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AFGL-TR-88-0217
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 450

AFGL-TR 86-450

An Assessment of Global Atmospheric Effects of a Major Nuclear Conflict

H.S. MUENCH
R.M. BANTA
S. BRENNER
D.A. CHISHOLM

10 May 1988

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ATMOSPHERIC SCIENCES DIVISION PROJECT 6670

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

"This technical report has been reviewed and is approved for publication"

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DONALD A. CHISHOLM, Chief
Atmospheric Prediction Branch

ROBERT A. McCLATCHEY, Director
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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
AFGL-TR-88-0217
AFSG, No. 450

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Air Force Geophysics Laboratory

6b. OFFICE SYMBOL *(If applicable)*
LYP

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
Hanscom AFB
Massachusetts 01731-5000

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
Air Force Weapons Laboratory

8b. OFFICE SYMBOL *(If applicable)*
AFWL/NT

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*
Kirtland AFB
New Mexico 87117

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62101F	6670	10	20

11. TITLE *(Include Security Classification)*
An Assessment of Global Atmospheric Effects of a Major Nuclear Conflict

12. PERSONAL AUTHOR(S)
Muench, H.S., Banta, R.M., Brenner, S., and Chisholm, D.A.

13a. TYPE OF REPORT
Scientific, Final

13b. TIME COVERED
FROM 2/1/84 TO 5/31/87

14. DATE OF REPORT *(Year, Month, Day)*
1988 May 10

15. PAGE COUNT
90

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Post-attack environment; Nuclear effects; Nuclear Winter; Atmospheric chemistry; Numerical weather modeling; Environmental impact

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

In the fall of 1983, evidence started emerging from the scientific community that a major nuclear conflict could result in substantial weather changes over vast regions of the globe, including severe surface cooling over the continents. Refined projections of the density and horizontal extent of persistent layers of smoke (soot) led to revised estimates of the magnitude of the postulated surface cooling. The term "nuclear winter" was coined to reflect the potential severity of the effects. At the request of the Air Force Weapons Laboratory, several studies that had been done (and were underway or planned at the time) were reviewed to assess the technical merits of the emerging hypothesis. In addition, a series of experiments was conducted with a "cloud-scale" numerical model to simulate the early stages of an urban fire after a nuclear explosion.

The early calculations proceeded with substantial uncertainties regarding the nuclear exchange scenarios; fuel capacity of urban and rural areas; smoke (soot) generation, transport and removal by atmospheric processes; and the optical and physical consequences of the soot. Nonetheless, the impact to the post-attack environment (even given the range

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Donald A. Chisholm

22b. TELEPHONE *(Include Area Code)*
617-377-4729

22c. OFFICE SYMBOL
AFGL/LYP

DD FORM 1473, JUN 86 — *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. Continued

of uncertainty due to the assumptions made) implied heretofore unrecognized consequences to the "quality of life" in vast regions and to effective national defense planning and execution.

Subsequent studies carried out in 1984 - 1986 sought, with some success, to reduce the uncertainties in the calculations, by clarifying some assumptions and replacing others with more complete and newer scientific data. They have resulted today in assessments which, while indicating smaller surface temperature effects than previous studies for a given amount of soot, do document with increased scientific certainty that secondary consequences of a nuclear exchange would complicate the "quality of life" of survivors for extended periods and over areas well removed from the geographic region directly involved in the exchange. The resulting period of abnormal optical path lengths due to smoke (soot) would also complicate national defense contingencies.

This report includes sections dealing with (a) an early diagnosis of atmospheric effects, (b) soot; properties and production, (c) atmospheric models, (d) a review of published comments and meetings and (e) potential impact on USAF operations.

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1. INTRODUCTION

In the fall of 1983, scientists worldwide started presenting new evidence that a major nuclear conflict could result in worldwide weather changes, including severe surface cooling over the continents. Dr M.C. MacCracken,[1] of Lawrence Livermore National Laboratory, summarized the weather effects as follows:

> "The smoke rising from burning cities, industrial areas, and forests, if such areas are attacked as part of a major nuclear exchange, is projected to increase the hemispheric average atmospheric burden of highly absorbent carbonaceous material by 100 to 1000 times. As the smoke spreads from these fires, it would prevent sunlight from reaching the surface, leading to a sharp cooling of land areas over a several day period. Within a few weeks, the thick smoke would spread so as to largely cover the mid-latitudes of the Northern Hemisphere, cooling mid-continental smoke-covered areas by, perhaps, a few tens of degrees Celsius. Cooling of near coastal areas would be substantially less, since oceanic heat capacity would help to buffer temperature changes in such regions.
>
> The solar radiation not being absorbed at the surface would be absorbed by the smoke in the upper troposphere (up to heights of perhaps 10 km). As the smoky layer warms, this heating of the middle upper troposphere would induce further mixing of the smoke up into the atmosphere, where the smoke could remain even longer than the 10 - 20 days that

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(Received for publication 5 May 1988)

1. "Nuclear War: Preliminary estimates of the climatic effects of a nuclear exchange. *Proceedings of the International Seminar on Nuclear War 3rd Session: The Technical Basis for Peace*, Erice, Italy, 19-24 Aug 83, Servizio Documentazione dei Laboratori Frascati dell'INFN, Jul 84, pp. 161-183, also available as Lawrence Livermore National Laboratory Report UCRL-89770, Livermore, CA.

normal scavenging now allows. The strong atmospheric stability created by the strongly warmed smoke layer overlying the cooled surface and lower troposphere would tend to reduce precipitation over both the ocean and the land areas, where evaporation would also be reduced due to surface cooling. The precipitation that does occur would likely be shallow and relatively ineffective in scavenging the higher smoke layer. Thus, solar absorption by the smoke and the reduction in scavenging would allow the smoke particles to remain in the atmosphere for longer times, thereby probably prolonging the darkness and continental cooling for perhaps several months. The net effect of a summertime nuclear exchange would be that summer conditions in mid-latitudes would turn to dark near winter-like conditions, while a wintertime nuclear exchange would lead to somewhat more severe winter conditions. Lower latitude temperatures would become more like those in middle or higher latitudes. The impacts of these climatic perturbations on society and agriculture remain to be evaluated."

The magnitude of the postulated surface cooling and the eventual global extent of changes took many people by surprise. Thus far, man-made effects on the atmosphere have either been large-scale but small in magnitude (carbon dioxide increase, ozone decrease) or small-scale and moderate in magnitude (urban heat "islands" of 2 - 5° F.). This so-called "nuclear winter" scenario represents a man-made effect far greater in combined scale and magnitude than anything scientists had previously postulated. It was at this point (early, CY84) that the Air Force Weapons Laboratory (AFWL) first asked for AFGL assistance "to assess the technical merit of recent studies concerning this hypothesis and to suggest follow-on work to further test the hypothesis." At this time there was a limited amount of published material to evaluate, principally a single paper in *Science* by Turco, Toon, Ackerman, Pollock, and Sagan[2] (often called "TTAPS"). Several organizations were known to have either started or planned to start programs of study in this area, but results would not likely be forthcoming for six months to a year. Consequently, a fact-finding trip was undertaken to four installations in late March 1984, sought to determine opinions of scientists on work performed, programs underway, and where difficult problems lay. The research centers visited were Los Alamos National Laboratory (contact: Dr R. Malone), Lawrence Livermore National Laboratory (contacts: Drs F. Luther and R. Parrott), NASA Ames Laboratory (contact: Dr O.B. Toon) and the National Center for Atmospheric Research (contact: Dr S. Thompson). Information gathered on this trip formed the basis for the initial report entitled, "An Assessment of Global Weather Changes Created by Nuclear War." An important conclusion of this report was "within the scientific community there appears to be unanimity in the view that researchers thus far have been very responsible in making their calculations. Their task has been especially difficult since pertinent data are scarce and there are many uncertainties. When estimation of various factors was necessary, they have chosen to assume median values - legitimate arguments can be made for either higher or lower values."

Since research on the global effect of nuclear conflict was expanding quite rapidly, AFWL asked for further technical assistance. AFGL agreed to undertake two related efforts: (a) dynamic cloud model studies to investigate precipitation scavenging of soot from urban fires and also plume penetration into the stratosphere and (b) a continuing assessment of related "nuclear winter" research.

Regarding the second aspect, attention turned to a close monitoring of scientific meetings and publications. A summary of monitoring activities is shown in Table 1. Typically, when a new field of

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2. Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B., and Sagan, C. (1983) Nuclear Winter: global consequences of multiple nuclear explosions, *Science* **222**:1283-1291.

Table 1. Activities monitored by AFGL Committee on Global Nuclear Effects. Includes Newspaper articles, journal discussions, scientific journal reports, scientific conferences, minor committee reports and major committee reports. @ symbol indicates attendence/participation by AFGL personnel.

Abbreviations:

BAMS	Bulletin American Meteorological Society
BG	Boston Globe
BWMO	Bulletin World Meteorological Society
DW	Defense Week
EOS	Bulletin of American Geophysical Union
AtMo	Atlantic Monthly
ForA	Foreign Affairs
LLNL	Lawrence Livermore National Laboratories
Nat	Nature (Na=Nat)
PhT	Physics Today
Sc	Science
Sch	Search (Australian Pub.)
SN	Science News
TTAPS	Turco, Toon, Ackerman Pollack and Sagan
WSJ	Wall Street Journal
ASUSSR	USSR Academy of Science
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSU	Colorado State University
DNA	Defense Nuclear Agency
GAO	General Accounting Office
IAMAP	International Association for Meteorology and Atmospheric Physics
IAPSO	International Association for the Physical Sciences of the Ocean
MIT	Massachusetts Institute of Technology
MPI	Max-Planck Institute
NASA	National Aviation and Space Agency
NCAR	National Center For Atmospheric Research
NOAA	National Oceanic & Atmospheric Administration
PSRC	Pacific-Sierra Research Corporation
SUNY	State University of New York (Stony Brook)
AAAS	American Association for the Advancement of Science
AMS	American Meteorological Society
BMO	British Meteorological Office
CanCC	Canadian Climate Center
ICPC	International Cloud Physics Council
LANL	Los Alamos National Laboratory
NRC/NAS	National Research Council National Academy of Science
R&D	R&D Research Associates
SCOPE	Scientific Committee on Problems of the Environment

		News-Paper	Journal discus.	Journal Reports	Scientific Conference	Minor Com. Rep.	Major Com. Rep
1983	Nov		.SN				
	Dec			•TTAPS	6•AGU @		
1984	Jan						
	Feb	.WSJ	.Sc				
	Mar		.Nat .BAMS	•NCAR	1•MIT @ 4•trip @		
	Apr		.Sc				204•AAAS
	May	.BG				30•NOAA draft 15•AFGL/AFWL	
	Jun						
	Jul		..Sc				
	Aug		..Nat .Sc		•ICPC @ •DNA		
	Sep		.SN .Na				
	Oct						
	Nov		.AtMo				
	Dec	.BG		•MPI			193•NRC NAS
1985	Jan		.Sch .Sc		6•AMS @		
	Feb		.SN .Sc		25•DNA @		
	Mar		.Sc			17•DoD/ Congress	
	Apr		.Sc .BWMO				

		News-paper	Journal discus.	Journal Reports	Scientific Conference	Minor Com. Rep.	Major Com. Rep.
1985	May			•CSU	3•AFWL-AFGL		
	Jun			•SUNY •NASA			
	Jul	2.BG .DW		2•NCAR •ASUSSR			
	Aug			•PSRC •CSIRO •R&D	21•IAMAP IAPSO @		
	Sep	.BG	.Nat .PhT .Sc, SN .Sc .SN				359•SCOPE1 524•SCOPE2
	Oct			•LANL			
	Nov						
	Dec			•SUNY			
1986	Jan		.Nat .Sch	•LANL •BMO			
	Feb				•DNA @		
	Mar					56•GAO	
	Apr		.Nat .SN	•CanCC			
	May		.Nat				
	Jun						
	Jul		.ForA	•NCAR			
	Aug		.EOS				
	Sep		.ForA				
	Oct			•LLNL			

investigation opens up, the first results are presented at scientific meetings and soon thereafter, papers are published in one of the journals that publish quickly, such as the weekly scientific magazines, *Science* and *Nature*. The detailed, more thoroughly reviewed scientific reports often are published up to a year later. During the two-year period, March 1984 through February 1986, members of the AFGL study group attended six scientific meetings, where at least a portion was devoted to nuclear environmental effects. There was a special seminar at MIT presented by the Soviet scientist Dr V. Aleksandrov (Mar 84), the ICPC/SCOPE meeting in Tallinn, Estonia (Aug 84), the AMS meeting in Los Angeles (Jan 85), the two DNA meetings in Santa Barbara (Feb 85) and Moffett Field (Feb 86), and the IAMAP/IAPSO meeting in Hawaii (Aug 85). During this same period, some 46 printed documents were collected, studied, and added to a growing archive ranging from newspaper clippings to 200-page reports and books.

The AFGL study group was really only one of several such groups tasked to evaluate the problem. The National Resource Council sponsored a large effort, setting up a special committee of 18 scientists, headed by Prof G. Carrier of Harvard, with contributions by 29 other scientists (some we had visited). In December 1984, this group published an authoritative document, "The Effects on the Atmosphere of a Major Nuclear Exchange." The Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions also undertook a comprehensive review, and in January 1986, published a two-volume set "Environmental Consequence of a Nuclear War, Volume I: Physical and Atmospheric Effects, Volume II: Ecological and Agricultural Effects." In addition, the Secretary of Defense was tasked by Congress to study the environmental effects and impact on defense strategy and a report, "The Potential Effects of Nuclear War on the Climate," was submitted to Congress in March 1985.

AFWL/WE requested that more quantitative assessments of the likely impact on AF operations of the post-attack nuclear environment be considered to satisfy planning requirements. However, the uncertainties noted in the first effort in early 1984 were quite large and progress on certain key issues such as fuel inventory and smoke (soot) production would likely be too slow to allow estimates to be made with any degree of confidence. Thus, we undertook a more conservative goal of compiling and documenting a "continuing assessment" of related 'nuclear winter' research.

The dynamic cloud model studies consisted of experiments using a "cloud-scale" numerical model to simulate the early stages of an urban fire after a nuclear explosion. These studies used a version of the numerical cloud model developed at Colorado State University, and the cloud model was run on the AFWL Cray 1 by Dr Banta. The model runs simulated the development of deep thunderstorm-type clouds, which can produce rain over intense, large-area fires. Some authors have hypothesized that this rain could wash a significant fraction of the smoke out of the atmosphere before the smoke could spread into a huge pall that could lead to "nuclear winter" effects.

The modeling studies, which consisted of five three-dimensional model runs, found that the stability and moisture of the ambient atmosphere and the intensity of the fire itself exerted controlling influences on the height of penetration of the smoke cloud. The model runs also found that the amount of immediate removal of smoke by precipitation ("scavenging") was small, in most cases less than 5 percent. These results were reported at several conferences and workshops, including the DNA Global Effects workshops in February 1985 and 1986 and the IAMAP Symposium on Climate Effects of Nuclear War in August 1985.

The present report describes the activities of AFGL in nuclear environment assessment from March 1984 through February 1986, and the current state of our knowledge obtained through model-simulation experiments and a thorough review of articles, reports, and symposia presentations. Even now, there is still considerable uncertainty about many aspects of the problem and for the reader to appreciate the difficulties, the discussion must address some technical areas. The intent is to avoid technical terminology (jargon) where possible, and define it when not avoidable. Ample reference is provided to allow more in-depth search of specific topics. We also recognize that with the large uncertainties present, even scientists who strive for objectivity may have a tendency to believe what they want to believe. Thus, published criticisms and related scientific papers are also quoted and discussed to present a balanced picture.

2. EARLY DIAGNOSIS OF ATMOSPHERIC EFFECTS

As long ago as the 1940's and 50's, when the first atomic and hydrogen bombs were exploded, some people were concerned that there might be widespread effects on our atmosphere. Most certainly there are enormous local effects as the air is suddenly heated to a million (or more) degrees as detonation takes place; however, radiation and convection rapidly diffuse this burst of energy through volumes of air, miles in each dimension, such that about 12 hours after a single blast, residual effects on atmospheric temperature and wind are down in the "noise" level of measurement.[3] Theoretically, after a single megaton-size H-bomb detonation, atmospheric behavior would never be exactly the same as if the blast did not occur, as there would be minute (immeasurable) effects on storm systems of all scales around the globe; however, the statistical characteristics of the atmosphere, such as average temperature and variability, precipitation totals and distribution would be unchanged. The above-ground testing of large weapons in the 1950's and early 60's did produce some important widespread atmospheric effects in the form of radioactive particles. In the fission-fusion reaction, some of the nuclear material and weapon casing as well as ground material (if a near-surface burst) is transformed into radioactive vapors, which soon condense into very small airborne particles, many of which are carried to altitudes of 50,000 ft or more as the "fireball" rises and cools on its way up to convective equilibrium level. High-altitude balloon and aircraft equipment regularly sampled stratospheric air, and sample measurements could determine much about the detonation as well as the manner in which stratospheric diffusion takes place, even though samples were obtained many thousands of miles from and months after an atmosphere test. The radioactive material did not remain permanently in the stratosphere, but natural circulations gradually brought material down into the troposphere (atmosphere below 50,000 ft) where it mixed rapidly downwards and was either washed out by precipitation or became attached to plants and soil. During the 1950's and early 60's, there were many major nuclear tests each year, and even though most testing was done in either the tropics (U.S.) or arctic (U.S.S.R), most of the material washed out at latitudes of 30° to 60° north, particularly in the

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3. More detailed descriptions of nuclear detonations may be found in: Glasstone, S. and Dolan, P.J. (1977) *The Effects of Nuclear Weapons*, DoD and ERDA, Government Printing Office, Washington, D.C.

spring season, and some isotopes such as strontium 90 reached alarming levels[4] in the food chain. Thus the U.S., U.S.S.R., and U.K. agreed to cease atmospheric testing.

Since the era of atmospheric testing, the nuclear arsenals have grown into thousands and then tens of thousands of weapons. Fears have also grown not only for the terrible devastation that their use could have on urban areas, but also that the long-term, slow fallout from stratospheric levels would "poison" even the areas not devastated. The fears of urban devastation are, of course, well founded and no doubt have deterred both East and West from open conflict for the past 25 to 30 years. On the other hand, the estimates of radioactive fallout based on the arsenals of the late 1960's indicated severe local conditions near targets and that the long-term fallout from the stratosphere would be unhealthy but not disastrous to the survivors and noncombatants.

Meantime, the knowledge of the chemistry relating to the ozone layer (found at levels of 50,000 to 150,000 ft) developed considerably since 1970. A new concern about widespread atmospheric effects arose when it became known that oxides of nitrogen (NO, NO_2) caused a catalytic reduction in ozone concentration. These oxides of nitrogen are produced only at very high temperatures which would be found in, for example, gasoline engines, power plants, forest fires, and nuclear explosions. The earth's ozone layer serves a vital role to life on earth by absorbing potentially harmful ultraviolet solar radiation.

While ozone concentrations in the middle of this layer are high enough to be toxic to most forms of life (about 15 parts per million), vertical mixing above 50,000 ft is very slow, allowing dilution by a factor of 100 or more before this air ever comes to the earth's surface. Computations of ozone depletion due to the nitrous oxide from nuclear weapons in a major war have ranged from 5 to 50 percent,[5] with the greatest depletion about 6 - 12 months after the exchange and slowly dropping to a 2 - 12 percent depletion some five years later. Depletions of 20 percent or more would be larger than the normal variability in the regions where sunlight is the strongest and likely would have significant, harmful effects on plants and animals. We must emphasize that these computations have been largely based on theoretical estimates of nitrous oxide formation in nuclear detonations, which have not been verified by direct measurement.

During the 1970's and early 80's, scientists realized that the production of many "small" (0.5 megaton or less) weapons with precision guidance had made previous computations of large-scale effects incomplete. Previously, strategic weapons were built for yields of 1 to 20 megatons, producing the best chance of target destruction from the shock waves resulting from a detonation several thousand feet above ground. Such weapons can produce a fireball that rises to 70,000 ft, injecting nitrous oxide well into the ozone layer, but picking up a relatively small amount of surface dust. On the other hand, the smaller weapons with precision guidance would be very effective in destroying a specific target with a ground burst, which would throw up much more dust (per megaton), though together with radioactive debris and nitrous oxide might only rise to altitudes of 40 - 50,000 ft. Several thousand small weapons have been constructed and the older, larger weapons have not yet

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4. Burton, J.D., Millburn, G.M., and Russell, R.S. (1960) Relationships between the rate of fallout and the concentration of ^{90}Sr in human diet in the United Kingdom, *Nature* **185**:498-500.

5. National Research Council (NRC) (1985) *The Effects on the Atmosphere of a Major Nuclear Exchange*, National Academy Press, Washington, D.C.

been retired. Thus, rather than just a shift of emphasis, there is a broadening of the whole environmental effect problem.

If a few thousand of these precision weapons were detonated at ground level, rather substantial amounts of dust would be quickly thrown up into the atmosphere. These dust particles would range from submicron size (too small for microscopes) to marble-size pebbles. The smallest particles come from condensation of rock and soil vapor, and the largest are swept up by violent inflow when the fireball rises. The largest would quickly fall out in a few minutes to an hour, but the smallest sizes would take months before mixing down to cloud levels and washing out in precipitation. Calculations of the clouds created by surface weapons were made in the TTAPS study which indicated that dust loading of the atmosphere would be comparable to that of the largest volcanic eruptions of the past 200 years. Such volcanic eruptions appear to have caused widespread, long-term surface cooling of about 1 - 2° C. (2 - 4° F.). The more recent, notable volcanic eruptions (St. Helens, El Chichon, Agung) were not as powerful as the "giants" of the 1800's, so their effects were almost lost in normal atmospheric variability. Thus it appears likely that the surface bursts in a large nuclear war could cause large-scale surface temperature cooling due to dust clouds that would be noticeable, but not disastrous.

In 1980, the Swedish Academy of Science sponsored an effort to reexamine nuclear weapons effects, based on the changed inventories that included many smaller strategic weapons. Crutzen and Birks[6] (Max Planck Institute) began looking at the atmospheric chemistry effects for lower levels than previously considered to take into account the smaller weapons. They soon realized that smoke from burning forests and cities could rise high enough to interfere with the sunlight, which is a factor in the chemistry calculations. When estimates of the smoke loading were completed they showed that a nuclear war involving about half the weapons available could lead to massive smoke clouds dense enough to significantly lower surface temperatures over entire continents. A number of other scientists, particularly Aleksandrov (USSR), MacCracken (LLNL), Toon and associates (NASA Ames), and Turco (R and D Associates), recognized this was a very important factor previously overlooked in studies assessing large-scale effects of a nuclear war. They quickly set about to refine the calculations of Crutzen and Birks, using recently developed models of atmospheric behavior. Both MacCracken and Aleksandrov presented papers at a meeting on large-scale effects held in Erice, Sicily (Aug 83), using models that included the thermal radiation balance and atmospheric motion. Their calculations indicated that mid-continent cooling in summer could produce temperature drops as great as 40° - 60° C. (70° - 100° F.) - a shocking result. The NASA Ames group, together with Turco and Carl Sagan, published the oft-quoted "TTAPS" paper in *Science*, Dec 83,[2] examining a variety of targeting scenarios, but with overall results quite similar to the other 1983 results reported. A simple comparison to these early studies is shown in Table 2.

To start from some assumed pattern of nuclear detonations and arrive at specifications of temperature changes 20 days later requires a long and involved chain of calculations, with many poorly-known factors involved. Thus, it must be quite surprising that the results for the last three studies in Table 2 are so similar. One possibility is that this is the classical case of verification of

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6. Crutzen, P.J. and Birks, J.W. (1982) The atmosphere after a nuclear war: Twilight at noon, *Ambio* **11**:114-125.

Table 2. Estimated Surface Temperature Change Due to Smoke - Early Studies (1982-83)

SOURCE	MODEL	CONTINENT TEMP. DROP.	DURATION OF MINIMUM-DAYS	50 PERCENT RECOVERY
Crutzen-Birks (MPI)	1-D	Large	---	Long
MacCracken (LLNL)	1-D	30 - 60C	10 - 60	2 - 3 Mo.
Aleksandrov (SAS)	3-D	20 - 40C	10 - 20	3 - 5 Mo.
TTAPS (Ames)	1-D/2-D	30 - 40C	25	1 - 4 Mo.

NOTE:
1. Annual mean atmosphere used for initial cond.
2. Investigators expect largest temp. drops in mid-continent in summer; smaller in winter, coast.
3. Recovery rate dependent on removal assumptions.

careful work through independent study. Another possibility is that there was sufficient interaction among the groups that they used the same assumptions, the same basic data, and slightly different models to arrive at the same answer. As we shall see, the answer probably lies closer to the latter possibility.

To start the calculations, one has to assume something about how a nuclear war might be fought - how many weapons of each type, against which targets, with what accuracy, and over how long a time. There is probably greater disagreement over this aspect of the problem than any other issue. (For an interesting discussion, the reader should consult "Nuclear Winter and Nuclear Strategy," *Atlantic Monthly*, Nov 84.) The purpose of huge nuclear arsenals is to prevent war, through the threat of unacceptable destruction to any nation that might consider starting such a war. Should this deterrence fail at some time, it is unclear how many weapons would be exploded and on what sort of targets. In the least tragic situation, hostilities might cease after only a couple of warheads were exploded (as happened with Japan in WWII). In the worst case, almost the entire arsenal (Pittock, *et al*[7] estimates 24,000 warheads, with an average yield of about 0.5 MT) might be expended, because of the fear that incoming missiles might destroy warheads before they could be used. Officials will deny any deliberate targeting of population centers*, but the side that fires second will be looking at empty missile sites and airfields, and the only remaining viable strategic targets would be transportation, communication centers, military bases, and military-related industry - primarily in or near cities. The TTAPS study in setting up a "baseline" scenario assumed the use of 40 percent of the strategic weapons, and of these, 20 percent of the yield occurred in urban areas, because "many high-priority military industrial assets are located near or within urban areas." The NAS/NRC and the SCOPE 28 studies assumed quite similar baselines.

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7. Pittock, A.B., Ackerman, T.P., Crutzen, P.J., MacCracken, M.C., Shapiro, C.S., and Turco, R.P. (1986) *SCOPE 28. Environmental Consequences of Nuclear War, Vol I Physical and Atmospheric Effects*. John Wiley & Sons, New York.

* To reduce targeting uncertainty, we were invited to examine classified documents, but declined to do so because periodic changes are made and because U.S. strategy might differ from France, Great Britain and the USSR.

While such a war would bring unthinkable havoc to civilization, destroying a thousand or more major cities, the arsenals are so large that retaliations out of anger or desperation conceivably might destroy many times that number.

The next step is to compute the smoke generated by the fires associated with nuclear detonations, which requires knowing the area that burns and the ratio of smoke to fuel. Within a few milliseconds after detonation, a large expanding luminous fireball forms, emitting very high radiant energy for about a second (less for small weapons). The TTAPS group, as well as later groups, assumed that flammable material within the radius exposed to 20 cal/cm^2 of illumination in the flash would ignite, and nothing beyond. This amount of energy (20 cal/cm^2) is equivalent to compressing 20 minutes of midday sunshine into one second, and would be devastating to unprotected animal and plant life. A highly destructive shock wave follows the flash and temporarily puts out existing fires (which then rekindle from hot embers) and starts others through electric short circuits, shattered stoves, ovens, and furnaces. The urban flammable loading was estimated at 3 gm/cm^2 overall, with 1.9 gm/cm^2 actually burning, and a smoke generation rate of 0.027 gm (smoke)/gm(burnt fuel) of which 20 percent is "carbonaceous" or "graphitic" soot, with a mean size of 0.1 micron. A similar set of values was applied for non-urban or "wild" fires. In principle, one should start computing the effects on the environment as soon as the smoke and soot emerge from the fires, particularly the thermal radiation balance. However, the early scene would likely be very chaotic, with irregularly-spaced fires, all at different stages of development, each producing very dense smoke plumes, small in relation to distance between fires. Since this stage would be very difficult to model on computers, the early investigators simply skipped ahead in time, perhaps one to four days, and assumed a spatial uniformity of the soot cloud over distances of 500 to 1000 km (300 - 600 miles) and extending from the surface to about 10 km (30,000 ft). This assumption allowed the modelers to adapt existing "climate" and "trajectory" models to evaluate the effect of the wind in redistributing the soot, and the effects of the soot on atmospheric temperatures. Thus, the modelers did leave a potentially serious gap by not calculating the behavior of the smoke from the initial burn time to widespread coverage, a few days later. The gap left open the question of how much soot would be removed or modified by atmospheric processes, especially those involving clouds and precipitation. There would be clouds and precipitation associated with urban fires, and the soot could be caught up in naturally-occurring clouds and precipitation. Even before the soot clouds merged to scales of 500 - 1000 km, there would be interactions with the atmosphere through heating and cooling effects.

Once the soot clouds have an appreciable size, their optical properties determine the immediate effect on the atmosphere. Combustion engineers[8] have conducted numerous laboratory experiments to determine the physical and chemical properties of soot, obtaining size distributions, shapes, and scattering and absorption coefficients. In addition, some measurement of the properties of soot in the free atmosphere have been made. Using these studies, the TTAPS group estimated the solar absorption coefficient of soot to be 2.0 m^2/g. This value is much lower than the 10 m^2/g determined for very pure soot, but allows for the contamination by oils and other combustion products that typically occur in uncontrolled fires with heterogeneous fuels. Knowing the absorption coefficients and the soot

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8. Donnet, J-B and Voet, A. (1976) *Carbon Black, Physics, Chemistry, and Elastomer Reinforcement*, Marcel Dekker, Inc., New York.

concentrations predicted by the models, the effect on the surface and upper air temperatures were computed on a day-to-day and week-to-week basis.

A useful gauge of the effect on sunlight at the surface is the "optical depth" of the soot cloud. With each unit increase in optical depth, the sunlight at the ground (overhead sun) decreases by a factor of 2.71 (the exponential "e"). The early studies all showed large areas of optical depths of 4 or greater, reducing sunlight to 2 percent of normal. As pointed out by Prof. Lindzen (Harvard U) at the Aleksandrov seminar at MIT, it would not matter whether the optical depth were estimated at 3 or 30, as in either case there would be virtually no sunlight at the ground, and the predicted temperature drop would be the same as long as the infrared computations were reasonably accurate. In fact, the models used for the studies shown in Table 2 had previously been calibrated using normal atmospheric temperatures, assuring that the infrared procedures were quite reasonable.

Perhaps the biggest differences among these early studies were due to their estimated soot removal rates. In the normal atmosphere, the rates vary from about 60 percent per day in the lowest kilometer (3,000 ft) to about 8 percent per day near 10 km (30,000 ft). In the atmosphere following a nuclear exchange, the land surfaces would be very cold and air above 5 km (16,000 - 18,000 ft) very warm, conditions likely to reduce precipitation, so that "washout" of the soot would be slower than normal. Following the minimum surface temperatures which the TTAPS model predicted two weeks after the fires, a "normal" washout had reduced soot concentrations sufficiently such that there was a 50 percent return to normal surface temperatures two months later. Using a "damped" scavenging (due to lower cloud tops and reduced precipitation), MacCracken found the minimum surface temperatures were a little lower, and both the times to minimum temperature and to a half-way recovery were twice as long as with the "normal" washout.

Considering what went into these early computations of environmental effect, there should be no surprise that the results were so similar. The investigators used either identical or similar estimates of soot production, size distribution, absorption coefficient, and all skipped the early stage of smoke-plume rise and spread. The models differed in the way they forecast large-scale dispersion and removal of soot, but since all models predicted optical depths greater than 3 for up to 2 weeks, they inevitably produced similar maximum surface cooling for mid-continents. While the studies of TTAPS, MacCracken, and Aleksandrov did quantify temperature effects postulated by Crutzen and Birks, of necessity, shortcuts and approximations were used. The challenge that remained for future researchers was to obtain better data, use better models, with more complete physical processes, and make better and more reliable computations of the environmental effects.

3. SOOT: PROPERTIES AND PRODUCTION

Without question, determining realistic climatic effects of a major nuclear exchange represents about the most challenging task ever attempted by atmospheric scientists. The complete solution is truly interdisciplinary and requires knowledge of the military/political factors that would affect the selected targeting scenarios and weapon yield, the microphysics of formation and evolution of soot particles, the dispersion of the soot on scales from a few meters to thousands of kilometers, and the interaction of the soot with the atmosphere through thermal and chemical effects. The impacts on AF operations, other survivors, noncombatants, plant and animal life, are even beyond the atmospheric effects. The early investigators established a scientifically legitimate basis for concern. Their work appeared reasonable, and since all studies yielded quite large optical depths, the overall picture would be significantly changed only if there were some sizable miscalculations in the complex chain of events. Considering the large number of assumptions and approximations that had to be made, sizable miscalculations must be considered a distinct possibility. A number of new studies were conducted during the two years that followed the early studies, all designed to reduce some of the uncertainties. As will be obvious later, many more such studies will still be needed to significantly reduce the uncertainties. To better appreciate the contributions of the newer studies and what is still left undone, we must take a closer look at the physical factors involved, particularly those that were crudely (if at all) considered in the early studies.

The physics problems begin with determining how much soot is generated, of what size, and to what altitude it rises, as the conflagrations take place. Realistic, large-scale field experiments are, of course, entirely out of the question. As an alternative, one has to resort to "models" (usually computer models) that may be difficult to calibrate or verify. To follow this modeling tack, one begins with estimates of available urban and natural fuels such as construction wood, plastics, asphalt, oil, brush, and trees, then determines the percentage that could burn, the smoke generated by each material, and then the soot and carbon content and size distribution. To obtain the vertical distribution of the smoke plume rise, the models require estimates of the heat and moisture released by the fires as they develop and knowledge of ambient atmospheric conditions.

In the following sections we discuss the problems of soot generation, removal, and distribution, which serve as inputs to the larger-scale models. We discuss these estimates by referring to very simple atmospheric models to put the smoke production estimates into perspective. We summarize results from more sophisticated models in later chapters. The important issues in describing smoke and "soot" (or elemental carbon) production are how much will be produced, what its properties will be, and how it will be distributed, in the horizontal and in the vertical. We discuss these questions in the following section.

There are many uncertainties in estimating the total amount of soot that would be produced worldwide in massive fires after a major nuclear exchange, and many more uncertainties in the optical (light) extinction properties this soot would have. To illustrate the effects of these uncertainties, we use a simple zero-dimensional model ("box model") of the atmosphere together with a simple mathematical (exponential) model of light extinction. We are assuming, in using the simple atmospheric model (for purposes of demonstration), that the soot introduced into the atmosphere is immediately mixed throughout the volume. Thus, the concentration of soot is uniform everywhere in the "box," which includes the depth of the atmosphere over some fraction of the earth's Northern Hemisphere.

The exponential model of radiation extinction is:

$$I/I_0 = e^{-\tau} \tag{1}$$

where

$$\tau = \sigma m/a \text{ "optical depth"} \tag{2}$$

I_0, I = incident, transmitted sunlight, respectively

σ = extinction coefficient (m^2/kg) m = total mass of soot {kg}

a = area over which soot is distributed {m^2}

Figure 1 shows that when $\tau = 2$, 86 percent of the sunlight is absorbed or reflected in the atmosphere by soot and does not reach the earth's surface. Thus there is little heating of the earth's surface by sunlight, and the surface cools. As τ increases beyond 2, there is little additional effect on the amount of sunlight reaching the surface, since most of the sunlight has already been absorbed when $\tau = 2$, that is, there is a "saturation effect" above $\tau = 2$. On the other hand, as τ decreases below 2 conditions improve rapidly, especially below $\tau = 1$. Therefore, we are interested in describing how τ depends on the total mass of smoke produced and in defining conditions when τ exceeds 2 or when τ is decidedly less than 2.

As shown in Eq. (2), τ is proportional to the mass of smoke produced times the extinction coefficient of the soot, which is a measure of the optical properties of the soot. The area, a, will be taken to be constant in the simple box model calculations, and equal to 1/2 the area of the Northern Hemisphere (or about $1.3 \times 10^8 km^2$). In the following subsections, we discuss the estimates of total soot emission and soot optical properties.

3.1 Soot Emission Estimates.

The total amount of soot produced depends upon the amount and type of fuel burned. A conceptual summary of the steps involved in estimating total soot emission is shown in Figure 2. The steps illustrated, which are described in greater detail below, are as follows. The total amount of fuel available for burning in the combatant nations includes wood and petroleum products, etc., used for construction or kept in storage. The fraction ignited in flaming combustion depends on a variety of considerations, including height of the nuclear detonation, amount of heat necessary to make materials burn, local topography at each target, etc. The fraction of material that turns to smoke - the "smoke emission factor" - is different for each material, and relies on combustion behavior. The elemental carbon fraction of the smoke, which depends upon factors similar to the smoke emission factor, is important in determining the optical absorption properties of the soot. Not all studies have followed each of these steps explicitly.

Total fuel consumed and total smoke produced are both strongly scenario-dependent. For example, (1) petroleum products produce soot more efficiently than wood products, and (2) fuels are more strongly concentrated in urban areas than in non-urban areas. Thus total smoke production depends upon urban vs non-urban targeting. These variations will be discussed further later.

3.2 Urban Fires.

Two basic approaches have been used to estimate the total amount of material likely to be burned in cities. We shall refer to the first, used in the NRC report (1985)[5], as the *area-exposed* method. Here we calculate the total urban area likely to be ignited in a nuclear exchange, determine a mean combustible loading per unit of urban area, and finally assume the fraction of this material that

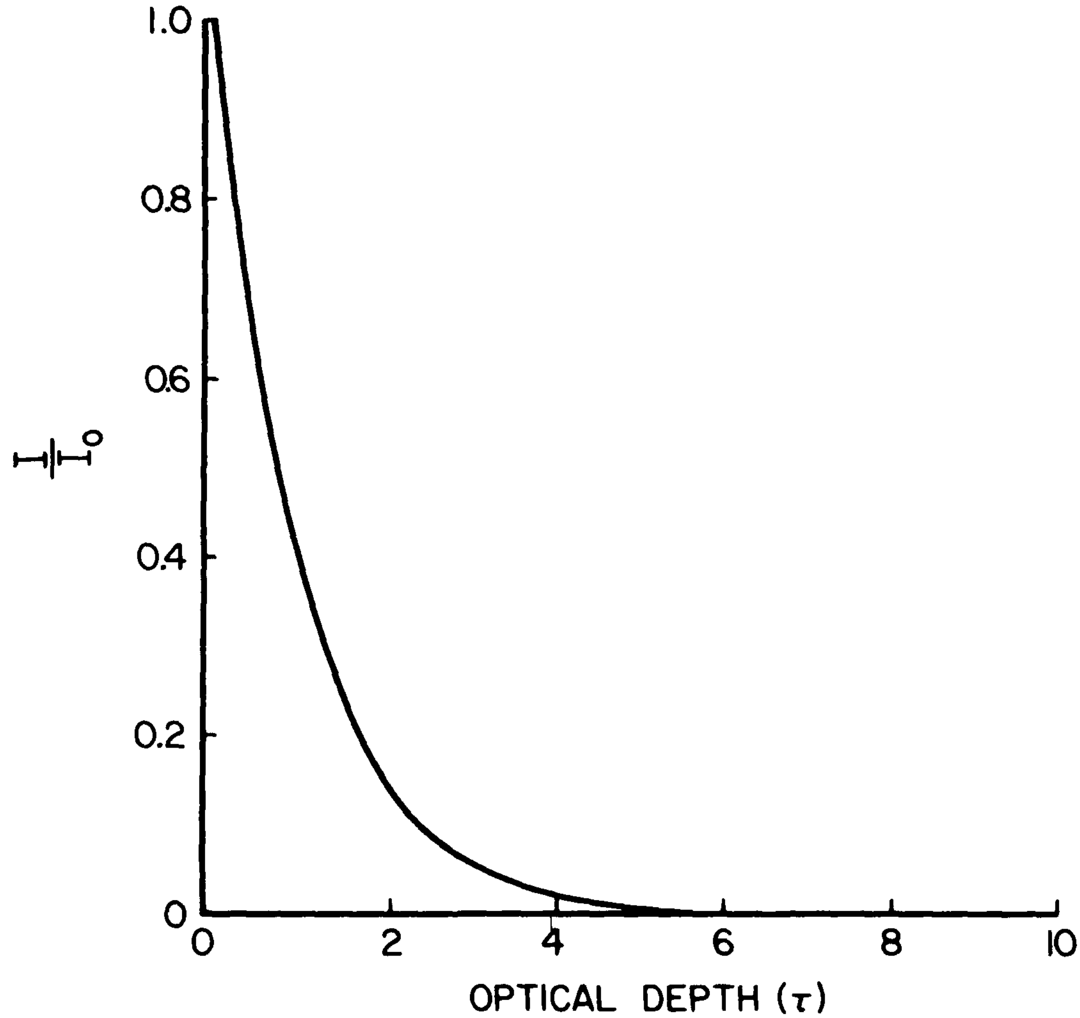

Figure 1. Fraction of Light Transmitted vs. Optical Depth

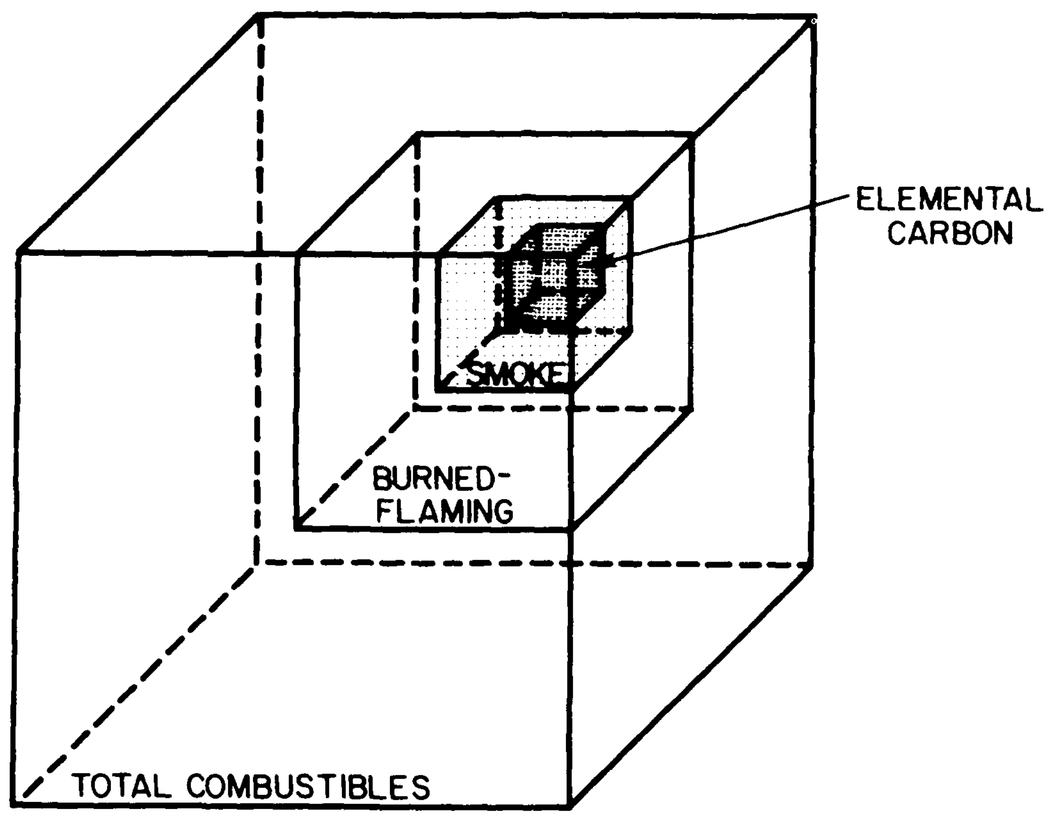

Figure 2. Factors in Production of Soot

would actually burn to produce smoke. The second or *inventory* approach, was used by Crutzen, Galbally, and Bruhl[9] (1984, referred to here and in several other sources, as CGB) and further interpreted by Pittock *et al.*, (or "SCOPE", 1986)[7]. These authors determined global inventories of combustible materials, and then determined the fraction of these global inventories that would likely be burned in a nuclear exchange. The two approaches thus followed the basic reasoning outlined in Figure 3, but differed in the interpretation of "total fuel available." In the first approach, this quantity represents the amount in all the warring nations subject to sufficiently intense heat for ignition, while in the second it represents the total inventory in developed nations. Both studies then went on to estimate the total amount of smoke produced and the appropriate light absorption and extinction coefficients. These quantities then imply values of optical depth for an assumed area over which the smoke is distributed. In the following subsections, we present estimates of these quantities by each of these two approaches (NRC Baseline and CGB) and calculate the implied optical depth for each, assuming that the smoke is distributed over half the Northern Hemisphere. We then present results of several recent studies that have performed more detailed analyses of urban fuel loading and firespread modeling of actual cities, and estimates of smoke emission factors and optical extinction coefficients. Finally, we consider how the uncertainties in these studies affect optical depth calculations.

3.2.1 NRC: AREA-EXPOSED APPROACH

In determining the total urban area subject to ignition in a nuclear exchange, the NRC (1985) assumed that 3,500 effective warheads with a total yield of 1,500 Mt would hit urban targets as air bursts. They assumed that the ignition zone would be defined by a conservative fire heat-flux value of 20 cal/cm^2 and that no fire spread would occur beyond this zone; they estimated an average burn area of 250 km^2/Mt from this. To determine the total area affected, they further assumed that 1/3 of the ignition zone area would overlap, leaving an effective "fire-starting yield" of 1,000 Mt. Thus the total area affected would be 250,000 km^2, which is equivalent to about half of the urban area in NATO and Warsaw Pact countries. Assuming a mean urban/suburban mass loading of 40 kg/m^2, the total mass susceptible to burning is 10^{16}g or 10,000 Tg.* Within this burn area, 75 percent or 7,500 Tg of the material was assumed to be ignited. CGB also performed this kind of analysis, and obtained 5,000 Tg of material burned. These estimates are sensitive to several factors that are very uncertain; for example, some other studies find that the assumed mean mass loading is too high.

The NRC assumed for their baseline case that the fuel would be 2/3 wood and other cellulosic material, and 1/3 petroleum and petroleum products. They adopted smoke emission factors (that is, the ratio of the mass of smoke produced to the mass of material burned) of 3 percent for the wood products and 6 percent for the petroleum products, which gives a weighted average of 4 percent for all materials. Thus 7,500 Tg of fuel would produce 300 Tg of smoke, of which 20 percent (or 60 Tg) was hypothesized to be elemental carbon. The NRC applied a factor of 50 percent to account for dry and wet atmospheric removal or scavenging processes (which will be further described in a later section), and

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9. Crutzen, P.M., Galbally, I.G., and Bruhl, C. (1984) Atmospheric effects from post-nuclear fires. *Climatic Change* 6:323-364.

* 1 Tg (teragram) = 10^{12}g is equivalent to a megaton (Mt) (million metric tons) of mass, and a metric ton is ~10 percent larger than an English ton.

LOS ALAMOS VERSION
CCM (MALONE, ET AL)
DAYS 15-20
UNITS: 10^{-9} GM/GM

NCAR VERSION
CCM (THOMPSON)
DAY 20
UNITS: 10^{-8} GM/GM

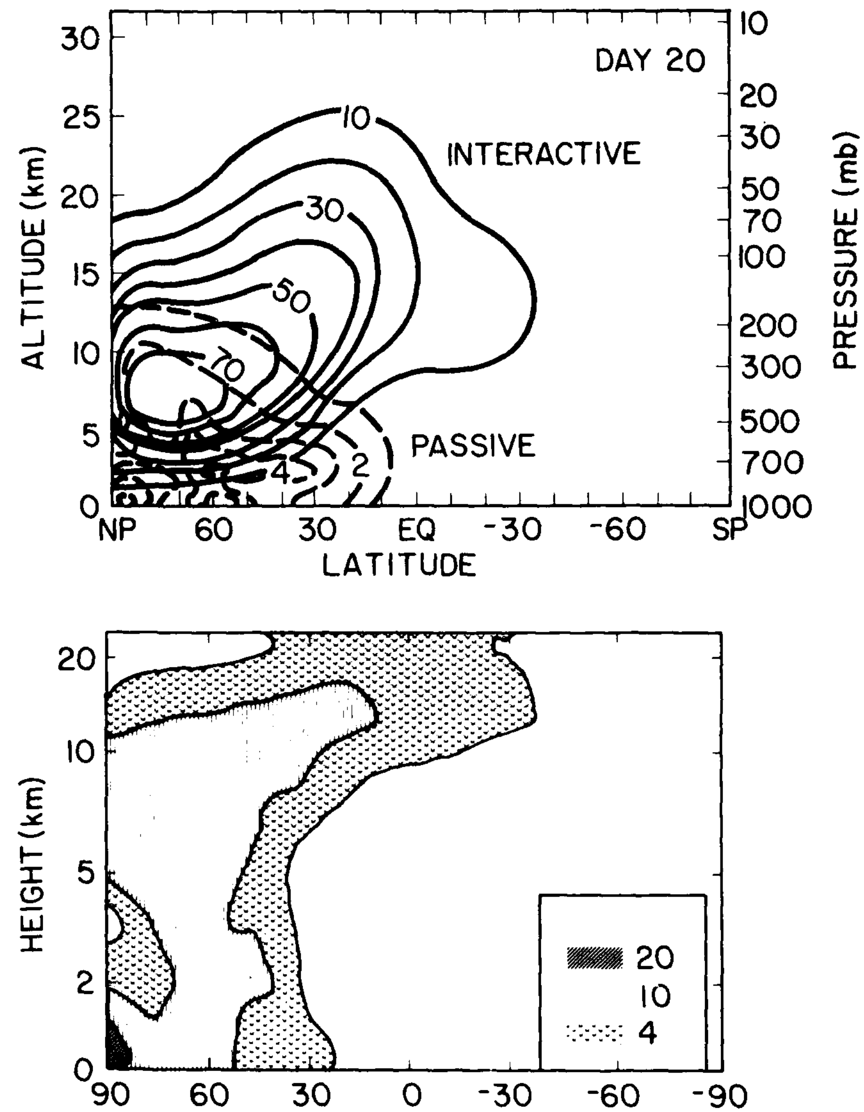

Figure 3. N-S Cross-Section of Smoke Concentration - July Case

adopted an optical extinction coefficient of 5.5 m^2/g for their baseline case. Distributed over half the Northern Hemisphere, this implies an optical depth of over 6, using Eq. (3). This value differs from the NRC's published baseline value of 4 because they included 30 Tg (no scavenging) of forest and wildland smoke, and their calculations assumed distribution over the entire Northern Hemisphere.

3.2.2 CGB: INVENTORY APPROACH

In this approach, CGB compiled inventories of major combustibles based on annual production rates, assumed lifetimes of materials, and figures provided by professional agencies. They estimated that 13,000 Tg of construction wood exists in the developed nations, 6,000 Tg of paper and other wood products (implied), 500 Tg of polymeric (plastic) materials, and 3,000 Tg ("worldwide") of petroleum and petroleum products, including asphalt. Assuming that 70 percent of the population of the developed countries live in cities and 30 percent of the cities burn, a factor of 0.21 is applied to each of these inventory quantities to determine total amount burned. A further factor of 50 percent is applied to the 4,000 Tg of wood and wood products, on the assumption that half of these fuels would burn in smoldering combustion, which does not produce black soot. Thus, CGB determined that 2,000 Tg of wood and wood products, and 700 Tg of oil, petroleum products, and polymeric materials would burn in flaming combustion. The advantage of treating wood products and petroleum products separately is that each has different burning characteristics (for example, smoke emission factors) and produces smoke with different optical absorption properties.

CGB recommended mean smoke emission factors of 1.5 percent for wood and 7 percent for petroleum. This would produce 80 Tg of soot, including 30 Tg from wood, which was hypothesized to contain 1/3 (or 10 Tg) of elemental carbon, and 50 Tg from petroleum products, which was hypothesized to contain 70 percent (or 35 Tg) of carbon. Assuming 1/3 removal by scavenging processes, and using optical extinction coefficients of 6.8 m^2/g for wood smoke and 10.5 m^2/g for petroleum smoke, the implied optical depth over half the Northern Hemisphere is 4.

3.2.3 RECENT STUDIES

Both NRC and CGB predict optical depths well within the "saturation range" of the simple extinction model in Eq. (3). It is interesting that even though the NRC estimates of material burned and smoke produced were much higher than CGB's, the ultimate implied optical depths are only 50 percent higher. This is because CGB assumed a lower initial scavenging factor and higher optical extinction coefficients. These comparisons are shown in Table 3. What this suggests is that there is considerable uncertainty in all of these quantities. In the following section, we describe the uncertainties, discuss how the uncertainties affect the optical-depth calculations, and seek to estimate more representative values for some factors. The analysis is summarized in Table 4. A similar analysis was recently accomplished by Penner.[10]

There are two important areas where previous estimates could be improved. The first would be to provide more detailed estimates of total amount of material available for burning, and the second, to

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10. Penner, J.E. (1986) Progress in developing the smoke source term for "nuclear winter" studies: Major uncertainties, *Nature* **324**:222-226.

Table 3. Total Combustible Table: NATO/W.P. Cities

[ ] = implied

	NRC Baseline	CGB-2/SCOPE	Bing (1986)
Total (Tg)	[20,000]	[20,000[1]]	7,700
Wood			6,400
Petroleum			1,330
(Primary/Secondary)			(480/850)
Burned-flaming, total (Tg)	7,500	2,700	-
Wood	5,000	2,000	
Petroleum	2,500	700	
Emission Factor	0.04(ave)	-	-
Wood	0.03	0.015	
Petroleum	0.06	0.070	
Smoke Produced (Tg)	300	80	-
Wood	150	30	
Petroleum	150	50	
EC (Tg)(percent of smoke)	60 (20 percent)	45	-
Wood		10 (33 percent)	
Petroleum		35 (70 percent)	
Extinction Coeff. (m^2/g)	5.5	-	-
Wood		6.8	
Petroleum		10.5	
Implied Optical Depth[2]	13	6	-

[1]As estimated by Bing (1986)

[2]Based on distribution over 50 percent of the Northern Hemisphere

obtain better estimates of fuel loading and probable fire behavior in some real cities. Toward the first goal, Bing[11] reviewed available literature on characteristics of housing and nonresidential buildings in the U.S., U.S.S.R., and Europe, as well as references on petroleum production, consumption, and storage. He found that the total amount of combustible material in urban and suburban centers of NATO and Warsaw Pact countries was 7,700 Tg, including nearly 6,400 Tg of wood and paper in buildings and 1,300 Tg of petroleum products. Since the NRC's 10,000 Tg was assumed to come from burning an area equivalent to half the urban area of the combatant nations (thus, implying a total combustible mass of 20,000 Tg), Bing's estimate is 30 to 40 percent or so of the loading implied in the other studies. In CGB's case, the implied total combustible mass was over 20,000 Tg for all developed countries, but this must be reduced by a factor of 0.87, representing the ratio of the populations of

11. Bing, G. (1986) *Estimates of total combustible material in NATO and Warsaw Pact countries*, UCRL-93192, Lawrence Livermore National Laboratory, Livermore, CA 94550.

TABLE 4. Smoke Production and Optical Depth: Low, median, and high values using Bing's estimates of urban fuel

	Median				Low				High			
	Wood	2-oil	1-oil	Tot	Wood	2-oil	1-oil	Tot	Wood	2-oil	1-oil	Tot
URBAN Total (Tg) Bing	6,400	850	480	7,700	6,400	850	480	7,700	6,400	850	480	7.700
Percent Burned Flaming	20	20	75		10	10	0		40	40	100	
Smoke Emission Factor (Percent)	2	7	7		1	2	2		6	10	10	
Smoke Production (Tg)	26	12	25	63	6	2	0	8	154	34	48	236
Extinction Coeff (m^2/g)	5.5	9.5	9.5		4	5	5		7.5	13.5	13.5	
Optical Depth	1.1	0.9	1.8	4	0.2	0.1	0	0.3	8.9	3.5	5.0	17
RURAL Smoke (Tg)	6				0.8				24			
Opt Dep. (σ)	0.3 (5.5)				0.02(4)				1.4(7.5)			
TOTAL Smoke (Tg)				69				8				260
Opt Depth				4				0.3				19

NATO/Warsaw Pact countries to the "developed world."[10] Thus Bing's estimate of total available fuel in NATO and Warsaw Pact cities indicates that the NRC (1985) and CGB estimates of fuel consumed are too high, and his estimate would place an upper bound of 7,700 Tg (6,400 Tg of wood products and 1,300 Tg of petroleum products) on the amount burned; the actual amount burned would of course be some fraction of this.

After determining available fuel, the next step is to prescribe the burning and release of combustion products for each structure (or group of structures) ignited. The model must account for fire development and spread by thermal radiation and "firebrands" (falling, burning debris). Laboratory measurements of heat, smoke, and soot released by different types of burning material have been made, and variations occur due to ventilation rate, inflow temperature, moisture content, and other factors through processes that are not fully understood. There are very little data on combustion products from a composite burning structure, such as a house, office building, or factory. The assumption has been made that combustion products can be easily determined from the laboratory tests, but transferring laboratory test results to a real burning structure will almost certainly produce surprises. A further complication is a positive feedback between ventilation rate and burn rate. A fire will develop its own inflow wind pattern associated with the rising plume over the fires, so that the faster the fire burns, the faster the inflow, and the faster the inflow, the faster the fire burns. The relation between ventilation and burn rate must be more accurately determined for different classes of materials and structures.

Reitter *et al.*, (1985[12]; this work is also summarized in Appendix 3A of Pittock *et al.*, 1986) used a numerical firespread model to investigate the hypothetical burning behavior of three cities. The model was divided into gridded squares or tracts, in which fuel loading and other important parameters could be independently specified for each tract. They simulated three metropolitan areas: a hypothetical uniform city in which fuel was evenly distributed over the entire urban and suburban area, and the cities of San Jose, California and Detroit, Michigan, using fuel distribution data gathered in the late 1960's. The uniform city case tested the model sensitivity to many of the quantities that needed to be specified. They found that the model was highly sensitive to many input quantities, including wind speed, atmospheric visibility, frequency of secondary fire starts, building density, and assumed window sizes - the last, because the intensity and duration of radiation penetrating to the interior of a building is an important mechanism for firespread. The extent and rate of firespread is ultimately limited by a second mechanism, the windborne transport of flaming debris or "firebrands," or, more specifically, by the distance such debris travels before starting new fires.

The study also found that the uniform city poorly represented the quantitative burning behavior of actual cities. The uniform city burned faster and hotter than the real cities, largely because of the effects of non-uniform fuel distribution (which produce lower mean fuel loadings) and the occurrence of fire breaks and bodies of water in and near the real cities. Other significant differences are that the real cities show strong dependence on the exact manner in which the war unfolds - that is, dependence on the location of "ground zero." For example, if the burst occurred directly over the city center, then the so-called "debris region" of the blast, where it is assumed there would be no flaming combustion, is the area of highest fuel loading. While the behavior of such "rubble fires" is another major inadequacy in our knowledge of fire phenomena, we can say that only a fraction of the fuel will burn to produce soot in this debris region.

The studies from the late 1960's of fuel distributions in real cities found a fuel loading of 7 kg m^{-2} for San Jose and 14 kg m^{-2} for Detroit, averaged over the occupied tracts. When vacant tracts were included in the calculation, these averages became 4 and 12 kg m^{-2}, respectively. If these values are representative of conditions in cities today, then it appears that the value of 40 kg m^{-2} used in earlier studies may be high by a factor of 3 or more. Reitter *et al.*,[12] stressed the inadequacy of our knowledge of physical processes that determine the behavior of large urban fires. Their results further show, as illustrated above, that treating the burning behavior in an average sense, hoping that this averaging will smooth over many of the uncertainties to produce useful estimates, can be deceiving.

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12. Reitter, T.A., S.-W. Kang, and Takata, A.N. (1985) *Toward quantifying the source term for predicting global climatic effects of nuclear war: Applications of urban fire codes*, UCRL-53647, Lawrence Livermore National Laboratory, Livermore, CA 94550.

3.2.4. ESTIMATING COMBUSTION FACTORS

We have attempted to estimate representative values of several factors deemed important in the combustion process, as shown in Table 4. These factors include (1) the *fraction* of urban combustibles which would burn in flaming combustion, (2) the smoke *emission factor*, (3) the percent of *elemental carbon* in the smoke aerosol, and (4) the *extinction coefficient* or *cross section* of the smoke. In each case we have included a "median" value and representative, not extreme, high and low values.

3.2.4.1 Fraction Burned

Table 4 shows the fraction of urban combustibles that would burn in flaming combustion. For wood, wood products, petroleum products (plastics, roofing asphalt, etc.), and secondary petroleum reserves (that is, distributed throughout urban areas in gas stations, vehicle fuel tanks, etc.), we adopted a median value of 20 percent, based on the following reasoning. The NRC estimated that about half the urban area of the warring nations would be subject to ignition. Of the material ignited, Reitter *et al*[12] estimated that about 50 percent might burn in flaming combustion, although they caution: This is clearly an average value. A higher number would be expected for wooden buildings, a lower one for masonry buildings, especially if their combustible contents were likely to be inaccessible to fire following building collapse.

The remaining 25 percent is reduced to 20 percent to account for a reduction of burning in the debris region. The small value of 10 percent or half the median value, could be arrived at by assuming, for example, that 60 percent of the affected area was in the debris region and no flaming combustion occurs there. For the large value, we assume that with the above processes tending to reduce the fraction, 50 percent is probably too high, and adopt a value of twice the median value, or 40 percent. For reference, Penner[10] used a value of 25 percent for this fraction for all cases.

For the fraction of primary petroleum reserves (refineries, tank farms, etc.), we assume a scenario which avoids these targets for our small value, a scenario in which all these targets are hit for our large value, and a scenario in which most (75 percent) of these targets are hit for our median value. Penner[10] has also considered separate scenarios for targeting primary petroleum stocks and for avoiding them.

3.2.4.2 Smoke Emission Factors

The smoke emission factor is the ratio of the mass of smoke produced to mass of fuel burned. The NRC (1985) report used 3 percent for cellulosic materials (wood, wood products including paper) and 6 percent for petroleum products, which resulted in a weighted average of 4 percent for all materials. CGB tabulated smoke emission factors which appeared in the literature for a variety of substances, then determined representative "mean" values for each. These mean values were 1.5 percent for wood, 7 percent for petroleum, 5 percent for plastics, and 6 percent for vegetation and forests. Pittock *et al.* reproduced these tables, noting that there is "at least a factor of 2 uncertainty in each of the categories" and that emission factors increase with larger fires. CGB also comment on the relationship between large fires and small confined fires: "forest fires produce about 5 times more aerosol than the burning of wood in fireplaces and laboratory tests," largely because of increased smoldering and decreased O_2 availability in the smaller fires. They also note that "the effect of the environments into which the fire volatiles are released is probably more important than the nature of the combustibles" in determining the emission factor.

Based on values presented in CGB's tabulations, we have adopted 2 percent as our median value for the emission factor for wood and wood products including paper (Table 4), with small and large values of 1 percent and 6 percent, respectively. The larger value was chosen from forest fire data to represent enhancement by large fires, as described above. The median value for petroleum and petroleum products of 7 percent is consistent with CGB's (7 percent) and NRC's (6 percent) values, while the small and large values of 2 and 10 percent are as cited by CGB and Penner.[10]

3.2.4.3 Elemental Carbon Percentages

The fraction of elemental carbon (EC, or "soot") in the smoke aerosol is important because the optical absorption properties of the smoke are related to this quantity, as discussed in Section 3.2.4.4. Like smoke emission, this fraction also depends heavily on the burning "environment." The NRC study estimates that 20 percent of the smoke produced in massive fires is elemental carbon. CGB tabulate EC fraction values along with the emission factors, and estimate probable "average" values. Their average for burning wood is 33 percent; petroleum, 70 percent; plastics, 80 percent; and vegetation and forests, 10 percent. These differences show that petroleum and plastics produce smoke that is richer in carbon, and thus more optically active.

3.2.4.4 Extinction Cross Section

The optical properties of the smoke are expressed in Eq. (2) as an extinction coefficient or "cross section," which is the sum of two quantities: an absorption cross section (σ_a) and a scattering cross section (σ_s). The NRC baseline value for σ_a is 2 m^2/g, and for σ_s, 3.5 m^2/g, giving an extinction cross section of 5.5 m^2/g. CGB indicate that for "fresh" soot, σ_a ranges between 5 and 20 m^2/g and σ_s between 3 and 4 m^2/g, but that these values decrease with age of the smoke and with decreasing EC fraction. The SCOPE study adopts the expression

$$\sigma_a = f_{EC} \cdot 10 \, m^2/g,$$

where f_{EC} is the EC fraction of the smoke, to reflect the dependence of σ_a on EC content, and a value of 3.5 m^2/g for σ_s. These imply σ_a values for wood of 0.8 to 4.0 m^2/g and for oil of 6.0 to 10.0 m^2/g. As a result, values of the total extinction cross section, σ, of 4.3 to 7.5 m^2/g for wood and 9.5 to 13.5 m^2/g for oil pertain. Penner and Porch[13] noted that the decrease in σ with age is due largely to the agglomeration of smaller particles into larger ones. Therefore, they found calculated ranges of the optical cross sections with and without coagulation as follows: σ_a for wood, 1.3 to 1.5 m^2/g, and for oil, 1.8 to 5.6 m^2/g; σ_s for wood, 2.7 to 5.1 m^2/g, and for oil, 2.2 to 3.9 m^2/g; these give σ for wood, 4.0 to 6.6 m^2/g, and for oil, 4.0 to 9.5 m^2/g (in each case the lower value is after coagulation).

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13. Penner, J.E. and Porch, W.M (1986) Coagulation in smoke plumes after a nuclear war, *Atmospheric Environment*, and UCRL-94359, Lawrence Livermore National Laboratory, Livermore, CA 94550.

From these values, we adopt median values of the extinction cross section of 5.5 m^2/g for wood and 9.5 m^2/g for oil. Our representative small values are 4 for wood and 5 for oil, and the large values, 7.5 for wood and 13.5 for oil. These values do not explicitly account for aging of the aerosol, although Penner and Porch's values with coagulation were considered in determining our low estimates.

3.2.5 URBAN EMISSIONS: OPTICAL DEPTH IMPLICATIONS

When we apply our high, low, and median estimates of "fraction burned in flaming combustion" and of smoke emission factors to Bing's values of total combustible loadings, we obtain estimates of smoke produced without scavenging, which we shall ignore for the moment. If we further apply the extinction coefficient estimates and assume smoke distribution over half of the Northern Hemisphere, we can obtain high, low, and median estimates of optical depth. These values, as shown in Table 4, are 4 for the median estimate, 0.3 for the low, and 17 for the high.

The total smoke production for the median case was 63 Tg, which is close to the value of 60 Tg that Berger[14] attributed to Bing, and is also close to CGB's estimate of 80 Tg. A major contributor to the total smoke production was the burning of primary petroleum stocks, in spite of the low total amount of available fuel. This is because a high percentage was assumed to burn in this scenario and the smoke emission factor was also high compared with that of wood. It is likely that the consumed amount of this class of combustible represents the major uncertainty for the median case, especially considering the high optical absorption properties of petroleum smoke. This conclusion agrees with CGB's assertion (referring to both primary and secondary petroleum stocks) that "this category contributes most to the soot production potential of a nuclear war, so that a detailed analysis is essential."

The low estimate of 8 Tg is even lower than that in Penner's[10] analysis (12 Tg) because we allowed the fraction consumed to drop to 10 percent, whereas she used 25 percent for all cases. Since these numbers are poorly established to begin with, we do not claim that this is a major improvement; however, for the purpose of setting reasonable bracketing values - as well as determining likely median values - of smoke production and optical depth, we feel that this approach is worthwhile. Our low estimate seems to be most sensitive to the small emission factor for petroleum fires and to the fact that no primary oil reserves were assumed to burn.

The high estimate of 236 Tg of smoke is low compared with the NRC's estimate of 300 Tg and Penner's high estimate of 388 Tg. The major reason that our value is low is because we based our calculations on Bing's work, which started with lower estimates of available fuel in the urban areas of the warring nations. Bing's careful estimates seemed to us to be the best available data at this time. The major uncertainty which leads to values as high as we found, was the high value for the emission factor for wood. Recall that this high value was adopted to account for an enhancement by large fires as described above. If such an enhancement were to occur with wooden combustibles in urban fires, smoke production could approach the large values of earlier studies, even given Bing's lower estimates of fuel loading. Lacking data, this point is speculative but it again points to the need for better data from large fires.

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14. Berger, A. (1986) Nuclear winter, or nuclear fall? *Eos* **67**(32):617-621.

3.3 Rural Fires

The calculations of combustion products from "wildfires" (forest, brush, and grassland fires) is also rather difficult. This type of fire would result from attacks on military targets (for example, missile silos) located in remote areas, and, in many cases, would be associated with near-surface detonations. Ideally, we should start with a worldwide census of naturally occurring surface fuels, their burn rates and combustion products. Unfortunately, only sparse data exist on typical fuel loads for different types of vegetation. For wildfires, the computation of soot generation is complicated by the sensitivity to surface moisture (mainly in the vegetation). During dry season or drought the fire ignition area is much larger and the burn can spread over areas many times larger than the initial ignition. In most areas, excessively dry periods are the exception rather than the rule, but they cannot be easily discounted. At any given time, some areas are likely to be quite dry and soot from the fires in the dry areas could easily exceed that from all the other areas. The data required to describe the combustion products from wildfires must include the sensitivity to moisture. There is a need for field tests that include simultaneous ignition over areas miles (or km) in size, as these may be more intense and heavier producers of soot than typical forest fires. The following section describes these effects in greater detail.

Many military targets are outside urban areas; thus, nuclear detonations at these targets could produce fires in nearby wildlands (forests and grasslands) and agricultural croplands. Neglecting grassland and cropland fires, both the NRC study and CGB considered, as a baseline, that 250,000 km^2 of forested land was ignited and 1,000 Tg of fuel was consumed in flaming combustion. CGB's smoke emission factor of 6 percent leads to 60 Tg of smoke produced, and NRC's 3 percent leads to 30 Tg.

A significant reduction in these estimates resulted from Small and Bush's[15] study, which pointed out that the majority of rural military targets were located in crop or grassland areas with low-density fuel loading and too little biomass to burn in most months, especially in the U.S. They considered 3,500 military targets in the U.S., U.S.S.R., and Europe, including missile silos and launchers, bases, and weapon-storage sites, and found that only 14 percent of the targets (mostly in the U.S.S.R.) were in forested land. Accounting for non-burning cropland, 35 percent of the area actually burned was forested, and forest fires accounted for 50 percent or more of the rural smoke produced because of higher fuel loadings.

Small and Bush[15] found very small smoke production (less than 1 Tg) for exchanges that took place in the winter months of November through March. This figure increases to ~3 Tg during July and August. Thus, compared with urban smoke emission estimates, their findings indicate that smoke amounts from rural fires are negligible, except for the low urban estimate (8 Tg) to which this summertime rural estimate would make an increase of over 10 percent.

Pittock *et al.*[7] considered Small and Bush's estimates to be a likely lower bound to actual rural-smoke production. They felt that firespread may be more important (especially in summer), and fires could ultimately consume two or three times more biomass (especially in temporally-spaced multiburst scenarios where earlier detonations could dry out fuels for later detonations), than Small and Bush assumed. Using these considerations along with different estimates of fuel loading, a study

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15. Small, R.D. and Bush, B.W. (1985) Smoke production from multiple nuclear explosions in non-urban areas, *Science* **229**:465-469.

cited by Pittock *et al.* found that smoke emissions could be "5 to 10 times greater than those derived by Small and Bush."

Still, Small and Bush's basic point - that a low percentage of rural military targets are actually in forests - stands, indicating that most rural detonations would occur in areas where biomass loading is small and seasonal. There are two important exceptions. First, tactical nuclear weapons that are used in forested battlefields were not considered. Being completely scenario dependent, their impact is very difficult to assess, but one could speculate that they could produce a significant addition to wildland smoke. Second, if drought conditions existed in the vicinity of some forested targets, a few detonations could trigger extensive forest fires. Significant increases in wildland smoke emissions, possibly comparable to urban contributions, could occur.

Setting these exceptions aside, we therefore assume that forests would add about 10 percent to the smoke emissions and optical depths calculated for the small, median, and large estimates for urban fires. *This increase recognizes* that the major contributor to smoke is likely to be urban emissions and does not account for seasonality. As shown in Table 4, this results in a median value of 6 Tg, with low and high estimates of 1 and 24 Tg respectively. The optical depth estimate remains at 4 and 0.3 for the median and low cases, and becomes 19 for the high case. Recall that our estimates so far have ignored scavenging.

3.4 Scavenging: Dry and Wet Removal Processes.

From the time the tiniest particles of soot are emerging from a fire, there are atmospheric processes acting that remove them from the atmosphere and ultimately deposit the material on the earth's surface. These microphysical processes are not easy to compute because they involve many different types and sizes of particle, and are strongly affected by water vapor, which is highly variable (and difficult to predict). The removal processes are indeed critical to the "nuclear winter" scenario, for should they be found to be very strong during the first week after the fires, there would be little soot remaining to block solar radiation and reduce surface temperatures. On the other hand, severe conditions would continue for many months, perhaps years if removal rates are very weak.

In the previous section, we estimated the amount of smoke produced in post-nuclear-attack urban and non-urban fires, ignoring the effects of atmospheric removal or "scavenging." We now discuss these processes. They include dry processes such as gravitational settling and moist processes such as rainout. The SCOPE study[7] contains an informative discussion of dry and moist scavenging, part of which is summarized below.

3.4.1 DRY SCAVENGING.

A number of processes can remove smoke particles without incorporating them into atmospheric hydrometeors (such as raindrops, snowflakes, or hail particles). Chemical transformation of the soot can be induced by reactive atmospheric gases such as ozone or by sunlight. Particles can diffuse to the earth's surface and adhere. But the dominant dry mechanism is the aggregation of smaller particles into larger ones, which then settle out by gravity. For smaller particles (less than 1 μm), collisions leading to aggregation occur through Brownian motion. For larger particles, collisions are induced by gravity or by atmospheric motions, including winds and turbulence, acting on particles of different sizes. Presumably, particles of the same size move at the same velocity and thus do not collide. There is a size range between these two regimes in which neither mechanism is very effective. Particles accumulate in this size range, which extends from radii of 1 to a few μm.

To form soot, carbon initially condenses from the flame into spheroids of about 50-nm diameter, which then form into chains while still at high concentrations. If dilution of the soot cloud occurs rapidly, the chains may be relatively short (less than 1 μm), but if concentrations remain high for a time, the chains may grow to 10 μm or more. Chains may then stick together into larger agglomerates. These agglomerates, however, do not settle out as rapidly as their size might suggest, because of their "fluffy" structure (for example, their aerodynamic cross section is large in relation to their mass). Recent laboratory work has shown that if soot agglomerates are incorporated into water droplets which then evaporate, they collapse into more compact particles which can then settle more efficiently by gravity. As discussed below, these particles may also acquire a coating of soluble material.[7]

In the atmosphere, there is a drag resistance to fall related to the fall speed and particle size (area), such that most particles at any time are close to a balance between gravity and drag (often called "terminal velocity"). For the typical submicron-size soot particle, this turns out to be less than 60 m (200 ft) per *year*. At such slow fall speeds, particles are often considered to be suspended. Even if almost suspended, the particles all have different motions and from time-to-time collide and attach to form larger particles. Such collisions tend to result in a faster fall speed because the area causing drag increases more slowly than the mass, which is acted on by gravity. Also, there is less light scattering and absorption for the two merged particles than from the two before merging.* Since smoke plumes may contain a million soot particles per cubic inch (60,000/cm^3), one would think that collisions would be very frequent. However, if we expand everything by a factor of 25,000, the cubic inch is now 2,000 ft (600m) on a side; the soot particles are somewhat like black snowflakes, 1/4 inch (6mm) in size, floating generally downwards about 30 ft (10m) per minute, and typically about 15 ft (5m) apart. From this perspective, there is just too much space between particles and too slow a motion to have collisions occur very often. Theoretical calculations have been made, which even include effects of solar heating on individual particles, but the calculations need to be tested for atmospheric conditions.

The dry removal of smoke particles that would result from large urban fires is not well understood. Those studies that have been performed show that, while dry processes do seem to contribute to the removal of smoke, the contribution is likely to be small, compared with precipitation or wet scavenging.

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* Soot particles revealed by electron microscope often look like bunches of grapes , in which case coalescence between particles would increase fall speed and decrease optical effects. Sometimes particles have chain-like structures, in which case coalescence would not significantly change fall speed nor optical properties.

3.4.2 WET SCAVENGING

Enormous amounts of combustion products enter the atmosphere each day, and intolerable conditions would develop everywhere if they were not removed far more rapidly than by gravitational settling alone (even with some growth by collision). Deep rising and sinking motion in the atmosphere alternately produce water vapor saturation and then drying. During the saturation process, water-soluble, "cloud-condensation-nucleus" particles grow into cloud droplets in regions warmer than about -30°C. The far less-numerous ice nuclei (clay particles) grow into ice crystals at temperatures less than about -7°C. A variety of microphysical processes take place in the atmosphere; some are now sufficiently well known that some fairly sophisticated models which simulate the development of clouds and precipitation systems are being run. These include heat and water-vapor diffusion and collisions with and without capture. The largest precipitation particles (rain, snow, and drizzle) fall relatively rapidly, and usually reach the ground before evaporating. Thus, they are effective in removing particulates from the atmosphere. However, the process is not simply the gathering of every particle in a droplet's path on its trip to the ground. Most of the smallest particles are swept around by the airflow and not captured. Thus, the smallest particles are only removed through a complex series of steps, often involving the incorporation of these particles into tiny cloud droplets, and then the collection of these suspended cloud droplets by falling or "precipitating" raindrops or ice particles. Modeling these complex processes for a normal atmosphere is not straightforward, requiring a number of empirically derived constants and factors. These factors also might not be correct for an atmosphere with an unusual temperature structure and unusually large numbers of small nuclei. An added complication is that there are two broad classes of particles, "hydrophilic" or water soluble and "hydrophobic" or water repellent, each with different removal processes.

The atmosphere is rather efficient at removing particles of water-soluble substances; such particles act as nuclei during condensation in the formation of liquid-water droplets. These droplets can then be incorporated into raindrops or precipitating ice (for example, hail or snow) so that the particles are removed from the atmosphere.

Elemental carbon particles (especially fresh, pure ones) are insoluble, or more specifically, water repellent (hydrophobic). Thus, wet-removal processes are inefficient for pure carbon particles. As for dry coagulation, the capture of smoke particles by water droplets depends upon the size of the particle. Collisions with water droplets, involving particles with radii of less than 0.1 μm, occur through the Brownian motion of the particle. Particles with radii greater than 1 μm are large enough to be collected by a falling raindrop (smaller particles are carried around the drop by the air flow). Between these two size regimes (0.1 to 1.0 μm) is a region referred to as the "Greenfield gap" in which both of these important removal processes are very inefficient. However, there are mechanisms for the capture of particles of this size; for example, phoresis effects can draw particles into the drop because of kinetic-energy gradients of the molecules in the vicinity of the drop.

Thus, as with dry scavenging, it is difficult to remove insoluble particles from the atmosphere by wet-removal processes if their radii are between 0.1 and 1 μm. But, while fresh laboratory soot is highly insoluble, aging by atmospheric chemicals and sunlight can alter the solubility of the soot particles. In addition, those particles which have been through cloud droplets that have evaporated, acquire coatings of soluble materials. It is likely that such particles would be highly susceptible to wet removal when they subsequently pass into atmospheric storm systems. Of course, the issue of how well smoke generated in the laboratory resembles smoke that would be produced in large urban or refinery fires is also an open question. It is possible that even the initial smoke particles may not be totally insoluble.

3.4.3 EFFICIENCY OF PROMPT REMOVAL PROCESSES IN CLOUD

Radke[16] has noted that the smoke plumes of nearly all large fires are capped by cumulus clouds. We know that such clouds are capable of removing soot from the observation of "black rain" after the bombings of Hiroshima and Nagasaki. But from forest-fire smoke palls that were observed thousands of kilometers from their sources in North America, Siberia, Australia, and other places, we also know that significant fractions of the smoke emitted can escape such immediate removal. There are no direct measurements of how efficient such a cloud might be in the wet scavenging of soot.

Research to estimate wet scavenging, however, has been pursued using three-dimensional, numerical models of the cumulonimbus cloud that forms over a large fire. Cotton[17] and Tripoli (1985 personal communication) have performed simulations using a Denver, Colorado springtime sounding. Banta (1987), in work sponsored by the Nuclear Technology Division of the Air Force Weapons Laboratory, simulated cases using a standard atmosphere. Both studies used essentially the same model (discussed in the next section), and both assumed only Brownian and phoretic scavenging were important. In all cases, wet scavenging removed only approximately 2 percent or less of the total emitted soot. This indicates that prompt removal of soot particles that are less than a few microns in radius is negligible. If this is true, it implies that the "black rain" resulted from the washout of soot particles larger than a few μm radius, which can be collected by falling raindrops. These particles would have eventually been removed by dry gravitational settling.

In more recent simulations, Tripoli (1986 personal communication) has performed model runs in which he assumed that the soot aerosol was fully soluble. The maximum scavenging in this case was approximately 20 percent of the total soot emission. This is still a small fraction, considering that NRC adopted 50 percent and CGB 33 percent for prompt removal. The reason for the low value in the 3-D simulations is that the capture of soot by ice particles, which is probably inefficient, is neglected in the model. The simulated clouds have very strong updrafts (often 50 m s^{-1} or more), so that air is rapidly carried up to where temperatures are very cold and most of the precipitation* forms via ice processes. The updrafts carry ice particles rapidly up into the anvil of the cloud. At these high levels, much cloud material blows out from the top of the cloud before large, precipitating ice particles can form. The cloud particles then evaporate outside the cloud, releasing any previously-captured soot to the atmosphere. Thus, model results indicate that prompt scavenging in a fire plume is small to negligible.

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16. Radke, L.F. (1985) Outline of a research plan for field studies to improve assessments of the nuclear winter scenario, DASIAC SR-216, Working Record of Global Effects Program Meeting, 12-14 Feb 85, Santa Barbara, CA (Defense Nuclear Agency), pp 185-200.

17. Cotton, W.R. (1985) Atmospheric convection and nuclear winter, *American Scientist* **23**:225-280.

* "Precipitation" refers to water and ice particles in the atmosphere which have a fall speed with respect to the surrounding air, as opposed to "cloud water" or "cloud ice," which travel with air.

This is not, however, the full story on scavenging. Before the smoke plumes merge to form a more or less uniform pall of smoke over vast regions, scavenging on a number of intermediate horizontal spatial scales occurs, which is probably more effective than the immediate scavenging just discussed. These intermediate-scale processes will be discussed next.

3.4.4 INTERMEDIATE-SCALE ATMOSPHERIC SYSTEMS

In a conceptual sense, input to global-scale atmospheric models requires soot to be mixed throughout a grid volume that may be 5° latitude by 5° longitude in the horizontal, and at least a kilometer or so in the vertical. This assumes that individual soot plumes (as just described) merge, and soot concentrations become more or less uniform within the grid volumes. Before this happens though, precipitation from large mesoscale to small synoptic-scale weather systems will remove some fraction of the smoke. Such atmospheric systems, which measure up to a few thousand kilometers across, consist of vertical circulations that have a rising portion and a sinking portion. The rising branch invariably drives cloud systems which can scavenge pollutants. As pointed out by Banta,[18] it is somewhat ironic that atmospheric eddies that are responsible for the diffusion of soot are also the ones that remove the soot from the atmosphere. Thus the ultimate fate of the soot depends on whether the time scale of the mixing is less than the time scale of the removal.

We can divide "intermediate-scale" processes into two groups: those which naturally occur in the atmosphere even with no soot present, and those which would be induced by the inhomogeneity or "patchiness" of the soot pall. The former group consists of smaller systems like thunderstorm complexes and larger systems like cyclonic storms (low-pressure systems). These normal tropospheric circulations typically produce pollutant residence times of a few days to a week in the lower troposphere, increasing to about a month in the upper troposphere. It is questionable whether these weather systems would maintain their usual form in the presence of soot plumes, which could provide strong local-heating sources and disrupt normal circulation patterns. (This could be an important issue for the prediction of fallout patterns, since forecast wind fields based on data obtained before the strike could be rendered obsolete in 12 to 24 hours.)

The second group of systems are those which would be produced by local temperature gradients resulting from the patchiness of the smoke pall before the plumes merge. The SCOPE report discusses analogies to several kinds of atmospheric systems, such as "mesoscale convective complexes," which appear to be radiatively driven (Pittock *et al.*, pp 115ff.).[7] Temperature differences between regions where the plumes exist and where they do not (or even between regions where the smoke concentrations are low and where they are high) could generate intense circulations with dimensions similar to those of the plumes themselves. These circulations would have moist ascending branches which would lead to smoke scavenging. A simple numerical simulation indicating this behavior was recently reported by Golding *et al.*[19]

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18. Banta, R.M. (1985) Numerical cloud simulations: Vertical distribution of soot from a nuclear city fire, DASIAC SR-216, Working Record of Global Effects Program Meeting, 12-14 Feb 85, Santa Barbara, CA (Defense Nuclear Agency), pp 105-122.

19. Golding, B.W., Goldsmith, P., Machin, N.A., and Slingo, A. (1986) Importance of local mesoscale factors in any assessment of nuclear winter, *Nature* **319**, 23 Jan:301-303.

It is probable that intermediate-scale weather systems of both types would remove a significant fraction of the smoke, especially since it is likely that much of the soot would have already been "processed" through a cloud previously, and thus be more susceptible to removal than would fresh soot. Unfortunately, it is extremely difficult to estimate the fraction that would be removed by these mechanisms. Even though numerical models on this scale poorly represent moist precipitation processes (so that scavenging formulations in these models will be even less reliable and highly dependent on rather nonphysical assumptions), such modeling efforts should be pursued, since they will provide insight into the effects of inhomogeneous heating on atmospheric flow, and thus on the validity of forecasts.

The NRC adopted a prompt scavenging fraction of 50 percent, while CGB assumed 1/3 of the soot would be immediately removed from the fire plume. Neither explicitly accounted for intermediate-scale scavenging. We noted in the previous section that prompt removal was likely to be a considerably smaller percentage, but if we generalize the NRC's and CGB's estimates to include all scavenging processes before plume merger (that is, prompt plus intermediate scale), then their estimates are more reasonable. For our own estimates of atmospheric smoke loading and optical depths, we adopt the NRC's value of 50 percent for low, median, and high estimates, as being reasonable. The resulting optical depths are 0.2, 2, and 10, respectively.

Given the crudeness of this scavenging estimate, we must consider the important issue addressed in this section to have been the consideration of the likely dominance of intermediate-scale atmospheric circulations, generated by inhomogeneities or patchiness of the smoke pall, in the meteorology of the post-strike environment.

3.5 Vertical Distribution of Soot

Another important input to global-scale numerical models is the vertical distribution or profile of the soot. Many global-scale model results are sensitive to the initial soot injection profile.

When soot leaves the fire plume and remains in the lower half of the troposphere, it is more susceptible to subsequent moist removal over time periods ranging from a few days to about two weeks. On the other hand, when soot penetrates upward into the lower stratosphere, it is likely to remain aloft for several months. Thus it is of critical importance to determine how high smoke is injected from the initial fire plume and how the initial vertical profile of soot should be represented.

The NRC report lists a number of factors affecting plume rise, including the strength of the heat source, the stability as represented by the temperature profile, the moisture profile, the strength of the horizontal wind in the surrounding atmosphere, and the size of the burning region. To investigate the importance of these factors, cloud-scale numerical models* have been used in several studies.

Cotton[17] reported on a fire-plume simulation using an unstable Denver, Colorado springtime atmospheric sounding. He used a strong heat source (comparable to those experienced in firestorms in Germany during the Second World War) in the Colorado State University (CSU) Regional Atmospheric Modeling System 3-dimensional cloud model. It showed that a significant amount of soot could penetrate up into the lower stratosphere - in this case more than 40 percent of the total emission.

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* Properties of these models are discussed in 4.2.3

Under the sponsorship of the Nuclear Technology Division of the Air Force Weapons Laboratory, Banta and Barnes[20] and Banta (1987, also described in the SCOPE report) ran simulations using the AFGL Cloud Model, a version of the CSU model, to test the response of the smoke profile to ambient humidity. Using a standard-atmosphere temperature profile with about 50 percent relative humidity in the troposphere, Banta found that 20 percent of the emitted soot reached the stratosphere, thus showing the effects of the more stable temperature profile in limiting the upward transport of soot. In an identical run with no moisture, all but a small percent of the smoke remained in the lower troposphere, showing that the energy required to carry soot into the stratosphere came mostly from latent heat released during the condensation of ambient moisture in the capping cloud over the fire plume. These simulations confirm that the smoke goes higher in an unstable environment than in a stable environment, and it goes higher in a moist atmosphere than in a dry atmosphere.

Another important effect, the magnitude of the heat flux from the fire, also proved to have a significant impact on upward smoke transport according to simulations by Penner *et al.*,[21] and by Tripoli and Cotton (1985 personal communication, described in the SCOPE report). Using a standard-atmosphere sounding, Penner *et al.* found smoke injection into the upper troposphere (8 - 10 km) when they used an intense heat flux comparable to the value used by Cotton (1985). When they reduced the heat flux to about 15 percent of this value, almost all of the smoke was injected below 4 km, (that is, in the lower troposphere). Similarly, Tripoli and Cotton ran a case using 10 percent of the heat flux used in the Cotton[17] study, and again found most of the soot remained in the lower troposphere. With their unstable Denver sounding, however, they found occasional cumulus towers pushing upward into the middle and upper troposphere and depositing some soot there after 30 minutes of simulated time.

The higher heat flux values are those characteristic of firestorms, which are not frequent events. The lower values are probably more characteristic of conditions apt to be found should a modern city burn, considering the types and distributions of the available fuel, including fire breaks (Reitter *et al.*;[12] Kang, 1986 personal communication). Thus, the significance of the modeling results is that most of the soot would be injected at lower levels if we assume the lower heat flux values to be representative of most-probable urban fires. This would be especially true in the winter when the atmosphere is more stable and contains less water vapor. During summer, on the other hand, the atmosphere is more unstable and contains more moisture, so that soot from some of the fires could reach the lower stratosphere. A more comprehensive analysis of this has been carried out by Banta (1987) using climatologies of atmospheric stability indices stratified by season.

3.6 Summary - Soot Production.

The major purpose of this chapter has been to provide estimates of atmospheric loading, the optical properties, and the spatial distribution of soot that would be produced by post nuclear-strike

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20. Banta, R.M. and Barnes, A.A. (1985) Modeling of atmospheric moisture effects on a nuclear mass fire cloud, IAMAP Symposium on Climate Effects of Nuclear War, Joint Assembly IAMAP/IAPSO, Honolulu, HI, 5-16 Aug 85.

21. Penner, J.E., Haselman, L.C., and Edwards, L.L. (1985) Buoyant plume calculations, Paper No. 84-0459 for AIAA 23rd Aerospace Sciences Meeting, Reno, NV, 14-17 Jan 85.

fires. The steps in estimating soot production are summarized in Figure 2, and the estimates of soot production and properties (neglecting scavenging) are given in Table 4. Adopting a value of 50 percent to represent precipitation scavenging, the median value for optical depth was determined to be 2, which implies that 14 percent of incident sunlight would reach the earth's surface according to Eq. (1) and Figure 1. Representative low and high estimates of optical depths of 0.2 and 10, implying 82 percent and 0.004 percent transmission respectively, show that uncertainties in the median estimate produce rapid deterioration or rapid improvement in the amount of sunlight reaching the ground. We noted previously that increases in smoke which produce increases in optical depth beyond 2 or 3 produce only small absolute decreases in the amount of light reaching the ground. We should quickly note, however, that further increases in smoke will increase the *duration* of low-light effects at the earth's surface.

The optical depth estimates in this chapter have been only for illustration to show the effects of the uncertainties in the determination of physical parameters (such as, smoke emission factors, optical extinction coefficients, etc.). For one thing, the atmosphere would not exhibit immediate mixing to uniformity over half the northern hemisphere (or over any specified area). Thus the hypothesized model is rather contrived. In the following chapters, the use of more realistic large-scale atmospheric models will be reviewed. Initial smoke-loading estimates such as those presented above will be used as input to these larger-scale numerical models to investigate the time-dependent response of the atmosphere to smoke concentrations of these magnitudes.

4. ATMOSPHERIC MODELS

The macrophysical problem is to describe the (a) evolution of the soot clouds in three dimensions as the atmospheric wind systems disperse the material in all directions, and (b) the interaction of the soot with the atmosphere. Some excellent numerical (computer) models of the atmosphere have been developed, which are quite capable of computing the transport of soot over large distances. A vigorous treatment of the problem would require tracking each soot particle throughout its lifetime, constantly determining the thermal effects on the atmosphere. Since the number of particles is something like 10^{28}, this is not feasible for even the biggest computer. As a compromise, investigators have applied a number of different computer models of the atmosphere in their determinations of the soot spread and interaction. For almost 100 years, scientists have known the equations that predict the behavior of fluids such as the atmosphere. These equations turn out to be a series of interrelated differential equations, involving quantities such as winds, pressure, temperature, and moisture, and can only be solved step-by-step on a high-speed computer. To obtain a solution, the researcher breaks the atmosphere up into separate volumes, computes the changes in each parameter (such as wind or temperature) in each volume, determines how each volume affects its neighbor, and repeats the process for each time step. The models differ from each other in how the volumes are set up, how many parameters are predicted, and how the variables interact.

Scientists quickly realized that the nuclear-effects problem involved the continents and adjacent oceans of at least the Northern Hemisphere, so they turned to the "general circulation" or "climate" numerical models to provide quantitative answers. A general circulation or climate model is broadly defined as a set of mathematical relationships based on physical principles that describes the behavior of the atmosphere. The model must simulate many physical processes that occur over a wide range of space and time scales. Except for the simplest cases, fairly complex numerical techniques must be used in which the atmosphere is represented by discrete points, one for each "volume." The computations are most valid when the parameters vary smoothly from point to point, or, if not, the effects of inhomogeneities on the smooth or average condition can be specified. This latter procedure is sometimes called "sub-grid scale parameterization". The complexity of the model is usually determined by the goal of the project, such as numerical weather prediction, climate simulation, sensitivity studies, as well as by the available computer resources.

4.1 Limited-Dimension Models

These models can be classified in order of increasing complexity according to the number of spatial dimensions. The simplest of the models is the zero-dimensional energy-balance model. In this case, the entire atmosphere is represented by one point and the model consists of a single equation representing the balance of incoming solar radiation and outgoing longwave (IR) radiation. The only information that such a model can provide is a representative value of the temperature of the atmosphere for some planet such as the earth.

The next level of complexity is the one-dimensional (1-D) model, commonly referred to as a "radiative-convective-equilibrium" model. This is the type of model used in the TTAPS study of 1983. In this case, the atmosphere is represented by a single vertical column, with anywhere from perhaps 3 to 50 separate points or layers, and no horizontal variations. The assumption is that any point represents globally-averaged conditions for that layer. Various parameterized physical processes such as radiation and convection can be included in the model. However, large-scale dynamical processes associated with the cyclones and anticyclones cannot be explicitly simulated in the model, since horizontal variations are not allowed. The major advantage of such models is that they are relatively inexpensive to run and, thus, can be used for sensitivity studies which cover a wide variety of conditions (for example, many targeting scenarios in the TTAPS study). However, the model results cannot be used to make any specific statements concerning changes in the atmospheric circulation and are limited to predicting the vertical distribution of temperature, soot, and other related quantities.

Next comes the two-dimensional (2-D) axisymmetric models such as the one used by MacCracken. In this type of model, the atmosphere is represented by a zonal average state, so that only the vertical and meridional (north-south) variations are explicitly treated. Thus, only the effects of east-west variability need be parameterized (which are usually less than north-south and vertical). The zonal mean circulations such as the important "Hadley Cell" (which results in rising motion in the tropics and sinking motion from 20 - 40 degrees north and south) can be explicitly predicted. As with the 1-D model, the large-scale dynamic circulations (cyclones and anticyclones) cannot be explicitly predicted, but since their activity is related to north-south and vertical temperature difference, it is easier to parameterize the effects of these circulations on the zonally-averaged quantities.

4.2 Three-Dimension Models

The most sophisticated of the models is the three-dimensional (3-D) general circulation model such as those developed and used at NCAR, Oregon State University, and several weather centrals. In such a model, all three spatial dimensions are treated explicitly, while the sub-grid scale processes are parameterized to various degrees of sophistication. At present, even the world's best computers cannot model the behavior of the entire atmosphere down to the effects on individual cities or river valleys. Thus a hierarchy of 3-D models has evolved, with different resolution models treating weather disturbances of different sizes, the different domain sizes. The models with the largest domain, the entire globe, are often called "general circulation" or "global" models. Models limited to a large continent or less are called "meso-scale", and particularly fine-resolution, small domain version is the "cloud" model.

4.2.1 GENERAL CIRCULATION MODELS

At present, general circulation models are used for two main purposes: a) short-to medium-range numerical weather prediction (one to ten-day forecasts), and b) climate simulation. In the former, the models typically have 9 to 18 layers in the vertical and a horizontal grid spacing of about 100 to 200 km (60 to 120 miles). The most elaborate models of today, such as those at the European Center for Medium-Range Weather Forecasts (ECMWF) and the National Meteorological Center (NMC) typically show forecast skill out to about six days (temperature and wind, less for precipitation). It should be noted that in numerical weather prediction, the goal is to accurately forecast the state of the atmosphere for as many days as possible. Accuracy has consistently been increased by major efforts to provide the model with detailed and accurate initial conditions (as well as including more factors related to precipitation) and finer spatial resolution. It is believed that the limit of predictability is somewhere in the range of two weeks to one month.

In the climate simulations, the goal is to model the long-term average state of the atmosphere and its response to various forcing functions, such as solar heating, carbon dioxide, shapes of continents, and so on. Typically, the model will run for long periods (several simulated months) and the results will be examined in terms of the average over some suitable time period of simulation and compared to averages with normal conditions. Usually the period studied is near the end of the run, in the hope that the model has reached some type of quasi-steady state and has effectively damped out any transient noise that might have arisen due to shocks or imbalances in the initial conditions. Rather simple initial conditions are usually chosen. To keep computation time to reasonable levels and yet attain many months of simulation, compromises are made on resolution and often only two to nine levels used, with a horizontal grid spacing of 600 to 1000 km (400 to 600 miles). The physical parameterizations also tend to be cruder than for the forecast models. While these climate general-circulation models can provide important information concerning the long-term average state of the atmosphere, one cannot look at conditions for a particular day and identify them with a weather forecast for that day.

Although these 3-D general circulation models are quite complex and compute many physical processes, they are limited by their spatial resolution, which is important for the nuclear-exchange problem. First, the horizontal resolution is too coarse to capture much of the effects of terrain such as hills, mountains, lakes and shoreline, so that the models are not very good at forecasting surface weather conditions for specific sites. To produce forecasts for specific sites, "limited-area" models covering a smaller area with two to three times better resolution are nested within the global model, and even then, the forecasts of surface wind, temperature, ceiling and visibility are made through statistical equations based on past model forecasts and on observations. It would seem unlikely that these statistical equations would still be valid for the extreme conditions of the post-nuclear environment. A second difficulty is that the coarse resolution of the general-circulation models results in poor representation of clouds and precipitation. The models must use parameterization to include the sub-grid effects of clouds and precipitation on the heat balance. While they correctly portray the wet and dry regions of the earth quantitatively, the precipitation amounts are typically off by 30 to 50 percent for the "normal" atmosphere. This would, of course, limit the accuracy in the calculations of soot scavenging.

4.2.2 LARGE MESOSCALE MODELS

Clearly, the general circulation models are capable of describing large-scale effects of a nuclear exchange on the atmosphere, but the "resolution" gap must be filled to obtain a complete and accurate description. As previously mentioned, the operational forecasters bridge this gap with two techniques. The first is the use of limited area, higher resolution, "nested" grid models that use data from coarser models for conditions at the boundaries. The second step is to use statistical models, based on many hundreds of past model forecasts, to make site-specific forecasts. As with the general circulation models, parameterizations are also necessary to provide the nested models with information on the effects of small-scale inhomogeneities. Without historical data to develop statistical relationships for the nuclear effects problem, and without representative test data for the parameterizations, a somewhat different approach must be taken. The use of higher-resolution models is obviously the direction to take, but one must go far below the roughly 100 km of the operational models to determine environmental impact down to the scale of airfields and other Air Force installations.

A number of experimental 3-D models have been developed, with horizontal resolutions ranging all the way down to less than 1 km (0.6 mi) and weather centrals are also developing higher-resolution prediction models. The goal is to simulate and forecast a variety of phenomena including hurricanes, thunderstorms, intense fronts, sea breezes and other local winds - important elements that cannot be directly forecast by larger-scale models. For the post-nuclear environment scenario, there are questions of frequency of fog, low clouds, unusual coastal storms, and downslope winds that must be answered. There have been three rather difficult hurdles on the road to high-resolution atmospheric models. The first problem is that of computer capacity. To go from a 100-km resolution model to, say, 10-km (which would handle hurricanes and large thunderstorm systems), to cover the same area, one would need ten times as many computation points in each horizontal direction. Also, since smaller-scale systems have more vertical detail, at least twice the vertical resolution would be needed. Finally, for computational stability (related to wind speed and grid separation), the time steps must be shortened by a factor of ten. The result is that 200 times as much memory is needed and 2000 times as many computations must be made. The operational 100-km resolution models have been developed for the "super-computers" of the early 1980's, and state-of-the-art computers have since then pushed on to computing speeds ten times as fast. There is still a very long way to go before having 10-km resolution models that cover all of North America, and researchers have resigned themselves to compromises in their models, particularly in the spatial coverage. Thus we find 10-km models running over a 600 × 600 km (380 × 380 mi) area. In studying the finer-scale post-nuclear effects, one would have to run such a model in several different types of terrain and distances from coastlines to get a representative picture.

The second major problem for the high-resolution models (with limited area) concerns how one makes computations at the boundaries, where the data points of the model stop, but the atmosphere continues. In computing the changes with time for a grid point, the equations require information for points on all sides, and when one gets to the boundary, there are no data values for points beyond. When the first computer forecast models were developed, scientists found that numerical errors generating at the boundaries propagated into the middle, causing the accuracy to degenerate with time. While efforts were made to improve the procedures at the boundaries, a more successful route was to get a bigger computer and push the boundaries further away so it would take longer to effect the central area. Thus, they soon had models covering most of the Northern Hemisphere, with the boundary in the equatorial region, where the lighter winds further slowed the propagation of boundary effects. The horizontal boundary problem completely disappeared when they went to global general-circulation models. However, the problem is back with us again with the high-resolution models appearing. Some clever numerical techniques have been developed to prevent internally-developed disturbances from bouncing back into the model area when they move up against a boundary - obviously an unrealistic behavior for thunderstorms and the like. Also, techniques allow the large-scale traveling weather systems of a larger model to interact with and move through the high-resolution models. These numerical techniques do extract a fee in terms of computer time and storage, but are quite necessary if the models are to realistically simulate weather patterns. There is, of course, concern in that these techniques have been developed and tested with "normal" weather conditions, and might have to be adjusted when running with a highly-disturbed temperature and heating pattern that has been indicated by the early nuclear-effects studies.

The third problem to be faced with high-resolution modeling is obtaining adequate weather data to initialize the model and to verify the behavior. Currently, balloon-borne radiosondes over Europe and North America measure atmospheric properties (pressure, temperature, humidity, and wind) twice a day, with about a 400-km (250 mi) separation (more widely scattered in Asia and the rest of the world). This density is adequate to determine the 3-D structure of large-scale weather systems and to initialize the global models prior to a simulation or forecast, but is not adequate for a 10-km resolution model. Modelers have argued that the high-resolution models will generate their own small scale patterns, even if not provided with high-resolution initial conditions. This generation takes place through interactions between larger-scale storm systems and through the effects of variable terrain on the atmosphere (terrain is much more realistic in high resolution models). Thus, these models might simulate the small-scale weather features quite well, but without the proper initial conditions, the models would not be sufficiently precise in the timing and location of storm development to make useful forecasts. However, some high-resolution data are required to prove that the models do, in fact, simulate small-scale weather patterns. Special field programs are conducted from time to time (for example, SESAME, GALE, and STORM) to gather data with much higher than normal time and spatial resolution, and provide invaluable data to the modelers. Even before proving the validity of the models, the special data sets are used to diagnose problems with the models in the development stage.

4.2.3 CLOUD-SCALE MODELS

A quantum leap in model resolution took place with the development of the so-called "cloud" models, in part because non-conventional, high-resolution data were available. One example of such a model is the Colorado State University model, discussed in Section 3.5. These models were developed with horizontal and vertical resolution of about 0.5 km (0.3 mi), and are quite compatible with weather-satellite imagery, weather radar measurements (including Doppler winds), and aircraft measurements of cloud and precipitation particles. The models use more sophisticated cloud physics than other models, separately specifying cloud water, rain water, and ice forms. The simulations of showers, thunderstorms, and mountain clouds are quite realistic; however, the models are only designed for runs simulating one to two hours, as in many cases, the interesting patterns may move past the lateral boundaries. Also, the large-scale conditions in the present configuration, are presumed constant with time (reasonable for one to two hours). To initialize, wind, temperature and humidity are taken from the nearest radiosonde ascent and are assumed to be horizontally uniform, but varying in height. Depending on the phenomona to be simulated, a reasonable, small perturbation in temperature (or other variable) may be placed near the center of the model at the initial time, so there is some control over where the development takes place - large-scale stability factors determine if development is to take place.

This type of model has the capability of emulating the behavior of fog and low stratus clouds, which would be necessary in determining local environmental effects of a "nuclear winter;" however, more work may be necessary to be certain that the models correctly simulate the microphysics of clouds near the ground, which are more stratiform in nature than the shower-type clouds the models currently emulate. An additional use for the "cloud" models would be to describe details of the high level convection that would occur each day due to the intense heating of the top of the soot clouds. This convection might serve to hasten the growth-by-collision of soot particles and might remove some soot through moist cloud processes.

In summary, if given information about urban fires (or wild fires), atmospheric scientists have a number of excellent computer models that can be applied to the problem of determining large-scale effects of a nuclear war. There is not sufficient computer power to make high-resolution computations over large areas for long time periods, so the problem must be broken up and different types of models used.

4.3 Review of Atmospheric Modeling Studies

After the early nuclear effects reports of the 1982-83 period, several major efforts were made to refine prior calculations, and some lesser efforts that focused on factors that were considered of secondary importance. Two groups (National Center for Atmospheric Research (NCAR) and Los Alamos National Laboratory (LANL) used a modification of the NCAR 3-D general-circulation model, commonly called the "Community-Climate-Model" (CCM), to look at changes in the large-scale weather patterns out to about 20 - 40 days. Two other groups, Colorado State University (CSU) and

Air Force Geophysics Laboratory (AFGL), modified the high-resolution 3-D "cloud model" developed at CSU, in order to examine the development of the urban fire plume, with emphasis on plume height and soot removal. Sensitivity studies were made using the Oregon State University (OSU) general-circulation model, by a group that included scientists from OSU, Lawrence Livermore National Laboratory (LLNL) and Stony Brook State University of New York. Two more noteworthy investigations were made using 1-D radiation-convection models: an effort at Max Planck Institute for Chemistry that reexamined the soot production problem, and an NCAR study that determined the impact of dust and long-wave soot emission on the calculations.

4.3.1 MAX PLANCK INSTITUTE MODEL STUDY

To start, a report on the Max Planck Institute 1-D model effort was prepared by P. Crutzen, I. Galbally, and Bruhl.[9] The report examines many aspects of the nuclear effects problem, from targeting to effects on surviving population. Details on targeting, fuel load calculations, and soot estimates were presented in Section 3. While estimates of burned wood were much less than previous studies (for example, TTAPS), more precise estimates of petroleum (and products) burned resulted in the total carbon release being quite similar to other studies of the time.

Using the estimated total soot production of 140 million tons, including 51 million tons of carbon, the authors went on to use a relatively simple 1-D model to compute the effects on the atmosphere. They made a simple analysis to point out the possibility of an over-abundance of cloud nuclei creating too many small droplets and hindering the precipitation process. The model did allow for aerosol coagulation, dispersion, and removal by rain, and for scattering and absorption of solar energy by soot. The removal rate was fixed at 3.3 percent/day in their upper layer (above 8 km) and 6.7 percent/day in the middle layer (2.5-8 km), with no soot present below 2.5 km. The simulated conditions that might be considered typical near the equinoxes, for the mid-continents at about 35°N, produced a surface cooling of about 40°C, similar to the cooling computed in TTAPS.[2] (In the TTAPS report, a 1/3 reduction in cooling was suggested to compensate for the lack of ocean in the model.) The model was run with a normal surface albedo of 12 percent; a 50 percent albedo was used, if temperature was below freezing at the surface, to represent the presence of a "dirty" or "sooty" snow cover. The model runs were for 120 days. With the removal present, there was a 90 percent recovery for the simulations at about 45 days for the normal albedo, and about 90 days when the 50 percent albedo was permitted. This could be an important factor in the recovery process for all but the midsummer cases.

4.3.2 3-D MODEL STUDIES AT NCAR

The NCAR Community Climate Model (CCM) is a well-documented model, maintained for use by scientists investigating the sensitivity of the atmosphere to a variety of factors, including sunlight, carbon dioxide, and glaciation variations. A group (Covey, Schneider, and Thompson)[22] at NCAR noted that they could fairly easily add routines to the CCM that would simulate the absorption of sunlight by a soot layer, and then examine the resulting effects on the winds, temperature, and

22. Covey, C., Schneider, S.H., and Thompson, S.L. (1984) Global atmospheric effects of massive smoke injections from a nuclear war: results from general circulation model simulations, *Nature* **308**:21-25.

moisture. In their first effort,[22] they placed a uniform soot cloud extending around the northern hemisphere from 30° to 60°N latitude, and from 1 to 11 km (3,000 to 34,000 ft) in height. The absorption optical depth was 3.0 (no scattering). Three simulations were run, starting with an early winter date, an early spring date, and an early summer date, using data from a prior long-term run (no soot) as the starting conditions so that results could be compared to the "no-soot" run. The first results, the July case, were published in March 1984, and a more complete report appeared in July 1985.[23] While the soot was fixed in location throughout each run, it was clear from the wind streamlines and temperature patterns, that if software were available to allow the soot to move, it would have spread well into the Southern Hemisphere and also several kilometers in the vertical. Comparing the "soot" to the "no-soot" July simulations, the clouds (water) above 5 km (16,000 ft) virtually disappeared, as the warmth of the soot layer due to absorbed solar radiation dropped relative humidities by 20 to 40 percent. Ten days into the summer simulation, surface temperatures dropped below freezing over most of North America and Asia to the north of 30°N latitude. Western Europe and the western U.S. were cooled to a much lesser extent. As had been anticipated by scientists before (note quote from MacCracken in the Introduction), the atmospheric effects computed were much worse in summer than in winter. The 30° - 60°N land average temperature for days 10 to 15 were about 25°C (45°F) cooler for July, 18°C (32°F) cooler for April, and 4°C (7°F) cooler for January.

Users of the CCM could add their own routines (or library) but could not change the basic dynamics software, as it would then interfere with other experiments. This restriction hindered attempts to use the model to simulate the redistribution of soot by the 3-D wind flow. However, Thompson was successful in using the physics package that transports water vapor to transport soot as well. The procedure was not ideal in that corrections were necessary to avoid negative soot concentrations that sometimes appeared. Thompson, in his *Nature*[24] article, noted the problem and concluded "but the present formulation is certainly sufficient to support the conclusions reached below." He recomputed the three early-season cases previously reported. Instead of an initial zonal soot band, the model injected some 180 million tons of 0.1-micron size soot over industrialized NATO and Warsaw Pact nations during a two-day period, with the soot rising to 7 km (23,000 ft). In the July case, after ten days, the wind systems had dispersed the soot to the extent that virtually all areas north of 10°N latitude had some soot aloft, though the concentrations varied by a factor of ten or more. Large scale convection associated with the solar heating of the soot drove the soot upwards to levels of 20 km (67,000 ft) and more, and lateral currents carried the soot as far south as 30°S latitude. Even with this spreading (and dilution), the surface temperature drops were nearly as large as with the fixed-soot case for each of the three seasons. A test was run with the soot injected only in the 0-2 km (6,600 ft) layer, and the model took about five days to lift the soot into the higher levels, but thereafter, its reaction was similar to the 0-7 km initial soot injection. Also, tests were run with 1/3 and with three times the "baseline" soot injection. For the land area 30° - 60°N, over days 10 to 15, the 60-, 180-, and 540-million tons of soot cases produced cooling of 14°C, 23°C, and 26°C, respectively. The relatively small

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23. Covey, C., Thompson, S.L., and Schneider, S.H. (1985) "Nuclear Winter": a diagnosis of atmospheric general circulation model simulations, *J. Geophys. Res.* **90**:5615-5628.
24. Thompson, S.L. (1985) Global interactive transport simulations of nuclear war smoke, *Nature* **317**:35-39.

difference between the last two indicates that the cooling is not a linear function of soot amounts. As pointed out in the report, "The simulations do not yet include smoke removal, which is primarily associated with water condensation and rainout." Thus, the computed temperature effects would certainly be somewhat too great. Thompson also noted that the heating had forced the tropopause down to" - between 5 and 8 km altitude ~ one week after the start of the smoke injection. Moisture condensation necessary for effective smoke removal is virtually eliminated above 5 km; however, smoke that remains at low altitudes for more than a few days would have a good chance of being removed by the remaining cloud scavenging processes." This series of experiments by Thompson represented a significant step forward in that the soot and the atmosphere freely interacted, with the soot heating the atmosphere and modifying the wind circulations, and the wind circulations redistributing the soot in three dimensions. The major shortfall of the experiment was that there was no mechanism for soot removal, even though allowance for removal had been made at early stages in computing the overall soot generation.

4.3.3 3-D MODEL STUDIES AT LOS ALAMOS NATIONAL LABORATORY

The Los Alamos group undertook a rather complete series of model simulations to determine nuclear effects, making important modifications to their copy of the NCAR Community Climate Model.[25] First, a complete three-dimensional transport routine was developed to model the spread of the soot. Next, a procedure was introduced that could remove soot through gravitational settling (a very slow process) and through precipitation washout, using the precipitation generated in the model simulation. Additionally, a newly formulated radiation and cloudiness scheme was employed, which had been shown to improve the response of the CCM. During preliminary tests, they found that more precision, particularly for vertical transport of soot, could be obtained with better vertical resolution and thus the number of layers was increased from 9 to 20. Before introducing soot into the model, some consistency tests were made. For example, simulated volcanic material was placed in the lower stratosphere and was found to move around in a thin layer just above the tropopause, as we typically see happen. In another test, when the removal process was inactivated, aerosol material that was placed in the model moved with the winds, faithfully preserving the original total mass to "within one part of 10^{11} after a 40-day simulation", no matter what the pattern, - obviously there was no slow systematic increase or decrease that sometimes happens in models. When the removal procedure was turned on and a "non-black" or "inactive" load of particulates was placed in the model, the removal rates agreed well with observation-based estimates for tropospheric sulfates, nitrates, and other particulates. Thus the modified CCM passed some important tests before the simulations with soot were begun.

To start the experiments, soot was introduced in a smoothly-varying pattern over the U.S. and Europe (including the USSR), with a total of 170 million tons (170 Tg) for their baseline case. Two different vertical profiles were tested: one with all soot initially between 2 and 5 km (6600 and 16,000 ft), called the "low" cases, and the other with soot initially from surface to 9 km (28,000 ft), the

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25. Malone, R.C., Auer, L.H., Glatzmaier, G.A., and Wood, M.C. (1986) Nuclear winter: three-dimensional simulations including interactive transport, scavenging and solar heating of smoke, *J.Geophys.Res.* **91**:1039-1053.

"NAS" profile. In both profiles, the density of the soot was constant in height. The soot was injected over seven days, at a constantly decreasing rate, such that half was generated in the first two days. In addition to the baseline case, there were simulations with soot masses of 5, 20, 60, and 500 million tons. Thompson, of NCAR, had also made computations with 1/3 and three times the baseline (there was close communication between the two groups) but the appearance of 5- and 20-million-ton soot generation may represent a response to indications that the estimates of 1983 and 1984 may be too high.

Some very important results of this Los Alamos study are the computations of the soot removal that took place primarily when and where the model dynamics indicated precipitation occurred. Table 5 is reproduced from the 1986 JGR report of Malone *et al.*, showing soot removal for eight

Table 5. Smoke Removal Rate From Eight Los Alamos Experiments (Malone *et al.*)

Season/Profile		Injected Mass (Tg)	% Mass Remaining	Removal Rate (% per day)	Residence Time (days)
July	NAS	5	7	6.0	17
		20	22	2.5	40
		60	35	1.0	105
		170	36	0.6	180
		500	28	0.5	217
July	Low	170	32	0.7	150
January	NAS	170	14	2.2	45
January	Low	170	4	7.1	14

Note: The percentage of injected smoke remaining in the atmosphere, the fractional removal rate (percent per day), and the 1/e residence time (days) are given at the last (40th) day of the interactive smoke simulations, as a function of season, vertical injection profile, and total injected mass.

different cases, with varying season, vertical profile, and generated mass. The table shows the mass at the end of 40 simulated days, the percent-per-day removal rate, and a "residence" time (time until mass decreases to 1/e times the initial value). For comparison, normal removal rates are about 30 percent-per-day near the ground, decreasing to about 5 percent-per-day near 12 km (40,000 ft) and in Table 5 we show some removal rates a factor of 10 or more slower. The fastest removal rates for the 170 Tg baseline case were for January, where the "low" injection was removed almost 1/2 as fast as normal. For the July case, the removal was much slower, confirming expectations of several previous investigators. The LANL authors noted that as the July baseline case began, the removal was fairly fast at the start, with 40 percent washed out in the first six days, but by day 40, the rate was down to 1/2 percent-per day. Increasing the soot by a factor of 3 did not decrease the rate appreciably, but the removal rates were progressively faster with smaller initial soot generation. Also, one notes that the removal for the "low" altitude January case was three times as fast as for the regular 0-9 km case, but in July, the difference was only 15 percent, indicating the low level soot in July was elevated as it was heated by the strong summer sun.

To appreciate why the soot removal was so much slower than normal, particularly for the July cases, we must look at the effects of the interaction with the atmosphere, changing the vertical distribution, the vertical temperature structure, and precipitation. Figure 3 (from the LANL JGR report) shows the north-south vertical cross section (pole-to-pole) of particulate concentration for both the Los Alamos and NCAR July baseline soot cases, about 15 - 20 days after the simulations began. For the Los Alamos experiment, there are two sets of lines, a dashed set representing "non-black" aerosols that did not interact with the atmosphere through heat absorption, and solid lines for the soot, which did absorb. Even though each began with the same amount of material, only quite small amounts of the "non-black" material remained, mostly below 5 km, while most of the soot was above 5 km, some above 25 km. The NCAR cross section is quite similar (the vertical scale is nonlinear) in that the soot rose above 20 km, and between 10 and 20 km pushed across the equator to 30° south latitude. The corresponding north-south vertical temperature cross sections are shown in Figure 4, for the Los Alamos summer baseline experiment, with the "norm" or "day zero" condition at the top, and the soot-perturbed condition on the bottom (average days 15 - 19). Near the 15-km level (50,000 ft) the solar absorption by the soot produced an enormous heating of some 100°C (180°F)! in the arctic, tapering to 60°C (108°F) near the equator. This heating in effect created a new tropopause some 5-7 km lower than normal, with most of the remaining soot lying above. In the soot layer above the tropopause, relative humidities were very low and a temperature-inversion condition existed (temperature increasing with increasing height) which all but prohibited the model from forming clouds and precipitation for scavenging and soot removal.

We must be careful when discussing the surface temperature effects simulated by the general circulation models. First, even the best current operational models show little skill predicting temperature at a specific point beyond about five days. The models continue to forecast the day-to-day ups and downs of temperature, but soon become out of phase, and forecast the right weather on the wrong day. Having a coarser resolution, the NCAR CCM is not as good a prediction model as the operational models, because as previously discussed, the CCM was designed primarily to study large-scale effects. Realizing these limitations, the scientists have preferred to express soot effects on temperatures in terms of the differences between model runs with and without soot. Further, they have averaged the differences over time to reduce the uncertainty in the phase of day-to-day changes. Time-averaged change of surface temperature differences for the July cases (both Los Alamos and NCAR) are shown in Figure 5, and the January cases in Figure 6. Both the Los Alamos and NCAR simulations for July indicated temperature differences greater than 15°C (27°F) over most of Asia and North America as well as parts of North Africa, Europe, and the Middle East. Changes in Southern Hemisphere temperatures did not show up on the Los Alamos simulations until after day 10, but were quite similar in magnitude to those computed by Thompson (which also occurred after day 10). The picture for the January simulations is very much different, with smaller negative temperature difference and smaller areas. In the Los Alamos test, there is an appearance of positive differences (surface warming) in Alaska and northern Europe that represent an east-west shift of a very large-scale weather pattern, indirectly due to the solar heating. The NCAR temperature differences appear smaller in magnitude, but the averaging period was longer (5 vs 25 days) and temperature patterns shifted spatially during the period and started to recover.

A comparison of area-averaged temperature drops indicated by the Los Alamos and NCAR models is shown in Table 6. These numbers are approximate, representing values estimated from

LOS ALAMOS VERSION
CCM (MALONE ET AL)
DAY 0 (170TG)

LOS ALAMOS VERSION
CCM (MALONE ET AL)
DAYS 15-20 (170TG)

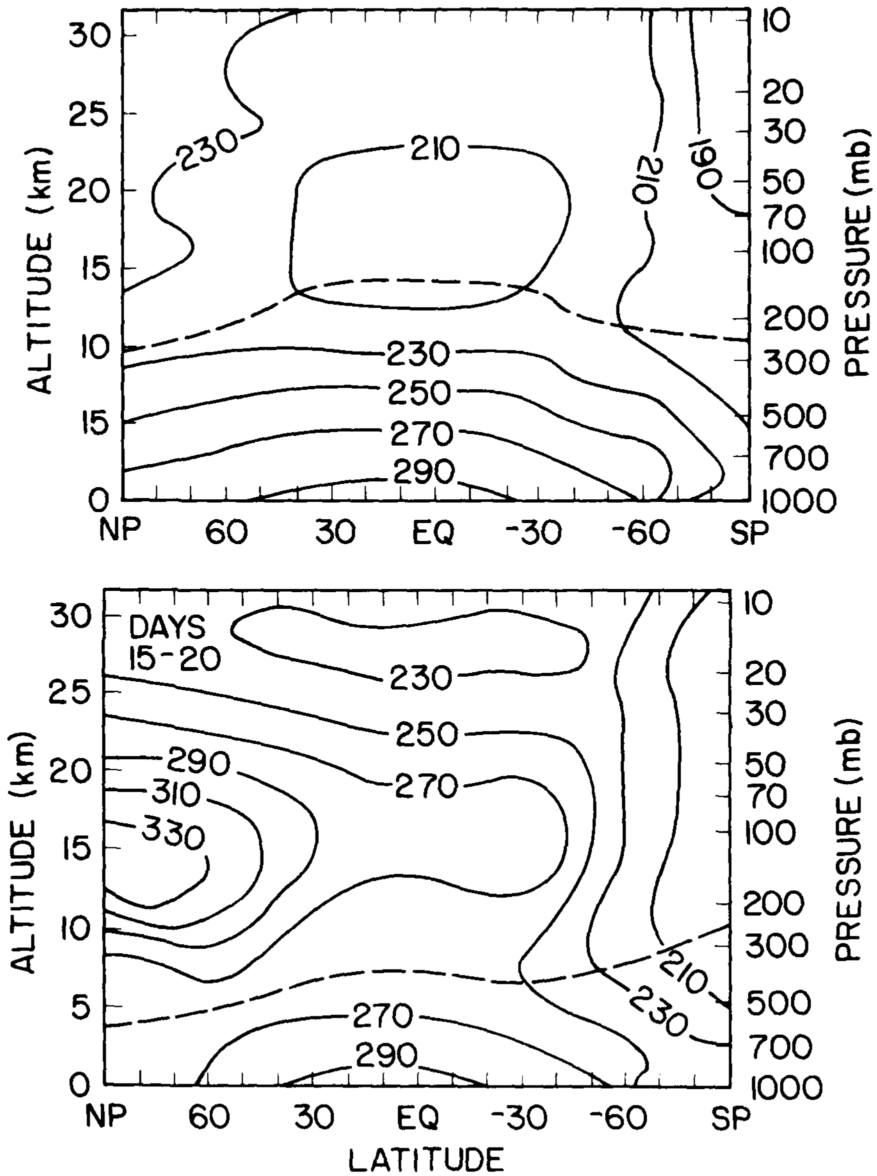
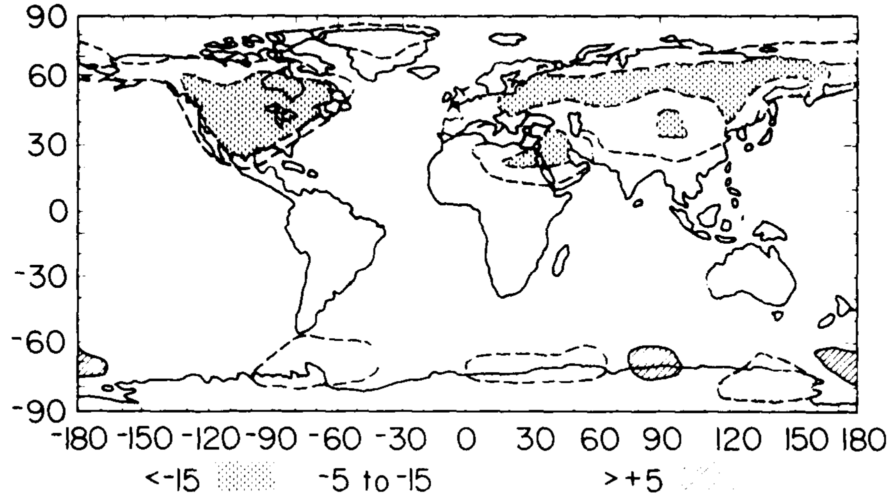


Figure 4. Cross-Section of Zonally Averaged Temperature - July Case

LOS ALAMOS VERSION
CCM (MALONE, ET AL)
DAYS 5-10 (170TG)



NCAR VERSION
CCM (THOMPSON)
DAYS 5-20 (180TG)

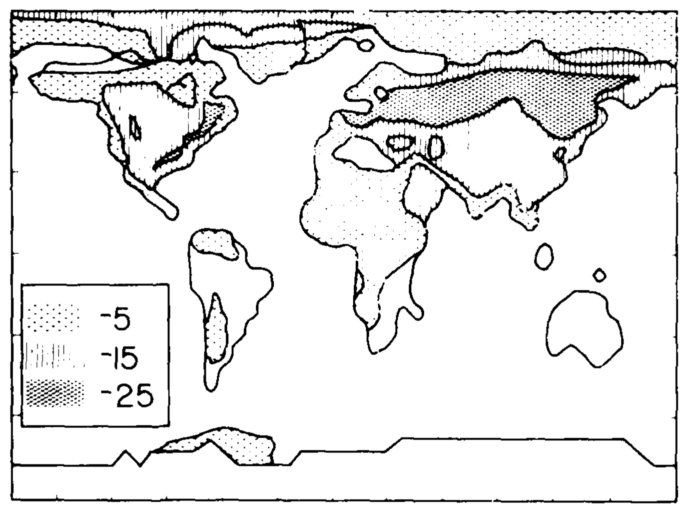


Figure 5. Surface Temperature Change Following Smoke Injection - July Case

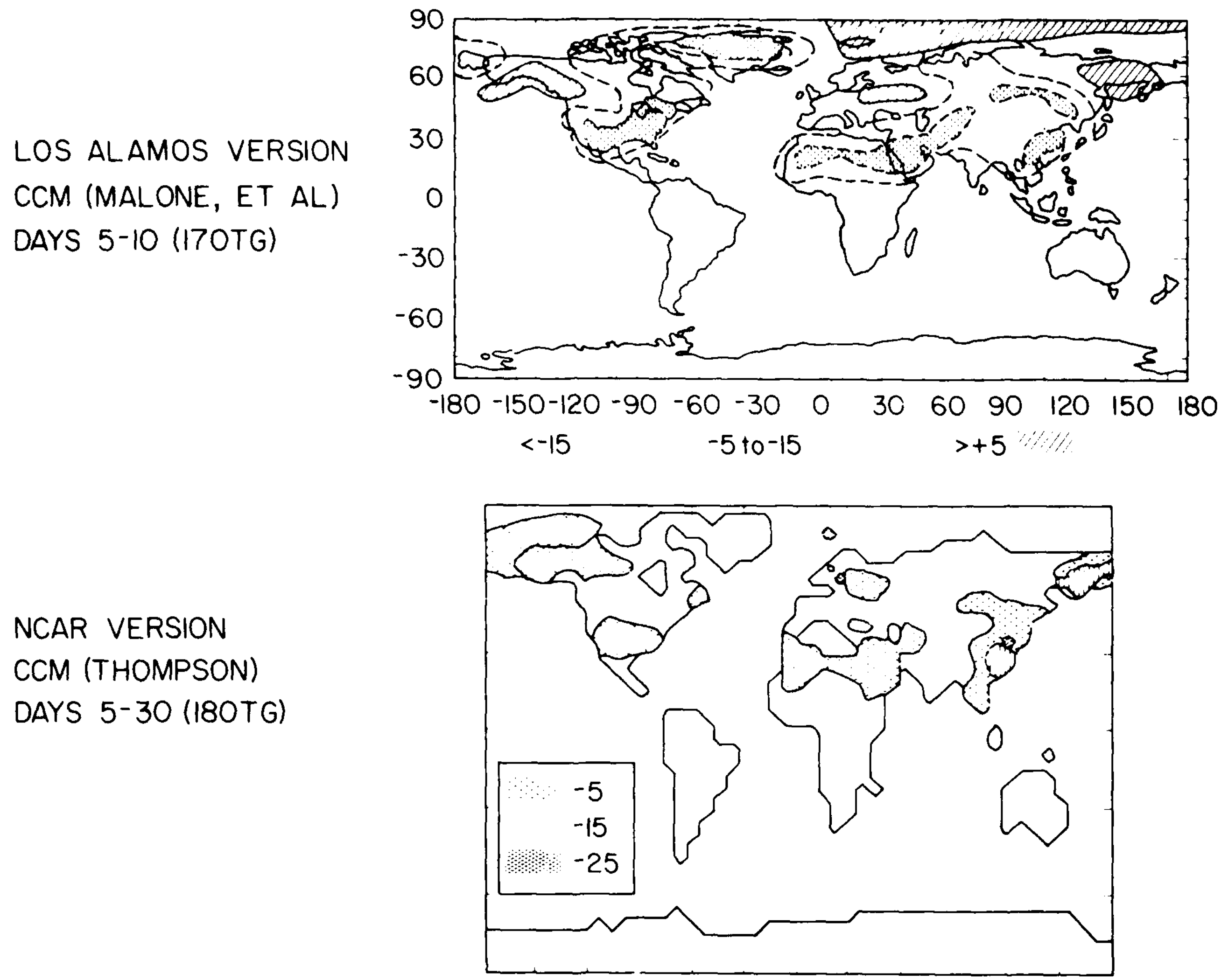


Figure 6. Surface Temperature Change Following Smoke Injection - Jan Case

Table 6. Esimated Surface Temperature Change (Continents)
Due to Smoke - 1985 CCM Computations, July

Version	Smoke Mass	Initial Ht. KM	Temp. Drop 30 - 60N	Temp. Drop 0 - 30N	Time Days
LANL	60Tg	0 - 9	10C	3C	0 - 14
NCAR	60Tg	0 - 7	14C	4C	10 - 15
LANL	170Tg	0 - 9	20C	8C	0 - 14
NCAR	180Tg	0 - 7	23C	12C	10 - 15
LANL	500Tg	0 - 9	30C	16C	0 - 14
NCAR	540Tg	0 - 7	26C	19C	10 - 15

Note: Temperature drops for continental areas were interpreted from discussions and charts in papers by Thompson and by Malone, *et al.*

charts and from text discussion. Overall, the figures for the three different soot generations are quite similar, with perhaps the Los Alamos temperatures being about 20 to 25 percent warmer due to the inclusion of precipitation removal. While the temperature drops for 30° - 60°N are much greater than for 0° - 30°N, the lower latitude temperatures react more strongly to increased soot loads. The overall magnitude of the simulated continental surface cooling in this table is less than that indicated by the 1-D models of the early investigators, as indicated in Table 2. The differences had been anticipated in that the 1-D models did not include the moderating effects of the oceans. The direct effects were indicated primarily along the coasts, but Covey *et al.* (NCAR), when examining the energy budget in detail, also noted that warm air from the oceans penetrated well inland above the surface and mixed downwards by turbulent diffusion.

The authors of the nuclear-effects reports based on the NCAR CCM clearly pointed out the limitations and uncertainties. The importance of accurate determination of soot generation and soot radiative characteristics has already been discussed, as well as the necessity of having higher-resolution models to determine effects in more detail. Malone *et al.* (Los Alamos), also cautioned about the problem of modeling cloud processes for very unnatural conditions ("possible suppression of precipitation due to 'overseeding'"). Both groups recommended that the effects of dust thrown up by surface bursts be included as well as the scattering of sunlight by soot and infrared soot absorption and emission.

4.3.4 1-D SENSITIVITY STUDY AT NCAR

While we prefer to use the 3-D models to provide complete realistic descriptions of the atmospheric effects, these models must be simplified to meet computer limitations. For example, the CCM studies of Los Alamos and NCAR did not include dust, scattering of solar radiation by soot, long-wave (infrared) interaction with soot, or any diurnal variation of sun angle ("constant sun" approximation). Investigators have been able to use 1-D models that behave much like the 3-D models (but faster on computers) to test the sensitivity of model behavior to factors missing or simplified in the CCM studies.

The first of these sensitivity studies was reported by V. Ramaswamy and J. Kiehl.[26] The article starts with an excellent description of the optical properties of soot and dust. Figure 7 from the article, illustrates the "extinction effectiveness" (which includes both absorption and scattering) for "smoke" (soot) and dust, and for sunlight (λ = .5 μm) and infrared (λ = 11 μm) as a function of particle size. For typical soot particles from fires, 0.05 to 0.3 μm, the extinction of solar radiation is much greater than the extinction of infrared (about half the visible extinction is absorption). Should the particles grow to greater than 2μm, the infrared extinction becomes more important. Dust also behaves much the same way. The 1-D model used in this study contains 28 vertical levels, extending from ground to 60 km (200 Kft), and includes comprehensive radiative physics with such gases as ozone, carbon dioxide, and water vapor. The model also includes convective parameterization and cloud simulation. For these experiments, the solar angle simulated conditions near the equinoxes. A soot loading of 0.5 g m^{-2} (5×10^{-5} g m^{-3}, surface to 10 km) was entered and kept constant with time. This value represents about 40 - 60 percent that used in the CCM studies. Dust loading was 0.2 g/m^2 (0.8×10^{-5} g m^{-3}, 10 km^{-35} km), representing about 80 percent of that used in the TTAPS baseline, but three times that suggested in the later NRC report. The model was repeatedly run, with and without soot, with and without dust, and with and without the longwave radiative effects of soot. The simulations went out to 20 days, by which time conditions were close to equilibrium. One result was that the addition of the dust layer above the soot layer heated the air near 33 km (100 ft) by some 55° to 60°C (100° to 110°F), but since some solar radiation was scattered out to space and also absorbed by dust, the soot layer near 9 km was heated about 15°C (27°F) less than the soot-alone case. At the surface, soot alone produced about a 32°C (58°F) cooling, and addition of dust increased this to a 40°C (72°F) cooling.

When the model was run to test the effect of longwave radiation interacting with soot, the surface cooling was about 7°C less when the longwave radiation was included. The CCM computations of Los Alamos and NCAR previously described were made without the soot longwave-IR effects and without dust, and these omissions tended to cancel in their temperature effects at the ground; however, near 9 km (30 ft), the addition of dust reduced the solar heating and presumedly this would increase relative humidity somewhat and increase the likelihood of precipitation and removal. The authors also noted the importance of size distribution of soot particles on solar transmission to the ground. With 0.5 g/m^2 of 0.05 μm radius soot, the optical depth would be 6, and only 2 percent of normal clear sky (no water clouds) sunlight would reach the ground. If the particles coagulated, growing to 0.5 μm, optical depth would only be 1.3, and 17 percent of the normal sunlight would reach the ground.

4.3.5 SENSITIVITY STUDIES BY CESS AND COLLEAGUES

Sensitivity studies were also conducted by R. Cess of New York State University of Stony Brook.[27] In the first report,[27] he used a 2 layer, 1-D model, with comprehensive radiation physics, and looked primarily at the solar radiation at the surface and the radiation reflected to space. Cess by-passed questions of soot loading and optical properties and instead inserted varying extinction

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26. Ramaswamy, V. and Kiehl, J. (1985) Sensitivities of the radiative forcing due to large loading of smoke and dust aerosols, *J. Geophys. Res.* **90**:5597-5613.

27. Cess, R.D. (1985) Nuclear war: illustrative effects of atmosphere smoke and dust upon solar radiation, *Climatic Change* **7**:237-251.

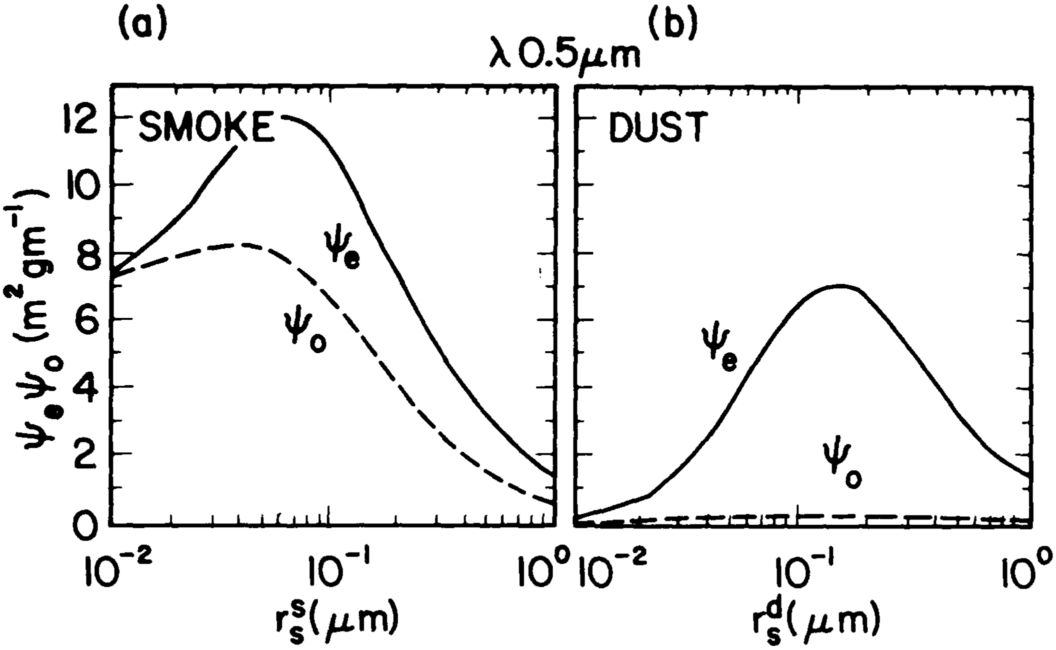

Figure 7a. Dependence of the specific extinction and absorption of (a) smoke aerosols and (b) dust aerosols at a wavelength of 0.5 μm on the mode radius. (From Ramaswamy and Kiehl, *J. Geophys. Res.*, **90**:5597-5613)

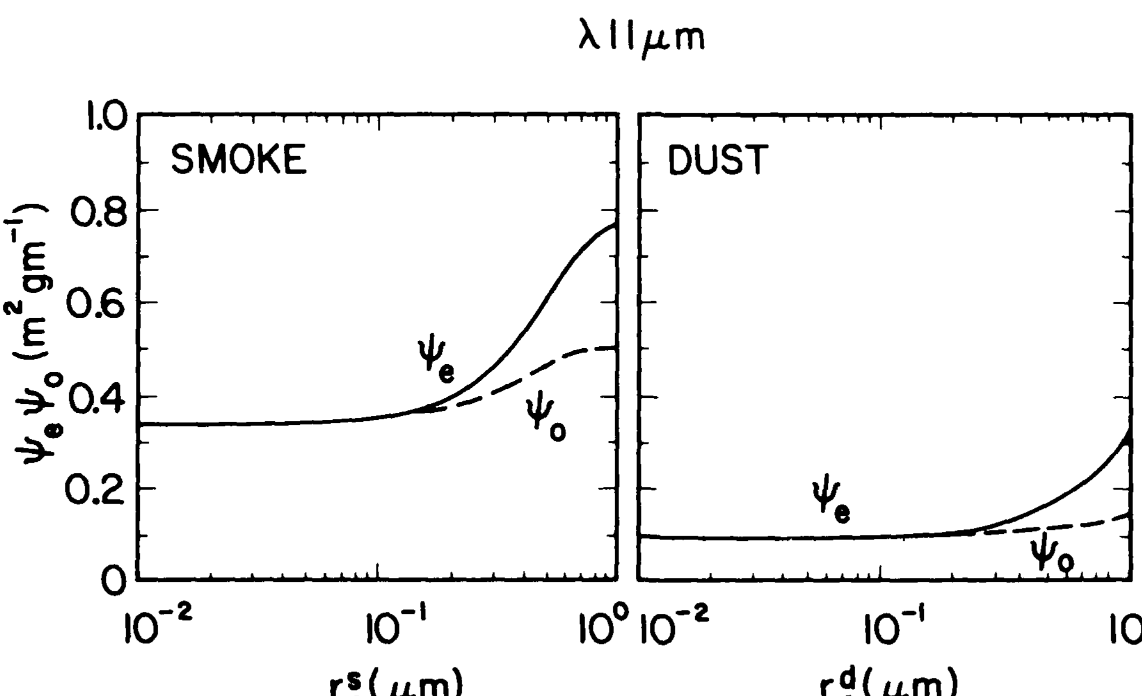

Figure 7b. Same as above, except at a wavelength of 11μm.

optical depth (including scattering and absorption) into his models and also the "single scattering albedo," which is the ratio of scattering to total extinction (nominally chosen to be 0.7). The model was run with soot optical depths of 0 to 3, corresponding to absorption optical depths of 0 to 0.9. By comparison, the CCM studies had absorption optical depths of about 2 to 3 in the early stages of the baseline cases. Thus, the computations of Cess would be applicable if soot generation estimates are revised downwards by a factor of 3, and even if not, would still apply to later stages when significant washout had occurred. In testing the sensitivity to dust, the run with both soot and dust resulted in a 5 to 10 percent greater decrease of surface sunlight by the particles (scattering and absorption) than when only soot was included.

The CCM model, with a coarse resolution, cannot simulate local winds and convection produced by the daily rising and setting of the sun (so-called "diurnal effects"), but must include net solar radiation to drive the large-scale wind systems. Consequently, they have been using a "constant sun" approximation, which uses the sunrise-to-sunset average radiation together with the percentage of daytime as fixed for a given latitude and season. Cess correctly pointed out that for important optical depths (greater than about 0.2), this constant-sun approximation results in an underestimate of the sunlight reaching the ground. For an equinox condition, the normal clear-sky (no water cloud) radiation reaching the ground was computed to be 250 W/m^2, and when soot was added (0.9 absorption optical depth) using the constant sun, only 41 W/m^2 reached the ground, but when the true diurnal computation was made, 55 W/m^2 reached the ground. The model was also run in a mode that emulated the NCAR radiation physics used by Covey *et al.*[22], in their Mar 84 paper, and Cess showed that the omission of soot scattering led to an overestimate of sunlight reaching the ground, compensating for about half of the underestimate made by using constant sun. Another point made in the study is that even when there is a large amount of solar energy depleted near noontime by soot, a substantial amount still reaches the surface. For example, for an optical depth of 1.5 (0.45 absorption) in April, about 50 - 60 percent of normal sunlight reach the ground near noontime: this could lead to convection over land, enhancing precipitation scavenging and mixing some of the upper-level warmth downwards. A high-resolution mesoscale model is needed to quantify this proposed effect.

In his second series of sensitivity studies, Cess collaborated with G. Potter and S. Ghan of Lawrence Livermore National Laboratory, and W.L. Gates of Oregon State University (OSU).[28] Two models were used: a 1-D model similar to that used in the previous study,[26] and the OSU general circulation model (GCM). Both models use two layers in the vertical, while the GCM used a horizontal grid of 4° latitude by 5° longitude (the NCAR CCM is 4 1/2° by 7 1/2°). Soot optical depths in the simulations were varied from 0 to 3 and the scattering albedo from 0.5 to 0.7. The soot optical depth was kept constant at all longitudes, from 20° to 90°N, and tapered off to zero at the equator. Dust with optical depth 1/3 that of soot was placed in an imaginary layer above the model top (200 mb), modifying incoming radiation only through scattering. The model was run without soot and dust out to 100 days, for perpetual July radiation conditions. Most of the results were based on simulations that started with conditions of the 90th day, and run out 10 days to compare with the 100th day. To

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28. Cess, R.D., Potter, G.L., Ghan, S.J., and Gates, W.L. (1985) The climatic effects of large injections of atmospheric smoke and dust: a study of climatic feedback mechanisms with one and three dimensional climate models, *J. Geophys. Res.* **90**:12937-12950.

test the impact of different initial conditions, 10-day simulations were made starting with days 70 and 80, and comparing to the no-soot simulations on days 80 and 90, respectively. Averaging over longitude for a given latitude, differing initial conditions did result in difference up to 2°C (3.6°F) in surface temperature, when optical depths of 1.5 to 3.0 were used. But averaging 20°N to 90°N, the differences were trivial, suggesting that spatial averaging is necessary for meaningful comparisons. (The authors did not use time-averaging as did the CCM investigators.) In one experiment, the OSU model physics were set up to mimic the CCM used by Covey *et al.*, in their Mar 84 report (no scattering, no dust, constant sun), but the OSU model produced about 7°C (12°F) more surface cooling than did the CCM. This difference was believed to be largely due to a downward vertical diffusion of heat that was much larger in the NCAR simulation (of some concern to Covey, *et al.*).

In another test, the optical depth was kept constant at 3.0, but the scattering albedo was changed from 0.7 to 0.5. This meant that the absorption optical depth was increased from 0.9 to 1.5, while the scattering optical depth dropped from 2.1 to 1.5. Without the change, the land surface cooling from 30° to 60°N was -11°C (-20°F) and after the change, -17°C (-30°F) showing that absorption is much more important than scattering. Sensitivity tests were also made to examine the effects of soot vertical distribution on the surface temperatures. In one set, the optical depth was split equally between the layers, simulating a constant density (mass of soot per volume), as used in the initial conditions of the Los Alamos simulations. In the other set, the optical depth was divided according to air density, constant mixing ratio (mass of soot per mass of air), as was used by Thompson in his NCAR simulations. The resulting surface cooling, from 30° to 60°N was about -11°C (-20°F) for constant mixing ratio, but about -15°C (-27°F) for constant density. In the former case, there was more solar absorption at lower altitudes where denser water vapor and carbon dioxide warmed the ground through infrared heating, even though in both cases the surface solar heating was the same. Constant mixing ratio might seem physically a more reasonable distribution, but the Los Alamos study showed that for the low level soot in summer, what was not lofted to higher levels by solar heating was soon removed by precipitation. There is an important point in that the initial vertical distribution from fire plumes does influence the outcome.

These sensitivity studies have examined the effects of a number of weaknesses that were present in the CCM studies, including the "constant sun" approximation, lack of dust, lack of soot scattering, neglect of soot IR effects, questionable vertical distribution, and a possible downward diffusion problem. Some of the weaknesses indicated the simulations were too cool, some too warm.

4.3.6 3-D CLOUD MODEL STUDIES AT CSU

Discussions of the global 3-D models indicate that the atmospheric effects are strongly dependent upon the vertical extent of the smoke plumes as well as the distribution of soot in the plume. While some estimates of plume height from large fires and volcanoes are available, (also discussed in Section 3.5) W. R. Cotton began a more rigorous approach by applying a 3-D "cloud" model, originally designed to simulate the development of thunderstorms. His model[17] was modified to include an urban area, 4-km radius, with a fuel load of 110 kg/m^2 burning over a 3-hour period. The microphysics in the model simulates precipitation growth from microscopic nuclei to rain, snow and hail, and allowed computation of the removal of 0.1-micron-size soot particles through interaction with particles of all sizes. The published report describes results of the computer model with initial conditions taken from a day in June at Denver, Colorado. Less than an hour after the model's "fire" started, an enormous smoke and cloud plume developed, with updraft speeds exceeding those of the most severe thunderstorm previously modeled. Because of these updrafts, the cloud rose well above the 9.6 km tropopause prevailing that day, transporting 44 percent of the soot to levels above, where further removal would be expected to be slow. Soot removal by processes in the atmosphere amounted to a few percent or less. Banta of AFGL has used this same model with different atmospheric and burning conditions and found that the plume height is quite sensitive to atmospheric moisture and temperature distribution (static stability). Thus Cotton's result was atypically high, except when thunderstorms were likely to occur naturally in summer. Plume rise would be several kilometers lower, particularly in fall and winter, when stable air masses more frequently contain much less moisture.

4.3.7 3-D MESOSCALE MODEL STUDY AT BRITISH METEOROLOGICAL OFFICE

The 3-D model simulations described thus far cover two extremes of the meteorological scale, the CCM with about a 500-km grid spacing and the cloud models with about 1/2-to 1-km grid spacing. The first effort to fill the gap was described by B. Golding, P. Goldsmith, N. Machin, and A. Slingo[19], of the British Meteorological Office. The model used was a mesoscale model being developed for short-range forecasting, has horizontal grid spacing of 15 km, and 16 levels. The model is non-hydrostatic, thus capable of predicting strong mesoscale convection, and it predicts distributions of water vapor, cloud water and turbulent energy as well as other dynamic variables. The physics of the model includes solar and infrared radiation, with both scattering and absorption. From static tests of the radiation routines, the authors found that the attenuation of solar radiation by soot could well be approximated using an attenuation coefficient of 1.5 m^2/g (slightly lower than the frequently-used value of 2.0 m^2/g).

The authors described the test as follows (See Figure 8 from Reference 19): "In the study, a smoke source was injected in a column of radius 75 km, near the center of the model grid. The vertical profile of the smoke was chosen to be consistent with the published data and to have a concentration of 6.1×10^{-4} kg m^{-2} over the model depth and a peak at 9 km of 1.1×10^{-7} kg m^{-3}. This profile was artificially constrained to be constant in the source area. The smoke was transported from this source by the model winds but was not affected by any other model variable." Over the stated model depth of 12 km, the soot concentration averaged 0.5×10^{-7} kg m^{-3}, which was half the value at the 9-km peak. The authors did not show the soot profile, but it appeared that the concentration started near zero at the ground, increased to the 9-km peak, and decreased to near zero at 12 km. The authors computed an absorptive optical depth of 0.91 which is similar to the values used in global simulations after the soot was uniformly spread over the Northern Hemisphere. A June day was chosen for the experiment, with fair weather and light winds at all levels. The model was run out to 12 hours, starting at 0600 LST. Rapid heating soon occurred near the 300-mb level (10 km), rising motion of 5 to 20 cm s^{-1} followed, and clouds formed downwind of the center of the source area. The authors noted "The cloud was absent in the control run and has a water content sufficient to produce precipitation which would evaporate in the dry air below the cloud base." Figure 9 illustrates these results. The authors also state "The model does not attempt to represent the physics of the interaction between the water and smoke; however, these results confirm that local circulations, capable of producing cloud formations that otherwise would not occur, can be set up by the local smoke plume."

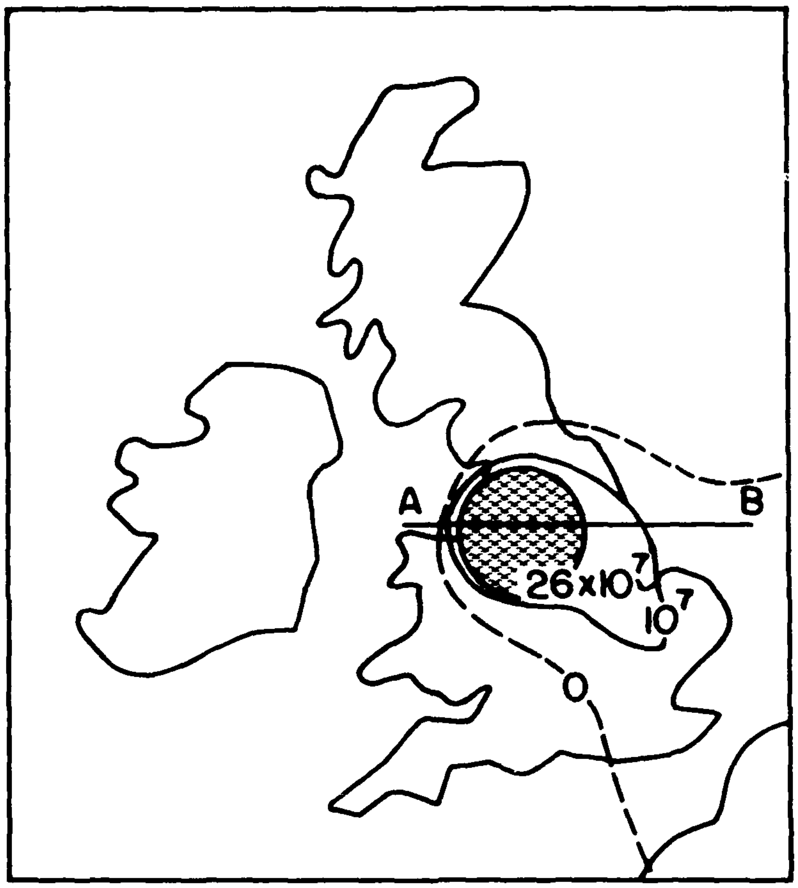

Figure 8. Smoke Concentration in kg per kg at 9 km Altitude (~300 mbar) after 12 h Integration. The Stippled area Shows the Source Region.

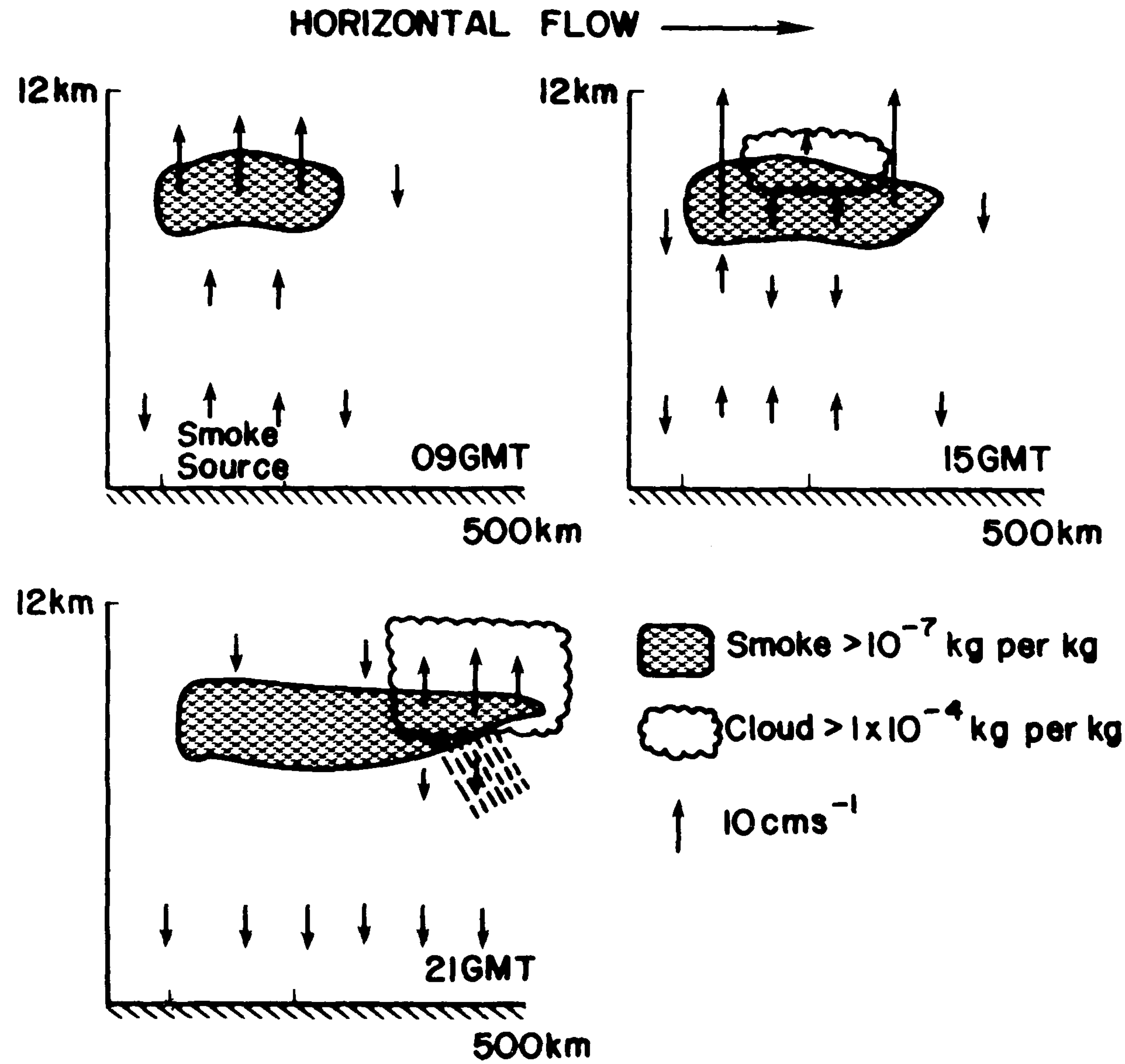

Figure 9. Schematic Representation of the Development of a Vertical Circulation About the Smoke and the Subsequent Formation of Cloud Seen in the Cross Section A-B in Figure 2.

This result is of considerable importance for two reasons. First, it demonstrates the possibility that a substantial amount of soot could be washed out in soot-generated high-level convection during the first few days after urban fires. Some careful cloud-physics modeling (and verification in the field) must still be done to determine cloud particle growth and scavenging in an environment containing many thousands of times the concentration of particulates normally present at those altitudes. The second consideration is that the smaller "precision" weapons detonated near the surface produce large quantities of highly-radioactive material that would spread out near the tropopause. This radioactive material would also be scavenged by the high-level showers and would present another hazard if the precipitation reached the surface.

4.3.8 MOST RECENT REPORTS

As the present report was being prepared, the group at NCAR began publishing results of a new series of 3-D model simulations, using the most complete set of physical effects to date. A report by Thompson and Schneider,[29] was published in *Foreign Affairs*. This choice of journal might seem unusual, but their results showed much smaller temperature effects than previous studies for a given amount of soot. Thus the article balanced a more dire picture presented by Sagan in the Winter 1983/84 issue of *Foreign Affairs*. The difference between estimates are clearly illustrated by Figure 10, taken from their article, presenting the average land temperature for 30° - 50°N, "following a hypothetical one-day nuclear war" (a July case, when effects are greatest). The NCAR climate model used in prior simulations was further modified to include aerosol removal processes (primarily rain), coalescence of particles, scattering of radiation, infrared effects for aerosols, and inclusion of dust from surface detonations. Writing for a political journal, the authors by-passed details of the simulations and discussed the political factors due to changing nuclear effects estimates, and also the potential impacts on survivors and peoples of noncombatant countries. A more detailed scientific article was prepared[30] which primarily describes the new physical effects added to the model and their impact on the calculations. In particular, the inclusion of the aerosol infrared effects results in about 6°C warmer surface temperatures and the coalescence and removal also lead to some warming. The effects of scattering were not directly computed, and only a minimum of information on dust effects was included, though it appears the effects were much smaller than found by Ramaswamy,[30] perhaps due to initial amount and height. The authors did note that some compromises were made in the formulation of the aerosol-radiation physics and also in cloud simulation (similar to other 1-D sensitivity studies) to keep CRAY-1 computer time at reasonable levels. Though these routines were not "state-of-the-art," they are believed to be sufficiently accurate to properly portray the effects of factors omitted from previous simulations.

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29. Thompson, S.L. and Schneider, S.H. (1986) Nuclear Winter reappraised, *Foreign Affairs* **64**:981-1005.

30. Thompson, S.L., Ramaswamy, V., and Covey, C. (1987) Atmospheric effects of nuclear war aerosols in general circulation model simulations: influence of smoke optical properties, *J. Geophys. Res.* **92**(D9):10942-10960.

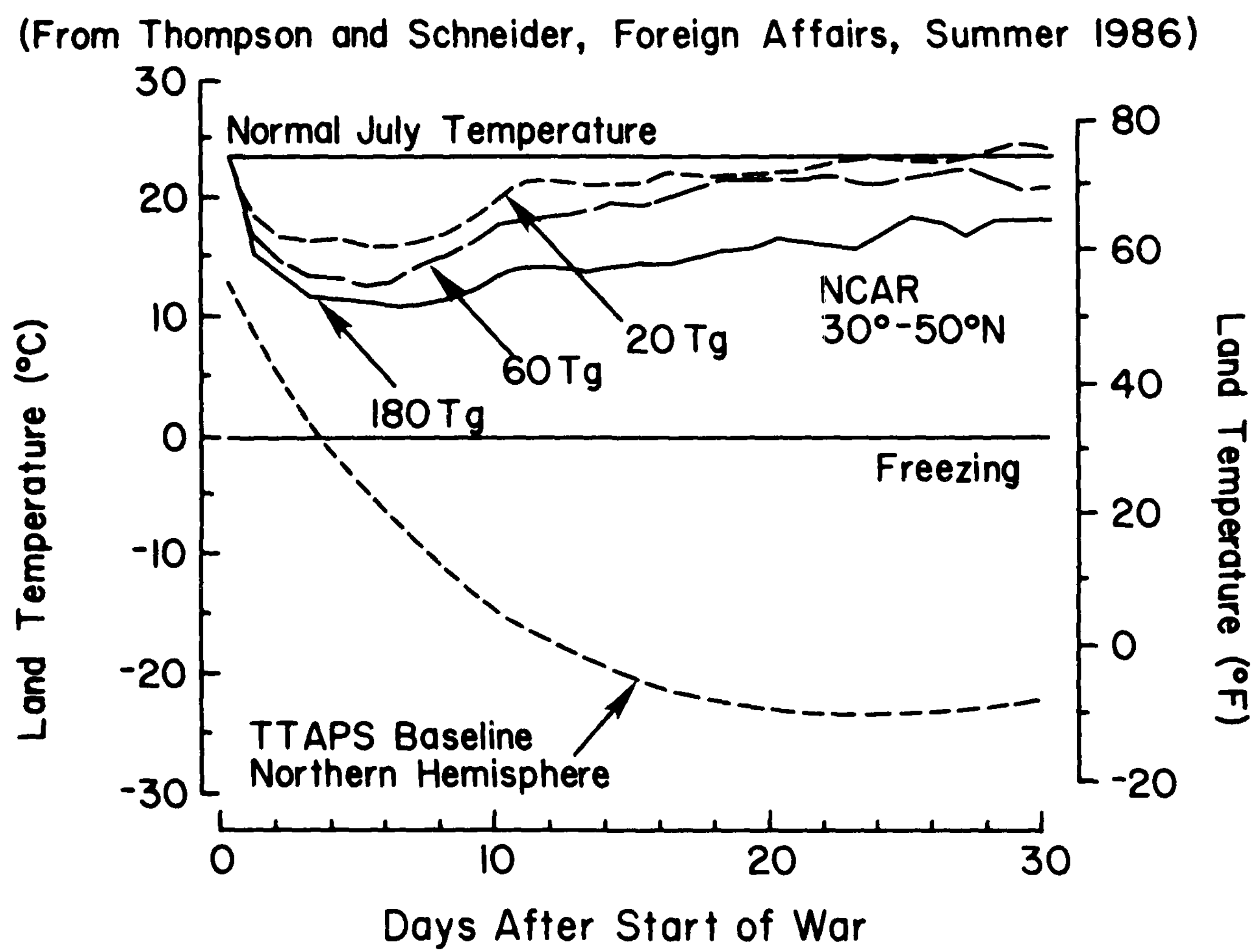

Figure 10. Surface Temperature Following Smoke Injection Calculated by Thompson and Schneider for July

5. REVIEW OF PUBLISHED COMMENTS AND MEETINGS

Rather than simply discussing all publications and meetings in chronological order, we will divide this section into reviews of: (a) comments on 1983-84 studies, (b) scientific news articles, (c) observations from forest fires, (d) letters in *Foreign Affairs*, (e) scientific conferences, meetings and seminars, (f) summaries of committee reports and (g) some recommended reading on nuclear effects.

5.1 Comments on 1983-84 Model Studies

It would be very unusual if a scientific discovery with the publicity given to "nuclear winter" did not also attract comments and criticisms. While most scientists either accepted the idea or adopted a "wait-and-see" attitude, some took the trouble to write their concerns and had them published. As previously mentioned, this is an important part of the overall review process, allowing readers a chance to reveal some "fatal" flaws, and the author the opportunity to strengthen or qualify an argument. Through the process, everyone usually gains a better understanding. We will also mention some scientific reviews of nuclear effects that were written in less technical magazines, as part of the process of presenting the idea to the general public of the world.

The first criticism that came to our attention was an article by Dr. S.F. Singer (University of Virginia) in the *Wall Street Journal*.[31] In this, he stated "I can make a case against a nuclear winter from both a scientific viewpoint and a military-strategic one". Considering the TTAPS study, "Prof. Sagan's scenario may well be correct but the range of uncertainty is so great both because of the set of assumptions used and what has been left out in discussing the physics of the situation, that the prediction isn't particularly useful". Singer argues first that dust and other particulates would "--make it difficult for heat radiation to escape into space" and that "the surface could become warmer rather than colder". He also suggested that the heat of smouldering fires had been ignored "which would make a big difference to the surface temperature". He discounted effects of oxides of nitrogen on stratospheric ozone, stating that "stratospheric ozone wouldn't remain destroyed: it reforms constantly and builds back up to its former value". In addition, dust and smoke would shield survivors from the ultraviolet radiation. Singer does not worry about a long duration of material in the stratosphere because "this would also destroy the temperature structure of the stratosphere itself" and "what had been the stratosphere would then become simply an upward extension of the troposphere, or lower atmosphere and would participate in its instability, rapid mixing and clean-up by rain". He also posed two questions "First, does prediction of a global holocaust really make nuclear war less likely? And second, should scientists therefore ignore scenarios that produce less-severe global outcomes?"

Unfortunately, we do not have a copy of the reply written by the TTAPS group in the *Wall Street Journal*, 16 Feb 1984 (p35); however, most of the points made were repeated in later letters to *Nature* and *Science* together with rebuttals. Why this first criticism should appear in *Wall Street Journal* is not known.

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31. Singer, S.F. (1984) The big chill? Challenging a nuclear scenario: *Wall Street Journal*, 3 Feb 68.

In the same issue of *Nature* that contained the first report of the NCAR CCM by Covey *et al.*[22] John Maddox[32] (an editor) wrote a commentary under the News and Reviews section. With regards to the TTAPS study of Dec 1983, "That document is less than convincing for two reasons - the promised detailed discussion of the assumptions remains unpublished, while the pardonable simplicity of the calculations of climatic effects, innocent as it is of the feedback mechanisms likely to occur in the atmosphere, is likely to exaggerate the severity of what is called nuclear winter. What Covey *et al.* have now done usefully complements the earlier calculations, but only on the second of its weak points". Maddox then noted that Covey's inclusion of clouds in the model was a plus, but that they still had left out the effects of dust from surface bursts and had not included any removal mechanism, even though the model ran out to simulate 20 days. Two conclusions: "The result is that while the new calculation shows that the grip of the nuclear winter will vary from place to place as much as does the weather, there is still a long way to go before its intensity can be calculated", and "If on the basis of the calculations so far published, some people should refuse to believe that there would be a long winter after a nuclear war, they can not easily be refuted". Three years have passed since this commentary was written, and in spite of the modeling studies completed in the interim, the last two statements are almost as true today as they were then.

The same report by Covey *et al.*[22] brought a strong response from Dr. Singer in a note to *Nature.*[33] He presented several points in his argument: 1. "The temperature change of the land surface (assuming small heat capacity) depends on a temporary imbalance between two very small heat fluxes: the inflow of solar radiation and the outflow of IR radiation as well as the inflow and outflow of other energy fluxes." Thus, "--one cannot be sure of even the sign of the temperature change until all energy fluxes have been considered". 2. He stated that the temperature change depends crucially on the particle size distribution "for the same initial mass, the coalescence of smaller particles into larger particles will increase optical depth in the IR and decrease it in the visible." 3. He noted that gases generated by the combustion would absorb and emit IR radiation. 4. He also said that water droplet clouds would effect the heat balance. 5. Continuing this line, he noted that total water vapor would double over burning areas, up to a million square kilometers with forest fires included, increasing the IR absorption and emission. 6. He again brought up the heat of combustion as a source of heat, one neglected in computations, particularly due to smouldering fires. He computed that 1 oz/ft^2 burning each day (smouldering) would release 50 W/m^2 of heat, many times the 8 W/m^2 minimum solar heating computed by TTAPS. 7. Singer also felt the washout would be faster than estimated, due to the convective activity in the sun-heated soot layer, and also due to convection associated with the land-ocean temperature contrast.

Thompson, Schneider and Covey followed with a reply[34] addressing the issues raised by Singer. 1. They were not clear on the discussion of the energy balance, but assured that all terms were present in the model which "resolved in favor of cooling". (More information on the energy balance was contained in their JGR report, 20 Jun 85, which showed that obscuring the sun by soot produced a very

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32. Maddox, J. (1984) Nuclear winter not yet established, *Nature* **308**, VII.
33. Singer S. F. (1984) Is the "nuclear winter" real? *Nature* **310**:625-626.
34. Thompson, S.L., Schneider, S.H., and Covey, C. (1984) Reply to letter by Dr. Singer, *Nature* **310**:625-626.

large initial imbalance). 2. They agreed that size is important but felt that soot particle sizes of 0.1 μm and smaller are to be expected initially and even if coagulated to 0.2 - 0.3 μm, the effect on optical depth of IR would be small. 3. "Of course 'greenhouse' gases such as C_2H_4, C_3H_6 and CO_2 will be generated by fires, but estimates of the amounts released are much too small to be capable of providing a substantial surface temperature compensating effect--". 4. On the water cloud comment, they noted that such clouds were in fact in the model, but they couldn't be sure that the "near surface" clouds were satisfactorily calculated. 5. They accepted Singer's argument about water vapor at the early stages but noted that the effect would be reduced to a hundredth by the time hemispheric spreading had taken place. 6. For the smouldering fires, they stated "areas near fires could receive significant heating as long as the fires burned" and went on to calculate that over the land area 30° to 70°N latitude, the average daily heating would be 1 W/m^2, much less than the lost normal solar heating of 200 - 300 W/m^2 per day. On the last point, they acknowledged that heating of smoke (soot) would cause mesoscale convection but noting the low relative humidities shown by the CCM simulations then questioned whether condensation would occur.

In this same issue of *Nature*, there was also an article under "Commentary", written by Dr. E. Teller[35] of Lawrence Livermore National laboratory. In this article he discussed several effects, including fallout, ozone change, dust and smoke. Overall, he took the position that many estimates of the effects were extreme and that lesser effects were more probable. In treating radioactive fallout, he focused on long-term, large scale effects (local, immediate effects would be severe) and noted calculations that 50-year doses of 20 to 250 rems would occur but would not be serious. Attacks on nuclear reactors would be a much more serious matter, but Dr. Teller thought this would be unlikely. On ozone, detonations of large numbers of multimegaton weapons could deplete ozone by 30 - 40 percent, increasing surface ultraviolet radiation, with possible effects on plant and animal life. Since the magnitudes of the changes were comparable to natural midlatitude variations, he felt "--problems related to a weakening of the ozone layer seem manageable" particularly since large weapons are being eliminated. The calculations for dust generation were, he noted, comparable to that for major volcanic eruptions, thus temperature effects would be noticeable but by no means severe on a hemispheric scale. He then went on to discuss soot and the TTAPS paper indicating that continental temperatures were expected to drop to -30°C and raised questions of soot removal in the two weeks until soot became widespread. He also noted an observation by Radke (University of Washington) that concentrations of the smallest soot particles were reduced in the capping cloud over a forest fire (only one case). He noted that the Mar 84 report of Covey *et al.* with a "somewhat more realistic model", that resulted in "the extent of the temperature reduction is lower by a factor of 2 to 10 (depending on the season) than in the Turco *et al.* study". Even in the NCAR study, he noted limitations. Teller also emphasized uncertainties of soot production by petroleum products. He concluded "Given the uncertainties and omissions in the theory on which nuclear winter is based, the concept of a severe climatic change must be considered dubious rather than robust. Nevertheless, the possibility of nuclear winter has not been excluded".

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35. Teller, E. (1984) Widespread after-effects of nuclear war, *Nature* **310**:621-624.

A slightly different type of exchange began with a note by R. J. Smith,[36] an editor of *Science*, in which he was quite critical of contributions of the Soviets to the nuclear-effects problem. He printed quotes by R. Turco (one of "TTAPS") that were highly critical and demeaning of the work by Aleksandrov, and a quote of Thompson (NCAR) pointing to model defects and an apparently incorrect conclusion. Smith went on to discuss the disappointment Turco had felt in efforts to exchange information with Soviets and questioned their motives. This note brought a reply each from Aleksandrov, Thompson and Turco,[37] published in the "Letters" section of *Science*. Aleksandrov pointed out the contacts and presentations he had made where criticism could have been made but was not. Thompson regretted that his statement "appeared in such harsh light", indicated that Aleksandrov's model had "weaknesses" rather than "defects", as all models do, and explained that the "incorrect conclusion" related to a problem in the later removal stage. He also praised Aleksandrov's "pioneering contribution". Turco also felt his comments "seemed particularly harsh" and applauded Aleksandrov's efforts. He explained his comments referred to overall limitations of the model, limited horizontal and spatial resolution, inadequate radiative properties, etc. But he noted "Aleksandrov's calculations were the first of their kind and deserved special recognition." (In fact, Aleksandrov revealed that his model used "a computer ten times faster but with less memory than an IBM Personal Computer" - few Western scientists would have undertaken GCM calculations with such limited computer support.) Turco confirmed his disappointment over further interchanges with Soviets, even though the scientists he met "are amicable, technically competent and apparently concerned about the prospect of a nuclear disaster." It appears that R. J. Smith was not very tactful in the way he presented some feelings of the scientists. However, we should note that Aleksandrov did not follow up his early modeling work with modifications that seemed logical. He disappeared the following March (1985) while attending a scientific meeting in Spain, never to be seen or heard from again. An associate, G. L. Stenchikov, continued the work with an interactive soot-GCM, but published only in a USSR Academy of Science Proceedings. In early 1984, there appeared to be an opportunity for developing some important East-West exchanges at the scientist level, but this never came to pass.

Criticisms of the original TTAPS paper were made by S. Singer and by C. Kearny, published in "Letters" to *Science* along with a rebuttal by the TTAPS authors.[38] Singer questioned whether "large particulates" and "complicated gaseous product of combustion" would increase infrared absorption, and whether water clouds and water vapor due to combustion would enhance the "greenhouse effect". He again brought up the heat of smouldering combustion. Singer then questioned the duration of nuclear winter, suggesting that lower-yield weapons would be used which do not project dust into the stratosphere, and the "stable stratosphere might be destroyed" by ozone destruction, and further, that convection would wash out smoke (soot). Kearny's criticism were directed first at soot generation by cities and second, generation by wild fires. For cities, he quoted a Soviet publication indicating little

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36. Smith, R.J. (1984) Soviets offer little help, *Science* **225**:31.

37. Aleksandrov, V., Thompson, S.L. and Turco, R. (1984) "Nuclear Winter" studies (3 letters) *Science* **225**:978-979.

38. Singer, S.F., Kearns, C.H., and Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B. and Sagan, C. (1985) On a "Nuclear Winter" (3 letters) *Science* **227**:356-362.

burning because flammable material would be buried in rubble. For wildfires, he felt TTAPS overestimated the burn areas and ignitable materials, such that the results were high by a factor of 10. He concluded by suggesting that it would be dangerous for us to overestimate nuclear-winter effects relative to what the Soviets believe as they could take advantage of our reluctance to act. The TTAPS scientists responded to Singer's comments by assuring that the infrared effects were just too small to be important, and dismissed the heat of smouldering fires argument "unless he is assuming that most of the planet might be set afire". They also conclude that Singer (as others) misinterpreted a result and emphasized that the nuclear winter effects were primarily due to soot and not to dust. Also, the heating of the soot would result in an increase in the particle lifetime. They countered Kearny's arguments by first stating that leaders would not purposely blast cities into rubble, but fires would occur when nearby targets were hit, and in Hiroshima and Nagasaki, in WW II, rubble did burn. They then recomputed the wildfire contribution, using more surface bursts, cutting total area in half, but due to more energy-per-unit-area, more fuel would burn and the change in soot production was but a small decrease. They did not find Kearny's comments on political and strategic implications to be convincing or even applicable.

5.2 Scientific News Articles

Several brief articles on "nuclear winter" have appeared in the weekly scientific magazine *Science News*. This magazine publishes articles on recent developments of interest prepared by its own staff to the scientifically-minded public. It is important not as a scientific journal, but as a source of scientific information for a large number of people. Thus, a week after the conference "The World After Nuclear War" (31 Oct - 1 Nov 83), an article by J. Raloff,[39] was published, describing the scenario and producing tables and diagrams based on material that TTAPS published in *Science* six weeks later. The article was essentially factual, though with a tendency to emphasize the extreme ends of the uncertainty. The following September, J. Raloff[40,41] reported on another conference, "The Conference on Large (Nuclear War) Scale Fire Phenomenology", organized as a coordination meeting by M. Frankel of Defense Nuclear Agency (DNA) and held at the National Bureau of Standards in Gaithersburg, MD. Short articles on this meeting appeared in two successive weekly issues of *Science News*. Much of the first item concerned the keynote address by E. Teller (LLNL) in which he suggested the TTAPS analyses may have been exaggerated and even the simple "constant sun" approximation could produce a serious overstatement of the surface cooling effect. Unfortunately, Dr. Teller's comments were inconsistent with a figure in the article (prepared by Cess, Potter and Gates). The following week, there were two notes by Raloff, "New Soviet 'Nuclear Winter' Maps", with diagrams from a more recent Aleksandrov study, and "Estimating Nuclear Forest Fires". The latter reviewed statements by C. Changler (forest fire consultant) that gave reasons for lowering the soot production estimates from forest fires, suggesting 1/2 to 1/3 the fuel-per-unit area would burn as compared to

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39. Raloff, J. (1983) Beyond Armageddon, *Science News* **124**, 12 Nov:314-317.
40. Raloff, J. (1984) Nuclear winter research heats up, *Science News* **126**, 22 Sep:182.
41. Raloff, J. (1984) New Soviet 'nuclear winter' maps, and estimating nuclear forest fires, *Science News* **126**, 29 Sep:204.

estimates of TTAPS. A letter published in *Science News*[42] of 16 Feb 1985 is perhaps of historical interest, as it took note of a science fiction story ("Torch" by C. Anvil, *Astounding Science Fiction*, April 1957) in which a nuclear warhead ignited an oil field and "--the smaller particles remain aloft and screen out part of the sun's radiation" with the result "--it's a good deal as if we'd moved the Arctic Circle down to about the fifty-fifth degree of latitude". Additional columns appearing in *Science News* were: 14 Sep 85,[43] reviewing the agricultural effects that were presented in the SCOPE 28 book, and, 12 Oct 85[44] discussing possibility of prehistoric soot layer associated with dinosaur extinction, and 19 Apr 86,[45] reviewing a 55-page Government Accounting Office report.

There were also two review articles published in the Australian general science magazine, *Search*, both written by Dr. A. B. Pittock. In the first,[46] he discussed results of the then recent studies of TTAPS, Covey *et al.* (NCAR), MacCracken, and Sagan, with figures and tables from these studies. Much emphasis was on Southern Hemisphere effect, but the full scenario was described. He also discussed published "Criticisms of Nuclear War", including those previously mentioned by Maddox, Singer, and Teller, and he noted "Overall, the critics tend to believe that the present simplifications and omissions would, if handled more rigorously (as all would want), tend to reduce the estimated effect. However, this is far from obvious...In my view, none of the criticisms to date has seriously undermined the credibility of the nuclear winter effect..." In 1986, Pittock[47] wrote an update discussing the conflicting evidence on early soot washout in plumes over fire, as well as the results of the 1984-85 climate models. The primary interest was in Southern Hemisphere effects, which though much less than in the Northern Hemisphere, might still adversely effect agriculture. He also reviewed the SCOPE 28 Volume 1 publication, presenting a rather bleak picture for civilization should such a war ever take place.

In 1986, K. Emanuel[48] (MIT) wrote a strong endorsement for a paper by Golding *et al.*[19] on mesoscale modeling of fire-generated smoke clouds (printed in the same issue). However, he was less than complimentary towards other scientists in the field. In particular, he questioned objectivity, criticized "failure to quantify the large uncertainties", "the highly approximate nature of the global circulation models", and "the appearance of the results in popular literature before being exposed to the rigours of peer review". He praised the work of Golding *et al.* and their more appropriate resolution in their 3-D model. Emanuel did note limitations in the model study, such as fixed soot pattern, lack of soot-water interaction, but concluded "The paper is a welcome step in transforming nuclear winter research from a means of political advocacy to a scientific exercise." Statements like this are sometimes made in meetings to provoke discussion, but rarely are they printed, and thus it is of no

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42. Parsons, T.G. (1985) Early forecast of nuclear winter, *Science News* **127**, 16 Feb:99.
43. Raloff, J. (1985) Nuclear Winter: Shutting down the farm? *Science News* **128**, 14 Sep:171-173.
44. Weisburd, S. (1985) Wildfires: Apocalypse then and now, *Science News* **128**, 12 Oct:228.
45. (In "Science and Society") (1986) Nuclear winter status report, *Science News* **129**, 19 Apr:249.
46. Pittock, A.B. (1984) Australia and nuclear winter, *Search* **15**:332-339.
47. Pittock, A.B. (1986) Rapid developments on nuclear winter, *Search* **17**:23-24.
48. Emanuel, K.A. (1986) Towards a scientific exercise, *Nature* **319**, 23 Jan:259.

surprise that Schneider, Thompson and Covey (NCAR)[49] wrote a reply. They took issue with some of the insinuations about political motivation as well as neglect of mesoscale removal processes, and pointed out that the mesoscale modelers still have much to do on the moist processes involving soot. They felt all of the related research, including Golding *et al.* are part of "a logical progression of scientific research." From our viewpoint, it would seem that had Emanuel made his comments two years earlier they would have been more to the point, as at that time, some statements and information were reaching the press with a minimum of peer review - principally through scientific meetings covered by the press. At such meetings, scientists do criticize studies, but this is not a formal peer review. We must also note that Emanuel did raise an interesting point about the objectivity when emotional issues are involved.

5.3 Observations from Forest Fires

During discussions among scientists, there had been talk of taking useful measurements in smoke plumes from forest fires, such as the controlled burn planned to take place in Chapleau, Ontario, in the summer of 1985. A memorandum from the Institute for Defense Analysis (IDA) on 11 Jun 85 described the planned burn to destroy insect infested timber, and invited observers and investigators to participate. An article in the *Boston Globe* on 18 July "Canada fire to test 'nuclear winter' theory" announced the planned forest-fire burn and the application to smoke production and removal problems. However, an article in *Defense Week* on 29 July "Nuclear winter researchers fiddle while west burns" described the frustration (and failure) of a scientist, Peter Hobbs, Univ. of Washington, in his attempts to obtain funding to finance instrumented aircraft flights over forest fires. The response of DNA was quoted as "An opportunity? Yes. A good opportunity, no.!" Thus, some intense forest fires in several western states were not measured by aircraft, nor were any aircraft available to measure and sample the Chapleau, Ontario burn. Fortunately, R. Turco of R&D Associates was present to observe the Chapleau burn that took place on 3 Aug 85, taking careful notes and writing a 10-page *Memorandum of the Chapleau Fire*, distributed to some 24 interested research groups. In this memorandum, he described the 3-stage burn of 6.4 km^2 (1,600 acres) of flattened timber, ignited by a helicopter spiraling outwards. An intense smoke plume rose from the fire to about 6 km (20,000 ft), with a capping cloud but no precipitation evident, and considerable amounts of smoke escaped from the sides. From GOES satellite imagery obtained from AFGL, he noted that the detectable plume had spread downwind in 4 hours and was about 110×27 km in size. About 2000 km^2 were "--covered with dense smoke". While there was no evidence for "washout" of soot by precipitation, there was no way to quantitatively determine any changes in the composition or size distribution of particulates passing through the capping cloud.

49. Schneider, S.H., Thompson, S.L., and Covey, C. (1986) The mesoscale effects of nuclear winter, *Nature* **320**, 10 Apr:491.

5.4 Letters in *Foreign Affairs*

The Thompson and Schneider article in *Foreign Affairs*[30] showing much lower cooling than the original TTAPS study, resulted in an interesting exchange of correspondence, in the next issue of *Foreign Affairs*.[50] The exchange started with a letter by Sagan pointing out that the reproduction of the TTAPS temperature curve was "misleading" in that it did not show the modifying ocean effects mentioned in the text. Also, he questioned the low altitude of the injected soot and the early removal in the latest NCAR test. Sagan mentioned long-term adverse effects and discussed questions of a weapons "threshold" level, targeting uncertainty (particularly if irrational leaders were in control), and expressed a belief that to avoid catastrophe, we must "reduce the global nuclear arsenals below the level at which nuclear winter could conceivably occur". He also discussed implications of Strategic Defense Initiative (SDI). A letter by Turco did not question the recent NCAR results, but did point out that summertime cooling of only 5° - 10°C (9° - 18°F) would cause severe agricultural problems, and steps towards weapons reduction and control of the arms race should be taken. In their letter, Rathjens and Siegel (MIT) were gratified to see the more "temperate" effects from "The most impressive modelling we have seen yet". They even suggest the term "nuclear fall" (rather than "nuclear winter") may overstate things, particularly since the 60-million-ton case may be the most reasonable. They concluded by downplaying nuclear winter as dwarfed by other effects, even a "diversion" from the other effects. Thompson and Schneider replied to these comments. First, they discounted the concept of a "threshold" level (between major and minor climatic effects) because of the great spatial variability of cooling and the targeting uncertainty. Also, they felt the diagram with the TTAPS curve was not misleading and that even adjusting for ocean effects, the difference would still be large. They agreed to some extent that effects beyond 30 days could be important, such as early fall frosts. They cautioned about Rathjen and Siegel's interpretation of small [3.5°C(6.3°F)] cooling from 10° to 30°N latitude as not serious because of both model uncertainty and possible disruption of monsoon rainfall that could cause massive starvation. Rather than debate about "nuclear fall", Thompson and Schneider stated a willingness to accept "nuclear winter" in a broader sense (reduced sunlight, severe fallout, massive air pollution) as "generally inimical to many forms of life".

5.5 Scientific Conferences, Meetings and Seminars.

Scientific meetings serve several purposes that are quite important to both the scientific community and the general public. The backbone of any meeting is usually the papers prepared many months in advance, but there is a flexibility for scientists to add last-minute results, and for conference organizers to add last-minute papers of great interest. Thus, one expects to find the most up-to-date information on the subjects covered at these meetings. Another advantage is that there is an opportunity for one-on-one discussion among scientists to clarify points and exchange stimulating ideas. Most meetings concerning meteorology are not covered by the press, but when "hot" topics are discussed on occasion, science reporters from *Science*, *Science News*, or even a press service may be present (this happened at the meetings relating to "nuclear winter" in the fall of 1983). A disadvantage

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50. Sagan, C., Turco, R.P., Rathjens, G.W. and Siegel, R.H., and Thompson, S.L. and Schneider, S.H. (1986) Nuclear Winter debate (3 letters and reply) *Foreign Affairs* **65**:164-178.

of the meetings is that one is often left with sketchy memories and handwritten notes, particularly for the items added at the last minute (which are often the most important). While published "preprint" or "proceedings" volumes may become available, they are often too brief and too dissimilar to the actual presentation to be useful. Because the meetings are a very quick way to exchange information, the scientists chose this means during the early stages of the nuclear-effects research.

After the 1982 report by Crutzen and Birks[6] (published in *Ambio*), a number of scientists recognized the potential seriousness of the fire-generated soot: thus, and after some simple modelling was done, a specially-assembled conference on "Longterm Worldwide Biological Consequences of Nuclear War" was held in Cambridge, MA on 25 - 26 Apr 83. The focus of the meeting was to uncover potential biological consequences from changing solar radiation and surface temperature. A committee representing the 40 attending scientists prepared a report of their findings and presented the report to the "Conference on the World After Nuclear War" held in Washington DC, 31 Oct 83. In addition, an article describing the findings was published in *Science*, 23 Dec 83, pp 1293-1300. The surface temperatures and surface sunlight used in their biological appraisal appear to be more extreme than the "baseline" case of the TTAPS scientists (published in same issue of *Science*), likely due to an earlier calculation.

On the other side of the Atlantic, a meeting specifically related to atmospheric effects of a nuclear conflict was held in Erice, Sicily, 17 - 23 Aug 83 - "The Third International Conference on Nuclear War". Aleksandrov (USSR Academy of Science), MacCracken (LLNL), and Cess (State University of New York at Stony Brook) all presented papers modelling the effects of soot on the atmosphere. Other scientists addressed changes in atmospheric chemistry (for example ozone), solar radiation, and global-scale radioactivity, as well as ecological effects.

Two months later, a conference "The World After Nuclear War" was held in Washington DC, 31 Oct - 1 Nov 83. There was no published preprint or proceedings volume, but a review by J. Raloff[39] was published in *Science News* (see Section 5.2). Many of the scientists who presented papers at Erice, Sicily, were present (perhaps repeating the talks) but, in addition, the results of the TTAPS group and of Schneider (NCAR) were presented. As mentioned previously, the "biological consequence" committee presented their findings.

Only six weeks later, 5 - 10 Dec 83, the American Geophysical Union (AGU) held two sessions on "Geophysical and geochemical consequences of nuclear explosives" during their annual meeting in San Francisco, CA. The presentations were primarily invited papers from researchers active in the nuclear winter area - Turco, Toon, Ackerman, Pollack, Sagan (TTAPS), MacCracken, Luther, Penner, Thompson, Covey, Schneider, Kiehl, Chang, *et al.* The AFGL representative present noted that due to advance publicity, it was "standing room only" at these sessions. Papers were largely repeats of previous presentations, but for many, this was the first in-depth exposure to the problem.

After the numerous meetings during the last half of 1983, the scientists apparently worked to improve the models and there were neither significant new results nor major conferences during 1984. As previously noted, Aleksandrov (USSR) presented a seminar at MIT on 7 Mar 84, describing his relatively simple 3-D model and the results of his simulations. The model showed less (but still important) cooling than the 1-D models (TTAPS) due to ocean effects and also showed a significant disruption of tropical wind patterns that are associated with the rainfall belts. At the end of his talk, he freely answered questions (excellent English) and the scientists present were favorably impressed with his capabilities, particularly obtaining results with limited computing power. Later in March, Brenner and Muench of AFGL participated in informal talks with scientists at Los Alamos, Lawrence Livermore, NASA Ames, and NCAR, discussing all aspects of the nuclear-effects problems and the approaches being taken. These meetings became the basis for the report submitted to AFWL in June 1984. At an international cloud-physics meeting in Tallin, Estonia (USSR), August 1984, a session was held with papers related to nuclear effect, with discussions covering a number of topics (some political): Banta of AFGL was present and noted little new information generated. A special meeting held by DNA in September 1984 at Gaithersburg, MD was not attended by AFGL scientists, but reports of the meeting were reviewed and discussed in Section 5.2.2 of this report.

The American Meteorological Society at their annual meeting held in Los Angeles planned a full session on 8 January 1985 on global nuclear effects, featuring invited papers from noted, active scientists and a presentation on the National Research Plan for assessing consequences of nuclear war. The AFGL attendant, Brenner, was disappointed in the session, as some papers including the National Research Plan were withdrawn, while others tended to repeat earlier results. Some model results of urban fires suggested earlier estimates of plume rise might be too low.

A comprehensive meeting on global effects of nuclear war was organized by DNA, and took place in Santa Barbara, CA 12 - 14 February 1985. An important feature of this meeting to note: not only were atmospheric physicists and modelers represented but also specialists on combustion were invited. Banta and Muench from AFGL attended, with Banta presenting a paper on urban fire-plume modeling. The AFGL participants noted in their summary "Overall, the papers presented did little to reduce the substantial uncertainty that exists in determining potential postnuclear exchange environments. However, the group did present interesting new evidence, and did focus attention on some major problems." Papers showing preliminary results of GCM simulations indicated a "lofting" of sunheated soot. Some important, unresolved issues raised were: fire intensity (important to fire-plume height), precipitation scavenging in fire plumes and later cloud systems, particle coagulation, and soot "blackness."

During the summer of 1985, nine important studies were published on nuclear effects (reviewed in Section 4.2), and most of these studies were also presented at the IAMAP/IAPSO meeting in Honolulu, HI, August 1985 (including a paper of Dr Banta's). The new GCM simulations of Los Alamos and NCAR showed more realistic evolution of the patterns with their interactions between soot and atmosphere, but the modelers were criticized for inadequate removal, and the neglect of both coagulation and soot infrared effects. Depletion of soot by ozone appeared to be a slow but possibly important factor. Some papers were presented on the effects of soot on snow cover in the arctic but were inconclusive due to incomplete model physics. The prepared summary pointed out the gap between urban fire-plume models and the 3-D global models. The first step towards filling this gap was a mesoscale model developed by the British Meteorological Office, simulating effects of solar heating of an elevated soot layer, which indicated high-level precipitation would likely occur.

During 25 - 27 February 1986, DNA again sponsored a major conference on nuclear environmental effects at the NASA Ames laboratory, Moffett Field, CA. Some 56 presentations were made, covering the whole field from fuel loading to combustion technology to atmospheric physics and modeling. There were a number of papers that indicated the effects of urban fires had previously been overestimated. Newer computations of fuel loading were down by as much as a factor of 3. Also, calculations of soot coagulation showed substantial reductions (up to a factor of 3) in optical depths might occur, for sunlight, with increasing low-level warming through infrared soot effects. Other papers covered plans and ongoing laboratory research to make improved measurements of soot properties with modern equipment. Similarly, field experiments have been planned to use aircraft to sample and measure smoke plumes from controlled fires (for example, Lodi Canyon, CA, fall 1986). Model simulations were presented that tested sensitivity of results to washout, coagulation of soot, and infrared soot effects. It was noted that these models needed to be validated with tests simulating behavior of natural aerosols (volcanic dust, man-made pollutants, dust storms), which unfortunately are not routinely observed in any detail.

5.6 Summaries of Committee Reports

Several organizations formed special committees to summarize and evaluate information on the effects of a nuclear exchange. In most cases, experts in the field were consulted, and the latest available information was collected and promptly published. The resulting publications were not independent in the sense that many, if not most, of the experts were consulted. Thus, these publications should be looked on as a sequence in time with the best available information.

5.6.1 AAAS REPORT

The American Association for the Advancement of Science (AAAS) held a symposium in Detroit, MI, in May 1983 on environmental effect, and material from that symposium was collected, edited, and published as a 204 page volume, edited by London and White.[51] At that early date, there was little quantitative information available on the atmospheric effect of fires generated by nuclear attacks, so the material presented on this aspect was sketchy and has since become obsolete. However, most of the book was devoted to other nuclear effects including release of radioactive material, bomb blasts, biological effects, and ozone reduction in the stratosphere. Some of the biological information was relatively new and differed from earlier estimates of tolerances to radiation.

5.6.2 NRC/NAS REPORT

In response to a request from the DoD, the National Research Council (NRC) of the National Academy of Science (NAS) assembled a special committee to assess possible atmospheric effects of a nuclear war. This committee consisted of 18 distinguished scientists with expertise in a wide variety of fields. After about a year and a half, a comprehensive report entitled, "The Effects on the Atmosphere of a Major Nuclear War" (192 pages), was published by the National Academy Press.[5] This is a rather technical document, intended for people with a scientific background. The report is also very complete, covering all aspects of the problem, most in more detail than we have in this report. The references are quite extensive. The following outlines the report by listing the chapters and principal subjects:

1. Summary and Conclusions: Background, the Committee's Baseline Case, Notes on the Nature and Significance of Uncertainty, Conclusion.

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51. London, J. and White, G.F. (1984) *Environmental Effects of Nuclear War*, AAAS Selected Symposium No. 98, AAAS, Washington, DC. Also published by Westview Press, Inc. Boulder, CO.

2. Recommendations for Research: Atmospheric Simulations, Fire Phenomena, Radioactive Fallout, Dust Effects, Ozone Depletion, Volcano/Meteorite Studies.

3. Baseline Nuclear Exchange: Selection of Case, Nuclear Arsenals.

4. Dust: Nuclear Cloud Dynamics, Dust Lofting, Sources of Dust, Observations, Particle Size Distribution, Optical Properties, Baseline Case Dust, Excursions.

5. Fire: Overview, Present-Day Emission and Removal, Historic Fire Experience, Ignition of Nuclear Fires, Combustible Materials, Smoke Emissions and Properties, Smoke Emission in Nuclear Exchange, Uncertainties, Summary. Appendices: Observation of Plume Heights, Water in Nuclear Clouds.

6. Chemistry: Gaseous Emissions for Nuclear Fireballs and Fires, Effects of Emissions.

7. Atmospheric Effects and Interactions: Overview; Early Spread; Direct Optical Effects; Thermal Effects in 1-D Models; Thermal and Circulation Effects in 2-, 3-D Models, Modification of Cloudiness, Precipitation and Winds; Analogs; Summary.

8. Use of Climatic Effects of Volcanic Eruptions and Extraterrestrial Impacts on the Earth as Analogs.

Appendix: Evolution of Knowledge About Long Term Nuclear Effects. For atmospheric modelers, the most important part of the report was the listing of soot loading and characteristics for their "baseline case," which is illustrated by Table 5.3 taken from the NRC/NAS report.

5.6.3 DOD REPORT TO CONGRESS

As part of a Defense Authorization Act, Congress directed that two actions be taken by the Department of Defense. First, that the Secretary of Defense participate in studies of consequences of nuclear war and implication to strategy and policy. Second, that an unclassified report be prepared by 1 March 1985 containing a detailed review and assessment of current studies on nuclear effects as well as implication on strategy, arms control, and civil defense and analysis of similar activities in the Soviet Union. To meet the second requirement, a 17 page report[52] was delivered to Congress by the specified date. The report is relatively non-technical and highly qualitative in the description, rarely stating any actual numbers. The first part described the potential climatic response, followed by a discussion of the TTAPS study, emphasizing weaknesses of the 1-D model and uncertainties in the results. A study by Small and Bush indicating far lower smoke emissions from wildfires than used in the TTAPS study was noted. The DoD study completed the review section by quoting some conclusions from the NRC/NAS report that stated it was clearly possible that nuclear war could produce severe climatic effects over large areas within the range of uncertainty. Next, the roles of DoD and Department of Energy (DoE) in the Interagency Research Plan were discussed in rather broad terms. Proceeding to "Current Appreciation of Technical Issues," DoD made the statement that it had "very little confidence in the near-term ability to predict this phenomenon quantitatively" because of uncertainties. The policy of deterrence was reviewed, noting "our strategy consciously does not target population" and that older deterrent systems that might risk climatic effects were being retired. Having flexibility in targeting, "these options may allow us to adjust our planning so as to reduce the

52. Weinberger, C. (1985) *The Potential Effects of Nuclear War on the Climate*, DoD Report to Congress.

danger of climatic effects as our understanding develops." Arms reductions through negotiations were discussed but expectations were that near-term reductions would not significantly reduce potential climatic effects. DoD felt that the Strategic Defense Initiative (SDI) might be an answer to the nuclear effects problem by making the weapons obsolete. The report concluded with a section on Soviet activities related to climatic effect, largely belittling their contributions, pointing to the model of Aleksandrov and Stenchikov as a "borrowed, obsolete U. S. model" and stating "their findings do not represent independent verification of the hypothesis." It also pointed out that the Soviet scientists "contributed very little,"* "the flow of useful technical work has been almost all one-way," and that U.S. requests to the Soviet for information related to pre-1963 nuclear tests and also large-scale fires were ignored. As for impact of nuclear effects on strategy, the report stated "If the Soviets see this issue as a matter that might substantially affect their policies, strategy or force structure, those views have so far been hidden from us." Overall, the report was a bit of a disappointment to many in that the models discussed were not current and the treatment of issues was shallow.

5.6.4 SCOPE 28 REPORT

In September 1982, the International Council of Scientific Unions** recognized the need for public understanding of the consequences of using nuclear weapons and urged that a special committee "prepare a report for wide dissemination that would be an unemotional, non-political and readily understandable statement of the effects of a nuclear war, even a limited one, on human beings and other parts of the biosphere." A standing committee, the Scientific Committee on Problems in the Environment (SCOPE)*** took on this task, forming the Environmental Consequences of Nuclear War (ENUWAR) group, and set about gathering information from scientists around the world. Much of the motivation no doubt arose from moral and ethical concerns about use of nuclear weapons, but nevertheless, the committee was to focus on "scientific knowledge" and not "political policy." With the aid and assistance of some 350 scientists around the world, the group worked for three years and published "Environmental Consequences of Nuclear War, SCOPE 28" in 2 volumes[7]: the first was "Physical and Atmospheric Effects," and the second, "Ecological and Agricultural Effects." The books were published by John Wiley & Sons, New York, 1985 (also Chichester, Toronto, Brisbane, and Singapore). The volume on atmospheric effects is somewhat less technical than the previously-discussed report by NRC/NAS and also benefits by having a 14-page glossary of technical words. By waiting until late 1985 for publication, they were able to include results from some fairly-complete model simulations and sensitivity studies, most of which were reviewed in section 4.3 of this study (several illustrations in Section 4.3 can also be found in the SCOPE volume 1). The volume on ecology

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* Considering that all of the U.S. model simulations reviewed in Section 4 of the present report were run on computers more powerful than any within the Soviet Union, there was in fact no opportunity for Soviet scientists to make similar contributions. Unable to obtain detailed solutions of the equations through computers, some scientists (for example, Golitsyn) made simplifications and obtained results valid for large optical depths of soot.

** The Council is composed of members from 66 Academies of Science, 20 Scientific Unions, and 19 Scientific Associates)

*** SCOPE had previously published 27 reports, mostly related to particular aspects of civilization's large-scale effects on the environment.

and agriculture examined sensitivity to changes of temperature, sunlight, precipitation, and radioactivity that might result from nuclear war. An important concern addressed was the feeding of the world after such a war, including the factors affecting crops and pasture from seeding to harvesting, as well as food distribution and reserves. The combination of a couple of summer months cooled by 2° - 4°C together with reduced sunlight and precipitation, and disrupted transportation could mean starvation for many (perhaps a billion) people. While considerable numerical data on crop sensitivity are presented, no attempt was made to make an overall "baseline" estimate. The following outline indicates the chapters and contents of the two volumes:

Volume 1, Physical and Atmospheric Effects

Foreword

Executive Summary

1. Direct Effects of Nuclear Detonation: Hiroshima and Nagasaki, Thermal Irradiation, Dynamic Phenomena, Radioactivity, High Altitude Explosions, Resume of Effects, Integration of Effects.

2. Scenarios for a Nuclear Exchange: Arsenals, Targets, Strategic Concepts, Scenarios, Implications.

3. Sources and Properties of Smoke and Dust: Origin of Smoke, Emissions from Urban/ Industrial Fires, Particulate Emissions from Wildland Fires, Microphysical Processes, Optical Properties, Attenuation of Visible Light, Dust, Appendix-Urban Fire Development.

4. Atmospheric Processes: Short-Term Response to Surface Fires, Mesoscale Response, Synoptic-Scale Response, Interaction with Solar and Infrared Radiation, Other Interactions, Geophysical Analogues.

5. Meteorological and Climatological Effects: Results of 1-D Models, Results of GCM's with fixed smoke, Results of GCM's with Interactive Smoke, Non-linearities and Thresholds, Summary of Modelling Results, Extrapolation from Model Results, Provisional Temperature Scenarios.

6. Nuclear and Post-Nuclear Chemical Pollutants Perturbations: Emissions and Short-Term Pollutants, Stratospheric Chemistry, Tropospheric Effects, Summary.

7. Radiological Dose Assessments: Local Fallout, Global Fallout, Internal Dose, Summary. Appendix: Radioactivity from Nuclear Fuel Facility.

8. Research Recommendations: Strategic Doctrine, Electromagnetic Pulse, Dust, Fuel Loading, Smoke Production and Properties, Fire and Plume Modeling, Chemistry, Radioactivity.

References (19 pages)

Appendix: Executive Summary of Volume II, Glossary, List of Workshop Participants and Contributors (about 350).

Volume II Ecological and Agricultural Effects

1. Ecological Principles Relevant to Nuclear War: Introduction, Ecophysiology, Plant Strategies, Seed Banks, Community Succession, World Biomes.

2. Vulnerability of Ecological Systems to Climatic Effects of a Nuclear War: Introduction, Potential Effects on North Temperate Ecosystem, on Temperate Grasslands, on Arid and Semi-arid Ecosystems, on Equatic Ecosystems, on Tropical Ecosystems, on Southern Hemisphere Ecosystems. Appendix.

3. Additional Potential Effects of Nuclear War on Ecological Systems: Introduction, Response and Effect of UV-B, Atmospheric Pollutants, Biological Response to Ionizing Radiation, Ecological Effects of Fire, Summary.

4. Potential Effects of Nuclear War on Agricultural Productivity: Introduction; Vulnerability to Climatic Perturbations; Potential Vulnerability of Northern Temperate Agriculture, of Tropical Agriculture, of Extratropical Southern Hemisphere Agriculture; Potential Effects on Agriculture of Alterations in Human Subsidies.

5. Food Availability after Nuclear War: Introduction; Methods and Assumptions; Results: Analysis of 15 Representative Countries, Sensitivity Analyses, Summary and Global Analysis.

6. Experiences and Extrapolations from Hiroshima and Nagasaki: Lessons from Hiroshima and Nagasaki, Extrapolations from Hiroshima and Nagasaki and other Disasters, Summary.

7. Integration of Effects on Human Populations: Introduction, Effects During the Initial Year, Effects During the Subsequent Years, Factors Affecting Long-Term Agricultural Redevelopment, Summary.

Appendices: A - List of Participants, B - Recommendations for Future Research, C - Executive Summary of Volume I

The subjects discussed in these two volumes are evidence of how thoroughly the ENUWAR group investigated the potential effects. They appear to have been reasonably objective in searching out material and presenting conflicting results when found. The news is by no means all bad, as can be seen in Table 7 summarizing ecological effects, which was extracted from Volume II of SCOPE 28. Since this is outside of our field of expertise, we present the results without any evaluation, except to point out that the primary concerns are temperature affecting agriculture and tropical forests, reduced sunlight affecting marine life, and radioactive fallout affecting conifers, all in the summer season. While crop damage due to the freezing of plant cells occurs quickly as temperatures fall (taking an hour or less), the other effects described would require anomalous conditions to persist over several weeks or months.

5.7 Some Recommended Reading on Nuclear Effects

Since this is a continuously-evolving field, any given publication is likely to become obsolete within a year or two. Thus we will suggest a few sources that provide excellent background material, although detailed results may be based on early, incomplete models. We will also indicate which scientific journals are likely to report the latest studies (including addresses where further information can be obtained).

1. Comprehensive Technical Reports

   "The Effects on the Atmosphere of a Major Nuclear Exchange", National Research Council/National Academy of Science, National Academy Press, Washington, D.C., 1985. (Reviewed in Section 5.4).

   "Environmental Consequence of Nuclear War": Vol I Physical and Atmospheric Effects; Vol II Ecological and Agricultural Effects" SCOPE 28, John Wiley & Sons, New York, 1986. (Reviewed in Section 5.4).

Table 7. Summary of Consequences for Ecological Systems*
STRESS/RESPONSE

SYSTEM TYPE	temp.	light	ppt.	rad.	UV-B	air pollutants	fire
agriculture	●●●●	●	●●●	●●	●	●●	●
tundra/alpine	◆ ◇	● ◇	● ○	● ○	● ○	● ○	● ○
boreal forests	●● ○	● ○	● ○	●● ○	● ○	● ○	● ○
temperate forests							
deciduous	●● ○	● ○	●● ○	●● ○	● ○	●● ○	●● ○
coniferous	●● ○	● ○	●● ○	●●● ○	● ○	● ○	●● ○
tropical forests	●●● ○○○	● ○	●● ○○	● ○	●● ○○	● ○	●● ○○
grasslands	●● ○	● ○	●● ○	● ○	● ○	● ○	●● ○
lakes and streams	●● ○	●● ○	●● ○	● ○	●● ○○	● ○	◆ ◇
estuaries	●● ○	●●● ○○	● ○	● ○	●● ○	●● ○	◆ ◇
marine	◆ ◇	●●● ○○	◆ ◇	◆ ◇	●● ○○	◆ ◇	◆ ◇

* Highly generalized representation of consequences of various physical stresses on biological systems resulting from nuclear war. Includes both acute and chronic stresses and reflects large-scale effects rather than localized situations. Stresses are:

temp.	air temperature reductions	UV-B	increased uv-B from ozone depletion
light	incident sunlight reductions	air pollutants	toxic gases (e.g., O_3, SO_2, NO_X)
ppt.	precipitation reductions	fire	initiated by nuclear detonations or from increased frequency later
rad.	fallout radiation		

Symbols in the chart reflect both the extent of the stress on the specified system and the vulnerability of that system to the specified stress. Open symbols represent consequences if stresses occurred in winter, closed symbols for stresses in summer. Symbols are:

summer	winter	
◆	◇	essentially no effect
●	○	low effect
●●	○○	medium effect
●●●	○○○	large effect
●●●●	○○○○	extremely large effect

ii. Comprehensive Non-Technical Report

"Planet Earth in Jeopardy, Environmental Consequences of Nuclear War", L. Dotto, John Wiley & Sons, New York, 1986. (Based on SCOPE 28 Volumes I, II; available in paperback).

New information on nuclear effects and/or related topics is apt to appear in any one of a variety of scientific journals, depending on the type of study (for example, GCM model, cloud physics, radiation) or how important the results appear to be. Based on publications of the past year and also more recent submissions, the following journals should be monitored.

i. Journal of Geophysical Research (Atmosphere-D), monthly, American Geophysical Union (2000 Florida Ave, NW, Washington, D.C. 20009) - model simulation studies, aerosol and cloud physics.

ii. Climatic Change, 6/year, D. Reidel Publication Co. (10 Phillip Drive, Assinippi Park, Norwell, MA 02061) - model simulations.

iii. Tellus (Series B: Chemical and Physical Meteorology), 5/year, Swedish Geophysical Society (Munksgaard, 35, Norre Sogarde, DK-1016, Copenhagen K, Denmark) - aerosol transport, cloud physics.

iv. Atmospheric Environment, monthly, Pergammon Press, Oxford, NY (Maxwell House, Fairview Park, Elmsford, NY 10523) - air pollution studies, model simulations.

v. Nature, weekly, MacMillan Journals Ltd (1134 National Press Building, Washington, D.C. 20045) - announcements, abridged model studies, commentary.

vi. EOS (Transactions), weekly, American Geophysical Union (2000 Florida Ave. NW, Washington, D.C. 20009) - announcements, abridged reports, abstracts from meeting presentations.

6. POTENTIAL IMPACT ON USAF OPERATIONS

6.1 Introduction

The many studies already performed on the atmospheric effects of a major nuclear conflict all indicate a potential for direct and indirect impacts of AF operations in the days and weeks following an exchange. There is considerable uncertainty about the many factors that must be known before computing potential impact on operations. Considering the uncertainty, it might be prudent to make only a general summary of potential effects, but this would be of little help to those responsible for contingency plans. As an alternative, we have made some computations based on low and high values of estimated soot and dust injections and removal rates, and use the limited-model simulations to indicate the time and space variations of some of the important elements (viz., optical extinction and visibility). Similarly, results of global model simulations are used to indicate time and space variations of temperatures at the surface and aloft. However, the simulations thus far have not had sufficient detail to estimate changes in surface winds, clouds, precipitation, and fog, so that only qualitative discussions of these factors are made.

In order to judge potential impact on AF operations, one would require a sizable quantity of information on the sensitivity of activities to the factors altered by the dust and smoke, and the scope of such a detailed analysis of potential impact is beyond our resources. The aircraft, weapons systems, and operational procedures have all been developed based on the "normal" variety of conditions found in the atmosphere. Thus, we can make an assessment of impact by pointing out large departures of conditions from those normally found, as being likely to affect operations.

The potential impacts have been separated into three different groups: those directly related to smoke and dust clouds, those related to the resulting changed weather patterns, and indirect impacts. As previously mentioned, two different initial loads of soot and dust were considered. In the first case, 24 Tg of smoke was assumed to be generated by urban fires, 6 Tg by rural fires (wildfires) and 20 Tg of dust (sub-micron in size) from near-surface detonations. These represent figures towards the low end of recent estimates of Bing,[11] Penner,[10] and Crutzen *et al.*[9] In addition, the absorption properties were assumed to drop off due to particle accretion (3 m^2/gm to 1.2 m^2/gm) and a 50 percent removal by precipitation in ten days and 80 percent in 30 days, which are somewhat faster than simulated by Malone *et al.*,[25] in their summer case. For a "larger" estimate to moderately bracket the uncertainty, 80 Tg of urban smoke was assumed, together with 30 Tg of rural smoke and 40 Tg of dust. These values are larger than what many investigators might feel to be a best guess, but are considerably smaller than earlier studies such as the "baselines" of the TTAPS[2] study and the NRC/NAS[5] report. Coalescence was assumed to drop absorption from 2.5 m^2/gm to 2.0 m^2/gm and a slower washout of 23 percent in ten days and 40 percent in thirty days was assumed, which while slower than that of Malone *et al.*,[25] might well occur if there were interference in normal cloud processes due to excessive numbers of small particles. The numbers for both the smaller and larger emissions are a little different than those shown in Section 3 of this report, as some adjustments were necessary to match the values used by model simulations reported in literature.

6.2 Direct Impact of Smoke and Dust

Near-surface bursts of nuclear weapons (attacking "hard" targets such as missile silos) produce clouds of debris that rise to altitudes of 10 - 12 km for small weapons and 15 - 25 km for multimegaton weapons. This debris consists of many sizes, from 0.2 micron particles (sub-microscopic) to sand grains to even small pebbles, though everything larger than about 20 microns falls out within an hour or two. While data on size distribution and composition are not very complete, they are sufficient to estimate production rates of sub-micron size particles as roughly 0.03 million tons per megaton of explosive power. There is scatter in the basic data (see NRC/NAS[5] report for details) indicating variations due to burst altitude and soil composition, but the production estimates are probably more reliable than those for soot. The dust is largely formed by the effects of melting, blasting, and vaporization of soil and rocks, and the particles formed vary from tiny glassy particles to some more crystalline in form. The potential direct impact comes from the very large number of small particles that scatter visible and infrared radiation, the abrasive characteristic of particles (for example, quartz and corundum), and the residual radioactivity from the detonated weapon.

Table 8 contains estimates of the optical effects of soot and dust clouds. The top line shows a representative cloud about three hours after detonation of a single 0.5 Mt surface burst, assuming no mixing with other clouds and no water particles remaining. This would be about a 10-km radius (6 nm) cloud, stabilizing between 10 and 15 km (30 - 50 kft), with about 200,000 tons of submicron particles. These particles would produce visibilities of about 190 ft (60 m) but variations of a factor of three (60 to 600 ft) should be expected due to turbulent mixing with the clear air outside of the cloud.

Table 8. Estimates of Soot and Dust Characteristics, for July Nuclear Exchange

A. Smaller Factors in Smoke and Dust Production

Time	Coverage NA-Eu-As (Pct)	Coverage NH (Pct)	Total Mass (tg)	Cloud Height (km)	Optical Depth	Spec. Extinct. (m/gm)	Spec. Absorpt. (m/gm)	Vis.Ext. Coeff. km^{-1}	Visual Range	IR-3μ Ext. Coeff. km^{-1}	Ir-11μ Ext. Coeff. km^{-1}
3-hr Initial dust			0.015	10-15	250	5	0.3	51	190 ft	19	3.6
3-hr Initial soot			0.10	0-10	800	8	3.0	80	120 ft	32	5.6
3-days Comb.	20%	20%	50	1-12	5.9	6	2.0	.53	3.4 mi	.21	.037
5-days Comb.	75%	40%	35	2-15	1.4	4	1.2	.10	17 mi	.040	.007
10-days Comb.	100%	80%	25	3-16	0.5	4	1.2	.04	48 mi	.015	.003
30-days Comb.	100%	100%	10	5-16	.16	4	1.2	.01	127 mi	.006	.001

B. Larger Factors in Smoke and Dust Generation

3-days Comb.	25%	20%	150	1-15	23	8	3.0	1.68	1.1 mi	.67	.118
5-days Comb.	75%	40%	120	2-16	8.2	7	2.5	.59	3.1 mi	.24	.041
10-days Comb.	100%	80%	105	3-18	3.1	6	2.0	.20	8.8 mi	.08	.014
30-days Comb.	100%	100%	90	4-25	2.1	6	2.0	.10	18 mi	.04	.007

This visibility reduction does not include effects of any ice crystals that might have resulted from the condensation occurring when the surface air rose and cooled. Of the three extinction coefficients, the lowest (greatest transmission) would be for the 11-micron IR radiation, but even in this case, 99 percent of the radiant beam would be scattered over a path length of 1 km. For most practical purposes, the initial dust clouds would be either opaque or translucent to visible and IR radiation over time periods out to at least three hours. Sometime beyond about three hours, the dust clouds (except from multimegaton bursts that rise to above 16 km) would merge with smoke clouds from urban fires and no longer could be treated separately.

Besides the optical effects of the dust cloud, there are mechanical effects due to the abrasiveness of the material to consider. Violent volcanic eruptions also contain similar types of submicron particles, and serious aircraft engine damage has occurred when aircraft penetrated plumes from Mt St. Helens as well as from volcanos in Mexico and the East Indies. (Some effort is now being made to monitor satellite images for sudden, remote eruptions, so that warnings can be issued to aircraft). The instances reported appeared to be related to quite fresh eruptions, whose concentrations most likely were diluted by mixing after a number of hours, to a point where engine damage was less likely. The dust clouds would also contain dangerous levels of radioactivity, but this is well known and no doubt has been discussed in other Air Force documents.

The optical properties of a single smoke cloud or plume from a "typical" urban fire are shown on the second line of Table 8. While many of the properties are similar to those of the dust cloud, the smoke cloud is larger because it represents more of a continuous source spread through a greater depth rather than a single high-level cloud such as the dust. Again, caution is required because variations by a factor of 3 (if not 10) would occur due to turbulent mixing. Also, the values presented for extinction and visibility do not include water particles (which cloud model simulations indicate would likely be present, at least, at earlier stages). As with dust clouds, extinction is much less at 3 and 11 microns than for visible radiation (this would not be true if water particles greater than a few microns in size were present), but still, the clouds would best be considered opaque or slightly translucent at these wavelengths.

After about two days of detonations, the clouds from urban fires, rural fires, and fireball dust would merge into several massive clouds, hundreds to thousands of kilometers in horizontal scale and covering about 20 percent of the land surface of North America, Europe, and Asia. For the small factors in smoke and dust release, an estimate of the average visibility in the cloud would be about 3.4 mi (5.4 km), which is comparable to conditions in the "dry haze" of summertime often found in the lower 6000 ft (2 km) over the eastern US and parts of Europe. A difference is that while the summertime haze consists of submicron-size particles, there is very little carbon content (mostly nitrates and sulfates and other pollutants), and absorption is relatively small. Inhomogeneities would likely result in variations of a factor of 3, but AF systems that tolerate summertime hazes would still be effective for this estimate of smoke-dust cloud conditions. For large smoke and dust factors, about 25 percent of the Northern Hemisphere continents would be covered by smoke and dust clouds after two days, with average visibilities of about 1.1 mile (1.8 km), varying again by a factor of 3. This is much lower than normal haze conditions and would likely create problems by reducing the distance at which targets can be recognized. However, as the clouds spread over larger area and becomes less dense by mixing with "clean air", conditions would steadily improve and by day 5, the cloud covering 75 percent of the continents would have average visibility of about 3 miles and the effects on AF operations within the cloud would be much less serious.

Because the smoke-dust clouds would be much thicker vertically than the typical summer haze, high altitude surveillance could encounter more serious difficulties than the visibilities would indicate. Detectors using visible and near-IR wavelengths would be affected most through the absorption of sunlight, the absorption of light returning to the detector, and the introduction of scattered light from clouds into the detector. Images from high-altitude systems would be much worse than summertime haze conditions for periods out to 10 days for the low estimate and 30 days for the high estimate. The optical effects on infrared (near 10 microns) would be only 7 percent as great as for visible light leaving the earth's surface, and would appear to be relatively unaffected. However, the abnormally high temperatures in the smoke clouds would add significant noise to IR images, even though the IR emission from the clouds would be small due to small particle size.

6.3 Effects due to Changed Weather Patterns

The major product of model simulations has been estimates of surface and upper-air temperature changes. Table 9 illustrates some changes that could be expected at the surface for both

Table 9. Estimated Temperature Change From Nuclear Exchange
(in Celsius degrees)

July (land, 30° - 60°N)

	Small Emission Factors Time period (days)					Large Emission Factors Time period (days)				
	1 - 3	4 - 7	8 - 13	14 - 24	25 - 35	1 - 3	4 - 7	8 - 13	14 - 24	25 - 35
Mean	-7	-7	-5	-3	-2	-8	-13	-13	-11	-10
Variations	±5	±6	±4	±3	±3	±6	±8	±9	±7	±6

January (land, 30°-60°N)

	Small Emission Factors Time period (days)					Large Emission Factors Time period (days)				
	1 - 3	4 - 7	8 - 13	14 - 24	25 - 35	1 - 3	4 - 7	8 - 13	14 - 24	25 - 35
Mean	-3	-4	-3	-2	-1	-4	-7	-6	-4	-2
Variations	±6	±7	±6	±4	±2	±7	±12	±12	–8	±5

summer and winter nuclear exchanges, using both the "smaller" and "larger" factors in smoke and dust production as described in Section 6.1. The "mean" values are smaller by a factor of 3 to 6 than some early estimates for continents, using 1-D models, demonstrating the modifying effects of horizontal motions, precipitation removal, and other physical effects added to the models. The mean values in Table 9 for the lower value for the small production factors show drops of about 7 to 13°C (12 - 23°F), for midsummer and 4 to 7°C (7 - 12°F) for winter. When these changes are added to the normal means, the resulting temperatures would be somewhat unusual, but would not require extraordinary protective measures. When variability is considered, there would be a risk that for small areas and short time periods, large negative departures could occur, and for the larger production factors in January, they could exceed 100-year records. In general, for the regions from 30° to 70°N, the temperatures at any season would not drop below what might be considered as moderately severe for winter, for which the military should be well prepared. However, problems could exist for personnel where nuclear detonations and fires destroyed clothing and shelter, and evacuation of these people to undamaged habitats would be necessary for survival, particularly in winter. For the fall through spring period, a nuclear exchange driving temperatures downwards would increase the probability of frozen (or freezing) precipitation which would require treatment of runways and roads for normal operations. As a rough approximation, a midsummer nuclear war would produce weather conditions typical of May or September, for the smaller production factors, or April or October for the larger factors. For the fall season, the nuclear war cooling would effectively advance the onset of winter by 1 - 2 months (2 for the larger production factors) and delay the seasonal warming by 1 - 2 months for the spring season. The temperatures for the winter season would for the most part be colder than normal.

The model simulations thus far have not had sufficient detail to indicate effects on fog, low clouds, and surface winds, which of course do effect AF operations, especially aircraft landings, takeoffs, and surveillance missions. About the best we can do at this time is to use the seasonal analogs discussed in the previous paragraph. Thus, for a summer nuclear war, the frequencies of fog, low clouds, and surface winds would resemble those of a normal September or October, and for a fall (spring) nuclear war, the frequencies would be similar to those 1 - 2 months later (earlier). The frequencies for winter might well change but there is no obvious way to get an approximate answer. We should also note that the local forecast techniques based on persistence probability would not be reliable under the smoke-dust cloud, particularly for the clearing of fog and stratus.

The temperature increases at upper levels in the model simulations have actually been more impressive than the surface cooling, with increases of 50 to 100°C in summer and 30 - 60°C in winter, for the 10 - 20km (30,000 - 65,000 ft) region. The summer simulations depicted temperatures far exceeding anything ever observed at these levels anywhere in the world. The combination of temperature-density-pressure (0° to 20°C at 300 - 100 mb) would likely affect aircraft engine performance as well as aerodynamics, though the extent of the effects could best be answered by engineers. Another impact on aircraft performance would be the daily convective turbulence occurring near the top of the soot layer, which would be at least as intense as that normally found near the earth's surface on a sunny day. During the months following a nuclear war, forecasting the conditions aloft would likely be difficult due to lack of routine observations. In addition, the intense warming aloft would totally disrupt large-scale wind and temperature patterns such that climatology charts and products would be quite useless for guidance or planning.

6.4 Indirect Effects on AF Operations

The effects discussed thus far are concerned primarily with the capability of AF hardware to function satisfactorily in a post-nuclear environment. We must also acknowledge that people are involved, and the systems function best when the needs (food, shelter, clothing, recreation) of people are met. The SCOPE 28 (Vol II) report included an extensive discussion of nuclear war effects on agriculture and food supply and showed a sensitivity that varied from nation to nation and season to season. Crops are necessary to civilization; they provide grain for food products, vegetables, and feed for livestock, and for each plant, there are optimum combinations of temperature, moisture and sunlight for maximum productivity. In the worst case of a summertime nuclear war, the coolings indicated in Table 9 could result in crop reductions of 30 to 90 percent for the major food-producing nations of the Northern Hemisphere. The U.S. and Canada have ample grain storage (which presumably would not be targeted) to last until the next harvest, even if one harvest failed. Also, some western European nations have similar storage. Elsewhere, particularly in Asia, the loss of a substantial portion of one harvest would cause severe food shortages, and might impact the operations at overseas AF bases.

Within the U.S., there is a food "chain" that extends from the fields to the mouth, and includes several stages of food processing and distribution. In a major nuclear exchange at any time of year, portions of this chain would suffer extensive damage (destruction of factories, warehouses, railroads and highways). Local food stocks would likely be sufficient for perhaps 1 to 3 weeks, but shortages would result if food processing and distribution were not back to normal at the end of this time period. For a summertime war, locally grown food could not be relied upon as a supplement because of reduced temperatures and sunlight.

The SCOPE report noted that the temperature effects were, in general, more serious to crops than reduced sunlight or reduced rainfall. Crops are matched to climatically normal weather, sometimes supplemented by irrigation, and model results indicate departures of temperatures in middle latitudes that are more extreme than for sunlight or precipitation. However, the summertime monsoon rains of southeast Asia depend on a thermally-driven wind circulation, and the models indicate the circulation would be seriously disrupted, so that in this area, moisture reduction could be more serious than temperature drops (particularly since temperature effects in this area were projected to be small in all but the most extreme of the soot and dust estimates).

Since military bases would likely be directly targeted in a nuclear war, extensive destruction of local housing could be expected. This would create urgent needs for emergency housing and clothing, made more urgent by abnormally low temperatures. No doubt, the situation would vary from base to base, and should be a factor in contingency plans. The low temperatures and reduced sunlight would also increase demand for fuel (which could be short due to storage destruction and supply problems), and for a particular site, the increases could be roughly estimated using values in Table 9 or previously discussed season analogs.

6.5 Summary of Impacts on AF Operations

The preceding discussions have shown that dust and smoke clouds resulting from a large-scale nuclear exchange could impact AF operations in a number of different ways. Should such a conflict take place, the first result on the atmosphere would be the generation from urban fires and from ground bursts of hundreds or thousands of clouds, each several miles in diameter. The clouds would occupy a tiny percentage of the airspace over continents, but would limit EO weapons because they are essentially opaque to visible and infrared radiation. In addition, the dust clouds from surface bursts would contain dangerous concentrations of radioactive material and abrasive dust. Over a period of days, the clouds would merge and spread, becoming significantly less dense and permitting ever-increasing transmission of visible light and more for infrared. However, surveillance from satellites or stratospheric aircraft would be hindered due to long optical path lengths.

Unless there has been serious underestimate of sub-micron size soot produced by fires, the smoke and dust would thin to a widespread haze in a couple of weeks and the atmosphere would return close to normal in 1 to 3 months. During this period, solar heating high in the atmosphere (20,000 to 50,000 ft) would create unusual turbulence and temperatures far exceeding design normals, possibly affecting aircraft performance. At the ground, a marked cooling would produce fall or winterlike conditions, which would aggravate conditions for survivors seeking shelter. Where food stockpiles are small (Africa, Asia), a nuclear war could lead to serious food shortages through crop loss from reduced temperatures and rainfall. Where fcod stockpiles are large (U.S., E. Europe, USSR), food problems could still occur if processing plants and distribution systems were substantially damaged.

References

1. "Nuclear War: Preliminary estimates of the climatic effects of a nuclear exchange. *Proceedings of the International Seminar on Nuclear War 3rd Session: The Technical Basis for Peace*, Erice, Italy, 19-24 Aug 83, Servizio Documentazione dei Laboratori Frascati dell'INFN, Jul 84, pp. 161-183, also available as Lawrence Livermore National Laboratory Report UCRL-89770, Livermore, CA.
2. Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B., and Sagan, C. (1983) Nuclear Winter: global consequences of multiple nuclear explosions, *Science* **222**:1283-1291.
3. More detailed descriptions of nuclear detonations may be found in: Glasstone, S. and Dolan, P.J. (1977) *The Effects of Nuclear Weapons*, DoD and ERDA, Government Printing Office, Washington, D.C.
4. Burton, J.D., Millburn, G.M., and Russell, R.S. (1960) Relationships between the rate of fallout and the concentration of ^{90}Sr in human diet in the United Kingdom, *Nature* **185**:498-500.
5. National Research Council (NRC) (1985) *The Effects on the Atmosphere of a Major Nuclear Exchange*, National Academy Press, Washington, D.C.
6. Crutzen, P.J. and Birks, J.W. (1982) The atmosphere after a nuclear war: Twilight at noon, *Ambio* **11**:114-125.
7. Pittock, A.B., Ackerman, T.P., Crutzen, P.J., MacCracken, M.C., Shapiro, C.S., and Turco, R.P. (1986) *SCOPE 28. Environmental Consequences of Nuclear War, Vol I Physical and Atmospheric Effects.* John Wiley & Sons, New York.
8. Donnet, J-B and Voet, A. (1976) *Carbon Black, Physics, Chemistry, and Elastomer Reinforcement*, Marcel Dekker, Inc., New York.
9. Crutzen, P.M., Galbally, I.G., and Bruhl, C. (1984) Atmospheric effects from post-nuclear fires. *Climatic Change* **6**:323-364.
10. Penner, J.E. (1986) Progress in developing the smoke source term for "nuclear winter" studies: Major uncertainties, *Nature* **324**:222-226.
11. Bing, G. (1986) *Estimates of total combustible material in NATO and Warsaw Pact countries*, UCRL-93192, Lawrence Livermore National Laboratory, Livermore, CA 94550.

12. Reitter, T.A., S.-W. Kang, and Takata, A.N. (1985) *Toward quantifying the source term for predicting global climatic effects of nuclear war: Applications of urban fire codes*, UCRL-53647, Lawrence Livermore National Laboratory, Livermore, CA 94550.

13. Penner, J.E. and Porch, W.M (1986) Coagulation in smoke plumes after a nuclear war, *Atmospheric Environment*, and UCRL-94359, Lawrence Livermore National Laboratory, Livermore, CA 94550.

14. Berger, A. (1986) Nuclear winter, or nuclear fall? *Eos* **67**(32):617-621.

15. Small, R.D. and Bush, B.W. (1985) Smoke production from multiple nuclear explosions in non-urban areas, *Science* **229**:465-469.

16. Radke, L.F. (1985) Outline of a research plan for field studies to improve assessments of the nuclear winter scenario, DASIAC SR-216, Working Record of Global Effects Program Meeting, 12-14 Feb 85, Santa Barbara, CA (Defense Nuclear Agency), pp 185-200.

17. Cotton, W.R. (1985) Atmospheric convection and nuclear winter, *American Scientist* **23**:225-280.

18. Banta, R.M. (1985) Numerical cloud simulations: Vertical distribution of soot from a nuclear city fire, DASIAC SR-216, Working Record of Global Effects Program Meeting, 12-14 Feb 85, Santa Barbara, CA (Defense Nuclear Agency), pp 105-122.

19. Golding, B.W., Goldsmith, P., Machin, N.A., and Slingo, A. (1986) Importance of local mesoscale factors in any assessment of nuclear winter, *Nature* **319**, 23 Jan:301-303.

20. Banta, R.M. and Barnes, A.A. (1985) Modeling of atmospheric moisture effects on a nuclear mass fire cloud, IAMAP Symposium on Climate Effects of Nuclear War, Joint Assembly IAMAP/IAPSO, Honolulu, HI, 5-16 Aug 85.

21. Penner, J.E., Haselman, L.C., and Edwards, L.L. (1985) Buoyant plume calculations, Paper No. 84-0459 for AIAA 23rd Aerospace Sciences Meeting, Reno, NV, 14-17 Jan 85.

22. Covey, C., Schneider, S.H., and Thompson, S.L. (1984) Global atmospheric effects of massive smoke injections from a nuclear war: results from general circulation model simulations, *Nature* **308**:21-25.

23. Covey, C., Thompson, S.L., and Schneider, S.H. (1985) "Nuclear Winter": a diagnosis of atmospheric general circulation model simulations, *J. Geophys. Res.* **90**:5615-5628.

24. Thompson, S.L. (1985) Global interactive transport simulations of nuclear war smoke, *Nature* **317**:35-39.

25. Malone, R.C., Auer, L.H., Glatzmaier, G.A., and Wood, M.C. (1986) Nuclear winter: three-dimensional simulations including interactive transport, scavenging and solar heating of smoke, *J.Geophys.Res.* **91**:1039-1053.

26. Ramaswamy, V. and Kiehl, J. (1985) Sensitivities of the radiative forcing due to large loading of smoke and dust aerosols, *J. Geophys. Res.* **90**:5597-5613.

27. Cess, R.D. (1985) Nuclear war: illustrative effects of atmosphere smoke and dust upon solar radiation, *Climatic Change* **7**:237-251.

28. Cess, R.D., Potter, G.L., Ghan, S.J., and Gates, W.L. (1985) The climatic effects of large injections of atmospheric smoke and dust: a study of climatic feedback mechanisms with one and three dimensional climate models, *J. Geophys. Res.* **90**:12937-12950.

29. Thompson, S.L. and Schneider, S.H. (1986) Nuclear Winter reappraised, *Foreign Affairs* **64**:981-1005.

30. Thompson, S.L., Ramaswamy, V., and Covey, C. (1987) Atmospheric effects of nuclear war aerosols in general circulation model simulations: influence of smoke optical properties, *J. Geophys. Res.* **92**(D9):10942-10960.

31. Singer, S.F. (1984) The big chill? Challenging a nuclear scenario: *Wall Street Journal*, 3 Feb 68.

32. Maddox, J. (1984) Nuclear winter not yet established, *Nature* **308**, VII.

33. Singer S. F. (1984) Is the "nuclear winter" real? *Nature* **310**:625-626.

34. Thompson, S.L., Schneider, S.H., and Covey, C. (1984) Reply to letter by Dr. Singer, *Nature* **310**:625-626.

35. Teller, E. (1984) Widespread after-effects of nuclear war, *Nature* **310**:621-624.

36. Smith, R.J. (1984) Soviets offer little help, *Science* **225**:31.

37. Aleksandrov, V., Thompson, S.L. and Turco, R. (1984) "Nuclear Winter" studies (3 letters) *Science* **225**:978-979.

38. Singer, S.F., Kearns, C.H., and Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B. and Sagan, C. (1985) On a "Nuclear Winter" (3 letters) *Science* **227**:356-362.

39. Raloff, J. (1983) Beyond Armageddon, *Science News* **124**, 12 Nov:314-317.

40. Raloff, J. (1984) Nuclear winter research heats up, *Science News* **126**, 22 Sep:182.

41. Raloff, J. (1984) New Soviet 'nuclear winter' maps, and estimating nuclear forest fires, *Science News* **126**, 29 Sep:204.

42. Parsons, T.G. (1985) Early forecast of nuclear winter, *Science News* **127**,16 Feb:99.

43. Raloff, J. (1985) Nuclear Winter: Shutting down the farm? *Science News* **128**, 14 Sep:171-173.

44. Weisburd, S. (1985) Wildfires: Apocalypse then and now, *Science News* **128**, 12 Oct:228.

45. (In "Science and Society") (1986) Nuclear winter status report, *Science News* **129**, 19 Apr:249.

46. Pittock, A.B. (1984) Australia and nuclear winter, *Search* **15**:332-339.

47. Pittock, A.B. (1986) Rapid developments on nuclear winter, *Search* **17**:23-24.

48. Emanuel, K.A. (1986) Towards a scientific exercise, *Nature* **319**, 23 Jan:259.

49. Schneider, S.H., Thompson, S.L., and Covey, C. (1986) The mesoscale effects of nuclear winter, *Nature* **320**, 10 Apr:491.

50. Sagan, C., Turco, R.P., Rathjens, G.W. and Siegel, R.H., and Thompson, S.L. and Schneider, S.H. (1986) Nuclear Winter debate (3 letters and reply) *Foreign Affairs* **65**:164-178.

51. London, J. and White, G.F. (1984) *Environmental Effects of Nuclear War*, AAAS Selected Symposium No. 98, AAAS, Washington, DC. Also published by Westview Press, Inc. Boulder, CO.

52. Weinberger, C. (1985) *The Potential Effects of Nuclear War on the Climate*, DoD Report to Congress.

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