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Surface Cooling Due to Forest Fire Smoke

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In four different cases of extensive forest fire smoke the surface temperature effects were determined under the smoke cloud. In all cases, daytime cooling and no nighttime effects were found. The locations of smoke clouds from extensive forest fires in western Canada in 1981 and 1982, in northern China and Siberia in 1987, and in Yellowstone National Park in northwestern Wyoming in 1988 were determined from satellite imagery. As these smoke clouds passed over the midwestern United States for the Canadian and Yellowstone fires and over Alaska for the Chinese/Siberian fires, surface air temperature effects were determined by comparing actual surface air temperatures with those forecast by model output statistics (MOS) of the United States National Weather Service. MOS error fields corresponding to the smoke cloud locations showed daytime cooling of 1.5° to 7°C under the smoke but no nighttime effects. These results correspond to theoretical estimates of the effects of smoke, and they serve as observational confirmation of a portion of the nuclear winter theory. This also implies that smoke from biomass burning can have a daytime cooling effect of a few degrees over seasonal time scales. In order to properly simulate the present climate with a numerical climate model in regions of regular burning it may be necessary to include this smoke effect.

1. INTRODUCTION

Every year, extensive forest fires, started by lightning, by accident or for land clearing, and other biomass burning for agricultural and hunting purposes, input smoke to the atmosphere. Although the typical lifetime for smoke is of the order of 1 week, in continuous burning cases the smoke can persist for as long as the burning continues, which can be for weeks or months during agricultural or deforestation burning.

The effects of this smoke on the climate have not been studied in detail before and are of interest for several reasons. The regional climate where persistent smoke loading occurs, such as in the Amazon during the months of August and September or in tropical Africa during the dry season, may be affected by the radiative effects of the smoke.

The cases discussed here have applications not only to normal biomass burning but also to nuclear winter. *Crutzen and Birks* [1982] first suggested that smoke from forest, urban and industrial fires ignited by nuclear weapons would be extensive enough to block out significant amounts of sunlight. Subsequent works, such as *Turco et al.* [1983], *National Research Council (NRC)* [1985], and *Pittock et al.* [1986], have pointed out that the smoke from urban and industrial fires (especially oil refineries) would probably be much more effective at preventing solar radiation from reaching the Earth's surface than forest fire smoke after a large-scale nuclear war. With both urban and rural targets, not only would more smoke be generated from urban targets, but its optical properties would make it more effective at blocking sunlight. However, the optical properties and surface temperature effects of forest fire smoke are important parts of the study of nuclear winter. A lot of forest fire smoke would still be generated in many nuclear war scenarios, especially those that include only nonurban military targets. In addition, it is useful to have some actual observations of the effects of smoke to compare to theoretical models of nuclear winter. In fact, the 1982 case presented here has been modeled by *Westphal and Toon* [1991], and comparisons of the results are discussed later.

Wexler [1950] presented anecdotal evidence of daytime cooling in Washington, D. C., at the surface of 2°C to 5°C from "The Great Smoke Pall" caused by extensive Canadian forest fires in 1950. *Veltishchev et al.* [1988] also presented anecdotal observations of daytime surface cooling caused by extensive Siberian forest fires in 1915. *Robock* [1988*a*] found maximum surface temperatures of as much as 20°C below normal caused by smoke trapped in a valley in northern California, but this was in a small region and there were large smoke optical depths due to the trapping. These works suggest that forest fire smoke can produce net cooling of surface air temperature over large areas, but do not provide an objective measure of the effect. In this paper, comparisons of observations to numerical model forecasts provide an objective measure of this cooling effect.

As will be shown later, smoke clouds were easy to detect with visible wavelength imagery but were invisible in infrared imagery on satellite photos. Submicron smoke particles strongly interact with the incoming short-wave solar radiation, scattering and absorbing it, producing visible images of smoke. The long-wave outgoing terrestrial radiation ($\lambda \cong 10$ μm) can easily pass through the smoke layer allowing the radiation to be detected by the satellite but preventing smoke detection in these wavelengths. Thus, based on only the satellite images, we would expect the smoke to have a net cooling effect on the surface, with less solar radiation reaching the surface to warm it but long-wave radiation able to leave the surface and cool it normally. The downward long-wave radiation from the smoke cloud would not be expected to compensate for the loss of solar radiation [*Vogelmann et al.*, 1988; *Turco et. al.*, 1990]. This is in contrast to the effects of the volcanic dust particles from Mount St. Helens, which were larger and, while also cooling during the day, caused compensating warming at night [*Robock and Mass*, 1982; *Mass and Robock*, 1982].

2. BRITISH COLUMBIA FIRES OF 1981 AND 1982

The location of smoke clouds from extensive Canadian forest fires was determined from satellite imagery for cases in the summers of 1981 and 1982. The smoke clouds were easy to detect with visible wavelength imagery (Figures 1-3), but were

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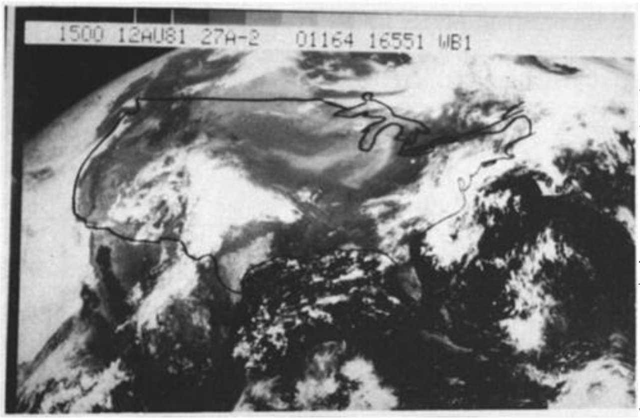

Fig. 1*a*

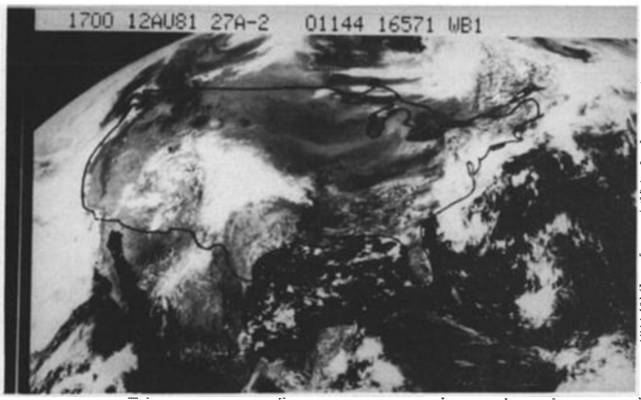

Fig. 1*b*

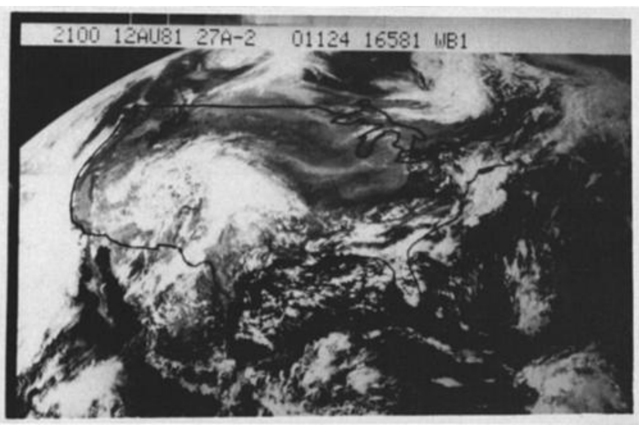

Fig. 1*c*

Fig. 1. Geostationary (GOES) satellite image in visible wavelengths (channel 1), August 12, 1981, for (*a*) 1500, (*b*) 1700 and (*c*) 2100 UT. The smoke can be seen as two curved gray bands extending southwestward from the Great Lakes.

invisible in infrared imagery. In the 1981 case (Figure 1), the smoke appeared to be in streaks, with patches of less dense smoke in between. Within 3 days of being produced, the smoke plumes in the 1982 case grew into an extensive shield covering about 10^6 km^2. There was some patchiness evident (Figures 2-3), but the smoke veil maintained a coherent structure for several days. The total area covered was about the same in both cases. *Robock* [1988*b*] presented a preliminary summary of these cases.

As these smoke clouds passed over the midwestern United States, surface air temperature effects were determined by comparing actual temperatures with those forecast using model output statistics (MOS) by the United States National Weather Service [*Glahn and Lowry*, 1972]. This MOS error technique had been used successfully before to determine surface air temperature effects of the Mount St. Helens volcanic eruption of 1980 [*Robock and Mass*, 1982; *Mass and Robock*, 1982]. The analysis was done in regions of high pressure where synoptic disturbances were not affecting the temperature. The errors are attributed to the presence of aerosols in the atmosphere, since the aerosol content is not a MOS predictor. The locations of all the MOS stations used in this analysis are shown in Figure 4.

1981 Case

During the second week of August 1981, numerous forest fires burned in western Canada [*Schneider et al.*, 1986]. Figure

Fig. 2*a*

Fig. 2*b*

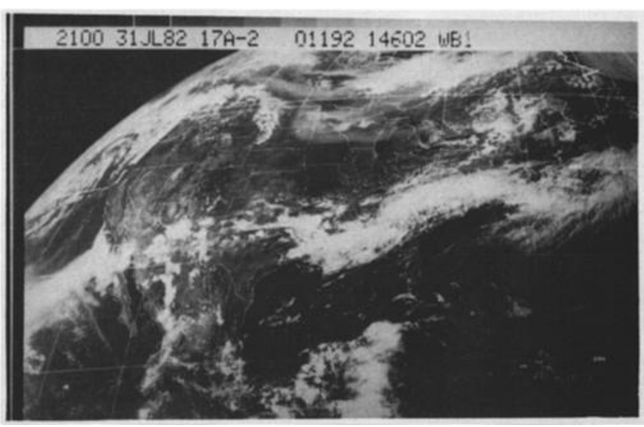

Fig. 2*c*

Fig. 2. GOES satellite image in visible wavelengths, July 31, 1982, for (*a*) 1501, (*b*) 1800 and (*c*) 2100 UT. The gray smoke makes an L-shaped pattern across the Dakotas and Minnesota. Another east-west band of smoke can be seen north of this one in Canada.

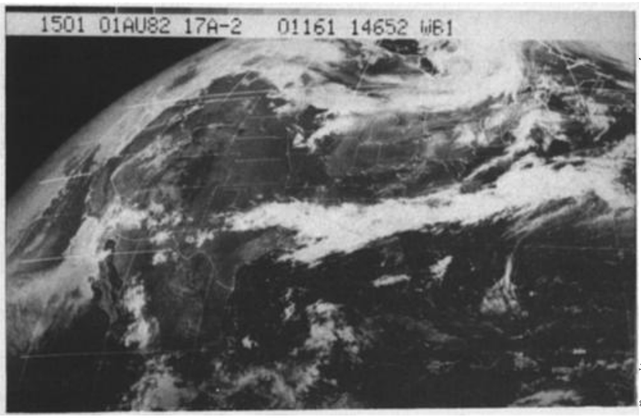

Fig. 3a

Fig. 3b

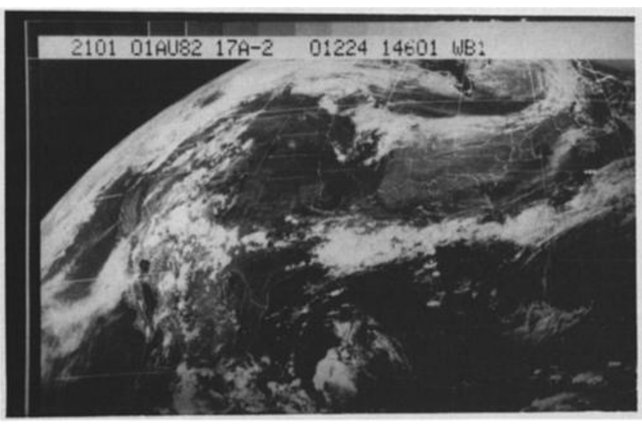

Fig. 3c

Fig. 3. GOES satellite image in visible wavelengths, August 1, 1982, for (*a*) 1501, (*b*) 1801 and (*c*) 2101 UT. The smoke can be seen as a gray area extending from Illinois all the way to the East Coast.

5 shows MOS forecast errors for 1500, 1800 and 2100 UT (1000, 1300, and 1600 CDT - LT) for the August 12, 1981, case, corresponding to the images in Figure 1. Daytime cooling of -1.5°C to -3°C is seen under the smoke.

Forecast errors of the same or greater amplitude are also evident in other locations in the figures. Upon close inspection each can be attributed to the presence or absence of water clouds or mesoscale features that were not well forecast by the limited-area fine mesh (LFM) numerical forecasting model, which provides the predictors for the MOS forecasts. In clear areas, however, the only large errors are under the smoke cloud.

For this case and the 1982 case, the results presented are from forecasts made from LFM runs 12 to 24 hours before the forecast time. Comparisons were made with forecasts made with

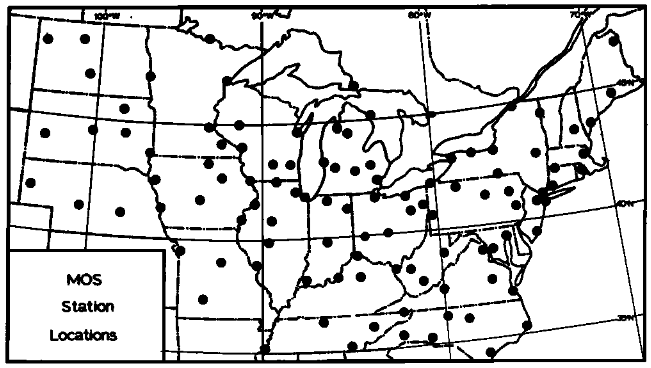

Fig. 4. MOS station locations for analyses shown in Figures 5-7.

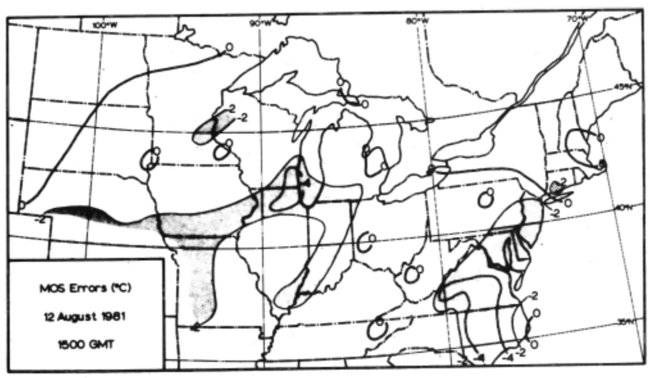

Fig. 5a

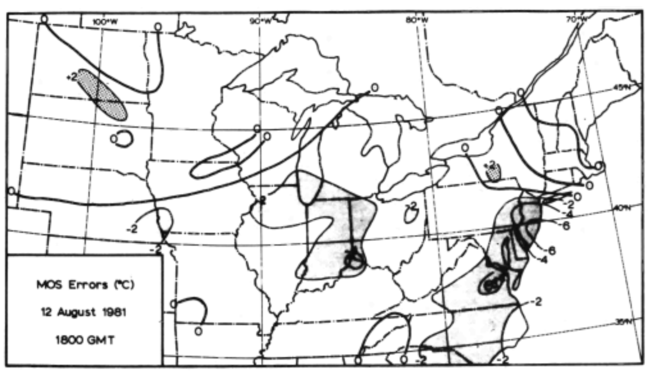

Fig. 5b

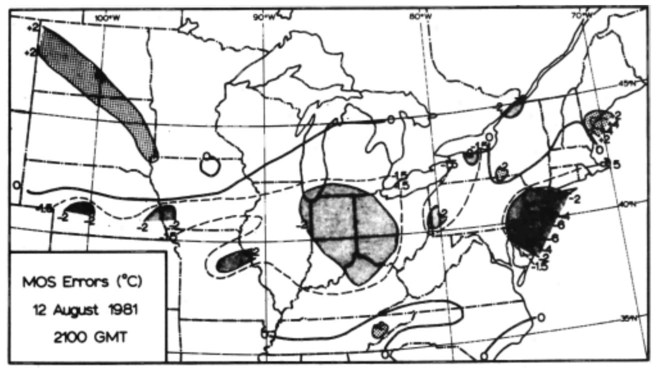

Fig. 5c

Fig. 5. MOS surface air temperature errors (°C, observations minus MOS forecasts), August 12, 1981, for (*a*) 1500, (*b*) 1800 and (*c*) 2100 UT. Errors less than -2°C are shaded. Errors greater than 2°C are shaded with grainier shading. The large negative errors correspond to the location of the smoke as seen in Figure 1.

earlier and later model runs, and the results were virtually the same. The errors (cooling) found were much larger than the run-to-run differences.

1982 Case

More information is available for the intense forest fires which burned in British Columbia, Canada, on July 29, 1982 [*Cowell*, 1983]. Smoke from these fires was transported by the prevailing winds and crossed the U.S. border in North Dakota on July 31. It proceeded across the Midwest and then east over the Middle Atlantic States and was reported over western Europe on August 5 and 6. Such was also the case for The Great Smoke Pall [*Wexler*, 1950], demonstrating the ability of the atmosphere to transport smoke over long distances before it is removed.

Figures 6 and 7 show MOS surface temperature forecast errors for July 31 and August 1, 1982, at 1500, 1800, and 2100 UT (1000, 1300, and 1600 CDT), each day corresponding to the satellite images in Figures 2 and 3. Smoke plumes appear gray in these images and can easily be detected over the Midwest. On the original images the smoke plume that was headed for Europe can be seen on August 1 over the Atlantic Ocean. Figure 8 shows nighttime MOS forecast errors for August 1, 1982, at 0600 UT (0100 CDT).

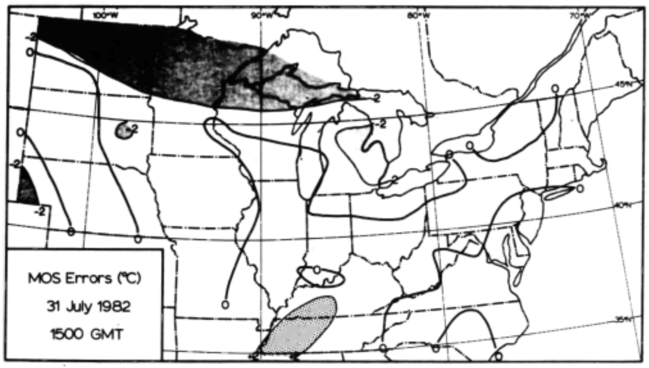

Fig. 6*a*

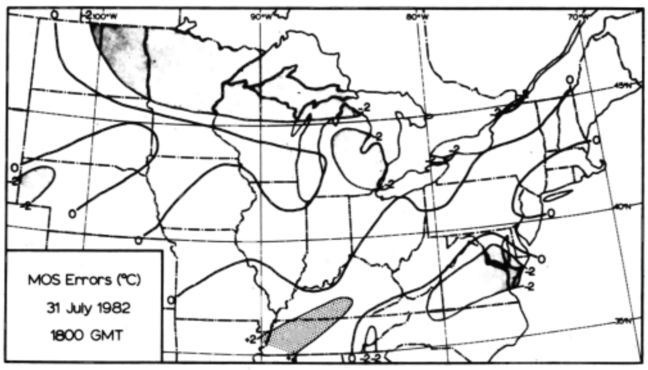

Fig. 6*b*

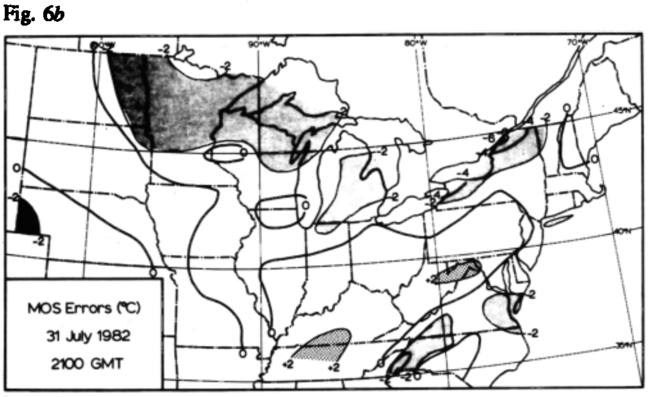

Fig. 6*c*

Fig. 6. MOS surface air temperature errors, July 31, 1982, for (*a*) 1500, (*b*) 1800 and (*c*) 2100 UT. The large negative errors correspond to the location of the smoke as seen in Figure 2.

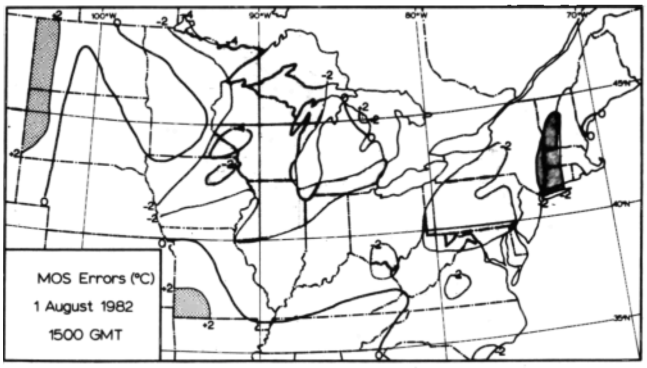

Fig. 7*a*

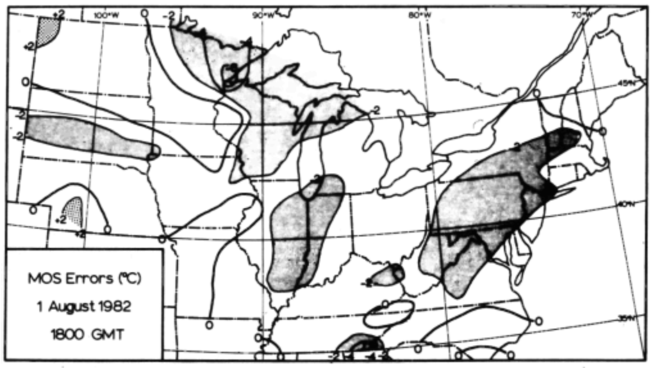

Fig. 7*b*

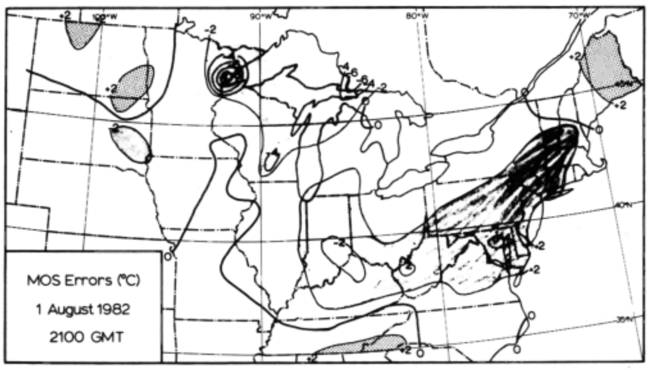

Fig. 7*c*

Fig. 7. MOS surface air temperature errors, August 1, 1982, for (*a*) 1500, (*b*) 1800 and (*c*) 2100 UT. The large negative errors correspond to the location of the smoke as seen in Figure 3.

Forecast errors of -2°C to -4°C are evident under the smoke plumes, although they are not evident under the smoke plumes at other times of the day. Since the errors are only evident at times of maximum daily insolation, their predominant effect on short-wave radiation is demonstrated.

Again, forecast errors of the same or greater amplitude are also evident in other locations in the figures; and upon close inspection, each can be attributed to the presence or absence of water clouds or mesoscale features that were not well forecast by the LFM. In clear areas, however, the only large errors are

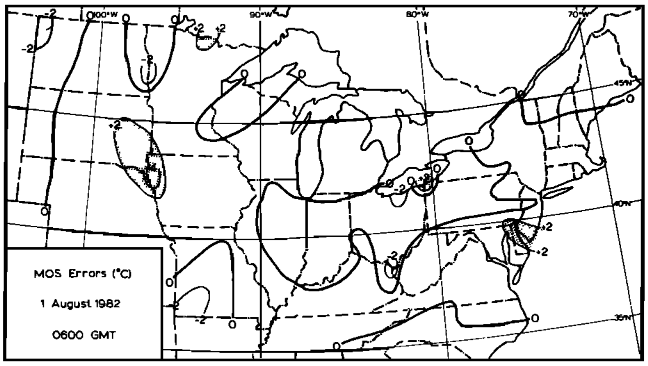

Fig. 8. MOS surface air temperature errors, 0600 UT, August 1, 1982. The smoke cloud location cannot be determined from the satellite image. It is intermediate between those in Figures 2c and 3a.

under the smoke cloud. For example, at 1500 UT on July 31 (Figure 6a), there is a negative area in eastern Michigan that can be attributed to an unforecast mesoscale region of cloudiness. A positive error region in western Tennessee and Kentucky is associated with a mesoscale clear area in an otherwise overcast region.

In Figure 6b for 1800 UT July 31, the same error regions are present as at 1500 UT except that an additional negative area appears in Virginia under a heavy water cloud bank, and small negative areas appear east and west of Lake Ontario. These latter areas become more extensive and of higher amplitude three hours later (Figure 6c). They are associated with strong cold advection behind a rapidly developing mesoscale low, the center of which is located on the Vermont-Canadian border. This is easily seen on the synoptic weather maps (not presented here) and presumably was not well forecast by the LFM, which does not handle small-scale weather systems well. In Figures 6b and 6c the moderating effects of Lakes Erie and Ontario are evident, as the maximum cooling associated with this cold advection is over the land areas between the lakes. The only other negative error area, and by far the largest one, is under the forest fire smoke veil. Areas of fair weather cumulus over Illinois, Indiana, and Ohio do not produce large MOS errors.

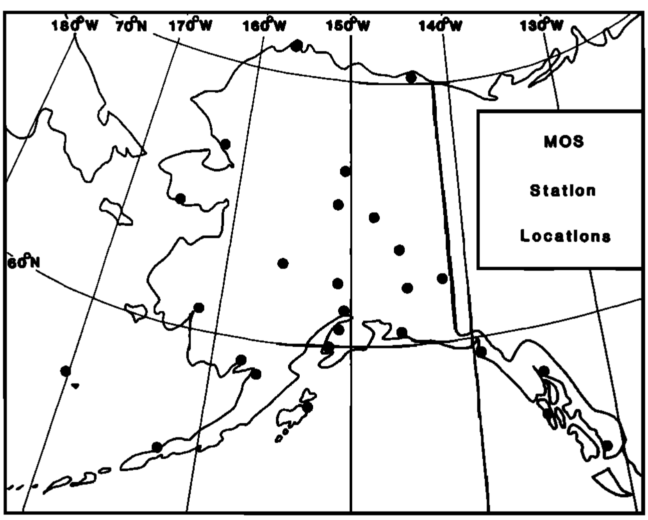

Fig. 9. Locations of stations in Alaska where MOS forecasts of surface air temperature are made every 6 hours.

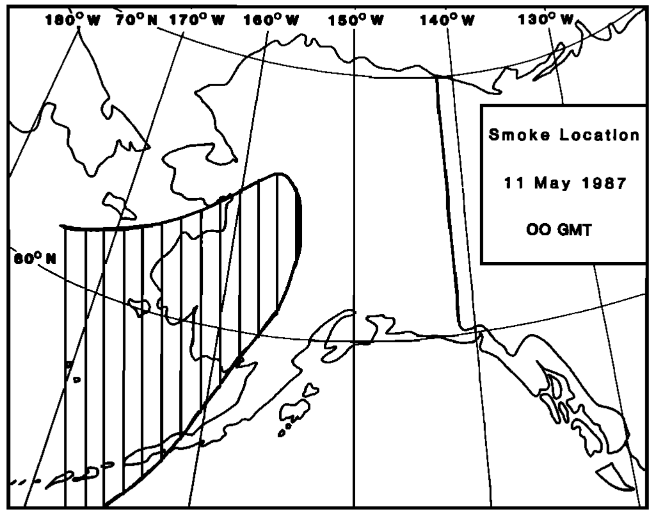

Fig. 10a

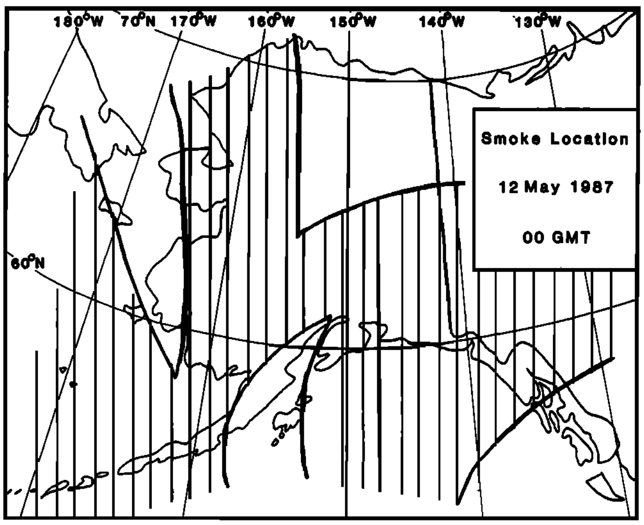

Fig. 10b

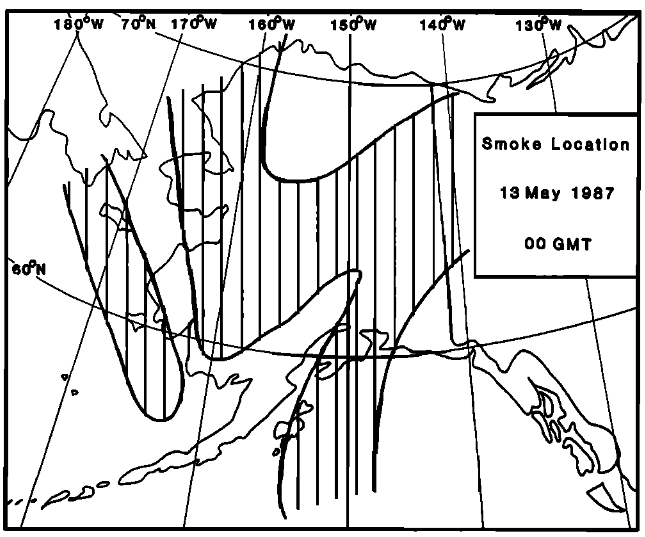

Fig. 10c

Fig. 10. Location of smoke as determined from visible satellite imagery at 0000 UT, for (a) May 11, 1987, (b) May 12, 1987, and (c) May 13, 1987.

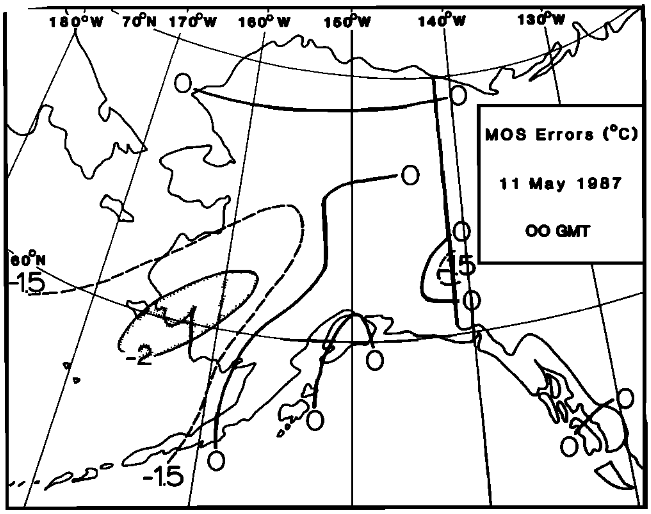

Fig. 11*a*

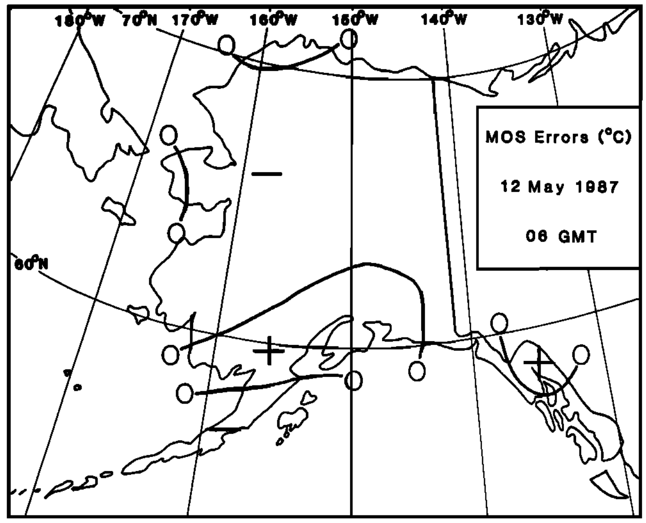

Fig. 12*a*

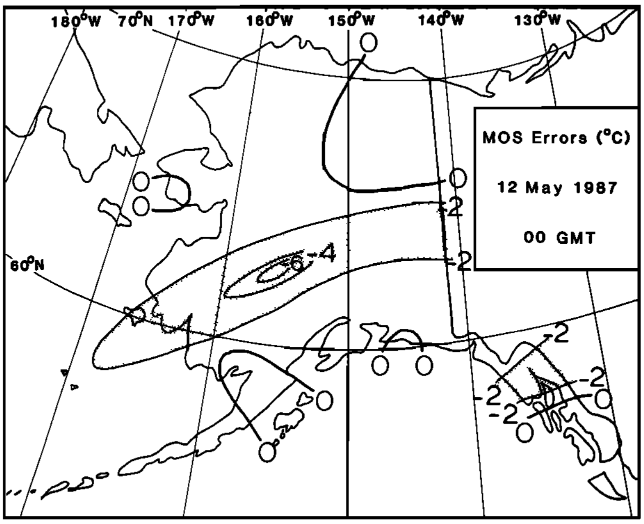

Fig. 11*b*

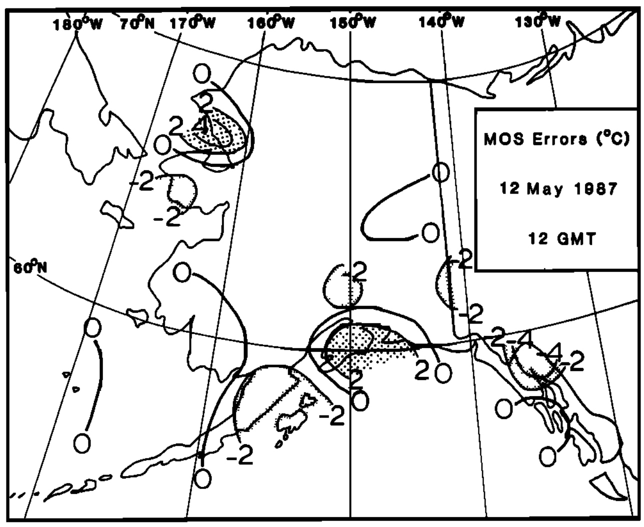

Fig. 12*b*

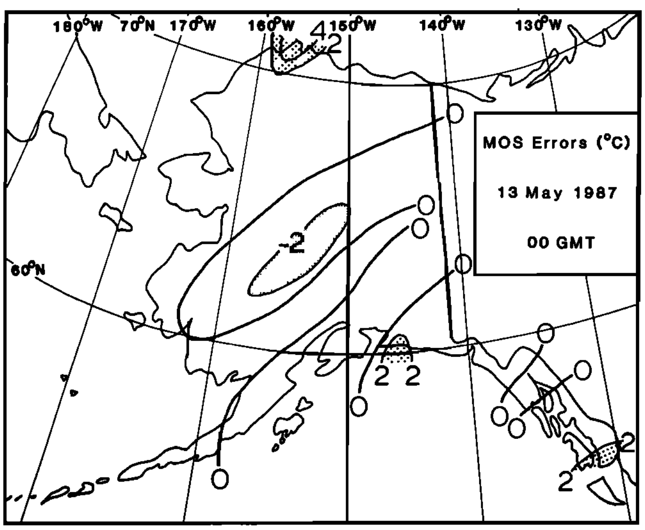

Fig. 11*c*

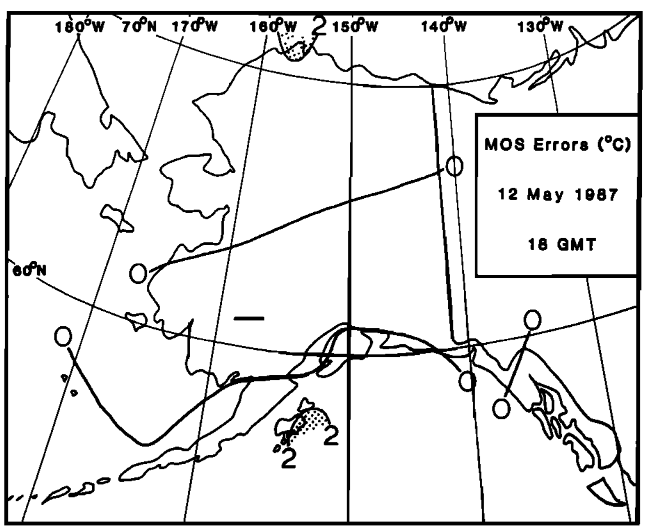

Fig. 12*c*

Fig. 11. Errors of MOS surface temperature forecasts for 0000 UT, on (*a*) May 11, 1987 (*b*) May 12, 1987, and (*c*) May 13, 1987. Contours are every 2°C. Errors less than -2°C are shaded. Errors greater than 2°C are shaded with grainier shading.

Fig. 12. Errors of MOS surface temperature forecasts for (*a*) 0600, (*b*) 1200, and (*c*) 1800 UT, May 12, 1987, showing smaller amplitude and scale of errors as compared to 0000 UT error patterns, as shown in Figure 11.

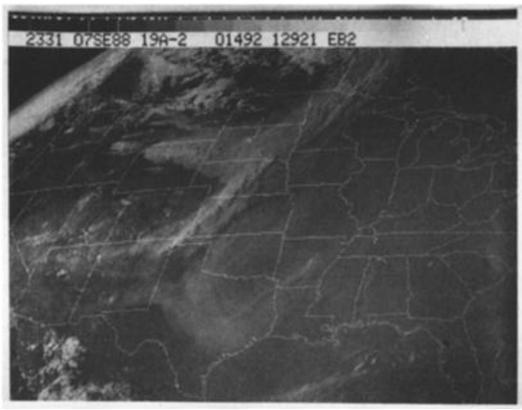

Fig. 13*a*. GOES satellite image in visible wavelengths, September 7, 1988, 2331 UT (1731 LT: mountain daylight time (MDT)) showing smoke from the Yellowstone forest fires.

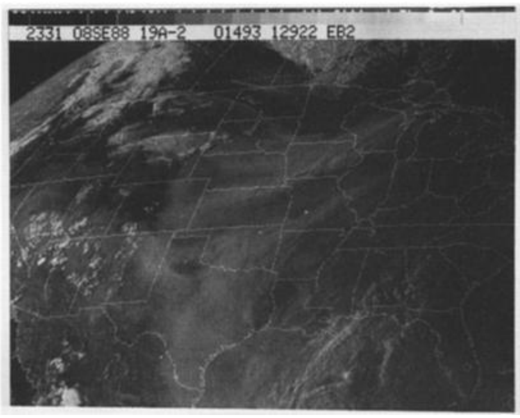

Fig. 13*b*. As in Figure 13*a* for September 8, 1988, at the same time. Note the smoke clouds covering most of the Great Plains. In Colorado the western half of the state is black, indicating no smoke since the Front Range of the Rocky Mountains, which runs north-south through the center of the state, blocks the smoke.

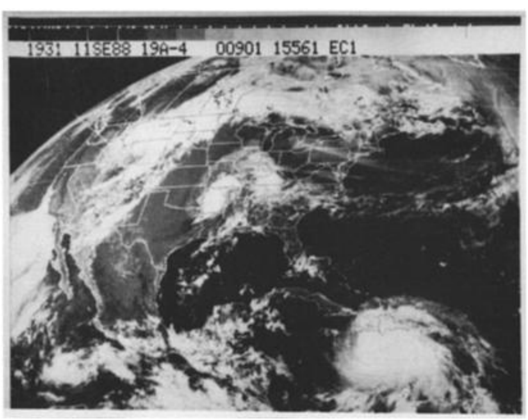

Fig. 13*c*. As in Figure 13*a* for September 11, 1988, at 1931 UT (1531 LT: eastern daylight time). Note: smoke is seen as a gray streak from Michigan, over northern Pennsylvania and New Jersey, and out into the Atlantic Ocean. Remnants of tropical storm Florence are seen over Arkansas, and Hurricane Gilbert is shown at the bottom, south of Hispaniola.

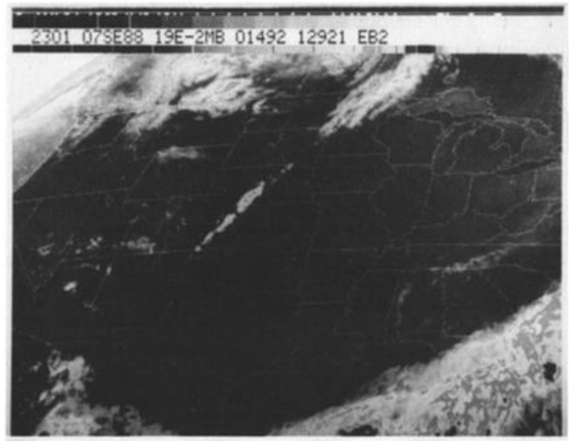

Fig. 13*d*. GOES satellite image in infrared wavelengths (channel 4) for September 7, 1988, at 2301 UT (1701 MDT), 30 min before the visible image in Figure 13*a*. Note that the only portion of the smoke cloud visible in this image is the very thickest smoke directly over the fire in northwestern Wyoming; also shown are water clouds associated with the cold front running from southwest to northeast in western Kansas, southern Nebraska, and northern Minnesota.

In Figure 7, on August 1 during the daytime the only large error regions (both negative) shown are associated with a small region of water clouds over Wisconsin and the forest fire smoke veil. The region around the Great Lakes under the smoke veil has errors between -1°C and -2°C, evidence again of a moderating effect of the lakes. The thickest patch of smoke appears over Baltimore, Maryland, at 2100 UT, and has an error of -4.1°C associated with it (Figures 3*c* and 7*c*).

Discussion

Attempts were made to estimate the height of the smoke as it passed over the Midwest. For the 1981 case, pilot reports over the Midwest on August 12 and 13 reported smoke from 2.5 to 7.5 km, and smoke motions for the thickest smoke corresponded to 400 mbar (7.5 km) winds [*Schneider et al.*, 1986]. For 1982, winds were examined at different levels during this time and compared to the motion of the smoke. The winds corresponding most closely to the motion were at 700 mbar (3.2 km). The jet of smoke headed to Europe on August 1 corresponded to winds between the 700 mbar and 500 mbar levels (3 km to 5.5 km).

A vertical profile study of lower level haze was conducted by chance on the next day over the eastern shore of Chesapeake Bay, due east of Baltimore at 1700 UT (E. Eloranta, personal communication, 1987). The portion of the smoke veil that was over Kentucky on August 1 appears from satellite images to have been over Maryland at that time. Eloranta flew up into the base of the forest fire smoke plume at an altitude of approximately 3.5 km, and at 4.5 km (the highest altitude reached) he was still in the smoke.

A cooling of 1.5°C to 4°C is found in the daytime under forest fire smoke plumes in two cases in 1981 and 1982. No effect is found at night. This corresponds to theoretical estimates of the effects of an elevated smoke plume [*Veltishchev et al.*,1988] with optical depth of approximately 2. The optical depth of the 1982 smoke cloud, based on multispectral satellite measurements, has been reported to be 2 to 3 [*Ferrare et al.*, 1990].

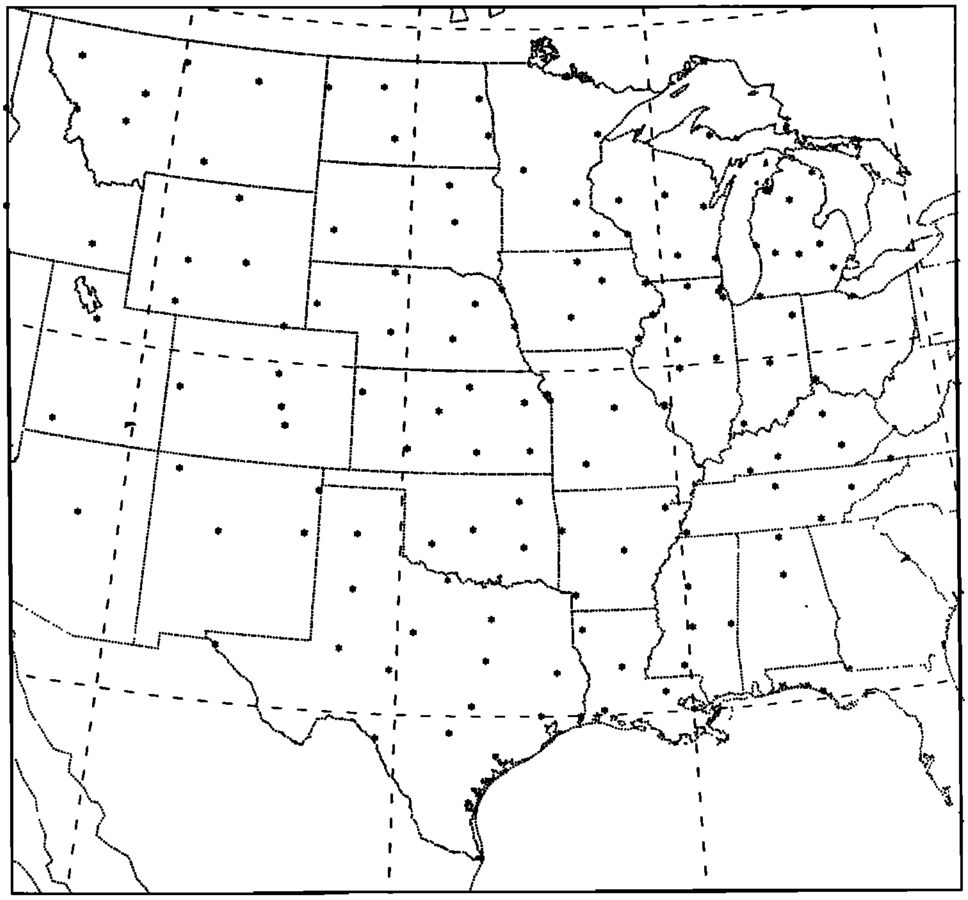

Fig. 14. Location of MOS stations used for analysis shown in Figure 15.

The 1982 case was investigated by *Westphal and Toon* [1991] by use of a high resolution numerical model which simulated the transport and radiative effects of the smoke. They found virtually identical cooling at the surface to that found here with the MOS error technique. When they did the same simulation but changed the optical properties of the smoke to be more like that from a burning city or industrial area (more absorbing and less scattering) they found surface cooling of 8°-10°C.

3. China and Siberia Fires of 1987

In May 1987, extensive forest fires burned in the People's Republic of China and in Siberia, USSR. In less than 1 month the fires burned more than 7,500,000 ha in China and 20,500,000 to 37,500,000 ha in Siberia [*Salisbury*, 1989]. Smoke from these fires was seen in polar orbiting satellite images over Alaska for several days starting on May 10. This demonstrates the potential for long-range transport of smoke in the atmosphere (> 4000 km in this case).

The same technique of using errors of the MOS surface air temperature forecasts in regions of little synoptic disturbance was used to search for surface temperature effects of the smoke in Alaska. Surface temperature forecasts are produced by MOS for 26 locations in Alaska (Figure 9) verifying at 6-hour intervals [*Maglaras*, 1983]. Since Alaska is between 130° and 170° west of Greenwich, forecasts verifying at 0000 UT are for the approximate time of day of maximum temperatures, the 1800 and 0600 UT forecasts are for early morning and early evening, and the 1200 UT forecasts are for the middle of the night.

The locations of the smoke plumes from the fires are shown in Figure 10 for 0000 UT for May 11-13, as determined from satellite images at the NOAA/Navy Joint Ice Center. The poor quality of the images prevented their reproduction for this article. It can be seen in Figure 11 that the smoke locations correspond to MOS errors representing surface cooling of 2° to 6°C and there are no large areas of positive MOS errors. For all other times such patterns do not appear, and the MOS errors are much smaller in amplitude and scale (e.g., Figure 12).

4. Yellowstone Fires of 1988

On September 7, 1988, forest fires already burning in Yellowstone National Park in northwestern Wyoming erupted into a massive conflagration, pumping a tremendous smoke plume into the atmosphere (Figure 13*a*). The next day the fires died down, but the smoke generated on September 7 had spread to cover the midwestern United States (Figure 13*b*). Three days later, on September 11, as the attention of weather watchers was riveted on the approach of Hurricane Gilbert, the smoke from the fires of September 7 was clearly seen as it passed over New York City on its way into the Atlantic Ocean (Figure 13*c*). Again, the smoke clouds were easy to detect with visible wavelength imagery but were invisible in infrared imagery (Figure 13*d*).

MOS errors were determined as in the other cases for the stations shown in Figure 14. For September 8 and 9 MOS errors were calculated every 6 hours based on the most recent MOS forecasts made at 0000 UT. The error patterns for three of the times are shown in Figure 15. It can be seen that during the daytime there is a large negative MOS error under the smoke, up to 7°C, indicating a cooling effect of the smoke. At night there is no net effect. Thus smoke from forest fires again produces a significant net reduction of surface temperature over a large area.

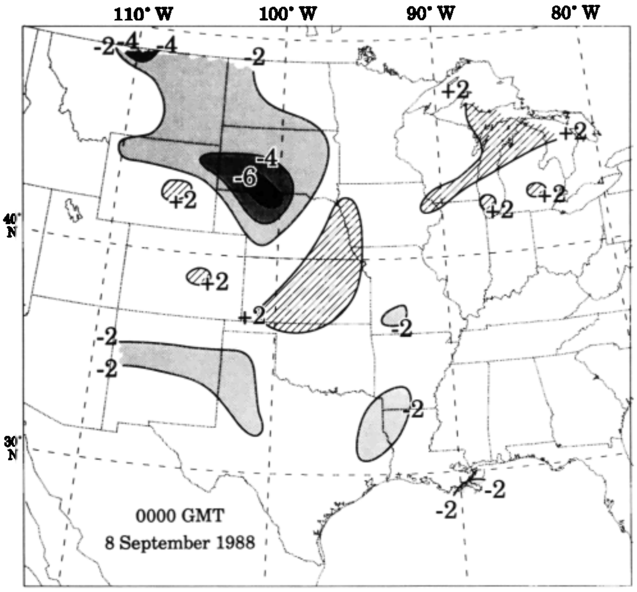

Fig. 15*a*. MOS surface air temperature errors for 0000 UT September 8 1988 (1800 LT: MDT, September 7), only 29 min after the image shown in Figure 13*a*, based on the MOS forecasts made 0000 UT on September 7. Contours are every 2°C, with the 0°C line left out. Errors less than -2°C are shaded, and errors greater than +2°C are striped. Note the negative MOS error under the smoke-covered region, indicating the cooling effect of the smoke.

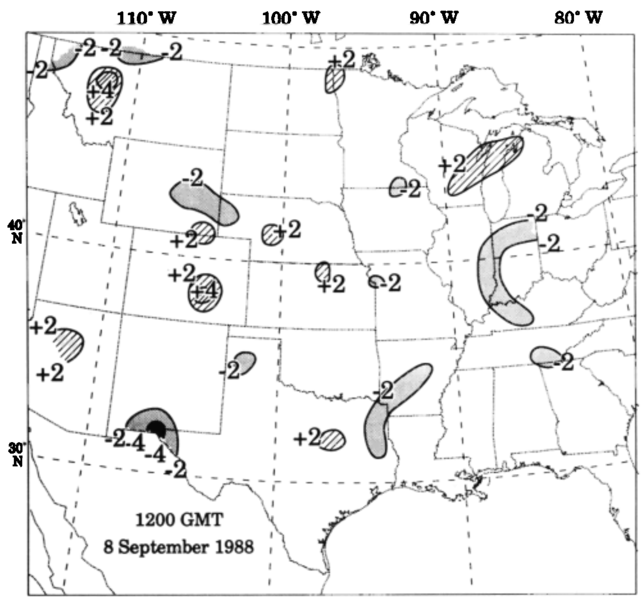

Fig. 15*b*. As in Figure 15*a* for 1200 UT September 8, 1988 (0600 LT), based on the MOS forecasts made 0000 UT on September 8. For this early morning period there are no large-scale errors, indicating no net radiative effect of the smoke.

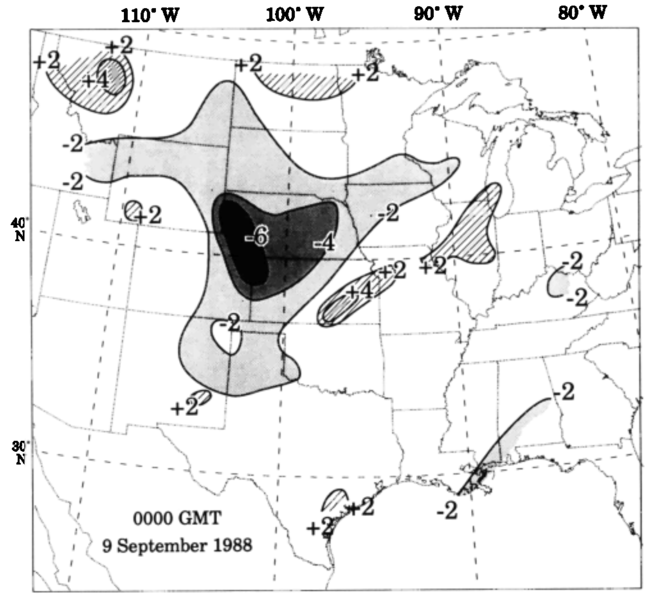

Fig. 15*c*. As in Figure 15*a* for 0000 UT September 9, 1988 (1800 LT, September 8), only 29 min after the image shown in Figure 13*b*, based on the MOS forecasts made 0000 UT on September 8. Again, note the negative MOS error under the smoke-covered region, indicating the cooling effect of the smoke during the daytime.

The MOS forecasts are not perfect and depend on input from the LFM numerical weather forecast model. To test the robustness of the above results, the MOS errors were examined for the same times but based on MOS forecasts from four different LFM runs. For example, for the 0000 UT September 9 errors, MOS forecasts were based on LFM runs at 0000 UT on September 7, 1200 UT on September 7, 0000 UT on September 8 and 1200 UT on September 8. In all cases the error patterns were virtually identical. Therefore the error patterns shown are not a quirk of a particular numerical forecast. Since the errors are close to 0 for the areas not under the smoke, and only isolated stations have errors with absolute value greater than 2°, with no large-scale biases, the error patterns shown are representative of the radiative effect of the smoke.

The cooling effect of forest fire smoke shown here is larger than that found previously for smoke which had traveled several thousand kilometers already. This is to be expected, as the optical depth of the smoke is larger in the present case, as determined from inspection of the visible imagery. This is in agreement with *Segal et al.* [1989] and *Hulstrom and Stoffel* [1990], who measured the optical depth of smoke from the Yellowstone fires for days before September 7 when the smoke was not as thick. The only known case where larger surface temperature effects were found from smoke was exactly one year earlier in the Klamath River Canyon of California, where smoke was trapped by an inversion in the valley and the smoke cloud became much thicker than here [*Robock*, 1988*a*].

5. CONCLUSIONS

These results reported here correspond to theoretical estimates of the effects of smoke and serve as observational confirmation of a portion of the nuclear winter theory. If this smoke had been more absorbing, characteristic of smoke from burning petroleum or plastics such as would result from a burning city or industrial facility, the surface temperature effects would have been even larger [*Westphal and Toon*, 1991; *Turco et al.*, 1990].

These results also imply that smoke from biomass burning can have a daytime cooling effect of a few degrees over seasonal time scales, as was recently also pointed out by *Crutzen and Andreae* [1990]. Further studies will be necessary to verify this using accurate measurements of atmospheric optical depth and standard meteorological variables in tropical regions where such data are currently unavailable. To my knowledge, the MOS technique used in this paper would not be applicable outside the United States because MOS is not used, with the results archived, in other parts of the world. In order to properly simulate the present climate with a numerical climate model in regions of regular burning it may be necessary to include this smoke effect.

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