# Global atmospheric effects of massive smoke injections from a nuclear war: results from general circulation model simulations

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*We report three-dimensional calculations of regional and global climatic effects of smoke generated by a large-scale nuclear war. Tropospheric aerosols of absorption optical depth 3, when injected into Northern Hemisphere mid-latitudes and maintained for 1–3 weeks, cause intense radiative heating of the mid-troposphere with substantial surface cooling over land. Mid-latitude surface temperatures in continental interiors can drop well below freezing in a matter of days regardless of season. Our results, although based on several assumptions, suggest that circulation changes caused by aerosol-induced atmospheric radiative heating could spread the aerosols well beyond the altitude and latitude zones in which the smoke was initially generated.*

LARGE fires have long been recognized as a possible consequence of a nuclear exchange[1] but with few exceptions (for example, see ref. 2) their regional and global scale environmental consequences have been ignored until recently. Crutzen and Birks[3] have pointed out, via a simple order-of-magnitude estimate, that fires ignited by a full-scale nuclear war could easily produce enough smoke to block out sunlight (that is, produce optical depths of order unity) over much of the Northern Hemisphere for a period of weeks or longer. Subsequent studies[4–7] confirm the magnitude of the problem and thus raise, for the first time, the possibility that global atmospheric consequences of nuclear war could be significant even when compared with the obviously devastating nature of the direct effects (blast, heat, short-term fallout)[8]. In this study we investigate, by using a three-dimensional general circulation model (GCM), the atmospheric consequences over a few weeks of smoke generated by a nuclear war—that is, perturbations in atmospheric and surface temperatures, winds, etc.

Turco *et al.*[4,5] studied the climatic implications with a one-dimensional annually averaged radiative–convective model (RCM) which averages all horizontal variations and considers quantities such as temperature and aerosols to be functions only of altitude (see ref. 9). When the heat capacity of the surface was set equal to a small value characteristic of a layer of soil, smoke aerosol injection scenarios resulted in a substantial decline in surface temperature (characteristically ~30 °C within 30 days, or enough to lower the global mean annual temperature well below the freezing point). At the same time the middle troposphere warms; both events are caused by the absorption of sunlight by mid-tropospheric smoke. But when Turco *et al.* used a surface heat capacity representative of an ocean mixed layer, only small temperature changes resulted (2–3 °C after 6 months). Of course, in the real atmosphere under the impact of the aerosol loading, land areas would be expected to cool much more substantially than the oceans, and those areas of the globe not covered by smoke would suffer a much smaller temperature perturbation (though precipitation or other weather elements could still be substantially perturbed). Turco *et al.*[4] extrapolated the results of others' simple climate models to estimate that ocean-to-land heat transport would reduce the land surface temperature drop by ~20% in the middle of continents and by 40% near the coasts. However, they also pointed out that the same winds that would ameliorate the surface freezing could—when enhanced by aerosol-induced temperature contrasts—spread the aerosols well beyond their original latitudes of injection, perhaps all the way into the Southern Hemisphere.

The conclusions of Turco *et al.* have been extended by calculations with higher-dimensional models for different, yet fairly comparable scenarios of atmospheric smoke injection. MacCracken[10] reports results from both a one-dimensional RCM and a two-dimensional (latitude/height) model. The one-dimensional model gave a land surface cooling of ~30 °C, in close agreement with Turco *et al.* The two-dimensional model, which parameterizes three-dimensional atmospheric motions to account approximately for thermal mixing, gave a ~15 °C cooling of land areas underlying the smoke. A three-dimensional model—but with only two layers in the vertical—has yielded similar results[11].

Clearly, the issues raised above should be addressed by fully three-dimensional models which include the important radiative processes present in RCMs (and the real atmosphere), and which also account for regional and seasonal heterogeneity and can calculate explicitly large-scale winds and their advection of heat—that is, three-dimensional atmospheric general circulation models. Ideally one should use a model which also accounts for aerosol transport and removal interactively, that is, calculates aerosol spreading and removal based on the atmospheric temperature structure and circulation which results from aerosol-induced heating. We have used a GCM developed at the National Center for Atmospheric Research (NCAR)—the Community Climate Model (CCM)—in an initial study which assumes a predetermined smoke aerosol distribution. As yet we do not have the capabilities to perform a three-dimensional fully interactive radiation, transport and removal calculation. Such numerical experiments must await considerable model development and validation.

## The model

The basic CCM is documented elsewhere[12–14] so we will give only a brief description here. The model uses the spectral transform technique for horizontal discretization with rhomboidal truncation at wavenumber 15, corresponding to a horizontal resolution of about 4.5° in latitude and 7.5° in longitude. In the vertical there are nine layers which encompass the troposphere and the stratosphere. (Relatively fine vertical resolution is necessary to compute adequately the important changes in atmospheric structure and circulation which result from the heating of the smoke.) Atmospheric winds, temperature and moisture are computed using standard conservation laws

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together with semi-empirical parameterizations which govern phenomena too small in scale to be resolved and computed explicitly by the model.

The CCM cloud/radiation scheme, of particular interest to our proposed study, is described by Ramanathan *et al.*[15]. The parameterization includes interactive clouds which form and disappear as determined by relative humidity and convective activity. Absorption of sunlight within the atmosphere by ozone, water vapour, carbon dioxide and molecular oxygen, with enhanced absorption and scattering in clouds, follows Sasamori *et al.*[16] and Lacis and Hansen[17], with cloud albedos constrained by available data. Long-wave processes are calculated by standard algorithms using improved values for water vapour and cloud emissivities[15].

In the CCM, as in most atmospheric GCMs, sea surface temperatures are prescribed as a lower boundary condition. This means that the small cooling of the sea surface expected after a few weeks of a nuclear war aerosol perturbation will not be simulated; instead, the sea surface will remain at its prescribed temperature and will release slightly more latent and sensible heat into the atmosphere than would be the case if it were allowed to cool interactively. On the other hand, the land surface is assumed to have zero heat capacity in the CCM (land surface temperatures are calculated by assuming no net energy flux across the surface) and so the initial cooling rate of the land surface will be overestimated. Neither of these two approximations should seriously compromise the qualitative inferences from the results obtained for times of a few days and up to a month. Of course, the detailed evolution of the regional response should not be taken literally.

## Simulation results

In our study, we forced the model in Northern Hemisphere mid-latitudes to absorb virtually all incident sunlight in the middle troposphere, leaving almost none to be absorbed by the surface. This forcing represents an optically thick layer of smoke which absorbs but does not scatter sunlight. For practical considerations, IR absorption and emission of the aerosols was not included. Fortunately, as IR absorptivity of smoke aerosols is about an order of magnitude less than solar absorptivity[4,5,18]

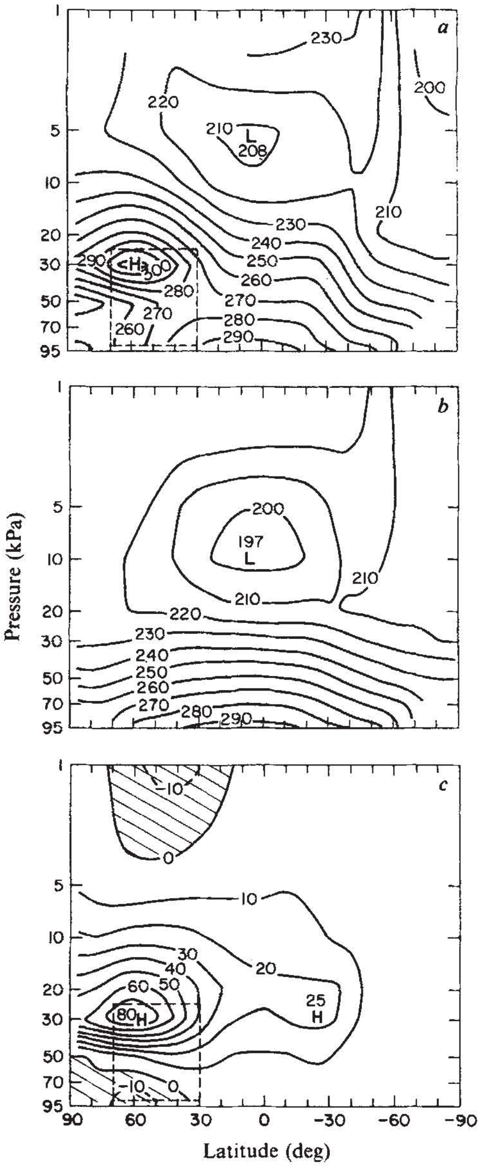

**Fig. 1** Zonally averaged temperatures (Kelvin), time-averaged for $t = 10$–$20$ days after the addition of smoke to the atmosphere in the 'summer' case. The perturbed case (smoke experiment, *a*), control case (equilibrium simulation without smoke, *b*) and the difference between the two (perturbed−control, *c*) are shown. Areas with negative numbers in the difference map (cooling) are shaded. The dashed lines enclose the approximate region in which smoke was added to the atmosphere.

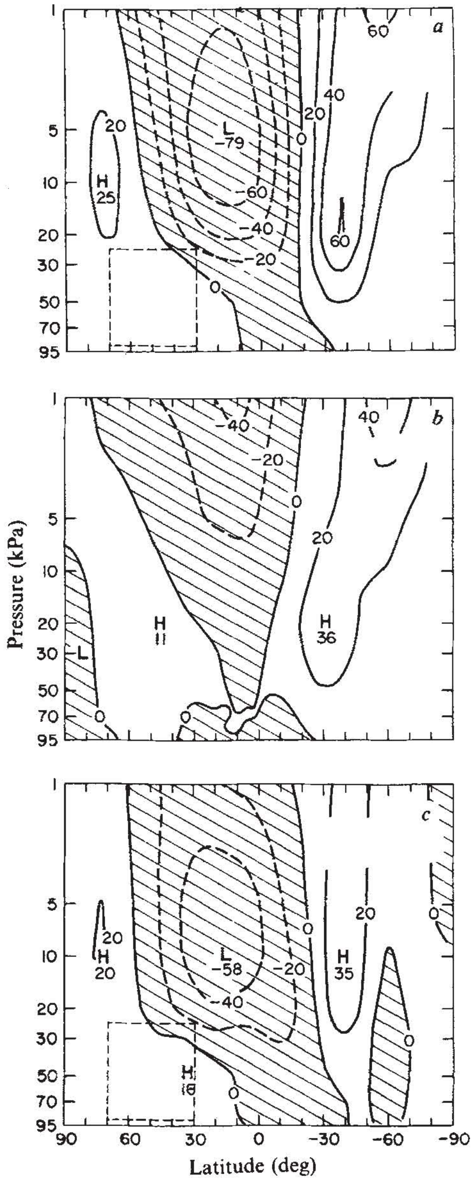

**Fig. 2** Same as Fig. 1 for zonal winds (m s$^{-1}$) in the 'summer' case. Westerly winds are by convention positive and easterly winds are negative (shaded).

our study will delineate a first-order approximation to the problem. We used a version of the CCM which includes specified seasonal variations of solar zenith angle, ozone, ocean surface temperatures, snow and sea ice cover developed by R. M. Chervin of NCAR in order to assess the seasonality of the atmospheric effects of the smoke injections.

In making assumptions about the amount and distribution of smoke aerosols generated by a nuclear war, we followed the US National Academy of Sciences 'baseline' case, which is intended to represent conservative estimates for a 6,500-megaton nuclear exchange[6]. We assumed that the zone between 30° and 70° N latitude was covered by $2\times10^{14}$ g of smoke evenly distributed between 1 and 10 km altitude. All the complex particle injection and removal processes which would occur in the early days after the fires started are supposed to be accounted for in this value of zonal smoke loading. However, it is not well understood how particle removal processes in the initially very dense smoke plumes would affect the eventual concentration of widely distributed smoke. Early removal of smoke particles, especially through coagulation, will be more effective at higher particle concentrations. Therefore, the rates of initial horizontal dispersal and fire burning may have important roles in determining the total smoke loading a few days after the fires.

The absorption coefficient of the smoke was assumed to be $1.8\ \mathrm{m^2\ g^{-1}}$, which gives a total absorption optical depth of 3.0. Specifically, a column density of $1.67\ \mathrm{g\ m^{-2}}$ was imposed for latitudes 31°–67° N with half this amount in the immediately adjacent zones, 27°–31° N and 67°–71° N, and no smoke elsewhere. The smoke was assumed to be evenly distributed in longitude on the basis that zonal winds would rapidly spread the smoke throughout the target latitude belt. In the vertical, equal amounts of smoke were placed in four layers of the model ranging from the 87 to 26 kPa pressure levels. Other than the overall absorption optical depth values, the details of the smoke aerosol and its optical properties are not central to our purpose of studying the first-order response of a three-dimensional circulation model to a plausible smoke aerosol. If the smoke optical depth were much greater or much less than 3, then these details of smoke optical properties would become much more important[18].

The smoke appears instantaneously in all simulations at time $t=0$ and remains fixed in place for the remainder of the model run, 20 days. This implies that a stabilized hemispheric scale aerosol is in place at day zero. (This corresponds to a time of a week or so after the fires started, essentially our $t=0$.) Three simulations were run: 'summer' ($t=0$ at 30 June), 'winter' ($t=0$ at 27 December) and 'spring' ($t=0$ at 22 March). Initial conditions for the model were supplied from a long-term (~20 yr) annual cycle simulation by R. M. Chervin.

Summertime perturbations will probably yield the largest response as more solar radiation is available for absorption by smoke. Figures 1–3 refer to the 'summer' case. The initial effect of the smoke perturbation is to cause almost all the solar flux available in the 30°–70° N latitude zone to be absorbed in the upper troposphere rather than at the surface. In the summer case, heating rates reach up to 20 °C per day in the upper troposphere as soon as the smoke is injected. The absorption of solar energy by the aerosol well above the surface, combined with the escape of IR radiation from the surface layers through the smoke cloud to space, creates the surface cooling and mid-tropospheric heating which the one-dimensional models predict. (This escape of IR to space is enhanced in our three-dimensional results because nearly all upper water tropospheric clouds disappear.) Figures 1 and 2 give the zonal averages of temperature and zonal wind as a function of altitude (pressure) and latitude. These are all averaged over the period $t=10$–20 days and compared with an unperturbed control case.

Figure 1 shows very high atmospheric temperatures in the upper levels of the smoke and significant cooling near the surface below the smoke. The largest atmospheric warming—many tens of degrees greater than the control—is within the smoke, but significant warming (at least 10 °C) extends well beyond the fixed smoke distribution up to the 5 kPa level and southward into the Southern Hemisphere subtropics. Clearly, atmospheric motions are transporting heat beyond the area of aerosol radiative heating. Water clouds largely disappear in the middle troposphere where the heating occurs because the relative humidity decreases and little water vapour is transported upwards through the stable temperature inversion. Near the surface, cooling below the smoke occurs poleward of 30° N and exceeds 10 °C (zonally averaged) between latitudes 50° and 70° N. Below 2 km altitude there is more cloud in the perturbed case.

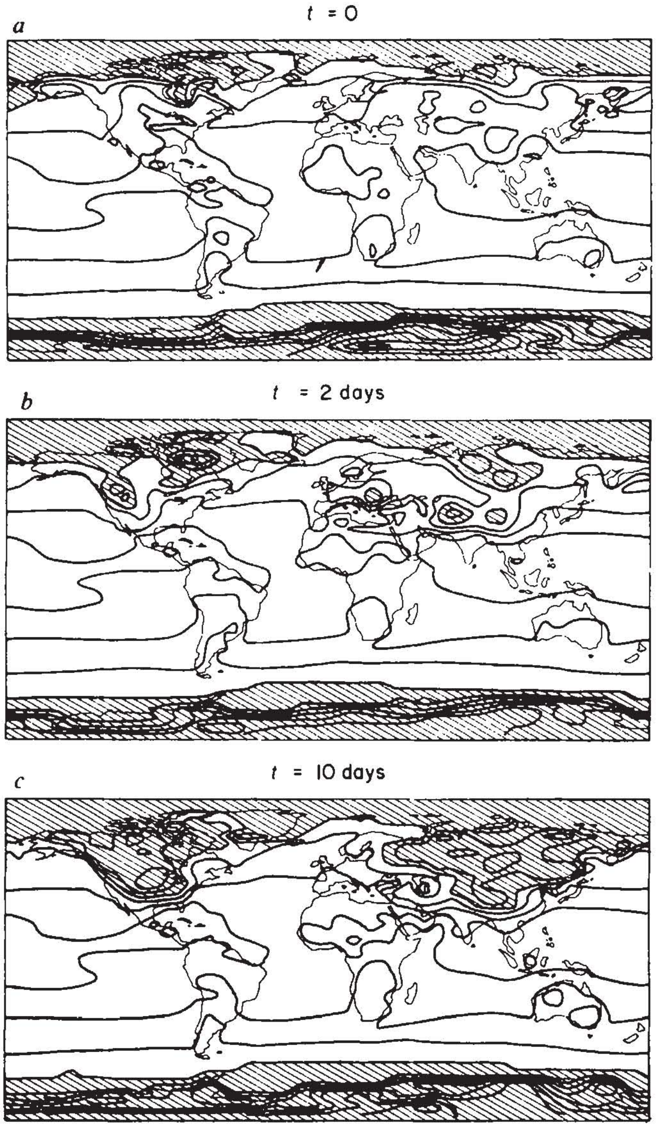

**Fig. 3** Surface temperature ($T$) at three selected instants of time: $t=0$ is the time at which smoke was added to the atmosphere in the summer case. Temperature contours are drawn for every 10 K. Areas with $T<270$ K (that is, well below freezing) are shaded. The warmest contour value in the tropics is 300 K.

The sharp mid-troposphere temperature gradients set up by the smoke heating support a significantly enhanced zonal circulation (Fig. 2). In the stratosphere (20–5 kPa) in the Northern Hemisphere, westerly winds are strengthened on the poleward side of the area of smoke heating and easterlies are strengthened on the equatorward side, results understandable in terms of the thermal wind relation. Substantially enhanced zonal winds exist near the surface: westerlies between 60° and 10° N, and easterlies between the Equator and 30° S. Once they have had time to develop, these enhanced winds may be expected to transport extra heat from the warmer oceans to the cooler continents.

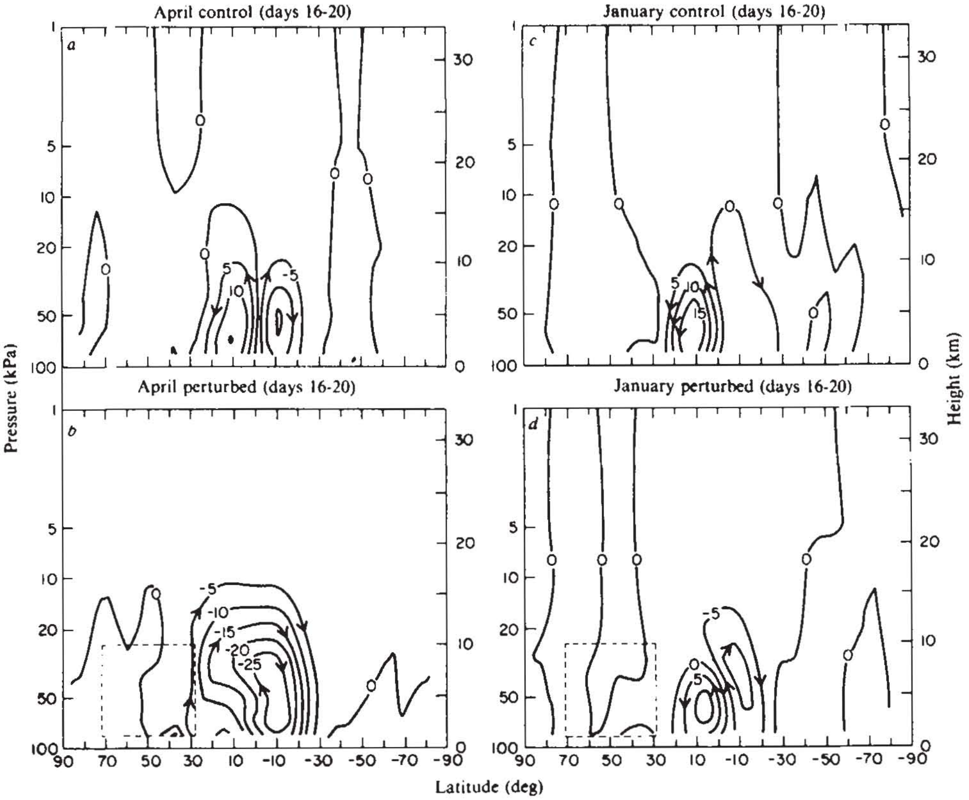

**Fig. 4** Zonally averaged meridional streamfunction in units of $10^{10}$ kg s$^{-1}$ for the spring case (*a*, *b*) and the winter case (*c*, *d*). Arrows indicate the direction of meridional and vertical motion. Time averaging was from $t = 16$ to 20 days. The area of imposed smoke loading is indicated by the dashed box as in Figs 1, 2. The control (equilibrium simulation without smoke) and perturbed (smoke experiment) cases are shown.

Figure 3 shows the initial (30 June) surface temperatures just before smoke injection and temperatures at two subsequent times. This is, of course, a tiny fraction of the large number of 'snapshots' from the experiment which need to be examined carefully, but several important points are apparent. Even at early times ($t = 2$ days) substantial cooling has set in, with areas of subfreezing temperatures occurring beneath the smoke. This suggests that in the real atmosphere, where the aerosol would be very heterogeneous initially, rapid freezing might occur wherever dense patches of smoke drift overhead and persist for more than a few days. In that case the areas of the world that would suffer quick, transient subfreezing temperatures could be, in effect, selected at random depending on initial winds and their proximity to plumes of smoke. (Even if the smoke were evenly distributed as in our simulations, the natural variability of the weather would result in different time evolutions of regional temperatures depending on initial weather conditions at the time of the nuclear exchange.) By $t = 10$ days, temperatures would fall below freezing over substantial areas of North America and Eurasia. The coastal areas, particularly in the western parts of continents, would generally escape the intense surface cooling of continental interiors, evidently because of the enhanced advection of heat from oceans to continents discussed earlier[19].

By $t = 10$ days the average land cooling under the smoke cloud for the 'summer' case is 15 to 20 °C. The ameliorating effect of the oceans is evident since temperature decreases of 30 to 40 °C would be expected on an oceanless planet[5]. Nevertheless, areas near oceans do not continuously escape subfreezing temperatures. For example, weather variability produces temperatures below freezing in Western Europe at $t = 8$ days (not shown) but not 2 days later.

The zonally averaged meridional circulation of the atmosphere is profoundly affected by the smoke perturbation. For the summer case discussed above, the normal cross-equatorial Hadley cell circulation is greatly enhanced. An even more dramatic effect is seen when the smoke injection occurs in the Northern Hemisphere spring. Figure 4*a*, *b* gives the meridional circulation for the spring case, averaged over $t = 16$–20 days after smoke injection. The two tropical Hadley cells which normally exist (Fig. 4*a*) are replaced by a massive circulation upwards and away from the smoke area. Similar results are obtained for the perturbed mean meridional circulation in the summer case. These meridional circulations may be instrumental in transporting heat away from its original site of deposition in the smoke cloud. In addition, in the real atmosphere the circulation would probably transport aerosol particles upwards and southwards, spreading them to regions beyond those in which the nuclear explosions occurred. This dynamic effect is clearly an important concern as it involves the spread of nuclear war environmental effects into areas that are not involved in the conflict[4,5].

Finally, in Fig. 4*c*, *d* we present the meridional circulation results for the 'winter' case, in which relatively little solar energy is available for absorption in the Northern Hemisphere mid-latitudes. Evidently there is little if any significant circulation change in the zonal average. At first sight it would appear that, in the winter case, smoke would probably not be transported out of the Northern Hemisphere mid-latitudes, but if we look at the actual three-dimensional wind patterns rather than the zonal average circulation, a different picture emerges. Streamlines of the wind at 20 kPa (about 12 km altitude) imply that smoke would be carried away from the mid-latitudes in 'streamers' for the winter (Fig. 5*a*) as well as for the spring (Fig. 5*b*) case. (Similar north–south streamlines were found in the mid-troposphere at the 50 kPa–500 mbar level.) Thus, depending on the initial north–south wind patterns, considerable amounts of smoke could be rapidly transported as far as the meteorological equator, where there would be sufficient solar radiation to create potentially large circulation perturbations. This result emphasizes the importance of using fully three-dimensional models to address the problem; the actual three-dimensional velocities associated with the circulation shown in Fig. 5*b* approach 50 m s$^{-1}$, whereas the corresponding zonally averaged velocities (see Fig. 4*b*) are nowhere greater than 5 m s$^{-1}$.

## Conclusions

Our results qualitatively agree with the fundamental conclusion of the lower-dimensional models, that is, for plausible scenarios, smoke generated by a nuclear war would lead to dramatic reductions in land surface temperature. Furthermore, the three-

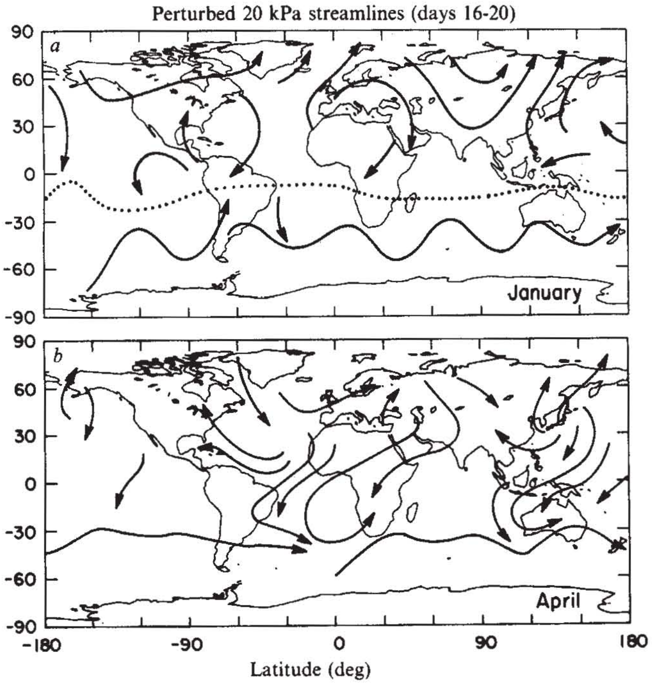

**Fig. 5** Streamlines estimated from 20 kPa (200 mbar) wind vectors for spring and winter cases. The dotted line in *a* indicates the southern limit of southward winds in the winter case. If the smoke is transported to this southern limit, it would be intensely heated by sunlight and probably generate new winds which might transport it even farther.

dimensional results suggest the possibility of rapid freezing of land surfaces under transient patches of smoke that may be randomly transported by atmospheric winds. We also find significant changes in atmospheric circulation which in many cases would probably spread the smoke far beyond the altitude and latitude zones in which it was initially injected.

Clearly, further study of current model results and a greater variety of smoke injection scenarios are necessary both to analyse thoroughly physical mechanisms and to examine additional important climatic variables. Also, it should be clear that the problem is intrinsically a dynamic one. Within a few days atmospheric winds and temperature would be so profoundly altered that any estimates of aerosol spreading or removal based on today's conditions become highly questionable.

More modest improvements in model simulation should include more realistic specification of the radiative effects of aerosols, that is, inclusion of IR absorption and emission and scattering of sunlight by the aerosols. One-dimensional sensitivity studies[18] indicate that inclusion of IR cooling due to smoke of visible optical depths less than ~10 would lead to only a small reduction in the amount of mid-atmospheric warming, and that the surface greenhouse warming would be quite small. The same studies imply that inclusion of scattering by the smoke aerosols would slightly decrease the amount of surface cooling because the aerosols will scatter some sunlight down to the surface. However, dust raised by the nuclear explosions, also not included in this study, will enhance surface cooling by backscattering sunlight so space, removing energy from the Earth–atmosphere system[4,5]. Moreover, such stratospheric dust or smoke scattering would also reduce the upper tropospheric heating rate for the purely absorbing smoke case, changing the calculated atmospheric circulation.

Physical processes incorporated into GCMs—including assumptions of fixed sea surface temperatures and zero land surface heat capacity, crude near-surface atmospheric representation, and sub-grid scale parameterizations for vertical and horizontal heat transport and for cloud properties—must also be critically examined. For example, vertical transport of heat by sub-grid scale processes would be affected by the dramatic increase in atmospheric stability obtained in our study. Nevertheless, our basic results for a $2\times10^{14}$ g stabilized smoke cloud—strong land surface cooling, mid-atmospheric warming, and profound changes in circulation—seem robust; they are confirmed both by the lower-dimensional models discussed above and by results from a simplified GCM with different sub-grid scale parameterizations and with more realistic (finite) surface heat capacity[20]. But important details such as the initial patchy freezing (Fig. 3*b*) are highly tentative, dependent on both the model and the initial conditions.

We believe the largest uncertainties in the nuclear aerosol/climate problem lie in translating the estimated inventory of burnable fuels in cities and forests into stabilized smoke clouds on a spatial scale suitable for global atmospheric circulation models. The way fires will burn (for example, firestorms), the height to which smoke is injected, the duration of fires, the particle concentration within the initial smoke plumes, and early particle removal by rainout in convective/mesoscale circulations all occur on spatial scales smaller than the resolution of any general circulation model now available. Unless the current estimates[5–7] of the effect of these processes are substantially in error, however, strong cooling of mid-continental land surfaces below regional-scale smoke clouds is very plausible. Moreover, patchy, transient subfreezing outbreaks could be plausible even if hemispheric scale stabilized smoke clouds were many times smaller than the $2\times10^{14}$ g we assumed.

Thus, the problem of long-term consequences of nuclear war represents not only an obviously critical issue for mankind, but also a stringent test of current understanding of the causes of climatic change. By subjecting models to the massive perturbation of several optical depths of aerosol, we gain insights into both model behaviour and properties of the real atmosphere which would not necessarily be as evident from studies of much smaller perturbations. Thus, we may draw implications for scientifically related problems such as the effects of volcanic eruptions on the climate and the possible massive dust injection resulting from the postulated impact of an asteroid on the Earth at the end of the Cretaceous period. It is our hope that a full hierarchy of models will be brought to bear on the question of nuclear war atmospheric effects.

We especially thank V. Ramanathan for his help in altering CCM radiation routines and for information on aerosol coagulation rates, R. M. Chervin for his annual cycle version of the CCM, J. T. Kiehl for assistance with radiation routines, and P. J. Rasch for his CCM streamfunction diagnostic package. We also thank W. Washington, M. C. MacCracken, H. N. Dalfes, P. Grutzen and A. Robock for comments on the manuscript. The National Center for Atmospheric Research is sponsored by the NSF.

Received 5 December 1983; accepted 19 January 1984.

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