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Atmospheric Perturbations of Large-Scale Nuclear War*

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Symposium on the Medical Implications of Nuclear War

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*The material upon which this presentation is based is drawn from two papers [Malone et al., 1985a,b]. Readers interested in a more comprehensive discussion including historical background, related research, technical details of the model, and more extensive references should consult these articles, particularly the latter.

Several of the preceeding papers have discussed the subjects of "nuclear winter," large fires, and the dynamics of smoke plumes from large fires. I would like to elaborate upon this theme by describing new computer simulations of the injection into the atmosphere of a large quantity of smoke following a nuclear war. I will focus on what might happen to the smoke after it enters the atmosphere and what changes, or perturbations, could be induced in the atmospheric structure and circulation by the presence of a large quantity of smoke.

To help you understand the significance of these "atmospheric perturbations" and the manner in which they arise, I would like to start by breaking the nuclear winter phenomenon into its component parts. A very simplified view of nuclear winter can be represented by the elements inside the dashed region labelled "A" in Figure 1. Contained therein is a vertical column of processes and a box to the side that represents smoke injected into the atmosphere. Ignoring the rest of Fig. 1 for the moment, you can see that there are two basic ingredients to nuclear winter. These are sunlight coming into the earth's atmosphere and the smoke which has been injected into the atmosphere by fires. The smoke absorbs some of the incoming sunlight, causing a reduction in sunlight reaching the earth's surface. A radiation deficit at the surface results because the surface continues to emit infrared radiation (heat). The smoke particles do not trap infrared radiation effectively, so the heat goes on back out to space (not indicated in Fig. 1). This continuing heat loss to space combined with reduced incoming sunlight causes the surface to cool. This is the origin of the so-called "nuclear winter" effect.

It is apparent that the magnitude of the cooling would depend on the amount of smoke injected and that the duration of the cooling would depend on how long smoke remains in the atmosphere.

The latter issue brings us to the next element of complication in this picture, which is the removal of smoke from the atmosphere by rainfall, indicated by the dashed box labeled "B". Precipitation scavenging of smoke, as this is also called, was considered in the TTAPS study of nuclear winter [Turco et al., 1983] and also in the National Academy of Sciences report on this subject [NAS, 1985]. However, with the models that were available at the time, it was necessary to assume that the removal of smoke by rainfall occurred at a rate that was prescribed based on the observed lifetime of smoke particles in the unperturbed atmosphere. Although it was recognized that changes in the atmosphere would occur, it was not possible to take these changes into account in the models.

It has now become possible to investigate these atmospheric changes with more complicated models that have been developed in the last few years. These changes are quite important because they influence the ability of precipitation to remove smoke from the atmosphere and, therefore, the duration of the climatic effects of smoke. We can now add the last elements, contained in the dashed box "C" of Fig. 1, to our diagram. The principal ingredient in box "C" is heating of smoke-filled air due to absorption of sunlight by smoke particles. This heating causes changes in the atmospheric circulation and structure (also indicated schematically in box "C") -- the "atmospheric perturbations" alluded to in the title of this presentation.

The first of these is a major change in the atmospheric circulation patterns that causes the heated air, and the entrained smoke particles, to rise. This carries some smoke particles well above the altitudes to which they were injected initially by the fires. The second change is one that takes place in the vertical thermal structure of the atmosphere, also brought about by the heating of smoke-filled air. As I will show you, both of these effects inhibit the ability of the atmosphere to purge itself of smoke. Specifically, they reduce the efficiency of smoke removal by precipitation.

In fact, there is a competition between rainfall, which removes smoke from the atmosphere, and these atmospheric perturbations, which acts to isolate smoke from removal by rainfall. Precipitation scavenging begins to act as soon as the smoke is injected into the atmosphere. It is able, in our model calculations, to remove a substantial amount of smoke during the first two weeks. During that time these perturbations develop and, at least for summertime conditions and large smoke injections, can become dominant.

These changes in the atmospheric structure and circulation are important in their own right, but it should be noted that they form a "feedback loop" in which elements of boxes "A", "B" and "C" are interconnected. In the full diagram the amount (and spatial distribution) of smoke remaining in the atmosphere at any time is influenced by the changes spawned by solar heating of the smoke itself. In a given season of the year, the intensity of heating depends on the amount (concentration) of smoke. Consequently, if larger injections of smoke are postulated, stronger heating results and causes larger atmospheric perturbations and greater inhibition of smoke removal by rain. Thus, the greater the amount of smoke injected, the greater is its ability to modify the atmosphere and, thereby, to inhibit its own removal. (For very large smoke injections another effect, discussed in Malone et al. [1985b], modifies this conclusion.) For a given amount of smoke injected, the intensity of heating depends upon the amount of sunlight available. Assuming that smoke would be initially injected only in the northern hemisphere, the heating of smoke and the resultant atmospheric perturbations would be greater in July than in January, simply because there is more sunlight in the northern hemisphere in July than in January.

The computer model that we used for our studies is what is called a "general circulation model" or "global climate model" or simply a "GCM". It is a three-dimensional model that solves on a computer the mathematical equations describing the evolution in time of the winds, temperature, moisture and other quantities throughout the earth's global atmosphere.

To study the nuclear winter problem, we added the capability of transporting aerosols (very small particles) with the simulated winds of the model. We modified the model's solar radiation scheme to allow for the absorption by smoke particles of sunlight coming into the atmosphere. We also added a very simplified treatment of the removal of smoke from the atmosphere by rainfall. For this we used rainfall as predicted by the model itself, so that changes in rainfall caused by the heat-induced "atmospheric perturbations" could be taken into account.

In the computer simulation studies that I will describe, smoke was injected into the model atmosphere over the United States, Europe and the western Soviet Union. The injection rate decreased linearly to zero at the seventh day; half of the smoke is injected during the first two days. The sensitivity of smoke transport and removal to the assumed initial vertical distribution of smoke was considered by using two profiles: a "low" injection with smoke distributed between 2 and 5 km altitude in the lower troposphere; and an "NAS" injection with constant smoke mass density between the surface and 9 km altitude [NAS, 1985], still within the unperturbed troposphere. Both January and July conditions were used, to reveal seasonal differences. The behavior of aerosols in the normal atmosphere was studied with a "passive tracer" which, like smoke, is transported by the model's winds and removed by the predicted rainfall, but unlike smoke, does not absorb sunlight. This last characteristic permits the model atmosphere to evolve unperturbed by the presence of the passive tracer. The contrasting behavior of interactive smoke and passive tracer illustrates clearly the importance of atmospheric heating due to sunlight absorbed by smoke particles.

The amount of smoke that is assumed to be injected into the atmosphere is an important parameter, but estimates of this quantity are quite uncertain. The National Academy of Sciences study [NAS, 1985] estimated a range from 20 Tg (1 Tg = 10^{12} grams = 1 million metric tons) up to as much as 640 Tg of smoke. I will present only results for 170 Tg, a value close to the NAS "baseline" value; results for other smoke amounts can be found in Malone <u>et al.</u> [1985b].

Now I would like to take you on a tour of Fig. 1, explaining more fully some of its elements. Using July conditions because the atmospheric changes are larger and more easily seen, I will show you first about smoke lofting, then show you how the structure of the atmosphere is changed. Next I will describe how these effects influence the removal of smoke by rainfall and the lifetime of smoke in the atmosphere. Finally, I will describe briefly our findings about the climatic impact of smoke.

Figure 2 contains a comparison of two calculations that illustrate nicely the influence of solar heating on the dynamics of the smoke. One calculation was done with interactive smoke; the results from it are shown with solid contours. The second calculation was done with a passive tracer; its results are shown with dashed contours. In both calculations the same amount of material, 170 Tg, was injected over the northern hemisphere continents in July at altitudes between 2 and 5 km ("low" injections). The contours indicate the concentrations of material (in parts per billion by mass) remaining at day 20 in the calculations, averaged over all longitudes. The display extends from the North Pole to the South Pole and from the surface of the earth up to about 30 kilometers, which is in the lower stratosphere. (I will explain a little more about the normal atmospheric structure in connection with Fig. 3.) These contours tell us now much of the material is left at day 20 and how it is distributed in latitude and altitude.

As you see, for the passive tracer, most of the material remains at low altitudes, where it was injected, because the passive tracer and surrounding air are not heated by sunlight. Since scavenging by rainfall is fastest in the lower atmosphere, the passive tracer is rapidly removed, as indicated by the relatively small values of concentration.

In the interactive case, on the other hand, the smoke does absorb sunlight. The heating drives vertical motions that carry smoke-filled air upward from the region of injection in the lower atmosphere. This takes some smoke up higher, completely out of reach of removal by precipitation. Also the heating of the atmosphere by the absorption of sunlight inhibits the formation of precipitation. This allows more smoke to remain, as you can see by the larger concentrations labelling the solid contours.

Before showing you how the structure of the atmosphere is changed by the heated smoke, let me first acquaint you with the atmosphere as it normally exists. Figure 3a is a plot of the longitudinally averaged temperature in the atmosphere for normal July conditions. The temperature contours are labelled in degrees Kelvin (273°K = 0°C). The structure of the atmosphere in its normal state is such that the temperature is warmest at the surface and decreases upward with height to an altitude of about 10 km. This region is called the troposphere. At about 10-15 km, the temperature becomes relatively constant with height and then increases with height in the stratosphere due to absorption of sunlight by ozone. The heavy dashed line in Fig. 3a shows the approximate position of what is called the tropopause, which is the boundary between the troposphere and the stratosphere.

For our purpose, the most important characteristic of the troposphere is that it is the region of the atmosphere in which storms and rainfall occur. Since precipitation is the primary removal mechanism for smoke, this is where smoke removal will take place.

Figure 3b also displays the longitudinally averaged temperature for July conditions but with the atmosphere perturbed by the injection of 170 Tg of smoke. The smoke was injected with constant density from the surface up to about 9 km ("NAS" injection), so that all of it is in the unperturbed troposphere and is initially subject to removal by rainfall. The heating by sunlight of this smoke, some of which is carried higher (Fig. 2), is quite intense and changes the vertical thermal structure of the atmosphere significantly. Fig. 3b shows a 5-day average of the temperature during the third week after smoke injection began. There is still a region in the lower atmosphere in which temperature decreases with height; that is, there is still a troposphere. However, the top of the troposphere is now at about 5 km, rather than 10 to 12 km that occurs in the normal atmosphere.

Higher up the solar heating of smoke has raised the temperatures by as much as 50-80°K above normal. A situation now exists in which the smoke has created its own "stratosphere". Above the lowered tropopause, indicated by the heavy dashed line, warm air overlies cooler air, a condition that inhibits convective motions that would bring about precipitation.

Consequently, precipitation is confined below the tropopause and most of the remaining smoke is above it, as illustrated in Fig. 4. The heavy dashed line again represents the tropopause, the boundary between the troposphere and the heated region, taken from Fig. 3b. The cross-hatching shows where precipitation is occurring; clearly it is confined below the tropopause. The black stippling, which indicates various concentrations of smoke, shows that smoke now resides primarily above the tropopause. Smoke that was below the lowered tropopause has been largely removed by precipitation. Because the remaining smoke is now separated physically from its primary removal mechanism, its lifetime in the atmosphere is greatly increased.

This increased lifetime can be seen in Fig. 5, which shows the temporal evolution of the total mass of material remaining in the atmosphere. The upper four curves apply to interactive smoke calculations with vertical injection profiles as indicated, while the lower pair of curves apply to passive tracer calculations with "low" injection profiles. Let me point out that the vertical axis has a logarithmic scale. The total injection in all of these cases was 170 Tg, which is near the top of the diagram. As a result of scavenging by rainfall, none of the curves ever reachs the 170 Tg level. A substantial amount of material is removed while the injection proceeds.

The passive tracer curves in Fig. 5 approximately represent normal aerosols in the unperturbed atmosphere. Following the cessation of injection at day 7, these curves fall in almost straight lines, which means that material is removed exponentially in time. These two curves provide useful validation of our model. They tell us is that aerosols in the normal atmosphere, as calculated by our model, have a residence time on the order of one week. This is in good agreement with observations.

Now contrast that with the behavior of interactive smoke indicated for July by the upper pair of dashed curves. During the first week or two, a substantial amount of smoke has been removed from the atmosphere. This is mostly smoke down low that can be easily removed by rain. But because there is strong solar heating in the northern hemisphere in July, the rate of removal of smoke is greatly decreased after the first two weeks. As explained above, this occurs because some smoke has been carried higher in the atmosphere, and because the atmospheric structure has been modified. Approximately one-third of the mass of smoke initially injected still remains in the model atmosphere after 40 days of the July calculations. This smoke has a very long lifetime in the atmosphere, as indicated by the slight decreases in the upper pair of dashed curves after day 15.

Up to this point, I have only talked about July because it is easier to illustrate the interesting effects for July conditions than for January. The upper pair of solid curves show the interactive smoke results for January. Smoke is removed faster in January than in July simply because there is less sunlight in the northern hemisphere to drive the atmospheric perturbations that enhance the lifetime of smoke. By the end of six weeks in our January calculations, the fraction remaining of smoke injected with the "low" and "NAS" profiles is about 5% and 15%, respectively, compared to 35% in the July cases. Nevertheless, solar heating of smoke does have a significant effect even under winter conditions. After three weeks, there is approximately a factor of three more smoke present in the atmosphere in January than would have been the case without the influence of solar heating (compare the passive tracer curve). In July the comparable ratio of smoke to passive tracer mass is about 10 after 3 weeks.

Figure 6 consists of two maps of the world showing the distribution of smoke looking down through the atmosphere at days 20 and 40. Most of the smoke is still concentrated in the northern hemisphere. Transport of smoke by the winds has made the geographical distribution of smoke fairly uniform in longitude, although some nonuniformities remain. Some low-level smoke lingers over the continents. This is possible because the surface cooling (Fig. 7) causes precipitation to decrease over the continents. Air over the oceans is clearer. Some smoke has reached the southern hemisphere. The quantity displayed in Fig. 6 is called the "absorption optical depth" and can be used to determine the attenuation at the surface of sunlight coming down through the atmosphere. The fractional attenuation is about 10%, 25%, 40% and 50% for optical depths of 0.1, 0.3, 0.5 and 0.7, respectively.

Figure 7 shows the changes in surface air temperature, relative to normal, predicted by the model when 170 Tg of smoke is injected in July. A 5-day average of the temperature change near the end of the first week is displayed in Fig. 7a. It shows cooling by 15°C or more over large areas of the interiors of the North American and Eurasian continents during this period when the smoke clouds are particularly dense over the regions of injection. The long lifetime of smoke under summer conditions causes significant reductions in the surface air temperature to last through the end of the calculation at day 40. Fig. 7b shows the simulated temperature changes during the sixth week; reductions of 5-15°C persist over the northern midlatitude continents. Note that the features in the southern hemisphere have nothing to do with what is going on in the northern hemisphere; they are due simply to normal weather fluctuations in the winter (southern) hemisphere.

In January, simulated surface air temperature reductions of 5-15°C occur over portions of the northern midlatitude continents during the first few weeks. However, the faster removal of smoke allows the temperatures to recover toward normal more rapidly than in July.

The discussion so far has focused on a baseline value of 170 Tg of injected smoke. However, it was pointed out in connection with Fig. 1 that the intensity of heating, the magnitude of the atmospheric perturbations, and the smoke removal rate all depend upon the concentration (hence, total mass) of injected smoke. Very small amounts of smoke have little impact on the atmosphere, which cause the smoke to be quickly removed from the troposphere, much like the passive tracer results in Figures 2 and 5. As the injected mass is increased in the simulations into the range estimated for a major nuclear exchange, the solar heating of smoke and the atmospheric perturbations increase in magnitude. The fractional mass remaining in the atmosphere at late times also increases and its rate of removal decreases. This trend continues up to injected masses comparable to the baseline value (170 Tg). With still larger values, another effect comes into play that causes the fractional mass remaining to stop increasing and even to decrease somewhat [Malone <u>et al</u>., 1985b].

Let me end with a short summary of our findings. Solar heating of smoke is a very important factor. It produces two effects. One is that some smoke is carried well above its initial injection height. The second is a modification of the atmospheric structure in which heating pushes the tropopause downward. This leads to an isolation of smoke above the tropopause from precipitation below, and causes an increase in the lifetime of that smoke relative to what one would find if solar heating of smoke were neglected. The magnitude of these effects depends on the season of year and the amount of smoke injected into the atmosphere by fires.

We find substantial cooling of the northern hemisphere continents during the first few weeks in both January and July. In the July case only, we find that the prolonged lifetime of smoke suggests that significant temperature reductions could persist for many weeks. We find that smoke spreads into the southern hemisphere in July as a result of the strong circulations driven by solar heating of smoke. There is very little spread into the southern hemisphere for January conditions; the smoke simply is not heated enough and is removed too fast.

The interested reader should consult the paper of Malone <u>et al.</u> [1985b] for a more complete discussion that includes the simulated surface climate impact of various smoke amounts.

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Figure Captions

Fig. 1. Schematic illustration of the interconnection of the processes which control the distribution and residence time of smoke in the atmosphere and the resulting surface climate change. Some arrows indicate that one process causes another, other arrows indicate only that a process influences the operation of the process to which the arrow points. For example, the presence of smoke in the atmosphere results in the absorption of sunlight, which causes heating, which causes both lofting of the smoke and lowering of the tropopause. These two effects influence (decrease) the efficiency with which precipitation removes smoke, by changing the vertical distribution of both smoke and precipitation. Removal by rain obviously changes the amount of smoke. Heating also modifies the winds, which influence the distribution of smoke.

Fig. 2. Longitudinally averaged mass mixing ratios for July conditions at day 20. The dashed contours apply to a passive tracer, while the solid contours apply to interactive smoke. In each case 170 Tg (1 Tg = 10^{12} g = 1 million metric tons) of material was injected over the northern-hemisphere continents with a "low" injection profile (see text). The contours of mixing ratio are labeled in units of 10^{-9} g material/g air.

Fig. 3. The longitudinally averaged temperature (K) in the simulated unperturbed (a) and perturbed (b) atmospheres, for July conditions. The perturbed distribution is a 5-day average beginning 15 days after the initiation of injection of 170 Tg of smoke with the "NAS" vertical injection profile. The unperturbed distribution in (a) is a long-term average. In

each figure the approximate position of the tropopause is indicated by the heavy dashed line.

Fig. 4. The relative positions of the modified tropopause (heavy dashed line) and the precipitation distribution (cross-hatched region below the tropopause), both averaged over days 15-20, and the smoke distribution at day 20 (stippled area above the tropopause) for the 170 Tg "NAS" case portrayed in Fig. 3b. Darker stippling indicates greater smoke loading; the smoke contour intervals correspond to mixing ratios of 10, 40, and 70×10^{-9} g smoke/g air. These may be compared with the solid contours in Fig. 2, which apply to a "low" injection July case, also at day 20.

Fig. 5. The mass of material remaining in the global atmosphere as a function of time. The upper four curves apply to smoke, the lower pair to passive tracer. Solid and dashed curves indicate January and July conditions, respectively. Labels indicate "low" and "NAS" injections. The slopes of the passive tracer curves at late times yield 1/e-residence times of 5 to 6 days, which agree well with observed residence times of aerosols in the lower troposphere.

Fig. 6. The vertically integrated solar absorption optical depth of smoke at day 20 (a) and day 40 (b) of the interactive July simulation with 170 Tg injected with the "NAS" vertical profile. The contours are in intervals of 0.1 with the lowest value being 0.1 on the southernmost contour. If τ is the absorption optical depth, the light reaching the surface from the sun

overhead is reduced by a factor of $e^{-\tau}$. For τ=0.1, 0.3, 0.5 and 0.7, the factor $e^{-\tau}$ is 0.90, 0.74, 0.61 and 0.50, respectively.

Fig. 7. The change in surface air temperature relative to the unperturbed atmosphere in July for 170 Tg of smoke injected with the "NAS" profile. Five-day averages of the perturbed case, minus the long-term average of the unperturbed case, are shown: (a) days 5-10, (b) days 35-40. Only changes larger in magnitude than 5°C are shown. Values are indicated in the legend at the bottom of the figure; the designation "<-15" refers to temperature reductions in excess of 15°C below normal. Note that the warm and cool regions near Antarctica are simply manifestations of storms which occur naturally in the wintertime circumpolar flow; they have no connection with the changes occuring in the northern hemisphere.

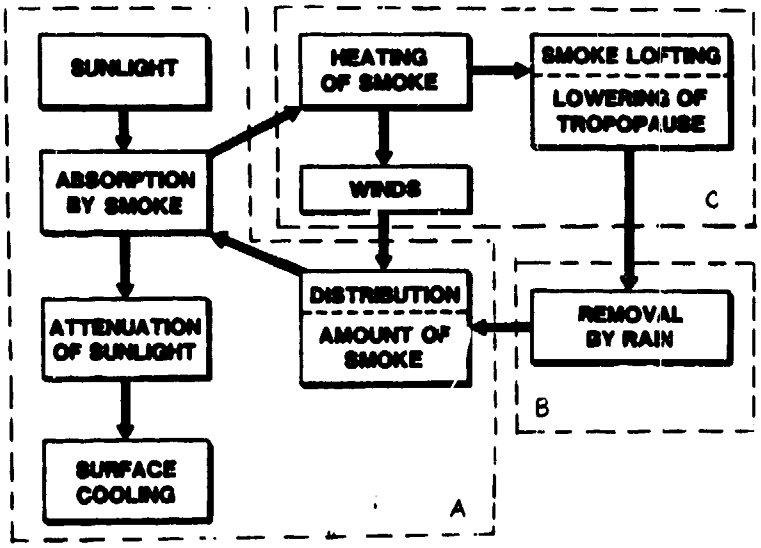

Figure 1

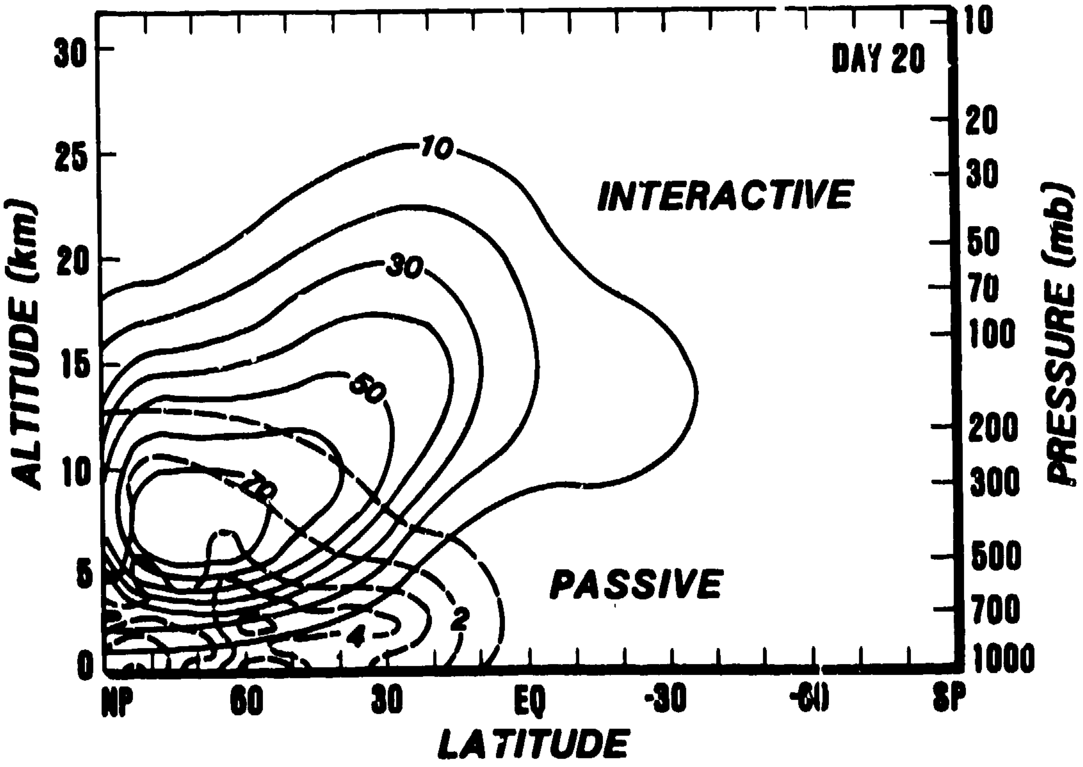

Figure 2

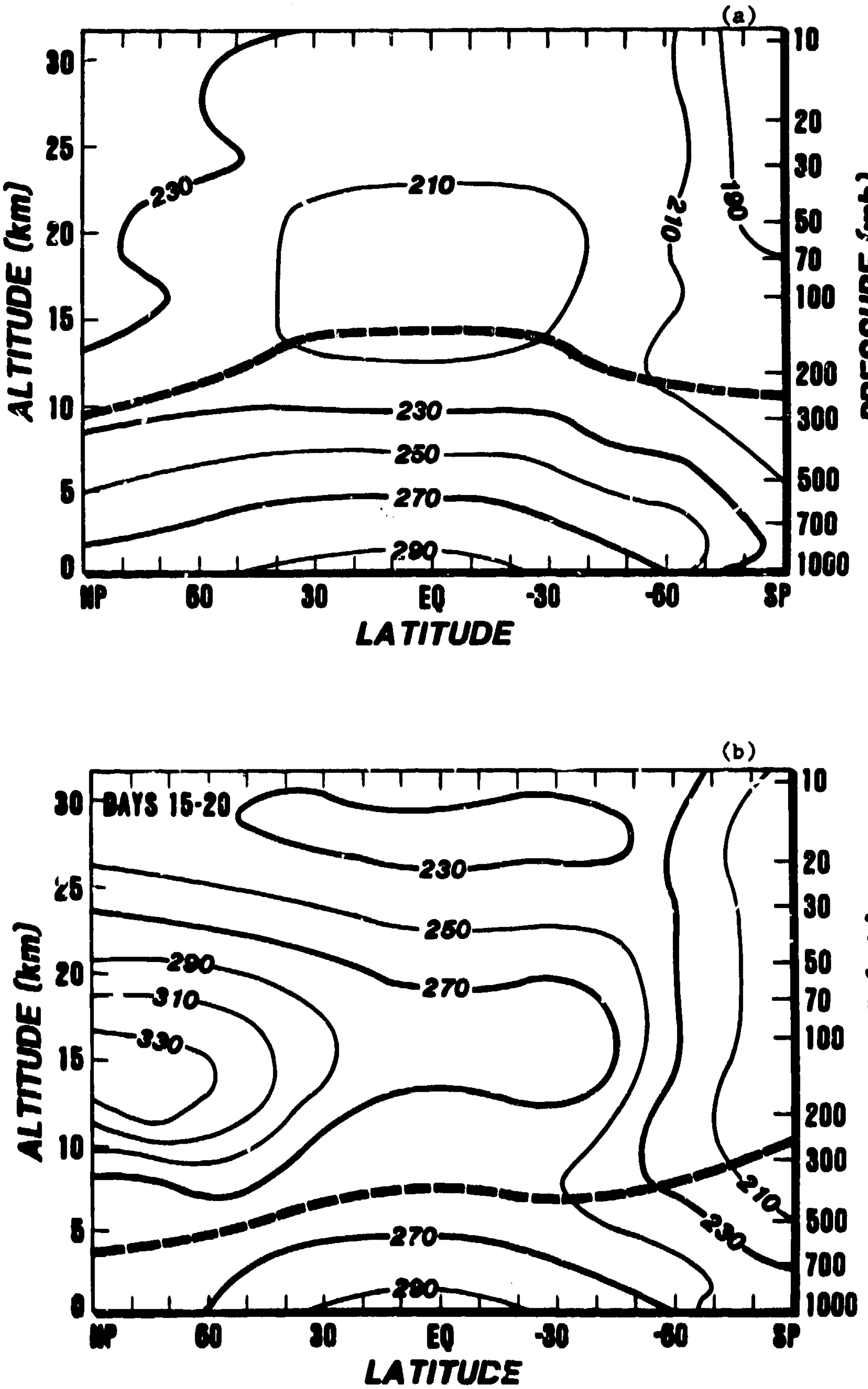
(a)
ALTITUDE (km)
PRESSURE (mb)
LATITUDE
230
210
210
190
230
250
270
290
0
5
10
15
20
25
30
10
20
30
50
70
100
200
300
500
700
1000
NP
60
30
EQ
-30
-60
SP
(b)
DAYS 15-20
230
250
270
290
310
330
210
230
270
290

Figure 3

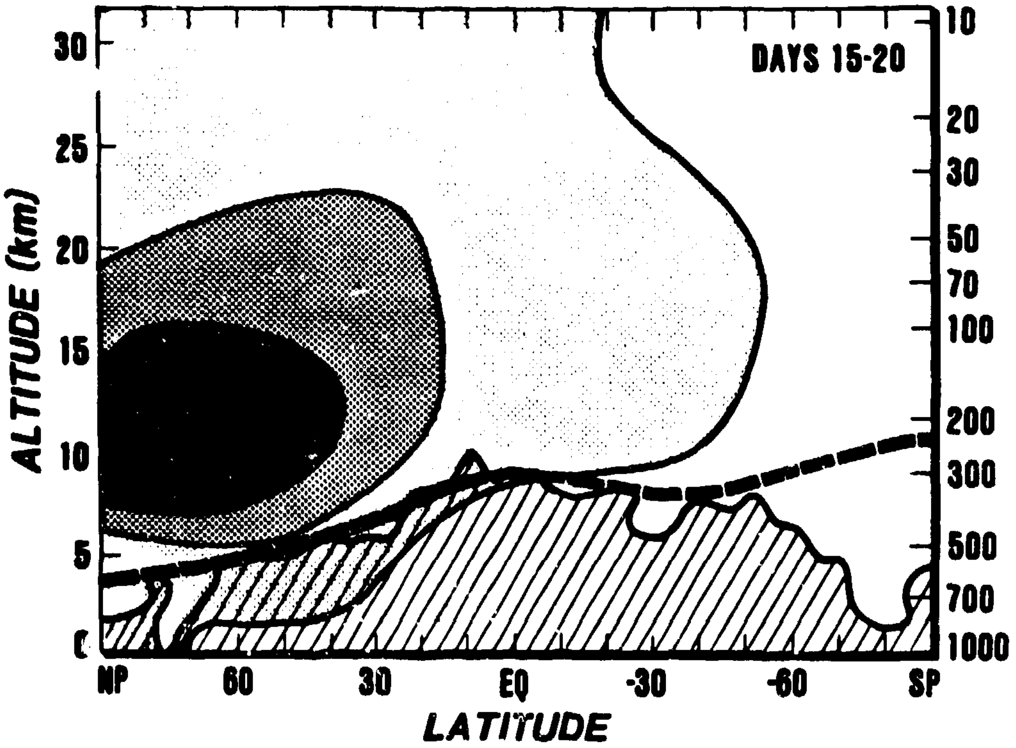

Figure 4

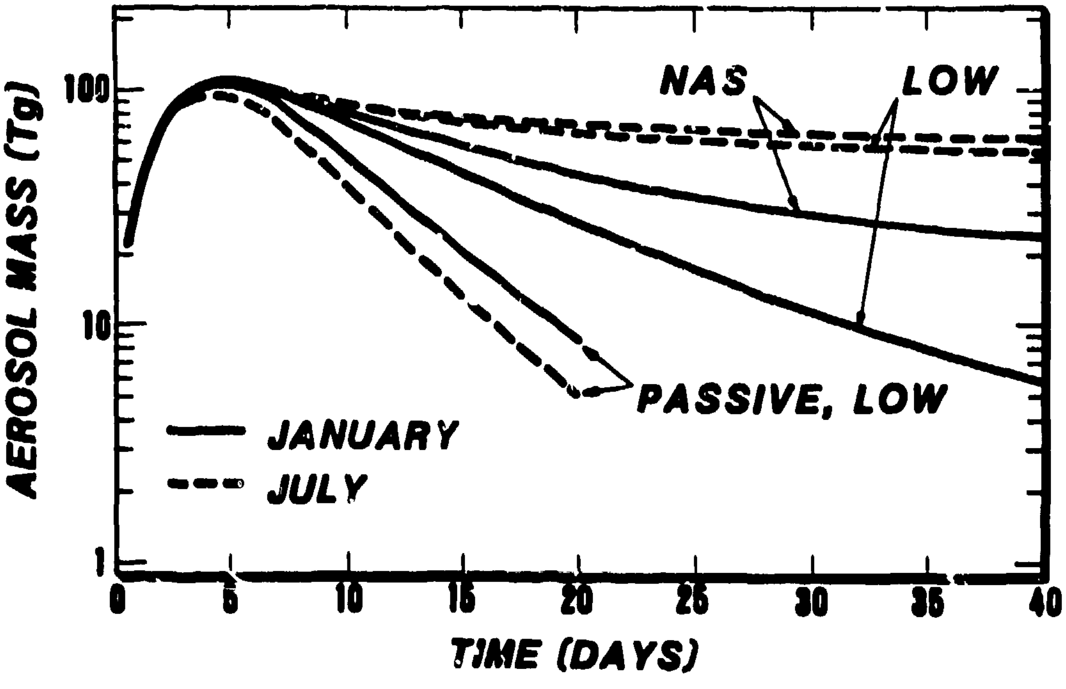

Figure 5

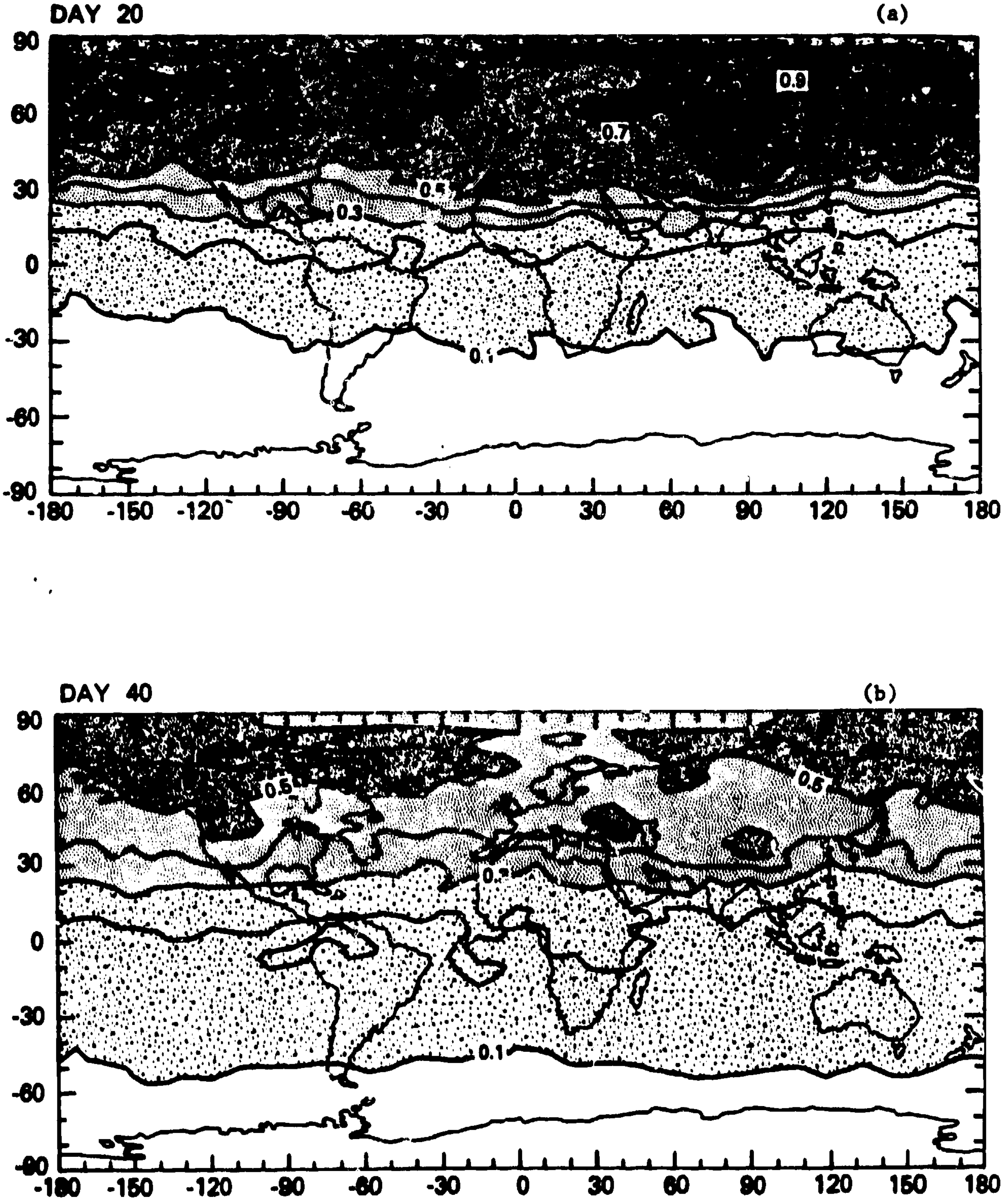
DAY 20
(a)
0.9
0.7
0.5
0.3
0.1
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
DAY 40
(b)
0.5
0.5
0.3
0.1

Figure 6

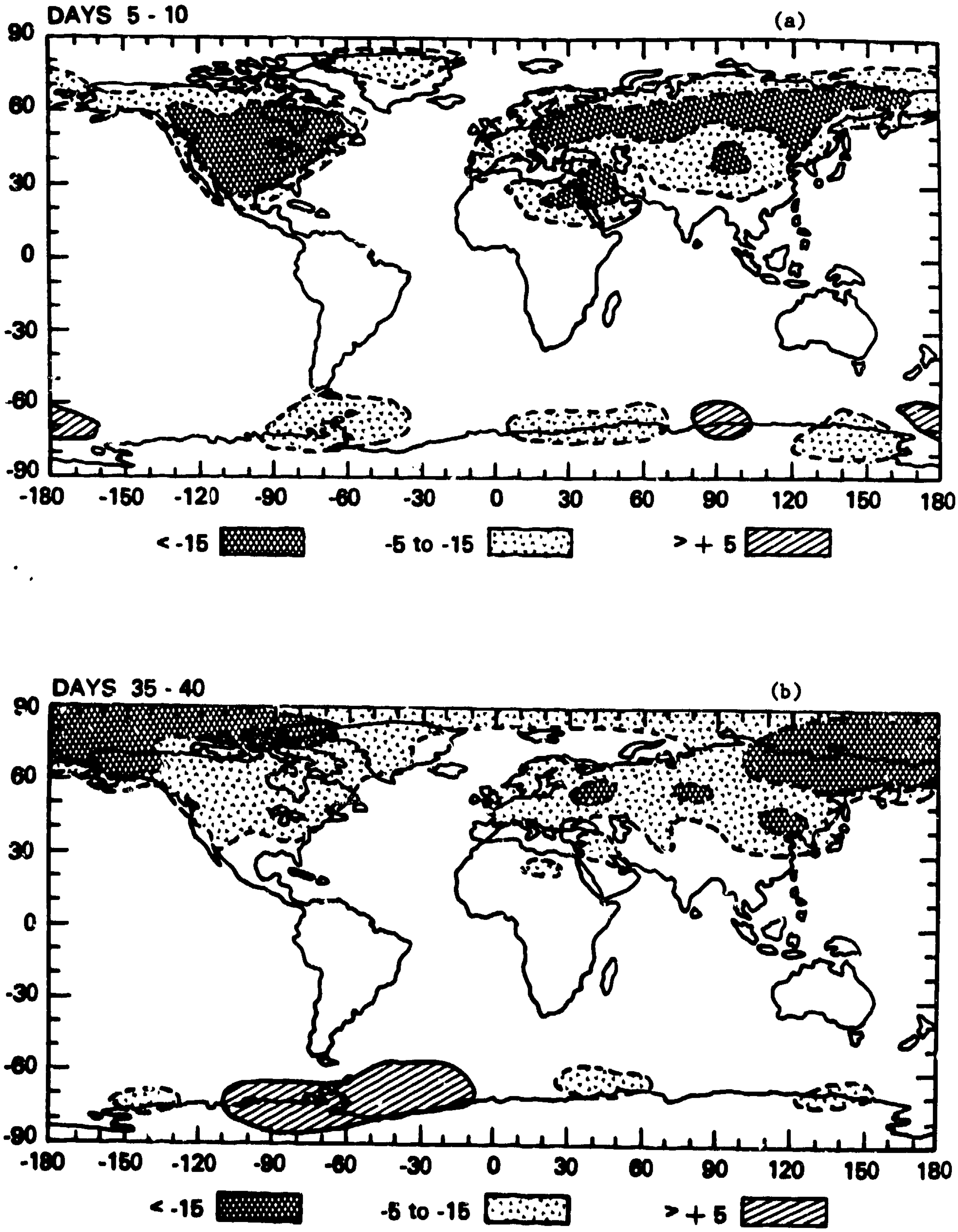
DAYS 5 - 10
(a)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
< -15
-5 to -15
> + 5
DAYS 35 - 40
(b)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
< -15
-5 to -15
> + 5

Figure 7