Uncertainties in the smoke source term for 'nuclear winter' studies

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Climate models have shown that the effects on climate of a major nuclear exchange depend on the quantity and optical properties of the smoke that is dispersed into the global atmosphere. Published estimates for each of the factors necessary to determine the smoke optical depth yield a wide range of values, which allows the prediction of either comparatively minor effects on climate or massive effects.

THE potential effects on climate of large amounts of smoke injected into the atmosphere following a major nuclear exchange have been widely analysed[1-4]. Although simplifications and uncertainties still exist in the application of climate models to calculate the effects of smoke, many of the simplifications that had to be made in the first studies have now been corrected. These improved climate models have shown that the effects of smoke on climate depend on the quantity and optical properties of the smoke that is generated and dispersed into the global atmosphere.

The amount of smoke and its optical properties can be summarized by the average optical depth that would result if the smoke were dispersed throughout half the Northern Hemisphere. If the extinction optical depth $\bar{\tau}_e$ is taken as the sum of the scattering and absorption optical depths, it may be calculated from $\bar{\tau}_e = (k_s + k_a)S/A$, where k_s and k_a are the scattering and absorption cross sections of the smoke (in $m^2 g^{-1}$), S is the amount of smoke (in g) and A is the area blocked by the smoke cloud (taken as half the area in the Northern Hemisphere, or 1.28×10^{14} m^2). The quantity of smoke may be calculated from $S = \varepsilon F(1 - f_r)$, where ε is the emission factor of smoke (g smoke per g of fuel burned), F is the amount of fuel burned, and f_r is the fraction of smoke removed by precipitation in the convection column above the fires and in the first few days after the war, during which the smoke is presumed to spread out to global scales. The original 'baseline' analysis of Turco *et al.*[2] resulted in an estimate for $\bar{\tau}_e$ of ~6 for smoke produced in urban fires. Their smoke had a single scattering albedo of ~0.5, so that $\bar{\tau}_a = k_a S/A$ was ~3.0. Consideration of the additional smoke from wildlands fires, long-term fires and dust from surface bursts increased the estimate for $\bar{\tau}_e$ to ~8. (Turco *et al.*[2] spread their smoke over the entire Northern Hemisphere, so that their published optical depths differ from these by a factor of 2.) All subsequent analyses have similarly implied 'best estimates' for $\bar{\tau}_e$ that were substantially greater than 1. Here I review the estimates for the various factors which contribute to $\bar{\tau}_e$ and $\bar{\tau}_a$, to obtain reasonable bounds on the range of magnitudes consistent with current knowledge. This range encompasses values that may be associated with major climatic effects if a large fraction of the available urban combustible load is burned. On the other hand, within the bounds set by current analysis, comparatively minor effects are also possible, especially if the targeting of weapons avoids refineries and other large storage facilities that contain petroleum or other fossil fuels. I then recommend several areas for research that could lead to more certain estimates of the effects of such a war.

Amount of fuel burned in urban fires

As pointed out in ref. 5, several methods have been adopted for estimating the amount of fuel that might burn in urban fires. These methods are not mutually consistent. In the method adopted by Turco *et al.*[2], which yields the highest fuel estimate, the amount of fuel burned in urban fires is determined from the product $F = \mathrm{FL} \times f_b \times A_i \times \mathrm{SF}$ where FL is the average areal fuel load within the burned-out region (in g m^{-2}), f_b is the fraction of fuel that is consumed by fire within the area that burns, A_i is the area that is initially ignited by the fireball (in m^2) and SF is the average areal spread factor for the fires.

An overestimate by this method may be caused by at least two factors. Most often, no account is taken of the overlap of burned areas when detonations take place near one another. Secondly, the entire ignited area and its radially expanded spread is assumed to coincide exactly with the urban fuel bed and with the average fuel load FL. This assumption may be seriously in error, for example, for targets such as airports that generally reside on the outer edges of cities. It is often argued that these effects are mitigated by the cnoice of a 'conservative' value for A_i—that is, one that corresponds to the area that would be ignited by a thermal fluence of 20 cal cm^{-2}, rather than the area associated with a thermal fluence of 7–10 cal cm^{-2}, which is considered sufficient to ignite at least the lighter fuel elements such as paper and twigs. In Nagasaki, where the presence of hills restricted the fire ignition area[6], the actual area burned ($A_i \times \mathrm{SF}$) corresponded to the area which would have received a thermal fluence of 20 cal cm^{-2}; whereas in Hiroshima, the area burned corresponded to the area which received only 7 cal cm^{-2}. It would therefore seem that the area corresponding to 20 cal cm^{-2} is indeed 'conservative', if SF = 1.

It is not known, however, whether the two effects mentioned above (overlap and improper average values for FL) would indeed be balanced by an underestimate for $A_i \times \mathrm{SF}$. Several lines of inquiry suggest that the overestimate may be significantly larger than the factor of 2 underestimate made by using a fluence area corresponding to 20 rather than 7–10 cal cm^{-2}. The analysis in ref. 7, which consisted of a large attack on cities, suggests that consideration of overlap may reduce the value of A_i by as

Table 1 Average combustible fuel load in cities

Authors	Fuel load (kg m^{-2})
Turco *et al.*[2]	
Baseline case	33.5*
100-Mtonne, city centre	200.0
Crutzen *et al.*[10]	40.0†
NRC[3]	40.0
Reitter *et al.*[8]	
Detroit, centre	34.5
Detroit/San Jose, suburbs	10.2

* Average of 100 kg m^{-2} in 'city centres' and 30 kg m^{-2} in suburbs.
† This estimate was not used in the final analysis of ref. 10 (see text).

much as a factor of 4. Also, overlap of ignition areas may reduce fire spread, if intense firestorms are generated which create inflowing winds. On the other hand, with more intense fires, the fuel may burn more thoroughly, increasing f_b.

The value used for the average fuel load can be checked by an analysis of some of the fire spread modelling results of Reitter *et al.*[8] (see also Appendix 3A of ref. 4). All previous studies of the amount of fuel that might burn have assumed average values for FL of ~40 kg m^{-2} (see Table 1), although values from 10 to 400 kg m^{-2} are quoted as possible[3]. Table 1 also shows the average areal fuel loads within the ignited areas corresponding to a 1-Mtonne nuclear explosion over the centre of Detroit and several 1- and 0.5-Mtonne bursts over detonation points above suburban Detroit and central San Jose, as taken from Reitter *et al.*[8]. These data imply that values closer to 10 kg m^{-2} should be used for most urban and suburban areas. Furthermore, if the fuel loads for Detroit are correct, values for FL of ~40 kg m^{-2} are appropriate only for weapons directed at the centres of large cities. The average fuel loads from Reitter *et al.* consider only those areas occupied by buildings, so that these average values do not account for any decrease in FL due to targeting on the fringes of cities or near lakes or parks which would have lower average fuel loads. The fuel loads were developed from surveys taken in the late 1960s, but recent analyses of fuel loads in San Jose[9] are similar to the average fuel load used by Reitter *et al.* for that city. The Detroit fuel loads used by Reitter *et al.* seem surprisingly low, but result from averaging the fuel loads in the centre of that city (which range up to 160 kg m^{-2} over small areas) with values near 10 kg m^{-2} in outlying regions. Note that Detroit has a population of >4 million. There are only 39 urban centres in the world with a population of >3 million, and only 80 cities in the NATO and Warsaw Pact countries with populations of >1 million. The oft-quoted "100-Mtonne central city" model of Turco *et al.*[2], assumed values for FL of 200 kg m^{-2} in 100 cities: these loads appear to be overestimated by a factor of 5. Of course, one must check whether European cities or cities in the eastern United States contain much higher fuel loads than those quoted here for Detroit. But it seems highly probable that the estimates for FL used previously are too large, especially in view of the analysis of total fuel load outlined below. Crutzen *et al.*[10] also rejected this method in favour of the inventory approach outlined below. Finally, note that the above analysis for FL assumed targets which were entirely contained within the urbanized areas occupied by buildings. Consideration of actual target locations, some of which will occur on the fringes of cities and some of which will fall near lakes or other low-fuel-density areas, will further reduce the estimate for FL.

Significant further reduction of the uncertainties using this approach requires a detailed analysis on a city-by-city basis, with consideration of specific target locations, fuel loads and overlap of fire areas. Here we consider an alternative approach, in which total combustibles are estimated directly and then a fraction is assumed to be ignited and burned.

The total inventory of combustibles has been estimated by Crutzen *et al.*[10] and by Bing[5], using different methodologies. Pittock *et al.*[4] also estimated inventories, but as ref. 4 is primarily a review of ref. 10, they will not be separately quoted here. Crutzen *et al.*[10] used production figures for various raw materials and estimates of their lifetimes to obtain estimates for the total abundance of cellulosic materials, polymeric materials and asphalt. Bing[5], on the other hand, gathered data from surveys of fuel loads in various types of structures and their contents for the United States, and extrapolated these data to Europe and the Soviet Union. The two sets of published figures are not directly comparable because Crutzen *et al.* estimate the amount of celluosic and polymeric materials in the developed world, whereas Bing's estimates refer only to the NATO and Warsaw Pact countries. Crutzen *et al.* and Bing also separately estimate the amount of petroleum available to burn, including petroleum stored as primary stocks and as secondary stocks. The figures of Crutzen *et al.* refer to the amount of petroleum stored globally, wheras Bing's numbers again refer only to that fraction contained within the NATO and Warsaw Pact countries. In order to consider similar models, I have reduced the inventories published by Crutzen *et al.* for the developed world by the ratio of the population of the NATO and Warsaw Pact countries to that of the developed world. Their estimates for petroleum were similarly reduced by the ratio of consumption rates in NATO and Warsaw Pact countries to that of the world. As shown in Table 2, Crutzen *et al.*'s inventory still implies 2.5 times more cellulosic material than does Bing's. Remarkably, as the methodologies were different, the estimates for petroleum-derived materials are similar. The total amount of fuel in primary stocks of petroleum is fairly well known and the two estimates are comparable. The amount of fuel in secondary stocks of petroleum is less well known. Two different sources of data have led to a difference of a factor of 2–4 for fuel in this category, as shown in Table 2.

The methodologies used in these two studies have obvious difficulties, and it is not clear which method is more appropriate. Note, however, that the totals for cellulosic and polymeric materials assumed by Crutzen *et al.*[10] are not entirely consistent with the fuel load estimates derived from Reitter *et al.*[8]. For example, we may use the average areal fuel load for urban and suburban areas from ref. 8, together with the total urban area in cities with population greater than 2,500 in the United States, 135,000 km^2, to arrive at a combustible load for the United States of 1,350 Tg. Consideration of 50 city centres with fuel loads similar to that of Detroit might increase this total to 2,000 Tg. This number is close to the value derived by Bing[5] for the United States (2,119 Tg), and thus lends confidence to his estimates. On the other hand, when Crutzen's numbers for the developed world are scaled by the ratio of population in the United States to that in the developed world (0.225) we arrive at 4,400 Tg, which is at least twice as large as the estimate above. In the analysis below, both numbers will be used to estimate the range of optical depths that are possible, given current uncertainties.

Table 2 Inventory of total available combustibles in NATO and Warsaw Pact countries (Tg)

Authors	Cellulosic materials	Primary petroleum stocks	Secondary petroleum stocks	Polymeric materials
Crutzen *et al.*[10]	16,500*	462†	198–462†	574*
Bing[5]	6,444	480	100	753

* Reduced from the estimate for the 'developed world' in ref. 10 by the ratio of populations, 0.87 (G. Bing, personal communication).

† Reduced from the estimate for the whole world in refs 4 and 10 by the ratio of consumption rates in NATO and Warsaw Pact countries to that of the world, 0.66.

Table 2 summarizes the inventories of combustibles in NATO and Warsaw Pact countries, derived by these two methodologies. To allow consideration of the range of smoke absorption properties from various fuel types, Table 2 divides the inventories into cellulosic fuels, petroleum-derived fuels and liquid fossil fuels. This last category has been subdivided into primary and secondary stocks of petroleum. Secondary stocks are considered to be distributed with other fuels, whereas primary stocks of petroleum are considered separately in order to calculate the effect of a concerted effort to avoid or include these targets (see estimates below).

Typically, only a fraction of the total available combustible material might actually burn in active, flaming combustion. Here I assume this fraction to be 25% of the distributed fuels (cellulosic and polymeric materials, and secondary stocks of petroleum) for both the high and low estimates. In this way the range of optical depth derived can be considered to be independent of any particular model, although more (or less) fuel might

burn if the warring nations made a concerted effort to try to ignite (or avoid burning) the available fuel. A 25% fraction might come about, for example, by associating ~65% of the total fuel with people who live in cities (the average proportion of city dwellers for Europe, the Soviet Union and the United States), and then burning 80% of the total fuel in cities, half in active, flaming combustion and half in longer-term, smoldering combustion. Alternatively, most city fuels might burn in active combustion but, because of clustering of targets and overlap of ignition areas, only 40% of the fuel in cities actually ignites and burns. The optical depths derived below could easily increase if the war involved, for example, attacks on oil rigs or on oil-producing countries whose whose fuel stores are not part of the inventory considered here. Similarly, if attacks included population centres outside the countries included here, the optical depths would increase. However, the NATO and Warsaw Pact countries contain 85% of the population of all countries in the developed world, and as the present model burns 40–80% of the urban fuels in these countries, it is certainly large enough to be considered a 'major' nuclear war. On the other hand, ~30% of the population in the develped world is concentrated in the 100 or so largest cities (see Table 3.1 in ref. 4), so that if 100% of the fuel of these cities is burned in active, flaming combustion, nearly the same total optical depth could be produced. However, the purpose here is not to develop war models, but to show the range in optical depth expected from current knowledge for a given model. These ranges can easily be adapted to other models.

Table 3 Smoke emission factor

Authors	Per cent of fuel
Turco *et al.*[2]	2.7*
Crutzen *et al.*[10]	
Wood	1.5
Oil, polymers, etc.	7.0
NRC[3]	
Wood	3.0
Oil, polymers, etc.	6.0
Range of values in flaming combustion[10]	
Wood	0.085–2.5
Oil	2–10
Plastics	1.2–50

* Weighted average of the 'net emission factors' of 1.1% for urban centres and 3.3% for suburbs. These values may include some allowance for scavenging by rain. Emission factors in an earlier version of ref. 2 were 2.5% for city centres and 5% for suburbs.

Smoke emission factor

The appropriate smoke emission factor in a large-area urban fire depends on a number of poorly estimated and poorly known factors. Emission rates can vary[11,12], depending on the type of fuel, the ambient air temperature, the availability of oxygen, the radiant intensity (as determined by the proximity of nearby fires), the geometric arrangement of fuel, and so on. Only very limited data from large fires are available, so most studies have used values consistent with the range of emission factors measured in laboratory-scale fires (see Table 3). These might be underestimates, if oxygen availability is truly limited in a large-area fire. On the other hand, Carrier *et al.*[13] have argued that oxygen availability should not be an issue, given the turbulent motions above the fire. In view of the lack of credible data for smoke emission factors from large-area fires, the values adopted here are estimated from the limited available data, and are highly uncertain. Table 3 also includes the range of estimates of the emission factor compiled in ref. 10, primarily from laboratory data. In the analysis below, I adopt a range of values for the emission factor, consistent with the best estimates chosen in refs 3 and 10; however, larger uncertainties apply because of the possible inapplicability of these emission factors to large-area fires.

Table 4 Absorption and extinction coefficients for smoke from urban fires

Authors	k_a ($m^2 g^{-1}$)	k_e ($m^2 g^{-1}$)
Turco *et al.*[2]	2.9	5.8
Crutzen *et al.*[10]		
Wood	3.3	6.8
Oil, etc.	7.0	10.5
NRC[3]	2.0	5.5
Penner and Porch[15]		
Wood, no coagulation	1.5	6.6
Oil, etc., no coagulation	5.6	9.5
Wood, after coagulation	1.3	4.0
Oil, etc., after coagulation	1.8	4.0

Optical properties of smoke

Just as the emission factor for smoke depends on the burning conditions and type of fuel, so does the chemical, morphological and optical character of the smoke. Nevertheless, various authors have estimated the absorption and extinction coefficients for smoke, based on a variety of measurements that have tended to emphasize the data available from smoke emitted under flaming conditions. The estimates are summarized in Table 4. In most recent evaluations, the optical properties of wood smoke are distinguished from those of smoke from fuels such as oil, plastics, and other polymers whose chemical structure has little available oxygen. These latter fuels tend to produce much blacker smoke. Table 4 shows wide variations in the estimates of the absorption and extinction coefficients for fresh smoke.

In addition to variations in average optical absorption and extinction from different evaluations of these properties for fresh smoke, two mechanisms may act to make aged smoke less absorbing (see ref. 4). The first mechanism is coagulation, which may act on short timescales (in very dense smoke plumes) or on longer timescales (from days to a week in the spreading global plume) to create larger particles. These larger particles would absorb and scatter less radiation, if they are spherical. Because some smoke particles are quite oily (and therefore spherical), while others appear as fluffy or chained agglomerates, it is not possible to predict the effects of coagulation on optical properties. Chained agglomerate particles might become spherical if they coagulated with oily smoke particles, or if they were to condense and re-evaporate in a cloud—a process which might allow the chains to collapse[14]. To the extent that the agglomerates remain in a chained formation, their absorption properties may not change significantly. Thus, in the following, I adopt two extremes. In the first case, coagulation is assumed to have no effect on optical properties; in the second, coagulation is assumed to reduce extinction and absorption by the amounts estimated in ref. 15 for several days of coagulation. This additional consideration widens the discrepancy between the lowest and highest estimates of absorption coefficient by an additional factor of ~3 for the highly carbonaceous, absorbing smokes. The extinction coefficients differ by a factor of >2. The absorption coefficient for less absorbing smoke is not significantly changed by coagulation.

Fraction of smoke scavenged by rain

The last factor which contributes to estimates of the average optical depth is the amount of smoke that is removed by precipitation occurring in the smoke plume over the fire and in the

Table 5 Fraction of smoke removed by rain

Authors	Fraction removed
Turco *et al.*[2]	
Suburban fires	0.25
Firestorms	0.50
Crutzen *et al.*[10]	0.30
NRC[3]	0.50
Cotton[17]	~0.02*
Penner and Edwards[18]	0.50†

* Fraction of smoke particles that enter cloud water by phoretic scavenging. The amount removed by precipitation may be less than this.

† Fraction of smoke particles that enter cloud water by nucleation scavenging. The amount removed by precipitation may be less than this.

first few days after the war. Several authors have estimated that, especially for large, intense fires, large quantities of water will condense above the fire[16,17], but there have been few attempts to quantify how much smoke is removed. In both Hiroshima and Nagasaki, a 'black rain' fell, coincident with the fires which followed the nuclear blasts of August 1945[6]. The black rain is presumably smoke that has been scavenged by rain. It is not known how much of the smoke was scavenged or whether the experience in Nagasaki and Hiroshima should be considered to be typical.

The amount of smoke scavenged by rain depends, once again, on properties of the smoke which are poorly known. For example, the number of smoke particles that act as condensation nuclei for cloud drops depends on the highest level of supersaturation attained above the fire. This depends on the total number of smoke and debris particles, their size distribution, and their affinity for water. Furthermore, the highest level of supersaturation depends on the updraft velocity within the plume as well as the growth rate of the drops which form. As the size and composition of smoke particles from the large-scale urban fire are poorly known, it is difficult to predict how much nucleation scavenging might occur. Initial studies, which assume idealized spherical particles, indicate that for conditions considered typical of smoke above fires, all particles with radii greater than 0.1 μm (or ~50% of a log-normal distribution with a mode radius of 0.1 μm) might be scavenged in this manner[18]. However, further studies with a more realistic description of smoke particles are needed.

Once drops have formed, other mechanisms may also act to attach smoke particles to cloud drops. These include electrical capture, phoretic forces and turbulent motions, although Cotton[17] has estimated that <2% of the smoke particles might be captured phoretically. Cloud drops may or may not form precipitation-sized rain drops. The probability of this occurring depends on the initial size of debris and smoke particles and on the number that become nucleated to form drops. Pruppacher[19] estimated that, although most of the particles would enter cloud drops by nucleation scavenging, rainout of the smoke would be relatively small because of overseeding effects. However, only one size distribution was considered and the updraft velocity was only 1 m s^{-1}. Consideration of more realistic fire plume conditions may alter this conclusion. Once the drops become large enough to obtain a significant fall velocity, they may capture more smoke particles by impaction scavenging. The probability of this occurring also depends on the size of smoke particle (with larger particles being more likely to be scavenged).

The capture mechanisms described above apply to warm-rain precipitation only. Additional mechanisms and pathways for capture must be considered in the case of ice formation, which can also lead to release of the smoke particles. Because the saturation vapour pressure over ice is less than that over water, when ice begins to form, water on drops may evaporate and recondense on ice particles, thereby releasing any smoke that was previously captured by nucleation scavenging. Recently G. Tripoli (personal communication) has used the cloud model developed by Cotton[17] to estimate that this process could limit any rainout of the smoke above the fire to <20%. In addition to the near-immediate rainout of smoke above the fire, mesoscale atmospheric circulations may be set up which lead to rainout on longer timescales[20].

The theoretical analysis of scavenging and rainout is complex and difficult, and further work is needed. For this reason, many authors have simply guessed a fraction for smoke that might be removed by rainout. These guesses range from ~0 to 50% (see Table 5), although the real range of possibilities might include values up to 100% in some cases[21]. Here I consider the range from 0 to 50%. Obviously, the range of average optical depths obtained could be larger, for example, if rainout removed 90% of the smoke.

Calculated optical depths and climate

If we combine all the choices described above, emphasizing the smallest factors in one case and the largest factors in the second,

Table 6 Calculated range of average optical depth from urban fires

Category	k_a ($m^2 g^{-1}$)	k_e ($m^2 g^{-1}$)	ε ($g g^{-1}$)	F (Tg)	$(1-f_r)$	$\bar{\tau}_a$	$\bar{\tau}_e$
Wood							
High	3.3*	6.8*	0.03†	16,500*/4	1.0‡	3.19	6.57
Low	1.3(1.5)§	4.0(6.6)§	0.015*	6,444‖/4	0.5†	0.12(0.14)	0.38(0.62)
Polymers, plastics, etc., and secondary stocks of petroleum							
High	7.0*	10.5*	0.07*	1,083¶/4	1.0‡	1.04	1.55
Low	1.8(5.6)§	4.0(9.5)§	0.06†	674#/4	0.5†	0.07(0.22)	0.16(0.38)
Primary stocks of petroleum							
High	7.0*	10.5*	0.07*	480‖	1.0‡	1.84	2.76
Low	1.8 (5.6)§	4.0 (9.5)§	0.06†	462*	0.5†	0.19 (0.61)	0.43 (1.03)

* From refs 4 and 10.

† From ref. 3.

‡ Based on ref. 17.

§ From ref. 15. Numbers in parentheses refer to the case with no coagulation.

‖ From ref. 5.

¶ This number is the sum of the average of high and low estimates for secondary stocks of petroleum from ref. 10 and Bing's[5] estimate for polymeric materials (see Table 2).

This number is the sum of Bing's[5] estimate for secondary stocks of petroleum and Crutzen *et al.*'s[10] estimate for polymeric materials (see Table 2).

Table 7 Average optical depth

Model	$\bar{\tau}_a$	$\bar{\tau}_e$
Distributed fuels only		
High	4.2*	8.1
Low	0.2†(0.4)‡	0.5(1.0)
With primary stocks of petroleum		
High	6.1§	10.9
Low	0.4‖(1.0)	1.0(2.0)

* Equivalent to 270 Tg of smoke with $k_a = 2\ m^2\ g^{-1}$.
† Equivalent to 12 Tg of smoke with $k_a = 2\ m^2\ g^{-1}$.
‡ Optical depths in parentheses refer to the case with no coagulation.
§ Equivalent to 388 Tg of smoke with $k_a = 2\ m^2\ g^{-1}$.
‖ Equivalent to 24 Tg of smoke with $k_a = 2\ m^2\ g^{-1}$.

we obtain the range in absorption and extinction optical depths shown in Table 6. Table 6 lists separately the optical depths from cellulosic fuels, from distributed fuels producing highly carbonaceous smoke (polymeric materials and secondary stocks of petroleum) and from primary stocks of petroleum. In the case of distributed fuels, one quarter of the total abundance in the NATO and Warsaw Pact countries, or 40–80% of the fuel in cities, is assumed to burn. As shown in Table 6, the burning of polymers and petroleum may contribute significantly to the total optical depth. To show its effect, we consider two models. In the first, the contribution of primary stocks of petroleum to the total optical depth is not included. This might result if the warring nations specifically tried to avoid targets, such as refineries, that would add disproportionately to the optical depth. As warring nations have never yet refrained from attacking the economic base of their enemies, this may be an unlikely model; but it is interesting to calculate the consequences should studies of 'nuclear winter' cause nations to re-evaluate their war plans. In the second model these targets are all included, so that 100% of the primary stocks of petroleum are burned. Table 7 summarizes the high and low estimates of optical depth for these two cases. If the primary stocks of petroleum are not included, the absorption optical depth varies from 0.2 to 4.2. Including these stocks increases the range of absorption optical depths to 0.4–6.1. In the first case, the low estimate is equivalent to 12 Tg of smoke with the optical properties assumed in ref. 3. This increases to 24 Tg of smoke if primary stocks of petroleum are included. This case is close to the lowest amount of smoke (20 Tg) considered by Malone *et al.*[22] in an advanced three-dimensional climate simulation. Their results are consistent with widespread temperature changes of −4 to −6 °C over the continents in summer. The largest average optical depth calculated here is equivalent to almost 400 Tg of smoke (assuming the absorption coefficient from ref. 3). This is somewhat less than the largest amount of smoke assumed by Malone *et al.*[22] (500 Tg) and would, according to their results, lead to profound climate changes, particularly as its removal would be inhibited by changes to atmospheric stability.

The range of values calculated here is disquieting, because I tried to choose values for each of the various factors that were thought to be a 'best estimate' by at least one of the authors cited here. Although the range derived is similar to that quoted in ref. 3, they developed their estimates from uncertainties about a median value, whereas the present estimates are developed using the best estimates from a number of authors. The calculated range would be larger if we also considered the uncertainty estimates for each of the factors. This is especially true for the range of values chosen for the emission factors. In this case, the range of published values is not very large, but, because so few relevant data are available, the published range may not even include the correct value. There are also uncertainties caused by the lack of good data on the optical properties of smoke and the effect of the clouds formed above large fires. Furthermore, as discussed above, little is known about the scavenging and rainout of smoke in fire plumes. Good data on the properties of smoke from large fires will only come from large fire experiments; but great care is needed in the design and interpretation of the large-scale fires which will be used in the re-analysis of the smoke source term. The planned experimental programs sponsored by the United States Defense Nuclear Agency should be helpful but must not stop after only the first few experiments. We must try to understand the more complex situations that will exist in a real nuclear fire. In addtion, more and greater emphasis must be placed on understanding scavenging and rainout. Here, progress may come through the development of advanced modelling capabilities, coupled with verification by large-scale fire experiments.

Conclusions

Although our lowest estimates for $\bar{\tau}_a$ and $\bar{\tau}_e$ may produce only minor climatic effects, models can easily be constructed in which more fuel is burned, so that even in the low-estimate case, the estimate for $\bar{\tau}_a$ would correspond to a major climatic impact if the war takes place in the spring or summer. On the other hand, it is entirely possible that such major effects could be avoided if the low estimates are correct and if targets such as refineries, oil and gas production fields and coal storage areas are avoided. The effects on climate could also be lessened if the war took place during the winter[4]. It seems clear, therefore, that 'nuclear winter' is not necessarily a probable outcome of nuclear war, although it is certainly possible. The full range of possible impacts can never be completely narrowed because we cannot have access to the war plans of the nations of the world, nor predict the course of any given war once it began. I have shown, however, that for the model considered here, that is, one in which 40–80% of the total distributed urban fuels are burned, further research is needed in order to be able to predict the effects on climate.

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