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NUCLEAR WINTER; IMPLICATIONS FOR CIVIL DEFENSE

C. V. Chester
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We believe the state of knowledge about nuclear winter is sufficiently developed to conclude

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- The principal threat from nuclear winter is to food production, and this could present problems to third parties who are without food reserves.

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The consequences of nuclear winter could be expected to fall more heavily on the Soviet Union than the United States due to its higher latitude and less productive agriculture. This may be especially true if disturbances of rainfall amounts and distribution persist for more than a year.

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NUCLEAR WINTER: IMPLICATIONS FOR CIVIL DEFENSE

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CONTENTS

CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

In 1983, a study was published on the climatological effects of injection into the atmosphere of hundreds of million of tons of smoke and dust by a large nuclear war. This study, entitled "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions" (nicknamed TTAPS from the initials of its authors; Turco, Toon, Ackerman, Pollack, and Sagan), predicted temperature depressions of 40 to 60° for some plausible values of the input parameters. Some cited these results as proof that nuclear war is not survivable and, hence, that civil defense is unfeasible.

A lively debate and vigorous research program followed with participation by atmospheric scientists and climatologists from several large U.S. laboratories.

A consensus on nuclear winter seems to be emerging. It is generally believed possible, for some range of heavy attacks directed against cities, that significant but not lethal climate alteration will ensue for at least a few weeks. While the TTAPS study has been subjected to severe criticism, with the aid of hindsight, the study did remarkably well, considering its limitations as a one-dimensional model of a dry planet. It identified a real possibility for climate upset for values of the input parameters subsequently judged to be reasonable. It produced results within a small factor (2 or 3) of those currently being produced by three-dimensional global circulation models.

Much of the criticism of the TTAPS study has been justly directed at the sensational way it was presented to the public and the way selected results were used in an attempt to achieve political ends. The authors of this study recognized the limitations of the study and clearly stated them. Political partisans subsequently ignored these limitations and caveats and presented results of pessimistic excursions of the calculations as inexorable reality.

Three-dimensional general circulation models being developed and used at Los Alamos, the National Center for Atmospheric Research, and Livermore National Laboratory for a reasonable attack size seem to be converging on a temperature depression of the order of 15° C averaged over the temperate regions of the Northern Hemisphere (Schneider & Thompson 1986). Temperature depressions as large as 25° C are predicted in the interiors of continents, should the attacks occur in the summertime. Wintertime wars would produce temperature depressions of only a few degrees, a critically important result. All the models suggest the possibility of episodes of freezing temperatures in the interiors of continents in the mid-to-high latitudes for attacks occurring in July and April, as well as January. Summertime and springtime attacks do not produce temperatures colder than those seen in normal January conditions at the latitude of interest.

Work at Livermore and Los Alamos has raised the possibility of a substantial reduction of convective precipitation due to suppression of convection in the troposphere by heating of smoke in the upper troposphere. This increases the possibility of drought as a major consequence of climatological disturbance form nuclear war. Ghan et al. (1985) indicate that suppression of convective precipitation occurs at much lower levels of smoke loading in the atmosphere than is required for significant temperature depression. The reduced scavenging of smoke due to its lofting from solar heating (Malone et al. 1986) suggests that significant levels of smoke could persist for many months after the attack. This persistence of smoke increases the possibility that rainfall disruption, at least disruption of the rainfall patterns, could occur in the second year after a war.

We have estimated the potential availability of water in the continental United States during a year-long 50% decrease in precipitation, using state and river-basin-level information. We have compared the availability to annual demands for water from central domestic systems, irrigated agriculture, and industry to determine whether sufficient water would be available, first, for potable needs and raising food and, second, for other economic purposes.

The analysis indicated that water availability for potable requirements would be more than adequate, in part, because these comprise only a few percent of total domestic central system use.

Agriculture which is unirrigated (dryland) or irrigated with surface water would be severely impacted by a drought of the magnitude postulated here.

Areas that obtain irrigation water from aquifers would be relatively invulnerable, providing electric power could be maintained or restored. Should drought conditions persist into a second growing season, cropping practices might have to be changed in areas with continuing supplies of groundwater to accommodate high-priority irrigated food crops for human consumption. If irrigated farmlands were entirely devoted to the raising of wheat, groundwater supplies alone could be adequate to supply more than half of the wheat needed to provide a minimum diet for the American population.

There are still very large uncertainties in the climatological consequences of nuclear war. Some of these are due to the limits on resolution of the models used. There is insufficient information ont he production and optical properties of smoke from combustion of urban environments.

The irreducible uncertainty is the nature and severity of a nuclear war. There is no way to predict in advance the size of an attack, the fraction landing on cities, or the fraction airburst or groundburst. Even where battle plans are known, the reliability and survival of the enemies' weapons as well as one's own are not predictable.

We have drawn some implications for civil defense of the possibility of nuclear winter:

1. <u>Nuclear cold nor drought is likely to be a direct threat to human survival</u>.

After an attack, a population which has the wherewithal to survive its local January climate will not be endangered by the cold from a nuclear winter. For that portion of the population not equipped with sufficient cold-weather clothing for the local climate, crowding into shelters and the improvisation of cold-weather clothing are expedient means of coping.

Supplies of potable water are estimated to be adequate in almost all areas of the United States even under drought conditions if electric power can be restored to water pumps.

2. <u>The principal threat from nuclear winter is to agriculture.</u>

There is a high likelihood (in case of a sufficiently severe war) of heavy losses of agricultural productivity for the crop year in which a spring or summer nuclear attack occurs. There will likely be episodes of freezing temperatures in the mid-to-high latitudes in the interiors of continents during the summer growing season. In addition, there is a likelihood that rainfall will be disrupted--either suppressed significantly or substantially altered in pattern.

3. <u>Nuclear winter does not present an entirely new threat from nuclear war to the United States or the Soviet Union.</u>

Both countries could reasonably expect to lose agricultural productivity in a springtime or summertime war due to fallout either killing the early crops by radiation or keeping the farmers out of the fields when they should be conducting time-sensitive operations. Both countries are believed to have at least a year's supply of grain in storage at all times. In the United States, grain stored on farms and grain held in distribution centers make up this reserve. The Soviet Union has long provided for heavily protected state grain reserves.

The possibility exists for reduced agricultural production in the second year (i.e. 12 to 14 months after a July attack) due to the disturbance of rainfall patterns. <u>Severe</u> loss of production in a second crop year i.e., to much less than 70 million tons of grain (from a prewar production of 350 million tons) would present a problem not presently considered in any civil defense studies that we have seen. We consider this unlikely, and in any case this probably poses less threat to the United States than to the Soviet Union even with a damaged agricultural economy, given the larger normal production and better rainfall distribution in the United States.

4. <u>The consequences of nuclear winter would fall more heavily on the Soviet Union</u>.

The Soviet Union is at a higher latitude than the United States and occupies a larger continent. It could be expected to see more severe temperature reductions. Under normal peacetime conditions the Soviet Union has difficulty in meeting its agricultural production targets due to marginal climate and managerial deficiencies.

Recommendations

We offer the following recommendations to deal directly with the potential effects of a nuclear winter. Note that these measures are needed in any case to deal with the potential effects of nuclear war even without climatological effects.

1. In a severe nuclear crisis, potential evacuees should be reminded to take their winter clothing with them when they go to nearby shelters or evacuate the area. Nuclear winter (or autumn) may or may not come, but January surely will. With unheated houses and no automobiles, people with no warm clothing will be forced to huddle in shelters, severely limiting their ability to carry out critical survival and recovery tasks.

2. Encourage families who can afford it to maintain a 30-day to a 1-year supply of stored food. Not everyone will have the resources to do it, but those who can will reduce the load on governmental emergency food organization.

3. Support agricultural policies that result in large amounts of grain in storage. Encouragement of large export activities in grain and especially grain-fed meat is one way to accomplish this. A large domestic production of grain-fed meat for the domestic market is also helpful.

4. Assure EMP-protected backup electric power for water supplies. Highest priority should be for underground potable water supplies in host areas. Plans should be developed for restoring power to drought-resistant irrigation-water supplies.

NUCLEAR WINTER: IMPLICATIONS FOR CIVIL DEFENSE

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ABSTRACT

"Nuclear Winter" is the term given to the cooling hypothesized to occur in the Northern Hemisphere following a nuclear war as the result of the injection of smoke from burning cities into the atmosphere. The voluminous literature on this subject produced since the paper was published in 1983 by Turco, Toon, Ackerman, Pollack, and Sagen (TTAPS) has been reviewed. Three-dimensional global circulation models have resulted in reduced estimates of cooling--15 to 25^{o}C for a summer war and a few degrees for a winter war. More serious may be the possibility of suppression of convective precipitation by the altered temperature profiles in the atmosphere. However, very large uncertainties remain in input parameters, the models, and the results of calculations.

We believe the state of knowledge about nuclear winter is sufficiently developed to conclude:

- o Neither cold nor drought is likely to be a direct threat to human survival for populations with the wherewithal to survive normal January temperatures.

- o The principal threat from nuclear winter is to food production, and this could present problems to third parties who are without food reserves.

- o Loss of a crop year is neither a new nor an unexpected threat from nuclear war to the United States and the Soviet Union. Both have at least a year's food reserve at all times. Both face formidable organizational problems in distributing their reserves in a war-damaged environment.

The consequences of nuclear winter could be expected to fall more heavily on the Soviet Union than the United States due to its higher latitude and less productive agriculture. This may be especially true if disturbances of rainfall amounts and distribution persist for more than a year.

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1. INTRODUCTION

The purpose of this study was to determine if present U.S. civil defense plans are consistent with the best estimates of the possibility of a climatological upset induced by nuclear war (Nuclear Winter). The study was prompted by the paper by Turco, Toon, Ackerman, Pollack, and Sagan, (TTAPS) published in Science in 1983 (Turco et al, 1983b; also referred to as the "TTAPS" paper). That paper, and its predictions of very low temperatures following a nuclear war, received wide publicity. Temperatures as low as -50°C, which were calculated for some pessimistic combinations of input assumptions called into question even the possibility of any effective civil defense measures.

1.1 BACKGROUND

The TTAPS paper stimulated a great deal of development of numerical modeling of the behavior of the atmosphere under the perturbations expected to follow a nuclear war. The three-dimensional global circulation models that were developed since the TTAPS paper took into account ameliorating effects such as the heat capacity of the oceans and the effects of the seasons and indicated much smaller temperature depressions. These models also identified effects that may complicate recovery, such as the suppression of convective precipitation and the persistence of the effects caused by lofting of smoke into the stratosphere by solar heating.

We think a case can be made for the position that, given present understanding of the atmospheric effects of nuclear war, these effects present no qualitatively new or unsurmountable obstacles to survival by the combatants, who have ample difficulties from the prompt effects and fallout from nuclear weapons. What is new about nuclear winter, and supported by improved calculations, is the impact, at least in the Northern Hemisphere, of climatological effects, especially on agriculture, on nations not directly involved in nuclear combat. Those without food reserves could face the possibility of famine. The recommendations made for U.S. civil defense could be helpful to any nation once it has a food reserve.

1.2 GEOLOGICAL PRECEDENTS FOR BIOLOGICALLY SIGNIFICANT CLIMATOLOGICAL DISTURBANCES

Present human experience is so accustomed to a stable, though annually cyclic, climate that the concept of a climate catastrophe is counterintuitive, and regarded with great skepticism by most people. We have found it helpful to review what is now known about past climate catastrophes to get a feel for the magnitudes and causes of these events.

In the last several years geophysicists and paleontologists have discovered evidence of catastrophic atmospheric events which significantly impacted plants and animals on earth. Lamarche and Hirschboeck (1984) have found evidence of a correlation between major volcanic eruptions and late spring and early fall frosts leaving annual ring damage on bristlecone pines extending backward in time for over four millennia. It is believed by many that the extremely cold summer in New England in 1816 was caused by the eruption of the volcano Tambora in Indonesia (Stommel and Stommel, 1979). It is believed that this eruption introduced enough fine dust particles and aerosol of sulphuric acid into the stratosphere to reduce sufficiently the sunlight reaching the surface of the earth to produce the observed cooling. Stothers (1984) reports on the densest and most persistent dry fog on record in AD 536 and relates it to the explosion of Rabaul, a volcano on the island of New Britain off New Guinea. It is believed to have caused major crop failures in Mesopotamia that year. From information in the historical record, Stothers was able to estimate an atmospheric turbidity optical depth of 2.2 for that fog. This would result in the reduction by a factor of 10 of unscattered solar energy at the surface.

Perhaps the most spectacular climate catastrophe which is believed to have taken place was that at the end of the cretaceous era, about 65 million years ago. In this occurrence, it is estimated that approximately 85% of the species extant on earth at that time disappeared. This included all land animals with a body mass greater than 15 kilograms, which included most of the dinosaurs. Based on the discovery of the layer of clay with an abnormally high iridium content in the geological strata corresponding to that date, it has been postulated by Luis Alvarez et al. (1980) that the species extinction and the abnormal clay composition were due to the same event--the impact of a stony meteorite approximately 10 kilometers in diameter. In a separate paper four of the TTAPS authors have applied their computational model to the asteroid impact (Pollack et al., 1983). They estimated temperature depressions comparable to those they calculated for a large-scale nuclear war. They also calculate recovery of temperature to nearly normal levels by the end of the year.

The asteroid would have kinetic energy approximately 10,000 times the total energy released in a 5000 megaton nuclear war. It is estimated that the asteroid actually produced worldwide dust with about 5000 times the mass postulated for the smoke production in a nuclear war.

The cretaceous-tertiary (KT) event is important in that it provides evidence that cataclysms with some similarities to nuclear war can cause severe environmental effects destructive to life but not so severe that all life is destroyed. This latter point is important because the KT event was approximately four orders of magnitude more severe than a large nuclear war.

It must be noted that the KT species extinction even if related to the asteroid impact does not confirm the cooling effect calculated for nuclear winter. The observed species extinction could have been caused by the interruption of photosynthesis at any temperature.

2. THE CLIMATIC EFFECTS OF NUCLEAR WAR

2.1 OVERVIEW

Ideas and perceptions concerning the possible climatic effects of nuclear war have undergone an interesting evolution over the past dozen years. Early interest focused on the effects of large quantities of dust that would be injected into the atmosphere by surface or near-surface explosions (NRC, 1975). Then Crutzen and Birks (1982) postulated that very large quantities of smoke could arise from fires ignited by nuclear explosions and that this smoke could have significant short-term effects on climate. They concentrated mainly on forest fires, estimating that something like 10^6 km^2 of forested area could be ignited, producing some 200-400 Tg of smoke which they estimated could reduce the intensity of sunlight reaching the earth's surface at noon by a factor as little as 2 or as large as 150. Crutzen and Birks (1982) also considered smoke from urban and industrial fires, but they lacked quantitative information on which to base estimates of the amount of smoke to be expected. Nevertheless, it was clear that the quantities of smoke, even if spread over a major part of the Northern Hemisphere, could be sufficient to prevent much of the incident sunlight from reaching the surface.

Turco et al. (1983a, 1983b) were the first to attempt a quantitative estimate of the temperature effects of the smoke and dust arising from a major nuclear exchange. They included estimates of the amounts of smoke that might be expected from urban and industrial fires, primarily arising from air bursts over or near cities. Turco et al. (1983b) obtained much lower estimates than Crutzen and Birks (1982) for the amount of smoke from forest fires, but this was offset by the smoke from urban fires which, in addition, is expected to be much blacker than smoke from forest fires and hence to absorb sunlight more effectively. Turco et al. (1983b) also estimated that dust would probably contribute much less to surface cooling than the smoke would. Although the relative importance of smoke and dust depends on the details of the assumed nuclear war scenarios (e.g., counterforce vs countervalue attacks), subsequent studies have confirmed the dominance of smoke in determining the climatic effects during the first few months after a nuclear war (NRC, 1985; Pittock et al., 1986). Thus, most recent analyses have focused on the climatic effects of smoke and neglected those of dust (e.g., Ghan et al., 1985; Malone et al., 1986). However, we shall return to the question of the potential role of dust in a later section.

While the results presented by Turco et al. (1983b) are well known, it is worthwhile to review them briefly because, along with Sagan's article in Foreign Affairs (Sagan, 1983) and some related activities, they stimulated a strong response and triggered intensive studies by several atmospheric modeling groups and others. The central finding of Turco et al. (1983) was of course the substantial reduction in surface temperatures that was calculated to result from the pall of smoke and dust (Fig. 1). For their baseline case, Turco et al. (1983b) found a temperature reduction of 36°C which, starting at an annual average temperature of 13°C, produced a minimum temperature of -23°C (250 K, -9°F). Below-freezing temperatures persisted for approximately 100 days and the surface temperature remained significantly below normal for more than a year. While the short-term effects, including the temperature minimum, are governed mainly by the smoke, the longer-term recovery period, up to a year or more, is dominated by the dust. According to this model, the smoke, assumed to be confined primarily to the troposphere, is removed from the atmosphere much more rapidly than the dust, most of which is assumed to be injected directly into the stratosphere where it would normally have a residence time in excess of a year. However, as will be discussed below, this model cannot take into account atmospheric perturbations induced by the aerosols, which will cause much more rapid exchanges of air between the troposphere and the lower stratosphere than is normally the case. Thus, the assumptions regarding the removal of dust from the "stratosphere" are at least open to question.

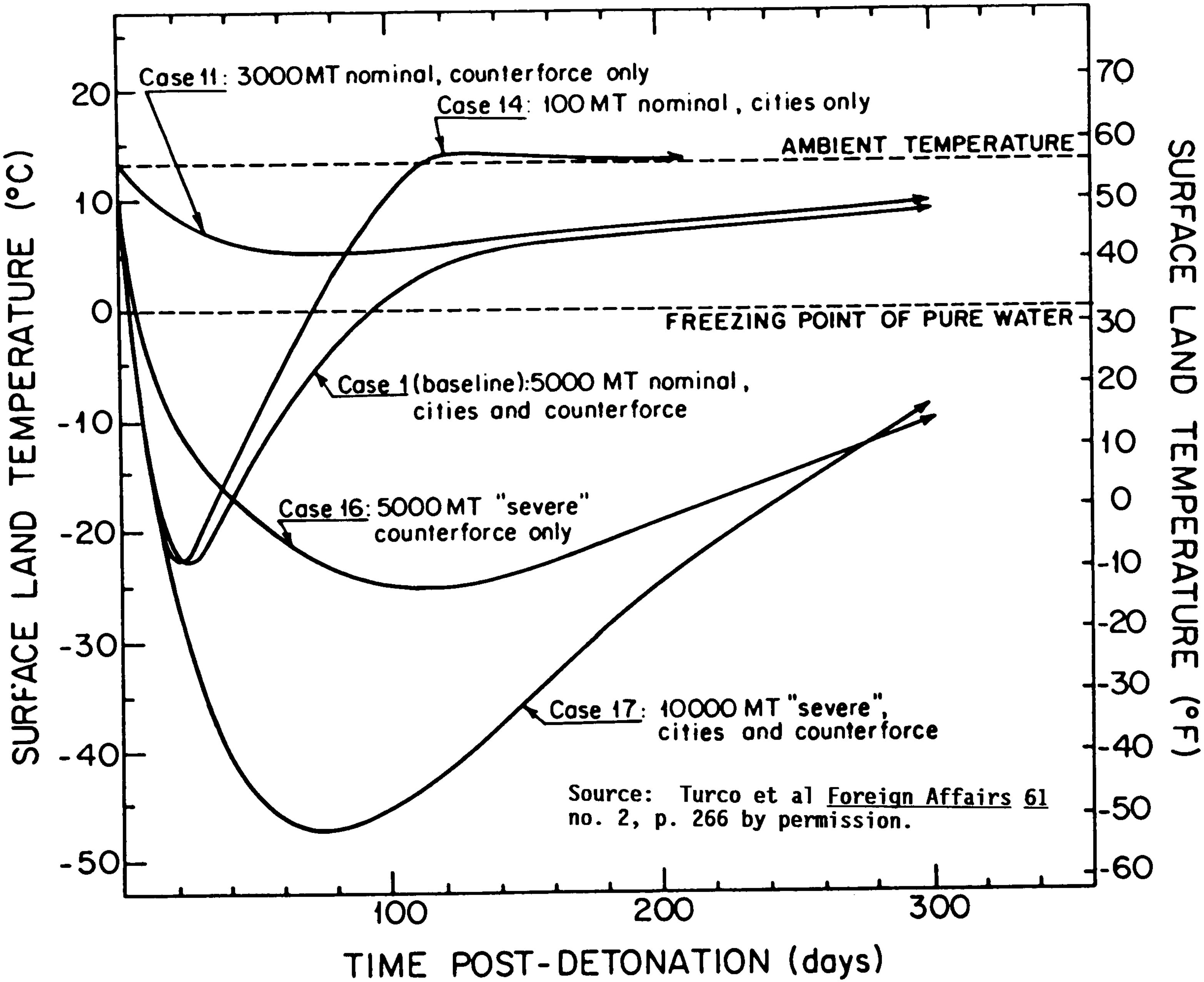

Fig. 1 Temperature effects of nuclear war cases

The potential climatic impact of a very large nuclear exchange was especially dramatized by several "severe" or "worst-case" scenarios, in which deliberately extreme assumptions were made regarding the number of detonations and the resulting quantities of smoke and dust, as well as their optical properties. These showed temperature reductions of as much as 60°C, with minimum temperatures close to -50°C and with subfreezing temperatures persisting for a year. While the baseline case was dominated by smoke, at least for the first few months, the extreme cases (as will be discussed below) were strongly influenced by dust.

There were several important difficulties with these calculations, most of which were pointed out by the authors themselves (Turco et al., 1983b). First of all, the calculations were performed with a one-dimensional radiation-convection model which cannot allow for the effects of large-scale atmospheric circulation. In particular, the moderating effect of the oceans (which cool very slowly, because of their enormous heat capacity and internal mixing) is not reflected in the figures given above. Turco et al. (1983b) estimated that those figures should be reduced by one-third for continental interiors and by two-thirds or more for areas closer to an ocean. Nevertheless, it was the unadjusted figures which attracted so much attention and which dominated most discussions of these results. That the magnitude of the cooling is greatly reduced by heat transport from the oceans has been amply confirmed by a number of subsequent simulations using three-dimensional general circulation models (GCMs) (to be discussed below). On the other hand, the GCM simulations have also made it clear that <u>average</u> temperatures, whether averaged over a time period of several days near the temperature minimum or over very large land masses (e.g., all land areas between 30° and 70° north latitude) or both, do not adequately disclose the full potential impact of smoke from a nuclear war. Much larger than average temperature reductions can occur for a few days at a time over large areas of the mid-latitude continents, especially in the continental interiors.

Another frequent objection to the calculations of Turco et al. (1983b) was that removal of smoke from the atmosphere was not well represented. Two points are at issue. The first relates to prompt removal of smoke from fire plumes by precipitation induced by the strong convective currents caused by the fires themselves. The second relates to the longer-term removal of smoke and dust from the atmosphere. With regard to the first point (prompt removal), the matter still remains quite unclear, despite a number of very detailed discussions of the topic (see for example, Chapter 3 of Pittock et al., 1986). Most authors have concluded that probably not more than half of the smoke initially present in the plume would be removed before being dispersed into the background atmosphere. Turco et al. (1983b) assumed that 50% would be removed and in this respect their work has not been seriously challenged.

With respect to longer-term smoke removal, the one-dimensional radiation-convection model could not allow for the very large perturbations in the atmosphere that would be caused by the aerosols. Again, two points are at issue. The first is the suppression of precipitation which is primarily responsible for the removal of fine aerosols from the normal atmosphere. The second relates to the lofting of smoke due to intense heating of the aerosols and the air masses in which they reside. With regard to the first point, Turco et al. (1983b) assumed scavenging rates for the aerosols as a function of altitude that were appropriate for the normal atmosphere. With surface cooling under the smoke layer and with the development of a temperature inversion up to some altitude (determined by the amount and vertical distribution of the smoke), convective activity in the lower atmosphere largely ceases and precipitation may be greatly reduced (see Ghan et al., 1985; Malone et al., 1986). Thus, the residence time of the aerosols in the atmosphere may be substantially increased. With respect to the lofting of smoke (recognized by Turco et al., 1983a, but not included in their model) some recent GCM simulations have incorporated the interactive transport of smoke (i.e., the aerosols are carried by air masses whose motions are themselves strongly influenced by the presence of the aerosols).

(Thompson, 1985; Ghan et al., 1985; Malone et al., 1986; Thompson and Schneider, 1986; Thompson et al., 1987). These simulations confirm that smoke, even if injected at low altitudes, may be lofted to altitudes well above the remaining precipitation and may remain in the atmosphere much longer than would otherwise be the case. It should be noted, however, that in those simulations with interactive parameterizations of precipitation and of aerosol removal processes (Ghan et al., 1985; Malone et al., 1986; Thompson and Schneider, 1986; Thompson et al., 1987), a significant fraction of the aerosol is removed during the first few days of the simulations, and the longer residence times due to lofting and reduced precipitation apply to the remaining fraction. The early removal rates (during the first few days) are more nearly those of the normal atmosphere. Therefore, although the smaller aerosol removal rates applicable at later times in the simulation may delay the recovery to normal temperature, they should have less effect on the minimum temperatures reached, which typically occur about a week after the nuclear exchange. It may be noted in this regard that the surface temperatures calculated by Turco et al. (1983b) dropped much more slowly than this, because in their model the surface temperature is tied to that of the lowest layer of the atmosphere, where the heat capacity of this layer delays the cooling. In most of the other simulations, the temperature of the surface, which is assumed to have zero heat capacity, is calculated separately from that of the lowest atmospheric layer and can therefore decrease much more quickly following interruption of the incident solar flux--much more like the rapid cooling that can occur at night after sundown.

Another consequence of the use of the one-dimensional radiation-convection model by Turco et al. (1983b) was the inability to deal with irregularities, or "patchiness," of the aerosol distributions. The assumption of instantaneous spread of the smoke and dust uniformly over the entire Northern Hemisphere is clearly a rough approximation of what would actually occur, especially during the first several days after their injection into the atmosphere from several thousand discrete sources. However, recent simulations with three-dimensional GCMs, modified to include interactive transport of the aerosols, have shed some light on the subject. For example, Malone et al. (1986) found a more uniform distribution a few days after injection for the interactive smoke than for a passive tracer.

In the passive tracer case, the geographical variability and episodic nature of precipitation continued to produce open areas in the tracer distribution. An appreciable part of the interactive smoke, however, was soon lofted to higher altitudes where it was both above the precipitation and rapidly distributed by strong zonal winds in the middle atmosphere. The result is a roughly zonally-symmetric smoke distribution with much stronger gradients in the north-south direction than in the east-west direction and relatively free of holes. This occurs within the first two or three weeks following injection, notwithstanding the fact that the initial smoke sources were concentrated in selected portions of the North American and Eurasian land masses. These results would suggest that the distinction between a hypothetical uniform distribution and a more irregular distribution, perhaps with some completely open areas (which of course would move about), is probably not a very urgent issue.

There remains of course the difficult question of mesoscale circulations (on a horizontal scale of a few tens of kilometers) which cannot be resolved by most current GCMs.

2.2 SMOKE FROM URBAN FIRES

Estimates of the amount of material that might be burned in urban fires following a nuclear exchange are still very unreliable. Two different approaches have been used to obtain such estimates. The first proceeds from the total yield of weapons assumed to be detonated over cities and has no explicit upper bound on the total amount of fuel available. The second proceeds from an inventory of the total amount of fuel at risk and has no explicit dependence on the total yield of weapons that might be required to ignite the fuel.

In the first approach, used by Turco et al. (1983a,b) and by the National Academy of Sciences (NRC, 1985), the amount of fuel burned is estimated with the formula

$$M = 10^{-3}\ YAmf\ , \qquad (1)$$

where Y is the total yield of nuclear weapons exploded over cities (MT, megatons), A is the area burned per unit of weapon yield (km^2/MT), m is the average areal density of combustible material ("fuel," kg/m^2), and f is the fraction of the fuel in area A that is actually burned. M is the total mass of burned fuel in Tg (1 Tg = 10^{12}g). The factor 10^{-3} converts kg/m^2 to Tg/km^2. The area A is calculated from the expression $A = A_i gS$, where A_i is an initial ignition area, S is a factor greater than one to allow for fire spread, and g is a factor less than one to allow for overlap of areas affectedby multiple bursts. Turco et al. (1983a,b) and NRC (1985) both assume that the area A_i is the area in which the thermal pulse from the fireball exceeds about 20 cal/cm^2, which they both take to be 250 km^2/MT, roughly independent of weapon yield. They take g = S = 1; that is, both spreading and overlap, which would tend to cancel each other, are neglected.* Turco et al. (1983b) estimate that m = 33.5 kg/m^2 (an average of 100 kg/m^2 over 5% of the urban area and 30 kg/ m^2 over 95% of the area). They assume f = 0.567, thus obtaining M/Y = 4.75 Tg of fuel burned per megaton of weapon yield. Assuming 1000 MT detonated over cities, they arrive at 4750 Tg of fuel consumed in urban fires.

NRC (1985), in the baseline case, also assumes A = 250 km^2/MT. They estimate that m = 40 kg/m^2, as a suitable average, and f = 0.75, leading to a value M/Y = 7.5 Tg of fuel burned per megaton. Thus, NRC (1985)

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* NRC (1985) actually assumed that g = 2/3 and applied this factor to a total weapon yield of 1500 MT (in their baseline scenario), obtaining an effective yield of 1000 Mt for airbursts over cities (i.e., the same as Turco et al. 1983).

estimates that 7500 Tg of combustible materials would be consumed in urban fires. This total is assumed to comprise 5000 Tg of wood and wood products, 1500 Tg of liquid fuels, and 1000 Tg of polymers (plastic, paints, resins, fibers). This breakdown is important because the last two categories of fuels produce much more smoke and much blacker smoke per unit of fuel burned.

The two principal difficulties with this approach are (1) the problem of determining appropriate average values for the factors in Eq. 1, and (2) the related problem that for large total yield, Y, the estimated amount of fuel burned may exceed the total amount available. Penner (1986) argues that the average areal loadings used by Turco et al. (1983b) and by NRC (1985) (30-40 kg/m^2) are in fact much too large to be representative for the large areas assumed to be burned. Penner's conclusions are based in part on a study by Reitter et al. (1985) in which models for fire ignition and spreading, developed for U.S. Civil Defense programs, were used to calculate fire-affected areas and quantities of fuel burned for two cities (Detroit and San José) for which fairly detailed descriptions of quantities and distributions of fuel were available.

Results were obtained for 1-MT and 0.5-MT bursts located at various points over the two cities. Notwithstanding the presence of small areas of very high fuel densities (e.g., downtown areas up to 200 kg/m^2 and industrial areas up to 100 kg/m^2), the average fuel densities over the areas burned were significantly lower than the 30-40 kg/m^2 assumed by Turco et al. (1983) and NRC (1985). However, the areas burned were larger than 250 km^2/MT, both because of fire spread and because of initial ignition outside the 20 cal/cm^2 contour. Thus, at least in the case of Detroit, the total fuel burned, as estimated by Reitter et al. (1985), was in some cases substantially larger than the 5-7 Tg/MT obtained by Turco et al. and by NRC. For San José, however, with a very different fuel distribution and with less total fuel at risk, the quantities burned per megaton were much less (i.e., around 1-2 Tg/MT).

The study did not include cases with smaller weapons (e.g., 100 kT) which could increase the ratio for Tg burned/MT.

It is not possible to extrapolate from these two case studies to obtain reliable averages for the 1000 or more largest cities in the NATO/Warsaw Pact countries. Even for those two cases, large uncertainties remain, owing to uncertainties in the data for each city, simplifications present in even the best fire models, and the models' sensitivity to conditions (e.g., wind velocity) that cannot be predicted in advance.

It is appropriate, therefore, to try to check results obtained with the first approach (Eq. 1) by trying to estimate the total inventory of combustible materials in areas at risk and then to estimate the fraction of this fuel that might actually be consumed in a nuclear war (Penner, 1986). Crutzen et al. (1984), whose estimates are presented in greater detail in Pittock et al. (1986), adopted this approach. Accumulated stocks were estimated by multiplying annual production rates by estimated average lifetimes for various classes of materials. Separate consideration was given to wood and wood products, pulp and paper products, plastics, paints and resins, synthetic fibers, asphalt and related roofing materials, and liquid fuels. Estimated inventories of combustible materials, grouped according to smoke characteristics, are presented in Table 1.

Table 1. Stocks of combustibles in the developed world and estimated quantities burned in a nuclear war

		Total stocks (Tg)	Quantity Burned Tg	Fraction
Wood & wood products	Crutzen et al. (1984)	12500	2000	1/6
	Pittock et al. (1986)	15000	2000	1/8
Petroleum & derived products	Crutzen et al.	~3000	700	1/4
	Pittock et al.	2500-3000	700	1/4- 1/3

Bing (1985), as cited in Penner (1986), estimated stocks of combustibles in another way (i.e., by extrapolating from detailed surveys for several U.S. cities). As presented by Penner (1986), Bing estimates total stocks in NATO and Warsaw Pact countries to be 6444 Tg for wood and wood products and 1333 Tg of petroleum and derived products, of which 480 Tg are primary oil stocks, 100 Tg are secondary oil stocks (held by distributors and consumers), and 753 Tg are polymeric materials.

Assuming, as Penner (1986) does, that 25% of this material might burn (in active, flaming combustion), the quantities burned would be about 1600 Tg of wood and wood products and about 330 Tg of oil and oil products. The latter quantity is much less than the 700 Tg estimated by Crutzen et al. (1984), although if a much larger fraction of the oil stocks were burned, the total for oil and oil-derived products would approach that figure. In either case, as will be shown below, the oil and oil products will probably dominate the total production of smoke in urban fires because of their much greater yield of elemental carbon in smoke per unit of fuel consumed.

As Penner (1986) points out, the 25% fraction of total fuel inventory assumed to be burned might come about by assuming that some two-thirds of that total could be in cities that might come under attack and that 80% of this fuel at risk would burn, half of it in active, flaming combustion and half in smoldering combustion which produces very little soot. This 25% is within the range found by Reitter et al. (1985) for Detroit and for San José, using Civil Defense fire-spread models. But it implies that a large part of all the larger cities in the NATO and Warsaw Pact countries would be attacked and would burn. It may be noted that two-thirds of the population of the United States live in some 240 metropolitan areas having populations of 100,000 or greater. (Rand McNally, 1986). However, these metropolitan areas, in addition to their core cities, typically include many smaller satellite communities and intermingled rural areas; that is, one cannot conclude that two-thirds of the total inventory of combustible materials is concentrated in continuous, high density, urban areas that would be vulnerable to fire spread. In short, even 25%, though not excluded as a possibility, seems like an improbably high fraction of the whole stock of combustibles to be burned in a nuclear war. If the inventory estimates cited above are roughly correct, it appears that 5000-7500 Tg must be regarded as a high estimate of urban fuels burned.

This does not necessarily mean, however, that previous estimates of total smoke production, or, more specifically, of the elemental carbon content of smoke produced by urban fires, were much too high. Since oil and oil-derived products produce more and blacker smoke than do wood and wood products, these increasingly important materials may largely determine the absorption optical depth of smoke from urban fires following a nuclear attack.

Crutzen et al. (1984) (see also Pittock et al., 1986) reviewed data from nearly two dozen sources regarding smoke and elemental carbon emissions from fires. They concluded that for cellulosic materials a smoke emission factor of 0.015 g smoke/g of fuel and an elemental carbon (EC) fraction of 33% may be appropriate, giving 5 g of EC per kg of fuel burned. For liquid fuels and synthetic polymers, they selected a representative value of 0.07 for the smoke emission factor, with an EC content of 70% giving 50 g of EC per kg of fuel burned. On the other hand, NRC (1985) worked with data from some of the same sources and estimated an average smoke emission factor of 0.04 (0.03 for wood and wood products, with a weighting of 2/3, and 0.06 for oil and oil products, with a weighting of 1/3). NRC adopted an average EC fraction of 20%, giving an average of 8 g of EC per kg of urban fuel burned. Thus, for the NRC baseline case, EC emissions are 60 Tg of elemental carbon (7500 Tg of fuel burned * 0.008), of which NRC (1985) assumed one-half is removed promptly by fire-induced precipitation scavenging, leaving 30 Tg of EC to be dispersed in the atmosphere. Crutzen et al. (1984), with a much smaller total amount of fuel burned, nevertheless calculate 45 Tg of EC (2000 Tg of wood and wood products * 0.005 + 700 Tg of oil and oil products *0.05), of which Crutzen et al. assume one-third will be removed promptly, leaving 30 Tg to be dispersed in the atmosphere - the same as NRC's figure. This quantity of EC, if distributed over an area equal to half that of the Northern Hemisphere (127 x $10^{12}m^2$), would give an average areal density of 0.24 g/m^2. Taken together with an estimated absorption coefficient of 10 m^2/g for elemental carbon, this yields an average absorption optical depth of 2.4 for both Crutzen et al. (1984) and NRC (1985). (The extinction optical depths are not the same, however; using a scattering coefficient of 3.5 m^2/g of aerosol in both cases, we obtain $\tau_e = 6.5$ for the NRC smoke quantities and $\tau_e = 3.8$ for the smoke quantities of Crutzen et al., 1984).

It is worth noting at this point that combustion of liquid fuels alone could produce enough sooty smoke to have a significant climatic impact. Annual world consumption of petroleum is approximately 2.8 billion tons. If primary oil stocks amount to about one-fourth of annual production (Crutzen et al, 1984) and secondary stocks (of oil products) also about one-fourth, then world stocks of liquid fuels are roughly 1400 Tg of oil and oil products. [Crutzen et al., 1984, estimate 1300 Tg; Pittock et al., 1986, 1000-1500 Tg; Bing (quoted in Penner, 1986), 600 Tg in NATO and Warsaw Pact countries or about 1000 Tg worldwide.] Using the estimates of Crutzen, et al. (1984) for smoke emission in flaming combustion (7% of fuel burned) and elemental carbon content (70% of smoke), the combustion of 1400 Tg of liquid fuels would produce about 70 Tg of elemental carbon. If spread uniformly over the whole globe (500* $10^{12}m^2$) and with an absorption coefficient of 10 m^2/g for EC, this quantity of EC would yield an absorption optical depth of about 1.4. Of course, not all of the liquid fuel stocks would burn, but neither would the resulting smoke be uniformly dispersed over the whole globe. Crutzen et al. (1984) also point out that a substantial additional amount of smoke could come from oil-field fires (not included in the foregoing estimates) which could burn for many days.

The agreement in absorption optical depth between NRC (1985) and Crutzen et al. (1984) (and Pittock et al., 1986) is largely fortuitous, and in any case, all of the factors involved in estimating these quantities are still subject to very large uncertainties. Penner (1986) considered ranges of uncertainty for the amounts of urban fuel at risk, for the smoke emission factors, for the fraction of prompt smoke removal by fire-induced precipitation, and for the optical properties of the aerosol dispersed into the atmosphere (but not for the fraction of the urban fuel inventory that might actually burn, which she fixed for comparison purposes at 25%).

Defining these uncertainty ranges only by the ranges of preferred values of these parameters adopted in a few recent studies and neglecting possibly large uncertainties in the fraction of fuel burned, which would depend in part on the assumed nuclear-war scenario, Penner still concluded that reasonable estimates of the absorption or the extinction optical depths could differ by more than an order of magnitude. Values for the absorption optical depth ranged from 0.2 to 4 without smoke from the burning of primary oil stocks (approximately 480 Tg) and from 0.4 to 6 including all the primary oil stocks. Values for the extinction optical depth ranged from 0.5 to 8 without the primary oil stocks and from 1 to 11 with them, all based on an assumed uniform distribution of the smoke over half the Northern Hemisphere. These ranges reflect more than a factor of 2 between high and low estimates for the amount of fuel burned, a factor of 2 in the fraction of soot removed by prompt scavenging, up to a factor of 2 in smoke emission factors, up to a factor of 4 in absorption coefficient (including a factor of 2 or more associated with uncertainty in the extent of particle coagulation that might take place and its effect on optical properties of the aerosol). Combined, these factors produce a 10- to 20-fold spread in optical depths. Yet they do not define the full range of possible values, even for this case of 25% consumption of all the stocks of combustible materials. Thus, as Penner (1986) observes, the possible climatic effects might range from negligible ($\tau_a = 0.2$) to very severe ($\tau_a = 6$) within the scope of remaining uncertainties.

Thus far, we have considered only smoke from urban fires. Additional amounts of smoke may come from other sources, including forest fires, brush fires, and grassland or cropland fires ignited near military targets in rural areas. Indeed, Crutzen and Birks (1982) considered primarily forest fires in their original analysis of the potential climatic impacts of nuclear war. They estimated that up to 10^6 km^2 of forest land might be burned, with an average fuel loading of 22 kg/m^2, of which 25% was assumed to be burned. With an estimated smoke emission factor of 7.5%, they obtained 400 Tg for the amount of smoke produced in forest fires ignited in a nuclear war.

Turco et al. (1983b) found that smoke production in a nuclear war could be dominated by urban fires, as discussed above, and most recent analyses have found the contribution of urban fires to be larger than that of forest fires, at least in terms of elemental carbon content and absorption of sunlight. Turco et al. (1983b), Crutzen et al. (1984), NRC (1985) and Pittock et al. (1986) estimate (or imply) elemental carbon emissions of about 30 Tg from urban fires (for war scenarios involving widespread attacks on cities). For EC emissions from forest fires, Crutzen et al. (1984) estimate 4 to 16 Tg of EC (the latter for fires covering 10^6 km^2 of forests which is probably much too high); NRC (1985) estimates 3 Tg of EC from forest fires, and Pittock et al. (1986) estimate 1 to 2 Tg of EC, which represents a substantial downward revision of the estimate of Crutzen et al (1984).

Small and Bush (1985), using much more detailed input data, obtained a much smaller estimate of the amount of smoke from wildfires. Most important, they took into account the fact that most strategic military targets are located in cropland or grassland areas which have much lower fuel loading than the forest environment assumed by Crutzen and Birks. Small and Bush identified 3500 military facilities as potential ICBM targets (mainly in the United States and the Soviet Union) and assumed that each one was targeted by two warheads, for an aggregate yield of approximately 4100 megatons compared with the baseline scenarios of Crutzen et al. and Turco et al. which used 4000 MT against wildland targets. Small and Bush found that only 14% of the targets were located in forest and over 80% were located in grassland or cropland. A comparison of Small and Bush's results with Crutzen and Birks, Turco and the National Academy of Science Study is shown in Table 2. Small and Bush's results show 100 to 1000 times less smoke produced by wildland fires than Crutzen and Birks, and 26 to 260 times less smoke from wildland fires than estimated by Turco, et al. (1983b). However, Ackermann et al. (1985), in a similarly detailed analysis, estimate considerably higher smoke emissions than do Small and Bush.

Table 2. Fuel burned and smoke produced in non-urban fires - A comparison of estimates

Study	Yield (MT)	Area ($10^3 km^2$)	Fuel burned (g/cm^2)	Emission factor (g/g)	Smoke (10^{12}g)
Crutzen & Birks (1982)	3800	1000	0.3-0.55	0.067-0.073	200-400
Turco et al. (1983b)	4000	500	0.5	0.032	80
Crutzen et al. (1984)	3800	250 1000	0.4	0.06	60-240
NRC (1985)	5000	250	0.4	0.03	30
Small & Bush (1985)	4100	30-190	0.01-0.20	0.03	0.3-3.0

Source: Small and Bush (1985)

From all of the foregoing considerations, we conclude the following:

1. It appears that the accumulated stocks of urban fuels that could be at risk in a nuclear war may be on the order of 10^{16}g and that up to a few *10^{15}g (5000 Tg, for example) could conceivably be burned in a war involving an all-out attack against cities.

   However, such quantities constitute a major fraction of all the fuel potentially at risk; they must lie at the upper end of the range of possibilities and would be unlikely to be realized in most attack scenarios, even those involving major attacks against cities.

2. Considering the composition of urban fuel stocks, and including stocks of liquid fuels, it appears that smoke emissions from urban fires could reach 100 to 200 Tg and that emissions of elemental carbon could total as much as several tens of Tg. However, we believe that these numbers are at the high end of the range of possibilities. In addition, some fraction of the smoke emissions - possibly as much as one-half - may be removed promptly by precipitation scavenging induced by the fire itself. As noted above, if smoke containing 30 Tg of EC were spread over one-half of the Northern Hemisphere (i.e., 127 * $10^{12}m^2$), the average absorption optical depth would be about 2.4, while the extinction optical depth would be around 4 to 7, depending on the proportion of non-absorbing particles in the smoke.

3. EC emissions from wildfires (forests, brush, grasslands) can hardly exceed a few Tg. The contribution from wild fires is masked by the large uncertainty in that from urban fires. The contribution from wild fires could be relatively important in a war that avoided attacks on cities and fuel storage facilities, but in that event total smoke emissions and consequent climatic effects would be much smaller than those described, for example, by Turco et al. (1983b).

2.3 IMPACTS ON SURFACE CLIMATE

2.3.1 Surface Temperature

The best currently-available indications of the magnitude of cooling to be expected after a nuclear war appear to be provided by the calculations of Malone et al. (1986), Thompson and Schneider (1986) (Fig. 2; also reported in somewhat more detail by Thompson et al., 1987), and Ghan et al. (1987).

Both the Los Alamos group (Malone et al.) and the NCAR group (Thompson et al.) now use GCMs that provide for fully interactive transport of smoke. The simulations of Thompson and Schneider also include scattering of sunlight and absorption of infrared radiation by smoke, which Malone et al. (1986) were not then able to do. Although the effects of infrared absorption by smoke were formerly thought to be minor (Ramaswamy and Kiehl, 1985), they are shown by Thompson et al. (1987) to be significant in comparison with the smaller temperature reductions being found in current simulations.

We consider first some roughly comparable cases in which about 180 Tg of smoke is injected into the atmosphere in July. Summer conditions are chosen because it has previously been shown (Covey et al., 1985) that the calculated temperature excursions are much larger for a July war, with strong solar forcing, than for a January war, with much weaker solar forcing. April simulations are intermediate between those for January and July. Of course, the initial temperatures (normal highs and lows) are higher in July than in April or January, so it is not obvious that a July war would have a more serious impact on agriculture than an April war. We shall return to this point later. Malone et al. (1986) assumed injection of 170 Tg of smoke (close to NRC's baseline case of 180 Tg, after allowance for 50% prompt removal from the fire plumes, NRC (1985), assigned an absorption coefficient of 2 m^2/g to the smoke (NRC, 1985), and used NRC's altitude profile for initial injection (uniform density

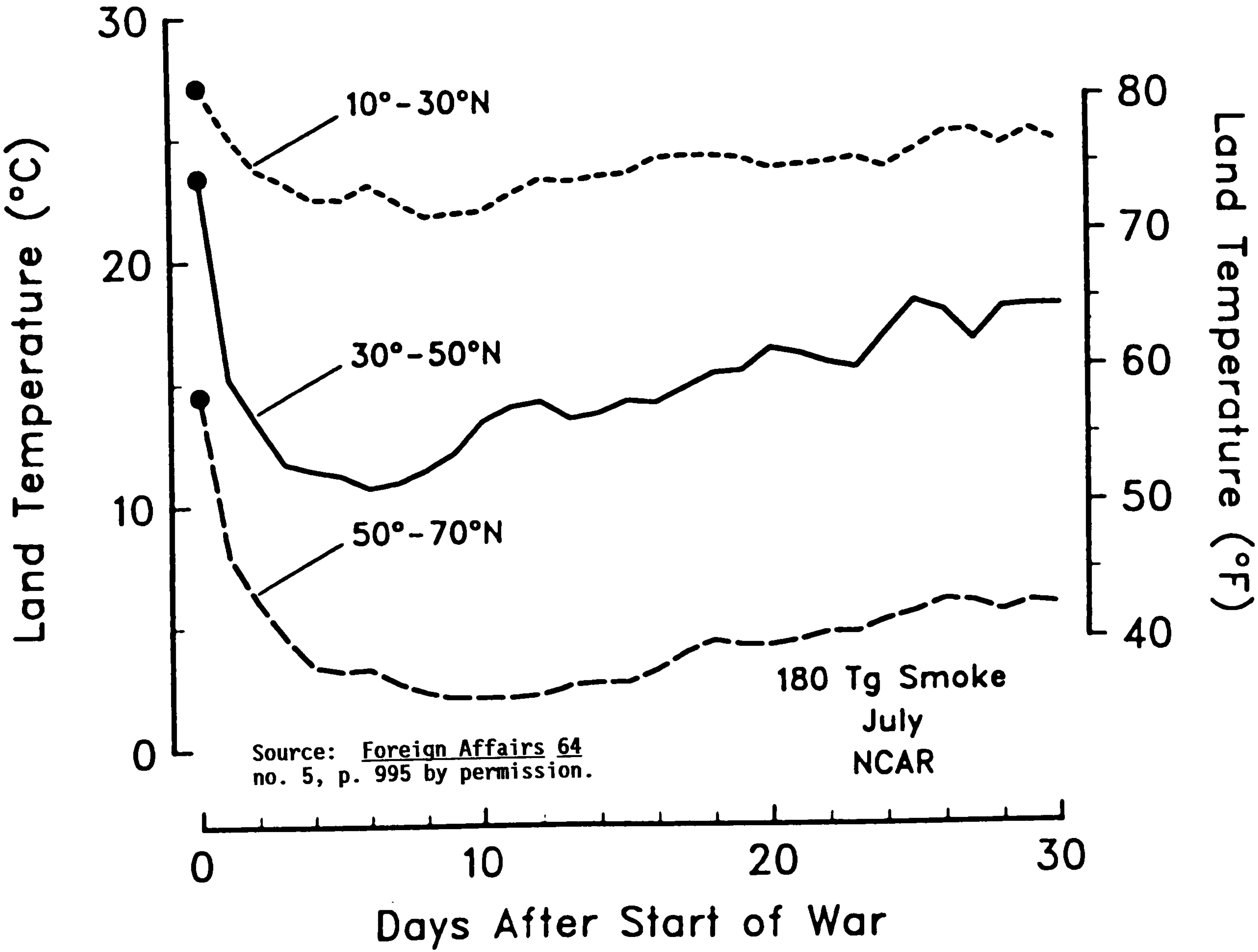

Fig. 2 Zonal average land surface temperature for three adjacent latitude zones (180 Tg smoke, July War)

from 0 to 9 km). The source regions were selected areas of the North American and Eurasian continents. For reference, this smoke if distributed uniformly over one-half of the Northern Hemisphere would have an average absorption optical depth of 2.7, which is close to the initial optical depth of smoke in the baseline case of Turco et al. (1983b). The simulations of Malone et al. included no dust.

During the first week or two after injection, Malone et al. found temperature reductions of more than 15° C over most of North America between 30° and 60° north latitude and most of the Soviet Union north of 50° N. Smaller regions in continental interiors showed temperature reductions up to 25° C. In much of the Soviet Union, it appeared that temperatures would remain 20 to 25° C below normal through the third week and 5 to 15° C below normal to the end of the simulation at 40 days. Of particular importance, episodic subfreezing temperatures were experienced widely. Considerable smoke was found to spread into the Southern Hemisphere - far more with interactive smoke transport considered than was found in a test case with a passive tracer. Significant cooling was indicated in these simulations for Australia and Southern South America (5 to 10° C).

Although Thompson et al. (1987) found that inclusion of infrared absorption by smoke reduces the magnitude of the smoke-induced cooling in mid-latitudes by 4 to 6° C on the average, it is not clear how these adjustments would be applied to time- and space-dependent temperatures calculated by Malone et al. (1986) or whether (or to what extent) such adjustments would limit the occurrence of subfreezing temperatures. Nevertheless, it seems clear that some moderation of the minimum temperatures calculated by Malone et al. should be expected if IR absorption by smoke were included in their model.

Thompson and Schneider (1986) and Thompson et al. (1987), using the NCAR Community Climate Model (CCM), a 9-level GCM, also considered (among others) a case with 180 Tg of smoke, chosen to conform to NRC's baseline case, although Thompson and Schneider now believe that this amount of smoke is close to the upper end of the range of plausible values (see Sec. 2.2). Although very little is said about it, this case also included dust, the amount and distribution of which were taken from the NRC baseline case (i.e., 450 Tg of dust) of which 36 Tg was in particles with radii less than 1 μm. The dust apparently has only a minor effect on climate impact. The simulation also includes the scattering of sunlight by smoke (single scattering albedo, ω_0 = 0.6, absorption coefficient = 2.2 m^2/g) and absorption of infra-red radiation by smoke. The model provides for full interactive transport of aerosols. The smoke was initially distributed vertically with a uniform mixing ratio from 0 to 7 km altitude, and the source region was distributed uniformly over the United States, part of Southern Canada, Europe, and most of the Soviet Union.

Results are expressed in terms of average surface temperatures over all land areas within certain latitude bands (e.g., 30° to 50° N, 50° to 70° N), and occasionally also over some time interval such as 5 to 15 days after injection starts. The maximum temperature excursion, relative to a control run for normal July conditions, was about 12 to 13°C (averaged over all land areas from 30° to 50° N), starting from a normal average July temperature of 23° C. Thompson and Schneider (1986) also found similar results for smaller smoke loadings of 60 Tg and 20 Tg (maximum cooling of about 11° C and 8° C respectively), indicating, as expected, that the cooling effect of increasing quantities of smoke is already approaching saturation for loadings as high as 180 Tg (see below).

It is difficult to make a direct comparison between the results presented by Malone et al. (1986) and by Thompson and Schneider (1986), partly because of the model differences mentioned above (e.g., inclusion of absorption of infrared radiation and scattering of visible light by smoke in Thompson and Schneider's calculations but not in those of Malone et al.). The comparison is difficult also because Thompson and Schneider present zonal average land-surface temperatures as a function of time, while Malone et al. present spatial distributions of 5-day-average temperature depressions (relative to a control case with no smoke) at selected time intervals after the start of smoke injection. What is important, however, is that both groups find (from results not explicitly displayed in their papers) that episodes of subfreezing temperatures are likely to occur in the continental interiors for a war occurring in July. Thus, extensive damage to crops may be expected even though the average temperature reductions are much less than those reported by Turco et al. (1983a,b) and by Sagan (1983).

2.3.2 Effect of Reduced Smoke Loadings

The Los Alamos and NCAR groups have both investigated the climatic impacts of smaller quantities of smoke and have found that the effects are not very sensitive to smoke loading in the vicinity of 180 Tg. This indicates, as expected, that absorption optical depths as large as 3 are sufficient to intercept most of the sunlight that would otherwise reach the surface and that the surface cooling effect is approaching saturation. Some further enhancement of cooling with increasing amounts of smoke is found, because the sunlight is absorbed at higher and higher levels in the atmosphere and because the smoke is more strongly lofted by the more intense solar heating and more smoke is elevated above the atmospheric layers in which precipitation can occur. The lifetime of the remaining smoke thus increases, and a strong absorbing smoke layer persists for a longer time.

Malone et al. (1986) considered amounts of smoke both smaller and larger than 170 Tg (i.e., 5, 20, 60, 170 and 500 Tg). For the 60-Tg case (summer conditions), they found temperatures 5^{o} to $10^{o}C$ below normal over widespread areas of the Northern Hemisphere, with localized reductions up to 15^{o} C. Maximum cooling found in the Southern Hemisphere was about $5^{o}C$. Recovery in this case was more rapid than for the 170-Tg case, with conditions approaching normal after about a month.

For the 20-Tg case, Malone et al. (1986) found maximum temperature reductions (five-day averages) of 4^0 to 6^0 C over large areas of the Northern Hemisphere, during the first two weeks, but by the third week, temperature fluctuations could hardly be distinguished from normal. No cooling was observed in the Southern Hemisphere.

For the 500-Tg case, which is probably outside the range of plausibility, the impacts were both more severe and more persistent than those for 170 Tg. Five-day average temperatures 25^0C below normal were widespread in the Northern Hemisphere, while over smaller areas temperatures dropped below normal by 35 to 40^0 C. In the tropics, temperatures fell by 5^0 to 10^0 C in the second week and had recovered only slightly by the end of the simulation (40 days). Again, it is not clear how much these results would be modified by the inclusion of infrared absorption by smoke. However, one would expect the effect to be larger for large smoke loadings, since the infrared absorption optical depth of the smoke could approach unity for the 500-Tg loading (if assumed to be spread over an area equal to one hemisphere (i.e., 255 * 10^{12} m^2) but would be very small for the lighter smoke loadings considered.

Thompson and Schneider (1986) also considered the impacts for reduced smoke loadings of 60 Tg and 20 Tg. Whereas, the maximum cooling observed for the 180-Tg case was 12 to 13 C (for a July war), the corresponding figures for 60 Tg and 20 Tg were 11^0 C and 8^0 C, respectively (Fig. 3). However, as noted above, these are averages over all land areas between 30^0 and 50^0 north latitude. Much larger temperature fluctuations can occur locally, and Thompson and Schneider found temperatures falling intermittently below freezing over large areas of the North American and Eurasian continents for both the 170 Tg case and the 60 Tg case.

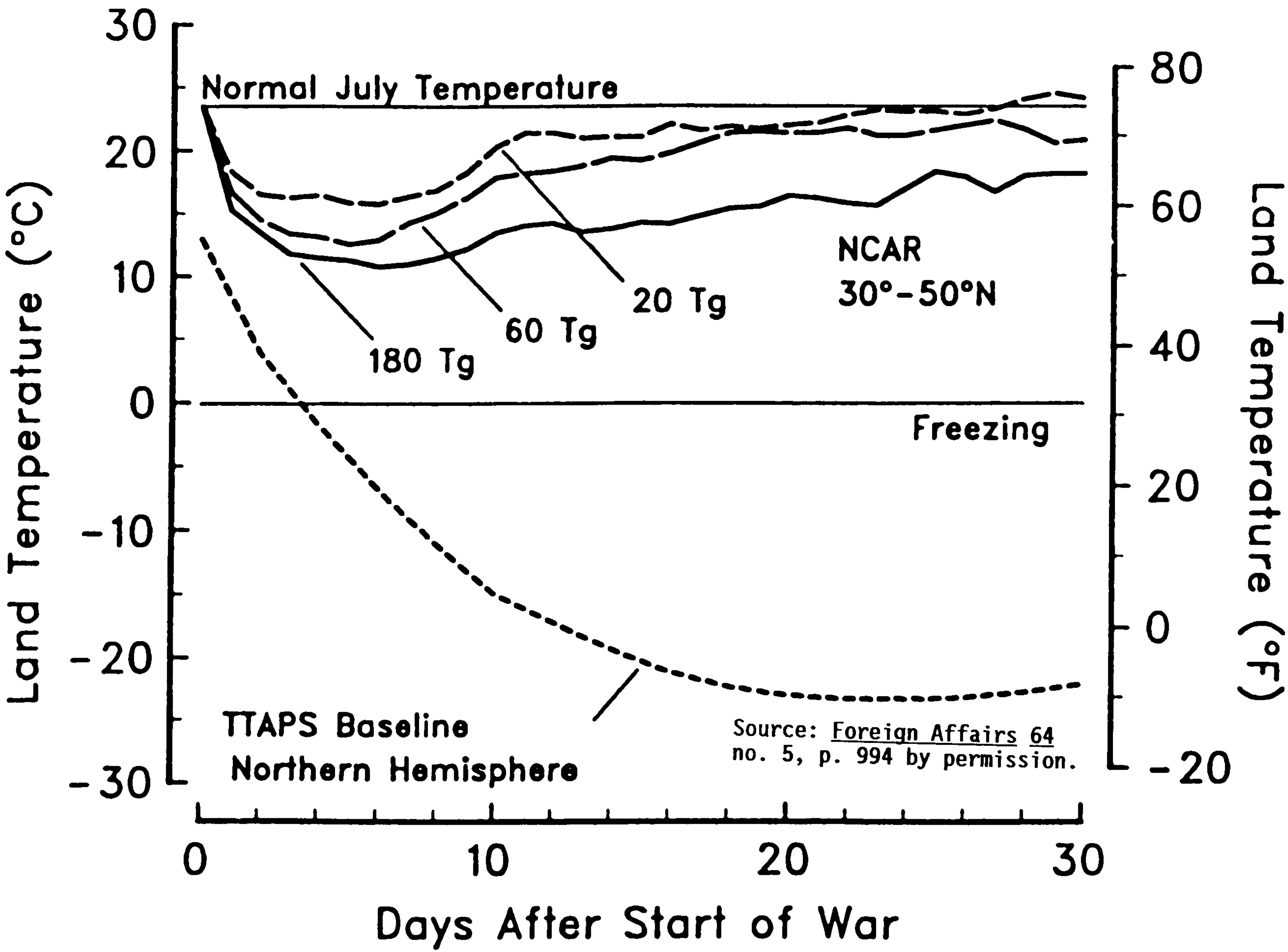

Fig. 3 Zonal means (land only) of total precipitation for control July simulation and for days 1-10, 11-20 and 21-30 following a 50 Tg injection of smoke

2.4 DUST REVISITED

As noted in Sec. 2.1, recent evaluations of the climatic effects of nuclear war (Turco et al., 1983b; NRC, 1985; Pittock et al., 1986) have found

that dust is relatively unimportant and that the climatic response is dominated by smoke, at least for the first several weeks or until the smoke is mostly purged from the atmosphere. For longer periods (six months to a year), the residual effects are small but are mainly determined by dust. This transition from an early response dominated by smoke to a longer-term response controlled by dust is the result of different assumptions regarding the removal of these two aerosols from the atmosphere. It was believed that most of the smoke would be introduced into the troposphere where it would be subject to removal by precipitation. However, a significant portion of the dust (determined by the distribution of yields of weapons used for surface bursts against hard targets) would be injected directly into the stratosphere, where it would have a residence time of one or two years. Recently, Thompson (1985) and Malone et al. (1986) have demonstrated the importance of smoke lofting in prolonging the atmospheric lifetime of smoke (with significant quantities of smoke carried up to altitudes of 20 to 30 km). These studies show, even more clearly than did the altered atmospheric temperature profiles apparent in the earlier one-dimensional simulations, that the region that was the lower stratosphere can no longer be considered to be isolated from the lower atmosphere during the early, most active phase of the postattack period.

There is evidently a much greater exchange of air masses between the (normal) stratosphere and the (normal) troposphere than is usually the case. Unfortunately, the GCM simulations do not reveal the possible importance of sub-grid-scale circulations (e.g., at horizontal scales less than a few hundred kilometers), nor do they indicate the fates of dust and smoke at times longer than thirty or forty days, since that is as far as the simulations have been carried out. Thus, it is not clear that the easy distinction between dust lifetimes (long) and smoke lifetimes (short) remains valid. Smoke lifetimes are longer than previously thought, because of lofting, and, for a complementary reason, dust lifetimes may be shorter.

Nevertheless, it may be premature to dismiss dust as a negligible part of the problem. It is worth recalling that the most extreme cases that helped to attract attention to the issue of "Nuclear Winter," (see Fig. 1) with very deep cooling (e.g., by as much as 60°C), lasting for a very long time (e.g., up to a year of subfreezing temperatures) were very strongly influenced by or dominated by dust. In these extreme cases, there was much more dust than in the baseline case, and the selection of parameters to characterize the dust made the dust appear more effective optically. The differences are illustrated in Table 3, in which it is shown that the optical effect of the dust in the extreme case (Case 17 of Sagan, 1983) is about forty times greater than in the NRC baseline case. It may also be noted that dust in the NRC baseline case (NRC, 1985) is only half as effective as the dust in the baseline case of Turco et al. (1983b), the difference being due mainly to different choices regarding the nuclear war scenario (i.e., a smaller total yield of weapons used against hard targets).

In the calculations summarized in Table 3, the particle size distribution in the initial, stabilized dust cloud was assumed to be given by

$$N(r) \approx r^{-1} \exp [-\alpha \ln^2(r/r_m)] \text{ for } 0 \leq r \leq r_0$$

and by

$$N(r) = n(r_0) . (ro/r)^{\beta} \text{ for } r_0 < r <_{max}$$

where

r = particle radius (assuming spherical particles)

r_m = mode radius, typically around 0.25μm

$r_0 = r_m \exp [(\beta-1) \ln^2 0]$

$\alpha = (2 \ln^2 \sigma)^{-1}$

σ = dispersion parameter of the log-normal portion of the distribution.

This composite distribution has been found to represent reasonably well the observed particle size distributions from the stabilized dust cloud from surface bursts, sampled at times from a half-hour to two hours after the detonation (Nathans et al, 1970). The maximum particle size in this initial distribution, r_{max}, is not well determined. NRC (1985) extended their integrations over the particle size distribution to r_{max} = $10^4 \mu$m(1 cm). However, one would expect such large particles to have fallen out of the cloud prior to sampling and hence not to be included in the measurements of dust mass in the stabilized cloud (Gutmacher et al, 1983), on which estimates of the lofting efficiency (Tg dust per MT of weapon yield) are partly based (NRC, 1985). In our calculations, a maximum radius of $10^3 \mu$m was employed.

In Table 3, attention is focused on the submicron fraction of the dust particles for two reasons. First, most of the optical effect is contributed by the smaller particles (those with radii comparable to the wave-length of visible light). Second, only particles with radii less than a few micrometers can remain in the dust cloud for many weeks or months after the attack. In this size range, settling velocities are approximately proportional to the square of the radius. A 10μm (radius) particle, for example, would fall from the altitude of 18 km in about a week, a 3μm particle in about 3 months, and a 1μm particle in about 2 years (neglecting, of course, effects of atmospheric circulation). Thus, for long-term optical effects of the dust, we need the submicron mass fraction of the original, stabilized cloud,

$$M_{rc} = \int_0^{1\mu m} n(r).r^3 dr \Big/ \int_0^{10^3\mu m} n(r).r^3 dr$$

and the average extinction coefficient (m^2/g), over the interval 0 to 1 m,

$$<\psi> = \frac{3}{4\rho} \int_0^1 Q(r).n(r).r^2 dr \Big/ \int_0^1 n(r).r^3 dr,$$

where ρ is the particle density, which we have assumed to be 2.5 g/cm^3, and Q(r) is the extinction efficiency (a function of the index of refraction and the size parameter, $2\pi r/\lambda$, λ = wavelength of light) which we have taken from Figure 1 of Ramaswamy and Kiehl (1985). It is the extinction coefficient defined in this way that is shown in Table 3, except for the value on the first line, which was taken from NRC (1985).

It may be noted that an optical depth of unity for dust is not equivalent to the same optical depth for smoke, since the dust mostly scatters visible light, whereas the smoke (especially smoke from burning oil and plastics) strongly absorbs the light. Nevertheless, an extinction optical depth much greater than unity would be expected to have an appreciable effect on the earth's albedo (reflectance for incident sunlight).

In the extreme case shown in Table 3, the choice of 1.0 Tg/MT for the dust lofting efficiency of a surface burst and the choice of 0.1 m for the mode radius (geometric mean radius) of the particle size distribution are probably both unreasonable. The first is perhaps a factor of 2 too large, (NRC, 1985; Gutmacher et al, 1983) and the second perhaps a factor of 2 too small (Nathans et al, 1970). However, other parameters of the size distribution, not varied by either Turco et al. (1983b) or by NRC (1985) are also subject to significant uncertainties and can have a large effect on the optical effectiveness of the dust. These are notably the standard deviation of the log normal size distribution used to characterize small particles (e.g., less than 1-μm radius) and the exponent of the inverse power law distribution used to characterize the

Table 3. Dust mass and optical effects for various dust scenarios

Case	Total yield of surface & near surface bursts (MT)	Lofting efficiency (Tg dust/ MT yield)	Mass of dust in initial stabilized cloud (Tg)	Parameters of dust particles size distribution ($r_m/\sigma/\beta$)	Fraction of dust mass with r ≤ 1 m (b) (submicron fraction)	Mass of dust with r ≤ 1 μm (Tg)	Areal Density of submicron dust (c) (g/m^2)	Extinction coefficient (d) (m^2/g)	Extinction optical depth	Relative optical depth	Fraction of dust mass in the stratosphere	Ref
:C base case	1500	0.3	450	0.25/2/4	0.08*	36	0.28	2.8*	0.8	1.3	0.41	(e)
:C base case	1500	0.3	450	0.25/2/4	0.106	48	0.38	1.58	0.6	1.0		
'APS base case	2850	0.33	940	0.25/2/4	0.084*	79	0.62	1.58	1.0	1.7	0.8	(f)
ıgan worst case (#17)	6300	1.0	6300	0.1/2/4	0.20	1260	9.9	2.45	24	41		(g)
I (a)	6000	0.6	3600	0.25/2/4	0.106	380	3.0	1.58	4.8	8		
!	6000	0.6	3600	0.1/2/4	0.20	720	5.7	2.45	13.9	23		
;	6000	0.6	3600	0.2/1.8/4.3	0.34	1220	9.6	2.08	20	34		

ı) Hypothetical cases with four times the yield and twice the lofting efficiency of the NRC base case and showing the effect of different assumptions regarding parameters of the particle size distribution.
ɔ) Calculated by us with maximum particle radius of l mm, versus 1 cm used by NRC; exceptions, marked with asterisks, were taken from the references.
:) Calculated by assuming a uniform distribution over an area equal to one-half of the Northern Hemisphere, $127 * 10^{12}$ m^2.
i) Calculated by us with values of extinction efficiency, Q(r), obtained from Figure 1 of Ramaswamy and Kiehl (1985), except for the first number, taken from NRC (1985).
ɛ) NRC (1985).
ᶠ) Turco et al. (1983b).
ȷ) Sagan (1983).

larger particles. For the first of these, a value 2 was chosen and, for the second, the value 4. However, it is clear from the report of the original measurements made on dust samples from the stabilized clouds from weapons tests in the 1950s and 1960s (Nathans et al, 1970) that these parameters are not precisely determined (Gutmacher et al., 1983; Heft, 1968; Nathans, 1970; Nathans et al., 1970a,b). In particular, a value of 1.8 for the standard deviation and a value of 4.3 for the exponent of the power-law distribution of larger particles are well within the experimental uncertainties. These values are incorporated in the hypothetical scenario H3, along with an assumed mode radius of 0.2μm. Adopting these values could compensate for a retreat from the extreme values of lofting efficiency and mode radius noted above, (1.0 Tg/MT and 0.1μm, respectively), leaving the question of the number and yield of surface bursts as the main issue in discussing the validity of the extreme cases shown in Table 3.

It is often assumed that only that portion of the stabilized dust cloud that is injected above the tropopause will have a long residence time in the atmosphere, e.g. up to a year or more. Table 2 shows a factor of two difference between the estimates of NRC (1985) and Turco et al (1983b) regarding the fraction of dust mass in the stabilized cloud that would be injected above the tropopause. This difference arises in part from somewhat different relations for the cloud heights (top and bottom) as functions of weapons yield for surface bursts and in part from different assumptions regarding the distribution of weapon yields that would be used against hardened targets.

In this discussion, we have deliberately played down the question of the distribution of the initial dust injection between the normal troposphere and the normal stratosphere, on the grounds that substantial mixing between these regions would in fact take place if sufficient smoke were present. Nevertheless, it is clear that the optical depths given in Table 3 should each be multiplied by a factor substantially less than one to indicate the potential effects weeks or months after the postulated attacks.*

2.5 PRECIPITATION

The simulation by Ghan et al. (1985) was performed with an adaptation of the Oregon State University (OSU) two-level Atmospheric General Circulation Model. A most important aspect of the results of these calculations is the finding that precipitation in mid-latitudes of the Northern Hemisphere may be very substantially reduced by the presence of an absorbing smoke layer even for amounts of smoke too small to produce long-term cooling at the surface (Fig. 4).

Cess et al. (1985), also using the OSU-GCM (but with fixed smoke loadings) as well as an analogous one-dimensional radiation-convection model, showed that smoke with an absorption optical depth less than about 0.4 would warm the surface rather than cooling it. Smoke with absorption optical depth $(_a)$ greater than about 0.4 would cool the surface. The transition from warming to cooling comes when the suppression of convective activity is sufficient to remove most sensible and latent heat transfer between the surface and the atmosphere, leaving the surface essentially in radiative equilibrium (which normally it is not). For all smoke loadings, there is an increase in solar heating of the surface-atmosphere system (i.e., the planetary albedo is decreased). This, by itself, would produce surface warming so long as the surface and the troposphere remain convectively coupled (i.e., for $_a < 0.4$). For larger loadings, with convective coupling largely eliminated, the surface cools (for lack of incident solar flux) while the atmosphere warms; the warming occurs at higher and higher levels as the smoke loading is increased. (These calculations were done with a uniform mixing ratio of smoke from the surface to 11 km.) For all smoke loadings, the calculations show a

* It is not our purpose in this report to argue details of nuclear war scenarios. We think it prudent to consider the possibility that rather large cumulative weapons yield could be used against hard targets.

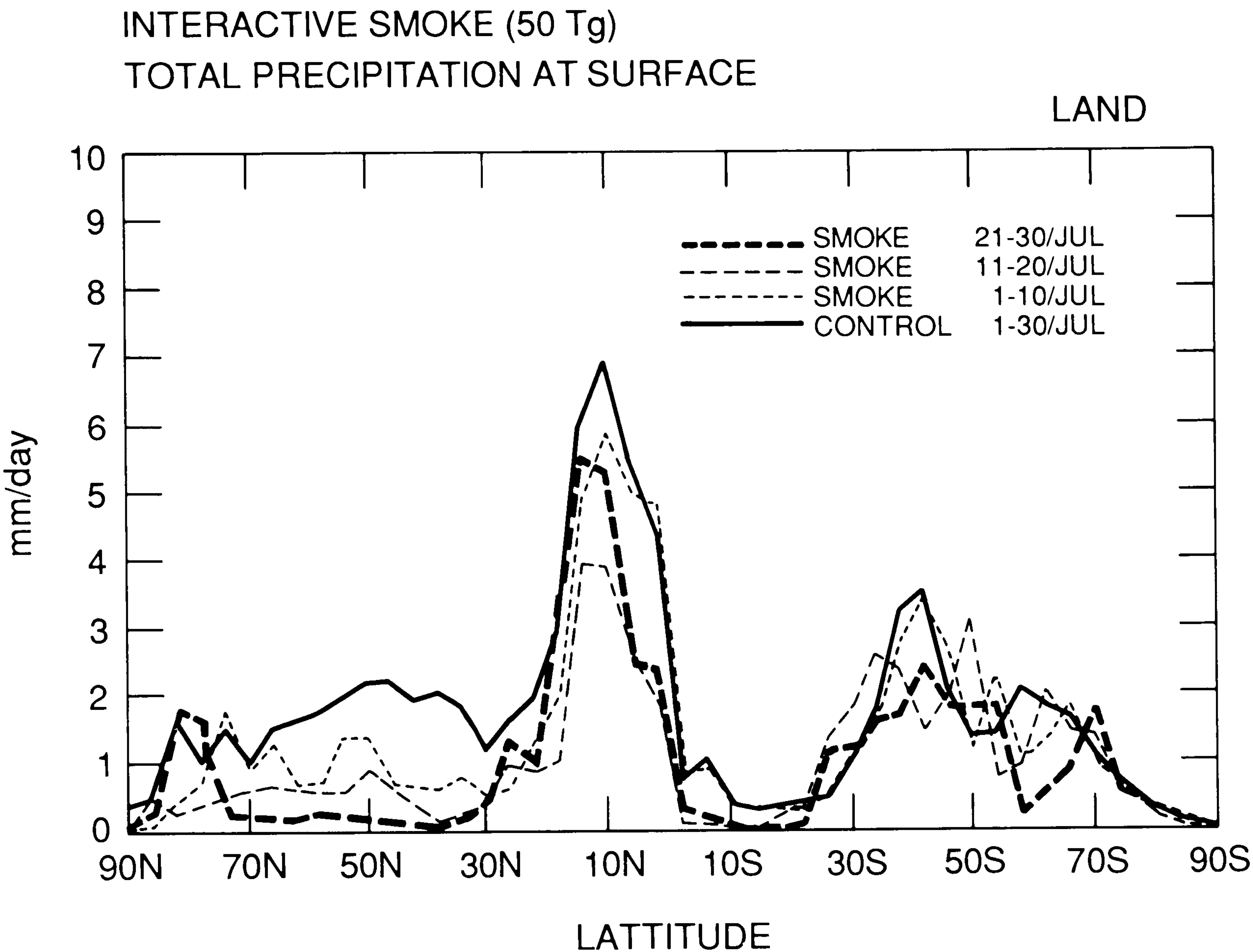

Fig. 4 Zonal means (land only of total precipitation for control July simulation and for days 1-10, 11-20 and 21-30 following a 50 Tg injection of smoke

rapid initial cooling of the surface after the sunlight is "switched off" (analogous to the diurnal temperature cycle), after which the surface temperature only gradually approaches the equilibrium warming (for small smoke loadings) or cooling (for larger smoke loadings). It is important to note that an absorption optical depth of 0.4 corresponds to a rather small quantity of smoke, even if the smoke is spread out over an area equal to one-half of the entire Northern Hemisphere ($127 * 10^6 km^2$). For moderately black smoke (single scattering albedo, ω_0, equal to 0.5), the smoke mass, so defined, is about 15 Tg (absorption coefficient a 3.5 m^2/g). For a less absorbing smoke (ω_0 = 0.7, σ_a = 1.5 m^2/g), the smoke mass is only about 34 Tg. Both of these quantities are much less than those that might be anticipated from urban fires in a nuclear war (see Sect. 2.2).

With the above considerations in mind, it is not surprising that one would find, as Ghan et al. (1985) have done, that even small smoke loadings can greatly reduce the amount of precipitation in regions where convective precipitation normally dominates (i.e., in low latitudes and summer mid-latitudes). Although an increase in large-scale (stratiform) precipitation in the Northern Hemisphere for a nuclear war occurring in summer; the decrease is by as much as a factor of 2 to 4 at northern mid-latitudes (see Fig. 4).

What precipitation there is over land masses is due to large-scale weather patterns, rather than local convective rainfall. For this reason, precipitation disruptions in summer would be far more serious than in winter. Ghan et al.'s (1985) simulations further suggest that, as a result, rainfall after a smoke injection is more uniform or less "noisy" over space than it is normally. Ghan et al. (1985) tentatively conclude, therefore, that normally dry areas are proportionally less affected than normally wet areas. However, Thompson (1985) stated that their runs thus far do not indicate any definite pattern of precipitation disruption (e.g., inland vs coasts).

However, such conclusions can only be preliminary at this point because of the need for more simulation. As such simulations are, in essence, a sample of possible outcomes, the resulting statistics are subject to sample error. This sample error is relatively small when the results are averaged over all longitudes. But such errors make it impossible to make conclusions for a local area with any confidence. Far more extensive simulations are required to produce statistically significant results for an area the size of, say, a river basin.

The significance of the finding that even relatively small quantities of smoke can cause a large reduction in precipitation over mid-latitude land areas lies in the question of the persistence of important climatic effects long after the war is over. In this connection, we must note that none of the GCM simulations extends for more than 30 or 40 days after the war (assumed to occur essentially instantaneously). Nevertheless, all of the simulations with interactive smoke transport agree in finding a progressive lengthening of aerosol residence time as smoke is lofted above the precipitation zone. For example, Malone et al. (1986) find, for 170 Tg of smoke initially injected into the atmosphere, that a third of the smoke still remains 40 days after the war and that the removal rate at that time has diminished to only 0.006-0.007 (fraction) per day, implying a mean residence time for the remaining smoke of 5 to 6 months (and presumably increasing as time goes by). One might suppose, therefore, that significant departures from normal rainfall could persist for as long as a year after the war and that these anomalies would be predominantly on the down side (less rainfall) over land, owing to a persistent reduction in convective activity.

We should note that prediction of changes in precipitation, as a result of various climatic forcings, is notoriously difficult for present-day GCMs. Such predictions are generally considered to be quite unreliable. Nevertheless, there does seem to be a straightforward connection between the expected weakening of convective activity and the reduction in precipitation found by Ghan et al. (1985) even for relatively small quantities of smoke. Thus, this finding remains as a provocative indication that important climatic variables other than temperature may continue to be anomalous, perhaps well outside normal fluctuations, for many months after a nuclear war.

2.6 HYDROLOGIC EFFECTS

2.6.1 Introduction

Nuclear winter could have effects upon precipitation, temperature, and vegetation. All three effects would, in turn, impact the hydrologic cycle and the availability of water for human consumption. In this section, we discuss in general terms the possible nature of these impacts. This will set the stage for the detailed analyses of Section 3.2.

The availability of water supplies for human use during nuclear winter would depend primarily on the amount of runoff, the quantity of water stored in reservoirs, and the level of groundwater tables. These quantities are the outputs of a complicated system: the hydrologic cycle (Fig. 5). Even if the exact effects of nuclear winter upon certain inputs to that system (precipitation, temperature, vegetation) were known, the impacts upon the outputs would be uncertain. The variety, variability, and complexity of hydrologic processes make it difficult to calculate these outputs without fairly specific information (on a basin-by-basin basis) on the values of important physical parameters (Callaway and Currie, 1985).

Making matters even more difficult is the fact that these outputs depend not only on the mean inputs, but also on their variance and distribution over space and time. But, as discussed above, only initial estimates of the effects of nuclear winter upon mean precipitation and temperature in the first month following a conflict have been reported.

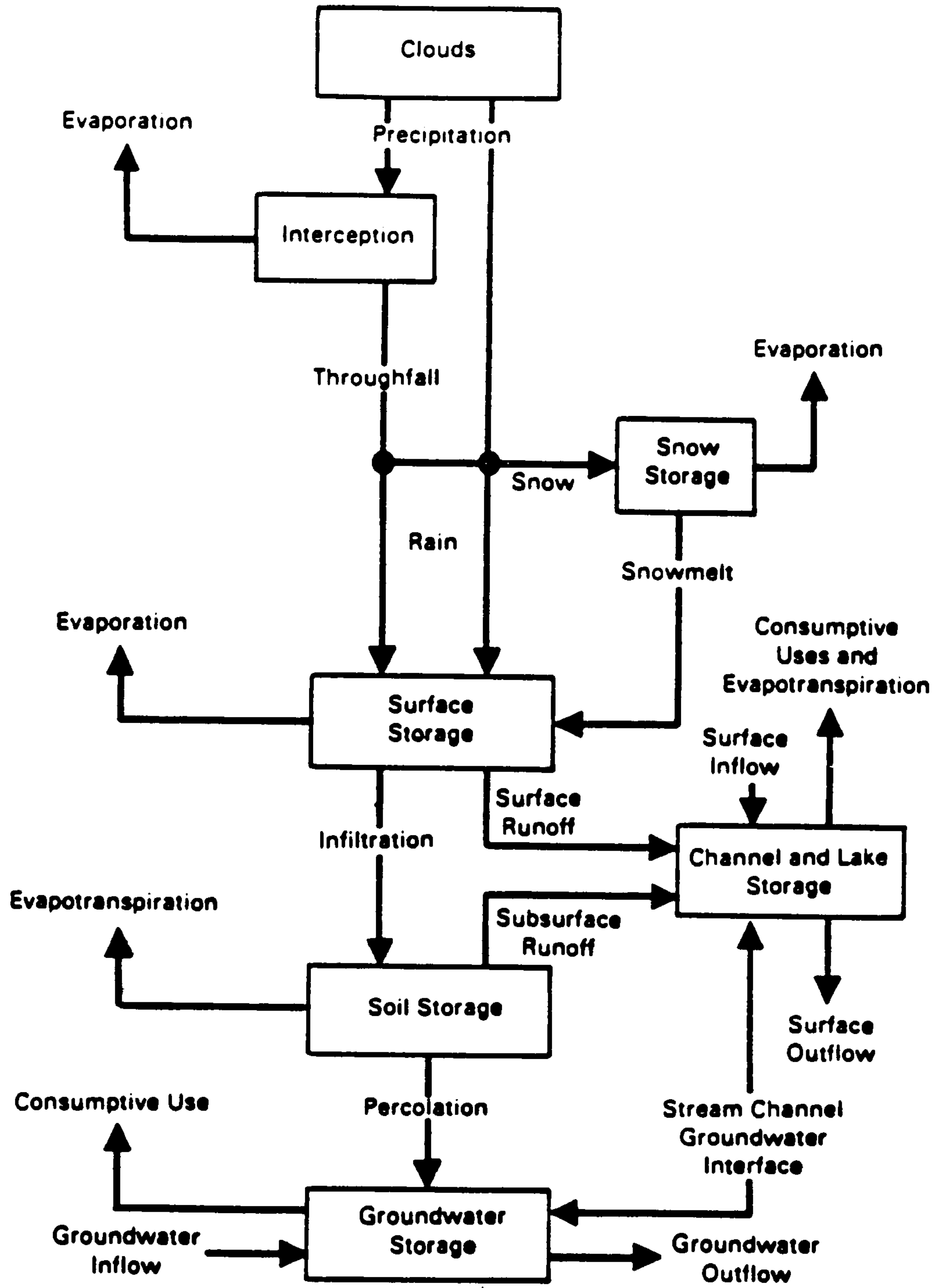

Fig. 5 Schematic diagram of the hydrologic system of a drainage basin.

Source: Callaway and Currie (1985)

Hence, at best only the most general and tentative of conclusions about hydrologic impacts of nuclear winter can be made.

In the rest of this section, we discuss the nature of nuclear winter's impact upon specific hydrologic processes shown in Fig. 5. Using the principle of mass balance, runoff and changes in groundwater levels can be expressed as (Fig. 5):

Runoff = Precipitation - Evapotranspiration - Percolation
- Net recharge by surface waters of groundwater
- Net increase in snow storage

Net Decrease in Groundwater Storage = Pumpage
+ Net regional groundwater outflow - Percolation
- Net recharge by surface waters of groundwater

Nuclear winter would affect precipitation and temperature, which in turn affect evaporation, snow accumulation, and vegetation. The last three then influence transpiration, interception, and percolation. All of these impact runoff, while runoff and percolation alter groundwater storage. Effects upon soil storage would be relatively small, in absolute terms; however soil moisture decreases could have drastic effects on vegetation. Below, the general nature of evapotranspiration, groundwater, and surface water effects are discussed.

2.6.2 Evapotranspiration

Evapotranspiration is a function of temperature, humidity, interception by plant material, the area of surface water, and transpiration by plants. Temperature is critical; in many regions of the United States, Stockton and Boggess (1979) found that the net runoff effect of a 10% fall in annual mean precipitation would be offset by the effect of a $2^{o}C$ temperature decrease. Stockton and Boggess (1979) argue that the effect of temperature upon evapotranspiration would be larger in humid regions; however, Maristany's (1979) regressions (Table 4, below) and ours in Appendix I contradict this.

As another example of effect of temperature on evaporation, the following equation expresses evaporation E_a (in mm/day) from an open pan as a function of air temperature T_a, dewpoint T_d (both in ^0C), and wind speed v_p 150 mm above the pan rim (in km/day) (Linsley et al., 1982):

$$E_a = 33.86[(0.00738T_a+0.8072)^8 - 0.00738T_d+0.8072)^8]^{0.88}(0.42+0.0029v_p) \; .$$

A decrease in T_a from 20 to 5^0C, accompanied by a decrease in T_d from 10 to 0 C would depress evaporation by 72% (3.8 mm/day) under a zero wind speed. Thus, nuclear winter would be expected to lower open water evaporation significantly. Decreased humidity, as represented by T_d, would only partially offset this effect.

Vegetation is responsible for the evaporation of huge amounts of water due to interception and transpiration. Since nuclear winter might lower vegetative cover because of freezing, drought, and decreased sunlight, interception and evapotranspiration by plants might decrease significantly. In the northern United States, the occurrence of summer frosts due to nuclear winter might lower evapotranspiration by plants by over 50%. Lower plant cover is also associated with lower infiltration rates; Callaway and Currie (1985) quote a finding by Johnson (1940) that, when vegetation is removed, infiltration rates can fall by 50% or more in the long run. But in the short run, the decrease in infiltration may be less than this because of the presence of dead plant material. The impact of nuclear winter upon plant cover is only speculative at this point and cannot be translated into more precise estimates of impacts upon evaporation without detailed ecologic and hydrologic modeling.

Decreased evapotranspiration would increase runoff, all else being equal. Lower temperatures, if they approach the freezing point, could also decrease infiltration and, ultimately, percolation. On the other hand, if temperatures decreased enough, then runoff would decrease because precipitation would be retained as snowpack. However, based on the conclusions in Section 2.3, above, it is not expected that summertime temperature decreases due to nuclear winter would have any more effect on runoff than those from a war in the late winter or early spring.

2.6.3 Groundwater

Groundwater levels would, on the whole, be negatively affected by nuclear winter. Temperature effects would have a mixed impact upon groundwater levels. Less evapotranspiration will mean less withdrawal of groundwater by phreatophytes, but diminished infiltration would mean less percolation. However, precipitation and runoff effects will dominate. Decreased rainfall would result in far less percolation. Net recharge of groundwater by surface waters would also diminish, because groundwater discharge or "base flow" would also be the main source of streamflows for many basins, just as it is during normal dry periods. The severity of these effects would be aquifer-specific. As a partial offset of these effects, net regional outflow of groundwater may decrease, particularly in coastal aquifers where groundwater is discharged to the sea. But this may also lead to saltwater contamination of wells near the coast.

Generally, shallow aquifers, such as those in glacier deposits or buried valleys, would be most affected by nuclear winter. The reason is that they are often tightly coupled to surface water systems or respond quickly to changes in percolation. On the other hand, deep aquifers, such as confined artesian aquifers, would react more slowly or not at all. Where water tables are lowered, small domestic wells would be most hard hit, because such wells rarely penetrate more than 10 ft below the water table. Irrigation wells, by contrast, are usually much deeper, penetrating (on average across the nation) 140 ft below the water table (K. McCray, National Water Well Association, personal communication). Municipal wells are also dug to depths well below the water table. As a result, such wells are unlikely to go dry, even in the most severe of droughts, although their yield might be reduced. Groundwater impacts experienced under historical droughts are discussed below, followed by a summary of groundwater sensitivity by region of the United States.

Little specific information is available on the effect of the drought of the 1930s upon groundwater levels. More recently, during the southern drought of the 1950's, groundwater levels declined in many areas by tens of feet and several hundred domestic supply wells became dry. The drought of the 1960s in the Northeast resulted in similar ground water level declines (Matthai, 1979).

The 1976-77 drought affected much of the nation to some extent, and was especially severe in western states. Generally, only shallow wells (less than 75 ft) were affected and the most severe declines in water levels were about 30 ft. Although it generally takes about two years for drought effects to become apparent in well data, in California some shallow wells began to go dry as early as 1975, not so much because of reduced recharge but because of increased pumping to make up for surface water deficits. Water levels in California declined by an average of 13 to 20 ft from 1975-77. In the Midwest, the same period saw hundreds of wells go dry, primarily in Minnesota and on Michigan's Upper Peninsula, where wells are generally less than 200 ft deep and deeper supplies are unavailable. The situation became serious enough to require hauling of water for several Upper Peninsula municipalities (Matthai, 1979).

The 1980-81 drought seriously affected much of the southern portion of the nation. In parts of Georgia and Alabama, declines were greatest in areas affected by pumping for irrigation, where ground water was heavily relied upon to supplement diminished surface supplies. In 1981, declines of as much as 15 ft in the Floridan aquifer occurred in one year (Carter, 1983).

Stockton and Boggess (1979) analyzed, in general terms, the effect of a 10% dryer and 2 warmer climate upon groundwater levels in each of 18 U.S. Water Resources Council (1978) regions. The regions, together with the "aggregated subregions" used in the water supply analyses of Section 3.2, are portrayed in Fig. 6. Of most interest here are their conclusions about the effects of a possible increase in the variance of streamflow, since those conclusions reflect the short-run effects of severe drought upon aquifers. Their conclusions for each region follow:

- Region 1 (New England). Great effect because of thin aquifers and their association with stream systems.
- Region 2 (Mid-Atlantic). Less water available from wells due to shallow aquifers and the large contribution groundwater discharge makes to the baseflow of streams.
- Region 3 (Southeast). No effect, because of the large amount of groundwater reserves.
- Region 4 (Great Lakes) and (Ohio River). Yields of shallow aquifers decrease as recharge decreases.
- Region 6 (Tennessee River). Decreased yield in shallow aquifers tied to surface water.
- Region 7 (Upper Mississippi). Shallow aquifers may be severely affected.
- Region 8 (Lower) Mississippi). Groundwater so vast that total effect is probably small.
- Region 9 (Souris - Red). Groundwater levels will decline, especially in shallow aquifers.
- Regions 10 (Upper Missouri) and 11 (Arkansas). Yields from shallow aquifers decrease.
- Region 12 (Texas-Gulf). Little effect, except in stream -connected aquifers.
- Regions 13 (Rio Grande), 14 (Upper Colorado), 15 (Lower Colorado), 16 (Great Basin), and 18 (California). Little change.

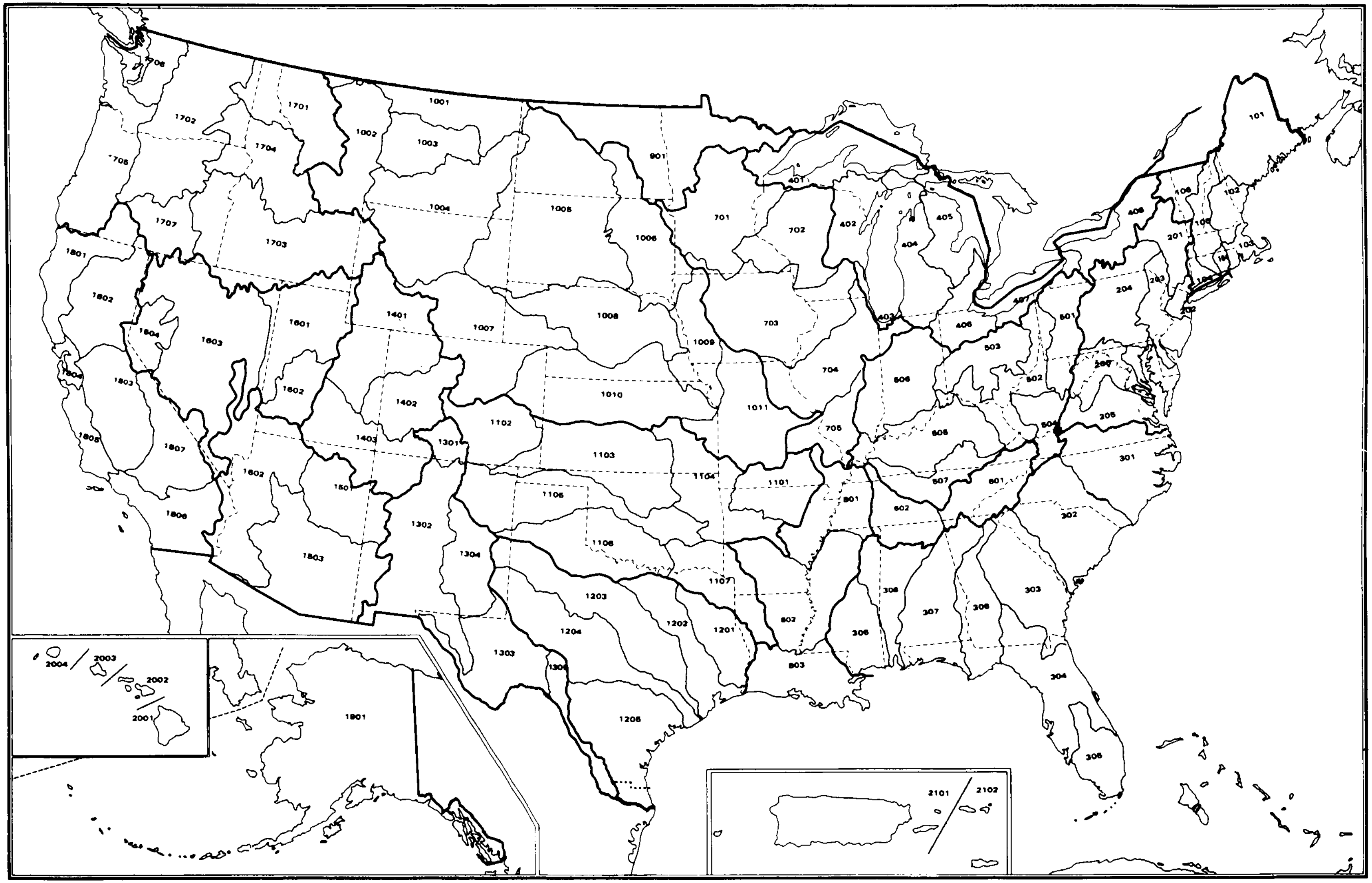

Fig. 6 Water Resources Council regions and aggregated subregions

- o Region 17 (Pacific Northwest). Groundwater yield is affected because of close tie with surface water.

2.6.4 Streamflows

Precipitation decreases would more immediately impact surface water than groundwater. Generally, given no change in temperature, changes in runoff are more than proportional to changes in precipitation. However, the exact effect on runoff depends not only on the change in total precipitation, but also on changes in intensity and temporal and spatial distribution. As Callaway and Currie (1985) put it:

"... the fact that enough is known about the physical principles of hydrology to characterize the structure and behavior the hydrologic system in an abstract manner does not necessarily make it easy to characterize the sensitivity of a specific drainage basin to changes in climate and vegetation. There are two reasons for this. First, more information is generally needed to characterize the nature of the changes in climate and vegetation than is generally available... Second, the extreme variety, variability, and complexity of the processes influencing hydrologic phenomena make it difficult to generalize about the indirect effects of climate changes on different drainage basins" (p. 56).

In spite of these difficulties, several attempts have been made to forecast the effects of climate change upon runoff in U.S. river basins (see the overviews in Callaway and Currie, 1985; Kates et al., 1985; Klemes, 1985; and Changnon, 1987). Generally, they conclude that a 1 to 2°C increase in annual temperature and a 10% decrease in annual precipitation would lower streamflows by 20% to 50%. These studies have used two types of methods:

1. empirical models, in which regression models relate runoff to precipitation, temperature, and other variables using historical data (e.g., Langbein et al., 1949; Revelle and Waggoner, 1983); and

2. causal models, in which the dynamic physical mechanisms of the hydrologic system are explicitly represented (e.g., Nemec and Schaake, 1982). Such models are calibrated using historical data, if available.

Most of these studies focus on the long-term effects of a rise in CO_2 levels, and study the impacts of a mean temperature change of ± 2 C and a precipitation change of $\pm 10\%$. These changes are, of course, smaller than those that have been postulated for nuclear winter. Examination of the historic record reveals that climatic changes as dramatic as those predicted for a nuclear winter have not been experienced in the last half-century. For example, the annual mean temperature for the state of Utah has been confined to a range of 46.5 to 52 F during 1931-1982 (NOAA, 1983). Only a handful of states have had calendar-year precipitation levels less than 50% of the historic average. Therefore, use of runoff models that have been calibrated with historic data to project the effects of nuclear winter can be no more than an exercise in speculative extrapolation. There is no guarantee that the historical relationships will hold outside the ranges of temperatures and precipitation previously experienced. As an example, causal models rarely represent vegetation explicitly; rather, coefficients for interception, evapotranspiration, and infiltration are based implicitly on the historic plant cover. Since nuclear winter could alter vegetative cover, these coefficients may no longer be valid. For illustration purposes, however, three examples of empirical models are given below, in order to offer some indication of the severity of nuclear winter's impacts upon runoff.

Revelle and Waggoner (1983) analyzed annual flow records, adjusted for upstream storage changes, for the Colorado River for 1931-1976 and derived the following regression model:

$$Q_t = 9274 + 52*P_t - 2400*T_t \qquad R^2 = 0.73$$

where Q_t is annual flow (in 10^6 m^3/year; mean = 16,430), P_t is annual average precipitation upstream (in mm/year; mean = 332),and T_t is annual average temperature (in ^{o}C; mean = 4.18^{o}). The impact of a 2^{o} increase in temperature would be a decrease in flow of 29%, while a decrease in precipitation of 10% would reduce flow by 11%. This demonstrates the importance of temperature, and not just precipitation, in determining runoff. If it were assumed that this relationship would hold under nuclear winter, a decrease in mean temperature of 6^{o} and a decrease in precipitation of 75% would actually cause runoff to increase by about 10% to 18,400 x 10^6 m^3/yr. This is because the temperature effect would dominate the rainfall effect. This volume is two-thirds of the rainfall in the watershed, which is not credible. A reason for this result is the linear form of the above equation; for small values of precipitation, a nonlinear form yielding non-negative flows might be more appropriate. A more realistic forecast might result if we disregard the temperature effect as being speculative, and only include the effect of a precipitation decrease. Then the streamflow would be projected to be 3500 x 10^6 m^3/yr, one-third the lowest flow observed during period 1931-1976, and one-fifth of the normal value.

As a second example of the empirical approach, Langbein et al. (1949) estimated the relationship of mean annual temperature (weighted by monthly precipitation to account for evaporation effects) and mean annual precipitation to mean annual runoff using cross-sectional data from 22 drainage basins in the western United States. Because this analysis is based on differences between basins, the relationship is a long-run one, in that it reflects adjustments of soils, vegetation, and landscape form to climate. In contrast, the time-series based analysis in the previous paragraph gives the short-term response for a single basin, with a given pedology, ecology, and geomorphology. The following function is a fair approximation to Langbein et al.'s results for rainfall of 400 mm or less:

$$Q_t = (0.1 + 0.0005P_t - 0.025T_t)P_t \quad ,$$

where Q_t and P_t are in mm/yr and T_t is in ^oC. Stockton and Boggess (1979) used the Langbein et al. (1949) relationship to analyze the possible effects of climate change in each of the 18 water resources regions covering the continental U.S. They found, for example, that a 10% decrease in mean precipitation and a 2 C decrease in mean temperature would lower mean streamflows in New England by 6%.

As an example of how Langbein et al.'s relationship might be used to estimate the magnitude of impact of nuclear winter, take a hypothetical basin with a mean annual temperature of 4 C and average precipitation of 600 mm. The projected runoff would be 180 mm/yr. If nuclear winter dropped the mean temperature to 0 and mean rainfall to 200 mm, the projected runoff would fall by nearly 80%. If the above equation were applied to the Colorado basin, a decrease of mean temperature from 4.18 to -1.82 C and a 75% decrease in mean rainfall would cause a 70% fall in runoff (from 15,900 x 10^6 m^3/yr to 4600 x 10^6 m^3/yr). However, the validity of this projection is doubtful because it is based on long-run, not short-run, relationships between precipitation, temperature, and run-off. All that could be concluded is that the impact upon streamflow is likely to be severe, and that apparently the precipitation effect is more important than the temperature effect. (Note the conflict with the result of the Revelle and Waggoner (1983) model, in which temperature seems to be more important.)

A third set of relationships was developed by Maristany (1979). He estimated a regression equation relating annual runoff to mean absolute temperature T and precipitation P for each of 10 regions in the United States. The equations were of the form $Q = aT^bP^c$. Within each region, time-series data from several stations were used to estimate the parameters; hence, the resulting functions are short-run relationships. Table 4 shows the results of inserting 30% and 50% of the annual streamflow in these functions, together with no decrease and a 5^oF decrease in the annual temperature. In 8 out of 10 cases, a precipitation decrease of 70% with no change in temperature caused streamflow to fall by at least 75%. In half of those cases, the fall was more than 90%. (The result for Zone 4, which contains the Colorado River, is consistent with that obtained using Revelle and Waggoners regression function for the Colorado above.) A cooling of 5°F (2.8°C) would only slightly ameliorate the fall in runoff, with the exception of Zones 8 and 9. These projections can only be taken as indicative of the changes that would actually occur, in part because the assumed levels of annual temperature and precipitation are outside the range of observation.

As Callaway and Currie (1985) point out, conclusions from these types of studies about the effects of hypothetical changes in climate upon water supply are extremely limited. There are several reasons for this.

Table 4. Runoff as a function of temperature and precipitation[a]

Zone[b]	Temperature Exponent	Precipitation Exponent	R^c	Mean T(°K)	Mean P(in.)	Streamflow as % of Flow Under Normal P and T: Normal T 30% P	Normal T 50% P	5° F Less 30% P	5° F Less 50%P
1	-24.8	1.5	0.67	300.1	64.6	16%	35%	13%	28%
2	-38.2	2	0.76	303.3	64.1	9%	25%	13%	36%
3	-36.6	2.4	0.63	287.6	56.8	6%	19%	8%	27%
4	-20.5	1.3	0.78	279.5	47.4	21%	41%	26%	50%
5	-34.9	2.2	0.88	284.3	58.9	7%	22%	10%	31%
6	-4.6	1.4	0.74	295.5	44.2	19%	38%	19%	40%
7	-40.7	1.9	0.74	295.0	51.6	10%	27%	15%	39%
8	-69.7	0.35	0.5	279.9	42.7	66%	78%	131%	157%
9	-45.3	0.64	0.73	282.3	43.8	46%	64%	72%	100%
10	-20.7	1.2	0.73	283.5	45.6	24%	44%	29%	53%
U.S.	-38.5	1.5	0.68	289.1	52.0	16%	35%	24%	51%

a. Exponents from Maristany (1979).
b. Zones are defined by the following boundaries: 40°N and 85°W, 95°W, 105°W, and 115°W. Zones are numbered from east to west, with Zone 1 being the southeast U.S., and Zone 6 being the northeast U.S.
c. Correlation coefficient for fitted equation.

1. The effects of nuclear winter upon temperature and precipitation are likely to be region specific.

2. Ecological changes, and the resulting effects upon evapotranspiration, are not considered.

3. Although global circulation models have shown that nuclear winter's effects would be less severe during the northern hemisphere winter, little beyond that is known about the month-by-month distribution of rainfall changes and how they depend on when the nuclear war takes place. Significant shifts in the annual distribution of precipitation would, in general, invalidate statistical models based on historical relationships. For a given level of precipitation, changes in timing might increase or decrease the effective water supply, depending on the temperatures, timing of agricultural water demands, and amount of storage available.

4. Little is known about how nuclear winter would affect the probability distribution of precipitation. The above analyses only consider average conditions. Conceivably, nuclear winter might increase the variance of streamflows, in addition to decreasing their mean, making severe droughts even more likely. In planning for water supply under climatological disturbance it is advisable to plan for extreme events, not median conditions.

Callaway and Currie (1985) summarize the information needed to project the hydrologic impacts of CO_2 increases; the bulk of their recommendations also apply here.

3. IMPLICATIONS FOR CIVIL DEFENSE

3.1 SHELTER

As discussed previously under pessimistic scenarios, nuclear war might result in decreases of temperature in the weeks following a large attack on cities. These temperature decreases are now believed to be 15^{o}C (Malone et al., 1986) or less (Thompson & Schneider, 1986) if the war occurs in January and 20 to 25^{o}C or less if the war occurs in the late spring or early summer. There may be disruption of rainfall patterns and possible marked decreases in rainfall over continental areas for several weeks or months.

A decrease in temperature, particularly in the summertime, simplifies the requirements for ventilation of populations crowded into fallout or blast shelters. Figure 7 shows the ventilation rates required in crowded shelters in the summertime in the United States to prevent heat prostration of the shelter occupants. Reducing the exterior temperatures by 25^{o}C (45^{o}F) eliminates heat prostration as a problem in sheltering population. Instead of 10 to 50 ft^3/min. required per shelter occupant, ventilation requirements would drop to that required to control carbon dioxide concentration in the shelters - approximately 3 ft^3/min.

A substantial drop in external temperature would decrease not only the temperature in the shelter but the humidity as well. This should result in decreased perspiration by the shelter occupants with a corresponding reduction in their requirements for water.

This does not mean that the standards for shelter ventilation specifications can be relaxed. For one reason, the cooling will not take effect for two or three days after the attack, time enough for significant temperature buildup in shelters in the southern part of the United States. A second reason is that, if the attack were to avoid cities to the extent that climatological cooling was not produced and a normal

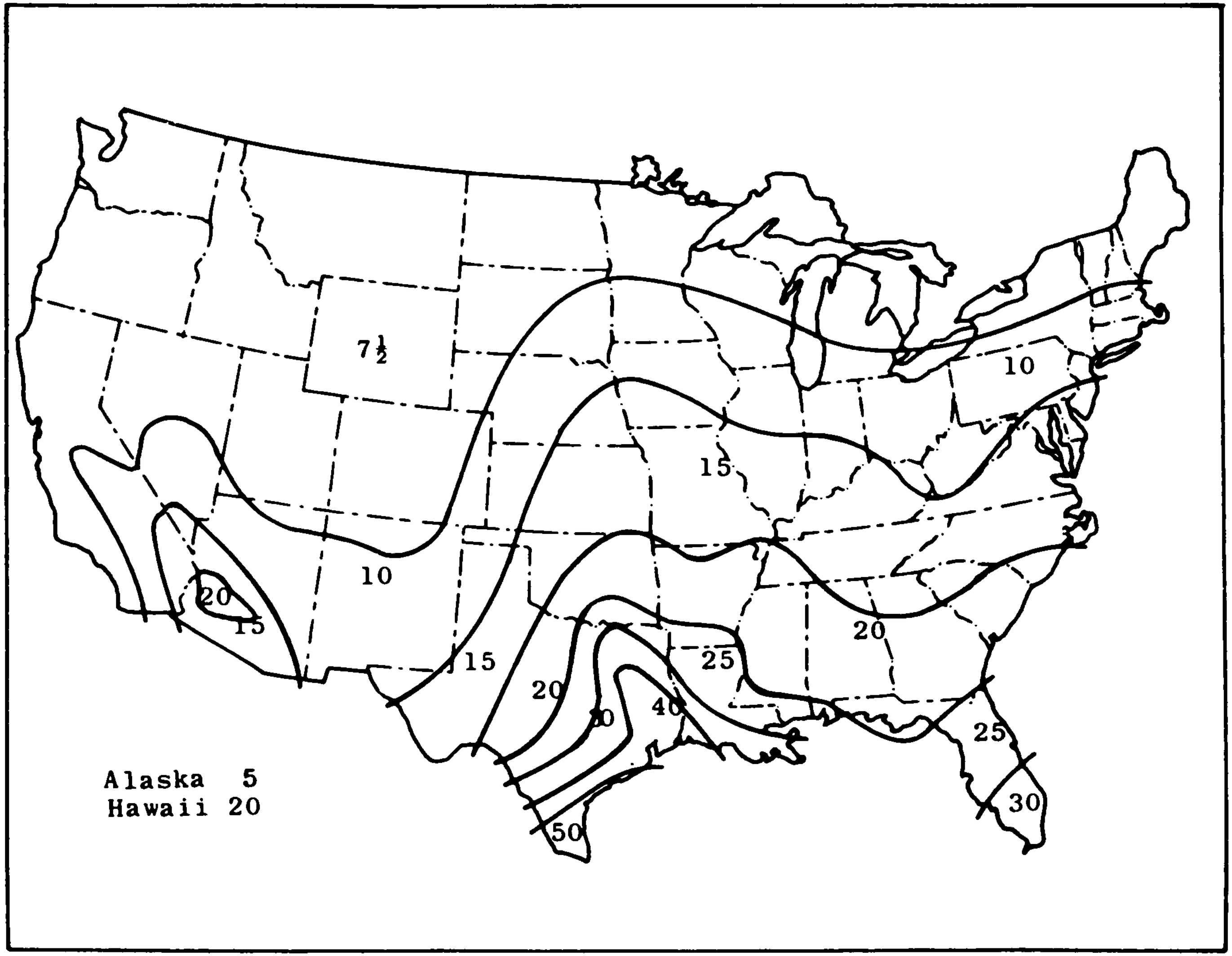

Fig. 7 ZONES OF EQUAL VENTILATION
(Rates given in Cubic Feet per Minute required for each sheltered person)

summer temperature followed, people who were in crowded shelters could be in serious trouble if cooling from nuclear winter had been depended upon. The temperature reduction in the event of a wintertime attack is expected to be manageable. Crowding into fallout shelters, especially if below grade, is an excellent expedient method of keeping warm should the population not have adequate cold weather clothing.

3.2 WATER

3.2.1 Introduction

In this section, the potential availability of water in the continental United States during a postulated year-long decrease of precipitation due to nuclear winter is estimated using state- and river-basin-level information. The availability is then compared to annual demands for water from domestic central systems, irrigated agriculture, and industry. We seek to determine whether sufficient water might be available, first, for potable uses and to raise food and, second for other economic purposes.

Any national analysis of the hydrologic responses to the unprecedented conditions of a nuclear winter must be interpreted cautiously. Reasons for this include:

1. uncertainties concerning the insolation, temperature, and precipitation changes that would be wrought by nuclear winter (see Section 2);

2. uncertainties concerning the response of the hydrologic system to these changes (see Section 2.6);

3. uncertainties concerning the needs for potable water, irrigation, and industrial water supply after a nuclear conflict; and

4. the coarse level of analysis, which looks only at entire river basins or states. Because of an absence of water storage and transport facilities (or perhaps the power that would be needed to operate them), comparisons of aggregate supply and demand within a region mask variations in local conditions. Water that cannot be brought to where it is needed useless, even if the region, on average, has plenty.

Therefore, this study should be viewed as a screening of regions in order to determine which ones are likely to be most vulnerable to a drastic decrease in precipitation. Our conclusions about the supply-demand balance in particular regions should be viewed as tentative. Detailed analyses which explicitly model the hydrologic processes and water storage and conveyance facilities in each basin are needed. But even then, the fundamental uncertainties listed above would still limit the conclusiveness of such studies (see Callaway and Currie, 1985). What this analysis attempts to do is to indicate the general magnitude and locations of water supply problems due to nuclear winter, and where further research is necessary.

We examine the availability of water from three sources:

1. groundwater;
2. streamflows, which, although reduced, would still be a significant source of supply in some basins; and
3. reservoir storage.

Below, groundwater is treated separately from the other two water sources. The vulnerability of groundwater supplies is discussed using state-level data on aquifer characteristics and groundwater uses. The ability of groundwater sources alone to sustain sufficient wheat production to feed the U.S. population is examined. For surface waters, a scenario of streamflows and storage is developed based, in part, upon historical low flows and regression analyses of streamflows as a function of temperatures and precipitation. We use the term "scenario" because the uncertainties just discussed mean that any particular estimate of supply can only be an indicator of the actual amounts that would be available. Surface water demands and supply scenarios are summarized by the approximately 100 aggregated subregions (ASRs) defined by the U.S. Water Resources Council (1978) (Fig. 8). Each ASR corresponds to a major river basin or set of basins.

Subject to the above qualifications, few ASRs appear to have insufficient supplies compared to the domestic water supply demands served by central water supply systems at this aggregate level of analysis. This is especially true if demands can be reduced to the minimal levels needed for survival. However, because (1) cities might be located far from water sources in an ASR, (2) water is difficult to transport, and (3) electric power is required to pump and treat water, shortages could nevertheless occur. Rural populations not served by central systems are likely to be seriously affected in many parts of the country because they depend primarily on shallow wells.

On the other hand, if we consider all water uses (including self-supplied industrial and irrigation), many ASRs, mostly in the arid west, may have problems meeting all surface water demands during a prolonged drought. These results are discussed in detail below.

3.2.2 Groundwater Supplies

Groundwater is the source of 38% of all water withdrawals in the United States for purposes other than cooling of electric power plants (U.S. Geological Survey, 1985). Thirty-five percent of all public water supplies are provided by this source, as is 40% of all irrigation water and nearly all rural domestic supplies. During an interruption of precipitation, groundwater sources would become even more important, because aquifers react more slowly than surface waters to changes in precipitation. Regions and economic sectors which depend heavily on groundwater would be relatively less vulnerable to water shortages during

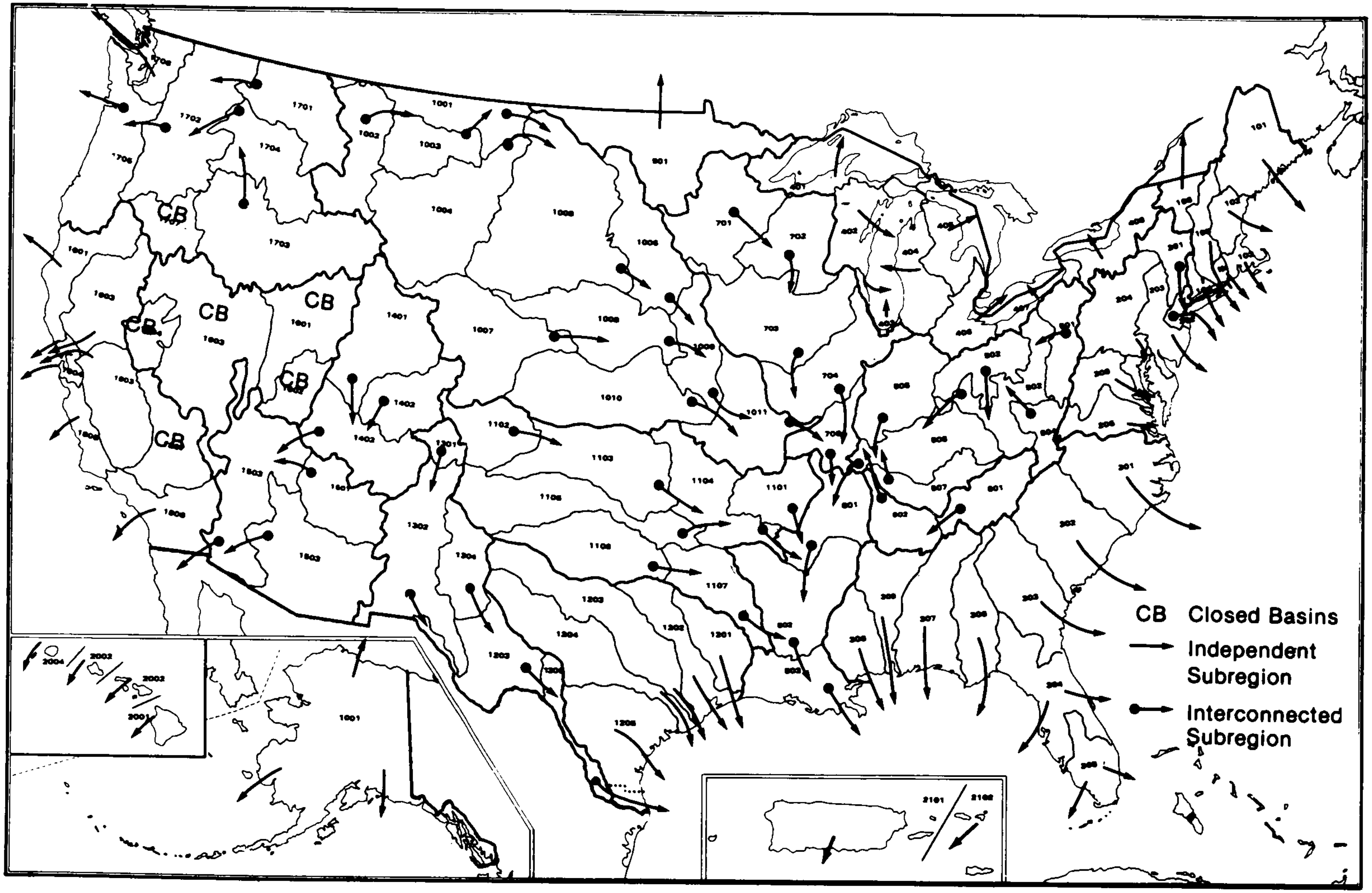

Fig. 8 Aggregated subregions and flow among them

a nuclear winter, assuming that pumping power is available. Table 5 shows the fraction of domestic, irrigation, and total freshwater withdrawals that come from groundwater for each state.

Figures 9-11 show our classification of states according to the relative importance of groundwater. We define a state as being groundwater dependent if half or more of its water withdrawals in a given category are from groundwater. Some of the data upon which these analyses are based are shown in Table 5. Our presumption is that the percentage dependence on groundwater will not change greatly in the future relative to 1975 levels. Figure 9, showing the overall dependence on groundwater, is exclusive of electric utility withdrawals, which in many states account for the bulk of freshwater withdrawals. Utility withdrawals are excluded, since the largest utility use, by far, is for once-through cooling of thermal power plants. Water used for this purpose is returned to the source (albeit, at a higher temperature, which increases evaporation later). (Table 5, however, includes utility use in the totals.)

Figure 9 shows that domestic central systems in Florida, the upper Mid-west, and the Rocky Mountain West are more dependent on groundwater than elsewhere. Hence, these systems are likely to be less vulnerable to disruption in the case of a precipitation interruption. The nationally important irrigation areas of Arizona and the High Plains use groundwater, and would suffer relatively little disruption. This is especially true for the many regions in which there is "mining" of aquifers which have relatively little recharge. Examples include the Ogallala aquifer of the High Plains and the deep "fossil" water of the Arizona basins.

However, as discussed in Section 2.6, some users of groundwater supplies would be vulnerable to a prolonged drought. In particular, water tables in shallow aquifers having high transmissivities could fall precipitously if their recharge source is precipitation or if the

Table 5. Groundwater Statistics by State

STATE	Groundwater Withdrawals as a Percentage of Total Fresh Withdrawals in each Category: Domestic Central	Irri- gation	Total	Irrigation Groundwater Withdrawals (acre-ft/yr)
Alabama	28	30	3	13440
Arizona	54	58	58	4144000
Arkansas	42	86	13	4256000
California	46	39	39	14000000
Colorado	8	19	18	3024000
Connecticut	17	8	11	1792
Delaware	38	63	59	4592
Florida	86	53	52	1792000
Georgia	29	66	18	425600
Idaho	94	25	35	4592000
Illinois	27	100	5	108640
Indiana	41	98	11	257600
Iowa	81	84	28	85120
Kansas	48	92	85	5824000
Kentucky	13	6	4	336
Louisiana	44	47	14	1108800
Maine	19	3	9	224
Maryland	9	54	13	14560
Massachusetts	24	28	13	5600
Michigan	17	37	4	86240
Minnesota	52	88	22	156800
Mississippi	18	35	54	909440
Missouri	22	75	7	109760
Montana	39	1	2	105280
Nebraska	77	67	59	7504000
Nevada	40	17	20	593600
New Hampshire	48	0	17	0
New Jersey	40	73	25	44800
New Mexico	90	44	47	1792000
New York	23	46	12	23520
North Carolina	12	30	10	43680
North Dakota	54	37	11	56000
Ohio	27	36	6	2128
Oklahoma	28	84	56	817600
Oregon	29	14	17	952000
Pennsylvania	16	14	6	24640
Rhode Island	15	9	22	560
South Carolina	22	27	4	16800
South Dakota	68	33	48	168000
Tennessee	40	51	5	7168

Table 5. (Continued)

STATE	Groundwater Withdrawals as a Percentage of Total Fresh Withdrawals in each Category			Irrigation Groundwater Withdrawals (acre-ft/yr)
	Domestic Central	Irri-gation	Total	
Texas	46	70	61	8960000
Utah	66	10	18	336000
Vermont	35	19	13	336
Virginia	17	29	7	8960
Washington	37	4	9	291200
West Virginia	27	8	4	112
Wisconsin	48	97	10	91840
Wyoming	33	8	10	414400

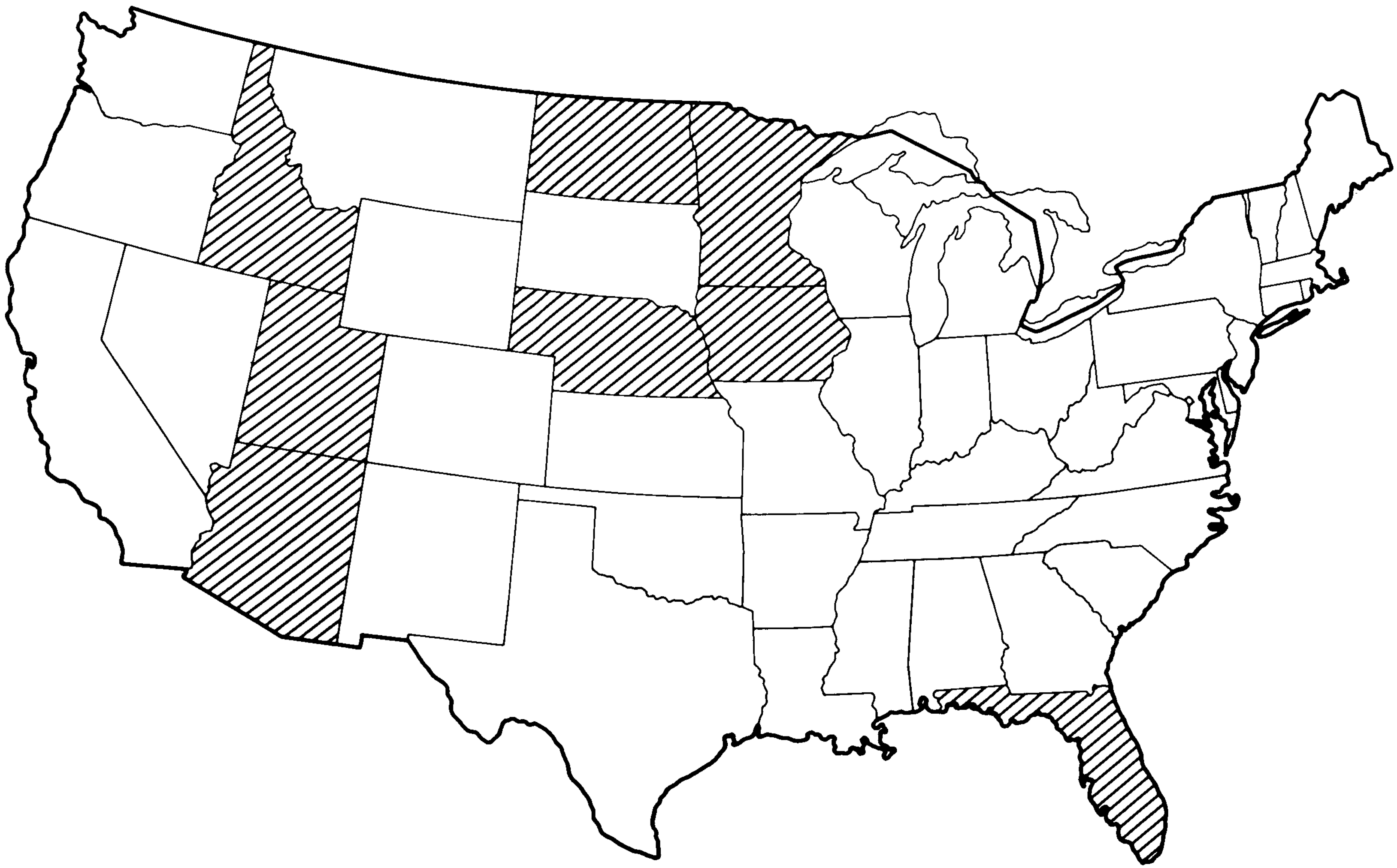

Fig. 9 States in which more than 50% of domestic central system withdrawals are supplied by groundwater

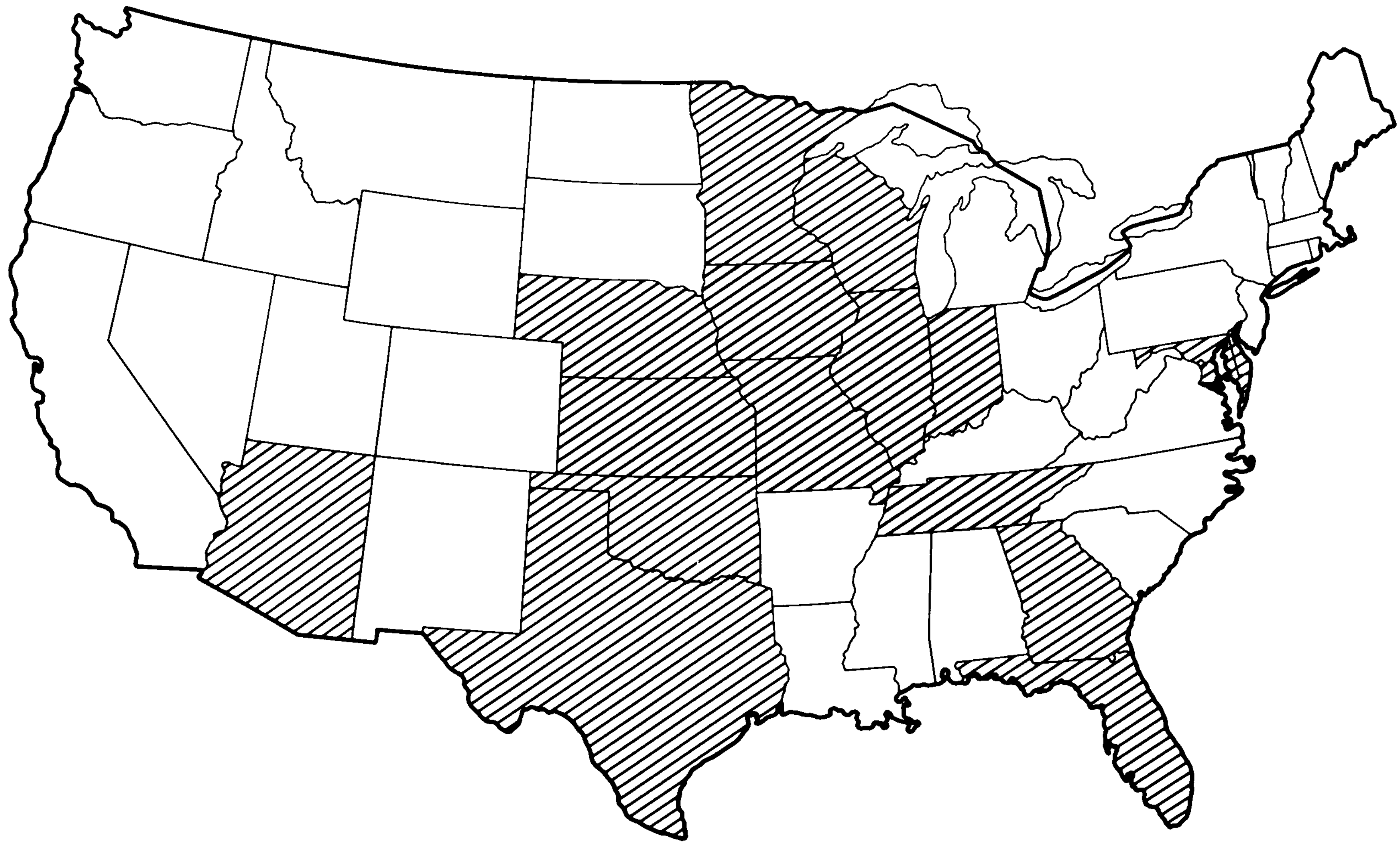

Fig. 10 States in which groundwater supplies more than 50% of irrigation water supplies

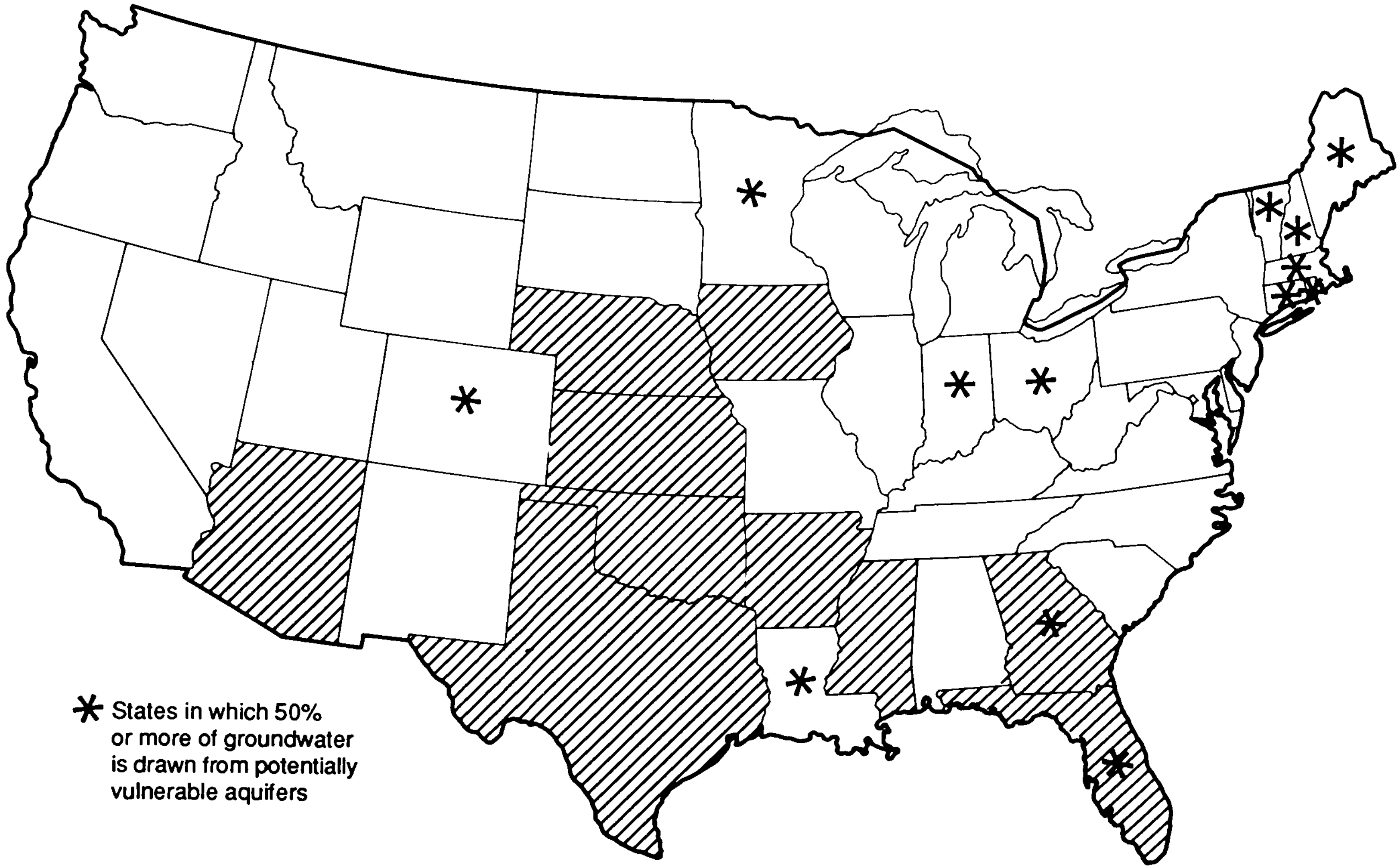

Fig. 11 States in which more than 50% of total water withdrawals are supplied by groundwater

aquifers are closely connected with surface waters. As a result, rural domestic users would be seriously affected in many regions, since their wells normally penetrate less than 10 ft below the water table. However, decreases in water tables would not be a serious problem for most irrigation, industrial, and municipal wells, since they usually penetrate 50 ft or more below the water table. The only exceptions would be in particularly thin aquifers, such as the stratified drift aquifers of some of the northern states, or where withdrawals would be sharply increased to make up for surface water shortages (as in the 1976-77 California drought; Matthai, 1979).

In order to identify which aquifers might be vulnerable to a prolonged interruption of precipitation, we have created a data base of 285 aquifers located in the continental United States (Appendix II). The data are drawn from U.S. Geologic Survey (1985), which describes the most important aquifers in each state in terms of yields, depth, uses, quality, recharge sources, and other hydrogeological parameters. We then screened these aquifers using the following criteria:

1. Delete all aquifers which are not recharged directly by precipitation or surface waters. Aquifers receiving no recharge, or which receive recharge from overlying aquifers or mountain runoff in desert areas are unlikely to experience abnormal water table decreases during the year following a nuclear conflict (assuming that withdrawals are not drastically increased.)

2. Delete all aquifers whose wells are more than 250 ft in depth, on average, unless the average well yields are 1000 gal/min (gpm) or more and their depth is 500 ft or less. These aquifers are so deep that the effects of diminished recharge will be delayed and are not likely to be felt in the year following a nuclear conflict. Exceptions might be aquifers with very high permeabilities, as indicated by large well yields. "Average" depth and yield are taken as the average of the ranges given in the U.S. Geological Survey

(1985), except for a few aquifers for which the true averages are given.

3. Delete all aquifers with mean well yields less than 500 gpm, unless their mean depth is less than 150 ft and their yields exceed 200 gpm. Aquifers with low-yield wells have low permeabilities, which means that water moves slowly and the effect of recharge is not felt as quickly as in other aquifers. Such aquifers are not usually important sources of municipal, irrigation, or industrial supplies. However, these aquifers are often the primary source for rural homes, and, if water tables fall, the shallow wells that are used for rural supplies may be severely impacted.

   The aquifers which survive this screening are listed in Table 6, and are the ones most likely to be impacted by a nuclear winter. Many of these aquifers are important ones for their states. The table also shows estimates of the amount of water withdrawn from each. In most cases, these are the lower bounds taken from the ranges given by the U.S. Geological Survey, 1985). A few of the aquifers of Table 6 located in the Mississippi and Ohio valleys, California, Washington State, and the High Plains are still unlikely to be affected by severe drought, even though they passed the screening; they are discussed later in this section. Excluding those aquifers, the total withdrawals from the aquifers in Table 6 amount to roughly 10% of the total groundwater pumpage in the continental United States. Compared to the national distribution of groundwater use, a disproportionate amount of the water from vulnerable aquifers goes to municipal and industrial users, while less is devoted to irrigation. The reason is that irrigators draw primarily from relatively invulnerable aquifers in the West.

Based on information in the U.S. Geological Survey (1985) and Table 6, the majority of the groundwater supplies in the following states may potentially be vulnerable to prolonged drought. These states are indicated by an asterisk in Fig. 11. By "vulnerable," we mean that yields from municipal, irrigation, and industrial wells might be significantly decreased. In rare cases, some such wells might dry up completely, especially if withdrawals are increased over normal levels.

1. Colorado. Its alluvial aquifers in the South Platte and Arkansas river basins are very shallow and productive, and are closely coupled with surface water systems. A severe drought could drastically lower the yields of the many municipal and irrigation wells that depend on it.

2. New England. The major sources of groundwater in each of the states in this region are shallow aquifers of glacial origin. Due to the thinness of these deposits, groundwater reserves are relatively small and large capacity wells may have their yields significantly diminished during a nuclear winter.

3. Florida and Georgia. The Floridan and Biscayne aquifers are the major sources of fresh water in these states. Both aquifers are relatively shallow and very productive. Many large-yield wells could dry up in a prolonged drought, or perhaps be endangered by infiltration of sea water. The 1980-81 drought in Georgia demonstrated this (Carter, 1983). On the other hand, Stockton and Boggess (1979) concluded that this region's groundwater resources would be among the least affected in the nation under a 10% dryer climate, because of the sheer size of the groundwater resource. If resources are available for drilling deeper wells, then this conclusion would probably also be applicable under a nuclear winter. In the shallow sand and gravel aquifers of extreme northwest Florida, however, deepening wells might not be feasible.

4. Indiana. Like the New England states, Indiana draws most of its groundwater from shallow aquifers of glacial origin.

5. Louisiana. The Chicot and alluvial aquifer systems of this state are very productive, and shallower wells may be affected by groundwater table declines.

6. Minnesota. Like Indiana and the New England states, thin aquifers of glacial origin are the major groundwater source and might be endangered by a prolonged interruption of rainfall.

7. Upstate New York. Groundwater withdrawn in this region is mostly from shallow valley-fill aquifers. Due to their close coupling with surface waters, these aquifers could suffer significant water table declines, drying up shallower wells and lowering the yields of deeper wells.

8. Ohio. Shallow coarse-grained unconsolidated aquifers are the major groundwater source in this state. Shallower wells would be vulnerable to a year-long precipitation interruption.

Of the above states, only Florida (69%) and Georgia (52%) obtain more than half of their non-electric utility supplies from groundwater. These are the only two states in Fig. 11 for which the majority of groundwater supplies might be vulnerable to a drought. Of the other states listed above, only Minnesota (48%) draws more than a third of its non-utility water from wells.

Several other states also obtain a majority of their groundwater from aquifers (see Table 6). However, for various reasons, they are still unlikely to be significantly affected by a year-long interruption of precipitation, as long as withdrawals are not greatly increased. These states include:

1. Arkansas, Mississippi, and Missouri. Their alluvial aquifers, especially in the Mississippi river plain, are enormously productive, but also very shallow. As Stockton and Boggess (1979) point out,

however, there is a huge amount of groundwater in the Mississippi river plain and a dryer climate would not significantly affect that resource. Therefore, only very shallow wells are likely to be affected.

2. California. Its Southern California and Central Valley aquifers are very productive. However, the former is in a dry area and receives relatively little recharge from precipitation, and the latter suffered water table declines during the 1976-77 drought primarily because of greatly increased withdrawals. These aquifers should be able to sustain the existing yields of irrigation and municipal wells throughout a year-long precipitation interruption.

3. Kansas. Most of its groundwater comes from the High Plains aquifer. However, this aquifer only barely passed the screening criteria we defined. It is deep and receives relatively little recharge, and therefore is unlikely to be greatly affected within a year after a nuclear conflict.

4. Kentucky. This state pumps a lot of water from the shallow alluvial aquifers along the Ohio River and its tributaries. These aquifers are extensive enough that, except for shallow wells, the impacts of a prolonged drought are not likely to be large.

Of the above six states, Arkansas (82%), California (38%), and Mississippi (82%) withdraw more than a third of their non-power utility water from wells.

The other major aquifer in Table 6 that is unlikely to be affected by nuclear winter is the Columbia River Basalt of Washington State. Its size and depth, together with the aridity of the region, render it relatively invulnerable.

In many cases in which well yields are vulnerable to nuclear drought, pumpage rates can be maintained or even increased by deepening wells or drilling deeper wells. The most important exceptions to this are the relatively thin aquifers of glacial origin in the northern United States. The cost and resource requirements of well deepening depend on many site-specific characteristics, including the age of the well, whether the existing pump can still be used, type of casing, and geology. In most cases, it is no more expensive to drill a new well. The average cost for new municipal water supply wells in 1983 was $34,400/well, including pumps and materials (K. McCray, National Water Well Association, 1987, personal communication). This cost depends on depth and geology, as, for example, the statistical analyses in Campbell and Lehr (1973) and Hobbs (1984) show. In the year following a nuclear conflict, shortages of drilling rigs are unlikely to limit drilling activity. The reason is that the water well-drilling industry suffers from overcapacity in both equipment and staff, and could accomodate a large increase in demand for its services (K. McCray, personal communication). Hence, if the energy is available, water supplies from many of the "vulnerable" aquifers identified above might be maintained during the nuclear drought.

An interesting question is whether there is enough farmland irrigated by groundwater to raise sufficient food for the American population in the second year following an attack. (Stored food supplies are more than adequate for the first year following an attack, see Sect. 3.3.) Table 5 shows, by state, the amount of water pumped annually for irrigation. If it is assumed that (1) 24 in./yr (or 2 acre-ft/acre/yr) are required to raise wheat, and (2) 50 bushels/acre (1.4 tons/acre) is the average yield, then the 63 million acre-ft/yr of groundwater used for irrigation would be sufficient to raise 1.6 billion bushels per year (44 million tons/year). This would cover over half of the approximately 70 million tons needed to provide a minimal diet to the pre-attack American population.

This calculation presumes that availability of seed, energy, agricultural machinery, pesticides, herbicides, and labor would present no constraint. It further assumes that if water tables fall drastically in certain areas due to the decrease in precipitation, then machinery, labor, and energy would be available to deepen wells where needed. It should be noted that only about 10% of the pumpage for irrigation is from the "vulnerable" aquifers listed in Table 6. It is also assumed that decreased insolation and temperatures in the second year would not greatly lower productivity. A final assumption is that, in places where groundwater is used at a greater rate than two acre-ft/acre/yr, there would be enough nearby unirrigated land that could be planted in wheat and use the excess water.

3.2.3 Surface Water: Supply Scenarios

Surface water supplies that would be available during a year-long reduction in precipitation would include (1) reservoir storage of streamflows previous to the conflict and (2) runoff occurring after the conflict. These quantities would depend on many factors, nearly all of which are random or poorly understood. These include (1) antecedent hydrologic conditions (such as reservoir levels, soil moisture, groundwater tables, etc.); (2) the time of year of the conflict; and (3) the exact effects of nuclear winter upon total amounts and distribution of precipitation and evapotranspiration (see Section 2.6). Because of these great uncertainties, we attempt only to produce a scenario of what stored water and runoff might be available during the year following a conflict, while making conservative assumptions to avoid overestimating the availability of supplies.

There are three general approaches to estimating streamflows under nuclear winter conditions:

1. Empirical observations of the same phenomenon. Are there historical precedents for droughts of the hypothesized magnitude? The answer is no. Precipitation deficits of 70% or more have not occurred in

Table 6. Potentially Vulnerable Aquifers

Aquifer	State	Recharge source[a]	Mean depth (ft)	Mean yield (gpm)	Muni use ?	Irri use ?	Approximate use (mgd)
ALLUVIAL	AR	P	125	1500	N	Y	3000
SOUTHERN CALIFORNIA	CA	P	475	1000	Y	Y	1720
BASIN-FILL/DESERT	CA	PM	210	850	Y	Y	100
SOUTH PLATTE ALLUVIAL	CO	MSI	90	800	Y	Y	905
ARKANSAS ALLUVIAL	CO	P	60	650	Y	Y	309.1
STRATIFIED-DRIFT	CT	PS	75	425	Y	N	150
UNCONFINED SURFACE	DE	PS	70	350	Y	Y	22.5
SAND-AND-GRAVEL	FL	P	200	750	Y	N	50
FLORIDAN	FL	PI	200	750	Y	Y	2000
BISCAYNE	FL	PS	95	750	Y	N	400
FLORIDAN	GA	P	470	3000	Y	Y	600
ALLUVIAL	IA	P	65	600	Y	N	21
VALLEY-FILL	ID	P	200	1000	Y	Y	850
GLACIOFLUVIAL	IN	P	40	300	Y	N	200
GLACIAL OUTWASH	IN	P	60	300	Y	N	200
ALLUVIAL	KS	P	80	255	N	Y	151
HIGH PLAINS	KS	P	230	750	Y	Y	5255
ALLUVIAL	KY	P	85	270	Y	N	115
CHICOT	LA	P	425	1500	N	Y	450
ALLUVIAL	LA	PS	175	1500	N	Y	180
STRATIFIED DRIFT	MA	P	90	550	Y	N	320
COLUMBIA	MD	PS	85	275	Y	N	8.1
GLACIOFLUVIAL ICE-CONTACT	ME	PS	85	525	Y	Y	70
GLACIOFLUVIAL	MI	P	112	500	Y	N	40
SURFICIAL DRIFT	MN	P	135	450	N	Y	60.5
ALLUVIAL	MO	SP	90	550	Y	Y	22
MISSISSIPPI ALLUVIAL	MO	SP	115	3000	N	Y	80
MISSISSIPPI RIVER ALLUVIAL	MS	SP	95	1750	Y	Y	672
CASTEL HAYNE	NC	P	135	350	Y	N	87
WEST FARGO	ND	P	175	505	Y	N	0.16
ENGLEVALE	ND	P	40	500	N	Y	0.51
OAKES	ND	P	50	250	N	Y	0.51
SPIRITWOOD	ND	P	150	500	N	Y	0.51
PALEOVALLEY ALLUVIAL	NE	P	100	750	Y	Y	100
VALLEY ALLUVIAL	NE	P	65	525	Y	Y	50
NIOBRARA	NE	P	135	525	Y	Y	5
STRATIFIED DRIFT	NH	PM	60	300	Y	N	50
GLACIAL VALLEY-FILL	NJ	P	155	550	Y	N	100.4
KIRKWOOD-COHANSEY	NJ	P	185	750	Y	Y	16.3
VALLEY-FILL	NM	PSI	125	300	Y	N	101
VALLEY-FILL	NY	PM	100	550	Y	N	90
COURSE-GRAINED	OH	P	112	300	Y	N	300.60
ALLUVIAL	OK	PS	100	350	Y	Y	70.70

Table 6. (Continued)

Aquifer	State	Recharge source[a]	Mean depth (ft)	Mean yield (gpm)	Muni use ?	Irri use ?	Approximate use (mgd)
DOG CREEK-BLAINE	OK	P	150	300	N	Y	10.10
UNCONSOLIDATED SAND/GRAVEL	PA	PS	110	550	Y	N	88
STRATIFIED DRIFT	RI	PS	100	400	Y	Y	14.20
VALLEY-FILL	UT	P	125	380	Y	N	56
STRATIFIED-DRIFT	VT	PM	55	215	Y	N	5.38
COLUMBIA RIVER BASALT	WA	PS	400	1575	Y	Y	110
GLACIAL DRIFT	WA	PS	150	500	Y	Y	135
ALLUVIAL	WV	P	65	775	Y	N	12.20

[a]The following codes are used for source of recharge:
I - Irrigation Percolation M - Mountain Runoff O - Overlying Aquifers
P - Precipitation S - Surface Water

Muni: Municipal water source; Irri: Irrigation water source
gpm: Gallons per minute; mgd: million gallons per day.

any calender year in any state during the last 60 years (National Oceanic and Atmospheric Administration, 1983). Only four states (Arizona, California, New Mexico, and North Dakota) have had a year in which precipitation was half or less of the average. On a month-by-month basis, far worse droughts have occurred, but their persistence falls short of the interruption hypothesized here under nuclear winter.

2. Physical modeling. By assuming a set of initial conditions, detailed models of rainfall-runoff processes and transient groundwater flow could be used to project streamflows during a precipitation interruption. However, this is only possible on a watershed-by-watershed basis, and then only after costly calibration studies.

3. Extrapolation of statistical models. This is the only feasible alternative in our case. Equations relating streamflows to precipitation and temperature could be developed, and then used to estimate the effect of a precipitation interruption. However, it is always dangerous to extrapolate such models, since there is no guarantee that the estimated functions are valid outside the range of observation. Section 2.6 discusses some limitations of this type of analysis. We estimate average streamflows under nuclear winter by extrapolating regression models of annual streamflows.

To avoid overestimating the availability of surface supplies, the following conservative assumptions are made.

1. In the absence of specific records of storage levels for reservoirs throughout the United States, we assume that during a nuclear winter, an amount of water equal to half of the design capacity of storage in each basin can be used to meet water demands. Storage values, taken from U.S. Water Resources Council (1978), include only ponds and reservoirs with over 50 acre-ft

(16.3 million gallons) of capacity, with the exception of some smaller dams exceeding 25 ft in height. The assumption that only half of the storage is available is made for several reasons. First, the possibility that the nuclear conflict would occur at the end of the summer when reservoirs have been drawn down must be accounted for, as must be the fact that storage may be reserved for purposes other than water supply, such as hydroelectric power. Also, in many cases, conveyance facilities will not exist to bring stored water to points of demand. Finally, water quality problems, which are exacerbated during droughts, may prevent use of some stored waters.

2. Precipitation during the entire year is 50% of the average level for each basin. Section 2.6, above, points out that that average precipitation might be as small as 25% of normal levels over land masses during the first month after a nuclear conflict. This depression of precipitation would last months, but not for the entire year, especially during the winter months; hence, a 50% value is more reasonable. As a sensitivity analysis, calculations are also made for precipitation levels 30% of normal.

3. Temperature is assumed to be depressed by only 5^{o}2F relative to annual averages. Greater temperature decreases would result in more water being available because of decreased evapotranspiration.

4. The amount of streamflow assumed to be available in a basin during the year following a nuclear conflict is assumed to be the lesser of two quantities:

    a. the lowest calender month flow of record, in million gallons per day;

b. the minimum streamflow calculated by inserting 50% of the normal precipitation and a $5^{o}F$ decrease in average temperature into a regression model relating annual streamflow to mean precipitation and temperature.

Not all of these flows will be available for off-stream use; we therefore assume that only half will be. This is because conveyance and storage facilities are not available in all basins to divert all streamflows, and quality problems may prevent use of some flows.

5. The regression equation estimated for each ASR is a linear one:

$$Q(t) = a + bP(t) + cT(t) \quad ,$$

in which a, b, and c are fitted constants, with b hypothesized to be positive, and c hypothesized to be negative. Q(t) is the flow in water year t in the ASR in question. The water year is defined as lasting from October to September, which is the standard period for defining annual flows. P(t) is mean precipitation, and T(t) is mean temperature in year t in the ASR in question, and all ASRs that drain into it (Fig. 8). The use of a linear regression model avoids understating the effects of drought because extra-extrapolation of a linear model will likely result in an under-estimation of the streamflow. This is because the response of watersheds is likely to be nonlinear for extremely low levels of precipitation; the negative flows that a linear model would predict in some basins are, of course, physically impossible. The nonlinearity is due, in part, to discharges from groundwater storage to streams. Even under zero precipitation, some watersheds would still have positive streamflows for this reason. The magnitude of this effect is difficult to estimate because of the absence of such severe precipitation interruptions from the historical record.

The use of a regression equation estimated from historical data assumes that the temporal and spatial pattern of precipitation under a nuclear winter will not differ in important ways from historical droughts. Further, it is implicitly assumed that the nuclear conflict occurs at the start of the water year or, equivalently, that the effects of a year-long drought resulting from nuclear winter would not depend on what month of the year the conflict takes place. These are, of course, strong assumptions. But the absence of specific information about the effect of nuclear winter upon the distribution of precipitation means that use of such functions is the only practical means of obtaining a scenario of surface water supply.

Data were compiled from published reports and unpublished records of the U.S. Water Resources Council, U.S. Geological Survey, and the National Oceanic and Atmospheric Administration. U.S. Water Resources Council (1978) gives total surface water storage by ASR and the lowest recorded calendar month runoff for selected streamflow gauges within each ASR. For many of the same gauges, records of annual (water year) streamflows have been obtained from the U.S. Geological Survey. Monthly data were obtained for precipitation and temperature for each state (National Oceanic and Atmospheric Administration, 1983, 1986). These data were converted into estimates of annual values for each ASR by weighting each state's value by the fraction of each ASR that occurs in each state. This procedure was made necessary by the absence of readily available ASR-level information on precipitation and temperature. Appendix I presents the mean values for streamflow, precipitation, and temperature for each ASR for which a regression analysis was conducted.

In general, regressions have been run only for ASRs in which there is not large amounts of storage. Also, equations have not been estimated for most of the ASRs in the Great Lakes basin (ASRs 401-408). It is assumed here that if storage is less that 75% of the average annual streamflow, then annual flows are not significantly altered by the operation of the storage reservoirs. (Use of a 50% threshold does not significantly change the results of the analysis below.) Essentially, this assumes that storage is operated only to redistribute flows within a water year, and not between years. If this assumption is not true, it would be necessary to adjust streamflows by changes in storage, for which nationwide data are unavailable. The impact of this assumption is to overestimate low flows, if reservoirs have been operated to increase streamflows during dry years. This analysis also assumes that changes in consumptive uses over time are not significant, relative to the levels of streamflows. Correction for this factor would require time-series data on water use, which are not available on a nationwide basis. The effect of this assumption will be to underestimate the available surface water supplies, since observed flows have already had consumptive uses subtracted from them.

Appendix I presents the estimated equations (Table A1), and four sets of estimates of streamflows (Table A2). Each set results from either 50% or 30% of the average precipitation and either no decrease in mean temperature or a 5^{0}F decrease. These four sets are presented to illustrate the sensitivity of the analyses to the inputs. Table 7 displays, for each ASR, the total surface storage, the lowest monthly runoff, and the estimated streamflow resulting from 50% of the mean annual precipitation and a 5°F decrease in average annual temperature. The storages shown are cumulative values, including all upstream storage. In general, a "cumulative" value for any variable is the sum of the value for the ASR in question plus the values for all ASRs that drain into it. Cumulative statistics are important, because the water supply available to an ASR includes not only the internal supplies, but also the net amounts provided to it by upstream basins.

To calculate cumulative totals, we generally used the relationships shown in Fig. 8 to determine which basins discharged to which. Four exceptions are made.

1. ASR 201 (upper Hudson) discharges directly to the Atlantic Ocean, because New York City cannot presently draw upon the Hudson River for significant amount of supplies.

Table 7. Surface supply scenario under 50% of normal rainfall (10^6 gal/dDay)

ASR	Cum. storage (10^9gal)	Flow historic monthly low flow	Supply with .5P and 5^oF less T	Scenario under 50% fall in P	ASR	Cum. storage (10^9gal)	Flow historic monthly low flow	Supply with .5P and 5^oF less T	Scenario under 50% fall in P
101	1676	5730	3139	3865	1003	6454	0	*	8841
102	997	1220	780	1756	1004	1017	991	5041	1889
103	202	415	196	375	1005	22020	0	*	30164
104	414	520	370	752	1006	22211	2270	*	31561
105	1363	1940	8317	2837	1007	2474	34	*	3406
106	71	1430	*	812	1008	2627	529	*	3863
201	1517	2520	0	2078	1009	24874	2590	*	35369
202	1942	3060	0	2660	1010	931	169	1374	1360
203	287	2830	706	746	1011	27161	4090	*	39252
204	402	1540	5681	1321	1101	3477	2540	0	4763
205	2245	400	0	3075	1102	416	5	*	572
206	165	441	32	242	1103	614	57	2296	870
301	1413	1080	17	1944	1104	4167	747	0	5708
302	3457	4260	0	4736	1105	1446	0	*	1981
303	1808	3350	0	2477	1106	1473	293	*	2164
304	382	4920	0	523	1107	2209	919	0	3026
305	2565	0	*	3514	1201	3065	324	*	4361
306	1496	6210	6774	5154	1202	1913	198	*	2720
307	1074	10300	4081	3512	1203	1032	44	0	1414
308	978	4920	554	1617	1204	1262	27	*	1742
309	207	2080	0	28	1205	387	184	115	588
401	1794	1710	*	3313	1301	114	0	*	156
402	746	2260	*	2152	1302	1071	0	*	1467
403	206	90	*	327	1303	108	90	*	193
404	260	6680	*	3696	1304	58	2	0	79
405	157	1910	*	1170	1305	1183	0	0	1621
406	109	0	*	149	1401	1677	389	*	2492
407	21	312	*	185	1402	948	684	3357	1641
408	0	3270	*	1635	1403	3327	659	5766	4887

Table 7. (Continued)

ASR	Cum. storage (10^9gal)	Flow historic monthly low flow	Supply with .5P and 5^0F less T	Scenario under 50% fall in P	ASR	Cum. storage (10^9gal)	Flow historic monthly low flow	Supply with .5P and 5^0F less T	Scenario under 50% fall in P
501	1520	1690	5917	2927	1501	50	0	225	68
502	2463	4090	18808	5419	1502	23289	343	*	32074
503	316	1030	2659	948	1503	1049	0	*	1437
504	147	192	1567	297	1601	680	55	*	959
505	8761	15000	0	12001	1602	178	4	*	246
506	336	942	0	460	1603	144	0	*	197
507	1785	636	4399	2763	1604	236	16	*	331
601	1801	4230	8187	4582	1701	3579	2530	8110	6168
602	3600	2970	641	5252	1702	6107	42200	83076	29466
701	1570	1470	4101	2886	1703	4082	3450	*	7317
702	2740	6810	9388	7158	1704	1061	4660	20059	3783
703	3394	8560	13829	8929	1705	1796	54100	78658	29510
704	3700	4920	0	5068	1706	1139	7880	892	2006
705	31392	15400	69655	50703	1707	76	133	0	104
801	48145	65500	0	65952	1801	1298	1640	4121	2598
802	51955	72500	375	71359	1802	5446	2520	*	8720
803	52040	53600	88	71332	1803	3717	68	*	5126
901	1430	162	2757	2040	1804	4507	42	*	6195
1001	6588	0	8322	9025	1805	412	19	*	574
1002	1373	1450	3880	2606	1806	24322	2	*	33319
					1807	183	22	*	262

* Not considered, because ratio of storage to annual mean flow exceeds 0.75.
Note: Supply Scenario equals one-half storage plus one-half of the minimum of the historic monthly low flow and the calculated flow under 50% of the annual rainfall and 5oF cooler average annual temperature.

2. We assume that ASR 203 (Delaware) is influent to ASR 202 (lower Hudson), because of the large diversions of water made from 203 to the New York City area.

3. Because of the large Owens Valley and Colorado River diversions to southern California, ASRs 1502 and 1807 are assumed to be influent to ASR 1806.

4. Because of large diversions to the San Francisco area, ASR 1803 is assumed to be influent to 1804.

Table 7 also shows the surface supply scenario we use in the vulnerability assessment of the next subsection. This scenario is one-half the sum of (1) normal storage capacity and (2) the minimum of the lowest historic calender-month streamflow and the calculated flow under a 50% decrease in precipitation. In most basins, stored water is by far the largest component of this scenario. Excluding the Great Lake ASRs, storage is half or less of the scenario for only eight ASRs, of which seven are in the east and four in the southeast.

3.2.4 Surface Waters: Vulnerability Assessment

The vulnerability assessment for surface water consists of a comparison of the needs of domestic central systems, irrigators, and others for surface water with the scenarios of surface water supply developed in Section 3.2.3.

Table 8 displays the levels of water demand by ASR used in this analysis, derived from U.S. Water Resources Council (1978). Total demands are disaggregated into groundwater and freshwater uses; consumption and withdrawals; and type of user (domestic central systems, irrigation, and electric utilities). Most of the demands are cumulative demands, which include both the ASR in question and upstream ASRs.

It is the demands for surface water that should be compared with the surface water supply scenario. The assumption is that ground and surface supplies cannot be substituted for each other; this is a

Table 8. Domestic central, irrigation, and total water demands (10^6 gal/day)

ASR	Yr 2000 cumulative demands: Dom. cent. with.	Dom. cent. cons.	Irrig. with.	Irrig. cons.	2000 total ASR with.	2000 Cum. total ASR cons.	1975 Cum. ground water with.	2000 Adjusted cum. tot. surface with.	2000 Adjusted cum. tot. surface consump.
101	50	4	6	4	432	263	44	380	231
102	102	7	8	6	354	53	126	106	25
103	655	57	23	17	1175	259	235	923	198
104	211	23	4	3	465	145	117	348	109
105	165	20	13	10	697	316	81	406	154
106	39	3	1	0	116	34	32	84	25
201	238	40	17	12	887	277	157	455	146
202	2926	477	384	282	2859	1760	1664	3515	1145
203	980	129	265	195	3383	1026	804	1516	631
204	560	66	27	20	2944	541	504	690	269
205	425	32	142	105	2404	684	232	1160	542
206	609	35	26	19	1511	370	104	1074	254
301	262	45	238	188	4368	1008	377	984	575
302	428	74	62	49	5032	1185	336	1316	718
303	162	35	66	52	2321	760	753	411	291
304	672	387	1481	1184	4564	2072	1865	1420	893
305	839	367	3665	2930	7340	3783	1173	4596	2946
306	222	54	271	212	1870	683	189	763	438
307	138	43	11	9	1620	885	330	587	395
308	154	14	6	4	2011	442	209	618	347
309	128	38	5	4	510	270	217	262	155
401	31	3	1	1	616	250	68	377	159
402	58	6	77	63	1215	363	96	374	242
403	1358	36	25	21	5176	1125	91	2990	942

Table 8. (Continued)

ASR	Yr 2000 cumulative demands: Dom. cent. with.	Dom. cent. cons.	Irrig. with.	Irrig. cons.	2000 total ASR with.	2000 Cum. total ASR cons.	1975 Cum. ground water with.	2000 Adjusted cum. tot. surface with.	2000 Adjusted cum. tot. surface consump.
404	202	17	149	122	1234	515	319	587	295
405	87	7	23	19	566	242	91	370	152
406	1148	109	28	23	3980	1109	258	2337	822
407	610	133	19	15	4998	766	143	1392	597
408	223	38	22	16	7900	371	149	479	178
501	282	28	1	1	776	291	170	498	208
502	1226	155	23	21	6023	2764	1274	3344	1750
503	551	82	14	12	1509	592	721	589	243
504	39	1	2	2	567	328	54	397	235
505	2336	266	137	111	4074	5457	2114	6585	3392
506	375	30	28	23	1680	609	343	626	273
507	141	16	8	7	2322	270	56	377	165
601	220	29	10	8	2206	629	181	882	471
602	323	39	24	19	3810	1107	271	1395	791
701	250	25	164	136	1252	401	446	388	190

Abbreviations: ASR = Aggregated Subregion; Dom. Cent. = Domestic Central; Irri. = Irrigation; Cum. = Cumulative, includes upstream ASRs; With. = Withdrawals; Cons. = Consumption

Table 8 . (Continued)

ASR	Yr 2000 cumulative demands: Dom. cent. with.	Dom. cent. cons.	Irrig. with.	Irrig. cons.	2000 total ASR with.	2000 Cum. total ASR cons.	1975 Cum. ground water with.	2000 Adjusted cum. tot. surface with.	2000 Adjusted cum. tot. surface consump.
702	332	33	313	258	741	784	691	641	350
703	748	73	356	294	2034	1598	1511	1108	581
704	1154	164	472	392	1928	2397	2104	1592	857
705	2736	487	41759	20559	2056	25237	12773	36752	16518
801	5880	995	53410	28640	3833	40083	24064	48193	22935
802	6222	1134	56986	31677	12025	44187	27377	49943	24315
803	6631	1353	58282	32634	9522	46659	28581	52693	25990
901	47	19	547	444	700	540	86	614	474
1001	33	13	10333	3657	1893	3862	92	10513	3828
1002	27	10	7681	2654	7866	2779	59	7807	2758
1003	29	11	8505	3004	846	3148	70	8642	3122
1004	31	10	9626	3045	9975	3250	165	9708	3176
1005	99	35	20916	7359	2743	8054	436	21330	7751
1006	130	43	21634	8026	853	8814	613	22006	8353
1007	353	87	7070	3385	8269	3867	1849	6048	2883
1008	433	103	13878	7932	7374	8589	4845	10090	5574
1009	743	181	35627	16056	1891	17709	5746	32291	14045
1010	98	27	5636	4090	6022	4326	4432	1540	1115
1011	1083	256	41271	20153	1675	22466	10407	34292	15398
1101	42	12	92	84	272	144	301	0	1

Table 8 . (Continued)

ASR	Yr 2000 cumulative demands: Dom. cent. with.	Dom. cent. cons.	Irrig. with.	Irrig. cons.	2000 total ASR with.	2000 Cum. total ASR cons.	1975 Cum. ground water with.	2000 Adjusted cum. tot. surface with.	2000 Adjusted cum. tot. surface consump.
1102	85	21	1380	675	1703	819	217	1466	716
1103	228	73	5296	3244	4357	3656	3836	2198	1197
1104	575	201	8706	5885	1423	7079	6791	3784	2290
1105	152	63	3305	2558	3704	2788	2805	898	681
1106	103	44	2530	2223	2999	2507	1657	1220	1038
1107	213	80	2605	2287	506	2795	1764	1599	1263
1201	131	39	230	189	1535	1046	163	905	635
1202	840	249	966	800	4829	2756	617	3443	2238
1203	174	69	3430	2950	4217	3430	4395	0	1
1204	168	63	2716	2096	3968	2749	1215	2298	1666
1205	252	88	945	831	1851	1317	832	920	693
1301	5	1	1200	851	1231	872	590	641	454
1302	210	113	1808	1176	2175	1382	611	1563	996
1303	16	9	452	357	606	443	679	0	1
1304	29	12	593	404	682	465	400	282	192
1305	41	23	1389	1204	1508	1276	55	1453	1229
1401	22	9	3237	1135	3659	1366	64	3578	1345
1402	28	6	2431	1046	2640	1155	24	2564	1111
1403	80	27	7687	3027	2237	3522	126	8327	3437
1501	12	6	197	77	295	140	70	227	111
1502	729	331	14302	6855	2030	8338	5134	11428	5283
1503	480	240	4715	2791	5804	3532	3978	1792	1103
1601	363	146	2542	1062	3203	1367	581	2608	1112
1602	20	7	878	470	1023	586	321	695	399
1603	19	6	2121	1371	2467	1626	433	2027	1342

conservative assumption, as, in truth, extra pumpage from wells can make up for surface shortfalls in some places. Domestic central, irrigation, and total demands upon surface waters are estimated by subtracting estimates of the respective groundwater demands from the totals in Table 8. For domestic central and irrigation uses:

$$WDC_s(i) = WDC_{sg}(i) - WDC_g(i)$$

$$WI_s(i) = WI_{sg}(i) - WI_g(i)$$

in which:

$WDC_k(i)$ = Forecast year 2000 withdrawals by domestic central systems, including industry supplied by central water supply systems, in ASR i from water source k (s = surface supplies, g = groundwater, sg = total surface and groundwater).

$WI_k(i)$ = Forecast withdrawals by irrigators in ASR i from water source k, in the year 2000.

Analogous equations are also used for consumption. Because groundwater demands by domestic central systems and irrigators are not available by ASR, we estimate these demands from state-level data in U.S. Geological Survey (1985). The percentage of total domestic central withdrawals in ASR i that is met by groundwater is assumed to be a weighted average of the percentages for the states lying within that ASR (Table 5). The weights are the fraction of the ASR that lies within each state. The resulting weighted percentage is multiplied by the total domestic central withdrawal to obtain an estimate of the groundwater pumped for central systems. This procedure is repeated for irrigation withdrawals. Consumption figures are obtained by multiplying the withdrawal estimates by the ratio of consumption to withdrawal for the use category in that ASR. Exceptions to these procedures were made if the resulting estimates exceeded the total groundwater withdrawals in Table 8; in those cases, the irrigation withdrawals are set equal to the total withdrawal minus the estimated domestic central withdrawal.

The total surface water demands in Table 8 are calculated as follows:

$$W_{TOTs}(i) = W_{TOTsg}(i) - W_{P2000}(i) + C_{P1985}(i) - W_{TOTg}(i)$$

$$C_{TOTs}(i) = C_{TOTsg}(i) - C_{P2000}(i) + C_{P1985}(i) - W_{TOTg}(i)*[C_{TOTsg}(i) - C_{P2000}(i)]/[W_{TOTsg}(i) - W_{P2000}(i)]$$

in which:

$W_{TOTk}(i)$ = Forecast fresh water withdrawals by all users in ASR i from water source k (s = surface supplies, g = groundwater, sg = total surface and groundwater).

$W_{Py}(i)$ = Forecast fresh water withdrawals by power utilities in year y in ASR i.

$C_{TOTk}(i)$ = Forecast fresh water consumption by all users in ASR i from water source k (s = surface supplies, sg = total surface and groundwater).

$C_{Py}(i)$ = Forecast fresh water consumption by power utilities in year y in ASR i.

In the above equations, total surface demands are adjusted downwards to exclude non-consumptive power plant withdrawals, since such withdrawals are almost always returned to the same water source and do not affect the total supply available. Year 1985 projections of power plant capacity are used, rather than year 2000, since the latter are too high, given the slower than anticipated rates of power growth that prevail now. Because no data were available on consumption of groundwater, groundwater withdrawals have been multiplied by the ratio of total non-power water consumption to non-power water withdrawals to estimate the amount of groundwater consumed. Power uses are excluded from that calculation because few power plants use groundwater for cooling.

Three sets of demands are compared against the supply scenario:

1. domestic central demands;

2. irrigation and domestic central demands; and

3. all demands, excluding nonconsumptive uses by steam power plants.

Each comparison is discussed below, and all are summarized in Figs. 12-14 and Tables 9 and 10. Table 9 presents ratios of the supply scenario to demands; ASRs whose ratios are less than one are displayed in Figs. 12-14. Table 10 shows the supply deficits (demand minus supply), where positive. These are cumulative deficits, which include supplies and demands from upstream ASRs.

Although there has been much publicity about the vulnerability of our major cities to drought, on a basin-wide basis, there would seem to be little difficulty in meeting central domestic demands (Fig. 12). Only the ASRs in which Boston and Washington, D.C., reside have year 2000 annual surface withdrawals that would exceed one-half the reservoir storage in the basin plus one-half the streamflow scenario. The ASR 103 deficit of 144 mgd (Table 10) would actually be much smaller because of the Quabbin diversion from the Connecticut basin (ASR 105) to Boston. On the other hand, the withdrawal deficit in the Potomac basin indicates that real problems would occur, as most of the withdrawals not consumed in that basin are discharged to the Potomac estuary, where they cannot be reused.

However, because of the absence of conveyance facilities, there will still be many other cities which would not be able to meet all demands on their system. An example is Philadelphia. Although the amount of water available in the Delaware basin, net of diversions to New York City, is likely to be sufficient in quantity, quality problems due to the advance

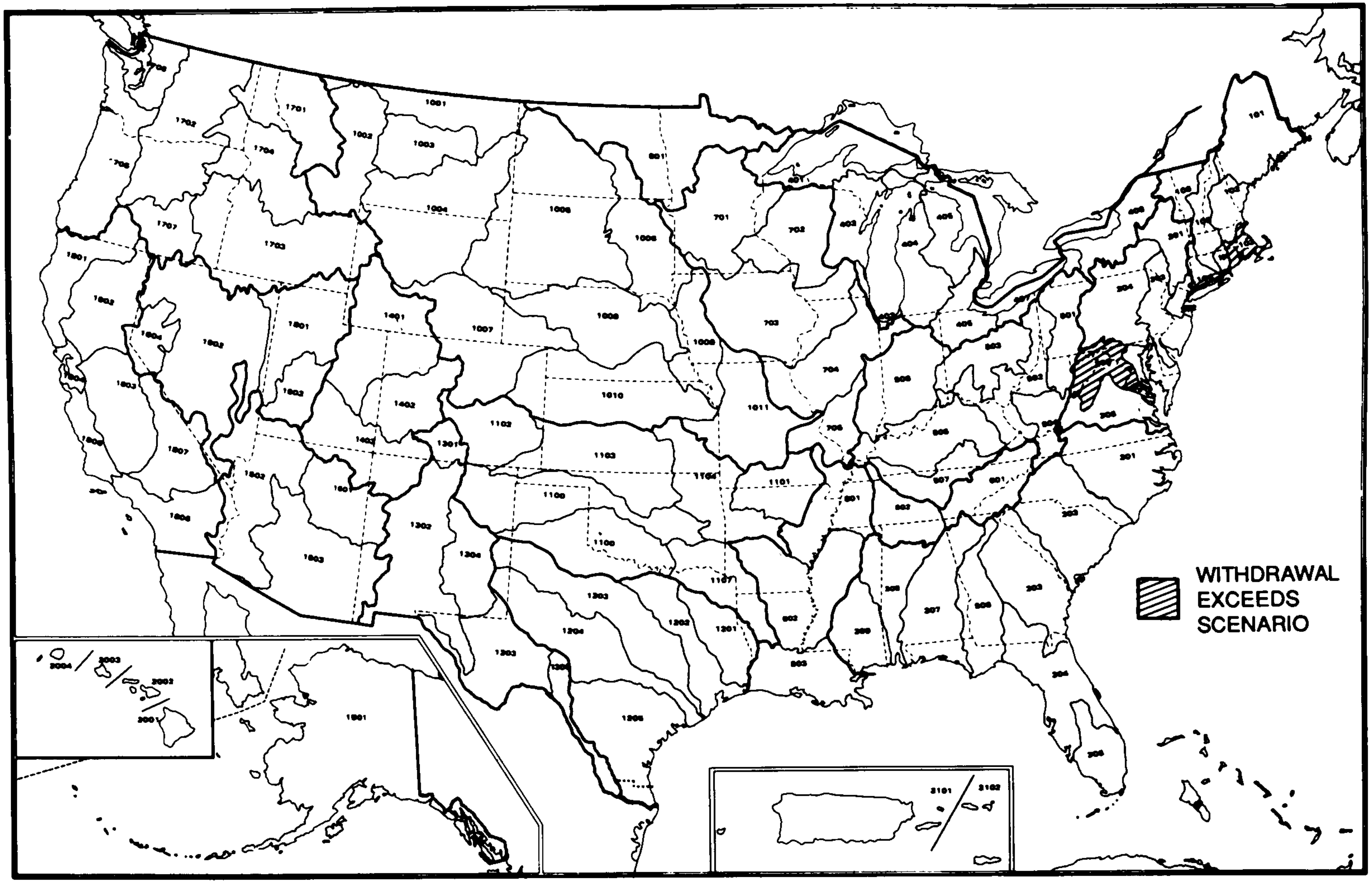

Fig. 12 ASRs in which the year 2000 withdrawals by domestic central systems exceed surface water supply scenarios

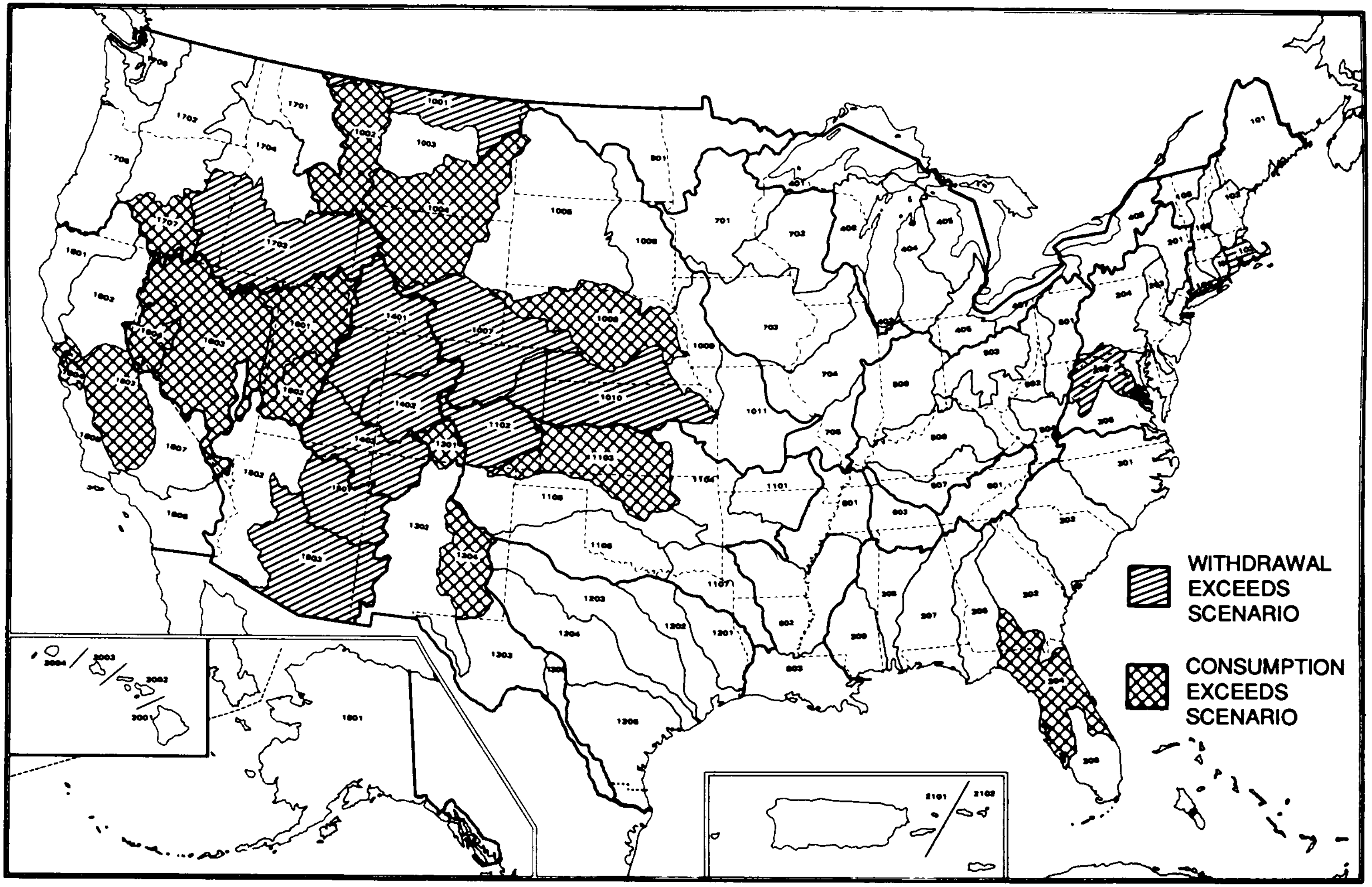

Fig. 13 ASRs in which year 2000 domestic central and irrigation surface demands exeed the supply scenario

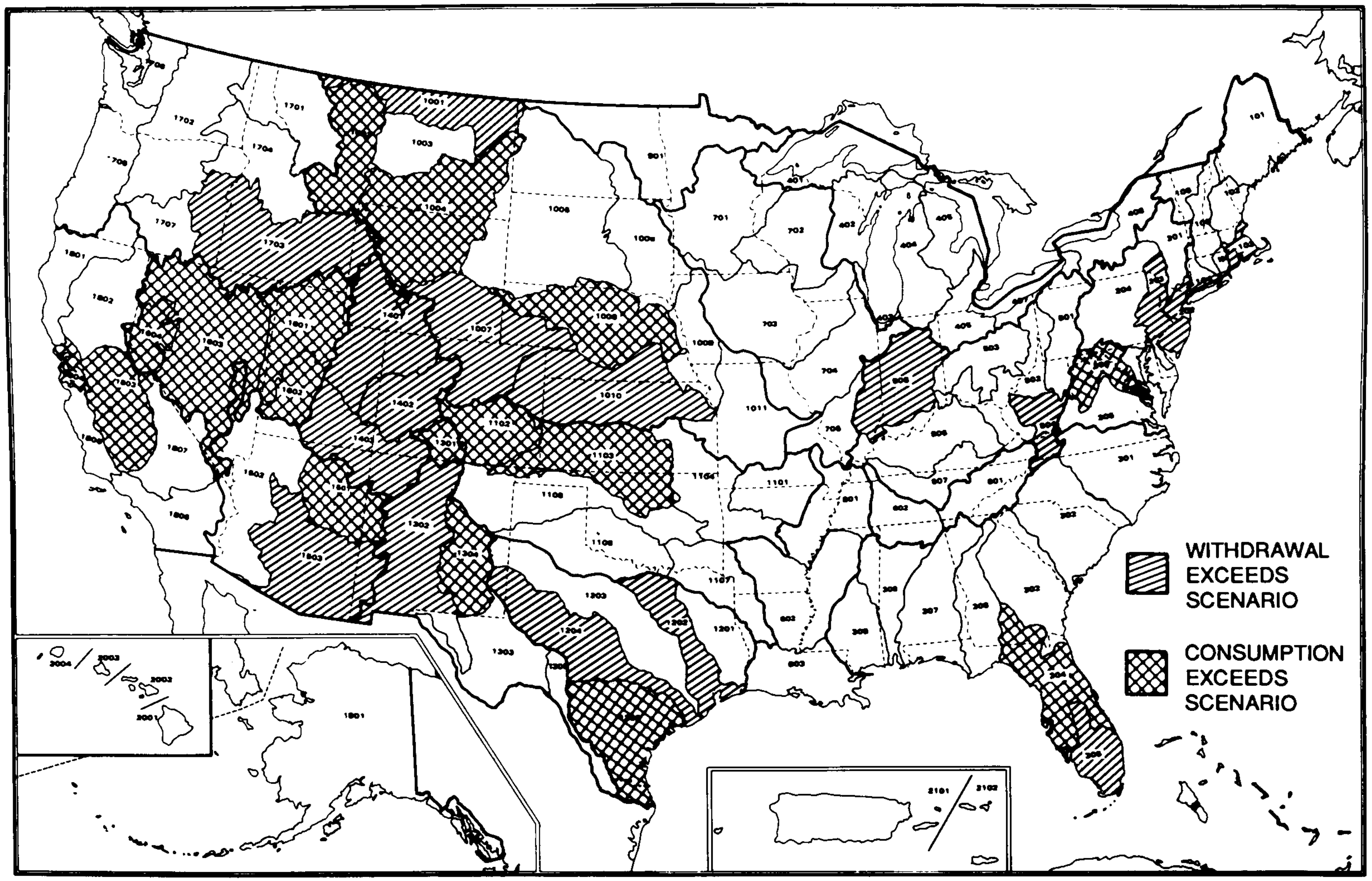

Fig. 14 ASRs in which year 2000 surface demands exceed the surface supply scenario

Table 9. Comparison of surface water scenarios and demands by ASR

ASR	Ratios of surface supply scenario to Yr 2000 demands: Domestic central Withd.	Domestic central Consump.	Irri. + Dom. Cent. Withd.	Irri. + Dom. Cent. Consump.	Total Withd.	Total Consump.
101	95.94	1199.19	83.82	544.02	10.17	16.72
102	27.51	400.93	24.6	174.65	16.56	71.27
103	0.72	8.3	0.7	6.38	0.41	1.9
104	4.37	40.05	4.28	35.11	2.16	6.93
105	26.28	216.77	23.82	130.97	6.99	18.38
106	29.72	386.35	28.98	386.35	9.67	32.99
201	11.46	68.21	10.9	56.07	4.57	14.21
202	1.3	8.02	1.19	5.56	0.76	2.32
203	1.04	7.9	0.86	3.62	0.49	1.18
204	2.86	24.25	2.73	18.78	1.91	4.9
205	8.61	114.3	6.87	32.84	2.65	5.67
206	0.48	8.39	0.46	5.71	0.23	0.95
301	8.84	51.46	5	11.34	1.98	3.38
302	13.53	78.23	12	49.46	3.6	6.6
303	22.8	105.52	18.29	55.58	6.03	8.52
304	1.68	2.93	0.58	0.81	0.37	0.59
305	29.91	68.39	1.05	1.65	0.76	1.19
306	128.27	527.35	16.95	45.67	6.76	11.77
307	35.34	113.43	32.8	94.25	5.98	8.9
308	14.08	154.92	13.6	122.61	2.62	4.66
309	2.7	9.1	2.62	8.4	1.08	1.83
*401	139.9	1445.64	137	1185.89	8.79	20.86
*402	59.94	579.41	40.63	121.79	5.75	8.89
*403	0.26	17.48	0.25	16.91	0.11	0.35
*404	18.89	224.42	11.08	28.57	6.3	12.54
*405	16.2	201.39	13.5	65.81	3.16	7.67

Table 9. (Continued)

ASR	Ratios of surface supply scenario to Yr 2000 demands: Domestic central Withd.	Domestic central Consump.	Irri. + Dom. Cent. Withd.	Irri. + Dom. Cent. Consump.	Total Withd.	Total Consump.
*406	0.17	1.79	0.16	1.54	0.06	0.18
*407	0.4	1.9	0.38	1.73	0.13	0.31
*408	9.52	55.88	8.91	43.14	3.41	9.21
501	12.91	130.03	12.86	125.47	5.88	14.05
502	5.84	46.55	5.74	41.45	1.62	3.1
503	2.4	16.12	2.35	14.4	1.61	3.9
504	9.92	386.7	9.38	120.69	0.75	1.26
505	7.01	61.45	6.71	46.76	1.82	3.54
506	1.94	24.28	1.94	23.61	0.74	1.69
507	27.54	242.73	26.14	171.47	7.33	16.75
601	29.71	225.37	28.7	185.78	5.2	9.73
602	23.5	194.1	22.12	138.12	3.76	6.64
701	23.88	238.78	20.6	102.87	7.44	15.2
702	43.98	442.57	37.78	187.25	11.17	20.43
703	29.35	299.86	26.59	159.62	8.06	15.36
704	8.54	53.55	8.03	40.29	3.18	5.92
705	32.06	174.23	1.52	3.92	1.38	3.07
801	17.33	103.99	1.68	4.19	1.37	2.88
802	17.74	98.78	1.74	4.25	1.43	2.93
803	16.74	83.94	1.7	4.09	1.35	2.74
901	92.36	228.48	4.02	5.41	3.32	4.31
1001	447.77	1137.24	0.88	2.5	0.86	2.36
1002	157.72	425.86	0.34	0.99	0.33	0.94
1003	498.33	1313.88	1.04	2.97	1.02	2.83
1004	95.82	297.05	0.2	0.65	0.19	0.59

Table 9. (Continued)

ASR	Ratios of surface supply scenario to Yr 2000 demands: Domestic central Withd.	Domestic central Consump.	Irri. + Dom. Cent. Withd.	Irri. + Dom. Cent. Consump.	Total Withd.	Total Consump.
1005	558.34	1575.26	1.47	4.31	1.41	3.89
1006	489.62	1445	1.49	4.21	1.43	3.78
1007	13.82	56.09	0.6	1.28	0.56	1.18
1008	14.57	59.92	0.4	0.91	0.38	0.69
1009	92.62	366.6	1.15	3.01	1.1	2.52
1010	28.19	102.33	0.99	1.4	0.88	1.22
1011	64.1	269	1.21	3.07	1.14	2.55
1101	173.64	607.74	>10	>10	>10	>10
1102	7.32	29.63	0.46	1.01	0.39	0.8
1103	5.3	17.19	0.46	0.9	0.4	0.73
1104	15.96	47.22	1.79	3.03	1.51	2.49
1105	27.62	66.63	2.21	2.91	2.21	2.91
1106	36.32	85.03	2.22	3.5	1.77	2.09
1107	23.56	63.06	2.84	4.59	1.89	2.4
1201	61.43	206.33	22.02	53.22	4.82	6.86
1202	6	20.23	2.29	6.3	0.79	1.22
1203	15.9	40.09	>10	>10	>10	>10
1204	20.32	54.19	1.04	1.85	0.76	1.05
1205	4.32	12.36	1.4	1.98	0.64	0.85
1301	32.33	161.67	0.24	0.34	0.24	0.34
1302	69.86	129.83	1.04	2.16	0.94	1.47
1303	22.33	39.7	>10	>10	>10	>10
1304	27.4	66.21	0.28	0.41	0.28	0.41
1305	73.2	130.48	1.18	1.38	1.12	1.32
1401	175.76	429.64	0.78	2.31	0.7	1.85
1402	69.96	326.49	0.67	1.6	0.64	1.48
1403	98.22	311.75	0.64	1.67	0.59	1.42

Table 9. (Continued)

	Ratios of surface supply scenario to Yr 2000 demands					
	Domestic central		Irri. + Dom. Cent.		Total	
ASR	Withd.	Consump.	Withd.	Consump.	Withd.	Consump.
1501	14.05	28.1	0.49	1.88	0.3	0.62
1502	99.34	225.75	2.91	6.64	2.81	6.07
1503	7.54	15.09	0.8	1.3	0.8	1.3
1601	7.31	18.18	0.4	0.97	0.37	0.86
1602	36.15	103.29	0.35	0.62	0.35	0.62
1603	17.3	54.79	0.11	0.17	0.1	0.15
1604	8.49	37.38	0.29	0.47	0.24	0.37
1701	96.96	325.67	2.27	5.83	2.08	5.18
1702	392.67	1570.67	2.98	5.46	2.9	5.18
1703	207.37	720.34	0.52	1.4	0.52	1.4
1704	577.22	2143.95	2.29	5.5	2.07	4.48
1705	190.99	1096.95	25.77	42.65	16.35	27.41
1706	12.84	86.07	5.83	13.04	2.39	4.87
1707	147.17	294.34	0.04	0.12	0.04	0.1
1801	71.58	409.98	1.25	2.98	1.15	2.36
1802	44.5	89.26	1.78	2.36	1.78	2.36
1803	20.46	40.84	0.53	0.69	0.53	0.69
1804	9.46	21.55	0.56	0.75	0.56	0.75
1805	7.99	20.05	1.08	1.55	1.08	1.55
1806	23.07	56.02	2.04	4.24	1.91	3.56
1807	8.14	16.56	1.88	3.23	1.88	3.23

Abbreviations: Dom. Cent. = Domestic Central; Irri. = Irrigation; Withd. = Withdrawals; Consump. = Consumption

*Calculations exclude storage in Great Lakes and are therefore unrepresentative of the actual water supply situation. These areas are excluded from Figs. 12-14.

Table 10. Scenarios of surface water deficits by ASR

ASR	Deficits (surface scenarios - 2000 demands) (10^6g/d)					
	Domestic Central		Irri. + Dom. Cent.		Total	
	Withd.	Consumpt.	Withd.	Consumpt.	Withd.	Consump.
101	0	0	0	0	0	0
102	0	0	0	0	0	0
103	144	0	163	0	548	0
104	0	0	0	0	0	0
105	0	0	0	0	0	0
106	0	0	0	0	0	0
201	0	0	0	0	0	0
202	0	0	0	0	855	0
203	0	0	123	0	770	0
204	0	0	0	0	0	0
205	0	0	0	0	0	0
206	263	0	289	0	832	12
301	0	0	0	0	0	0
302	0	0	0	0	0	0
303	0	0	0	0	0	0
304	0	0	375	125	897	370
305	0	0	0	0	1082	0
306	0	0	0	0	0	0
307	0	0	0	0	0	0
308	0	0	0	0	0	0
309	0	0	0	0	0	0
401	0	0	0	0	0	0
402	0	0	0	0	0	0
403*	940	0	965	0	2663	615
404	0	0	0	0	0	0
405	0	0	0	0	0	0

Table 10. (Continued)

	Deficits (surface scenarios - 2000 demands) (10^6g/d)					
	Domestic Central		Irri. + Dom. Cent.		Total	
ASR	Withd.	Consumpt.	Withd.	Consumpt.	Withd.	Consump.
406*	741	0	769	0	2188	673
407*	282	0	301	0	1207	412
408	0	0	0	0	0	0
501	0	0	0	0	0	0
502	0	0	0	0	0	0
503	0	0	0	0	0	0
504	0	0	0	0	100	0
505	0	0	0	0	0	0
506	0	0	0	0	166	0
507	0	0	0	0	0	0
601	0	0	0	0	0	0
602	0	0	0	0	0	0
701	0	0	0	0	0	0
702	0	0	0	0	0	0
703	0	0	0	0	0	0
704	0	0	0	0	0	0
705	0	0	0	0	0	0
801	0	0	0	0	0	0
802	0	0	0	0	0	0
803	0	0	0	0	0	0
901	0	0	0	0	0	0
1001	0	0	1251	0	1488	0
1002	0	0	5043	22	5201	152
1003	0	0	0	0	0	0
1004	0	0	7603	1009	7819	1288

Table 10. (Continued)

ASR	Deficits (surface scenarios - 2000 demands) (10^6g/d) Domestic Central Withd.	Domestic Central Consumpt.	Irri. + Dom. Cent. Withd.	Irri. + Dom. Cent. Consumpt.	Total Withd.	Total Consump.
1005	0	0	0	0	0	0
1006	0	0	0	0	0	0
1007	0	0	2261	0	2642	0
1008	0	0	0	0	0	0
1009	0	0	0	0	0	0
1010	0	0	8	0	180	0
1011	0	0	0	0	0	0
1101	0	0	0	0	0	0
1102	0	0	676	0	894	144
1103	0	0	1024	95	1328	328
1104	0	0	0	0	0	0
1105	0	0	0	0	0	0
1106	0	0	0	0	0	0
1107	0	0	0	0	0	0
1201	0	0	0	0	0	0
1202	0	0	0	0	723	0
1203	0	0	0	0	0	0
1204	0	0	0	0	556	0
1205	0	0	0	0	332	105
1301	0	0	485	298	485	298
1302	0	0	0	0	96	0
1303	0	0	0	0	0	0
1304	0	0	203	113	203	113
1305	0	0	0	0	0	0
1401	0	0	703	0	1086	0

Table 10. (Continued)

ASR	Deficits (surface scenarios - 2000 demands) (10^6g/d)					
	Domestic Central		Irri. + Dom. Cent.		Total	
	Withd.	Consumpt.	Withd.	Consumpt.	Withd.	Consump.
1402	0	0	794	0	923	0
1403	0	0	2754	0	3440	0
1501	0	0	71	0	159	43
1502	0	0	0	0	0	0
1503	0	0	355	0	355	0
1601	0	0	1411	29	1649	153
1602	0	0	449	153	449	153
1603	0	0	1575	944	1830	1144
1604	0	0	820	381	1025	563
1701	0	0	0	0	0	0
1702	0	0	0	0	0	0
1703	0	0	6631	0	6631	0
1704	0	0	0	0	0	0
1705	0	0	0	0	0	0
1706	0	0	0	0	0	0
1707	0	0	2514	760	2618	897
1801	0	0	0	0	0	0
1802	0	0	0	0	0	0
1803	0	0	4460	2289	4460	2289
1804	0	0	4812	2046	4812	2046
1805	0	0	0	0	0	0
1806	0	0	0	0	0	0
1807	0	0	0	0	0	0

*Calculations exclude storage in Great Lakes and are therefore not representative of the actual water supplysituation. These areas excluded from Figs. 12-14.

of the salt front in the Delaware estuary would endanger Philadelphia's supply. Such problems can only be identified by studying, on a basin-by-basin basis, the configuration of individual water supply systems.

In terms of just meeting the survival needs of the population, no ASR shows any problem. Steel and McGee (1979) give the following figures for average domestic use in the United States:

- 5 gal/capita/day (gcd) for culinary and drinking uses
- 20 gcd for sanitary uses
- 10-25 gcd for bathing and washing.

These typically constitute much less than half of the total domestic central system demand, and could themselves be lowered in emergencies. In none of the ASRs would demands of this magnitude exceed the supply scenario. Of course, local problems would still arise because of conveyance or quality problems. Estimation of the seriousness of such problems would require detailed basin-specific studies.

As indicated in Fig. 10, much of our irrigated cropland depends on surface water supplies. Our comparison of surface water demands by irrigation and central domestic systems with the surface supply scenario indicates that many western states would have insufficient supplies (Fig. 13). Of course, the deficits are worst when supplies are compared to withdrawal rates rather than consumption figures, since the former are 2 to 5 times the latter. Because irrigation return flows are reused (sometimes several times), the cross-hatched areas in Fig. 13 may be a truer reflection of the problems that would occur. The aggregate consumption deficit (Table 10, excluding overlaps of cumulative ASRs) is approximately 7 billion gal/day, while the aggregate withdrawal deficit is about 50 billion gal/day for the entire nation. Assuming that power is available, part of this deficit would be made up by increased groundwater pumping, as it was during the 1976-77 California drought.

The problems in Fig. 13 are mostly in the western states (aside from the northeastern urban areas where irrigation is unimportant). Important irrigated areas in the Central Valley of California, the Great Basin, and elsewhere in the Rocky Mountain west are vulnerable. Future work should include an assessment of the extent of the problems in terms of amount of cropland and production affected by basin. On a national basis, the withdrawal deficit of 50 billion gal/day would be equivalent to 40,000 sq mi of irrigated land, assuming that an average of 24 in./year of water is applied.

Figure 14 compares the total surface demands by all users to the supply scenario. In terms of consumption figures alone, metropolitan areas that would have problems include Denver, San Francisco, and Washington, D.C. Because irrigation is the largest user in most of the west, the pattern of shortages for total consumption is similar to that for just irrigation and domestic central system use (Fig. 13). However, use of consumption figures alone underestimates the problem, since return flows are not always available to other users. As an example, many cities discharge their wastewater to estuaries or the oceans.

In terms of withdrawals, the major metropolitan areas of the northeast and Texas would also have shortfalls of supply. The irrigation dominated basins of the Colorado, Great Basin, Rio Grande, Texas-Gulf, Central Valley, and Upper Missouri all show that the surface supply scenario would not meet projected surface demands. Two ASRs in the Ohio basin also show deficits; however, those are mostly due to the unreasonably high growth rates assumed for industrial use by U.S. Water Resources Council (1978).

Because the hydrologic effects of nuclear winter are so uncertain, a sensitivity analysis was performed based on annual precipitation rates 30% of normal levels, rather than 50%. The resulting projections of streamflows, based on the regression models, are shown in Appendix II.

This decrease in precipitation only slightly alters our results. Only five of the zero entries in Table 8 became non-zero as a result, signifying that this change has little effect on the number of basins whose demands exceed the supply scenario. The new non-zero entries occur in ASR 203 (Delaware basin; domestic central withdrawals and total consumption); ASR 204 (Susquehanna basin; total withdrawal); ASR 504 (Kanawha basin; total consumption); and ASR 1801 (Klamath-North Coastal; total withdrawal).

3.3 FOOD

3.3.1 Effects on Current Crops

The expected effects of nuclear war on agricultural productivity include widespread radioactive fallout as well as climatological effects of depressed temperatures and reduced rainfall. As discussed previously, amounts of atmospheric smoke and dust which would cause insignificant temperature depression can cause very significant reduction or alteration in rainfall patterns. As demonstrated by the El Nino phenomenon, apparently very subtle changes in the ocean or atmosphere can be accompanied by dramatically altered patterns of rainfall.

While now the average temperature depression in the Northern Hemisphere expected from even a severe nuclear war is only 10 to 20°C, this can produce local episodes of below-freezing temperatures.

Below-freezing temperatures, even for a single night, can severely reduce the yields of such crops as corn and soybeans if they occur during the period of active growth.

3.3.2 Food Reserves

Even before the postulation of nuclear winter, it was widely recognized that in an all-out nuclear war, agricultural areas of both the

United States and Soviet Union would likely experience heavy levels of fallout contamination. Grain crops are only about an order of magnitude more resistant to gamma radiation than are humans (Bottino and Sparrow, 1970). It has been assumed by many planners that a total crop failure was possible and even likely in both countries due to fallout in the event of a nuclear war in the spring or summer. Even without intensities high enough to kill the standing plants, the presence of fallout radiation could prevent farmers from entering the fields in a timely manner to carry out necessary planting, cultivating, or harvesting tasks.

Attention then turned naturally to the food reserves available at harvest minimums. Figure 15 shows the storage of grain on and off farms in the United States over the years 1981-1985. It can be seen that total grain stock at the harvest is at a minimum in the third and fourth quarters - approximately two years' supply of food (at 3000 calories per day) for the entire population of the United States (Kerley et al. 1987). Thus, the loss of a crop year due to nuclear winter does not present a new hazard to the United States, the Soviet Union, or, for that matter, to other countries that produce food in great excess of their population requirements, such as France and Canada (which are likely to be involved in a nuclear war).

However, many countries that would otherwise have been bystanders in a U.S.-Soviet war could now be confronted with a previously unexpected emergency. This is particularly true of those countries that do not produce large food surpluses and/or do not have a sizeable livestock industry that requires the storing of large amounts of grains.

3.3.3 Seed Production

Seed for most of the food produced in the United States is produced by farmers specializing in that activity who themselves are rarely engaged in the end result--food production. The seeds used in U.S. agriculture are responsible for much of its productivity and are the

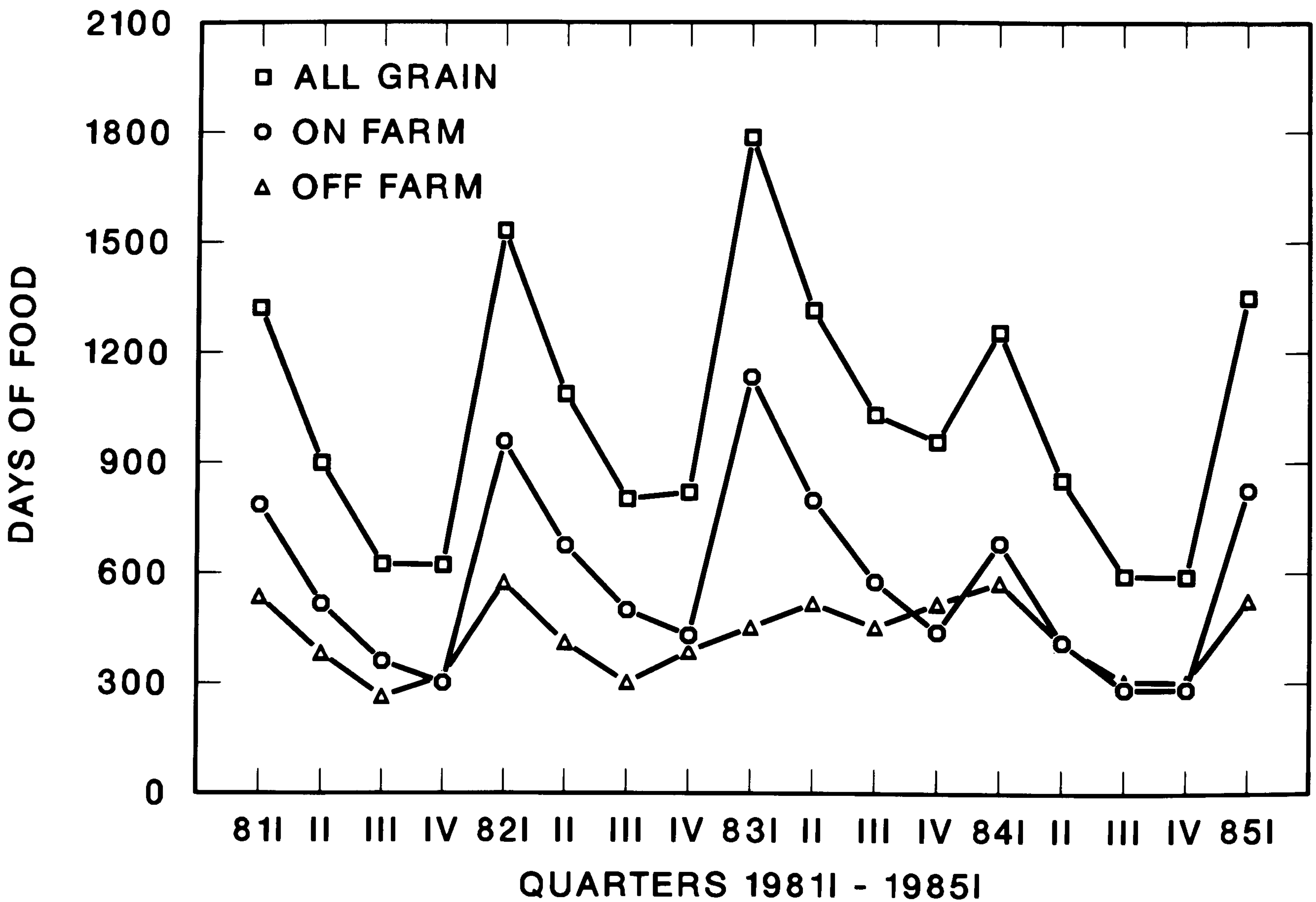

Fig. 15 Quarterly changes in U.S. grain stocks 1981-85.
Days of food for the U.S. population.

process to get from the plant breeder to the food-producing farm. The production of new varieties of seed typically will take several years of selection and cross breeding, ultimately resulting in a strain which is accepted for commercial production by the agricultural authorities of a given state. Initially, there may be only a few bushels of this strain available, and these are used by the plant breeder to breed a quantity useful for the first stage of commercial production. This seed is called foundation stock and is used by the seedsmen to produce what they call stock seed (Garrison, 1961).

Stock seed, which may be an inbred variety or first cross, is reproduced by the seed production farm under very carefully controlled conditions to prevent contamination with other genetic material or noxious weeds. In its production, it is subject to hand weeding in the field to remove deviant plants (called "roguing") and careful seed cleaning on harvesting with stringent precautions against contamination by other seeds in the seed handling equipment. The seed-producing farm then uses some of the stock seed to produce what is called the market crop which is sold to the food producers. It is in production of the market crop that the final hybridization is carried out for the production of hybrid seeds (Airy et al., 1961).

Typically each planting will produce of the order of 100 times the seed that was used in the planting. A year's supply of stock seed is about 1% of the annual production of market seed which is in turn of the order of 1% of the grain production if the seed is for production of a grain. Most seed-producing operations will carry over 1-3 years of stock seed as insurance against a crop failure (Garrison, 1961).

A climatological upset and/or fallout from a nuclear war would destroy not only the food crops, but also, the market seed crop and the stock seed crops. Assuming the seedsmen carried over enough stock seed to grow a new market crop, it would still be two years after the missed crop before another food crop could be grown. Depending on the time of the upset, this time might be shortened by one growing season, as is present practice, by growing seed for northern summer crops over the winter in Mexico, South Texas, or the Caribbean.

Until normal seed production could be re-established, farmers in food-producing operations would be forced to use stored grain for the following year's crop. In an emergency, it would produce edible food but at reduced yield. It is estimated that the yield from hybrid corn used as seed would be approximately 80% of the yield from the F-1 cross (Airy et al., 1961). There would also be increased danger of weed seeds contaminating the grain and low germination rates because in general, food grains are not handled as carefully as are seed crops. In particular, if the crop had been subjected to high temperature grain drying or if it had been allowed to heat in the storage bin before being adequately dried, it might have a very low germination rate (Stevens et al., 1961).

Farmers expecting to be forced to use the previous year's crop for seed could check their stored grain for its germination capability indoors months before the planting season. Part of the emergency planning in agricultural areas should include plans for germination tests of the grain stored in the area and plans to distribute viable seed to all farms that had the capability to grow it.

3.3.4 Long-Term Effects

As discussed in Chapter 2, the phenomenon of smoke lofting due to solar heating could cause the movement of smoke into the stratosphere where its removal time is greatly extended. The possibility exists that significant climatological effects may persist into a second year after a war with the possibility of a degree or two temperature depression and reduction of convective rainfall in the following growing season.

The National Defense University has conducted a study of crop yields and climate change (National Defense University, 1986). Figures 16 through 19 are contours of estimated crop yield variation with changes in temperature and rainfall for corn, soy beans, spring wheat, and winter wheat for the United States and some comparable country. In general, crop yields or reductions are proportional to rainfall reductions about the present level of rainfall and temperature. In the United States, for most crops a degree or two reduction in temperature will cause a slight increase in yield which is true also of Brazil and Argentina. Canada and the Soviet Union can be expected to undergo significant reductions in yield in the event of a temperature reduction of more than a degree or two. This is due to the fact that the Soviet Union and Canada are high-latitude countries and are pushing the range of wheat cultivation right to its margin.

Small changes in atmospheric circulation patterns can cause significant disturbance to agriculture, particularly in areas of marginal rainfall as in much of the Soviet Union.

3.4 CLOTHING

As shown previously, the climatological effects from a spring or summer war, generally are thought to produce transient temperatures less cold than the normal January temperatures for a particular region. Neal et al. (1982), in a study of emergency weather preparedness in north-eastern Ohio, provided some evidence that at least in that area over 75% of the population believed they were adequately clothed for weather extremes. In a nuclear war scenario, even people who do not have adequate cold weather clothing would find considerable protection against cold in fallout shelters if they were crowded in at 1 person/10 sq ft.

As suggested by Fig. 2, people at lower latitudes in the Southern United States would experience much smaller temperature decreases than people who were farther north. Thompson and Schneider (1986) estimate an average temperature (summertime) minimum over 70°F.

CORN: *Argentina*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

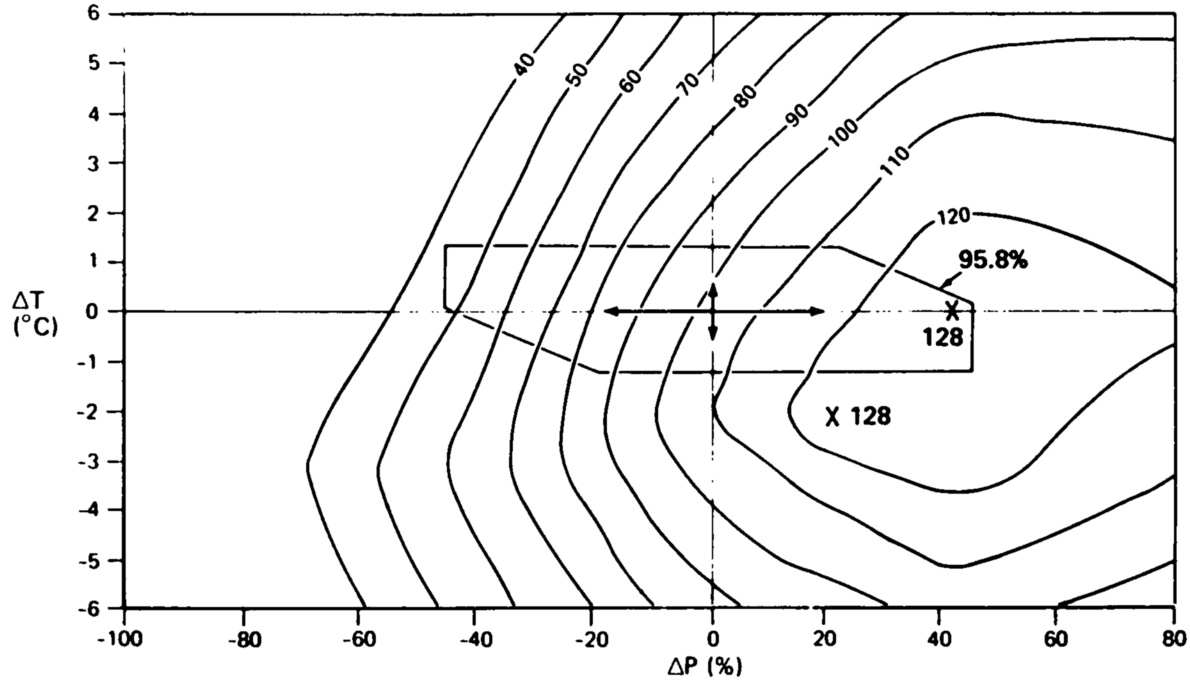

Figure V-2

CORN: *U.S.*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

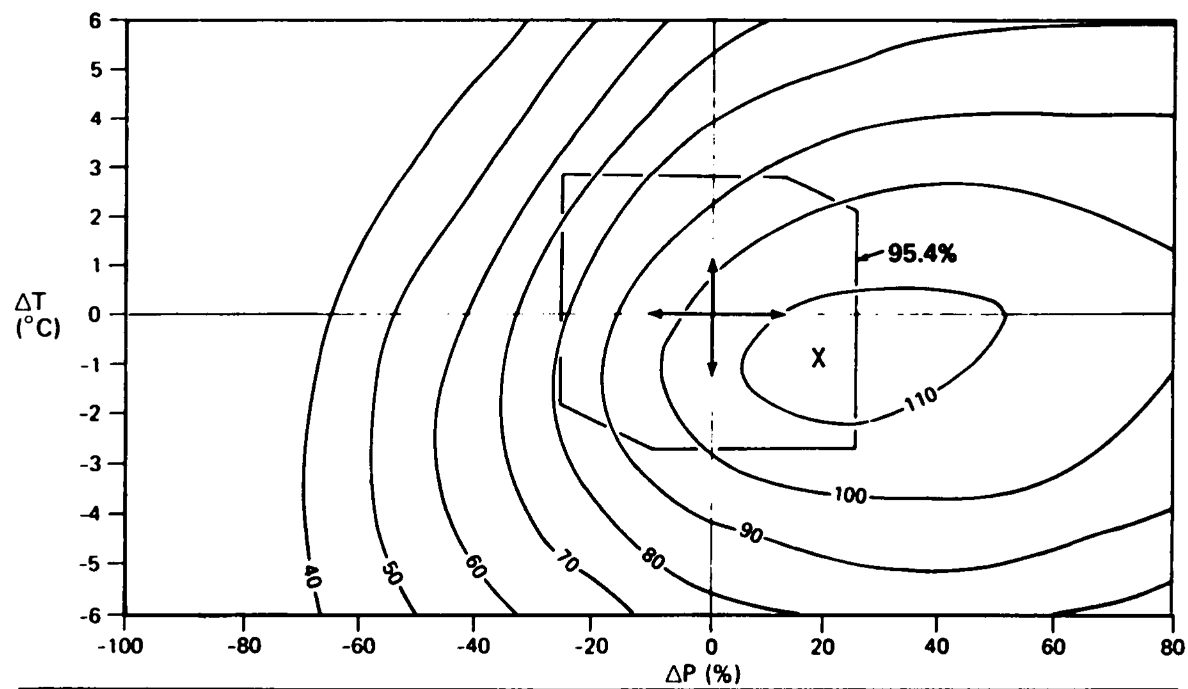

Fig. 16 Yield response surfaces for corn in the U.S. and Argentina

SOYBEANS: *Brazil*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

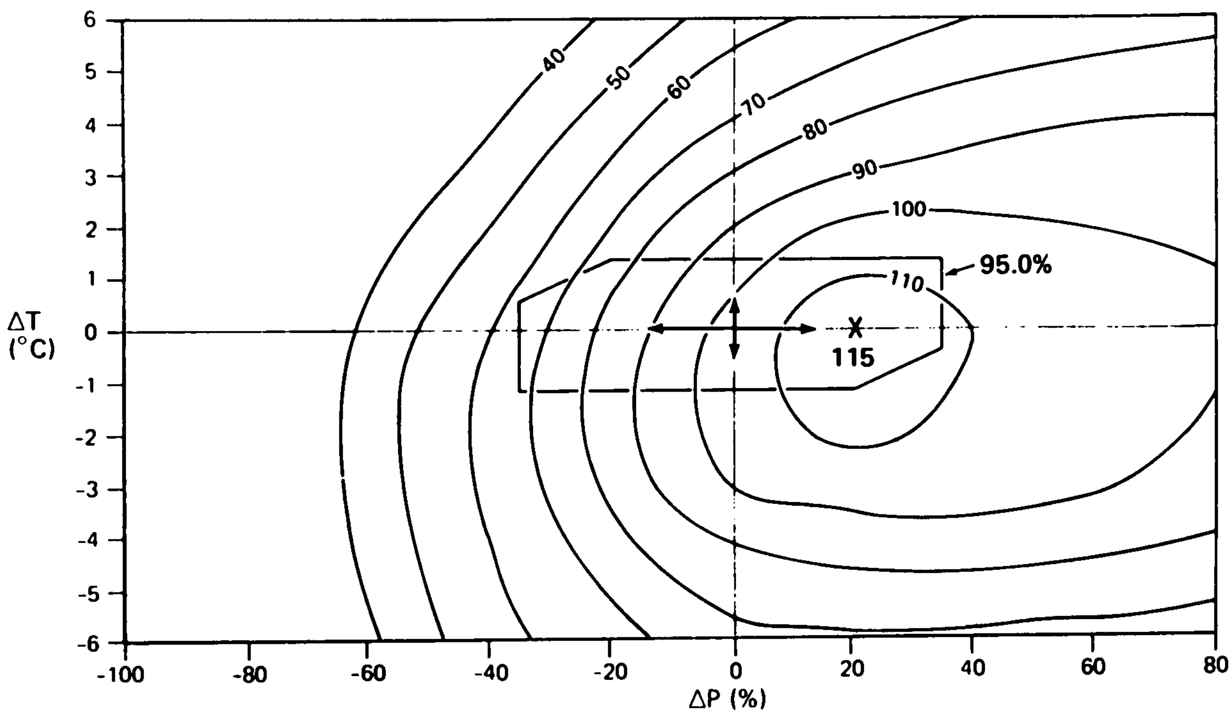

Figure V-6

SOYBEANS: *U.S.*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

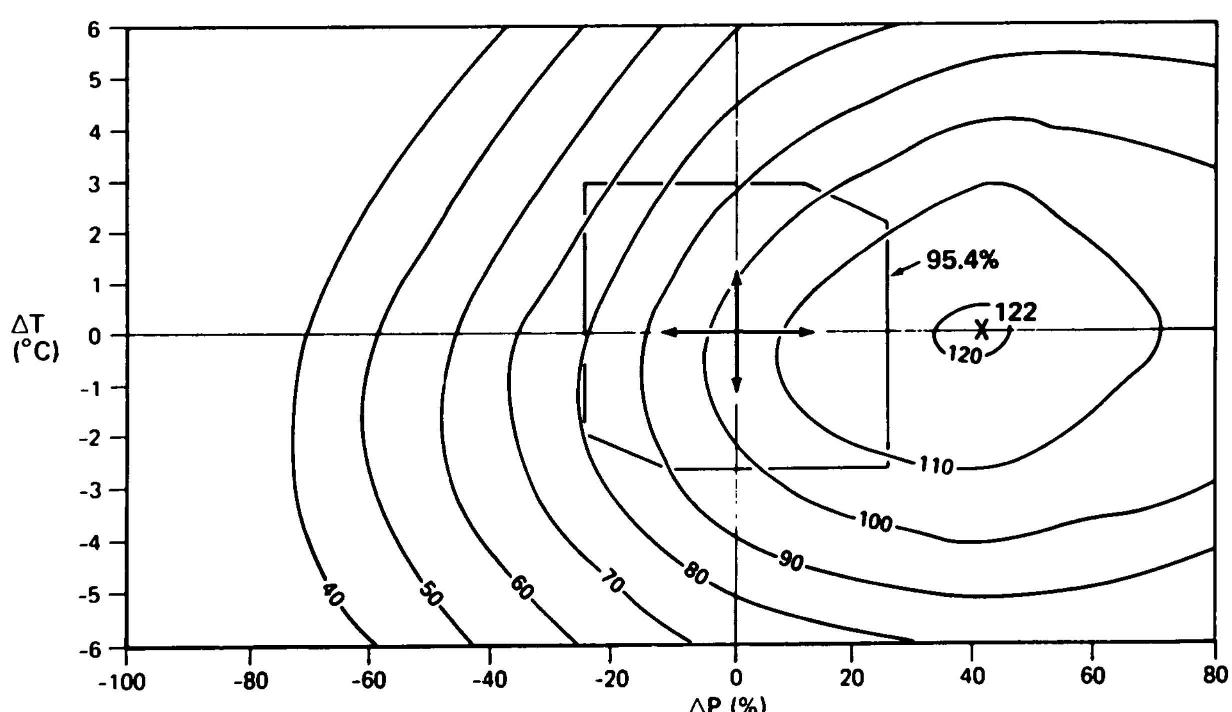

Fig. 17 Yield response surfaces for soybeans in the United States and Brazil

SPRING WHEAT: *Canada*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

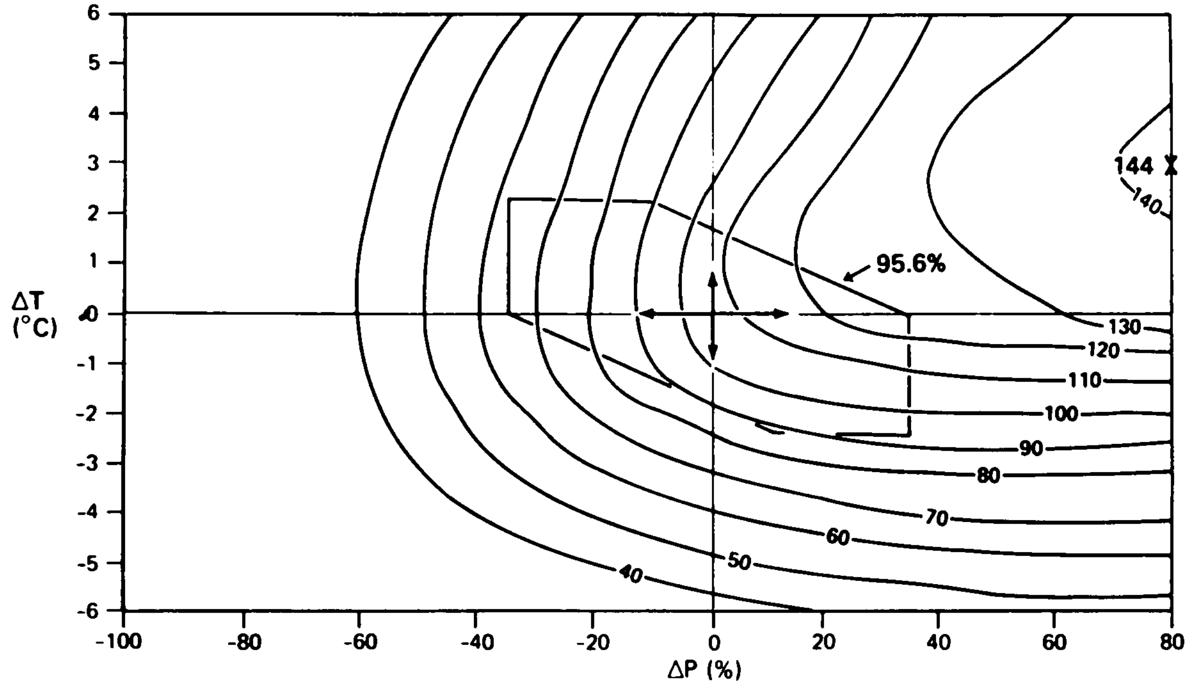

Figure V-8

SPRING WHEAT: *U.S.*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

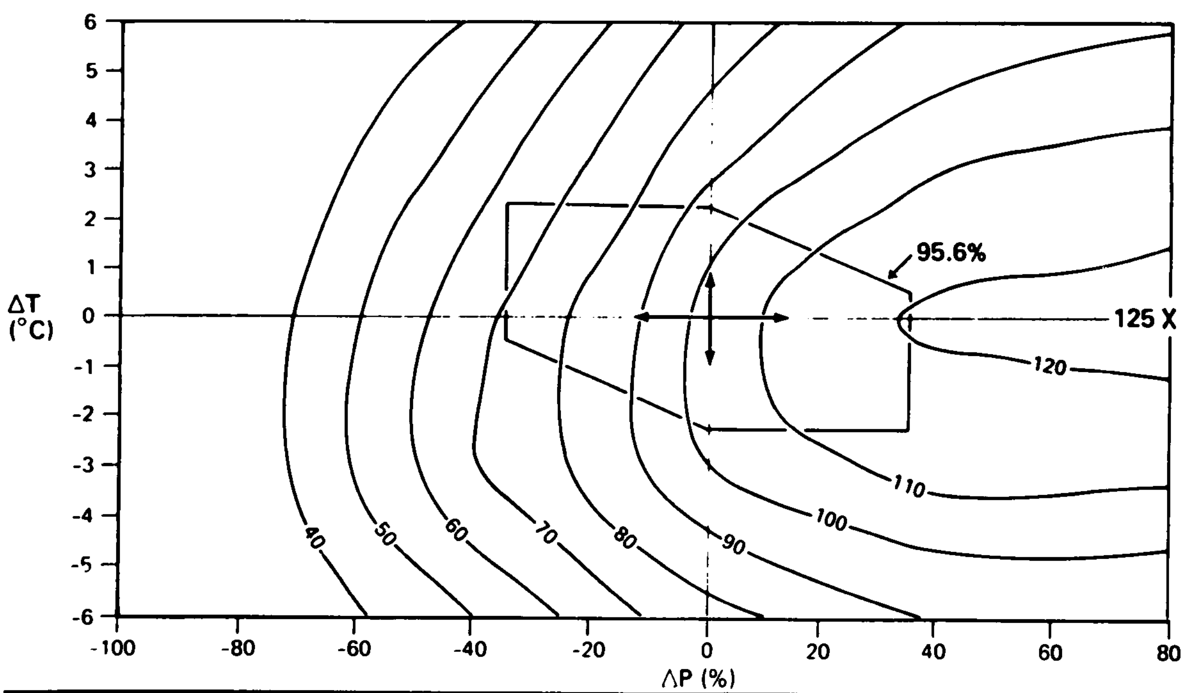

Fig. 18 Yield response surfaces for spring wheat in the United States and Canada

WINTER WHEAT: *U.S.*
Annual-Yield Response Surface (100 Base-Period Expected Yield)

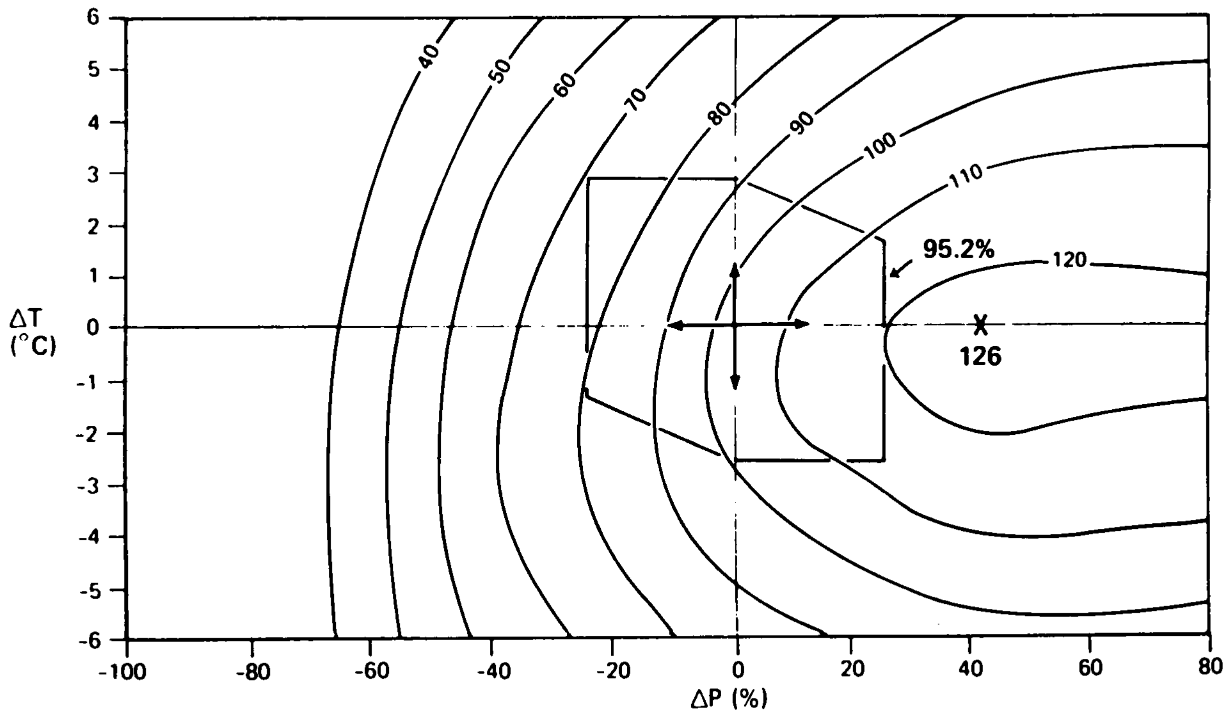

Figure IV-15

WINTER WHEAT: *USSR*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

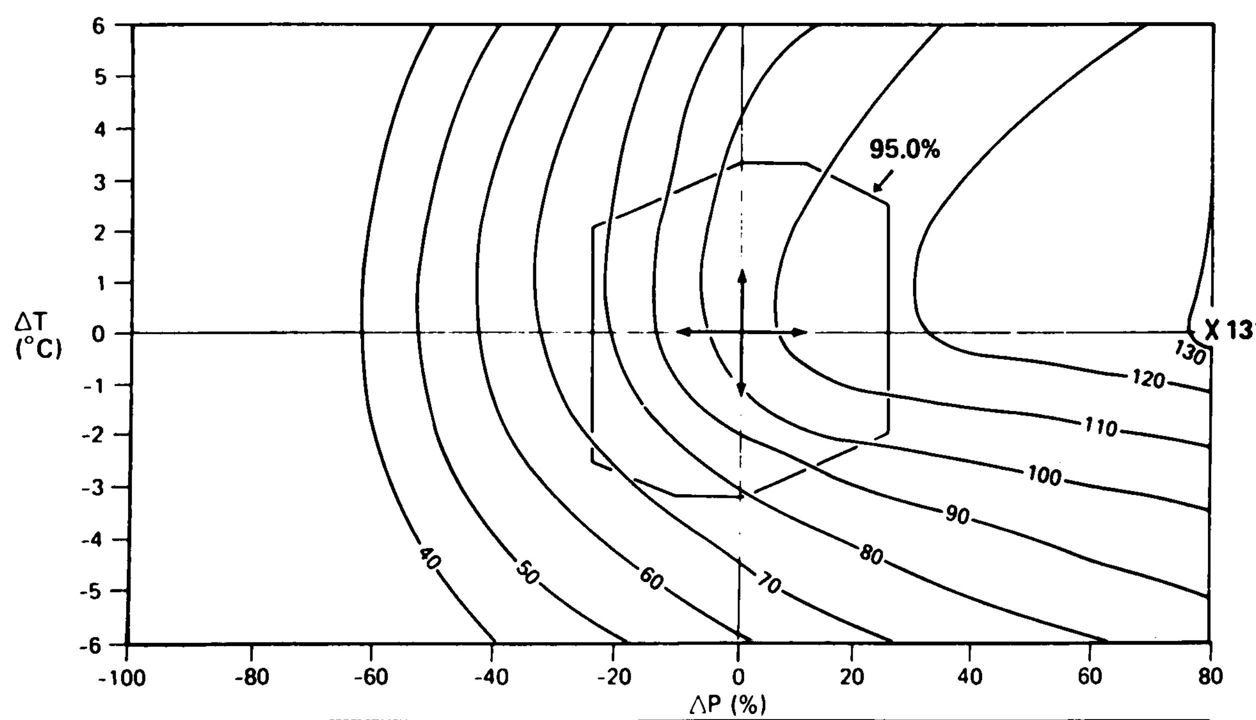

Fig. 19 Yield response surfaces for winter wheat in the United States and the Soviet Union

While the existence or nonexistence of nuclear winter is arguable and is certainly dependent on the size and nature of the attack, there is absolutely no question about the return of cold weather in January following the attack. If weapon effects destroy the utilities that provide space heating or much of the housing stock, as expected, the survivors of a nuclear war are going to face an exposure problem, especially in northern parts of the United States, even without a nuclear winter. This problem can be managed as previously mentioned by crowding inadequately clothed population into shelter.

Technology exists for improvising cold-weather clothing using newspapers, plastic bags, towels, and multiple layers of lighter clothing. Illustrated directions for these techniques are given in some detail in Kearny (1979, Chap. 15).

Paradoxically, the net effect of nuclear winter could be to reduce the vulnerability of a surviving population to exposure the following January. Awareness of nuclear winter should result in more emphasis on instructions for the civilian population to take along their winter clothing when evacuating or moving to expedient shelter. In a summertime crisis, it would be easy for many families to overlook the vital importance of their winter clothing. Fear of nuclear winter might reduce the number of instances where winter clothing would be left behind and would be subsequently destroyed by fire in the residential areas that are destroyed by blast and thermal pulse.

3.5 ENERGY REQUIREMENTS

Contrary to most people's expectations, the possibility of nuclear winter adds little to the requirement for energy, at least for space heating for the survivors of a nuclear attack. As mentioned above, emergency needs for keeping warm can be met by warm winter clothing, improvised clothing, and crowding into shelters for a month or two after the attack.

The reduced temperature in a spring or summer attack would reduce the energy requirements for ventilation that would normally be experienced in the southern part of the United States. Since it is expected that ventilation would be manually powered, savings in energy consumption would be insignificant.

Possibly the most urgent demand on energy imposed by nuclear winter is the requirement for restoration of electrical supply for pumping water (Voelker 1986). If the effects of nuclear winter do include nuclear drought, it is expected that surface water supplies would be most heavily impacted. The water supplies which are expected to remain available are underground supplies which are invariably pumped. Nonelectrical, expedient methods can be devised easily for obtaining water from surface streams and lakes (which are also likely to be contaminated with fallout).

While expedient manual methods can be and have been devised for drawing water from deep, underground wells, flow rates as high as 1 gal/min are difficult to achieve, and water from this source could be expected to supply only the direct drinking needs of a relatively small population.

If the disturbance of rainfall patterns persists into a second year, re-establishment of irrigated agriculture in those areas with sufficient underground water supplies would be critical for survival.

Restriction of the area where farming is possible will increase slightly the requirement for transportation fuel for the movement of agricultural products. However, this incremental requirement would be minute compared to the national requirements for fuel. Perhaps 1 or 2% of a preattack fuel production capability would be required for moving food from growing areas to highly populated areas (Haaland et al., 1976). Further restriction of areas in which food can be grown should increase this by only a few percent.

4. CONCLUSIONS

In the study of nuclear war, a consensus on nuclear winter seems to be emerging among climatologists. It is generally believed possible, for some range of heavy attacks directed against cities, that significant climate alteration will ensue for at least a few weeks. While the original study by Turco, Toon, Ackerman, Pollack, and Sagan (TTAPS) has been subjected to severe criticism, with the aid of hindsight, the study did remarkably well, considering its limitations as a one-dimensional model of a dry planet. It identified a possibility for climate upset for values of the input parameters subsequently judged to be reasonable. It produced results within a small factor (2 or 3) of those currently being produced by global circulation models. Much of the criticism of the TTAPs study has been justly directed at the sensational way it was presented to the public and the way selected results were used in an attempt to achieve political ends. The authors of this study recognized the limitations of the study and clearly stated them. Political partisans subsequently ignored these limitations and caveats and presented results of pessimistic excursions of the calculations as inexorable reality.

4.1 TEMPERATURE

Three-dimensional global circulation models being developed and used at Los Alamos, the National Center for Atmospheric Research, and Livermore National Laboratory for a reasonable attack size seem to be converging on a temperature depression of the order of 15°C averaged over the temperate region of the Northern Hemisphere. Temperature depressions as large as 25°C are predicted in the interiors of continents for attacks in the summertime. Wintertime wars produce temperature depressions of only a few degrees, a critically important result. All the models suggest the possibility of episodes of freezing temperatures in the interiors of continents in the mid-to-high latitudes, should the attacks occur in July or April, as well as January. Summertime and springtime attacks do not produce temperatures as cold as those seen in normal January conditions at the latitude of interest. People with the resources to survive normal January temperatures will be able to cope with the temperature epressions from Nuclear Winter.

4.2 PRECIPITATION

Work at Livermore and Los Alamos has indicated the possibility of substantial reduction of convective precipitation due to suppression of convection in the troposphere by heating of smoke in the upper troposphere. This raises the possibility of drought as a major consequence of climatological disturbance from nuclear war. Work at Livermore (Ghan et al., 1985) indicates that suppression of convective precipitation occurs at much lower levels of smoke loading in the atmosphere than is required for significant temperature depression. The reduced scavenging of smoke due to its lofting from solar heating (Malone et al. 1986) suggests that significant levels of smoke could persist for many months after the attack. This prolonged persistence of smoke would increase the possibiity that rainfall disruption, at least of the rainfall patterns, could occur in the second year after a war.

Except for local shortages, the analysis in Sect. 3.2 indicates that water supplies during a "nuclear drought" would generally be more than adequate for potable requirements. This is because requirements for potable water are only a few percent of total domestic central system use. However, even this quantity may present problems if electric power cannot be restored to surviving water systems or if treatment or delivery facilities have been damaged by hostile action.

Unirrigated (dryland) agriculture would be severely impacted by a drought of the magnitude postulated here. A significant fraction of agriculture is irrigated by surface water, which would be similarly impacted. Areas obtaining irrigation water from aquifers would be relatively invulnerable, provided that (1) drilling rigs were available to deepen wells in those places where falling water tables would cause problems and (2) power supplies could be maintained or restored.

Should drought conditions persist into a second growing season, cropping practices might have to be changed in areas with continuing supplies of groundwater to accommodate high-priority irrigated crops for human consumption. Production of crops for animal feed or luxury vegetables for human consumption could be discontinued under these circumstances. If irrigated farmlands were entirely devoted to the raising of wheat, groundwater supplies alone could be adequate to supply more than half of the wheat needed to provide a minimal diet for the American population.

4.3 UNCERTAINTIES

There are still very large uncertainties in the climatological consequences of nuclear war. Some of these are due to the limits on resolution of the models used. There is fundamental ignorance on the production and optical properties of smoke from combustion of urban environments. Both of these uncertainties should be reduced with continued work.

The irreducible uncertainty is the nature and severity of a nuclear war. There is absolutely no way to predict in advance the size of an attack, the fraction targeted on cities, or the fraction airburst or groundburst. Even where battle plans are known, the reliability and survival of the enemies' weapons as well as one's own are not predictable. One can only estimate a reasonable upper limit.

4.4 IMPLICATIONS

Neither cold nor drought is likely to be a direct threat to human survival. After an attack, a population with the wherewithal to survive its local January climate will not be threatened by the cold from a nuclear winter. For that portion of the population not equipped with sufficient cold-weather clothing for the local climate, crowding into shelters and the improvisation of cold-weather clothing are expedient means of coping.

The principal threat of nuclear winter is to agriculture. There is a likelihood that a nuclear war could produce heavy losses of agricultural productivity for the crop year, should the attack occur in the spring or summer. There could be episodes of freezing temperatures in the mid-to-high latitudes in the interiors of continents during the summer growing season. In addition, there is a likelihood that rainfall will be severely disrupted - either suppressed significantly or substantially altered in pattern.

Nuclear winter does not present an entirely new threat to the United States or the Soviet Union. Both countries could reasonably expect to lose agricultural productivity in a springtime or summertime war due to fallout either killing the early crops by radiation or keeping the farmers out of the fields when they should be conducting time-sensitive operations such as planting, cultivating, or harvesting. Both countries are believed to have at least a year's supply of grain in storage at all times. In the United States, unsold grain stored on farms and grain held in distribution centers make up this reserve. The Soviet Union has long provided for heavily protected state grain reserves.

The possibility exists for reduced agricultural production in the second year due to the disturbance of rainfall patterns. This probably poses a small threat to the United States even with a damaged agricultural economy, given its normal production of more than seven times the annual requirement to feed its population.

The consequences of nuclear winter would fall more heavily on the Soviet Union. The Soviet Union is at a higher latitude than the United

States and occupies a larger continent. It can be expected to see more severe temperature excursions.

Much Soviet agriculture is in areas subject to frequent drought. It can be expected that reductions in rainfall will impact these areas more severely.

Under normal circumstances, the Soviet Union has difficulty in meeting its agricultural production targets due to organizational and managerial deficiencies. However, under normal circumstances, it still manages to produce 2.5 times the quantity of grain needed to sustain its population on an all-grain diet.

5. RECOMMENDATIONS

The following recommendations are offered to deal with potential climatological effects of a large-scale nuclear war. Note that they are also required by previously-known effects of nuclear war:

1. In conjunction with the Department of Interior and the Department of Energy make plans for restoring electric power to domestic water supplies, particularly those depending on underground water.

2. Support USDA policies which result in continued maintenance of large grain reserves in storage. Large supplies of stored grain are an immense asset to recovery from a variety of catastrophes. It would be particularly helpful if some of that grain were stored in the same geographical area (but outside target areas) as the bulk of the population in the country.

3. In conjunction with the USDA, determine those areas of the country where crops are irrigated by underground water or other drought-resistant supplies. Priority for restoration of electric power to those supplies should be given, as well as priority for planning for transport of the produce from those areas to populated areas of the country. At the same time, the feasibility of conversion from low priority crops (e.g., cotton, alfalfa) to high priority crops (wheat, beans) should be examined.

4. In instructions for the general population on evacuation or on the construction of expedient shelter, re-emphasize a reminder to take their winter clothing with them even if the crisis occurs in the summertime.

5. Continue to encourage the population to maintain a household reserve of storable foods capable of supporting the family for several weeks.

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APPENDICES

APPENDIX I

REGRESSION EQUATIONS FOR ANNUAL STREAMFLOWS

Table A.1 shows the estimated equations relating annual (water year) streamflow by ASR to average rainfall and temperature. Each equation is of the form Flow = a + bP + cT where a, b, and c are the estimated coefficients. For each equation, the table includes the standard errors of the coefficients, R_2, the mean precipitation P and temperature T, the streamflow gauge number for which the equation was estimated, the mean streamflow, and the total area of the ASR (including upstream ASRs). (Note: because of missing streamflow records, the predicted streamflow at the mean P and mean T does not necessarily equal the mean streamflow.)

Equations were not estimated for a number of ASRs whose "normal" storage, as given in U.S. Water Resources Council (1978), Vol. 3, Appendix II, exceeds 75% of the annual average streamflow. Equations were also not estimated for most of the Great Lakes ASRs, since most major cities in those regions can draw upon the Great Lakes for water supplies.

Table A.2 portrays the results of application of the regression equations under four sets of assumptions:

- 30% of the average annual precipitation, no temperature change
- 50% of the average annual precipitation, no temperature change
- 30% of the average annual precipitation, decrease of -5^{O}F in temperature
- 50% of the average annual precipitation, decrease of -5^{O}F in temperature

In the analyses of Section 3.2, the latter two cases are used. The other sets of results are shown to demonstrate the sensitivity of the results to the input assumptions.

Table A.1 Estimated Equations for Annual Streamflows

ASR	Intercept [cfs]	P Coef. (SE) [cfs/in.]	T Coef. (SE) [cfs/°F]	SE of Y Estim.	R^2	Mean P [in.]	Mean T [°F]	Gauge #	Mean Flow [cfs]	Area, incl influent ASRs [mi^2]
101	4309	409.72 (32)	-214.06 (159)	1262	0.77	41.16	41.80	1-0345	12222	31712
102	-5288	309.51 (27)	0.00 (0)	1034	0.72	41.99	44.23	1-1000	7754	8819
103	736	26.39 (2)	-23.41 (14)	112	0.72	44.85	48.74	1-1125	770	4959
104	-1488	88.86 (7)	0.00 (0)	384	0.74	46.41	48.80	1-2055	2636	3905
105	9088	181.36 (89)	0.00 (0)	3406	0.07	41.94	45.32	1-1840	16694	11323
106	-1245	75.93 (7)	0.00 (0)	209	0.72	39.14	44.49	4-2905	1729	8685
201	-14338	704.80 (51)	0.00 (0)	1365	0.84	39.45	46.01	1-3580	13710	14928
202	-3291	69.71 (10)	0.00 (0)	295	0.52	40.07	46.72	1-3895	1106	18723
203	-9611	507.41 (44)	0.00 (0)	1601	0.72	42.20	49.78	1-4635	11800	16285
204	15923	1582.30 (152)	-904.43 (557)	4897	0.69	40.84	48.60	1-5760	36980	26223
205	-8047	342.11 (37)	0.00 (0)	1454	0.65	43.13	55.45	2-0375	6663	25185
206	-11124	517.56 (64)	0.00 (0)	2369	0.55	43.18	53.99	1-6465	11223	15708
301	-8028	333.90 (48)	0.00 (0)	1794	0.48	48.24	60.02	2-0805	8083	58734
302	-7383	196.62 (33)	0.00 (0)	1293	0.47	48.82	61.67	2-1715	2313	42022
303	7083	655.11 (53)	-407.55 (-273)	2295	0.76	50.34	64.59	2-2260	13727	35687
304	-15344	493.69 (75)	0.00 (0)	2890	0.51	52.02	66.98	2-3235	10573	10631
305	-558	14.98 (2)	0.00 (0)	115	0.44	54.40	70.71	2-2565	255	18493
306	-2216	466.38 (129)	0.00 (0)	5905	0.20	54.53	70.21	2-3587	23298	34820
307	3191	950.09 (100)	-402.30 (503)	4640	0.70	56.20	63.57	2-4295	32930	25805
308	-26021	956.97 (136)	0.00 (0)	4860	0.65	56.18	63.70	2-4700	26374	19737
309	-13689	418.26 (31)	0.00 (0)	1882	0.80	56.11	64.11	2-4895	9882	16223

Abbreviations: SE = Standard Error; ASR = Aggregated Subregion;
R = Coefficient of Determination for Equation; P = Precipitation;
T = Temperature; Y = Indendent Variable (Annual Streamflow)

Table A.1 (Continued)

ASR	Intercept [cfs]	P Coef. (SE) [cfs/in.]	T Coef. (SE) [cfs/°F]	SE of Y Estim., R2	Mean P [in.]	Mean T [°F]	Gauge #, Mean Flow [cfs]	Area, incl. influent ASRs [mi2]
402	-2153	198.46	0.00	1031	31.40	44.08	4-0845	17672
		(41)	(0)	0.31			4079	
405	-1285	91.51	0.00	439	31.65	44.89	4-1560	15306
		(21)	(0)	0.28			1634	
501	13877	588.46	-379.86	2270	41.63	49.63	3-0495	17901
		(79)	(294)	0.57			19550	
502	122967	4366.53	-3942.26	12058	41.14	51.58	3-2550	79916
		(676)	(2678)	0.72			96805	
503	17050	290.91	-398.41	1616	38.25	51.41	3-1500	19655
		(52)	(154)	0.45			7632	
504	-5436	600.54	-110.60	1795	44.20	53.88	3-1980	12441
		(58)	(24)	0.71			14978	
505	-71284	13281.23	-4581.71	30070	44.82	54.71	3-6115	273324
		(908)	(1541)	0.82			275052	
506	-28269	1723.68	-229.70	535	39.46	52.00	3-3775	31991
		(148)	(214)	0.74			27795	
507	45765	1264.76	-1345.09	6361	50.02	57.47	3-43822	18204
		(137)	(778)	0.66			32295	
601	57833	1280.45	-1434.24	5675	51.09	59.28	3-57185	22992
		(145)	(756)	0.64			38237	
602	-113134	2243.95	-1007.49	8981	52.38	59.95	3-6095	44469
		(210)	(959)	0.70				
701	29709	1225.53	-1075.22	5307	26.83	42.01	5-3445	46607
		(224)	(534)	0.42			17419	
702	25171	1748.62	-939.07	8054	28.09	42.47	5-3895	75427
		(385)	(907)	0.34			35670	
703	84829	3926.50	-3059.06	14432	30.05	45.01	5-4745	135898
		(609)	(1449)	0.52			65103	
704	-143038	7765.34	0.00	24058	31.79	11.39	5-5875	173562
		(1144)	(0)	0.51			106286	
705	495725	15158.64	-17827.52	46599	23.28	36.65	7-0220	699942
		(3414)	(8606)	0.48			202588	
801	499483	34570.24	-18334.68	97635	41.34	64.37	7-2890	1088758
		(5144)	(9308)	0.60			586998	
802	690832	33343.75	-20563.15	94940	41.38	64.28	7-2890	1209597
		(4661)	(9451)	0.62			586998	
803	-2427	122.73	0.00	1095	41.77	64.33	8-0155	1239729
		(78)	(0)	0.13			2533	
901	25179	249.09	-653.36	2028	21.44	41.08	5-1025	63495
		(98)	(155)	0.36			3663	
1001	32279	170.56	-565.79	2910	24.57	42.96	6-1855	91552
		(238)	(320)	0.11			10679	
1002	15030	588.09	-352.29	1891	14.83	42.97	6-1095	40308
		(135)	(185)	0.34			8703	
1003	13286	534.43	-279.76	2754	14.86	42.98	6-1320	63873
		(189)	(257)	0.18			9205	

Table A.1 (Continued)

ASR	Intercept [cfs]	P Coef. (SE) [cfs/in.]	T Coef. (SE) [cfs/^oF]	SE of Y Estim., R2	Mean P [in.]	Mean T [^oF]	Gauge #, Mean Flow [cfs]	Area, incl. influent ASRs [mi2]
1004	29618	1219.85 (161)	-803.50 (210)	1897 0.65	13.94	42.72	6-3295 12267	64024
1010	27334	737.48 (124)	-719.16 (496)	3267 0.63	24.41	52.56	6-8925 6765	58707
1101	10648	1011.92 (102)	-29.01 (26)	5188 0.72	45.91	5.90	7-0745 22395	18963
1103	34162	596.92 (109)	-789.00 (393)	2804 0.57	24.39	53.16	7-1645 6754	63835
1104	-51653	3333.45 (414)	0.00 (0)	11978 0.64	27.74	56.81	7-2635 38718	151424
1107	-37698	2061.89 (218)	0.00 (0)	8336 0.64	33.47	63.21	7-3555 31113	72866
1201	-7438	520.32 (79)	0.00 (0)	3055 0.46	30.17	65.35	8-0305 8265	20440
1202	-10015	628.58 (63)	0.00 (0)	2444 0.65	27.48	65.20	8-0665 7257	22324
1203	-12092	733.46 (113)	0.00 (0)	2706 0.70	26.47	64.41	8-1145 6146	45469
1204	-4476	261.89 (41)	0.00 (0)	1185 0.54	26.47	64.41	8-1625 2332	44380
1205	-451	45.78 (16)	0.00 (0)	560 0.16	27.48	65.20	8-2110 809	41925
1304	-516	51.56 (11)	0.00 (0)	227 0.33	13.12	53.82	8-4075 161	21002
1305	-4638	340.59 (115)	0.00 (0)	1019 0.37	18.30	56.02	8-4750 1735	135207
1402	24297	648.38 (121)	-579.21 (221)	1810 0.54	14.72	46.20	9-1805 7505	22099
1403	33102	1472.95 (346)	-799.52 (589)	4380 0.39	13.24	47.42	9-3800 14658	116209
1501	4435	50.09 (7)	-81.48 (23)	118 0.68	12.62	59.04	9-4020 245	25070
1602	-258	42.21 (15)	0.00 (0)	227 0.16	11.63	48.56	10-2240 229	16624
1603	-399	75.45 (21)	0.00 (0)	288 0.25	8.95	49.99	10-3350 281	73255
1701	43775	1560.73 (560)	-1169.04 (907)	7915 0.49	18.18	43.83	12-3986 28258	38506
1702	56614	6051.84 (2980)	0.00 (0)	18795 0.51	23.85	46.00	14-1447 201833	204323
1704	107782	3552.19 (557)	-2787.93 (2030)	7995 0.73	20.49	45.56	13-3530 55997	107476
1705	42492	6377.29 (2905)	0.00 (0)	18039 0.55	24.91	46.39	14-1447 201833	244913
1706	-159	80.74 (6)	0.00 (0)	241 0.79	38.20	48.10	12-0395 2854	14613
1707	198	23.49 (3)	-13.19 (11)	83 0.55	27.25	48.46	10-3935 178	18072

Table A.1 (Continued)

ASR	Intercept [cfs]	P Coef. (SE) [cfs/in.]	T Coef. (SE) [cfs/°F]	SE of Y Estim., R2	Mean P [in.]	Mean T [°F]	Gauge #, Mean Flow [cfs]	Area, incl. influent ASRs [mi2]
1801	-6450	1111.59 (133)	0.00 (0)	4469 0.68	23.10	56.73	11-5305 19587	25987
1803	-7874	580.98 (45)	0.00 (0)	1995 0.76	22.07	58.62	11-3035 4946	33353
1804	-1762	187.53 (13)	0.00 (0)	543 0.83	21.89	58.94	11-4670 2369	4095

Abbreviations: SE = Standard Error; ASR = Aggregated Subregion;
R = Coefficient of Determination for Equation; P = Precipition;
T = Temperature; Y = Indendent Variable (Annual Streamflow)

Table A.2 Annual streamflow scenarios resulting from regression analysis

	Temperature and Precipitation Scenario:				
	Mean Annual Temperature			5°F Cooler	
ASR	Mean Annual [cfs]	30% of P [cfs]	50% of Mean P [cfs]	30% of Mean P [cfs]	50% of Mean P [cfs]
101	12227	422	3795	1492	4865
102	7707	-1390	1209	-1390	1209
103	779	-50	187	67	304
104	2636	-251	574	-251	574
105	16693	11369	12891	11369	12891
106	1727	-354	241	-354	241
201	13465	-5997	-436	-5997	-436
202	1106	-849	-291	-1021	-462
203	11799	-3188	1094	-3188	1094
204	36598	-8642	4284	-4119	8806
205	6709	-3620	-669	-3620	-669
206	11223	-4420	50	-4420	50
301	8081	-3195	27	-3195	27
302	2217	-4503	-2583	-4503	-2583
303	13736	-9347	-2752	-7309	-714
304	10338	-7639	-2503	-7639	-2503
305	257	-314	-151	-314	-151
306	23214	5413	10499	5413	10499
307	31012	-6365	4314	-4353	6326
308	27737	-9894	858	-9894	858
309	9781	-6648	-1954	-6648	-1954
402	4078	-283	963	-283	963
405	1612	-416	163	-416	163
501	19520	2373	7272	4272	9171
502	99259	-26486	9441	-6775	29152
503	7694	-95	2130	1897	4122
504	15147	-3432	1876	-2879	2429
505	275146	-141546	-22491	-129139	-10085
506	27798	-19810	-6208	-18662	-5059
507	31724	-12558	94	-5833	6819
601	38226	-7564	5519	-393	12690
602	64797	-17475	6032	-22512	994
701	17424	-5597	980	-221	6356
702	34420	31	9856	4726	14552
703	65141	-17461	6139	-2166	21435
704	103814	-68982	-19612	-68982	-19612
705	195290	-51756	18828	37381	107966
801	588808	-411651	-125806	-319978	-34132
802	587731	-378221	-102235	-275405	581
803	2700	-889	137	-889	137
901	3677	-62	1006	3205	4273
1001	12165	9232	10070	12061	12899
1002	8615	2508	4253	4269	6014
1003	9202	3644	5232	5043	6631

Table A.2 (Continued)

ASR	Temperature and Precipitation Scenario: Mean Annual Temperature: Mean Annual [cfs]	Mean Annual Temperature: 30% of Mean P [cfs]	Mean Annual Temperature: 50% of Mean P [cfs]	5°F Cooler: 30% of Mean P [cfs]	5°F Cooler: 50% of Mean P [cfs]
1004	12296	395	3796	4413	7813
1010	7534	-5065	-1465	-1470	2130
1101	22347	-10173	-882	-10028	-737
1103	6777	-3412	-501	533	3444
1104	40812	-23914	-5421	-23914	-5421
1107	31309	-16996	-3194	-16996	-3194
1201	8259	-2729	411	-2729	411
1202	7256	-4834	-1379	-4834	-1379
1203	7325	-6267	-2384	-6267	-2384
1204	2457	-2396	-1010	-2396	-1010
1205	807	-74	178	-74	178
1304	160	-313	-178	-313	-178
1305	1595	-2768	-1522	-2768	-1522
1402	7077	398	2307	3294	5203
1403	14692	1040	4940	5037	8938
1501	257	-185	-59	222	348
1602	233	-111	-13	-111	-13
1603	276	-196	-61	-196	-61
1701	20911	1050	6724	6895	12570
1702	200921	99906	128768	99906	128768
1704	53549	2592	17151	16532	31091
1705	201348	90149	121920	90149	121920
1706	2925	766	1383	766	1383
1707	199	-249	-121	-183	-55
1801	19225	1252	6387	1252	6387
1803	4945	-4029	-1465	-4029	-1465
1804	2344	-530	291	-530	291

APPENDIX II

SUMMARY OF AQUIFER DATA BASE USED IN WATER SUPPLY ANALYSIS

Table A-3

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approximate use (mgd)**
CITRONELLE-MIOCENE	AL	P	300	350	Y	Y	*
FLORIDAN	AL	P	225	300	N	Y	*
TERTIARY SEDIMENTARY	AL	P	700	525	Y	Y	*
CRETACEOUS	AL	PS	850	650	Y	Y	*
PALEOZOIC CARBONATE	AL	PS	300	300	Y	N	*
PENNSYLVANIAN SANDSTONE	AL	P	150	5	N	N	*
IGNEOUS-METAMORPHIC	AL	P	200	5	N	N	*
SPARTA SAND	AR	P	750	1000	Y	N	*
WILCOX	AR	P	925	275	Y	N	*
NACATOCH SAND	AR	P	650	225	Y	N	*
OZARK	AR	P	1500	225	Y	N	*
ALLUVIAL	AR	P	125	1500	N	Y	3000.00
COCKFIELD	AR	P	425	225	Y	N	*
ALLUVIAL	AZ	M	1000	1000	Y	Y	*
SANDSTONE	AZ	M	1000	25	N	Y	*
BEDROCK	AZ	N	500	1	N	N	*
COASTAL BASINS	CA	PS	275	750	Y	N	*
SOUTHERN CALIFORNIA	CA	P	475	1000	Y	Y	1720.00
CENTRAL VALLEY	CA	PM	275	775	Y	Y	0000.00
BASIN-FILL/DESERT	CA	PM	210	850	Y	Y	100.00
LARAMIE-FOX HILLS	CO	PMS	1150	150	Y	N	*
SOUTH PLATTE ALLUVIAL	CO	MSI	90	800	Y	Y	905.00
ARKANSAS ALLUVIAL	CO	P	60	650	Y	Y	309.10
SEDIMENTARY	CT	PS	200	25	Y	N	*
STRATIFIED-DRIFT	CT	PS	75	425	Y	N	150.00
CRYSTALLINE BEDROCK	CT	PS	200	12	Y	N	*
CARBONATE ROCK	CT	P	200	25	Y	N	*
PINEY POINT	DE	O	400	300	Y	N	*
CHESAPEAKE GROUP	DE	O	175	300	N	Y	*

gpm,mgd: Gallons per minute, million gallons per day
Muni: Source of municipal water supply (y = yes, n = no)
Irri: Source of water supply for irrigation (y = yes, n = no)

* The following codes are used to designate source of recharge:
I - Irrigation Percolation   M - Mountain Runoff   O - Overlying Aquifers
P - Precipitation   S - Surface Water

** Where entry is zero the quantity is not calculated as aquifer does not satisfy criteria for vulnerability.

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approximate use (mgd)**
RANCOCAS	DE	O	225	75	Y	Y	*
MAGOTHY	DE	O	175	15	N	Y	*
POTOMAC	DE	OP	370	250	Y	N	5.00
UNCONFINED SURFACE	DE	PS	70	350	Y	Y	225.00
INTERMEDIATE	FL	P	350	200	Y	N	*
SAND-AND-GRAVEL	FL	P	200	750	Y	N	50.00
UNNAMED SURFICIAL	FL	PS	225	100	Y	N	*
FLORIDAN	FL	PI	200	750	Y	Y	2000.00
BISCAYNE	FL	PS	95	750	Y	N	400.00
FLORIDAN	GA	P	470	3000	Y	Y	600.00
CLAIBORNE	GA	P	235	375	N	Y	*
CLAYTON	GA	P	370	425	Y	Y	*
CRETACEOUS	GA	P	390	575	Y	Y	100.00
PALEOZOIC	GA	P	1500	25	N	N	*
CRYSTALLINE ROCK	GA	P	320	12	N	N	*
BURIED-CHANNEL	IA	P	75	55	N	N	*
DAKOTA	IA	P	350	175	Y	N	*
MISSISSIPPIAN	IA	P	200	75	Y	N	*
SILURIAN-DEVONIAN	IA	P	450	275	Y	N	*
JORDAN	IA	P	1150	550	Y	N	*
DRESBACH	IA	P	700	475	Y	N	*
ALLUVIAL	IA	P	65	600	Y	N	21.00
GLACIAL-DRIFT	IA	P	195	7	N	N	*
BASALT	ID	P	550	1800	Y	Y	*
VALLEY-FILL	ID	P	200	1000	Y	Y	850.00
SEDIMENTARY/VOLCANIC	ID	P	1500	1300	Y	Y	*
PENNSYLVANIAN-MISSISSIPPIAN	IL	P	370	15	Y	N	30.00
CAMBRIAN-ORDOVICIAN	IL	P	950	575	Y	N	*
MOUNT SIMON	IL	P	1750	575	N	N	*
SAND-AND-GRAVEL	IL	P	275	500	Y	Y	235.00
SHALLOW DOLOMITE	IL	P	275	500	Y	N	*
WISCONSONIAN TILL	IN	P	60	45	N	Y	*
SILURIAN-DEVONIAN	IN	P	150	55	N	Y	*
GLACIOFLUVIAL	IN	P	40	300	Y	N	200.00
GLACIAL OUTWASH	IN	P	60	300	Y	N	200.00
MISSISSIPPIAN	IN	P	85	13	N	N	*
OZARK	KS	N	1150	90	Y	N	*
ALLUVIAL	KS	P	80	255	N	Y	151.00
GLACIAL-DRIFT	KS	P	155	55	N	N	*
HIGH PLAINS	KS	P	230	750	Y	Y	5255.00
GREAT PLAINS	KS	P	110	55	N	N	*
CHASE AND COUNCIL GROVE	KS	P	110	15	N	N	*
DOUGLAS	KS	P	200	25	N	N	*
ALLUVIAL	KY	P	85	270	Y	N	115.00
PENNSYLVANIAN	KY	P	140	3	Y	N	1.00
MISSISSIPPIAN	KY	P	250	6	Y	N	*
ORDOVICIAN	KY	P	125	6	N	N	*

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approxi-mate use (mgd)**
TERTIARY	KY	P	350	50	Y	N	*
CRETACEOUS	KY	P	250	15	Y	N	*
1200′ SANDS	LA	PS	1800	1000	Y	N	*
CHICOT	LA	P	425	1500	N	Y	450.00
ALLUVIAL	LA	PS	175	1500	N	Y	180.00
400′ AND 600′ SANDS	LA	PS	450	750	N	N	126.00
EVANGELINE/JASPER	LA	PS	1200	700	Y	N	*
COCKFIELD/SPARTA	LA	PS	550	925	Y	N	*
WILCOX/CARRIZO	LA	PSO	350	95	Y	N	*
TERRACE	LA	P	100	220	N	N	*
CARBONATE ROCK	MA	P	200	25	N	N	*
CRYSTALLINE BEDROCK	MA	P	250	10	N	N	*
STRATIFIED DRIFT	MA	P	90	550	Y	N	320.00
NEWARK	MD	PS	315	55	N	N	*
APPALACHIAN	MD	PS	415	12	N	N	*
CARBONATE	MD	PS	415	100	N	N	*
PIEDMONT	MD	PS	415	31	N	N	*
CHESAPEAKE	MD	PS	295	205	Y	N	*
PINEY POINT	MD	PS	350	130	Y	N	*
AQUIA	MD	PS	325	135	Y	N	*
MAGOTHY	MD	PS	500	275	Y	N	*
POTOMAC	MD	PS	640	550	Y	N	*
COLUMBIA	MD	PS	85	275	Y	N	8.10
CARBONATE BEDROCK	ME	PS	410	20	N	Y	*
CRYSTALLINE BEDROCK	ME	PS	410	6	N	N	*
GLACIOFLUVIAL OUTWASH	ME	PS	75	45	Y	N	*
GLACIOFLUVIAL ICE-CONTACT	ME	PS	85	525	Y	Y	70.00
TILL	ME	PS	20	1	N	N	*
TILL	MI	P	112	100	N	N	*
MARSHALL	MI	O	112	300	Y	N	21.00
SAGINAW	MI	P	165	200	Y	N	*
SILURIAN-DEVONIAN	MI	P	85	155	N	N	*
CAMBRIAN-ORDOVICIAN	MI	P	85	105	N	N	*
PRECAMBRIAN	MI	P	210	25	N	N	*
GLACIOFLUVIAL	MI	P	112	500	Y	N	40.00
LACUSTRINE	MI	P	65	290	N	N	*
BIWABIK-IRON FORMATION	MN	P	385	500	Y	N	*
BURIED DRIFT	MN	P	230	350	Y	Y	*
CRETACEOUS	MN	P	450	130	N	N	*
UPPER CARBONATE	MN	P	300	350	Y	N	*
ST. PETER	MN	P	362	175	N	N	*
PRAIRIE DU CHIEN-JORDAN	MN	P	540	750	Y	Y	*
RED RIVER-WINNIPEG	MN	P	370	175	N	N	*
IRONTON-GALESVILLE	MN	P	405	220	Y	N	50.00
MOUNT SIMON-HINCKLEY	MN	P	610	550	Y	N	*
NORTH SHORE VOLCANOES	MN	P	475	15	Y	N	*
PROTEROZOIC METASEDIMENTARY	MN	P	265	35	Y	N	*

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approximate use (mgd)**
PRECAMBRIAN	MN	P	480	15	N	N	*
SURFICIAL DRIFT	MN	P	135	450	N	Y	60.50
SIOUX QUARTZITE	MN	P	710	50	Y	N	*
ALLUVIAL	MO	SP	90	550	Y	Y	22.00
MISSISSIPPI ALLUVIAL	MO	SP	115	3000	N	Y	80.00
WILCOX/CLAIBORNE	MO	SP	750	1800	Y	N	*
MCNAIRY	MO	SP	1050	600	Y	N	*
OZARK	MO	N	950	360	Y	Y	*
KIMMSWICK-POTOSI	MO	P	200	360	Y	Y	*
MISSISSIPPI RIVER ALLUVIAL	MS	SP	95	1750	Y	Y	672.00
MIOCENE	MS	SP	775	775	Y	N	*
OLIGOCENE	MS	SP	575	80	N	N	*
COCKFIELD	MS	SP	550	505	Y	Y	*
SPARTA	MS	SP	800	505	Y	Y	*
WINONA-TALLAHATTA	MS	SP	550	205	N	N	*
MERIDIAN-UPPER WILCOX	MS	SP	950	1050	Y	Y	*
LOWER WILCOX	MS	SP	1100	800	Y	Y	*
RIPLEY	MS	SP	575	155	N	N	*
COFFEE SAND	MS	SP	525	205	N	N	*
EUTAW-MCSHAN	MS	SP	800	255	Y	N	*
TUSCALOOSA	MS	SP	550	775	Y	N	27.00
PALEOZOIC	MS	SP	350	500	N	Y	*
CITRONELLE	MS	SP	125	175	Y	N	*
FORT UNION FORMATION	MT	PM	175	20	N	N	*
HELL CREEK/FOX HILLS	MT	P	325	12	Y	N	*
JUDITH RIVER	MT	PM	400	10	N	N	*
EAGLE SANDSTONE	MT	PM	450	15	N	N	*
KOOTENAI	MT	PM	1000	20	N	N	*
ELLIS GROUP	MT	PM	1150	0	N	N	*
MADISON GROUP	MT	P	1750	0	N	N	*
ALLUVIAL/BASIN-FILL/GLACIAL	MT	PM	65	75	Y	Y	*
SURFICIAL	NC	P	50	112	Y	Y	*
CRYSTALLINE ROCK	NC	P	135	20	N	N	1.00
YORKTOWN	NC	P	100	50	Y	N	*
CASTEL HAYNE	NC	P	135	350	Y	N	87.00
WEST FARGO	ND	P	175	505	Y	N	0.16
FORT UNION	ND	P	450	50	N	N	*
HELL CREEK-FOX HILLS	ND	N	1000	75	Y	N	*
GREAT PLAINS	ND	N	3000	35	N	N	*
MADISON GROUP	ND	N	3100	0	N	N	*
ENGLEVALE	ND	P	40	500	N	Y	0.51
OAKES	ND	P	50	250	N	Y	0.51
PAGE	ND	P	95	150	N	Y	*
SPIRITWOOD	ND	P	150	500	N	Y	0.51
SUNDRE	ND	P	175	250	Y	N	*
HIGH PLAINS	NE	P	265	750	Y	Y	*
DAKOTA	NE	P	335	525	Y	Y	*

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approximate use (mgd)**
CRETACEOUS	NE	P	685	55	N	N	*
PALEOZOIC	NE	P	1115	105	Y	Y	*
PALEOVALLEY ALLUVIAL	NE	P	100	750	Y	Y	100.00
VALLEY ALLUVIAL	NE	P	65	525	Y	Y	50.00
NIOBRARA	NE	P	135	525	Y	Y	5.00
CRYSTALLINE BEDROCK	NH	PM	350	5	Y	N	*
STRATIFIED DRIFT	NH	PM	60	300	Y	N	50.00
HIGHLAND CRYSTALLINE	NJ	P	415	25	N	N	*
ATLANTIC CITY 800′ SAND	NJ	P	700	700	Y	N	*
WENONAH-MT. LAUREL	NJ	P	325	150	Y	N	*
POTMAC/RARITAN/MAGOTHY	NJ	P	925	750	Y	N	*
NEWARK GROUP	NJ	P	765	255	Y	N	*
VALLEY + RIDGE SEDIMENTARY	NJ	P	275	250	N	N	*
GLACIAL VALLEY-FILL	NJ	P	155	550	Y	N	100.40
KIRKWOOD-COHANSEY	NJ	P	185	750	Y	Y	16.30
BASIN-FILL/HIGH PLAINS	NM	PSI	300	300	Y	Y	*
SANDSTONE	NM	PSI	1100	75	Y	Y	*
LIMESTONE	NM	PSI	750	600	N	Y	*
VALLEY-FILL	NM	PSI	125	300	Y	N	101.00
BASIN-FILL	NV	M	300	600	Y	Y	*
VOLCANIC ROCK	NV	M	650	510	N	N	*
CARBONATE ROCK	NV	M	1300	525	N	Y	*
CRETACEOUS	NY	P	350	300	Y	N	*
VALLEY-FILL	NY	PM	100	550	Y	N	90.00
SANDSTONE	NY	PM	250	75	Y	N	5.00
CARBONATE ROCK	NY	PM	155	100	Y	N	*
MAGOTHY	NY	P	625	625	Y	N	*
LLOYD	NY	P	625	525	Y	N	*
STRATIFIED DRIFT	NY	PM	155	30	N	N	*
UPPER GLACIAL	NY	P	275	550	Y	N	*
FINE-GRAINED	OH	P	112	75	Y	N	*
SHALY SANDSTONE/CARBONATE	OH	P	65	3	N	N	*
SANDSTONE	OH	P	165	15	Y	N	*
SHALE	OH	P	25	2	N	N	*
CARBONATE	OH	P	165	150	Y	N	*
SHALY CARBONATE	OH	P	25	3	N	N	*
COURSE-GRAINED	OH	P	112	300	Y	N	300.60
ROUBIDOUR	OK	P	1000	150	Y	N	0.10
ANTLERS	OK	P	425	275	Y	Y	*
RUSH SPRINGS	OK	P	300	400	N	Y	*
GARBER-WELLINGTON	OK	P	500	200	Y	N	25.00
VAMOOSA-ADA	OK	P	300	200	Y	N	*
KEOKUK-REEDS SPRING	OK	P	175	5	Y	N	1.00
ARBUCKLE-SIMPSON	OK	P	1300	600	Y	Y	*
ARBUCKLE-TIMBERED HILLS	OK	P	1450	345	Y	N	1.00
ALLUVIAL	OK	PS	100	350	Y	Y	70.70
HIGH PLAINS	OK	P	300	550	Y	Y	*

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approximate use (mgd)
DOG CREEK-BLAINE	OK	P	150	300	N	Y	10.10
BASIN-FILL/ALLUVIAL	OR	MP	175	300	Y	Y	*
VOLCANIC + SEDIMENTARY	OR	MP	350	175	Y	N	*
COLUMBIA RIVER	OR	MP	350	350	Y	Y	*
UNCONSOLIDATED SAND/GRAVEL	PA	PS	110	550	Y	N	88.00
SANDSTONE + SHALE	PA	P	140	62	Y	N	*
CARBONATE	PA	P	175	250	Y	N	*
CRYSTALLINE BEDROCK	PA	P	112	15	N	N	*
STRATIFIED DRIFT	RI	PS	100	400	Y	Y	14.20
FLORIDAN	SC	P	165	200	Y	N	*
BLACK CREEK	SC	P	450	225	Y	N	*
MIDDENDORF	SC	P	1100	450	Y	Y	*
TERIARY SAND	SC	P	200	125	Y	Y	*
PIEDMONT/BLUE RIDGE	SC	P	175	20	N	N	*
SHALLOW/SURFICIAL	SC	P	60	7	N	N	*
DAKOTA/NEWCASTLE	SD	N	2150	26	Y	N	*
INYAN-KARA	SD	N	2550	42	N	N	*
SUNDANCE	SD	N	2750	52	N	N	*
MINNELUSA	SD	N	3450	52	N	Y	*
MADISON	SD	N	4550	55	Y	N	*
RRED RIVER	SD	N	5400	52	N	N	*
DEADWOOD	SD	N	5120	26	N	N	*
GLACIAL DRIFT/ALLUVIAL	SD	PS	210	26	Y	Y	*
NIOBRARA/CODELL	SD	P	225	16	N	N	*
HIGH PLAINS	SD	P	290	52	Y	Y	*
F. UNION/H. CREEK/F. HILLS	SD	P	1050	21	Y	N	*
ALLUVIAL	TN	P	42	35	Y	N	*
KNOX	TN	N	950	5	Y	N	6.00
PENNSYLVANIAN SANDSTONE	TN	P	150	27	Y	N	*
ORDOVICIAN CARBONATE	TN	P	100	12	N	N	*
MISSISSIPPIAN CARBONATE	TN	P	125	27	Y	N	*
CAMBRIAN-ORDOVICIAN	TN	P	200	202	Y	N	*
TERTIARY SAND	TN	P	700	600	Y	N	*
CRETACEOUS(COFF. S./MCNAI.)	TN	P	800	275	Y	N	*
CRYSTALLINE ROCK	TN	P	100	27	Y	N	*
CARRIZO-WILCOX	TX	P	600	550	Y	Y	*
EDWARDS	TX	P	550	800	Y	N	*
EDWARDS/TRINITY	TX	P	225	125	Y	Y	*
GULF COAST (CH./JA./EVANG.)	TX	N	850	900	Y	Y	550.00
TRINITY	TX	P	275	200	Y	N	*
ALLUVIUM + BOLSON DEPOSITS	TX	P	550	700	Y	Y	*
HIGH PLAINS	TX	P	400	550	N	Y	2400.00
VALLEY-FILL	UT	P	125	380	Y	N	56.00
BASIN-FILL	UT	P	300	600	Y	Y	*
SANDSTONE	UT	P	559	275	Y	Y	*
CARBONATE ROCK	UT	P	0	0	N	N	*
BRIGHTSEAT	VA	P	575	200	N	N	*

Table A-3. (Continued)

Aquifer	State	Recharge Source*	Mean depth (ft)	Mean yield (gpm)	Muni ?	Irri ?	Approxi-mate use (mgd)
YORKTOWN-EASTOVER	VA	P	115	252	N	N	*
CHICKAHOMINY-PINEY POINT	VA	P	200	180	Y	N	*
AQUIA	VA	P	250	110	Y	N	*
POTOMAC	VA	P	700	800	Y	N	*
COLUMBIA	VA	P	40	125	N	N	*
MESOZOIC BASIN	VA	P	175	55	N	N	*
CRYSTALLINE	VA	P	115	8	N	N	*
BLUE RIDGE	VA	P	225	7	N	N	*
CRYSTALLINE BEDROCK	VT	PM	350	5	Y	N	*
CARBONATE BEDROCK	VT	PM	200	12	Y	N	*
STRATIFIED-DRIFT	VT	PM	55	215	Y	N	5.38
COLUMBIA RIVER BASALT	WA	PS	400	1575	Y	Y	110.00
CRYSTALLINE ROCK	WA	P	110	5	N	N	*
GLACIAL DRIFT	WA	PS	150	500	Y	Y	135.00
TERRACE/VALLEY-FILL	WA	P	175	495	Y	N	*
ALLUVIAL	WA	P	35	26	N	N	*
SILURIAN DOLOMITE	WI	P	115	25	N	N	*
PRECAMBRIAN	WI	P	75	5	N	N	*
SANDSSTONE	WI	P	525	255	Y	N	*
SAND AND GRAVEL	WI	P	65	55	N	Y	*
ENGLISHTOWN	WN	P	525	400	Y	N	*
UPPER PENNSYLVANIAN	WV	P	175	15	N	N	6.00
LOWER PENNSYLVANIAN	WV	P	175	50	Y	N	2.00
MISSISSIPPIAN	WV	P	125	50	Y	N	1.00
HAMPSHIRE/CHEMUNY	WV	P	175	12	N	N	*
ORISKANY/HELDERBERG	WV	P	175	100	Y	N	*
TOND./WLS. CRK./WLLMSPRT.	WV	P	175	50	Y	N	*
MCK./CLINTON/TUSCA.	WV	P	145	12	N	N	*
JUNIA./OSWEGO/MRTSBURG	WV	P	125	15	Y	N	*
TRENTON/BLACK RIVER/ST.PAUL	WV	P	235	200	Y	N	*
CONOCOCHEAQUE/ELBROOK	WV	P	250	100	Y	N	*
CHILHOWEE	WV	P	125	12	N	N	*
ALLUVIAL	WV	P	65	775	Y	N	12.20
CARBONATE AND SANDSTONE	WY	P	2250	400	N	Y	*
STRUCTURAL BASIN	WY	PS	170	25	Y	N	*
HIGH PLAINS	WY	P	250	475	Y	Y	*
ALLUVIAL	WY	P	45	75	N	Y	*

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Interagency Agreement: FEMA No. EMW-89-E-1737

"Nuclear Winter" is the term given to the cooling hypothesized to occur following a nuclear war as the result of the injection of smoke from burning cities into the atmosphere. The voluminous literature on this subject produced since the paper was published in 1983 by Turco et al, has been reviewed. Three-dimensional global circulation models have resulted in reduced estimates of cooling--15 to 25°C for a summer war and a few degrees for a winter war. More serious may be the possibility of suppression of convective precipitation by the altered temperature profiles in the atmosphere. However, very large uncertainties uncertainties remain in input parameters, the models, and the results of calculations. We conclude:
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(contd)

(contd)

- Neither cold nor drought is likely to be a direct threat to human survival for populations with the wherewithal to survive normal January temperatures.
- The principal threat from nuclear winter is to food production, and this could present problems to third parties who are without food reserves.
- Loss of a crop year is neither a new nor an unexpected threat from nuclear war to the United States and the Soviet Union. Both have at least a year's food reserve at all times. Both face formidable organizational problems in distributing their reserves in a war-damaged environment.

The consequences of nuclear winter could be expected to fall more heavily on the Soviet Union than the United States due to its higher latitude and less productive agriculture. This may be especially true if disturbances of rainfall amounts and distribution persist for more than a year.

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