The Short-Term Influence of the Mount St. Helens Volcanic Eruption on Surface Temperature in the Northwest United States

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ABSTRACT

The surface temperature effects of the 18 May 1980 eruption of the Mount St. Helens volcano were examined for the two days immediately following the eruption. The volcanic signal was investigated by examining regional maps of surface temperature, 24 h surface temperature differences and Model Output Statistics (MOS) errors, as well as the detailed temporal evolution of surface temperature and MOS errors at selected stations. The analysis was simplified by the presence of a large anticyclone which dominated the synoptic situation both before and after the eruption. During the daytime hours immediately after the eruption, temperatures in eastern Washington State were up to 8°C colder because of the volcanic plume. That night, because of low-level volcanic dust, temperatures were up to 8°C warmer in Idaho and Montana. These effects, caused by large aerosols in the troposphere, quickly diminished the following day as the volcanic dust cloud dissipated and moved toward the east.

This is believed to be the first study of the local temperature effects of a volcanic eruption. The results should help improve forecasting in similar events, and shed some light on the radiative effects of volcanic plumes.

1. Introduction

On 18 May 1980 at 1532 GMT (0732 PST) the Mount St. Helens volcano began a violent eruption which destroyed the summit, devastated hundreds of square kilometers of adjacent land, and injected large amounts of volcanic ash, water vapor and other gases into the troposphere and stratosphere. During the early hours of the eruption the plume was observed to reach more than 20 km MSL, well above the unusually high tropopause at 13.5–14 km. Carried by generally west to northwest winds aloft, the plume quickly spread eastward, bringing darkness and reduced visibility.

Nearly all studies of the meteorological influence of volcanic eruptions have dealt with long-term or climatic effects with scales ranging from months to years. Theoretical studies of the radiative effects (Pollack *et al.*, 1976; Harshvardhan, 1979), comparisons of eruption dates with climatological data (Mitchell, 1961; Oliver, 1976; Mass and Schneider, 1977; Taylor *et al.*, 1980) and numerical modeling experiments (Schneider and Mass, 1975; Hunt, 1977; Hansen *et al.*, 1978; Robock, 1978, 1979, 1981a) have indicated that volcanic eruptions may be an important cause of climatic change. In these studies the estimated impact of volcanic dust clouds on the surface energy budget was based on indirect evidence from radiation measurements made away from the volcano or on theoretical radiative calculations.

While the Mount St. Helens eruption is not believed to have been large enough to significantly influence the hemispheric or global climate (Robock, 1981b), it certainly had a large, but relatively brief, local effect on several meteorological parameters. To the best of our knowledge no study has examined such local effects; even the most extensive study of a volcanic eruption, that of Krakatoa (Symons, 1888), and the most comprehensive survey of volcanic eruption effects (Lamb, 1970) fail to include any mention of local temperature or weather effects. This deficiency can be at least partially explained by the inaccessible or isolated locations of most eruptions and the concomitant lack of representative regional data. In contrast, the Mount St. Helens eruption occurred upwind of a relatively dense network of National Weather Service, Federal Aviation Administration and military stations, most of which report observations hourly. In this study these stations were used to establish a mesoscale surface network downwind of the volcano which included the states of Washington, Oregon, Idaho, Utah, Montana, Wyoming, Nevada and Colorado (Fig. 1). This network was the main tool used to explore the influence of the Mount St. Helens dust cloud on surface temperature during the 24 h following the eruption.

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Since in this study we are trying to isolate the effects of the eruption, it is fortunate that during the days preceding and following the eruption there was little synoptic-scale activity over the Pacific Northwest. The mean sea-level pressure field just prior to the eruption (Fig. 2) was dominated by high pressure over Idaho and Wyoming. This pattern remained nearly unchanged during most of the next day, after which a Pacific frontal system began to move inland across the Washington Coast. Fig. 3a shows the GOES-SMS visible satellite picture at 1515 GMT, less than a half-hour before the eruption. The Pacific Northwest is generally cloud-free except for some middle-level cloudiness over the Idaho-Wyoming border and northwestern Colorado as well as low-level marine stratus and some overlying cirrus over western Washington and Oregon. During the subsequent daylight hours (Fig. 3b and 3c) there is a diurnal increase in convective cloudiness as well as an eastward progression of the high cloudiness in western Washington and Oregon. These clouds, associated with a weak short-wave trough aloft, continue to move through the region (Fig. 3d–3f) during the remaining period of the study.

In the following sections we examine the short-term effects of the volcanic plume; first, by calculating the temperature differences throughout the mesoscale network before and after the eruption and second, by comparing the temperature predictions of Model Output Statistics (MOS), probably the best objective forecasts of what would have happened without the eruption, and the actual observations. Finally, we discuss the implications of the above results on the importance of volcanic aerosols on the infrared and visible radiation budgets.

2. Methodology

For the mesoscale network of surface stations in the northwest United States (Fig. 1), hourly maps

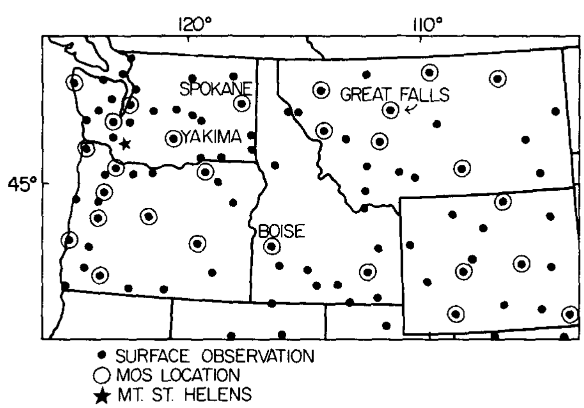

FIG. 1. The domain of this study. The locations of hourly surface observations, MOS stations and the Mount St. Helens volcano are also indicated.

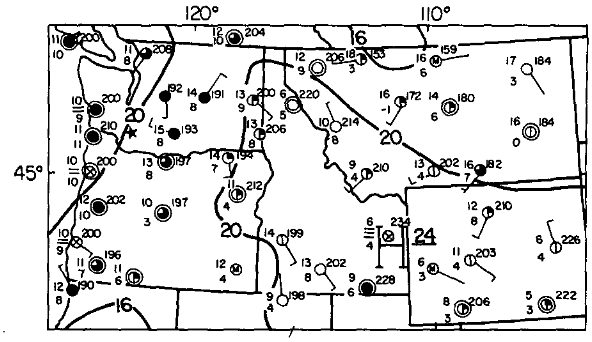

FIG. 2. Surface synoptic chart at 1500 GMT 18 May 1980 (Chart N090, National Weather Service. Temperatures and dew points have been changed to °C.)

of surface observations were constructed from 1500 GMT on 17 May 1980 until 1200 GMT on 20 May 1980 with data acquired from the National Climatic Center and the National Weather Service. Except for some warming, the synoptic situation did not change significantly between 17 May and 18 May, the day of the eruption. Assuming that without the eruption the surface temperature patterns would have been similar, we next created a series of maps of the 24 h temperature change between the 17 May and 18 May observations. This method also has the advantage of removing local effects such as terrain height or land use. Other than the regional warming, the temperature variations between the two days were predominately the result of the eruption.

The Techniques Development Laboratory (TDL) of the National Weather Service (NWS) has used multiple linear regression equations with predictors from the Limited-Area Fine Mesh (LFM) numerical forecast model output to forecast maximum and minimum surface temperature (max/min) and surface temperature at 3 h intervals since June, 1978 (Dallavalle *et al.*, 1980). This MOS technique has shown considerable skill at forecasting surface temperatures (Glahn and Lowry, 1972; Klein and Glahn, 1974). In order to investigate the effects of the Mount St. Helens eruption on surface temperature, we decided to use the "early" MOS 3 h temperature forecasts as a representation of what the temperatures would have been in the absence of a volcanic eruption. Early MOS has skill equal to or better than the official local NWS forecasts in the Western Region and has only a slight (few tenths of a °C) positive bias. We calculated the difference between the MOS forecasts and the actual temperatures after the eruption as an indication of the effect of the eruption on surface temperature. This technique of deriving physical insight from MOS "errors" has only been used once before, by Dewey (1977), who investigated the effects of snow cover on the MOS forecasts.

In order for the difference between the MOS forecasts and the observed temperatures to be physically

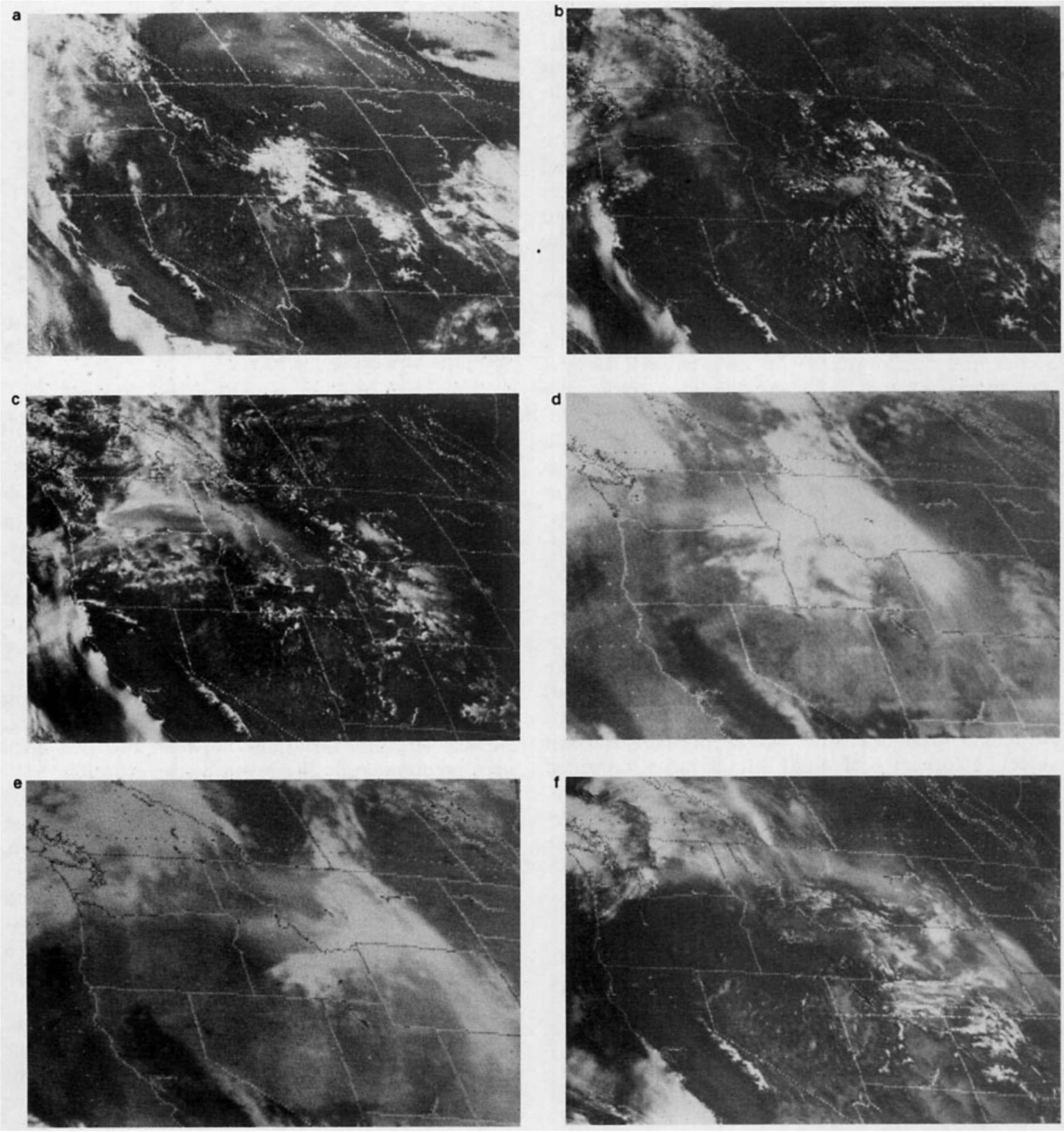

FIG. 3. SMS/GOES visible satellite imagery at (a) 1515 GMT, (b) 1815 GMT and (c) 2345 GMT on 18 May 1980, and (f) 1815 GMT on 19 May 1980. Infrared imagery at (d) 0645 GMT and (e) 1145 GMT on 19 May 1980. The Mount St. Helens plume is clearly seen.

significant, they must be larger than the errors produced routinely by the MOS technique. While TDL does not routinely calculate the errors of the 3 h forecasts, errors from the max/min forecasts are archived. These errors are almost identical to the 3 h errors for the same period (Dallavalle *et al.*, 1980) and can be used to represent the skill of the 3 h forecasts. Figs. 4a and 4b show an average of the April and June 1980 mean absolute MOS errors for the 24 h max/min MOS forecasts. These errors generally range between 2 and 4°C.

The extent of the eruption cloud was defined by means of visible and infrared GOES/SMS imagery, supplemented by surface observations.

3. Evidence of Volcanic Influence

a. Surface temperature fields

While the surface observations, 24-h temperature differences and dust boundaries were mapped every hour, and the MOS errors every three hours, for the sake of brevity we present the maps every six hours beginning at 1800 GMT on the day of the eruption (Figs. 5–9). In addition, visible and infrared satellite imagery at these times are shown in Fig. 3. At 1800 GMT, less than 2½ h after the eruption, the dust plume (Fig. 5a) extended east-northeast into eastern Washington. The surface temperatures (Fig. 5b) suggest weak cooling just east of the Cascades in eastern Washington. The 24 h temperature differences and MOS errors (Figs. 5c and 5d) indicate the volcanic signal more clearly, with temperature depressions exceeding 4°C in parts of eastern Washington. Also at this time another relatively cool area in the 24 h temperature differences (Fig. 5c) appears near the Idaho-Wyoming border; this was caused by a mesoscale area of cloudiness and showers (see Fig. 3b).

Six hours later, at 0000 GMT, the dust plume had rapidly spread eastward, reaching northern Idaho and far western Montana (Fig. 6a). The surface temperature chart (Fig. 6b) shows a band of minimum (<16°C) temperatures stretched southeastward in an area nearly coincident with the plume. The 24 h temperature differences and the MOS errors (Figs. 6c and 6d) indicate more than an 8°C temperature suppression in areas of eastern Washington.

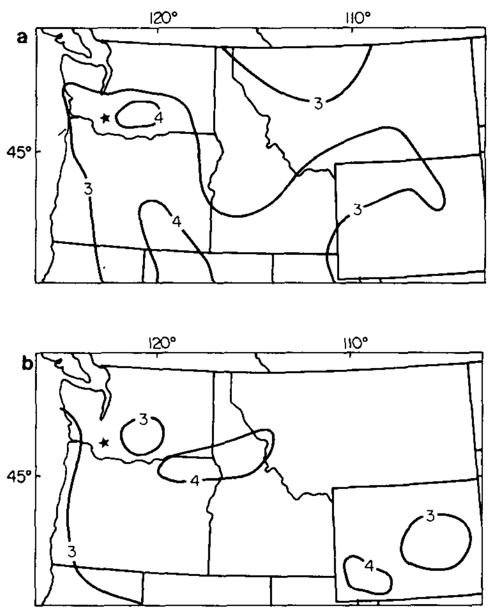

FIG. 4. Average mean absolute error (°C) for April and June 1980 MOS forecasts: (a) 24 h minimum temperature and (b) 24 h maximum temperature.

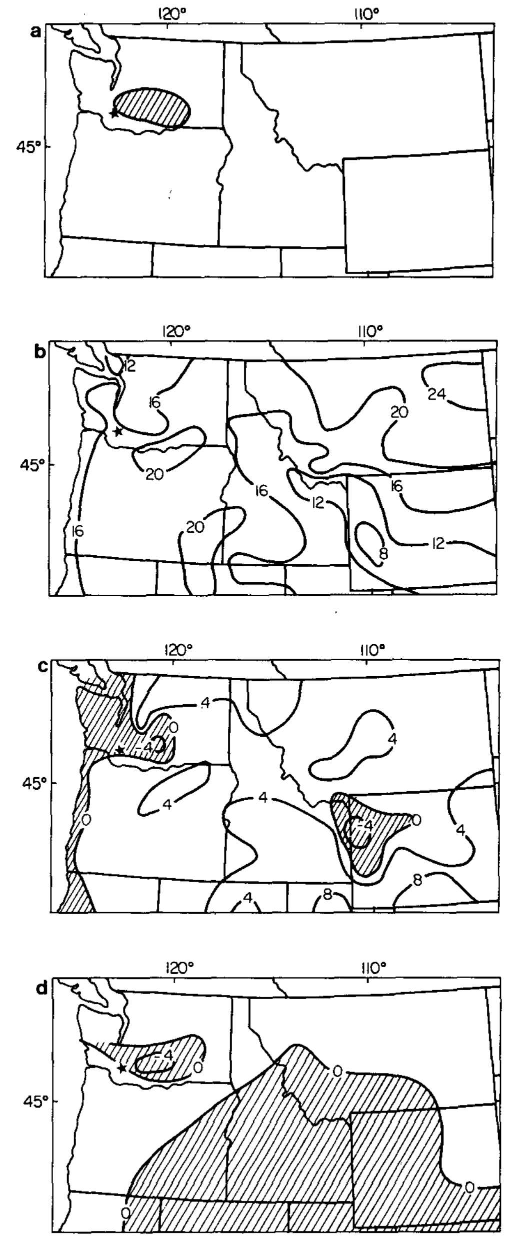

FIG. 5. (a) Dust plume boundary, (b) surface temperature (°C), (c) 24 h temperature differences (actual temperature minus previous day's temperature, °C), and (d) MOS errors (observed minus MOS forecast, °C) for 1800 GMT on 18 May 1980. The dust plume in (a) and negative values in (c) and (d) are shaded.

At 0600 GMT, a few hours after sunset, the patterns were significantly changed. The coldest and thus highest part of the volcanic plume was then over northern Idaho and the western half of Montana; in addition, dust was still evident at low levels over eastern Washington (Fig. 7a). No longer are temperatures lowered by the plume; rather, it appears that the volcanic cloud increased the temperatures in this

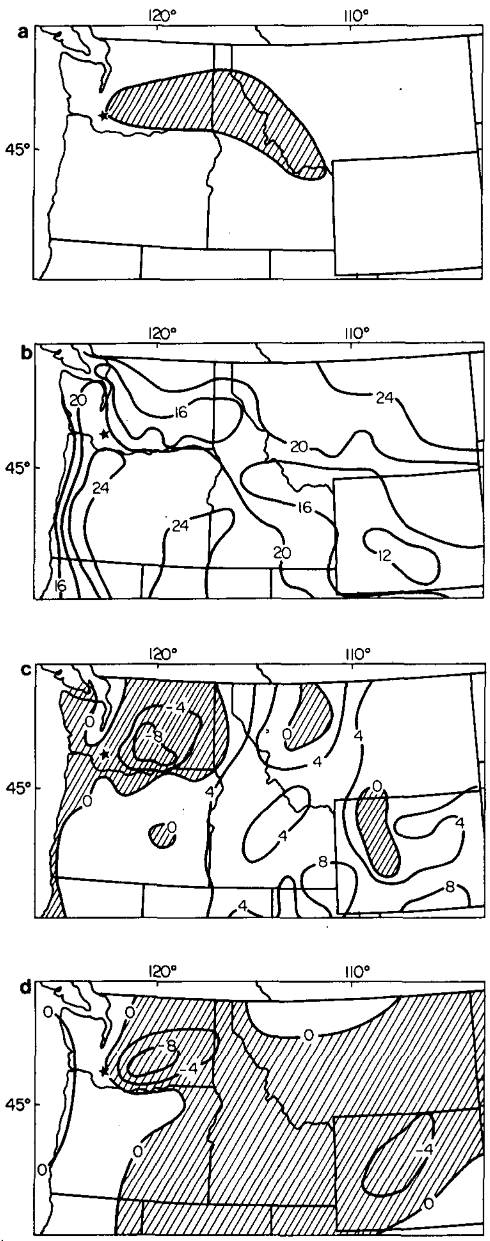

FIG. 6. As in Fig. 5 but for 0000 GMT 19 May 1980.

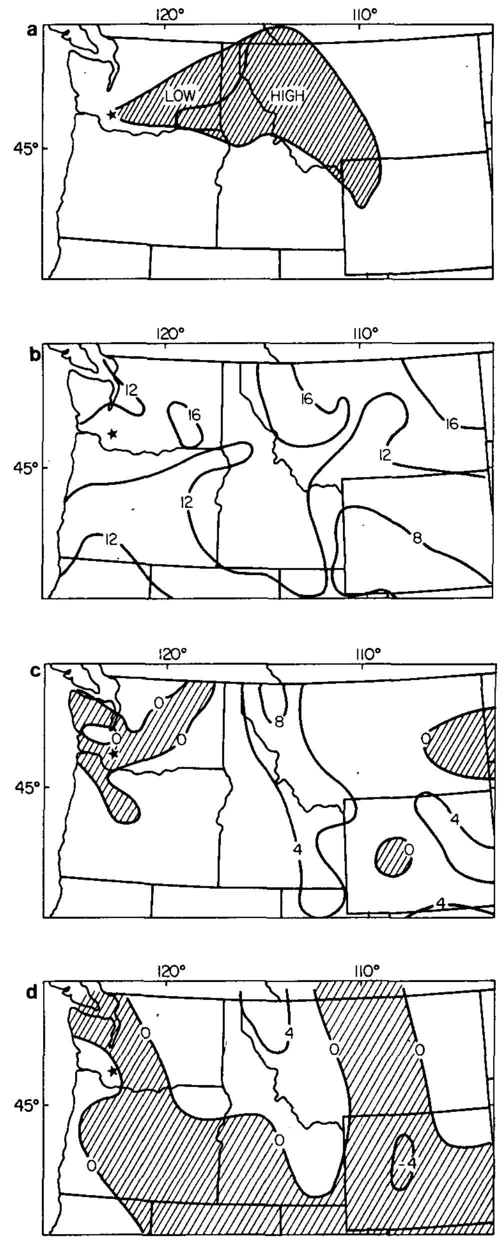

FIG. 7. As in Fig. 5 but for 0600 GMT 19 May 1980.

area. For example, the 24 h temperature differences suggest enhancements of 8°C (Fig. 7c), while the MOS errors are just over 4°C (Fig. 7d). Part of the observed temperature differences can be explained by the synoptic-scale warming associated with warm advection on the western side of the eastward moving region of high pressure. The MOS errors, therefore, should be better estimates of the volcanic effect than the 24 h differences, since the warm advection was presumably considered in the MOS forecast.

At 1200 GMT, just before sunrise in the Pacific Northwest, the volcanic enhancement had grown substantially larger as the plume continued its eastward movement (Fig. 8a). Enhancement values over Montana range from 8°C for MOS (Fig. 8d) to over 12°C for the 24 h differences (Fig. 8c). Even the unmodified surface temperatures indicate a clearcut volcanic influence (Fig. 8b).

During the next 6 h the dust plume, rapidly dispersing, continued its southeastward motion. The dust boundaries at this time (1800 GMT) are difficult to delineate; furthermore, cloudiness associated with a frontal system began to move into western Washington during this period (Fig. 9a). Tempera-

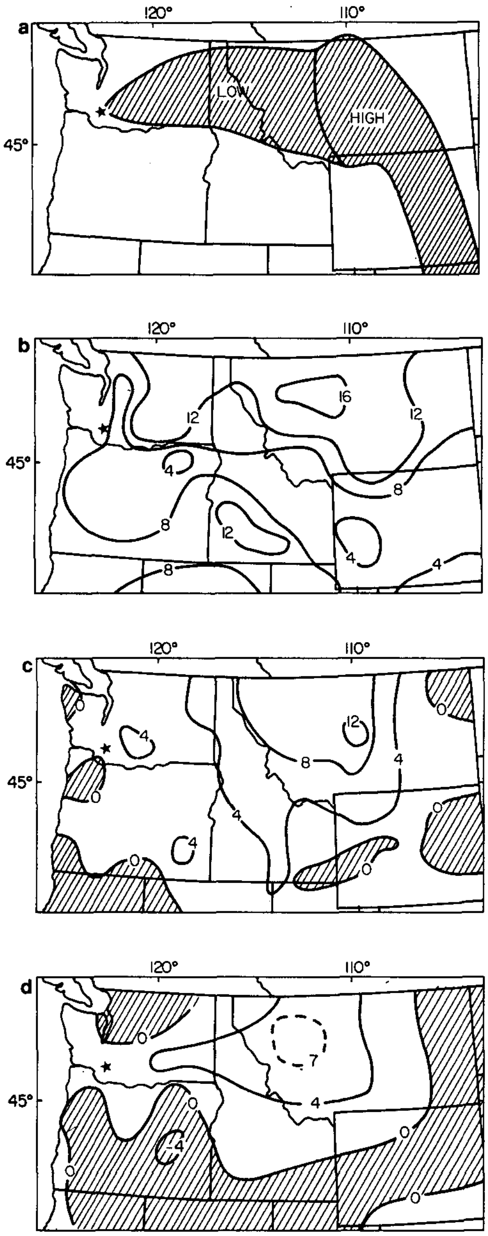

FIG. 8. As in Fig. 5 but for 1200 GMT 19 May 1980.

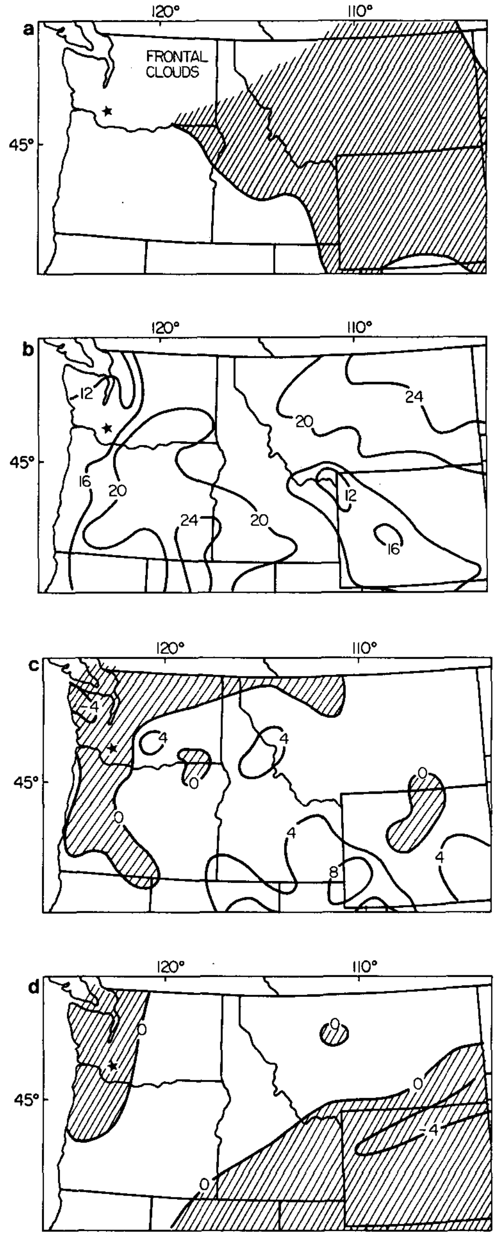

FIG. 9. As in Fig. 5 but for 1800 GMT 19 May 1980.

ture effects of the volcanic plume are hard to distinguish at this hour (Figs. 9b–9d). It is possible that volcanic warming and cooling effects are just about equal at this late morning time, and therefore cancel.

In summary, the above maps suggest a well-defined surface temperature signal forced by the Mount St. Helens volcanic plume. During the daytime hours the plume produced suppression which exceeded 8°C (both MOS and 24 h difference method) in areas of eastern Washington. That night, as the upper-level plume drifted eastward with low-level dust left in its wake, the suppression was replaced by substantial enhancement with values equaling (MOS) or exceeding (24 h differences) 8°C in parts of Montana. Finally, at 1800 GMT, slightly more than 24 h after the eruption, the temperature effects of the dispersing plume appear small.

b. Individual station temperatures

Another way of investigating the temperature effects of the volcanic plume is to examine the evolution of surface temperature at several stations in and out of the plume's domain. This was done for

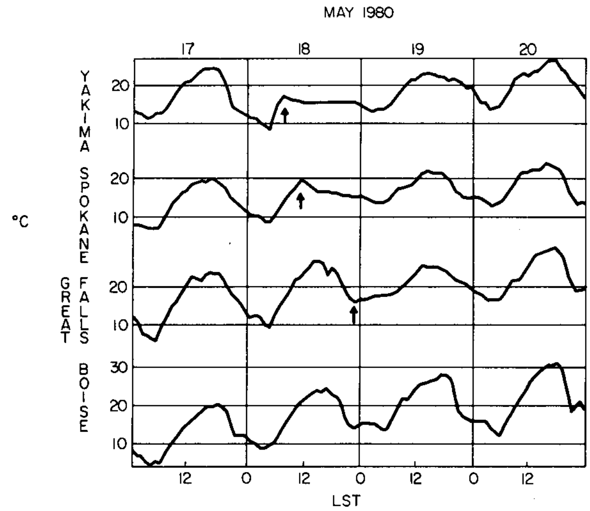

FIG. 10. Surface temperature variation from 17–20 May 1980 at Yakima and Spokane, Washington; Great Falls, Montana; and Boise, Idaho (see Fig. 1 for locations). The arrows indicate times of the arrival of the Mount St. Helens plume.

four stations (Yakima and Spokane, Washington; Great Falls, Montana; and Boise, Idaho) during the period 17–20 May 1980; the results are shown in Fig. 10. Beginning with Yakima, the station closest to the eruption, we note a diurnal rise on 17 May to 24°C and a fall to 8°C that night. This was followed by a steady rise until 0800 PST on 18 May, when the temperature reached its peak as the volcanic plume reached the station. During the next four hours the temperature slowly dropped to 15°C, where it remained for 11 straight hours. The temperature did fall slightly (2°C) during the subsequent early morning hours. On the 19th the temperature rebounded substantially to 23°C during the day, but fell that night to only 13°C. The next day brought further recovery. The diurnal temperature range on the 17th through the 20th (beginning at 0900 PST) ranged from 16°C on the 17th to 3°C on the day of the eruption. On the 19th and 20th the diurnal temperature range rapidly increased to 9°C and 15°C, respectively, the latter being close to the pre-eruption value.

At Spokane, 300 km northeast of Yakima, the plume arrived a few hours later. Therefore, unlike at Yakima, the temperature on the 18th rose to nearly the previous day's maximum (19°C). With the appearance of the volcanic cloud the temperature declined to 16°C, after which it slowly fell during the remaining hours of daylight. Substantial temperature enhancement was observed during nighttime hours followed by relatively uninhibited warming during the subsequent day. The diurnal temperature ranges (beginning at 1500 PST) from the 17th to 20th were 12, 3, 10 and 12°C, respectively.

Further east at Great Falls, Montana, the dust was not observed until around midnight PST. Before this time the temperature had been rapidly falling, but with the first sign of the plume the temperature began a slow rise which continued through the night. On the next day (19 May) the temperature rose to nearly the previous day's level, but that night the temperature fall continued to be suppressed. The diurnal temperature ranges (beginning at local midnight) at Great Falls from the 17th to the 21st were 18, 17, 9, 13 and 20°C.

Fig. 10 also shows the temperature variation at Boise, Idaho. This location, situated outside of the plume throughout the period, experienced a relatively constant diurnal range with a superimposed slow warming trend. The diurnal temperature ranges (beginning at local midnight) from the 17th to the 20th were 16, 15, 14 and 19°C.

In summary, these individual station records indicate that when the plume arrived by day it quickly shut off the solar insolation and produced nearly steady temperatures for several hours. On the other hand, at night the plume suppressed infrared cooling or produced infrared warming. It is apparent that the maximum temperatures recovered more quickly than the nighttime minima, suggesting that the effect on the infrared flux was more longlasting than that on the shortwave insolation. As discussed in Section 4, this is probably due to the significant amounts of low-level dust that persisted for several days. Finally, the diurnal temperature range was drastically limited by the plume but recovered almost completely within two days.

c. Individual station MOS errors

As further evidence of the effect of the Mount St. Helens volcanic plume on surface temperature, Fig.

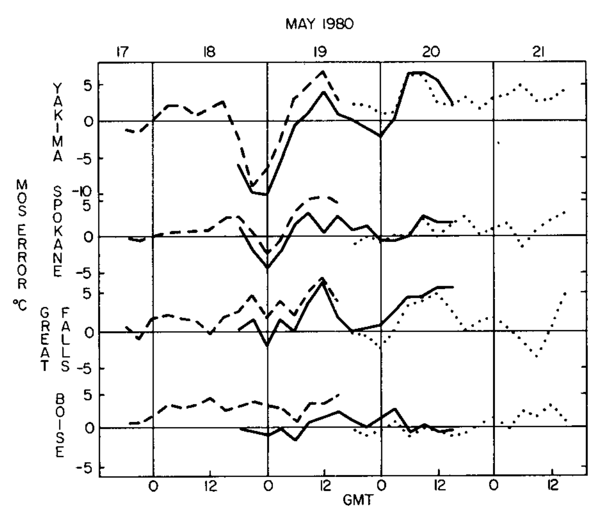

FIG. 11. Errors (observed minus forecast) of the 3 h MOS surface temperature forecasts for the 1200 GMT runs on 17 May (dashed), 18 May (solid) and 19 May (dotted) for Yakima and Spokane, Washington; Great Falls, Montana; and Boise, Idaho.

11 shows MOS errors for the four stations discussed in the previous section. Results are shown from the three 1200 GMT MOS runs on the 17th through the 19th. Results from the 0000 GMT runs are essentially identical.

At Yakima, the large negative error (as much as 12°C) occuring at or just before 0000 GMT on the 19th (1600 PST on the 18th) is due to the volcanic dust from the eruption that morning. During the next two early mornings (1200 GMT), positive errors of 7°C were found; however, the daytime cooling dramatically attentuates by the second day and is even replaced by positive errors on the 19 May 1200 GMT run. At Spokane the cooling on the 18th and subsequent nighttime warming is smaller than in Yakima, due to the later arrival of the dust on the day of the eruption and lower concentrations of surface dust. A larger nighttime enhancement (6°C) is found at Great Falls, Montana. At this location there is little evidence of daytime cooling due to the volcanic plume. Finally, the MOS errors at Boise remain relatively small and are clearly not of volcanic origin.

It is interesting to note that the MOS runs starting on the 19th, which include the volcanic effect on the predictors, show MOS errors as large as the pre-eruption runs. Thus the eruption did not have a large enough effect on the MOS predictors to influence the temperature predictions.

4. Discussion and conclusions

In this paper the local short-term surface temperature effects of the Mount St. Helens eruption have been examined in what is probably the first such study of local volcanic influence. [Preliminary results were reported by Robock and Mass (1982).] We have found large temperature effects consisting of substantial cooling (~8°C) in eastern Washington during the first day and nearly equal warming over Idaho and Montana the following night.

Tropospheric observations of the particle size distribution of the plume (Hobbs *et al.*, 1981) indicate that during the first day after the eruption the size of the volcanic ash ranged from a few tenths to tens of microns, with the greatest concentration enhancement occurring for those particles larger than 1 μm. The existence of such a size distribution indicates a strong interaction between the particles and infrared and visible radiation. According to the calculations of Pollack *et al.* (1976), large particles which would predominate during the days immediately after an eruption would produce infrared warming which would totally cancel or in some cases overwhelm cooling due to scattering and absorption of visible radiation. A net warming (averaged over a day) in excess of the non-volcanic large-scale trends is apparent at several stations during the days after the Mount St. Helens eruption (Figs. 10, 11). Subsequently, sedimentation and gas-to-particle conversions increasingly skewed the size distribution toward smaller particles which are less active in the IR.

The cooling observed in eastern Washington during the first day of the eruption was caused by the increase in albedo produced by the dust in both the troposphere and the stratosphere. This reduced shortwave insolation sufficiently to overcome any warming by the enhanced IR emission of the dust cloud. Insolation at several stations was almost cut off completely with darkness described as being similar to a moonless night accompanying the plume. That night, when low-level dust was observed from eastern Washington into central Montana and the upper-level plume had moved into central and eastern Montana, warming was observed over a broad region centered over western Montana. The area of greatest warming was not identical to the region of the upper-level plume. Rather, it appears that the low-level dust played the crucial role in producing the observed warming since the density of the low-level dust cloud was sufficiently large and the resulting IR optical depths sufficiently short that the surface reached radiative equilibrium with levels in the lowest part of the troposphere. At Great Falls, Montana, the temperature actually rose as visibility fell during the arrival of falling volcanic ash. At the time of arrival (2300 LST) a low-level inversion had undoubtedly begun to form under clear skies since such an inversion was observed the previous night and the synoptic situation was nearly unchanged. The addition of ash into the lower troposphere produced warming since some of it radiated at the temperature of the higher and thus warmer levels above the surface. In contrast, a stratospheric volcanic dust cloud, which would be radiating at a colder temperature than the ground, would cause less nighttime cooling, but not warming.

It is important to note that other effects can also produce nighttime warming, although generally weaker and of shorter duration. During the same night (18–19 May) at Boise and during the previous night at Great Falls there was a temporary rise in temperature at about midnight (Fig. 10). In both cases there was a sudden appearance of clouds, overcast at 25 000 ft (7620 m) at Boise and scattered at 6000 ft (1829 m) at Great Falls. However, the radiation from the clouds themselves would not be enough to cause warming, so another effect suggested by Pinker and Landsberg (1976) might also be at work. They found at some sites with adjacent lower topography that after the onset of a nocturnal inversion, cold air would drain into the lower areas, and the surface temperature at the site would temporarily warm due to subsidence. Heat flux from the subsurface would provide a negligible heat source (Pinker, personal communication).

The pattern of nighttime temperature enhancement on the night following the eruption (Figs. 8c and 8d) shows a maximum in western Montana. The lack of large positive temperature anomalies in eastern Washington can be explained by the dust cloud's suppression of the daytime rise. Stations further east received more solar insolation before the arrival of the dust cloud and thus achieved higher maximum temperatures; this explains the maximum of enhanced nighttime temperatures in northern Idaho and western Montana. The lessening of the temperature anomaly toward eastern Montana resulted from the late arrival and progressive attenuation of the dust cloud as it moved eastward.

During the next day (19 May) the maximum surface temperature was not suppressed by the volcanic dust in Yakima, Spokane and Great Falls (Fig. 11), yet during the following night the minimum temperature was elevated at all three stations. (Boise, with no volcanic dust, had a normal diurnal cycle.) It can be seen in the satellite pictures (Fig. 3) and from the dust boundaries (Figs. 5a–8a) that the high portion of the volcanic cloud had already blown past these stations. Low-level dust was still evident in both satellite pictures and surface observations and continued to enhance nighttime surface temperatures.

In contrast to the short-term effects discussed in this paper, theoretical estimates of the climatic impact of volcanic plumes suggest a net cooling due to the smaller particles and greater height of the long-term plume. For such a plume the loss of solar radiation due to scattering, reflection or its absorption at stratospheric levels would outweigh the warming due to enhanced infrared absorption and re-emission by the volcanic aerosols.

Finally, the use of MOS errors for delineating areas of volcanic influence was quite successful and suggests its validity as an important tool for other investigations.

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