# NOTES AND CORRESPONDENCE

## Frontal Analysis in the Light of Abrupt Temperature Changes in a Shallow Valley

FREDERICK SANDERS

*Marblehead, Massachusetts*

EDWIN KESSLER

*Purcell, Oklahoma*

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ABSTRACT

The authors examine selected cases of abrupt temperature changes in a shallow valley in rural Oklahoma and examine their wider associations. All changes in the valley, whether rise or fall, are accompanied by a northerly wind shift at or shortly before the time of the abrupt change. Cases of cooling show a drop of as much as 20°F (11°C) in less than 1 h. The pattern of surface potential temperature over the central United States indicates that these cases represent ideal cold-front passages, although little or no weather accompanies them.

Cases of abrupt warming, which are entirely nocturnal, on the other hand, are associated with weak regional temperature gradients and with strong nocturnal cooling prior to the event under nearly clear skies and with light winds. The imputed surface inversion does not occur at a nearby urban location, and the breakdown is an important factor in the temperature rise at the rural site.

The important distinction between these cases and the cold-front passages that produce strong cooling at the rural site is the lack of organized surface temperature gradient over Oklahoma on the synoptic scale at the time of the event at Great Plains Apiaries. The abrupt warming at the rural site may be incidental and attributable to local topography. It is urged that in these cases the wind shift be denoted a "trof" rather than a cold front. In present practice the shift to a northerly wind with rising pressure and cold advection is evidently considered sufficient evidence for a cold front, despite the lack of strong surface temperature gradient.

### 1. Introduction

For several years, instrumentation including a hygrothermograph obtained data from Great Plains Apiaries (GPA), the farm home of E. Kessler at Purcell, Oklahoma. Purcell is about 27 miles south-southeast of Will Rogers International Airport (OKC), which is on the southwest side of Oklahoma City. The GPA site is in rolling farmland at an elevation of 331 m, 66 m lower than OKC, which is on the flat top of a small butte. Features of particular interest in the thermograph record are abrupt changes of temperature, sometimes almost instantaneous. These events are almost always shown on surface analyses produced by the National Weather Service (NWS) as cold-front passages, whether the abrupt change is upward or downward. The purpose of this work is to study the character of examples of these changes and to examine them in the light of the NWS analyses.

A selection was made of rapid changes, ranging in magnitude from 2° to 11°C, during 1977–84, the period when the thermograph was operating. Sixteen cases are specified in Table 1.

Case 5 displays two abrupt changes in a period of not more than 3 h. These are regarded as two instances within a single synoptic setting. Eight cases were temperature rises and nine were drops. The latter were larger by a factor of nearly 2. The four most pronounced cases of warming occurred within 2 h of midnight, suggesting that the breakdown of a nocturnal inversion was an important process. Although recorded wind data are not available from GPA for these cases, some fortuitous personal observations by Kessler identified coincidence between temperature rises and the onset of surface breeze following calm conditions.

In contrast, the four most pronounced cases of cooling occurred between 1000 and 1600 Central Standard Time (CST), indicating an enhancement of frontal contrast by diurnal heating of the warmer air, as discussed by Segal et al. (1993).

A study of surface maps for these episodes resorted first to the maps for 1200 UTC (UTC = CST + 6 h),

*Corresponding author address:* Dr. Frederick Sanders, 9 Flint Street, Marblehead, MA 01945.
E-mail: fnmisander@aol.com

TABLE 1. Selected cases of abrupt temperature change at GPA.

| Case | Date | Time (CST) | Temperature change (°F) | NMC analysis |
|---|---|---|---|---|
| 1. | 14 Feb 1997 | 0200 | +12 | Cold front |
| 2. | 18 Feb 1997 | 2100 | +3 | Trough |
| 3. | 16 Nov 1977 | 1800 | +4 | Cold front |
| 4. | 20 Nov 1977 | 1200 | −15 | Stationary front to south |
| 5a. | 23 Mar 1978 | 1100 | +4 | Stationary front to south |
| 5b. | 23 Mar 1978 | 1400 | −12 | Stationary front to south |
| 6. | 24 Apr 1978 | 2400 | +9 | Cold front |
| 7. | 29 Dec 1978 | 1200 | −13 | Cold front |
| 8. | 13 Jan 1979 | 0300 | −10 | Cold front |
| 9. | 14 Feb 1979 | 2000 | +6 | Warm front |
| 10. | 15 Feb 1979 | 0800 | −10 | Cold front |
| 11. | 11 Dec 1979 | 1100 | −13 | Cold front |
| 12. | 6 Jan 1980 | 1600 | −20 | Cold front |
| 13. | 18 Dec 1980 | 1600 | −14 | Cold front |
| 14. | 1 Oct 1981 | 0100 | +8 | Cold front |
| 15. | 7 Mar 1984 | 2300 | +12 | Cold front |
| 16. | 15 Mar 1987 | 1600 | −14 | Double cold front |

published as the Daily Weather Maps. To add more spatial and temporal resolution, copies of portions of the NWS North American analyses were obtained. These portions are at 3-h intervals and cover the area from the western Gulf of Mexico to southern Canada, in the United States from roughly the Appalachians to the Rocky Mountains.

Because of the considerable variation of land elevation from near sea level to almost 2000 m on the high plains, the plotted surface temperatures were converted to potential temperatures. Since many stations do not transmit surface pressure, an approximate method was used to make this conversion. Because the dry-adiabatic lapse rate is very nearly 1°C per 100 m and because the mean elevation of the 1000-mb surface is about 100 m, the correction in degrees Celsins was taken to be $(Z - 100)/100$, where $Z$ is the station elevation in meters. The error in this approximation will be 1°C if the elevation of the 1000-mb surface deviates 100 m from its mean value. This would correspond to a departure of sea level pressure from its mean value of 1016 mb by about 7.5 mb. The error is usually not larger than this amount.

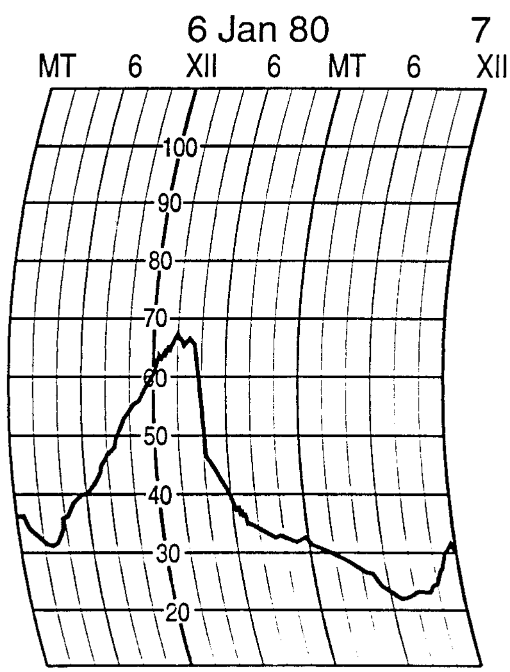


FIG. 1. Portion of the GPA thermogram for 5–7 January 1980. Temperatures are in °F.

## 2. An example of abrupt cooling

As an example of abrupt cooling, the trace at GPA in case 12 appears in Fig. 1. The temperature plunged from 66° to 46°F (19°–8°C) in less than 1 h around 1600 CST on 6 January 1980. Figure 2 shows the hourly values at GPA, read from the trace, from 6 h before to 6 h after the time of rapid cooling. It also shows hourly temperatures and surface winds observed at the same tunes at OKC. There the temperature had dropped from 63°F (17°C) at 1455 CST, with the wind from 300° at 18 knots (9 m s$^{-1}$), to 46°F (8°C) with the wind from 340° at 26 knots (13 m s$^{-1}$) 1 h later. The temperature fall at OKC was slightly earlier than at GPA, consistent with the southward motion of the cold front shown on the NWS analysis (Fig. 3). At OKC the wind had been from 190° at 23 knots (12 m s$^{-1}$) at 1254 CST, while the pressure reached a minimum 2 h earlier. Evidently a pressure trough and a substantial wind shift had occurred with little immediate effect on temperature. This sequence is often observed (Hutchinson and Bluestein 1997), but in this case the time lag between the wind and pressure signal and the temperature drop was no more than 2 h, probably small enough to escape detection in the synoptic-scale NWS analysis.

The analysis for 1200 CST (Fig. 3), transcribed from the North American surface analysis, shows a pressure

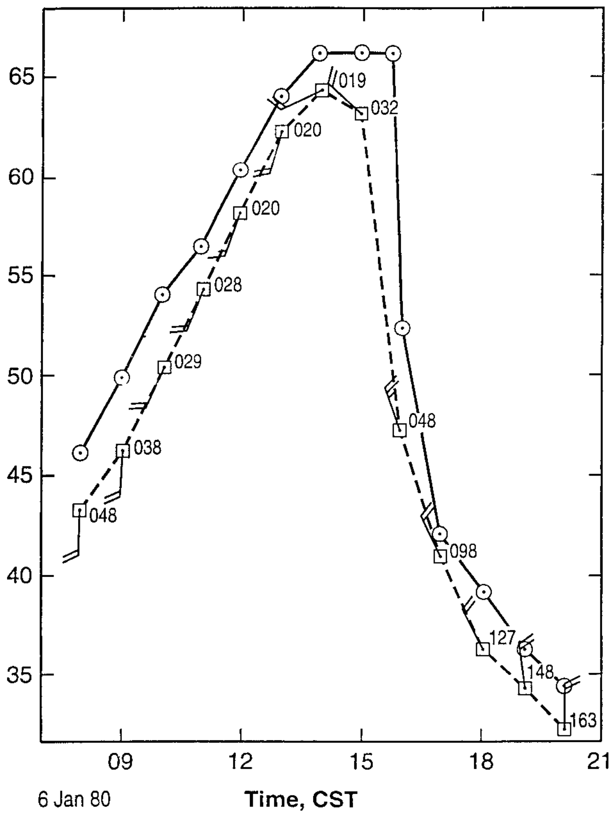


FIG. 2. Enlargement of GPA hourly record (solid line) and hourly temperatures, sea level pressures (in tenths of mb), and winds observed at OKC (dashed line) from 0800 to 2000 CST 6 January 1980.

trough running west-southwest from a low center in southeastern Kansas. There was a region of extremely high potential temperature in the Texas Panhandle and strong warm advection to the east of it and south of the trough. A strong gradient of potential temperature lay just north of the pressure trough from western Oklahoma to the western edge of the analysis in southeastern Colorado, where the gradient reached 22°C 100 km$^{-1}$. The NWS analysis showed the cold front near the warm edge of the strong gradient and north of the pressure trough in Oklahoma and Kansas, between southwesterly and northwesterly wind. Other examples of frontal analysis based primarily on wind shift are presented by Sanders and Doswell (1995).

Three and six hours later (not shown) the zone of strong temperature gradient extended eastward to southwestern Missouri but weakened in maximum intensity to 17° and then 14°C 100 km$^{-1}$. The pressure trough and wind shift lay along the warm edge of this zone at the latter time, and the NWS frontal analysis coincided with it.

## 3. An example of abrupt warming

A contrasting example is case 1 (Fig. 4) in which the rapid nocturnal fall of temperature at GPA was interrupted around 0200 CST 14 February 1977 by a sudden rise of 12°F (7°C). There was no such rise at OKC (Fig. 5), where the temperature fell steadily from 64°F (18°C) at 1600 CST to 50°F (10°C) at 2200 CST. Thereafter, the temperature fluctuated in a narrow range until a modest fall began at 0300 CST, with a strong northerly wind replacing the weak southwesterly that had prevailed earlier. Again, the main wind shift and the pressure minimum preceded the start of this latter cooling by an hour or so.

Shortly before the warming event, at 0000 CST 14 February (Fig. 6), a cold front was depicted in a trough of low pressure extending from eastern New Mexico across Texas and Oklahoma into a weak low in northern Missouri. Potential temperatures showed an ill-defined cold area in northwest Oklahoma. Cold and warm regions lay south of the analyzed front in central Oklahoma and farther south. A ridge of maximum warmth extended across southern Kansas north of the analyzed front. The most important aspect is that no pronounced gradients matching those in Fig. 3 were seen. Since clear skies and calm wind characterized the cool area, the relatively low temperature can be attributed to nocturnal cooling.

On its face it seems perverse to denote the event at GPA as a cold-front passage, as indicated in the NWS analysis. Indeed, Fig. 5 shows that at 0100 CST, just before the warming at GPA, the temperature there was 10°F (6°C) colder than at OKC, suggesting that the structure might be regarded as a warm front. The contrast between OKC and GPA, however, was due to absence at OKC of a thin boundary layer strongly cooled by nocturnal surface radiation. This is not the usual situation for a warm front.

We cannot say that the warming at GPA was more than an extremely localized event, dependent on the strong preceding nocturnal cooling. Locations not experiencing this cooling would not be expected to display the abrupt temperature rise noted at GPA. The regional temperature analyses in Figs. 3 and 6, however, show a significant difference in pattern between the two cases.

## 4. Mean patterns of temperature and other surface elements

To see what consistency there might be among cases of rapid temperature change, the average departure of potential temperature from that at OKC, for the four most pronounced instances of sudden cooling (cases 4, 12, 13, and 16 in Table 1), was calculated and is mapped in Fig. 7. OKC lay near the warm edge of a zone of strong gradient. This zone extended from southeastern Kansas southwestward through central Oklahoma, thence northwestward to eastern Wyoming. This interpretation is representative of an ideal cold front, in good agreement with the interpretation on the NWS analyses.

Similarly, a composite of the four strongest instances of warming (cases 1, 6, 14, and 15 in Table 1) appears

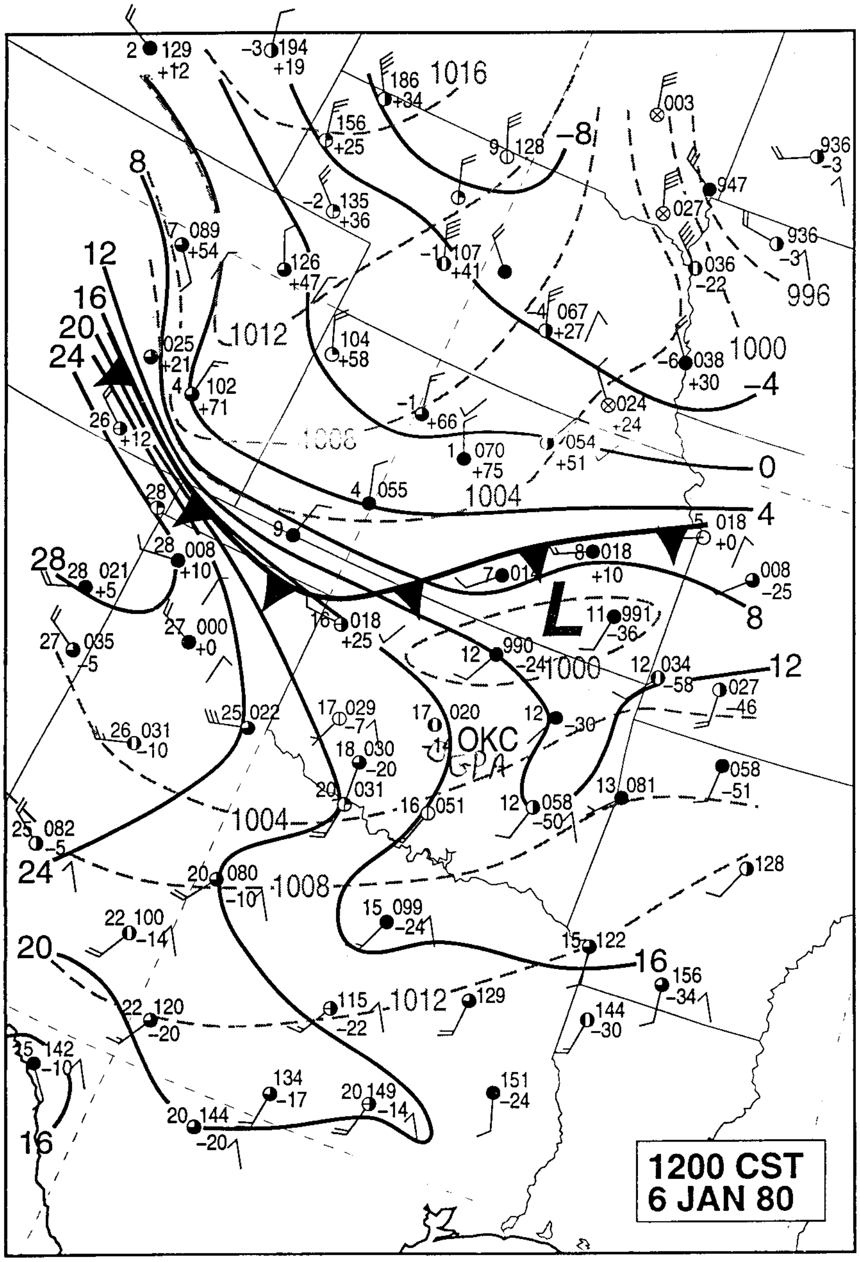


FIG. 3. Isotherms of surface potential temperature (solid lines) at intervals of 4°C and isobars of sea level pressure (dashed lines) at intervals of 4 mb for 1200 CST 6 January 1980. The heavy solid line is a cold front depicted on the NWS surface analysis for the same time. Station plots are in conventional format.

as Fig. 8. The pattern is quite different from that in Fig. 7 over most of the map area. OKC lies in a region of weak gradient that extends south to the edge of the map. To the north of OKC there is no strong gradient, the most intense reaching about 4°C 100 $km^{-1}$ in eastern Colorado. Indeed, the magnitude of the gradient to the north of OKC is only about 15% greater than the climatological average for the time of year (see Fig. 6 in Visher 1966). The difference in the patterns shown in Figs. 7 and 8 shows that the behavior at GPA reflects the synoptic-scale structure over a broad area.

Sometimes a cold front is considered to mark the leading edge of synoptic-scale cold advection, or the beginning of cooling over some time interval longer than 1 h and perhaps on the order of a day. It seems useful, however, to reserve the use of the term ''front'' for the truly intense contrasts seen in Figs. 2, 3, and 7, which conform closely to the Bjerknes paradigm.

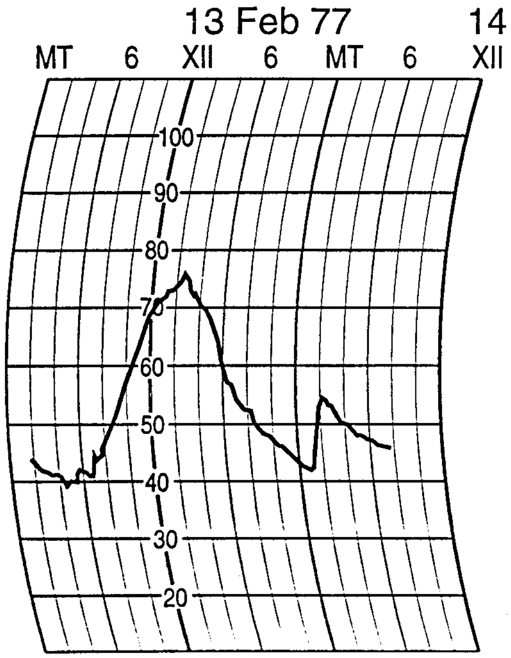


FIG. 4. Same as Fig. 1 but for 13–14 February 1977.

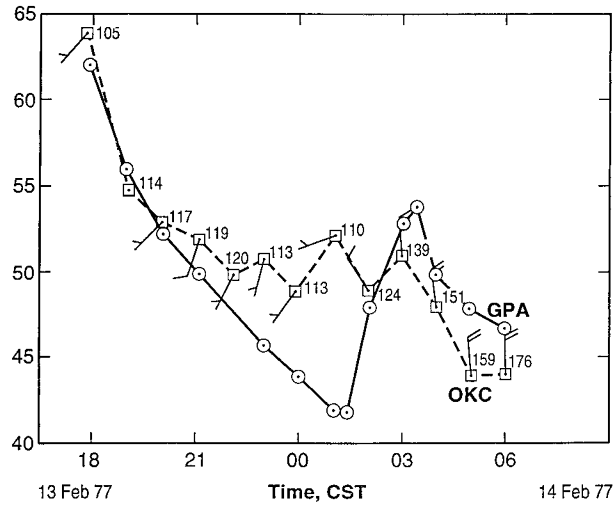


FIG. 5. Same as Fig. 2 but for 1800 CST 13 February–0600 14 February 1977.

The cases of temperature rise at GPA might then be incidental and dependent on local topography. The rise may be smaller than the scale of events appropriately shown in synoptic analyses. In an attempt to estimate the areal extent of the sudden warming, a brief examination was made of 3-h temperature changes just north of the wind-shift line and just south of it. There was much station-to-station variability, indicating a strong influence of local topography, but no significant difference in the average changes on either side of the line. This lack is a reflection of the weak gradient in these cases, but it was not possible to estimate from this source the extent of the abrupt warming.

To add to the view of the synoptic circumstances characterizing these cases, the hourly observations at OKC for the four cooling cases yielding Fig. 7 were examined from 6 h before to 6 h after the event at GPA. The results appear in Table 2. Note that no precipitation accompanied these frontal passages, contrary to the pattern of intense showers postulated by Bjerknes and Solberg (1921). Inspection of the upper-level data showed that a 500-mb trough lay to the east of OKC in these cases, with northwesterly winds aloft. The synoptic-scale forcing was for descent and evidently dominated any tendency for saturation that might otherwise have accompanied the mesoscale frontal circulation. The lack of cloud and precipitation also reflected the extreme dryness of the air involved in the front.

In at least some instances, a cold front existed across Kansas a few hours before the event at GPA, with a strong temperature gradient and showers and thunderstorms due presumably to a frontal circulation that existed at that earlier time. These aspects had vanished by the time of the event, and they did not reliably reappear the following day. Thus a significant transformation had occurred, although the origin of the wind shift was probably the earlier cold front.

The wind shift to northerly was noted as a remark in the observations in all four cases (although it was characterized as gradual in the instance of strongest temperature drop). The pressure minimum occurred 2–6 h prior to the event at GPA, consistent with the passage of a trough with no immediate impact on temperature.

A similar tabulation was made for the four cases of strongest warming and is shown in Table 3. Precipitation was lacking in these cases as well. In fact, there was little cloud aside from high cirrus before and at the time of the event at GPA. Again these cases of clear skies were accompanied by northwesterly upper-level winds. Surface winds at OKC were light during this interval, providing conditions favorable for strong nocturnal cooling of a thin boundary layer, as noted above. As in Table 2, a pressure minimum was noted a few hours before the event at GPA. A strengthening of northerly wind characterized these cases, as well as the cases of strong cooling. The shift was pronounced enough to warrant a remark in cases 14 and 15 (although there was no sudden temperature drop as might be expected to accompany a cold-front passage.) Evidently the wind shift and beginning of cold advection led to interpretation of the feature as a cold front.

## 5. Discussion

The cases of sudden temperature drop present no problem. They are cold fronts, as introduced by Bjerknes (1918), and are shown as such in the NWS analyses. The warmings, in contrast, present a problem because they are associated with only weak surface temperature gradients on the synoptic scale. The GPA

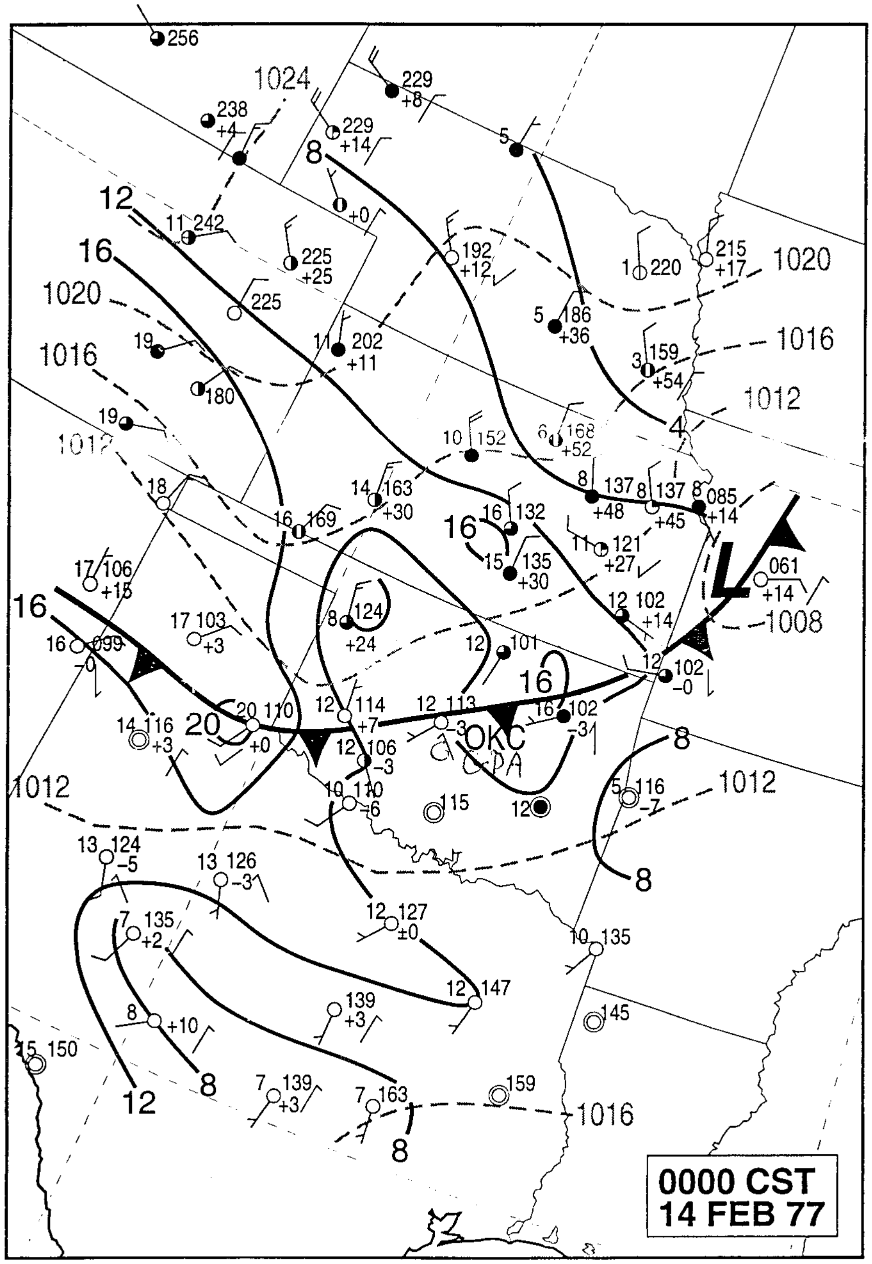


FIG. 6. Same as Fig. 3 but for 0000 CST 14 February 1977.

warmings are of nearly the same magnitude, and show the same preference for nocturnal occurrence, as ''heat bursts,'' first so denoted by Williams (1963) and more recently studied by Johnson (1983) and Bernstein and Johnson (1994). These are almost always associated with convective activity. The cold air at the surface is due to thunderstorm outflow and the breaking of the surface inversion is caused by mesoscale downdrafts that are part of the circulation of the system. The present study shows that such sudden warmings can occur in the absence of convective activity and through a different mechanism.

We suggest that the solution for the problem of faulty identification of cold fronts in these warming cases of weak synoptic-scale gradient should be to denote the structures as wind shifts or ''trofs,'' a term already in use. Analysis of the surface field of potential temperature would afford a means of distinguishing between cold fronts and these nonfrontal wind-shift lines.

It is possible to imagine that in these cases of abrupt warming a cold front is present above a shallow surface inversion. No tower or other local sounding information is available to check on this possibility by direct observation. This interpretation, however, is unlikely be-

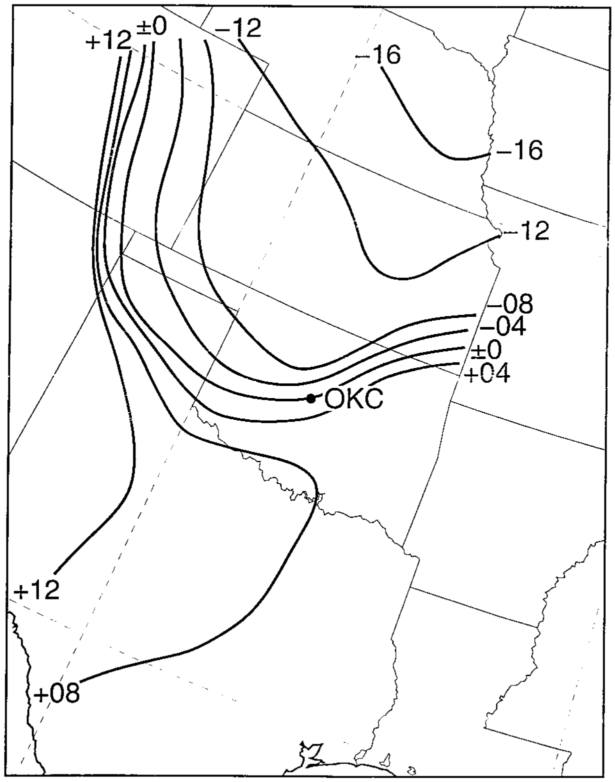


FIG. 7. Mean departure of surface potential temperature from that at OKC, for four cases of abrupt cooling at GPA, at NWS map time nearest the time of the event. Isotherms at intervals of 4°C.

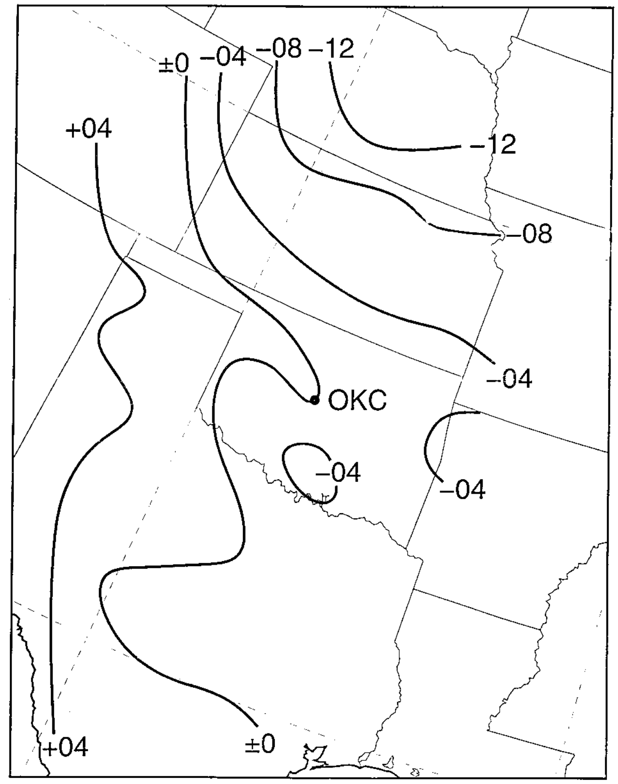


FIG. 8. Same as Fig. 7, but for four cases of abrupt warming at GPA.

TABLE 2. Selected OKC observations [in surface aviation observation (SAO) format] for four cases of strong cooling at GPA. $T_o$ is the time of occurrence of the event at GPA.

| Case | Change | Date | $T_o$ (CST) | Time (hours) | SAO |
|---|---|---|---|---|---|
| 4 | (−15°F) | (20 Nov 1977) | 1200 | 0600 | 19 OVC 051/68/61/200/19G27 pressure minimum |
| | | | | 0900 | 17 SCT 085/67/60/210/17G24 |
| | | | | 1200 | 17 SCT 111/60/46/340/20 Wind shift; frontal passage |
| | | | | 1500 | 20 SCT 250 SCT 136/56/31/350/23G29 |
| | | | | 1800 | 250 SCT 177/45/21/360/25G34 |
| 12 | −20°F | 6 Jan 1980 | 1800 | 1000 | 250 OVC 029/50/40/180/21G27 |
| | | | | 1300 | 250-BKN 000/62/39/190/23G30 |
| | | | | 1600 | 140 SCT 250 OVC 068/47/33/340/20G33 Wind shifted gradually |
| | | | | 1900 | 20 SCT 100 OVC 148/34/18/350/20G30 |
| | | | | 2200 | 20 SCT 100 SCT 168/31/13/350/20G29 |
| 13 | −14°F | 18 Dec 1980 | 1600 | 1000 | 250-BKN 080/55/46/190/09 |
| | | | | 1300 | 250-OVC 072/61/45/290/06 Pressure minimum; wind shift |
| | | | | 1600 | 100 OVC 4F 112/49/44/340/19G34 |
| | | | | 1900 | 12 OVC 172/37/33/360/21G30 |
| | | | | 2200 | 25 OVC 214/36/24/010/21G27 |
| 16 | −14°F | 15 Mar 1984 | 1600 | 1000 | SCT 118/71/58/190/22G28 |
| | | | | 1300 | CLR 126/80/56/220/18G22 |
| | | | | 1400 | Pressure minimum; wind shift; frontal passage |
| | | | | 1600 | 250-OVC 155/64/46/350/20G24 |
| | | | | 1900 | 80 SCT 250-OVC 207/46/38/340/18 |
| | | | | 2200 | 13 OVC 224/45/36/360/18 |

TABLE 3. Selected observations (in SAO format) at OKC for four cases of strong warming at GPA. $T_o$ is the time of occurrence of the event at GPA.

| Case | Change | Date | To (CST) | Time (hours) | SAO |
|---|---|---|---|---|---|
| 1 | (+12°F) | (14 Dec 1977) | 0200 | 2000 | (2–13) 250-SCT 117/54/35/220/05 |
| | | | | 2300 | (2–13) 250-SCT 113/51/38/190/08 |
| | | | | 0100 | Pressure minimum |
| | | | | 0200 | 250-BKN 124/49/35/330/11 |
| | | | | 0500 | 80 BKN 250 OVC 159/48/29/360/22G31 |
| | | | | 0800 | 80 BKN 250 OVC 197/43/29/360/20G27 |
| 6 | +9°F | 24 Apr 1978 | 2400 | 1600 | Pressure minimum |
| | | | | 1800 | 120 SCT 250 SCT 176/73/34/350/15 |
| | | | | 2100 | CLR 183/63/33/010/07 |
| | | | | 2400 | CLR 208/57/35/020/12 |
| | | | | 0300 | (4–25) CLR 223/50/36/360/07 |
| | | | | 0600 | (4–25) CLR 224/43/37/350/10 |
| 14 | +8°F | 1 Oct 1981 | 0100 | 1700 | (9–30) Pressure minimum |
| | | | | 1900 | (9–30) 250-BKN 130/85/53/160/09 |
| | | | | 2200 | (9–30) 250-BKN 143/74/57/160/09 |
| | | | | 0100 | 29 SCT 250-BKN 165/74/58/300/17G31 Wind shift; frontal passage |
| | | | | 0400 | 50 OVC 178/67/57/360/16G23 |
| | | | | 0700 | 30 OVC 189/62/49/360/18 |
| 15 | +12°F | 7 Mar 1984 | 2300 | 1700 | CLR 167/63/17/240/13 Pressure minimum |
| | | | | 2000 | 200-SCT 173/54/19/180/05 |
| | | | | 2300 | CLR 191/49/21/230/05 Wind shift; Frontal passage |
| | | | | 0200 | (3–8) CLR 227/45/29/360/12 |
| | | | | 0500 | (3–8) CLR 248/35/22/360/14 |

cause there is no evidence for a strong horizontal temperature gradient over a broad region, as shown in Figs. 6 and 8. Nor is there such evidence in the time series of observations at OKC as seen in Fig. 5. Further, the surface potential temperature at the end of the rise represents the lower limit of the potential temperature of the imputed cold air, so that little horizontal contrast above the inversion is likely.

Theoretically, moreover, Hoskins and Bretherton (1972) have shown that a collapse toward discontinuity as required for a front is likely to occur only at a solid surface where the opposing thermodynamic effect of adiabatic temperature changes is precluded. It could be argued that the surface inversion resists vertical displacement almost as much as a solid surface does, but even a small vertical displacement in the presence of strong stratification would produce substantial adiabatic effects. Thus, there is little support for the idea of a front above the surface inversion. In all cases, however, strong nocturnal cooling at GPA preceded a warming instance. This condition was absent at OKC, where the somewhat elevated anemometer recorded substantially stronger average surface winds, tending to maintain a mixed layer. The evidence indicates that the wind was northerly at the time of these instances, so that transport of warm air from OKC to GPA could have contributed to the phenomenon. In the absence of recorded wind data at GPA it is not possible to assess the importance of horizontal temperature advection.

We trust that this paper will not be the last nor most comprehensive to report on these structures in the surface boundary layer. Currently in Oklahoma, data from 114 well-distributed surface stations, all reporting at least the usual set of meteorological observations, are recorded centrally at 15-min intervals. Data include temperature and wind averages and peak gusts during 5-min intervals. More than 3 yr of observations are already logged and promise to be the richest source of mesoscale surface data ever archived (Oklahoma Climatological Survey 1996).

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