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Airborne Studies of the Smoke from the Kuwait Oil Fires

Peter V. Hobbs* and Lawrence F. Radke

Airborne studies of smoke from the Kuwait oil fires were carried out in the spring of 1991 when ~4.6 million barrels of oil were burning per day. Emissions of sulfur dioxide were ~57% of that from electric utilities in the United States; emissions of carbon dioxide were ~2% of global emissions; emissions of soot were ~3400 metric tons per day. The smoke absorbed ~75 to 80% of the sun's radiation in regions of the Persian Gulf. However, the smoke probably had insignificant global effects because (i) particle emissions were less than expected, (ii) the smoke was not as black as expected, (iii) the smoke was not carried high in the atmosphere, and (iv) the smoke had a short atmospheric residence time.

As the Iraqi army fled Kuwait in February 1991, they damaged or destroyed 749 oil wells, storage tanks, and refineries, 610 of which were ignited (*1*). The resulting fires produced a large plume of smoke that had significant effects on the Persian Gulf area and the potential for global effects. To evaluate the effects of the smoke, we obtained airborne measurements from two aircraft during the period 16 May through 12 June 1991 (*2*). The goals of the study were to determine the chemical and physical nature of the smoke and to investigate its potential effects on air quality, weather, and climate. We give here an overview of this study and describe some of the results (*3*).

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Overview of the Fires and Smoke Plumes

The main oil fields in Kuwait (Fig. 1) can be divided broadly into those north and those south of Kuwait City. The individual fires in these fields generally produced distinct, isolated plumes over short distances, after which they merged. Low-level, stable atmospheric layers (*4*) were common in the region. When the smoke reached these layers, it generally fanned out horizontally. During our measurements, smoke was never detected above an altitude of ~6 km and was generally well below this level. The composite plume of smoke from the north fields generally merged with that from the south fields to produce a supercomposite plume, which was ~40 km wide 25 km south of Kuwait City (Fig. 2). Between ~0.3 and 1.2 km in altitude, the winds were nearly always from the north or northwest and were often quite strong (the "Shamal" wind), whereas at higher altitudes the winds were more westerly. The tops of the smoke layers were generally flat, although, on occasions, they contained wave-like features, including breaking waves and shallow convective features (Fig. 3). The base of the smoke plume was normally between ~0.5 and 2 km high and was also generally quite flat.

Close to the fires the smoke rained oil drops (Fig. 2). This oil, together with soot fallout, coated large areas of the desert with a black, tar-like covering. Oil spewing out from uncapped wells formed large pools of oil on the desert, some of which were alight (*5*).

Individual fires produced different plumes, ranging from black to white in appearance (Fig. 4). A few fires, presumably of natural gas (CH_4), produced no visible plume. Before our airborne measurements it was speculated that the white plumes were due to the presence of water. However, this explanation can be discounted because the dew points in these plumes were not measurably different from that in the ambient air, and relative humidities were low. These plumes contained a considerable mass of salt (*6*), which scattered light efficiently to produce the white appearance. More than 80% of the mass of the particles in one of the white plumes was salt (mostly NaCl). The salt no doubt originated from oil-field brines expelled from the wells together with the oil (*7*). Very little soot (~4% by mass) was present in the white smoke; the black smoke contained 20 to 25% soot and variable amounts of salt. Fires associated with pools of oil on the desert produced the blackest smoke, which contained up to 48% soot by mass. The mass of the smoke particles in the supercomposite plume was ~30% salt, 15 to 20% soot, 8% sulfate, and ~30% organics.

The optical properties of the supercomposite plume were dominated by submicrometer-sized particles, with number and volume size distributions sharply peaked near 0.1- and 0.3-μm diameter, respectively (*8*). These were the primary combustion particles and the building blocks for chain aggregates of soot (*9*). When the submicrometer aerosol was heated to 300°C to remove volatiles (including sulfate), about 30% of the mass was removed (*8*). Near the lateral edge and in the upper regions of the plume, where the solar radiation was greatest, there was photochemical production of nucleation-mode particles (~0.01 μm). Total particle concentrations within a few kilometers of the fires frequently exceeded 10^5 cm^{-3}; at 300 km from the fires the concentrations were ~5,000 to 15,000 cm^{-3}, and beyond 1000 km they approached background levels (~300 to 500 cm^{-3}). The supermicrometer fraction of

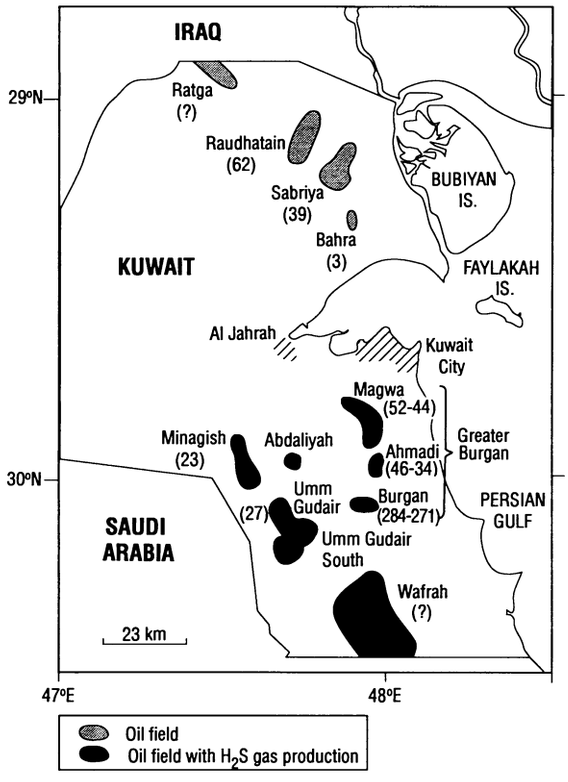

Fig. 1. Locations of the principal oil fields in Kuwait. The first number in parentheses is an estimate of the number of fires burning at the beginning (16 May 1991) of our field study; the second number estimates the number of fires burning at the end (12 June 1991) of our field study; one number in parentheses indicates that the number of fires burning during that period did not change (*30*).

Fig. 3. Breaking waves at the top of smoke from the Kuwait fires. [Photo courtesy of P. V. Hobbs]

Table 1. Ranges of typical concentrations and approximate maximum concentrations (in parentheses) of some of the gases measured in the plume from the Kuwait oil fires. Near-field refers to ~50 km from fires, mid-field to ~450 km from fires, and far-field to ~1000 km from fires.

Gas	Near-field (ppbv)	Mid-field (ppbv)	Far-field (ppbv)
CO_2	4.0×10^5–4.6×10^5 (4.9×10^5)	3.75×10^5	Near background ($\approx 3.6 \times 10^5$)
CO	100–500 (700)	100–200	Near background (~100)
SO_2*	100–500 (1000)	5–20	1–3 (Background <1)
NO_x†	5–20 (30)	2	Near background (<1)
O_3‡	20–45 (45)	35–65	Near background (~35–50)

*The maximum value of ~1000 ppbv was measured 15 km south of the Burgan oil field. †NO_x = NO + NO_2. ‡Ozone was depleted in the near-field but it was produced at greater distances downwind (see text).

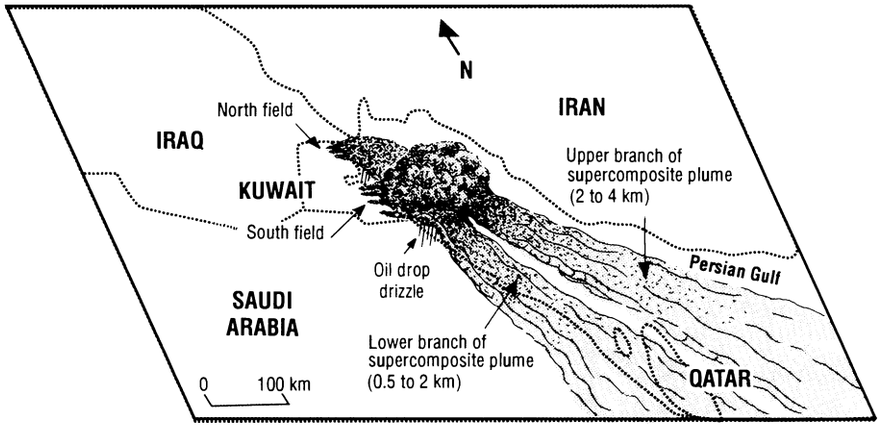

Fig. 2. Sketch of the smoke plumes from the Kuwait oil fires observed during the period 16 May through 12 June 1991.

the smoke particles comprised chain aggregates, salts, and oil droplets. Some of these particles contained considerable soot, and others were rather transparent. Close to the fires, the largest oil drops approached millimeter size and rained out quickly; smaller oil drops fell out within a distance of ~50 km from the fires. The majority of particles were such as to serve as cloud condensation nuclei (CCN) in cumuliform or stratiform clouds (*8*).

The mass concentration of particles <3.5 μm in diameter 20 km downwind of the fires in the composite plume from the south fields was ~840 μg m^{-3}. In the supercomposite plume, 160 km downwind of Kuwait City, it was ~210 μg m^{-3}. For comparison, the U.S. primary national ambient air quality standard (NAAQS), "to protect public health and welfare," for total particulate loading is an average of 150 μg m^{-3} over a 24-hour period (*10*).

Some of the soot particles in the black plumes from individual fires formed chained aggregates within a few seconds of combustion; few chained aggregates were detected in the white plumes (*9*). The aged smoke in the supercomposite plume contained some nonspherical particles but fewer than in the black smoke from individual fires (*9*).

Optical properties of the smoke. The single-scattering albedo (*11*) was 0.95 for the white plumes, 0.35 for the blackest plumes, and 0.5 to 0.6 for the supercomposite plume (*12*). These values are not as low (that is, the smoke was not as black) as for smoke from aviation fuel (*13*). This was due, in part, to the relatively high efficiency of the combustion (*14*). Even so, the specific absorption (*11*) of the aged, supercomposite plume was 1.3 to 1.8 m^2 g^{-1}, which suggests that the mass fraction of soot was ~20 to 30% (*12*).

The optical depth (*11*) of the supercomposite plume for visible radiation at about 100 km from the fires was 2 to 3 (*15*). About 10% of the sun's radiation was transmitted through the thickest parts of the supercomposite plume, 75 to 80% of the sun's radiation was absorbed, and the remainder was scattered by the smoke in the supercomposite plume (*15*). The absorption

Fig. 4. Photograph of a few of the individual Kuwait oil fires showing the variety of plumes, including black and white. [Photo courtesy of R. Bumpas]

of the sun's radiation by the smoke should have caused significant decreases in surface temperatures in regions of the Gulf affected by the smoke (*16*). The absorption of solar radiation by the smoke produced an instantaneous heating of the smoke that, near noon, was ~25°C per day (*15*). This should have made the smoke buoyant with respect to the surrounding air and therefore produce self-lofting (*13*). Although some self-lofting was observed, it did not cause the smoke to be carried very high.

Gases in the smoke. The concentrations of CO, O_3, NO_x, and CO_2 in the smoke were below typical urban levels in the United States and primary NAAQS (Table 1). Average concentrations of CO, SO_2, and NO_x in the plume 80 km downward of Kuwait City on 30 May 1991 were 127, 106, and 9.1 parts per billion by volume (ppbv), respectively, above background concentrations (*17*). Both CH_4 and H_2S were only slightly elevated above ambient values in the smoke because of their efficient combustion and because most of the nonburning oil wells were capped before our measurements. Ozone depletion, probably produced by the reaction of O_3 with NO, was measured in the core of the smoke plume within a few kilometers of the fire (*17, 18*). Farther downwind, O_3 was further depleted, probably because of reactions with alkenes and possibly on the soot particles (*18*). In the diffuse regions of the plume, where the ultraviolet radiation was greater, O_3 was produced (*18*). The average rate of O_3 production throughout the plume during its first 3.6 hours of transport was 1.8 ppbv per hour (*17*).

The concentrations of total nonmethane gaseous hydrocarbons (NMHC) in the plume ranged from 55 to 827 ppbv of carbon (*17*), which is typical of the clean to moderately polluted troposphere. The NMHC were dominated by alkanes (65 to 82% NMHC on a per carbon basis); alkenes, or olefins, made up 7 to 23% of the NMHC, aromatic hydrocarbons 5 to 19%, and alkynes 1 to 7% (*17*).

The smoke plume was often associated with a well-defined convergence zone, where the wind speeds reached ~10 m s^{-1} and a local maximum in SO_2 (~125 ppbv) was measured (*19*). This convergence line could have been the result of local changes in the thermal structure of the atmosphere, caused by the strong absorption of solar radiation by the smoke, as well as dynamical effects produced by the coastline of the Persian Gulf.

Amounts and rates of emissions. From measurements within the supercomposite plume, made at a distance of ~160 km from the Burgan oil field, particles (<3.5 μm in diameter), soot, total organic carbon in particles, total (nonmethane) organic carbon in vapor form, CO, CO_2, CH_4, SO_2, and NO_x accounted for 1.6, 0.3, 0.5, 0.7, 0.5, 83, 0.16, 1.6, and 0.05%, respectively, of the fuel burned (*20*), where for particles, SO_2, and NO_x the percentages refer to the total mass of the emitted species and in the other cases the percentages refer to the mass of carbon in the species. The depletions of SO_2 and NO_x in the plume (due to transformations rather than dilution) were very rapid in the first 3 to 4 hours of travel time in the atmosphere (50 and 60% per hour, respectively) (*6*). It is unclear where all of the SO_2 and NO_x went. For example, the measured increases in fine particle (<3.5 μm in diameter) sulfate in the plume are not nearly large enough to account for all of the depletion of SO_2 (*21*).

Shown in Table 2 are estimates of the rates of emission of various materials from the Kuwait oil fires (*6, 12, 20*). To place these emissions in context, the last column in Table 2 contains some comparisons with other sources. From measurements of the total flux of carbon in the supercomposite plume, the rate at which oil was being burned during the period of our measurements was deduced to be 4.6 ± 1.2 million barrels per day (including gas, estimated at 7% of the total carbon)

Table 2. Estimates of emissions (in metric tons per day) from the Kuwait oil fires.

Species	Emissions from		Total emissions from all fires*	Comparisons with other sources
	North fields	Greater Burgan field		
CO_2	0.13×10^6	1.7×10^6	1.8×10^6	= 2% of global emissions from fossil fuel and biomass burning
CO	0.12×10^4	0.89×10^4	1.03×10^4	= 0.1% of worldwide emissions from all sources
SO_2	0.08×10^4	1.9×10^4	2.0×10^4	= 57% of emissions from U.S. electric utilities
Soot (elemental carbon)†	0.016×10^4	0.31×10^4	0.34×10^4	= 13 times the soot emissions from all U.S. combustion sources‡ (*31*)
Particles (including soot)†	0.08×10^4	1.1×10^4	1.2×10^4	= 10% of global emissions from biomass burning

*Assumes that the north fields and greater Burgan field account for 97% of the emissions (*30*). †For particles <3.5 μm in diameter. ‡The emission rate of soot from the Kuwait fires is equivalent to the soot emitted by about 3 million heavy-duty diesel trucks being driven at 30 miles per hour.

(22). This is slightly less than the U.S. daily import of oil.

Global Effects

The Kuwait oil fires had marked effects on air quality and some aspects of the weather in the Persian Gulf. However, the smoke from the fires probably had only small effects beyond the Gulf region and insignificant effects on a global scale (23). Our studies help explain why significant amounts of smoke have not been reported beyond the Gulf region. Relatively efficient combustion produced smaller fluxes of soot from the Kuwait fires than anticipated [about 1/20 of that of some worst-case predictions (24)]. Furthermore, the smoke was not as (optically) black as expected. The smoke was never observed to rise above 6 km, even after traveling up to a distance of 1600 km over 48 hours. This is well below the base of the stratosphere in the region (~13 km). This prevented rapid transport over large distances. Also, the character of the fuels and the unusually rapid depletion of SO_2 and NO_x in the plume produced particles that were efficient CCN. Therefore, as a result of scavenging by clouds and precipitation, the average residence time in the atmosphere of these particles should have been short (~days).

Implications for nuclear winter. The nuclear winter scenario predicts that the large quantities of smoke that would be produced by a nuclear war would absorb sufficient solar radiation to cause significant decreases in surface temperatures worldwide (25). Because soot is highly light-absorbing, it plays an important role in the nuclear winter scenario. It has been predicted that in a nuclear war the burning of primary and secondary petroleum materials would produce about 34% of the soot emissions (26). In the latest nuclear winter calculations (26), the range of emission factors for soot from the burning of petroleum is taken to be 3 to 10% (with an average of 6%). For the composite plumes from the Kuwait oil fires, we measured average emission factors for soot ranging from ~0.3 to 0.6%. However, in a nuclear war, most of the oil fires would likely be more similar to large fires of pooled oil than to oil well fires. Our measured values of soot emission factors for two pool oil fires in Kuwait were 1.6 and 2.8% (20). Therefore, if comparisons are valid, the emissions of soot assumed in the nuclear winter calculations may be too high.

The value for the single-scattering albedo ($\tilde{\omega}$) for the complex mix of smokes from urban fires assumed in recent nuclear winter calculations (26) is 0.6 to 0.65. For comparison, measurements give $\tilde{\omega}$ = 0.32, 0.35, 0.5 to 0.6, and 0.83 for smoke from pools of aviation jet fuel (13), the pool oil fires in Kuwait (12), the supercomposite smoke plume from the Kuwait fires (12), and biomass fires (27), respectively.

In order to have worldwide effects, the smoke from a nuclear war would need to have a long residence time in the atmosphere and be transported rapidly over large distances. This requires that the smoke be carried high into the atmosphere. Apart from smoke carried aloft by nuclear blasts, the height to which the smoke would rise in a nuclear war would depend on the heats generated by the fires and the stability of the atmosphere (4). As predicted (28) and as observed by us and Johnson *et al.* (3), the Kuwait oil fires were not sufficiently intense, nor was convective mixing in the region sufficiently deep, to cause the smoke to penetrate the low-level temperature inversions that were ubiquitous in the region. When confined to the troposphere, smoke probably has a relatively short residence time due to its removal by cloud and precipitation processes; this is particularly true for the smoke particles from the Kuwait fires, which were good CCN. In earlier nuclear winter studies it was generally assumed that half of the smoke washes out of the atmosphere immediately, although Turco *et al.* (26) suggested that ≤10 to 25% would be removed in this manner. As noted earlier in this paper and by Sagan (29), in some regions of the Persian Gulf the smoke from the Kuwait fires produced a small-scale imitation of the nuclear winter scenario.

Concluding Remarks

The airborne studies of the smoke from the Kuwait fires provided a large quantity of data on the physical and chemical properties of thick oil smoke plumes and their transformations in the atmosphere. These studies also provided a well-documented study of gross air pollution from a relatively small source region. Use of these data for input and verification of numerical simulations should increase understanding of the effects of smoke on the composition of the atmosphere and on weather and climate.

REFERENCES AND NOTES

1. Uncontrolled releases of oil began in January 1991, and the oil field fires began in late February 1991.
2. The aircraft were the University of Washington Convair C-131A [P. V. Hobbs, L. F. Radke, J. H. Lyons, R. J. Ferek, D. F. Coffman, *J. Geophys. Res.* **96**, 18735 (1991)] and the National Center for Atmospheric Research Lockheed Electra (*NCAR/Research Aviation Facility Bull. 4*) (1989)]. The Convair facility was augmented (by F. Valero and P. Pilewskie) with upward- and downward-pointing radiometers for obtaining multiwavelength measurements of the direct and diffuse solar radiation. The Electra facility was augmented with lidars (B. Morley and D. R. Schweisow), a soot detector (R. Schnell), aerosol sizing and thermal volatility instruments (A. Clarke), and instruments for measuring aerosol optical properties (G. Mulholland), CCN (J. Hudson), aerosol chemistry (C. Twohy and B. Huebert), particle chemistry and morphology (P. Sheridan), and gas chemistry (A. Bandy, T. Conway, G. Kok, and P. Zimmerman).
3. An airborne study of the smoke from the Kuwait fires was carried out in March 1991 by D. W. Johnson *et al.* [*Nature* **353**, 617 (1991)]. Their measurements and conclusions are generally similar to ours, but see (22) and (31).
4. Stable layers are regions of the atmosphere where the temperature either increases or changes little with height. When rising parcels of air (or smoke) encounter such layers, they tend to spread out horizontally.
5. Coating of the desert with oil increases the absorption of solar radiation by the surface. This may affect the atmospheric heat budget of the region even after the fires are put out.
6. R. J. Ferek, P. V. Hobbs, J. A. Herring, K. K. Laursen, *J. Geophys. Res.*, in press.
7. All hydrocarbon reservoirs contain water. The water is usually in the form of aqueous salt solution; many formation waters in petroleum reservoirs have salt concentrations exceeding that of seawater [H. J. Neumann, B. Paczyńska-Lahme, D. Severin, *Composition and Properties of Petroleum* (Enke, Stuttgart, 1981), p. 28].
8. J. G. Hudson and A. D. Clarke, *J. Geophys. Res.*, in press.
9. R. E. Weiss, V. N. Kapustin, P. V. Hobbs, *ibid.*, in press.
10. *Air Quality Criteria for Particulate Matter and Sulfur Oxides* (U.S. Environmental Protection Agency, Research Triangle Park, NC, 1982).
11. The single-scattering albedo ($\tilde{\omega}$) is the ratio of the light-scattering coefficient (σ_S) to the light-extinction coefficient (σ_E) ($\tilde{\omega} = \sigma_S/\sigma_E$). Because $\sigma_E = \sigma_S + \sigma_A$, where σ_A is the light-absorption coefficient, $\tilde{\omega} = \sigma_S/(\sigma_S + \sigma_A)$. Therefore, the greater the value of $\tilde{\omega}$, the more light is scattered. Specific absorption (B_A) ≡ σ_A/(particle mass per unit volume of air). If the sun's radiation produces an irradiance $E_{\lambda\infty}$ (in watts per square meter) per unit wavelength interval at wavelength λ on the top of the smoke layer, then, at any point within the smoke, $E_\lambda = E_{\lambda\infty} \exp(-\sigma_\lambda)$, where σ_λ is the optical depth of the smoke at that point. Clearly, for an optical depth of 1, the irradiance is reduced by a factor e (= 2.7).
12. R. E. Weiss and P. V. Hobbs, *J. Geophys. Res.*, in press.
13. L. F. Radke, J. H. Lyons, P. V. Hobbs, R. E. Weiss, *ibid* . **95**, 14071 (1990).
14. A measure of the inefficiency of combustion is the ratio of CO to CO_2. The CO/CO_2 ratio for the Kuwait fires was about 1%, which is relatively low. Hence, the fires burned rather efficiently. The low concentrations of H_2S and NMHC in the plume confirm this deduction. The low concentrations of NO_x indicate low-temperature combustion.
15. P. Pilewskie and F. Valero, *J. Geophys. Res.*, in press.
16. The average temperature for Bahrain (about 400 km from Kuwait) in May 1991 was about 4°C below normal, the coldest May in 35 years.
17. W. T. Luke *et al.*, *J. Geophys. Res.*, in press.
18. J. A. Herring and P. V. Hobbs, *ibid.*, in press.
19. L. F. Radke, D. Baumgardner, R. L. Schwiesow, W. A. Cooper, *ibid.*, in press.
20. K. K. Laursen, R. J. Ferek, P. V. Hobbs, R. A. Rasmussen, *ibid.*, in press.
21. The missing SO_2 and NO_x may have deposited onto dust particles blown up from the desert.
22. The rate at which oil was burned was calculated (6) from airborne measurements of the total flux of carbon through the supercomposite plume and the carbon content of oil, 850 g kg^{-1} [H. J. Neumann *et al.*, in *Composition and Properties of Petroleum* (Enke, Stuttgart, 1981), pp. 1 and 48]. Johnson *et al.* (3) derived an oil burn rate of 3.9 ± 1.6 million barrels of oil per day from measurements of SO_2 fluxes in the plume. However, this results in an underestimate of the oil burn rate because, as shown by our measurements, SO_2

was rapidly transformed in the plume.
23. It has been suggested that the smoke from the Kuwait fires reached Hawaii and Wyoming (B. A. Bodhaine, J. M. Harris, J. A. Ogren, D. J. Hofmann, *Geophys. Res. Lett.*, in press). This does not contradict our conclusion that the smoke had insignificant effects on a global scale because the amounts of smoke claimed to have reached Hawaii and Wyoming are small and would have insignificant effects on climate.
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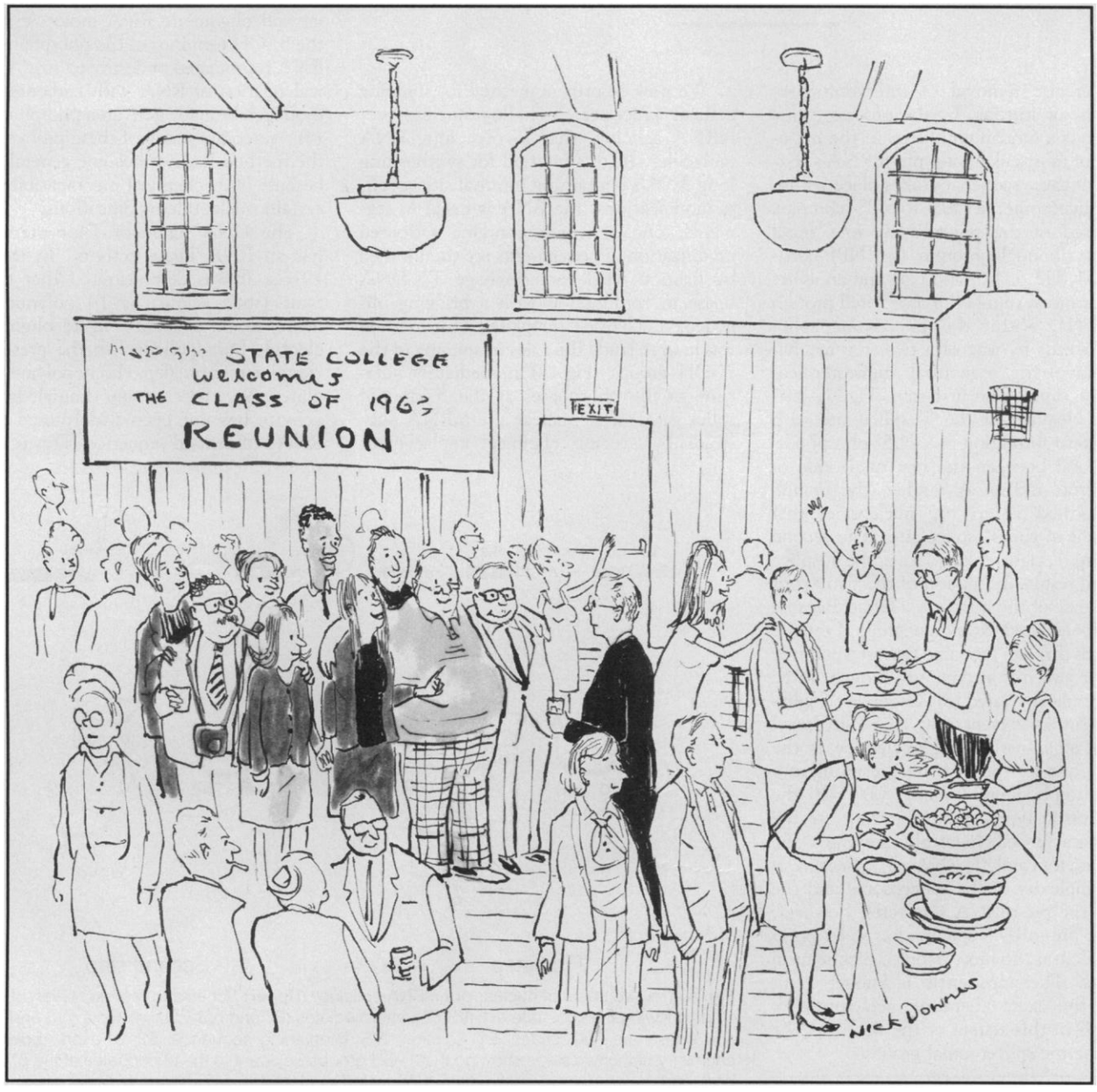
26. R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, C. Sagan, *Science* **247**, 166 (1990).
27. L. F. Radke *et al.*, in *Aerosols and Climate*, P. V. Hobbs and M. P. McCormick, Eds. (Deepak, Hampton, VA, 1988), pp. 411–422.
28. R. D. Small, *Nature* **350**, 11 (1991); K. A. Browning *et al.*, *ibid.* **351**, 363 (1991).
29. C. Sagan, *Science* **254**, 1434 (1991).
30. The number of fires is based on daily reports from the Kuwait Oil Company as compiled by the Arabian Gulf Program Office, National Oceanic and Atmospheric Administration.
31. Johnson *et al.* (*3*) reported total soot emissions of 1.75×10^4 metric tons per day. However, they actually measured total particle volume, converted it to mass, and assumed all this mass was soot. Our measurements show that ~40% of the mass of particles was salt and sulfate. We measured 1.2×10^4 metric tons per day of particles (of all compositions) with diameters <3.5 μm. About 20% of the oil well fires were extinguished between the time of the measurements of Johnson *et al.* and ours.
32. The U.S. Interagency Airborne Study of the Kuwait oil fires, which was supported by the National Science Foundation, the Department of Energy, the National Oceanic and Atmospheric Administration, and the National Geographic Society, would not have been possible without the dedicated efforts of many individuals. In particular, we thank R. Greenfield and R. Anthes for coordinating funding. We also thank all of the scientists, engineers, and pilots who participated in this project. In Bahrain, M. Isa provided office space and K. Fakhro helped in coordination.



"We were a control group back in Behavioral Sciences 202 and we've been together ever since."