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TITLE AN OVERVIEW OF CLIMATIC EFFECTS OF NUCLEAR WINTER

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AN OVERVIEW OF CLIMATIC ASPECTS OF NUCLEAR WINTER

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Introduction

In the past few years the physical science community has come to realize that a major nuclear war could have important climatic consequences. Smoke injected into the atmosphere as a result of numerous nuclear explosions would block sunlight from reaching the surface. In addition, the smoke clouds would be relatively transparent to infrared radiation so the ground would cool. This surface cooling, which could last for several weeks at least, has given rise to Richard Turco's descriptive term "Nuclear Winter."

Studies of nuclear winter have only taken place since 1982, yet in those three years our understanding of the atmospheric consequences of a nuclear war has increased dramatically. Although considerable uncertainty remains and we are a long way from being able to make quantitative predictions of the length and severity of a nuclear winter, it seems appropriate at this time to summarize the state of our understanding and to give qualitative assessments which might guide the thinking and planning of those contemplating the biological and human impacts.

In this paper we will begin with a short history of the subject, followed by a discussion of the important physical processes and parameters, and a brief portrayal of a plausible nuclear winter. We will conclude with a discussion of the use and mis-use of analogs, some general statements about nuclear winter, and a reiteration of uncertainties.

History

Nuclear winter comes about because the thousands of fires that might occur in a major nuclear war will inject smoke into the atmosphere. Throughout the first two decades that nuclear explosives existed (1945-1963) it was known, of course, that intense fires could be set. The only two uses of nuclear weapons in war (Hiroshima and Nagasaki) both set intense, city-consuming fires. However, because these two explosions and all of the subsequent atmospheric nuclear tests were well separated in time and space, no one developed an appreciation for the potential cumulative consequences of hundreds or thousands of explosions and resulting fires.

The first progress came in 1980 from an unexpected direction. Discovery of apparently extraterrestrial material in the Cretaceous-Tertiary (K-T) boundary clay led to the plausible theory that the impact of a comet or asteroid on the Earth 65 million years ago placed a very large amount of dust in the atmosphere. Planet-wide cooling resulted and may have triggered mass extinctions. (We note that although the fact of an impact having caused emplacement of the K-T boundary clay seems well-established, much work remains to be done on the climatic and biological consequences. We will return to this point at the close of this paper).

No matter how studies of the Cretaceous-Tertiary event turn out, the theory of particulate-induced cooling set several groups to thinking about similar effects in the nuclear war case. At first, attention was focused on the effects of dust known to be lofted by near-surface bursts. Preliminary estimates suggested that cooling of the order of that experienced in 1815-1816 as a result of the eruption of Tambora might be expected. However, in 1982 Crutzen and Birks called attention to smoke production and published an estimate of the amount that might be produced. Although their estimates where necessarily crude, they correctly surmised that the climatic consequences could be far greater than the dust-only estimates suggested. The reason for this is that smoke is generally a much better absorber of sunlight than is dust or the sulfate particles that dominate volcanic clouds.

Close on the heels of the Crutzen-Birks insight two other efforts got underway. One was a study by the TTAPS group which ultimately resulted in the first numerical estimates of the nuclear winter effect. The calculations done by this group were done in one dimension--a good way to start. By "one dimension" we mean that the calculations were able to describe what was going on as a function of height but could provide no information about variations with latitude or longitude. Although their calculations (and especially the attendant publicity) tended to emphasize extreme cases, the

TTAPS calculations performed the twin service of getting people's attention and providing a basis of discussion.

The second major effort stimulated by the Crutzen-Birks paper was a study undertaken by the National Academy of Science for the Defense Nuclear Agency. The chairman of that group was Dr. George Carrier of Harvard University. In its report the Carrier committee emphasized the considerable uncertainties in estimates of the many parameters involved in nuclear winter calculations (smoke production, scavenging rates, and many others) and in description of important physical processes. The report of the Carrier Committee pointed to two significant areas of research which could reduce the uncertainties. One was work on fires. How much smoke would be produced, over what period of time, and what would the all-important optical properties be? A second area would be attempts to simulate the full three-dimensional (altitude, latitude, and longitude) response of the atmosphere.

There has not been significant progress in the characterization of fires, in part because the questions must be addressed largely through experiments. The questions to be answered and experimental designs are still being formulated. However, in the area of numerical simulations considerable progress has been made in the past two years. A description of the results of that work, carried out by Malone and co-workers at Los Alamos forms much of the remainder of this paper.

The Important Processes

Nuclear explosions over cities, industrial areas, or even grasslands and forests will ignite fires. We have the direct evidence of the Hiroshima and Nagasaki fires and the experience gained from the days of nuclear testing. In addition, we have the evidence of a forest fire ignited in Siberia in 1908 by the explosion of a large meteor in the atmosphere. Although this explosion was certainly not nuclear, its other characteristics were applicable enough to support the contention that intense explosions can set fires. During a nuclear war, fires might be set by direct ignition of flammable materials or might result from blast breaking gas lines, causing electrical shorts, and so on. Although a single explosion might ignite many small, widely scattered fires, breakage and dispersal of flammable materials will promote the prompt creation of a mass fire covering a large area. Such fires create tall plumes of rising, hot air which carry smoke particles at least a few kilometers into the atmosphere.

As the plume cools it's rate of rise slows and the largest particles begin to settle out under the influence of gravity. In addition, if the column contains significant amounts of water vapor (much of it produced in the fire), rain drops form which can wash more of the particulates out of the cloud. The "black rain" which fell on Hiroshima resulted from this process.

In all likelihood, the cloud will encounter winds at altitude which will shear it and create a long trailing plume, much like those we see downwind of tall smoke stacks or at the tops of thunderheads. Wind shear will, therefore, tend to give the smoke cloud a "footprint" -- a surface area at least partially obscured by the smoke -- much larger in area than that of the fire itself.

As the smoke cloud moves with atmospheric winds there will be times when, particularly over the oceans, rain will form, seeded in part by the smoke particles. More of the smoke will consequently be removed. Intermittent smoke removal will continue until another process -- solar induced lofting -- effectively separates the smoke from rain-producing layers of the atmosphere.

During daylight hours the smoke, as an efficient absorber, will be heated by the sunlight falling on it. Because the smoke particles are typically quite small they cool efficiently by conduction, each particle heating a small parcel of air around it. This packet of warm air is buoyant and will tend to rise, carrying smoke particles with it. Compensating subsidence will occur in adjacent regions of clear air.

There is another consequence of the heating and subsequent lofting of the smoke-containing air masses: The temperature structure of the atmosphere is modified and with it the distribution of precipitation.

In the normal atmosphere most incident sunlight passes unimpeded to the ground where most is absorbed and the rest is reflected back into space. The heated ground re-radiates much of this energy at infrared wavelengths. The lower part of the atmosphere is heated by infrared radiation absorbed by water vapor and carbon dioxide and by convective motions (the buoyant motion of packets of air heated by contact with the ground), which also spread water vapor as high as convective motions reach. These processes cause the atmosphere to be hottest near the ground and to grow progressively colder up to an altitude of roughly 10 kilometers. Above that altitude there are significant abundances of species like ozone which can absorb enough sunlight to heat that part of the atmosphere. Consequently, above 10 km the atmospheric temperature rises with altitude. A layer in which temperature increases with altitude is convectively stable, consequently the moisture-bearing bubbles of the lower, unstable atmosphere (the troposphere) can not penetrate into the overlying stable layer (the stratosphere). The boundary separating these two regions is called the tropopause.

In the perturbed atmosphere following a nuclear war, heating of the smoke clouds changes the temperature structure. The net effect is that the tropopause (and with it the moisture-ladened region from which smoke can be removed by precipitation) moves closer to the surface. Over the continents, where surface cooling can be significant, the troposphere could conceivably disappear for a time, at least locally.

The oceans respond rather differently. Because water moves freely and has a large heat capacity, the ocean surface is very difficult to cool. A slight decrease in the surface temperature would quickly cause the cooled water to sink and be replaced by warmer underlying water. Because the mass of the oceans is much greater than that of the atmosphere, a nuclear winter of plausible duration would have no substantive effect on oceanic temperatures. The ocean surface will remain at a fairly constant temperature. This will ensure the presence of at least a modest, water-bearing troposphere over the oceans. Warm, moist air over the oceans will flow with the prevailing winds onto windward shores, moderating the effects of nuclear winter at the ocean margins and contributing to persistent precipitation at least in the lowest part of the atmosphere. This precipitation should keep the near-surface layers of air relatively smoke free.

A final process we need to mention is gravitational settling of smoke particles. In the absence of precipitation, the very small smoke particles will fall out of the atmosphere very slowly. Nonetheless, settling does occur on time scales of months. During that same period particles will occasionally collide and stick together. The larger particles thus created will tend to settle out more rapidly. These particles, once they fall into the remnant troposphere, will be rapidly removed by precipitation.

Parameters

There are many numbers which could be specified for a nuclear winter simulation: the time of year when the war occurs; the number, yield, and targeting of the weapons; the extent of the fires produced; the amount and characteristics of the smoke; it's vertical injection profile; and so on. Some of these parameters are simply unknowable. Description of the "war" is an example. However, we can learn a great deal about the phenomenon of nuclear winter by examining plausible cases and plausible ranges of the parameters. In doing so we can learn which parameters and processes are important and require further study, and which are relatively unimportant and can be approximated.

The approach being taken by the Los Alamos group is to examine a small number of cases (resembling the "baseline case" and excursions described in the Carrier Committee Report) with which the importance of physical processes can be tested as well as the effects of two dominant parameters. These parameters are the amount of smoke injected into the atmosphere and the time of year

Specifying the amount of smoke lumps together a number of parameters and processes related to war scenarios and fire dynamics and chemistry. Given our limited state of knowledge it would be virtually impossible to do better than crudely estimate the amount of smoke to be expected from a given war scenario. The Carrier Committee estimates that their baseline case -- a war in which roughly half of the existing weapons are actually detonated -- between 20 and 650 million metric tons of smoke would be injected into the atmosphere. The committee recommends 180 million metric tons as a plausible mid-range value. The modeling results to be discussed shortly concentrate on this 180 million ton estimate, although we will make some mention of the effect of different values of this most important parameter.

We further assume that the fires and resultant smoke will be concentrated over the United States and Europe, including the western part of the Soviet Union. One might also include minor sources elsewhere on the planet but, as we will see, lateral dispersal of the smoke clouds is fairly rapid so that details of the initial distribution in latitude and longitude are relatively unimportant.

We should also mention that the initial vertical distribution of the injected smoke will depend on the intensity of the various fires and on local meteorological conditions. Because there are likely to be a many of fires occuring under a variety of circumstances, modeling the injection is complex. In the early, one-dimensional studies performed before the importance of solar-induced lofting was appreciated considerable attention was paid to the effect of varying the injection profile. However, it turns out that lofting is so dominant that the results are less sensitive to the injection profile than previously thought. Nonetheless, we will discuss two general cases which should span the plausible range: a "low" injection profile in which the smoke is deposited between 2 and 5 kilometers altitude, and an "NAS" profile which uses the Carrier Committee recommendation of uniform smoke density between 0 and 9 kilometers.

A final parameter of importance is time of year. During the northern summer when the sun shines more or less directly down on the majority of the smoke, heating of the cloud is strong and modification of the vertical profile of atmospheric temperature is dramatic. Further, the absolute decrease in the amount of sunlight reaching the surface is quite large and, consequently, cooling of the surface can be substantial. In winter when sunlight strikes the northern hemisphere obliquely, the effects are much reduced. Although simulations have not yet been done with realistic temporal variations of solar illuminations (the day/night cycle and the slower change from day-to-day), cases done for mean July and January conditions illustrate the expected seasonal variation. Because the atmosphere responds to change on timescales of several days, effects of the day/night cycle are expected to be minor.

Simulations of Nuclear Winter

The ability to do three-dimensional simulations of the dynamics of the normal atmosphere has existed for many years. There are a small number of groups who have developed computer programs called "general circulation models" or "global climate models", GCM's for short. One of the principal groups is at the National Center for Atmospheric Research (NCAR) at Boulder, Colorado, and their computer code is called the Community Climate Model. These computer programs have much in common with weather prediction codes, but they have been designed to study the long-term behavior of the atmosphere -- the phenomenon of climate.

In general the more sophisticated climate models do rather well. They predict the existence and approximate locations and strengths of jet streams, the amount and distribution of precipitation, and the run of atmospheric temperature profiles. They are less capable of predicting short-term variations or details of the surface temperature. The latter is particularly important for interpretation of nuclear winter simulations and we will return to this point shortly.

A global climate model is the appropriate starting point for generating nuclear winter simulations. However, much work had to be done before appropriate simulations could be produced. The models, having been designed to study the normal atmosphere only, lacked representations of physical processes central to nuclear winter. Examples include transport of particulates (the smoke and dust), absorption and scattering of sunlight and heating of air by embedded particles, and removal of particles by rain.

The work is not complete and, in particular, the code used for the Los Alamos studies does not yet treat some secondary radiative effect of the particles. Also, work remains to be done on treatment of the near-surface atmospheric layers, which strongly influence surface temperature, the predicted quantity of greatest interest.

Nonetheless, we have learned a great deal about the problem with the computer model as presently modified and can now give a general, qualitative picture of nuclear winter.

The simulation we will describe involved the injection of 170 million metric tons of smoke (but no dust) in July over the United States, Europe and the western Soviet Union, as illustrated in Figure 1. Figure 2 shows the result of solar-induced lofting. In the cases illustrated here smoke was injected between 2 and 5 kilometers altitude. There are two sets of curves in the figure; both illustrate the concentration of particles. The dashed curves -- labeled "passive" -- result from a simulation in which the particles do not absorb solar radiation. Such particles are moved by the simulated winds and are removed by the simulated precipitation but have no affect on the atmosphere. The contours indicate particle concentrations, averaged over longitude, twenty days into the simulation. The maximum concentration of passive particles is still located in the lowest five kilometers of the atmosphere, where the particles were injected. The solid curves -- labeled "interactive" -- show the concentration of smoke particles which interact with (absorb) solar radiation in addition to being transported by winds and scavenged by precipitation. It is evident that the smoke has been lofted by solar heating and that the concentrations are larger. Compared to the passive tracer, more smoke remains in the atmosphere because lofting and modification of the atmospheric temperature profile due to solar heating of smoke have effectively separated the smoke from the precipitation which would remove it.

These effects are illustrated in the next three figures. Figure 3a shows the normal structure of the atmosphere; we have drawn contours of temperature (in degrees kelvin) and indicated the location of the tropopause by a heavy dashed curve. The second figure of the set (Fig. 3b) indicates the structure of the perturbed atmosphere with the lowered tropopause and heated stratosphere evident. In the third figure (Fig. 4) we have indicated the location of smoke with the dotted regions and that of precipitation with the striped markings. Most of the remaining smoke is above the tropopause and most of the rain is below.

The consequence of this separation of smoke from precipitation is a pronounced decrease in the removal rate after the atmospheric structure has changed. This is illustrated in Fig. 5, which shows the change with time of globally integrated smoke mass. The uppermost pair of dashed curves apply to interactive smoke injected with "low" and "NAS" vertical distributions; the curves show a very slow decrease of smoke mass after about two weeks. For comparison, the dashed curve labelled "passive, low" shows how the removal would proceed without solar heating of smoke.

As mentioned above, the smoke was initially injected over the United States, Europe, and the Soviet Union. If there were no variation of wind speed with altitude, latitude or longitude, the patchy distribution of the smoke would persist. However, even the normal atmosphere has considerable variation in wind speed and direction and even more variation is present in the perturbed atmosphere. These variations, together with the great vertical distribution of of the lofted smoke, ensure that before long the initially patchy distribution becomes more uniform over much of the northern hemisphere. Figure 6a indicates the smoke distribution in latitude and longitude at day 20 of the interactive simulation. Some patchiness has persisted. For instance, there is a relatively clear space over the north Atlantic where roughly half of the direct sunlight can penetrate to the surface. At this same time the heavier concentration over central Asia means that only about a third of the incident sunlight can get through. By day 40, shown in Fig. 6b, more of the smoke has been removed or has spread southward, the distribution has become more uniform, and over much of the northern hemisphere between half and three-quarters of the incident sunlight is getting through.

The prediction of nuclear winter simulations that have the greatest importance for agricultural and other human activities is surface temperature. Although several improvements to the model are needed to increase our confidence in its predictions, we can indicate general trends from the current simulations. Figure 7a indicates temperature departures, relative to normal conditions as predicted in the GCM simulation of the unperturbed atmosphere, for a July war. Averages over Days 5-10 are plotted. In the cross-hatched regions over most of North America and the Soviet Union temperature decreases of more than 15 degrees centigrade might be expected. These qualitative predictions are in agreement with the expectation that the greatest cooling should occur near the centers of the major land masses in the northern middle latitudes. Notice the less severe effects over the west coast of North America and most of the NATO areas produced by the influx of relatively warm air from over the oceans. Figure 7b indicates temperature changes averaged over Days 35-40. The long lifetime of smoke in July causes reductions of 5-15°C to persist over the continents north of 30° N.

The simulations we have just discussed were done for July conditions. In January, when the sun angle is lower, solar-induced lofting is less important. Less separation of smoke and precipitation occurs, so smoke is removed more rapidly, as indicated by the solid curves in Fig. 5 labelled "NAS" and "low." However, smoke removal is still less rapid than without the influence of solar heating, illustrated by the solid "passive, low" curve. Figure 8 shows the January smoke distribution at day 20. Compared with the July simulations there is only about half as much smoke to be found over any given location.

Finally, in Fig. 9 we show an average over Day 5-10 for a January case. Cooling by as much as 15°C is widespread over the northern hemisphere continents during the first two weeks. The temperature returns toward normal faster than in the summer case because smoke removal proceeds more rapidly in winter.

Analogs

The concept of nuclear winter was born out of the Alvarez hypothesis that the impact of an asteroid or comet with the Earth some 65 million years ago threw a great cloud of dust into the atmosphere and that the resultant global cooling led to mass extinctions of organisms ranging from marine plankton at the base of the food chain to dinosaurs at the top. In connection with both the Alvarez and Nuclear Winter hypotheses, much interest has been paid to episodes of unusually cold weather associated with great volcanic eruptions. The volcanic and impact cases have some relevance to the physics of nuclear winter. However, as the Carrier Committee emphasizes in its report, these analogs have often been cited uncritically.

Let us briefly discuss first the Cretaceous-Tertiary phenomenon and then the volcanic evidence.

The two things that seem well established about the sudden end to the Cretaceous are that many kinds of organisms died--that there were mass extinctions--and that the triggering event was the impact of an asteroid or comet of about 10 kilometers diameter. What we do not know are the environmental stresses that led to the mass extinctions and, in particular, to the pattern of extinctions. Much has been said and written about the potential of nuclear winter to have biological consequences of a magnitude comparable to the K-T event. However, in the absence of better knowledge about the events of sixty-five million years ago (or indeed of other instances of impacts which surely must have occurred but which did not make as lasting an impression in the biological record) it is premature to speak of nuclear winter as a threat to the continued existence of terrestrial life.

That is not to say that nuclear winter might not be a severe threat to survivors of the prompt effects of a nuclear war. The war itself would likely kill hundreds of millions of people and destroy the transportation and communications networks on which modern societies depend. Add to that the possibility of episodes of sub-freezing weather or, at least, of a significantly shortened growing season following the war and the survivors would be even more severely stressed.

We have an indication from the volcanic analogs of the nature of the effects that might be expected during the late stages of a nuclear winter. During the Nineteenth Century two very large volcanic explosions occurred in the Indonesian Archepelago: Tambora in 1815 and Krakatau in 1883. Both occasioned unusual sunsets and at least in the case of Tambora there seems to have been a period, particularly in 1816, when episodes of freezing weather occurred in mid-summer. The year 1816 has been called -- with drama but not with accuracy -- The Year Without a Summer. A book with that sub-title and a companion piece in Scientific American have been published by the Stommels.

In April 1815 Mount Tambora on the island of Sumbawa suffered a series of explosive eruptions which threw approximately 100 cubic kilometers of the mountain into the air. This is about 100 times the material ejected by the May 1980 eruption of Mt. St. Helens. Although most of the ejecta fell nearby, the skies in that part of the world were blackened. "The darkness occasioned in the daytime by the ashes in Java was so profound, that nothing equal to it was ever witnessed in the darkest night." So wrote Sir Thomas Raffles, then temporary Lt. Governor in the Dutch East Indies.

By the summer of 1816, the cloud had probably spread over much of the world. Steve Schneider has estimated that the global mean temperature reduction was about 0.3° Centigrade (0.5° F), but it is clear that local variations could be much greater. As summarized by the Stommels, the summer of 1816 had some very unusual weather. Records are not extensive for that period, but in New England, where there are quite a few records of weather and temperature, we know that mean temperatures were depressed by several degrees at New Haven, for example, and, perhaps more importantly, there was snow in mid-June as far south as the northern Massachusetts border and killing frosts on July 9th and August 21st and 30th. The effects were by no means uniform and depended strongly on latitude, local topography, and distance from the sea. Nonetheless, 1816 was generally a bad year for farmers.

Similar phenomena were reported in western Europe but not, as far as we can tell, in China or Japan where rice crops were normal.

One very important point which should be made at this juncture is that comparison of the volcanic experience with the nuclear war case is fraught with peril. All too often one reads "The Tambora explosion, with an explosive energy estimated at X megatons, produced a global temperature decline of one degree centigrade. Therefore, a one thousand megaton nuclear war....." The simple fact is that the particulates injected into the atmosphere by a major volcanic explosion have very different optical properties. The sulfate and dust particles ejected by volcanos scatter sunlight rather than absorb it. Therefore, they have relatively little effect on the temperature structure of the atmosphere and do not self-loft. The cases are very different.

Nevertheless, the volcanic experience does suggest that, in the late stages of a nuclear winter, even for small reductions in the mean temperature there could be local fluctuations of much greater magnitude with important consequences.

General Statements About Nuclear Winter

The computer simulations which have been done to date suggest a few general conclusions.

- Heating of the smoke by sunlight is extremely important and produces several effects which decrease the efficiency with which precipitation removes smoke from the atmosphere. First, the heating gives rise to vertical motions which carry smoke well above its original injection height. Second, the tropopause, initially above the smoke, reforms below the heated smoke layer and separates it from precipitation below. Although much smoke is scavenged while the thermal structure is being altered, the residence time of the remaining smoke is greatly increased. We find, particularly for July conditions, a longer lasting "nuclear winter" effect than in earlier modeling studies in which normal tropospheric residence times were assumed. In January, the smaller solar flux in the northern hemisphere allows faster removal of smoke than in July.

- These effects also decrease the sensitivity of the residence time to the poorly known vertical distribution with which smoke would be injected into the atmosphere.
- The movement of smoke to higher altitutdes speeds its dispersal over the hemisphere because the horizontal winds are stronger aloft.
- The greatest effects occur with July conditions.
- Typical temperature decreases will tend to be less severe than those predicted in TTAPS. However, because the smoke and precipitation become physically separated, recovery to normal temperatures may occur more slowly. We anticipate that noticeable cooling following a summer war could persist for several months, if as much smoke is produced as assumed in the studies described here.
- If the smoke mass is a factor of ten smaller, which is within the range of current estimates, only small temperature changes lasting a few weeks will occur. Smoke masses greater than 170 million metric tons primarily increase the duration and global extent of the climate change, rather than its severity in the northern hemisphere.
- The simulations do not yet accurately predict surface temperature variations. However, it is reasonable to expect that occasional local variations will be greater than the mean changes indicated here.

Uncertainties

It is important to emphasize the tenative nature of nuclear winter predictions. Although great strides have been made in understanding the relevant physical processes, we have a long way to go both in understanding the amount and characteristics of smoke produced by large fires and in the development of computer models. The global climate simulations are done with physical resolution roughly the size of the state of New Mexico, yet it is clear that processes that occur during the first few days on much smaller scales will be important in determining the initial smoke loading and distribution. We need to know more about the physical and optical properties of smoke produced in large urban fires and about the dynamics and chemistry of those fires. Such information will be difficult to obtain. In addition, we need to gain confidence in the reliability of the simulations, a task also made difficult by a lack of experimental data against which to test results. In this latter area appeal to data obtained from spacecraft about the atmospheres of other planets, particularly Mars, may be fruitful.

At present we can not offer detailed predictions, only trends and indications of the general character of a nuclear winter.

Figure Captions

Fig. 1. Geographical pattern of smoke injection. Smoke or passive tracer is injected over the United States, Europe and the western Soviet Union at a rate which is maximum at day 0 and decreases linearly to 0 at day 7; half of the mass is injected during the first two days.

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.

Fig. 8. The same as Fig. 6a, except for January conditions. The small areas with the darkest stippling have optical depths in excess of 0.5.

Fig. 9. The same as Fig. 7a, except for January conditions.

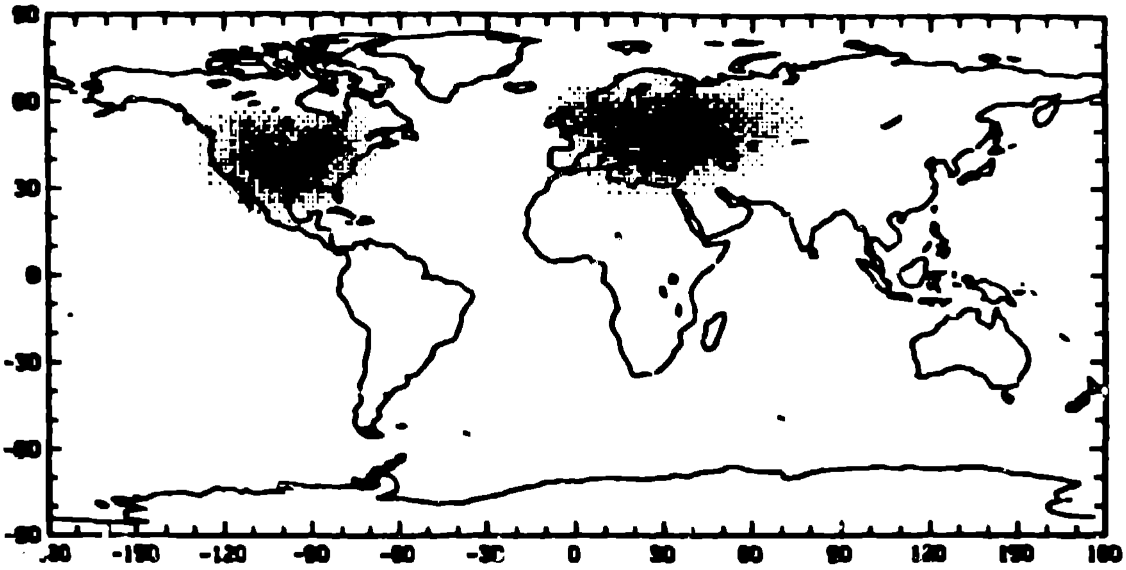


Figure 1

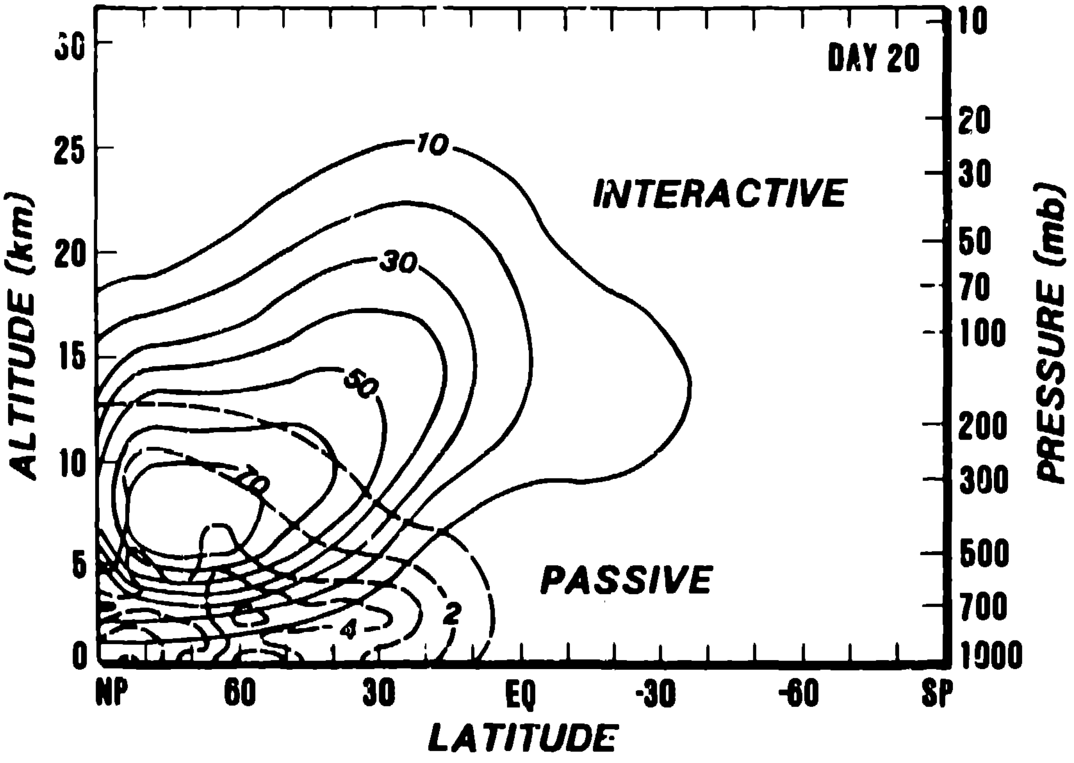
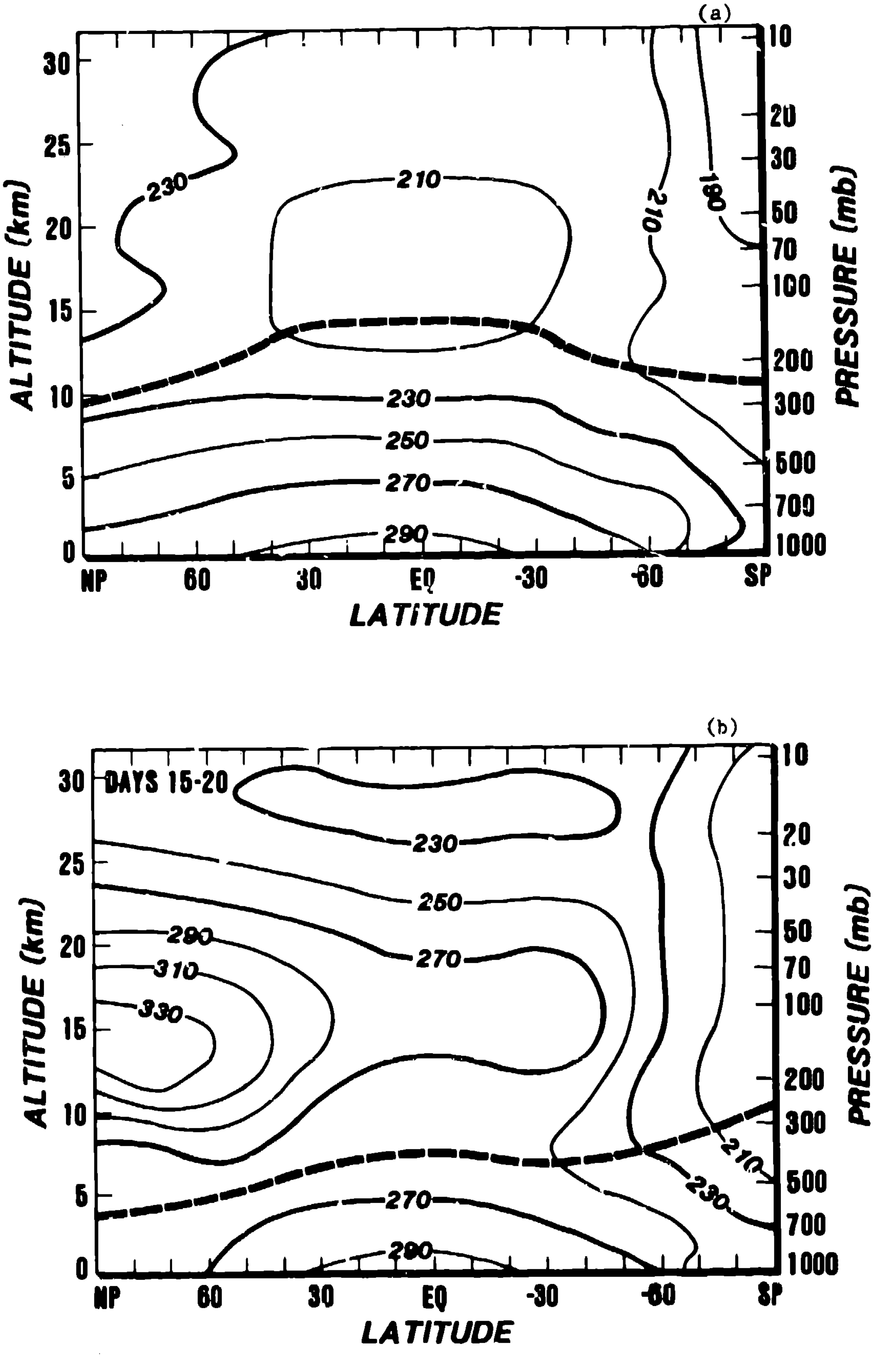


Figure 2


(a)
ALTITUDE (km)
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230
250
270
290
310
330
210
230
270
290
NP
60
30
EQ
-30
-60
SP
LATITUDE

Figure 3

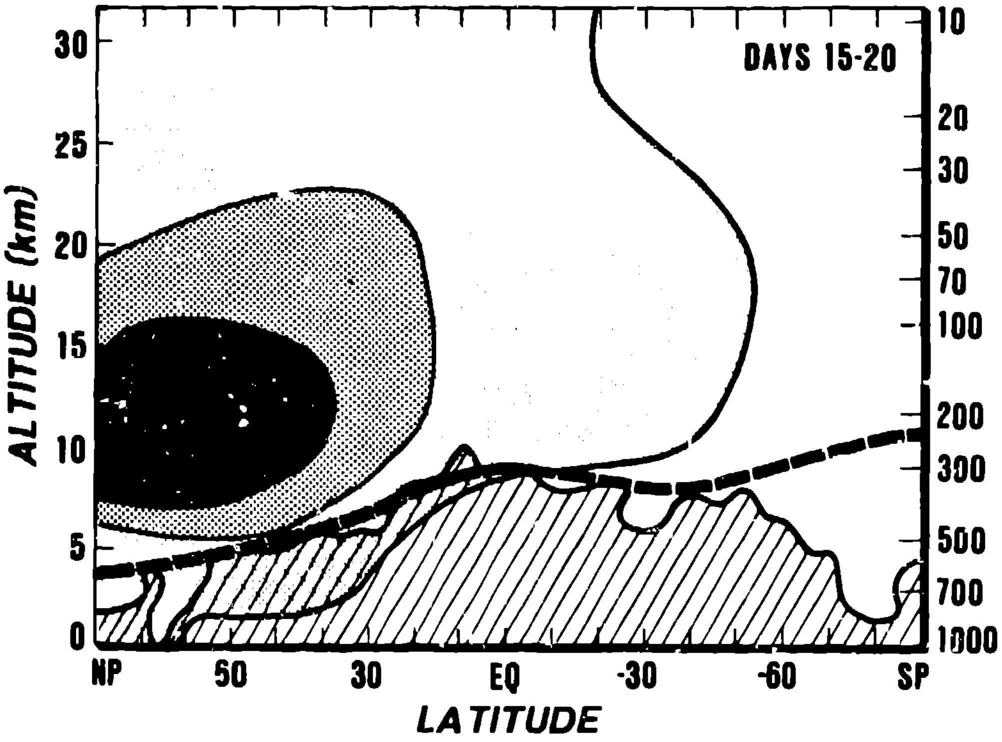

Figure 4

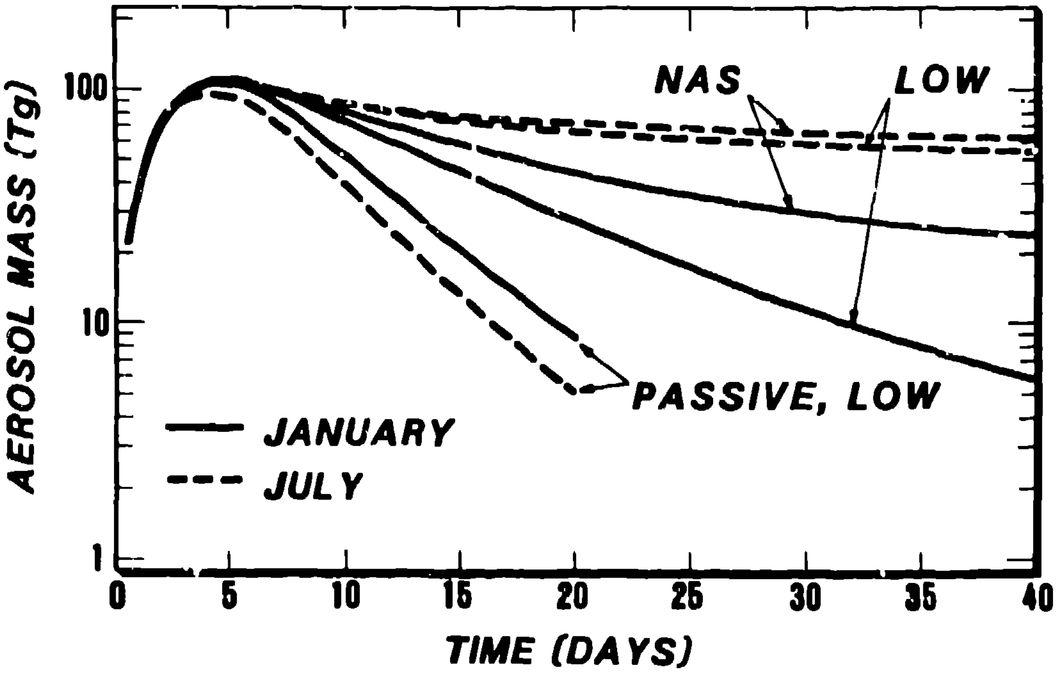

Figure 5

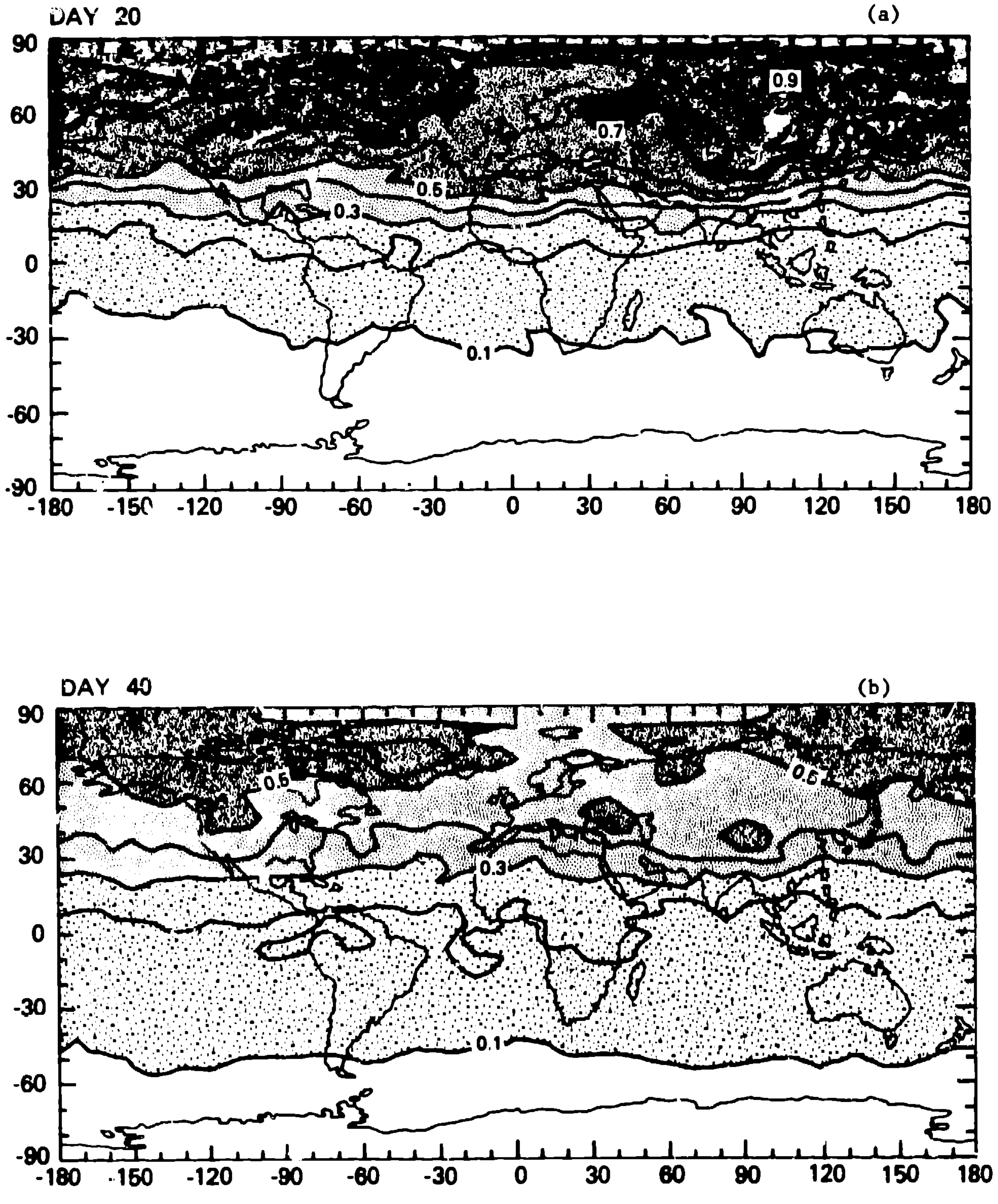
DAY 20
(a)
0.9
0.7
0.5
0.3
0.1
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
DAY 40
(b)
0.5
0.5
0.3
0.1
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180

Figure 6

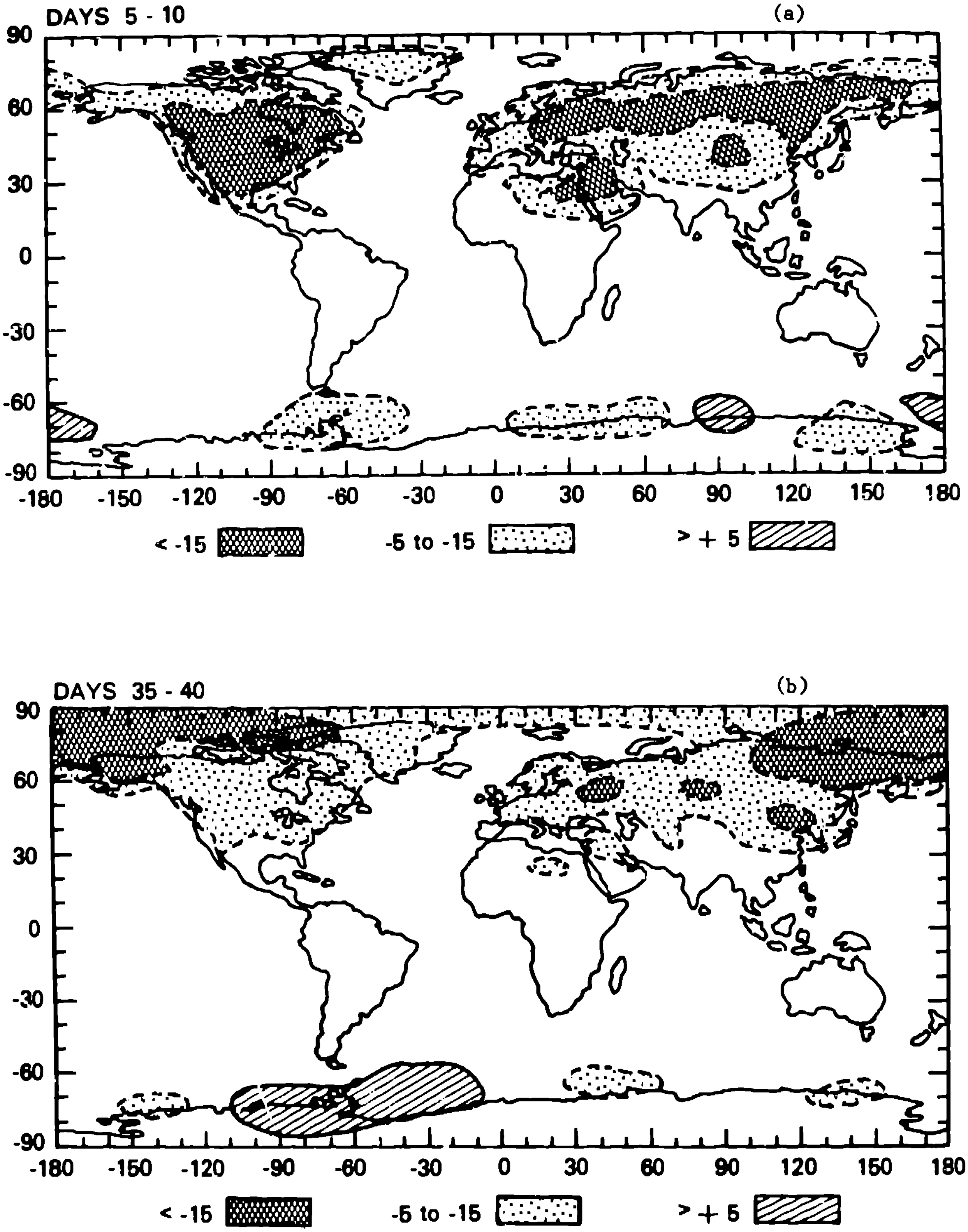
DAYS 5 - 10
(a)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
< -15
-5 to -15
> + 5
DAYS 35 - 40
(b)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
< -15
-5 to -15
> + 5

Figure 7

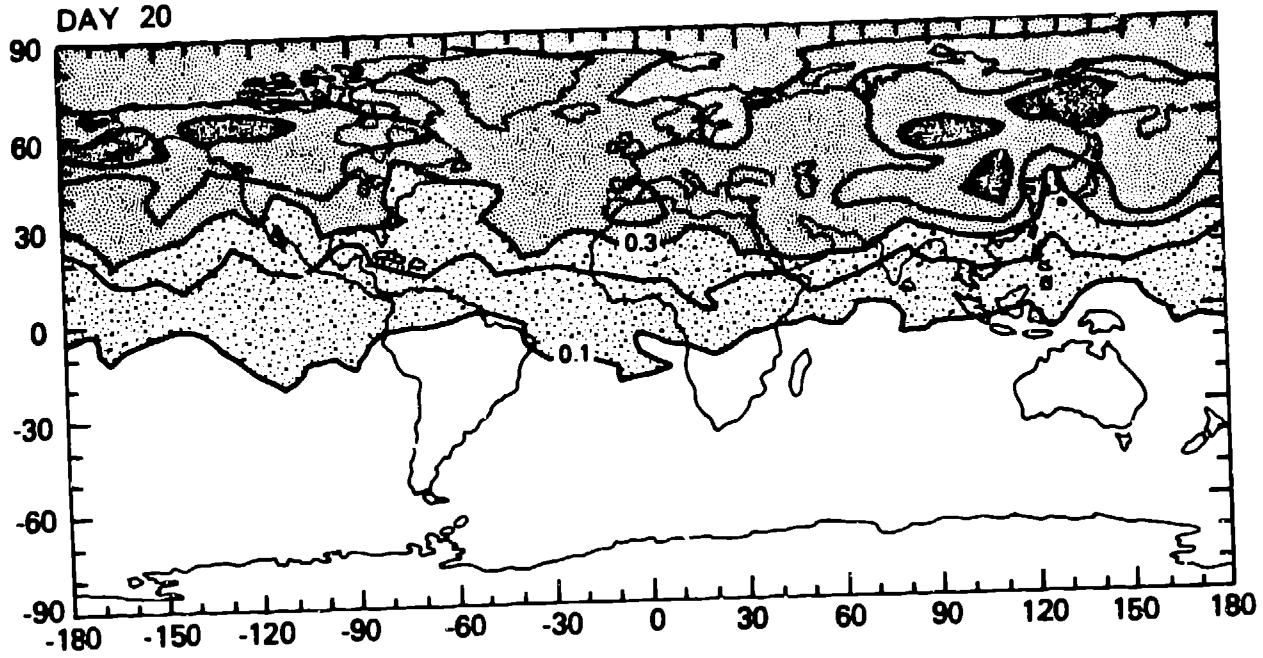

Figure 8

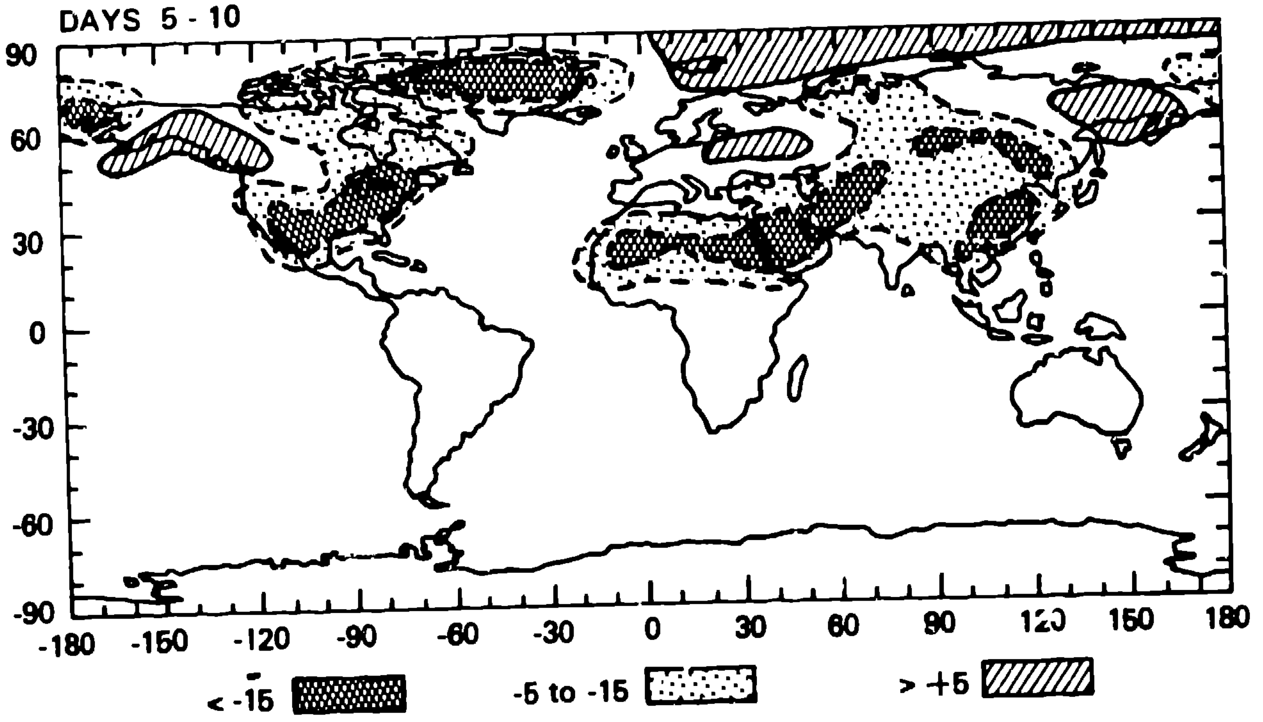

Figure 9