NOTES AND CORRESPONDENCE

Some Effects of the Yellowstone Fire Smoke Plume on Northeast Colorado at the End of Summer 1988

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ABSTRACT

Extensive fires in Yellowstone National Park, Wyoming, during the summer of 1988 resulted in considerable smoke transport to surrounding states. The present note provides an observational evaluation of the effects of this plume on (i) surface global solar radiation, (ii) the breakup of the surface nocturnal temperature inversion during the morning, and (iii) surface heating in eastern Colorado. Significant effects in each of these categories are shown.

1. Introduction

During the summer of 1988, extensive forest fires were persistent in the Yellowstone National Park, Wyoming. During most of the period from 24 August–9 September 1988 large smoke plumes from these fires were observed over fairly large regions, nearly blanketing nearby states to the east and south. These plumes were detected both on satellite imagery and by visibility observations from surface reporting sites. Extremely heavy smoke was observed over eastern Colorado on 25 August and 6 September 1988. The note provides satellite illustrations of the smoke features on those two days, as well as a brief discussion of the impact of the smoke on certain meteorological parameters.

2. Observations

a. General information

1) SATELLITE IMAGERY

Visible GOES images were collected through the PROFS/SERS (Program for Regional Observing and Forecasting Services/STORM Education and Research System) at Colorado State University on 24 and 25 August, and 6 September. These images provide various scales of view of the Yellowstone smoke plume extent and concentration. The regional scale visible image on 25 August (Fig. 1a), for example, shows large areas of Wyoming and northeast Colorado covered by smoke. Colorado scale images for the hours 1300, 1330, 1400, and 1430 MST (Fig. 1b) give an indication of the relative density of the smoke plume, assuming that the brightness of the plume correlates with smoke particulate concentration (compare the smoke brightness with that of the cumulus clouds at the southeast corner of the imagery domain). Note also that the smoke over Colorado covers most of the PROFS mesonet surface stations (Fig. 1c and Fig. 4).

A word of caution must be given regarding the use of satellite imagery to imply plume particulate concentration—especially when the particulates in the plume are relatively large (as in dust, or smoke). In these cases, there is a considerable difference between the amount of incident radiation back-scattered and forward-scattered. This difference in scattering may result in different appearances of the plume, depending on the satellite used and the time of day. For example, in Fig. 2, notice the extreme difference in appearance of the plume when viewed from GOES-West (long 135°W) and GOES-East (long 75°W) at around 0900 MST 24 August 1988. This difference in appearance is because of strong forward-scattering by the smoke into the GOES-West sensor and weak back-scattering toward GOES-East. This effect may also be seen when comparing the GOES-East and GOES-West images presented in Fig. 1.

In the second smoke event (6 September 1988), the regional satellite imagery at 0915 MST shows a large smoke plume over eastern Colorado (Fig. 3a) similar

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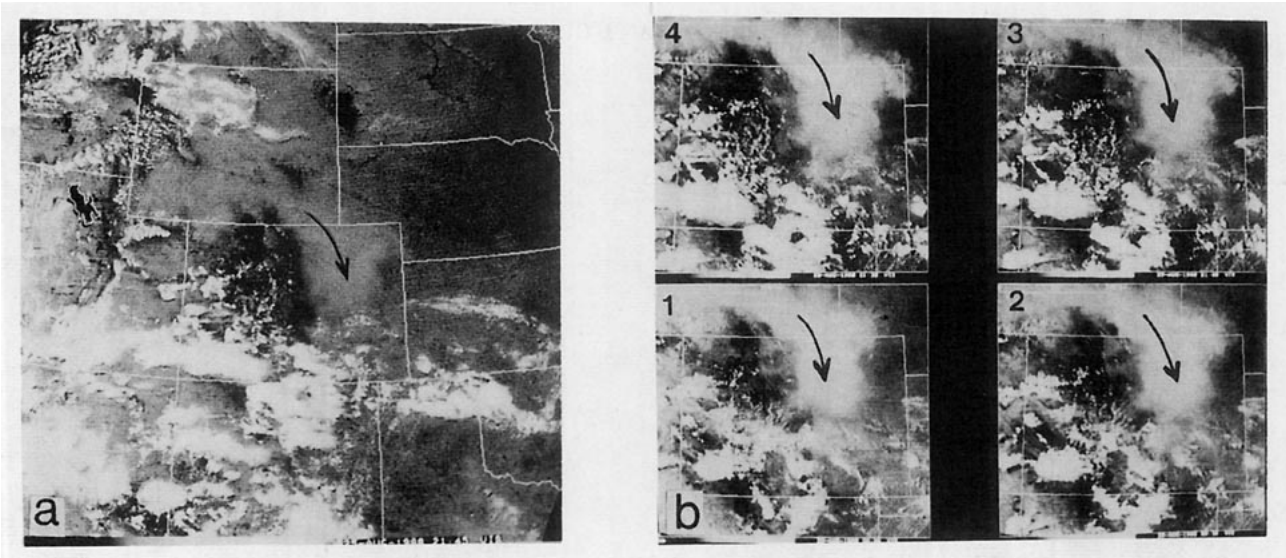


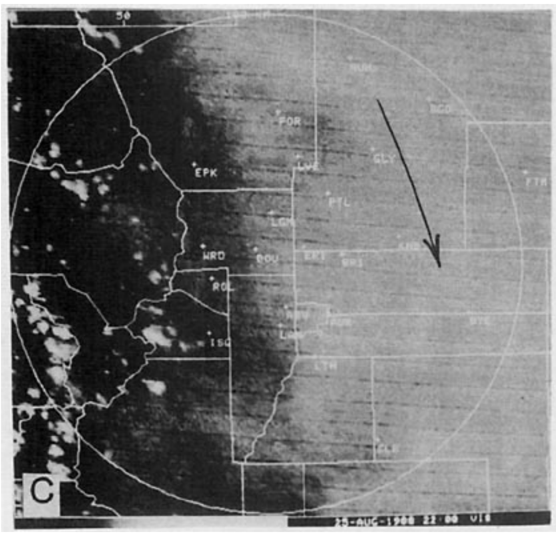


FIG. 1. GOES visible imagery during the smoke event of 25 August 1988: (a) GOES-West regional scale imagery (1445 MST); (b) GOES-East image of Colorado 1) 1300, 2) 1330, 3) 1400, and 4) 1430 MST; (c) GOES-East image of the PROFS mesonet area (1500 MST). The smoke plume is indicated by arrows. Data are remapped to Lambert conformal projection.

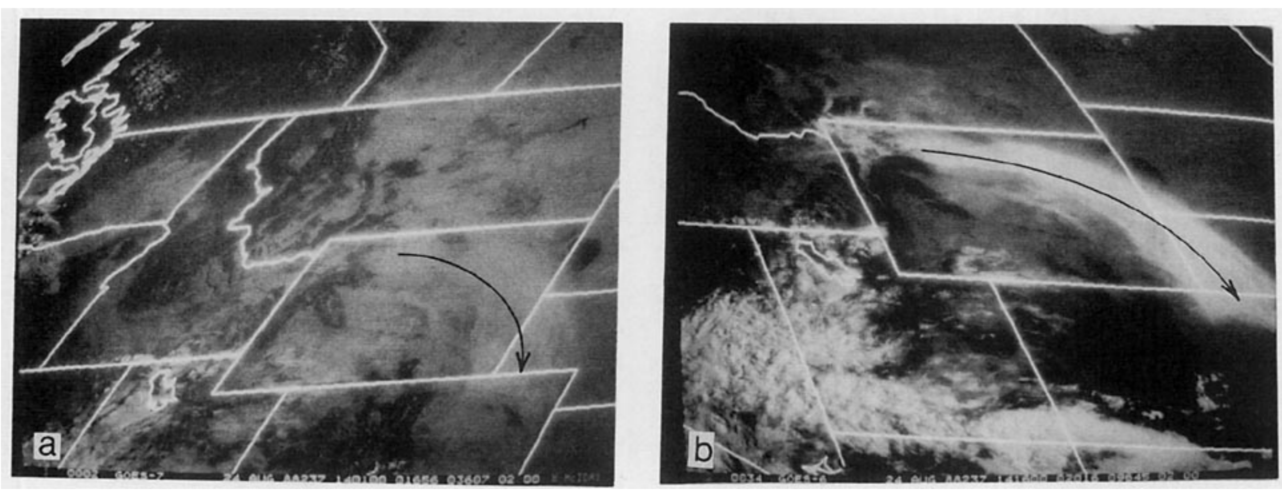
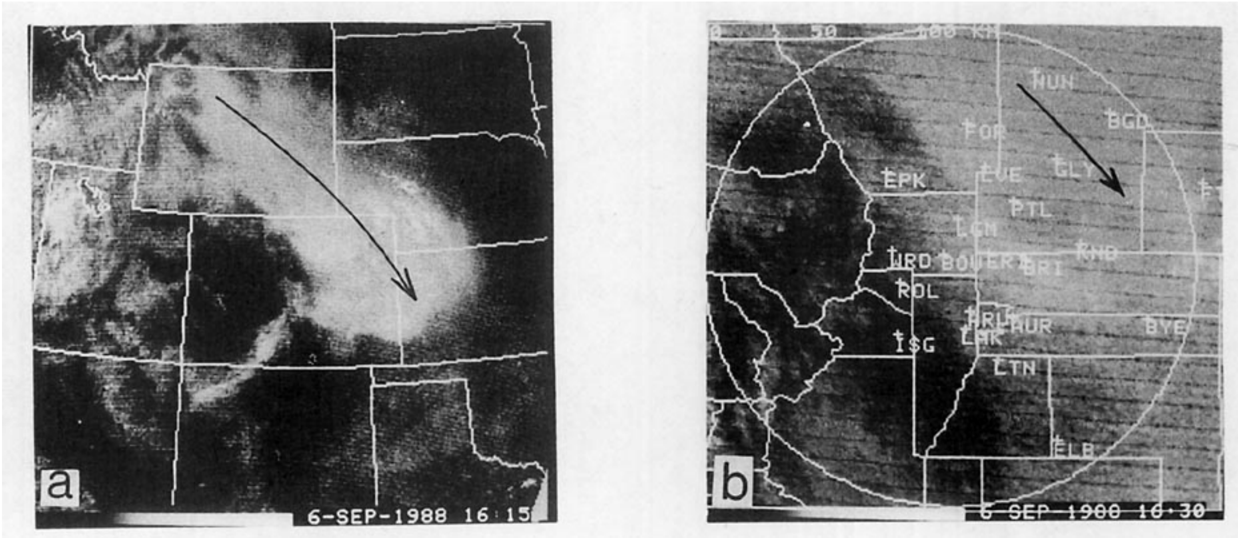


FIG. 2. GOES visible satellite imagery from 24 August 1988: (a) GOES-East at 0900 MST, and (b) GOES-West at 0915 MST. The smoke plume is indicated by arrows.



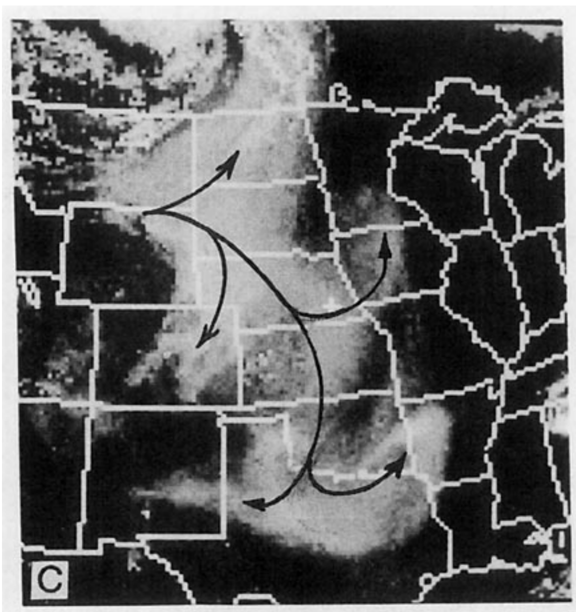


FIG. 3. GOES visible imagery during the smoke event of 6 September 1988 (a) GOES-West regional scale image (0915 MST), note some imbedded cloudiness within the plume over western Nebraska; (b) GOES-East image of the PROFS area (0930 MST); (c) GOES-West national scale image of the smoke plume on 7 September 1988 (0815 MST). The smoke plume is indicated by arrows. Data are remapped to Lambert conformal projection.

to that in the 25 August case. Visual plume characteristics seen on the local scale (Fig. 3b) are also similar to those shown previously. Finally, Fig. 3c shows the southward advection of the smoke plume a day later. By that time, the plume covered most of the panhandle of Texas and portions of Oklahoma and Arkansas.

2) VERTICAL PROFILES

Because the impact of the smoke plume was more pronounced on 6 September, and since more data were available for that case, most of this discussion will be centered on that day. The Denver, Colorado (DEN) radiosonde temperature profile from 0500 MST on 6 September 1988 showed a strong surface inversion to a depth of about 0.4 km capped by a fairly stable layer through a depth of about 1.5 km, then a neutrally stable layer above it, reaching to a height of about 5.4 km AGL. By afternoon, the radiosonde profiles at DEN and Lander, Wyoming [LND—the closest National Weather Service (NWS) radiosonde station to the location of Yellowstone fires] indicated a deep daytime boundary layer which (reaching 5.2 km AGL in DEN), in turn, suggests a deep vertical mixing of the smoke.

Measurements of the relative particulate concentration were made by the NOAA Lidar Group at Boulder, Colorado. Measurements indicated a significantly greater particulate concentration on 6 September than what would normally be expected in a typical clear air situation. At 0930 MST, particulate concentrations were found to be quite well mixed to a depth of about 4 km. The top of the smoke layer was between 4 and 5 km, where the particulate concentration increased by a factor of ~3. At 1440 MST, the lidar measurements indicated some reduction in particulate concentration as compared to the morning level, where the affected layer reached ~7 km AGL. Thus, it is clear that the Yellowstone smoke plume was affecting a significant depth of the atmosphere at great distances from the plume's source.

b. Global solar radiation (GSR)

The PROFS mesonet (Fig. 4), is located along the Front Range of northeastern Colorado. The daytime variations of the GSR at eight selected mesonet stations on 25 August are given in Fig. 5a, along with those for 23 August, which was a nearly clear sky day. The temporal variations of GSR at some sites for the smoke plume case follow approximately a sine curve, as in the clear sky day. However, due to absorption and scattering by smoke aerosols, the related amplitudes were, in general, about 0.6–0.8 of the clear day. During the morning hours the reduction of the GSR in some sites was around 0.5 of the clear day values. Similar features were observed on 6 September (Fig. 5b), although some cloud effects on GSR were evident.

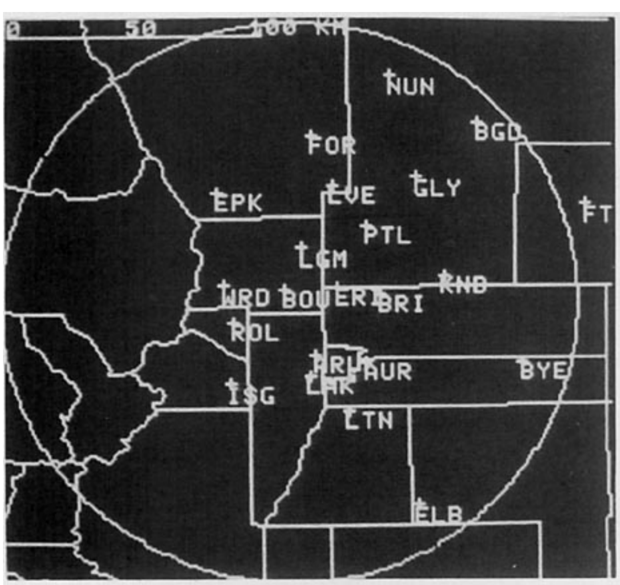


FIG. 4. Counties of north-central Colorado with locations of the PROFS stations (ARV, Arvada; BOU, Boulder; FOR, Fort Collins; BGD, Briggsdale; FTM, Fort Morgan; KNB, Kennesburg; LAK, Lakewood; NUN, Nunn).

c. Breakup of the surface inversion during the morning

The rate of breakup of the surface nocturnal inversion depends on the intensity of the inversion and the time integrated surface sensible heat flux, H_s. Typically, the magnitude of H_s is about 0.3 of the GSR. Following Tennekes (1973), for example, the time needed for the breakup of the morning surface temperature inversion is proportional to the magnitude of $H_s^{-1/2}$. Reduction by about 0.5 in GSR during the morning hours, as observed in both cases at some sites, suggests an increase of the time required for the breakup of the inversion of at least a factor of $\sqrt{2}$.

Temperature profiles, observed at the Boulder Atmospheric Observatory's (BAO) 300 m meteorological tower on the morning of 4 September 1988 (which was a clear and synoptically unperturbed day) are provided in Fig. 6a. Temperature profiles for the same time period for 6 September 1988 are given in Fig. 6b. In both cases the 0820 and 0840 LST profiles are missing. On the second day, the Boulder area was affected in the morning hours by relatively high temperatures due to a downslope flow component. Analysis of Fig. 6 reveals that the thermal energy needed to breakup the surface temperature inversion to a height of 150 m is somewhat larger in the clear sky case. Notice, however, that the rate of breakup of the inversion to that height on the clear day happens faster than on the day affected by smoke. Examination of Fig. 5b also suggests that the reduction in solar radiation during the morning hours due to the smoke in Boulder was quite moderate as compared to some of the other PROFS sites. This suggests that the rate of breakup of nocturnal surface temperature inversions at the other PROFS sites, that were more heavily effected by the smoke, might have been even slower.

d. Observations along the South Platte River basin on 6 September 1988

1) GOES IR TEMPERATURES

The visible satellite imagery indicated heavy smoke concentrations along the South Platte River basin in Colorado on 6 September 1988. Comparing the GSR measured there (see Fig. 5b; Fort Collins, Nunn, Fort Morgan) with measurements at sites away from the river basin (see Fig. 5b; Lakewood, Arvada) also suggests a heavier smoke concentration in the South Platte River basin area. Horizontal differences in albedo and different absorption by the smoke due to its nonuniformity could be expected to result in corresponding variations in the surface skin temperature as sensed by the GOES-IR sensor. The reduction in GOES IR radiance that was observed in the infrared temperature field (Fig. 7) may be attributed in part to this effect.

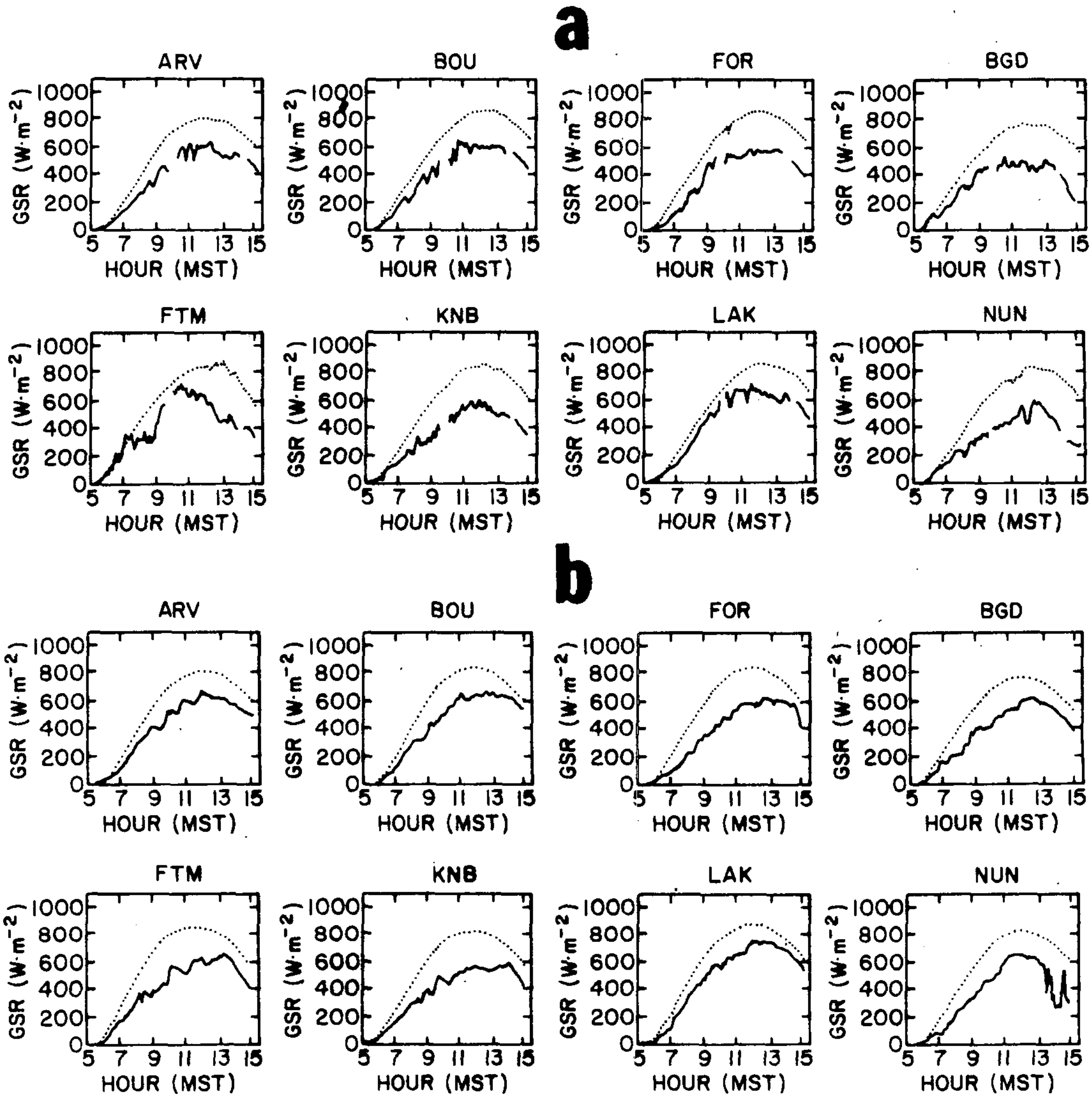


FIG. 5. The daytime variation of the GSR at several PROFS stations: (a) on 25 August 1988—smoke affected day (solid curve), as compared to 23 August 1988—clear day (dotted curve); (b) on 6 September 1988—smoke affected day (solid curve), as compared to 4 September 1988—clear day (dotted curve).

The South Platte River basin area between Fort Collins and Akron exhibits a substantially lower IR temperature (292 K) compared to the nearby northern and southern areas (306 K). Another contribution to that IR temperature may be related to radiation from the smoke layer itself. Thus the horizontal variations in the IR temperature may be due, in part, to the variations in smoke layer depth/concentration. The lower IR temperatures surrounding Greeley, as compared to the shelter air temperature at Greeley (see Table 1), provide further indication of such a contribution. It should also be mentioned that irrigated crop fields in portions of river basins, have been shown to reduce IR surface temperature during the midsummer (e.g., Segal et al. 1988). However, by the beginning of September, most of the crops are either harvested, or at least mature, and their transpiration should contribute only mildly to a reduction in satellite observed IR surface temperatures that were observed in the South Platte River basin.

2) SURFACE OBSERVATIONS

Daily maximum air shelter temperatures for 5 September 1988 (a relatively clear day), and 6 September (the smoke plume case under discussion), are presented in Table 1. A difference of 2–4 K between the two days is noted for the stations along the South Platte

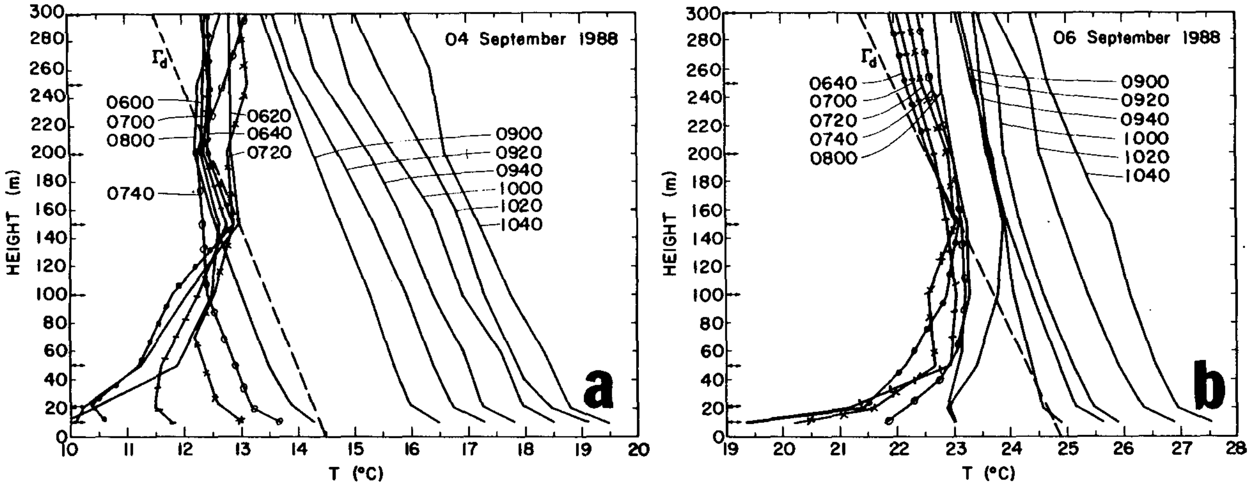


FIG. 6. Morning vertical temperature profiles at the Boulder Atmospheric Observatory (BAO) meteorological tower (a) on 4 September 1988 (clear day); (b) 6 September 1988 (smoke affected day). Here, Γ_d indicates the dry adiabatic lapse rate. The measurement levels are indicated by arrows.

River basin. This alone does not prove that the observed cooling occurred due to the plume; however, nearby sites outside the concentrated plume area were as warm (or even warmer) than on the previous day. Thus, the implication is strong that the drop in the air temperatures is directly related to the smoke. Note also that the cooler stations are associated with sharp decreases in GSR. The daily GSR values are about 60 to 70 percent of those recorded on the previous clear day. Following model and analytical evaluations in Segal et al. (1986), reduction of the GSR to 60–80 percent of its clear sky level (which is about the case in the smoke days), would result in a drop of 2–4 K in noon hour meteorological shelter temperatures. According to Segal et al. (1986) this corresponds to a decrease in surface skin temperature of 4–8 K. Thus we suggest that at least half of the IR skin temperature gradient discussed earlier may be caused by a reduction in solar radiation reaching the surface. Finally, the drop in the daily pan evaporation on 6 September, as compared to the previous day, is explained by the corresponding decrease in the GSR and the air temperature.

3. Discussion

The significant extent of the Yellowstone National Park smoke plume on 25 August and 6 September 1988 is clearly revealed by visible satellite imagery. The plume advected a distance of several hundred kilometers, and was still thick enough to reduce the GSR

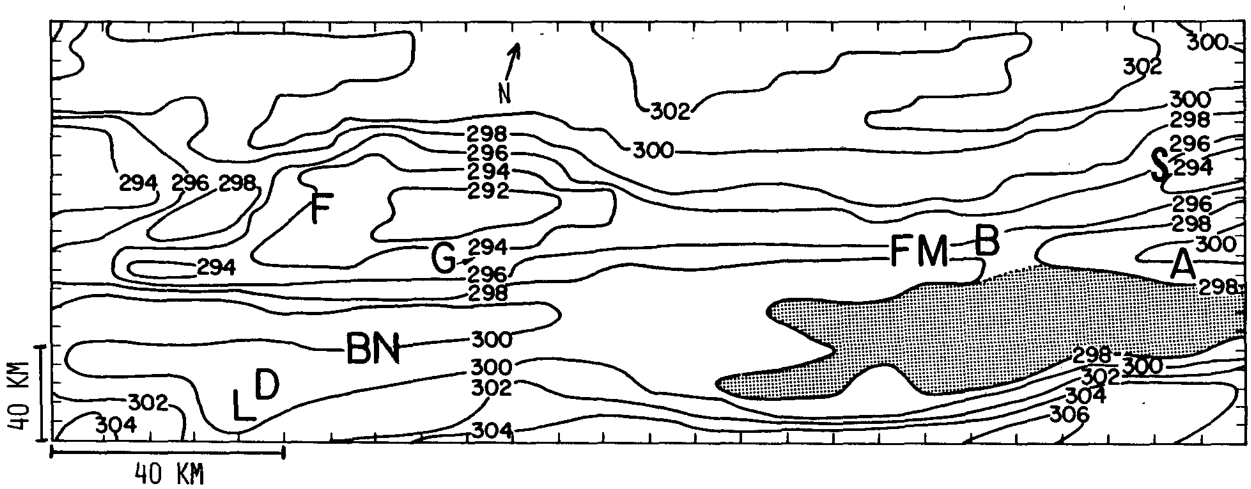


FIG. 7. GOES IR window temperature, (K), for the south Platte basin area on 6 September 1988 1130 MST; shading indicates cloudiness (A, Akron; B, Brush; BN, Brighton; D, Denver; F, Fort Collins; FM, Fort Morgan; L, Lakewood; S, Sterling).

TABLE 1. Meteorological shelter daily maximum air temperature, T_a; the daily amount of global solar radiation GSR_d and the daily evaporation from water pan E, at several sites along the South Platte basin (see Fig. 7 for their location) as measured on 5 and 6 September 1988.

Station	T_a (K) 5 Sept	T_a (K) 6 Sept	GSR_d (MJ) 5 Sept	GSR_d (MJ) 6 Sept	E (cm day^{-1}) 5 Sept	E (cm day^{-1}) 6 Sept
Greeley (G)	301.6	299.0	24.8	15.6	—	—
Fort Morgan (FM)	303.6	299.1	24.3	15.9	—	0.51
Sterling (S)	303.4	300.1	23.1	16.9	0.66	0.38
Brush (B)	303.3	300.0	23.5	16.6	0.69	0.38
Brighton (BN)	304.1	305.8	—	—	—	—
Lakewood (L)	301.9	304.7	—	—	—	—

in eastern Colorado at noon to between 60 and 80 percent of clear sky values.

The rate at which the nocturnal surface inversion broke-up, in the morning, was noticeably reduced by the heavy smoke compared to that of a clear day. Also, a drop in the near surface air temperature and the evaporation rate was observed, which we were also able to relate (at least in part) to the presence of the plume. The problem of how the observed temperature reductions might affect the intensity of the daytime thermally induced upslope flows in the area, was not addressed due to the difficulty in establishing an adequate comparison with clear days and in separating the various boundary layer phenomena and advection occurring over the complex terrain of Colorado. The intensity of the daytime thermally induced upslope flow was found in Segal et al. (1986) to be proportional to $H_s^{1/2}$. Thus, assuming the H_s is proportional to GSR, a drop in the GSR to 60–80 percent of clear day solar radiation could result in a corresponding reduction in the upslope flow of 75 to 90 percent of the clear sky case. The reduction in the amount of solar radiation that arrives at the surface, and consequently in H_s, suggests some decrease in the potential for convective cloud development.

The massive plume event presented in this note is obviously not a frequent occurrence. However, such observations can be useful for comparative purposes in the evaluation of haze effects on daytime boundary layer development. Also, the features presented may imply, in a very limited manner, some factors of importance in evaluating "nuclear winter" effects.

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