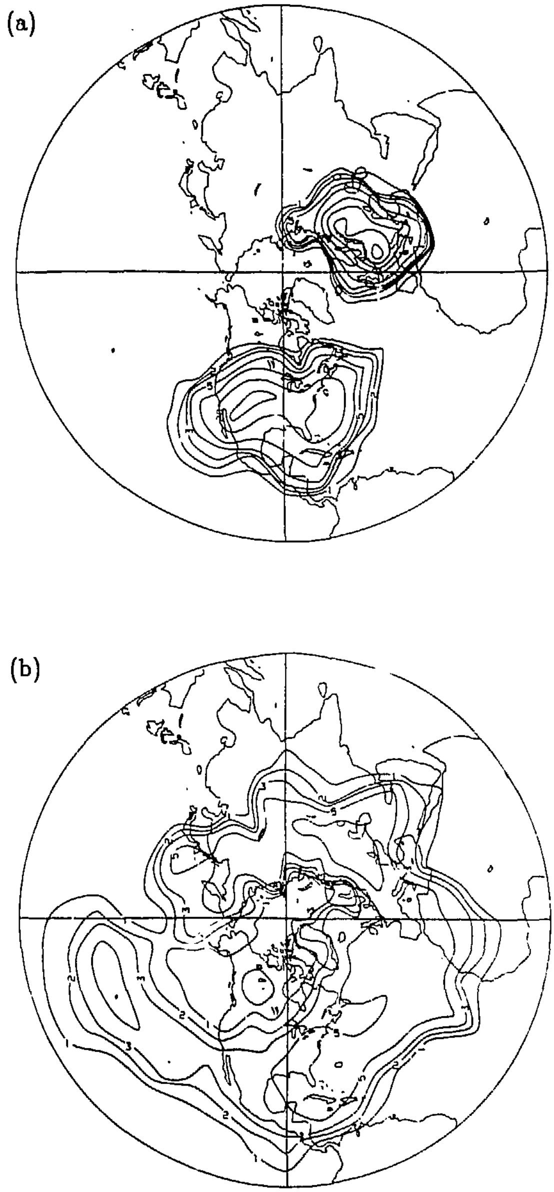


FIGURE 1. Contours of optical depth after injection of 150 Tg divided equally among sources in eastern and western North America, Europe, and western Asia. (a) Day 1 and (b) Day 10.

small regions of relatively high rain rates instead of over larger regions with relatively low rain rates. Thus, as our parcels move around, they are experiencing a relatively low rainfall rate over a large area rather than an intense rainfall rate over a small area. One of the improvements we want to make is to have some of the parcels experience more intense rain and others experience no rain. This should lead to more patchiness than our model calculations now exhibit.

By day 20, the smoke has spread nearly uniformly over the hemisphere, except in low latitudes. There are still a few regions where optical depth reaches ten, but most of the hemisphere is covered by smoke with an optical depth of two, which is approximately the average for the Northern Hemisphere. By day 20 smoke has also started to spread to the equatorial and sub-tropical latitudes of the Southern Hemisphere.

Figure 2 presents these results in terms of dot plots with each of the dots representing an equal mass of smoke aerosol spread over a volume of about 600,000 $km^3$. The plot is broken up to show concentrations in three different layers in the atmosphere: the lowest 3 km, the layer from 3 to 6 km, and the tropospheric layer above 6 km. Smoke is injected with equal mixing ratio in height, or about equally, in terms of mass, in each of the three layers. By day 5, the winds have sheared the smoke in many directions (Figure 2a). The dot plot shows only the regions with the highest smoke concentration; therefore, there is some spreading beyond what is shown into regions with lower smoke concentrations. The figure also shows more rapid spreading at high altitudes than at low altitudes.

By day 10, further spreading has occurred at all levels; gaps in the smoke field result from a stretching of the smoke, leaving lower concentrations because of the wind shear. By day 30, the higher concentration of smoke particles occurs in the upper layer (see Figure 2b). In the lower layer, concentrations are reduced because of the rising of the warmed air, more rapid dispersion and scavenging by precipitation.

Figure 3 shows the dot plots from another view—looking west from the dateline (180° longitude) at 20° latitude (approximately Hawaii). The continents, particularly Asia, Africa, and South America are shown on the bottom of the figure. These plots show only the large particles and each dot represents about 5 kt of mass. The sequence of plots from day 5 to day 30 shows an upward and southward movement of the smoke, with scavenging and dispersion lowering smoke concentrations in the lower troposphere. Remember that the large particles are removed about four times as rapidly as the smaller particles.

By taking a zonal average of the smoke mixing ratio, we can compare the extent of transfer of smoke for various wind and precipitation fields. If we use the winds and precipitation as simulated by the control simulation (that is, if we use winds generated by the model with no smoke), there is virtually no transport of smoke to the Southern Hemisphere during the 30 day simulation; most of the smoke has moved toward the pole and spread out in the Northern Hemisphere. Using winds and precipitation from the case with uniform-smoke, ($\tau = 2.4$), which is similar to the situation modeled by NCAR (Covey et al., 1984) and Aleksandrov and Stenchikov (1983), we get modest transport of smoke to the Southern Hemisphere as a result of the perturbed wind fields; there is, however, less poleward transport from the Northern Hemisphere mid-latitudes. For the case with interactive smoke, even more transport to the Southern Hemisphere is induced.

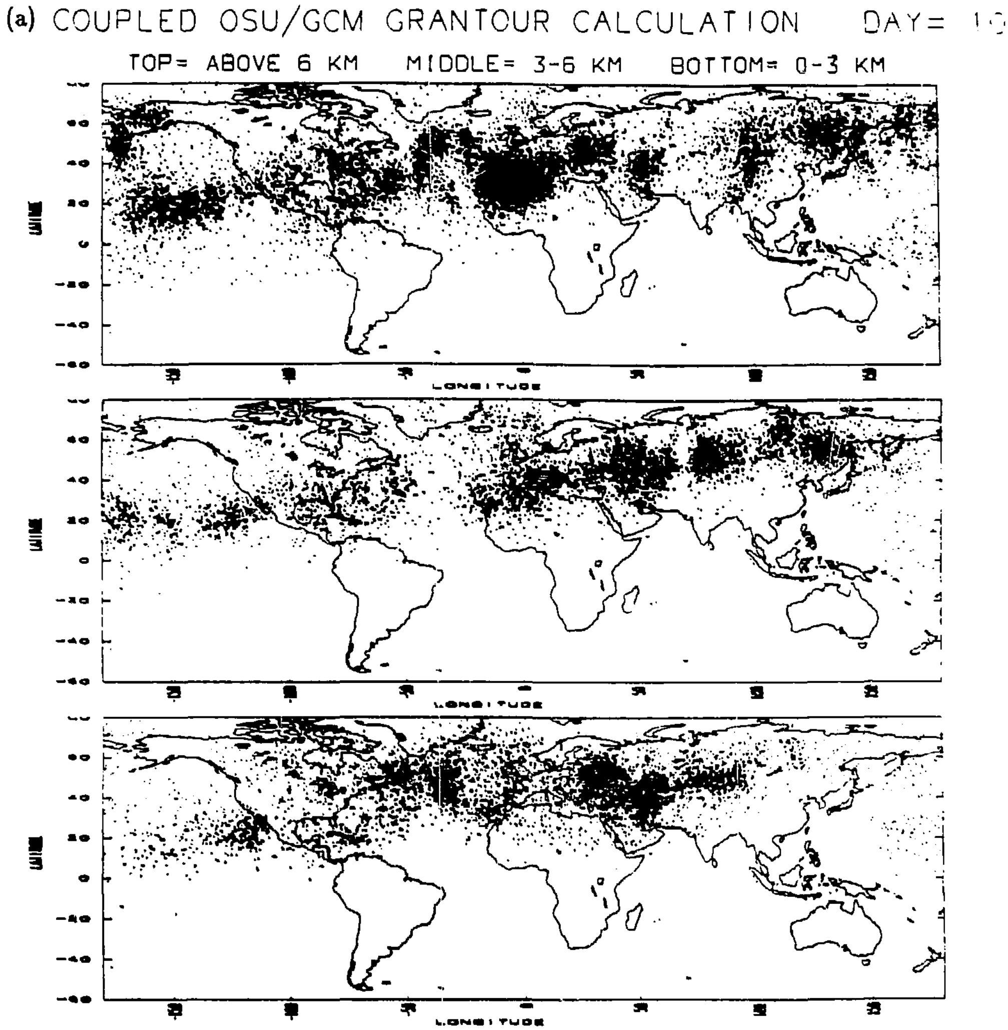
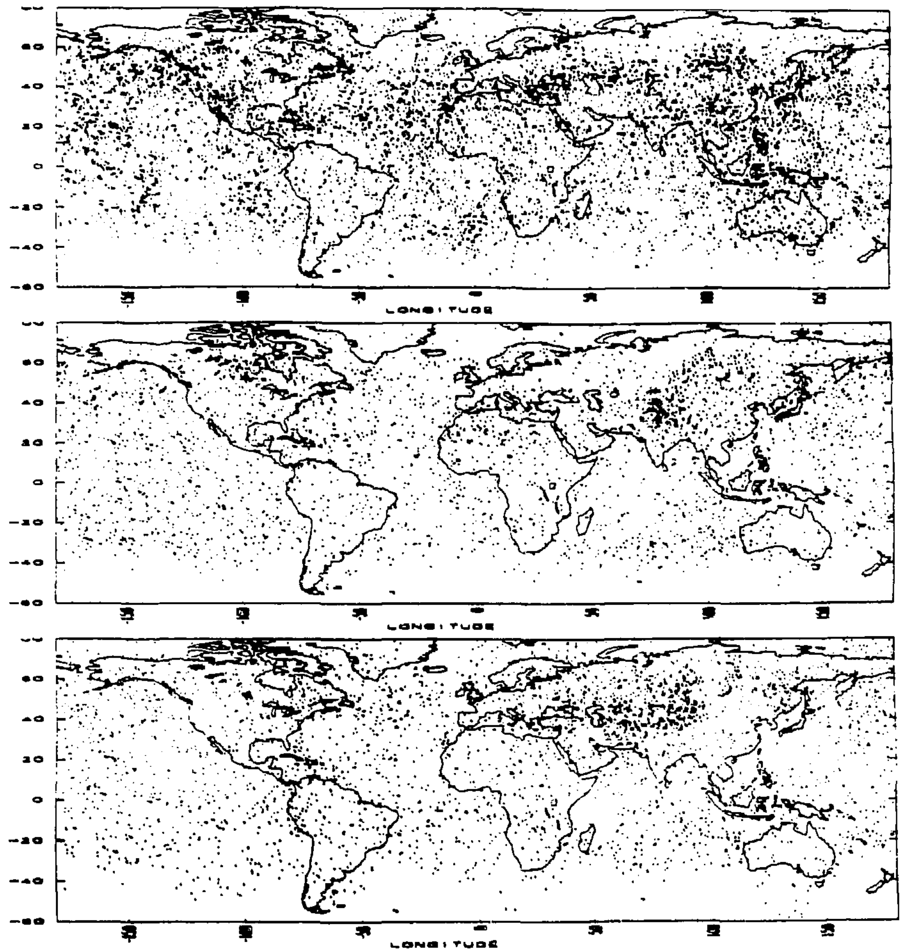



FIGURE 2. Dot plots proportional to concentration of smoke particles in three atmospheric layers. (a) Day 10 and (b) Day 30.

Figure 2 cont'd.

(b) COUPLED OSU/GCM GRANTOUR CALCULATION DAY= 30

TOP= ABOVE 6 KM MIDDLE= 3-6 KM BOTTOM= 0-3 KM



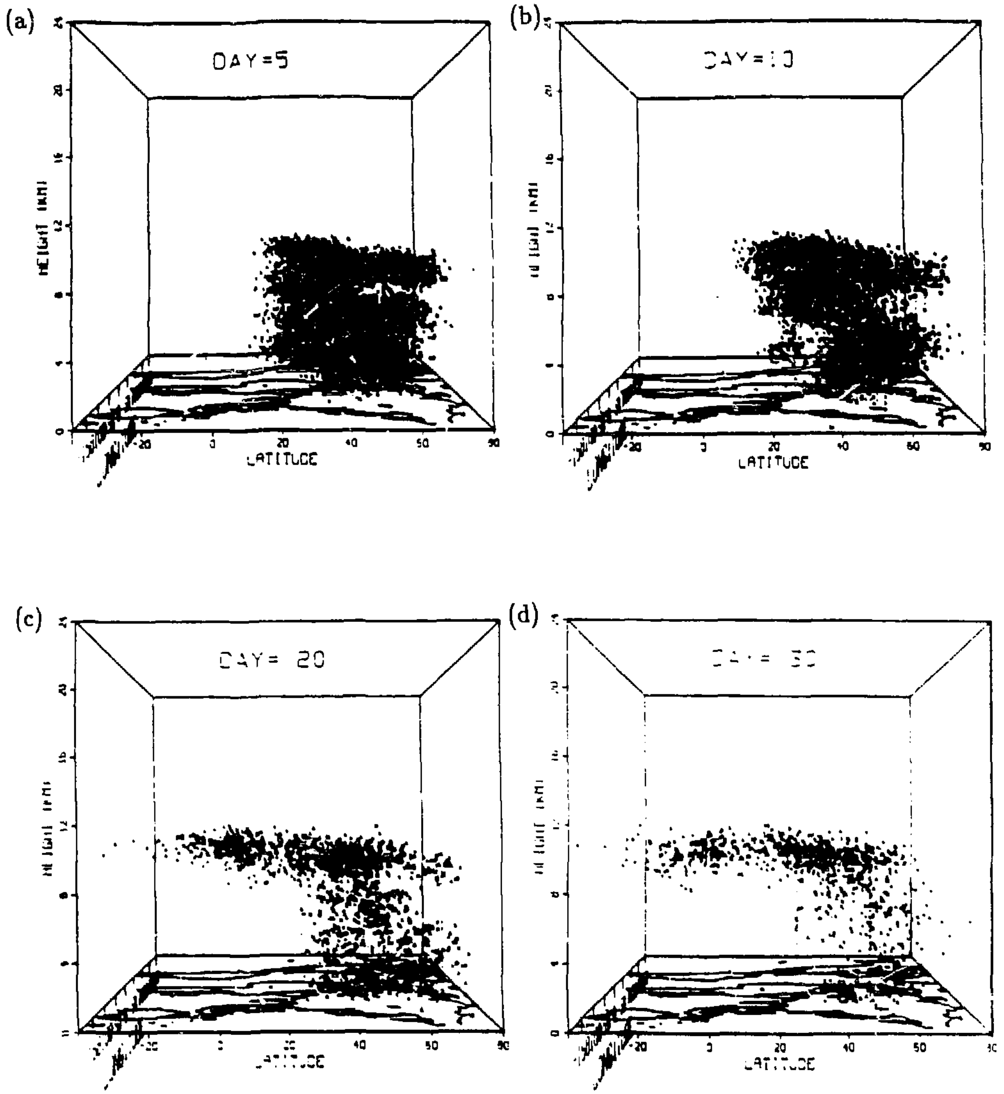



FIGURE 3. Dot plots proportional to concentration of smoke particles with diameters >1 μm as viewed from the dateline looking west. (a) Day 5; (b) Day 10; (c) Day 20; (d) Day 30.

We have also looked at the wet removal rate of smoke from the atmosphere. The wet removal rates used by Turco et al. (1983) were drawn from estimates for the removal rate of elemental carbon in the present atmosphere (Ogren and Charlson, 1983). The smoke removal rate in this calculation is based on the GCM precipitation rates and is somewhat slower than used by Turco et al. (1983), even for the unperturbed atmosphere; this may be in part because we are considering a July injection in mid-latitudes rather than an injection pattern similar to that for elemental carbon. For example, the average removal rate for summer, which we are calculating, is probably slower than for winter. Part of the difference between our results and those of Turco et al. (1983) may also arise since the GCM simulation produces too little rainfall in summer because the average temperature is too warm; thus, there is not as much precipitation as observations suggest would normally occur on an annual average basis, which is what Turco et al. (1983) assumed. When we used winds and precipitation from the uniform-smoke case to calculate the scavenging rate, it decreased substantially, because, we believe, of the strong stabilization of the upper troposphere with respect to the lower. For winds and precipitation from the interactive case, the removal rate is reduced, but not as substantially as in the case where scavenging is based on data fields from the uniform-smoke case. We are still studying the causes of these variations.

## TEMPERATURE RESPONSE

The temperature response for the case of uniform-smoke is shown in Figure 4, which is essentially the same perturbation considered by Cess et al. (1984). Figure 4a shows the average surface air temperature change for days 1 to 10. Temperature drops of 10–15°C occur over the continents during this period. By days 21 to 30 (Figure 4b), the temperature drop from this uniform-smoke case has reached 20 to 30°C over the continents. The relatively large temperature changes over the continents extend to the southern boundary of the smoke. These results are in agreement with what previous studies by other research groups have shown. Because this OSU/GCM simulation for July is relatively warm compared to the NCAR simulation, temperatures do not drop below freezing as predicted by the NCAR model results.

For the simulation with interactive smoke, the pattern of temperature change is somewhat different, as shown in Figure 5. For days 1 to 10, the average temperature drop is sharper than for the case with fixed smoke (Figure 5a). Over mid-continent Asia, temperature drops reach more than 20°C on land surfaces beneath dense smoke. Where there was no smoke during this period, which in this case included China and southern Asia, temperature changes were not significant compared to normal synoptic variations. Thus, patchy smoke makes the situation worse under the smoke, but much less severe in the absence of smoke. For the 11 to 20 day average (Figure 5b), the temperature dropped as much as 35°C over Asia. The temperature change over North America, however, was much less, since much of the smoke moved off the continent and was replaced by clean Pacific air. Where the smoke is, in this case, determines where the temperature changes occur. In addition, North America is a smaller continent, so oceanic buffering of the temperature drop is more pervasive. In the 21 to 30 day period, temperature changes are starting to occur in the Southern Hemisphere. These are not "quick freezes" as suggested by Covey et al. (1984), but there is a cooling occurring in low latitudes.

Figure 6 compares the temperature change for the interactive and uniform-smoke simulations. The case with interactive smoke indeed causes greater temperature change than uniform-smoke under the smoke, and less change elsewhere. This is especially true at early time. After a few weeks the smoke has spread to almost uniformly cover the hemisphere and there is, in the Northern Hemisphere, relatively little difference between the interactive and uniform-smoke cases. For the Southern Hemisphere, however, it requires a few

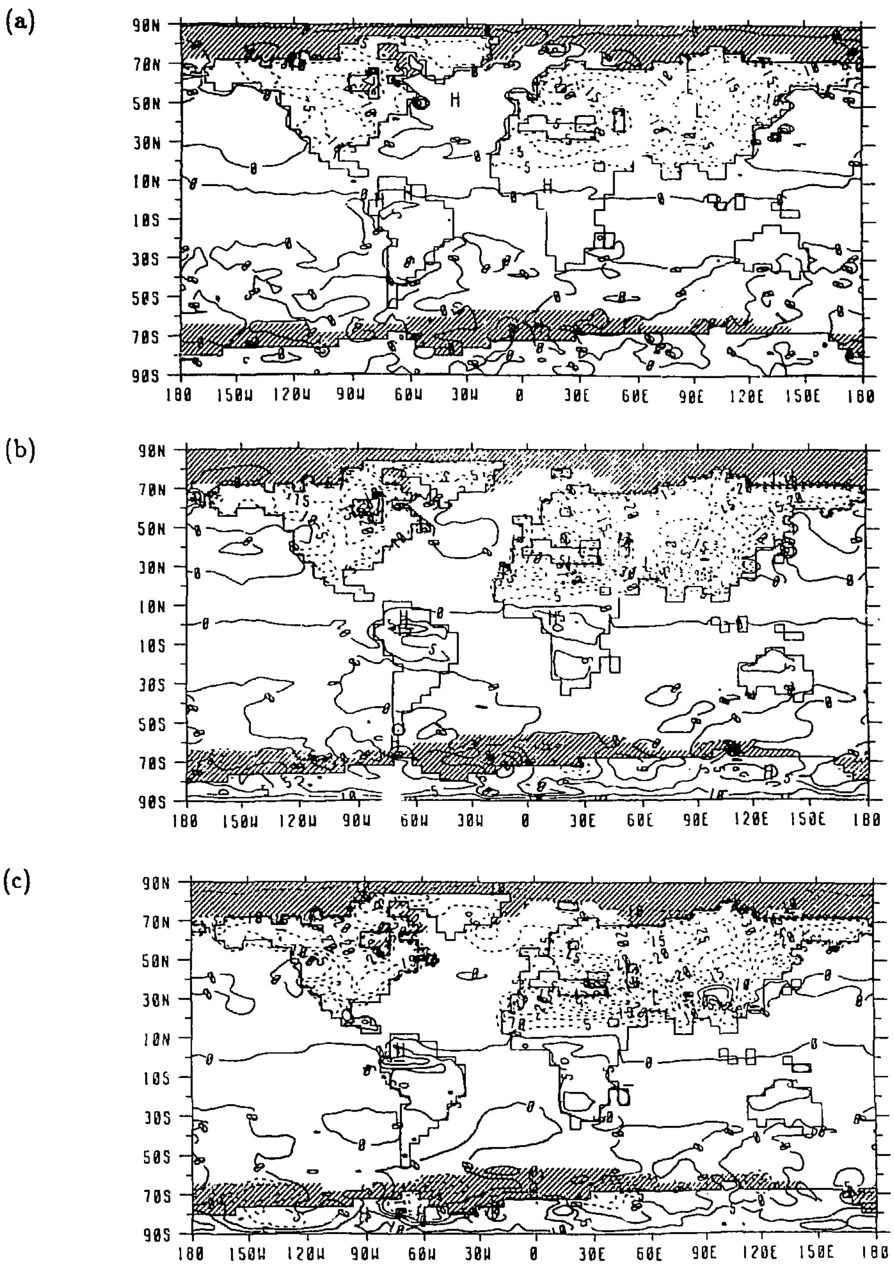



**FIGURE 4.** Average surface temperature change for the case of fixed smoke uniformly spread around the Northern Hemisphere (average extinction optical depth of 2.4). (a) Days 1–10; (b) Days 11–20; (c) Days 21–30.

(a)

(b)

(c)

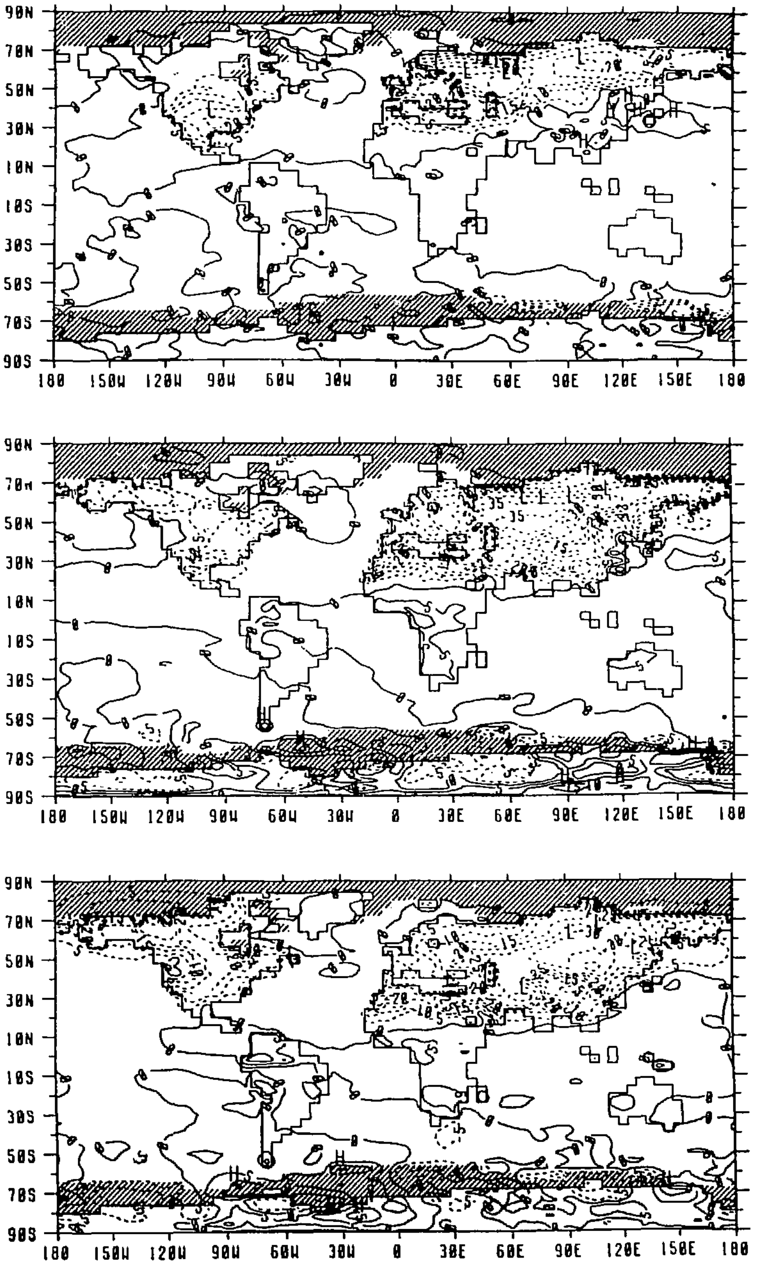



**FIGURE 5. Average surface temperature change for the case of 150 Tg injection from four source regions and being interactively transported and scavenged by the climate model. (a) Days 1–10; (b) Days 11–20; (c) Days 21–30.**

weeks before the moving smoke can start to directly induce temperature changes (indirect changes can be induced more rapidly via smoke-induced changes in the circulation patterns).

The average land-surface temperature changes for the uniform-smoke case as a function of latitude are shown in Figure 7. Most of the temperature drop has occurred during the first 10 days. By the last 10 days of this 30 day run, the situation has not changed significantly, with temperature decreases of 10 to 15°C, which are comparable to what other groups have been calculating. The modest warming in the subtropics of the Southern Hemisphere is apparently due to increased subsidence in this region that is apparently induced by the smoke-warmed air in the Northern Hemisphere moving southward, as suggested by Aleksandrov and Stenchikov (1983).

With interactive smoke, a similar temperature drop occurs over mid-latitudes in the Northern Hemisphere, even though there are some regions that are relatively unaffected and some that are very cold (Figure 8). The total temperature drop over 30 days is, however, ultimately only a little bit greater than for the uniform-smoke calculation. The rather large perturbation over the very limited land area at about 50°S is believed to result from changes in winter storm tracks and cirrus cloud cover unrelated to the smoke, although this deserves further consideration.

We have also made calculations with 10% of the smoke and optical depth shown in our two baseline calculations. For uniform-smoke with hemispheric average optical depth of 0.24, there are virtually no significant temperature changes; there may even be a little warming due to a slightly reduced planetary albedo. With an injection of 15 Tg of smoke equally divided over our four source regions, there are some regions with dense patches of smoke at early time. Under these smoke patches, cooling of up to 10°C does occur, but the temperature drops are not as large, of course, as for the 150 Tg smoke injection. In addition, these temperature drops only occur, at early time before the smoke becomes *extensively spread out.*

Finally, Figure 9 shows the model-calculated temperature changes at a few grid points for the 150 Tg injection. These results are shown only to provide an indication of what such changes might look like—not as a projection. These Numerical results should be viewed only in terms of their general features, not as quantitative estimates. Figure 9a shows the time history of a grid point for the central U.S., and may be representative of a dry agricultural area in summer. The solid line shows temperature variations in the control simulation; note that the normal diurnal cycle exhibits a relatively large temperature variation. The temperature is also not simply constant; there are cool periods and warm periods as different synoptic disturbances pass through; thus the normal course of weather is exhibiting noticeable fluctuations. For the uniform-smoke case with optical depth three at this latitude, there is still some light getting through to the surface as a result of scattering by the smoke particles. With this smoke amount, temperatures decrease, but continue to show a diurnal cycle, although the daily variation is not quite as large as it was without the smoke. Note that the resulting temperatures are not substantially cooler than cool periods in the control simulation; maximum daily temperatures with smoke are not much cooler than the minimum temperatures without smoke.

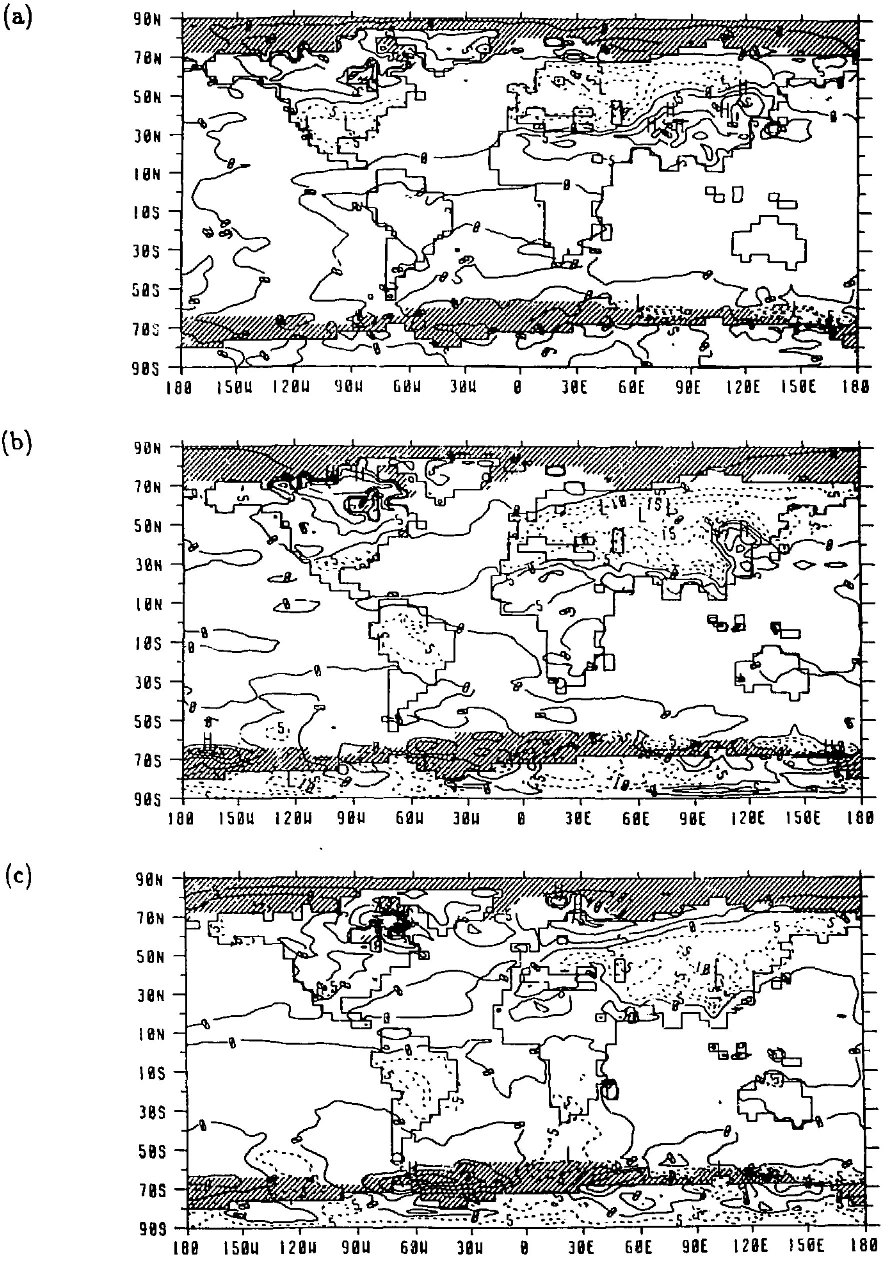



**FIGURE 6. Difference in average temperature change between the cases of interactive and fixed smoke uniformly spread around the Northern Hemisphere. (a) Days 1–10; (b) Days 11–20; (c) Days 21–30.**

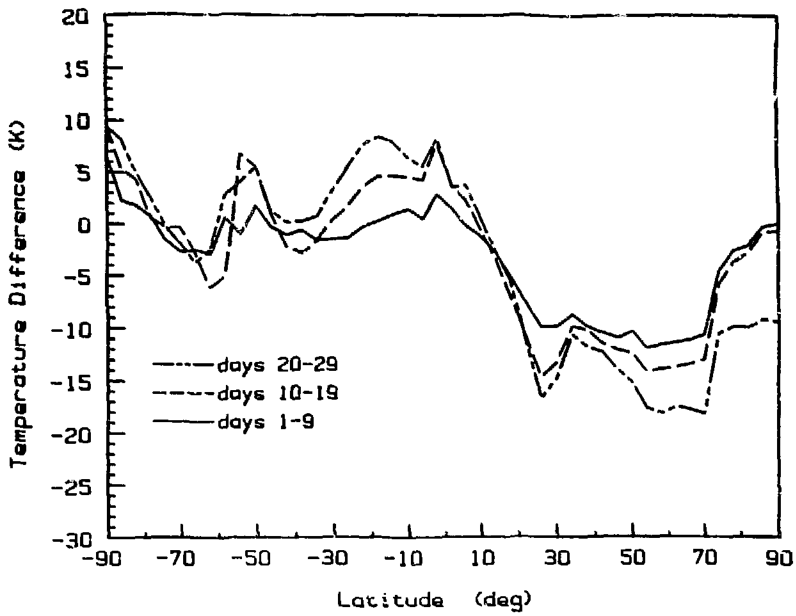



FIGURE 7. Ten-day average surface temperature change over land as a function of latitude for the case of fixed, uniformly spread smoke for days 1–9, 10–19, and 20–29.

For the simulation with moving smoke, the results, in this simulation, are quite different. There is initially a relatively rapid decrease in temperature and the diurnal cycle disappears; the smoke is so thick that virtually no sunlight reaches the surface. Following this sharp cooling, temperatures at this grid point recover to levels very near the control case. This occurs because clean Pacific air has replaced the initial smoky air mass. Later in the simulation, as the smoke dispersed and again moved over the U.S., temperatures decreased again and, after 30 days, average temperatures were similar in the two simulations. The reduction of the diurnal variation at late time and the general cooling are apparently the result of a return of cloudiness to the region (at early time cloudiness dropped due to upper layer heating and subsidence induced by lower layer divergence).

Figure 9b shows similar data for a west coast station in North America. In this case, due to the proximity of the ocean, temperature changes are relatively small, even showing warming at a few times, perhaps due to local circulation perturbations. In the interactive simulation, not much change occurred during the first 20 days, and then smoke apparently appeared and the temperature decreased. Figure 9c shows similar data for a mid-continental grid point in western Asia. Because Asia is a very large continent, temperature changes are similar in pattern to North America, but even more severe. For the case of uniform-smoke, there is a relatively gradual, but steady temperature decrease to values about 20–25°C below the control case temperature. The persistence of the diurnal cycle, even in the presence of uniform smoke, occurs for several reasons. With a

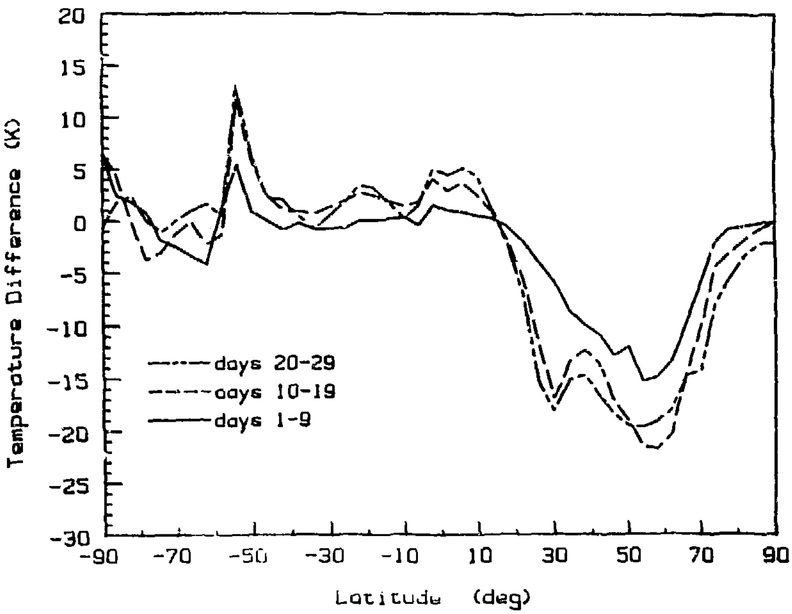



FIGURE 8. Ten-day average surface temperature change over land as a function of latitude for the case of 150 Tg injection of smoke from four source regions for days 1–9, 10–19, and 20–29.

temperature inversion, latent and sensible heat loss from the surface is reduced; this heat is then available to drive the diurnal cycle of surface temperature, which, in the presence of an inversion, strongly influences surface air temperature in this model. Second, temperatures are colder, so that a larger diurnal range is needed to cause a comparable flux change in upward IR emission. Third, the presence of the smoke reduces cloudiness (by heating the upper layer, but causing subsidence to make up for lower layer divergence), thereby helping counter the influence of the smoke on the downward solar radiation at the surface.

For the dense smoke in the interactive simulation, however, there is a very sharp temperature drop that persists until the smoke has spread more evenly over the hemisphere. Note also that the diurnal temperature cycle completely disappears during the first two weeks, indicating virtually no sunlight is reaching the surface. Because the control case temperature for this grid point is about 35–40°C, which is somewhat warmer than the observed average summer temperature, temperatures only decrease to just below freezing. We do not believe, however, that summer temperatures can get much colder (e.g., as cold as Turco et al. suggest), because summer solar radiation is larger than the annual average radiation amount used in the Turco et al. study. The late time reduction (beyond 26 days) in diurnal range and general cooling apparently results from the return of cloudiness, as was the case over the middle of North America. Figure 9d shows a grid point in the Mediterranean. Because of ocean buffering, relatively little temperature decrease occurs

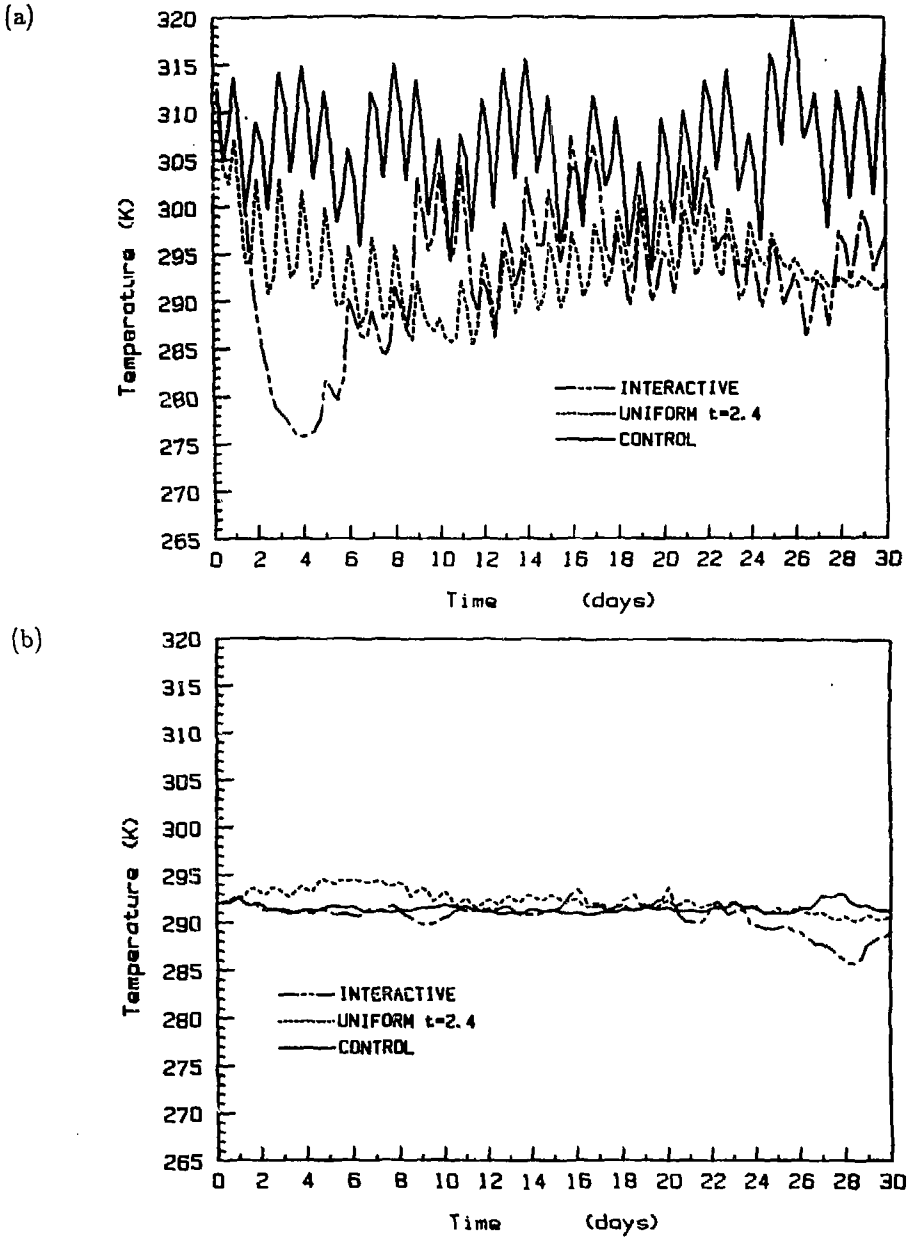
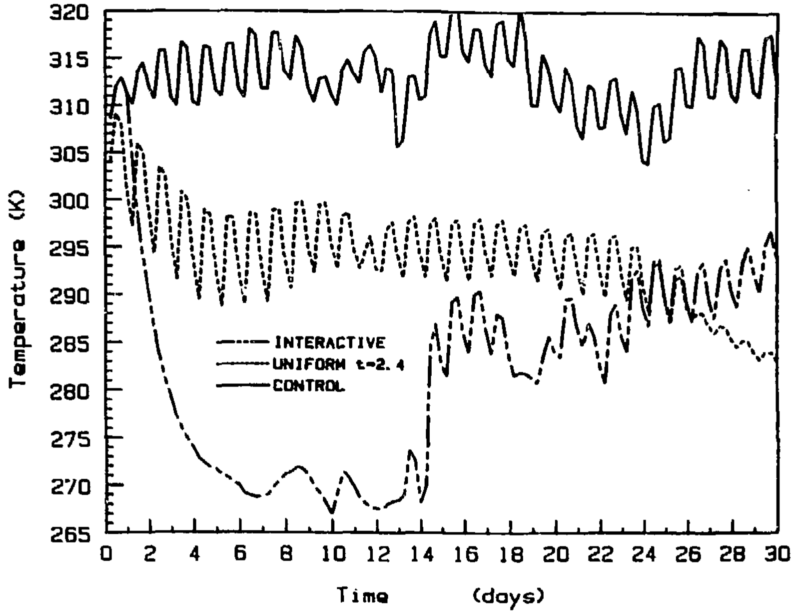


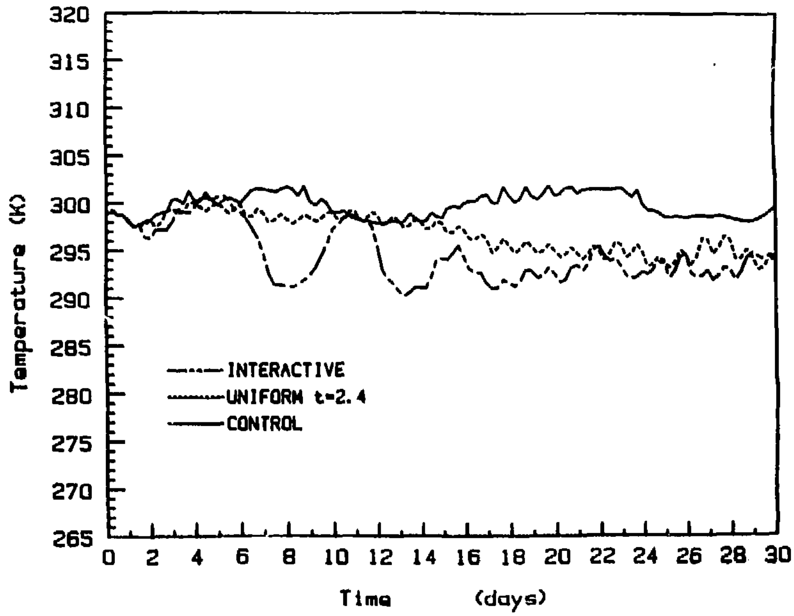

FIGURE 9. Thirty day temperature record at various grid points for the control (solid line), fixed uniformly-spread smoke with an average optical depth of 2.4 (dashed line), and 150 Tg interactive smoke simulations (dot-dashed line). (a) Midwestern U.S.; (b) West coast U.S.; (c) Western continental Asia; (d) Mediterranean.

Figure 9 cont'd.

(c)




(d)



with the uniform-smoke case. With the interactive smoke, however, there are again cooling pulses, although the temperatures do not approach freezing.

Evaluating the biological effects of this pulsing situation will probably be much more difficult than for Ehrlich et al. (1983), who had only to estimate what would occur if temperatures everywhere dropped to 20° below zero. At a biology-ecology workshop in June 1984 at Stanford University (Kercher, Mooney et al., 1984), there was concern that having the variations in cooling that we are calculating could potentially have more severe biological and ecological effects than a sustained, uniform drop in temperature followed by an uninterrupted recovery. The reasons for this concern are that many plants, at least temperate-zone plants, may be able to recover after a single or even double loss of leaves, but cannot do so indefinitely because of depletion of their food reserves. If, however, they were exposed to continuous cold, they might be able to retain the capability to resprout once the temperature had recovered. Thus, the notion that there may be a situation less than a deep freeze and that temperature changes may be quite variable does not make the situation necessarily any easier to evaluate, nor potentially less serious.

## SUMMARY

The results of these simulations indicate, as the earlier calculations have done, that high altitude injection of very large amounts of highly-absorbing smoke, whether treated as patches or as uniformly spread, can lead to significant cooling over land, although not necessarily to summer temperatures much below freezing. The patchiness of the smoke does indeed make some areas colder and other areas warmer than for uniformly spread smoke. Because these areas of temperature change may move with the smoke, shorter duration, but greater, decreases in temperature than with uniformly dispersed smoke may occur over some large mid-latitude land areas. There also is some evidence in the interactive simulation for a slowing of the scavenging processes and some potential acceleration of transport of the smoke to the Southern Hemisphere. While the absolute temperature changes predicted by the available models must be treated with caution, there is as yet no indication that the problem will become significantly less serious as model simulations become more complete, unless the amount of smoke injected is reduced by factors of a few or more.

## ACKNOWLEDGEMENTS

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