

Snow and ice feedbacks prolong effects of nuclear winter

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Recent studies using climate models¹⁻⁶ have suggested that drastic surface cooling (the "nuclear winter"¹) caused by smoke and dust would follow a large-scale nuclear war, with possible drastic effects on the biosphere⁷. None of these studies looked at the long-term effects of time of year on the results. Moreover, although the general circulation model experiments of Covey *et al.*⁴ had snow/albedo feedback on land, none of the experiments considered long-term seasonal cryospheric interactions with the forcing, especially the sea ice/thermal inertia feedback⁸. Although, in the previous studies, the presumed transport of smoke and dust to the Southern Hemisphere was mentioned, no detailed investigation of its effects has been made. I investigate here the interactions of snow and sea ice with the forcing, and look at the effects over a period of several years for a variety of strengths of the forcing and latitudinal distribution of the nuclear smoke and dust, including Southern Hemisphere injection. The seasonal dependence of both the forcing and the response are also investigated. Previous results are supported and possible longer lasting effects are revealed. The considerable uncertainties that remain are discussed.

The experiments were conducted with a seasonal energy balance climate model based on that of Sellers^{9,10}. This model, described in detail elsewhere⁸, has been used to simulate the effects of volcanic eruptions¹¹⁻¹⁴ and several other forcings^{14,15} on climate. It uses 15-day time steps and solves for surface air temperature over land and water separately, in 10° latitude bands. Incoming and outgoing radiation are considered in detail and horizontal energy transports by the atmosphere and ocean are parameterized. Although energy balance climate models successfully reproduce mean properties of the observed climate system, details which may be important for the nuclear winter problem cannot be considered explicitly. Variations of atmospheric lapse rate, such as surface inversions, cannot be modelled. The three-dimensional circulation of the atmosphere, and its response to, and interaction with, the smoke and dust must be externally specified in this experiment, rather than internally calculated. The simple ocean model, with fixed mixed layer depth (from 90 m at the Equator to 40 m at the poles) and diffusive heat transport, prevents detailed consideration of ocean dynamical response. This climate model has the advantage, however, that it can be run rapidly on the computer and considers snow and ice feedbacks explicitly. The experiments reported here must, therefore, be interpreted as indicative of possible long-term interactions with the climate system that may result from forcing by nuclear smoke and dust. The exact surface-temperature responses would be different if the above details were included in a more complex model.

This climate model represents an energy balance for the vertically integrated surface-atmosphere system. In this experiment, the model is used to simulate the climate system beneath the nuclear smoke and dust layer. Turco *et al.*'s calculations¹ of the solar-energy flux at the ground for different scenarios were used to force the model. The scenarios of Turco *et al.* were first extrapolated to 400 days where the reduction of solar radiation went to zero for all cases. To force the model, the solar flux at each latitude band where there was smoke and dust was reduced by the same percentage for the particular scenario as given in their Fig. 4. Because Turco *et al.*'s values were for smoke and dust spread evenly over the Northern Hemisphere, they were adjusted according to the formula:

$$T' = T^f$$

where T' is the per cent transmission of solar radiation actually

Table 1 Forcing variations of the experiments

Time dependence of the forcing

Reduction of insolation according to Turco *et al.*¹ (their Fig. 4)

Case	
1	5,000 MT-baseline
14	100 MT-city attack
17	10,000 MT-severe

Latitudinal dependence of forcing

		f
Ref. 4	30-70° N	2.273
Ref. 3	10-90° N	1.205
Global	90° S-90° N	0.500
Gradual Southern Hemisphere (SH)	10-90° N	1.205
	0-90° N	0.667
	0-90° S	

Time war begins

Winter (1 January)
Spring (1 April)
Summer (1 July)
Autumn (1 October)

Control case

Ref. 4 (30-70° N), $f = 2.273$
Ref. 1 5,000 MT-baseline (case 1)
Summer (war begins 1 July)

used as forcing, T is the per cent transmission from ref. 1, and f is a latitudinal factor equal to the reciprocal of the percentage of the Earth covered by the smoke in units of Northern Hemisphere area. The equation was derived by considering that solar flux reduction is due to an exponential decrease in radiation for a linear increase in smoke amount. The values of f are given in Table 1 for the different cases used here.

All other components of the climate model were not changed, including the outgoing long-wave radiation. This way of forcing the model implies that the smoke and dust layer is high in the atmosphere where it has little impact on the long-wave radiation, due to its particle size distribution. The long lifetime of the smoke in the upper troposphere follows from the results of MacCracken² and Turco *et al.*¹ that convection is essentially cut off due to the extreme solar absorption by the smoke. The results that follow depend on these assumptions.

Table 1 also summarizes the forcings used in these experiments. Three of Turco *et al.*'s scenarios were used for the time dependence of the forcing, case 1 (5,000 MT-baseline), case 14 (100 MT-city attack) and case 17 (10,000 MT-severe). These scenarios do not necessarily represent the most realistic or most probable radiative forcings, but were chosen to allow the climate model to assess the importance of feedbacks on the long-term response. The effects of the time of initiation of the war were tested by starting the forcing in four different seasons. Four different latitudinal distributions were used, two to correspond to previous GCM experiments, from ref. 4 (30° N-70° N uniformly distributed) and from ref. 3 (10° N-90° N uniformly distributed), a globally uniform case as an extreme limit, and a case called Gradual Southern Hemisphere where the smoke spreads gradually to the Southern Hemisphere after 3 months. This last case tests the suggestions of previous models that a cross-equatorial circulation would develop due to the large temperature gradient caused by the smoke which would then transport the smoke to the Southern Hemisphere even if no bombs were exploded there.

Because of the many different possible combinations of forcings that could have been used, it was decided to perform a control case, and then change one factor at a time from this. The control case chosen used Turco *et al.*'s 5,000 MT-baseline scenario (their case 1) and Covey *et al.*'s⁴ latitude distribution (30° N-70° N), with the war beginning in summer.

Nine different runs were made. They are listed in Table 2 and the changes in surface temperature from the pre-war values are plotted in Fig. 1 as a function of latitude and time of year. Only the first 4 yr of results are shown. After this time, the temperature response shows a slow oscillation with the same pattern as in year 4 as the effect gradually diminishes. The same behaviour

Table 2 List of results shown in Fig. 1 and maximum cooling produced

Run	Latitudinal dependence	Time dependence	Time war begins	Results shown for:	Maximum temperature change (°C)
1a	Ref. 4	Ref. 1 Case 1 (baseline)	Summer	Land (control)	-21.4
1b	Ref. 4	Ref. 1 Case 1	Summer	Ocean	-10.7
1c	Ref. 4	Ref. 1 Case 1	Summer	Zonal average	-15.4
2	Ref. 4	Ref. 1 Case 1	Autumn	Land	-8.3
3	Ref. 4	Ref. 1 Case 1	Winter	Land	-8.1
4	Ref. 4	Ref. 1 Case 1	Spring	Land	-16.9
5	Ref. 3	Ref. 1 Case 1	Summer	Land	-21.1
6	Gradual Southern Hemisphere (SH)	Ref. 1 Case 1	Summer	Land	-19.4
7	Global	Ref. 1 Case 1	Summer	Land	-18.3
8	Ref. 4	Ref. 1 Case 17 (10,000 MT-severe)	Summer	Land	-22.9
				(year 2)	-16.4
9	Ref. 4	Ref. 1 Case 14 (100 MT-city)	Summer	Land	-19.3

can be seen in response to forcing from volcanic eruptions both for a 9-yr climate model simulation^{11,12} and in surface temperature observations for the past 90 yr (ref. 16).

Results 1a, 1b and 1c (Table 2) are all from the same control run, and present the surface-air temperature change for land grid areas, ocean grid areas and the zonal average. The effect is initially much larger over land, due to the lower thermal inertia. The maximum cooling is 21.4°C and occurs in the 50–60° N latitude band 45–60 days after the beginning of the war. The Northern Hemisphere average land cooling at this time is 11.5°C, which agrees well with MacCracken². Over the ocean grid boxes, the maximum effect is delayed and smaller, but occurs in the northernmost grid box, due to lower thermal inertia here caused by the presence of sea ice, and has a value of 10.7°C 90–105 days after the war starts. Even in the mid-latitude ocean areas, large temperature drops are found, which have not been found in any of the previous studies. A much more detailed ocean model than the mixed layer with fixed depth and diffusive heat transport used here is needed to investigate these effects further. The zonal average maximum effect of 15.4°C agrees almost exactly with MacCracken's results, as does the land value with the other previous results.

The climate model response in the first year after the war begins can be easily understood as a linear response to decreased insolation. During the second year, as the forcing disappears, the nonlinear effects of the snow and ice feedbacks become apparent. The large area of cooling of more than 5°C found in the mid and high latitudes in the summer over land is due to the snow/albedo feedback. The additional snow produced due to the large previous cooling reflects more solar radiation, enhancing the cooling. This feedback is only important in the summer when there is substantial insolation⁸. Over the ocean, the largest cooling in the second year is at the poles in the winter. This pattern, produced by the sea ice/thermal inertia feedback⁸, is caused by the enhanced amplitude of the seasonal cycle of temperature. This occurs when cooling produces more sea ice which lowers the thermal inertia of the ocean. The sea ice/albedo feedback, which in the absence of the thermal inertia feedback would produce the same pattern that the snow/albedo feedback produces on land, with enhanced sensitivity in the summer, is completely overwhelmed by the much stronger thermal inertia feedback over the ocean. (The feedbacks discussed here ignore possible effects of smoke particles settling on the snow and ice and hence lowering the albedo until the next snowfall¹⁷. These dirty snow effects may weaken, or even enhance, these feedbacks.)

The mixture of these two feedbacks from land and ocean can be seen in the pattern of the zonal average for the second year. The overall pattern over land begins to resemble the ocean pattern at the end of the second year, as the ocean effects dominate due to the horizontal mixing. In the third year, only a small area of sensitivity is evident in the summer high latitudes over land from the snow/albedo feedback. By the end of the

second year, 18 months after the start of the war, cooling over the oceans is of the same amplitude as over land, and after that it is even larger, as the ocean thermal inertia slows the recovery to pre-war temperatures. Note that these feedbacks and patterns are also evident in the equilibrium response of the climate model to external forcing, such as changing solar constant or CO₂ (refs 8, 18), as opposed to the transient response shown here.

Because of the cryosphere feedbacks discussed above, the response of the climate to nuclear war is longer and larger than previously found by Turco *et al.*¹ who did not include these feedbacks. It would presumably be very difficult to grow crops not only in the summer of the year that the war began, but also in the summer of the next year, with temperatures over land almost 6°C (>10°F) colder than normal.

Several other experiments were conducted to test the effects of time of year that the war begins, latitudinal spread of the smoke, and strength of the forcing. To save space, only the response over land is shown for comparison with the control case. The response over land is probably of more interest anyway, because it is larger than the first year response over the sea, and humans and agriculture are affected. The relative effects over the ocean, as shown for the control, are the same for all these cases.

Runs 2, 3 and 4 tested the effects of beginning the war in autumn, winter and spring. As can be seen in Fig. 1, the effects in the autumn and winter cases are not as large as in the control. This is because there is less insolation at the time of the maximum atmospheric loading from smoke and dust, and, therefore, less absolute reduction of incoming energy. In the autumn case, the initial effect is larger than the largest effect for the winter case, but it occurs in the autumn and does not last as long. The cooling during the following summer, however, is more than 4°C during the entire summer from 40° N to the Pole. In the winter case, although the initial effect is small, enough smoke remains to cause a large effect the following summer, with a cooling as large as 8°C. This effect was not seen by Covey *et al.*⁴ because they ran their winter experiment for only 20 days. The spring case is quite similar to the summer case with large cooling during the first summer, and substantial, although not quite as large, cooling during the second summer.

Runs 5, 6 and 7 illustrate the effects of spreading the nuclear smoke and dust over a greater latitudinal extent. In the Aleksandrov-Stenchikov³ case (run 5), the results are almost the same as the control case, but the cooling extends over more latitudes and persists at a slightly larger amplitude in the years after the war. Although the smoke concentration is lower in this case than in the control, there is still so much smoke that almost all of the sunlight is initially prevented from reaching the ground. (The small regions of enhanced or decreased sensitivity found in the tropics in this and the following runs are due to a small model instability relating to its inability to calculate the circulation correctly under such extreme forcing. They are not real, and a slight smoothing would produce a more realistic response.)

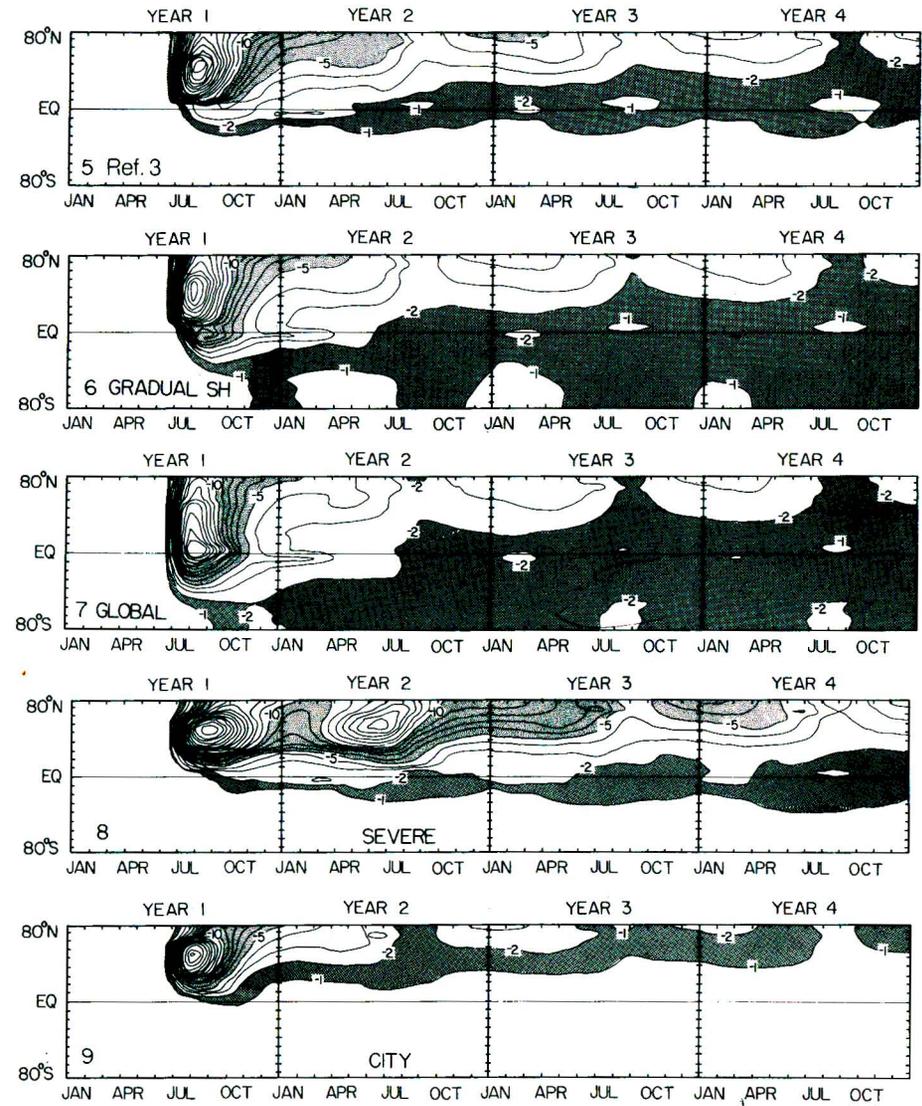
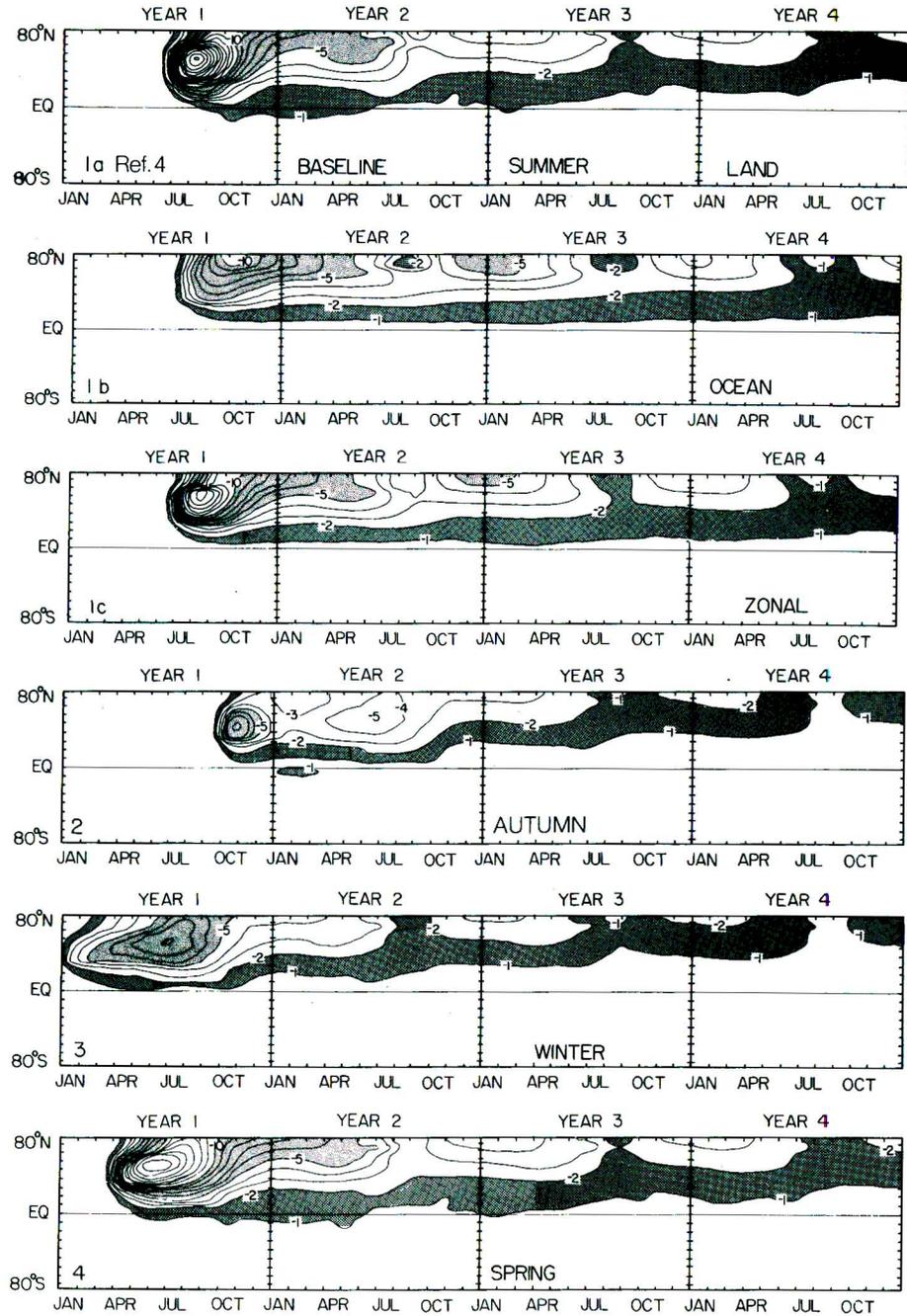


Fig. 1 Temperature change (nuclear war experiments minus unperturbed climate) as function of latitude and time for the runs listed in Table 2. Contours are every 1 °C starting at -1 °C. Temperature drops between -1 °C and -2 °C, and between -5 °C and -10 °C, are shaded.

In the Gradual Southern Hemisphere case (run 6), the Northern Hemisphere response is again about the same as in the control. Although the response is slightly less in year 2, it is larger in years 3 and 4 because the forcing at lower latitudes makes the effects last longer through ocean cooling. In this case, we see maximum cooling of about 8 °C in the tropics, and much smaller cooling in the Southern Hemisphere. The smaller Southern Hemisphere effect is caused by the much larger thermal inertia due to the much larger percentage of oceans in this hemisphere, as well as the lack of land in the high mid-latitudes on which to produce a snow/albedo feedback. This effect is illustrated in run 7, where the forcing is the same at all latitudes, but the response is much less in the Southern Hemisphere. This is partly because the forcing started in Southern Hemisphere winter. A global run starting in Southern Hemisphere summer (not shown here) produced about the same response in the Southern as in the Northern Hemisphere. The larger Southern Hemisphere thermal inertia almost exactly compensated for the larger forcing.

The effects of using the severe 10,000 MT forcing¹ are shown in run 8. The results during the first year are virtually the same as in the control case, with the maximum cooling not even 2 °C larger. The dramatic difference comes in the second year, where the snow/albedo feedback produces a cooling of more than 16 °C during the summer 1 yr after the war begins. The effects persist for several years after this, with year 4 in this case resembling year 2 in the control case. Although this result is almost a 'worst case' scenario (more latitudinal spread would make it even worse), it should receive serious consideration¹ because it is plausible. Run 9 shows that even the smaller 100 MT-city attack can have virtually the same effects as the control case, in agreement with Turco *et al*¹.

These experiments show that the climatic effects of a nuclear war might persist longer than previously calculated. The use of a model which includes snow and ice feedbacks and ocean response shows that the effects can be large even 1 yr after the war begins. Latitudinal spread of the nuclear smoke and dust can produce large cooling in the tropics where life is more sensitive to cooling due to the absence of a natural seasonal cycle⁷, but the cooling there is not as large as would be expected from a global average model.

The results presented here must be considered as preliminary, since the climate model used cannot consider many of the

complex interactions that might result. These include the dynamical and radiative interactions between the atmospheric circulation and the smoke, the possibly patchy nature of the smoke distribution, long-wave radiative interactions, ocean circulation and mixed-layer depth responses, atmospheric hydrological cycle responses (including changes in cloudiness and changes in washout rates due to changes in precipitation), the effects of considering diurnal solar forcing (R. Cess, personal communication), and the effects of placing dust over the smoke rather than having them evenly mixed¹⁹. What the initial distribution of smoke and dust would be is also not well known and depends on untested assumptions about numbers and sizes of fires, number of particles produced per fire, initial rainout and washout, particle size distribution and coagulation rates, vertical distribution, targeting strategies and initial weather conditions. All these processes must be included to produce realistic results. In the absence of proof that these assumptions would drastically change the results, the prospect of a nuclear winter following virtually any scenario for a nuclear war must be taken very seriously.

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