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SCIENCE

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Smoke emitted from forest fires in northern California in September 1987 was trapped in a valley by an inversion for 3 weeks. Daily maximum temperatures on the valley floor were more than 15°C below normal for 1 week and more than 5°C below normal for 3 weeks. The smoke strengthened the inversion by preventing surface warming by solar radiation, thereby enhancing the smoke trapping and the surface cooling in a positive feedback loop. These results may have implications for nuclear winter.

Crutzen and Birks (*1*) were the first to suggest that smoke from forest, urban, and industrial fires ignited by nuclear weapons would be extensive enough to block out significant amounts of sunlight. The resulting surface cooling calculated with a climate model was so large that it was called "nuclear winter" (*2*). Smoke from urban and industrial fires (especially oil refineries) would be much more effective at preventing solar radiation from reaching the earth's surface than forest fire smoke after a large-scale nuclear war (*2, 3*); with both urban and rural targets, not only would more urban smoke be generated but its optical properties would make it more effective at blocking sunlight.

In this context, the effects of forest fire smoke are of interest for two reasons. First, a lot of forest fire smoke would still be generated in many nuclear war scenarios, especially those that include only nonurban military targets. The optical properties and surface temperature effects of this smoke are important parts of the study of nuclear winter. Second, it is useful to have some actual observations of the effects of smoke to compare to theoretical models of nuclear winter. Extensive urban and industrial smoke plumes are not readily available for study. Each year, however, a number of forest fires are generated by lightning, in some cases producing extensive smoke plumes. Anecdotal observations from extensive Siberian forest fires in 1915 (*4*) and Canadian forest fires in 1950 (*5*) indicated a daytime surface cooling of several degrees Celsius. In addition, Robock (*6*) found similar surface temperature effects of forest fire smoke plumes over the midwestern United States in the summers of 1981 and 1982 and over Alaska in May 1987 by examining objective errors of numerical temperature forecasts. In all these cases, elevated smoke layers produced daytime cooling but had no nighttime effects. I now describe a feedback process that produced much larger and longer lasting surface temperature effects, caused by smoke from forest fires in northern California in September 1987. Smoke was trapped in valleys for more than 1 week by an inversion that was strengthened by the cooling.

On 30 August 1987, orographic thunderstorms in northern California and southern Oregon ignited severe forest fires that burned for more than 1 month, consuming 203 km^2 of forest. (This is less than 0.1% of the area that might burn in a nuclear holocaust.) For the first 2 weeks of the fires, except for the time when a weak cold front passed over the area on 2 September, a high-pressure system prevailed over the region. The result was a subsidence inversion, which trapped smoke in the mountain valleys, particularly in Klamath River Canyon, which extends from Happy Camp at the north to Orleans at the south (Fig. 1). Each day, more smoke accumulated beneath the inversion, with the surface cooling produced by the blockage of sunlight strengthening the inversion and trapping more smoke (*7*). Because the smoke has a higher albedo than the wooded surface (Fig. 2d), the result is a net cooling of the entire atmosphere-surface system. Virtually all the sunlight that is not reflected by the smoke is absorbed before it reaches the ground, thereby strongly cooling the ground while slightly heating the air, although not enough to destabilize the air with respect to the synoptic scale inversion. This positive feedback effect of the smoke enhanced both the amplitude and the duration of the cooling.

I examined surface air temperature data for the region between 39°N and 45°N and west of 120°W to the Pacific Ocean, in northern California and southwestern Oregon (Fig. 1), using data from 96 National Weather Service stations for which 30-year normals have been computed (*8*), another 65 National Weather Service climatological observing stations (*9*), and 85 Forest Service stations (*10*), for a total of 246 stations. Not all of these stations made observations each day during this period, but for September it was possible to use more than 70 stations in the region to calculate deviations from normal and more than 200 stations to calculate

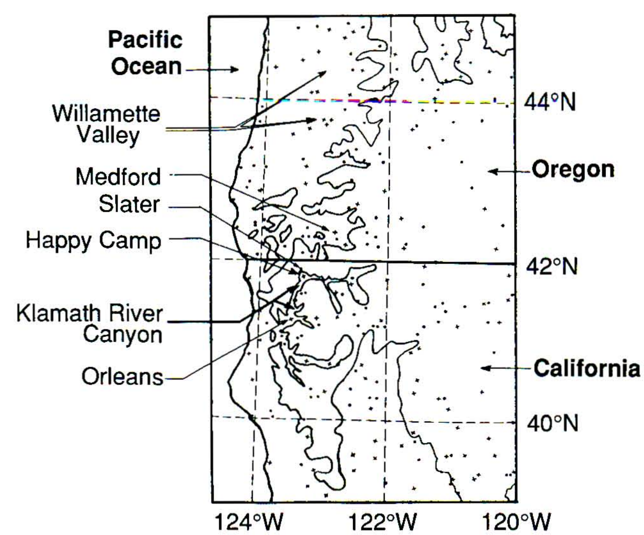

Fig. 1. Map of the study area in northern California and southern Oregon. Stations for which normals are available are plotted as crosses, and the remaining stations are plotted as dots. Contour of 1000-m elevation and observation stations mentioned in the text and Figs. 3 and 4 are shown.

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daily maximum, daily minimum, and range of temperatures.

On 7 September 1987, which was typical of all the days from 4 through 12 September, a region of large negative anomalies of maximum temperature can be seen in northwestern California (Fig. 2) in Klamath River Canyon. At the same time, no minimum temperature anomalies are evident. Anomalies in this region began on 2 September and lasted through 22 September, with only a brief respite on 14 and 15 September due to the passage of a strong cold front.

I analyzed the maximum temperature anomalies for Happy Camp and Orleans, California, which were in the smoke-filled canyon, and Medford, Oregon, which was not (Fig. 3). Orleans, near the mouth of the canyon, did not cool quite as much as Happy Camp because it experienced some ventilation from the ocean to the west.

From 2 to 5 September, as the inversion strengthened, the maximum temperature plummeted in Happy Camp while it rose in Slater, California, 11 km to the north on the ridge top and cut off from the influence of the smoke (Fig. 4). As the wind shifted to southerly starting on 9 September, the maximum temperature in Slater fell as smoke was blown over. The minimum temperature in Happy Camp stayed virtually constant the whole time; the minimum temperature fell toward the end of the period in Slater, where it was cool at night as the smoke cleared as a result of the normal diurnal mountain-valley wind.

This dramatic temperature contrast at stations at different altitudes demonstrates the large smoke effects. Normally the maximum temperature in Happy Camp, at a lower elevation, is higher than that in Slater and the minimum temperature is lower, and this was true for every day in the month of August 1987, for example. The average maximum temperatures for August were 37.0°C for Happy Camp and 30.7°C for Slater, and the minima were 8.9° and 15.4°C, respectively. The reversal of the maximum temperature difference (Happy Camp minus Slater) from 6.3°C to as much as −20°C shows the smoke effects. The August average temperatures should also be compared to those in Fig. 4. The maximum temperature in Happy Camp on 30 August, the day of the lightning that started the fires, was 42.2°C, so the cooling shown in Figs. 3 and 4 was even larger than the difference from the normal maximum temperature, although some of this cooling may have been due to synoptic variation.

Northerly winds on 16 September blew the smoke out of Klamath River Canyon into a long plume that moved southward off, and parallel to, the California coast. For the next week cooling persisted in the canyon, but the cooling was not as intense as for the earlier period.

The smoke trapped in Klamath River Canyon produced harmful effects on those living there. By the end of the first week, more than 400 persons per day were being treated for respiratory problems (*11*). Tomato plants in gardens in Happy Camp died and produced no fruit (*12*).

A mechanism has been identified that enhances the surface cooling effect of forest fire smoke. Smoke was trapped in a valley by an inversion that was strengthened by the surface cooling. This strengthening trapped more smoke, which produced more cooling, thus creating a positive feedback. Only a strong synoptic scale front was finally able to destroy this amplifying cycle. It had been suggested (*2, 4*) that although elevated aerosol layers would produce cooling, layers at the surface would have a net warming effect. In this case, because of the high albedo of the smoke, not only did an aerosol layer at the surface produce cooling but it enhanced the cooling.

The example presented here demonstrates that smoke in the atmosphere produces cooling in the daytime and little effect at night, resulting in net cooling at the surface. This is what theory would predict for smoke particles that have high optical depths in visible wavelengths but are relatively transparent in the infrared. Although the small spatial scale of the cooling shown here does

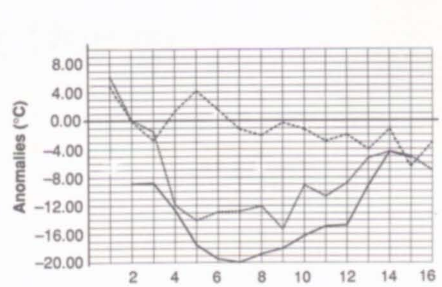

Fig. 3. Maximum temperature anomalies for Happy Camp, California (bottom curve), Orleans, California (middle curve), and Medford, Oregon (top curve), for 1 to 16 September 1987. See Fig. 1 for station locations.

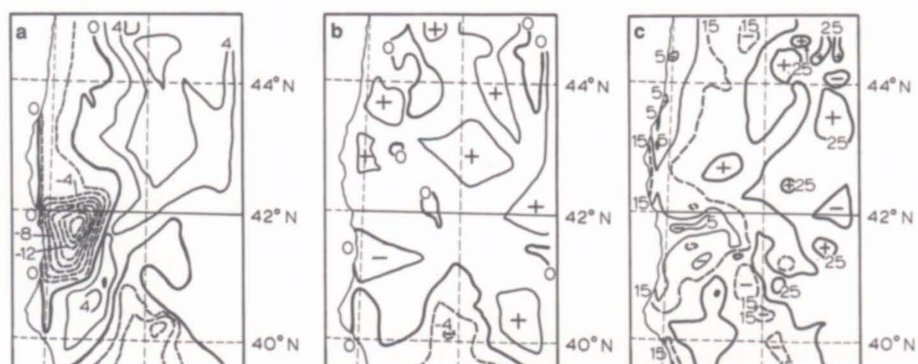

Fig. 2. (**a**) Anomalies of maximum surface air temperature (maximum temperature minus normal maximum temperature) for 7 September 1987. Contours are every 2°C. The 0°C contour is thick. Negative contours are dashed. (**b**) Anomalies of minimum surface air temperature for 7 September 1987 (minimum temperature minus normal minimum temperature). Contours are as in (a). (**c**) Daily temperature range (maximum temperature minus minimum temperature) for 7 September 1987. Contours are every 5°C. Contours of 5°C and 10°C are thin. The 15°C contour is dashed; 20° and 25°C contours are thick. (**d**) Satellite image for 2115 GMT (2:15 p.m. PDT).

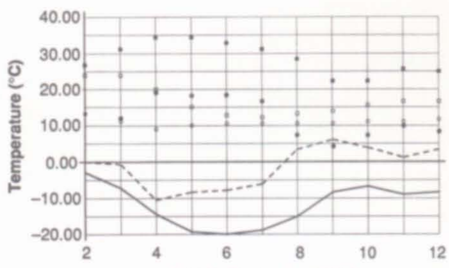

Fig. 4. Maximum and minimum temperatures and their differences for Happy Camp, California, located at an elevation of 351 m in the Klamath River Canyon, and Slater, California, located 11 km north of Happy Camp at an elevation of 1423 m: (□) Happy Camp maximum; (■) Slater maximum; (○) Happy Camp minimum; (●) Slater minimum; (—) maximum difference; (- - -) minimum difference. See Fig. 1 for locations.

not by itself imply large-scale cooling in a nuclear winter scenario, this example demonstrates that smoke can cause cooling and shows the existence of a feedback mechanism that can enhance and prolong the expected cooling.

REFERENCES AND NOTES

1. P. J. Crutzen and J. W. Birks, *Ambio* **11**, 115 (1982).
2. R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, C. Sagan, *Science* **222**, 1283 (1983). These first calculations have since been verified by extensive research with more complex climate models (*3*).
3. National Research Council, *The Effects on the Atmosphere of a Major Nuclear Exchange* (National Academy Press, Washington, DC, 1985); A. B. Pittock *et al.*, *Scientific Committee on Problems of the Environment 28, Environmental Consequences of Nuclear War*, vol. 1, *Physical and Atmospheric Effects* (Wiley, New York, 1986); *Study on the Climatic and Other Global Effects of Nuclear War* (Report A/43/351, United Nations, New York, 1988).
4. N. N. Veltishchev, A. S. Ginsburg, G. S. Golitsyn, *Izv. Akad. Nauk CCCP Fiz. Atmos. Okeana* **24**, 296 (1988) (in Russian).
5. H. Wexler, *Weatherwise* **3**, 129 (December 1950).
6. A. Robock, in *Aerosols and Climate*, P. Hobbs, Ed. (Deepak, Hampton, VA, in press). Similar effects on Alaska temperatures were found for smoke from Chinese and Siberian fires in May 1987 (A. Robock, in preparation).
7. C. Fontana, D. Willson, D. Gettman, personal communication.
8. *Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951–80, California*, Climatography of the United States No. 81 (by state) [National Oceanic and Atmospheric Administration (NOAA), Asheville, NC, 1982]; *Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951–80, Oregon*, Climatography of the United States No. 81 (by state) (NOAA, Asheville, NC, 1982).
9. *Climatol. Data, California, August 1987* **91** (no. 8) (NOAA, Asheville, NC, 1987); *Climatol. Data, California, September 1987* **91** (no. 9) (NOAA, Asheville, NC, 1987); *Climatol. Data, Oregon, August 1987* **93** (no. 8) (NOAA, Asheville, NC, 1987); *Climatol. Data, Oregon, September 1987* **93** (no. 9) (NOAA, Asheville, NC, 1987).
10. R. W. Furman and G. E. Brink, *The National Fire Weather Data Library* (USDA Forest Service General Technical Report RM-19, U.S. Department of Agriculture, Fort Collins, CO, 1975).
11. D. Willson, personal communication.
12. C. Fontana, personal communication.

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