A Case for Detailed Surface Analysis

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Abstract

Detailed analysis of the temperature and moisture fields based on routine hourly surface observations in North America can provide a rational basis for surface feature analysis, thus clarifying the present confusion. Recognition of surface features is an important part of weather forecasting and is especially needed in a careful diagnosis for the prospects of deep convection.

Surface temperature gradients are advocated as the primary basis for identifying fronts; examples are given of gross discrepancies in current operational practice between the surface temperature fields and the associated frontal analyses. Surface potential temperature, selected as a means of compensating for elevation differences, is analyzed in the western United States for a period in which a strong, damaging cold front develops and dissipates over a period of less than 24 h. Frontogenesis-related calculations, based on detailed surface temperature analyses, help to explain a case of focusing of heavy precipitation in northern Kentucky that produced a flash flood.

Conditions for the initiation of intense convection are illustrated by detailed analyses of the surface moisture and temperature fields. These are used to estimate the buoyancy of surface air lifted to midtroposphere and show the relationship of this buoyancy to ensuing convection. The analyses aid in recognition of the surface dryline (a feature commonly misanalyzed as a cold front) and those convectively produced pools of cold air at the surface that often play a major role in the subsequent redevelopment of convection.

The proposed analyses might be difficult to achieve manually in operational practice during busy weather situations, but this could be facilitated by using objective methods with present and prospective workstations. Once surface features are identified, their temporal and spatial evolution must be followed carefully since they can change rapidly.

1. Introduction

The perception that current surface analyses are often unsatisfactory is widely shared (e.g., Young and Fritsch 1989; Mass 1991). This problem was the topic of a 1991 workshop convened at the National Meteorological Center (NMC), with results reported by Uccellini et al. (1992). In hopes of contributing toward improvement of the situation, we are urging the routine analysis of surface temperature as a basis for surface frontal analysis, as a guide in the forecasting of deep convection, and for other short-term forecast applications. In current operational practice, temperature analyses are performed at all other standard levels but surface isotherms and isodrosotherms (or some other representation of humidity) are not routinely disseminated. Their appearance even in research analyses is surprisingly infrequent.

Given the abundance of surface observations over midlatitude land areas, this lack seems ironic in view of the considerable public interest in the current weather (Cressman 1971), and especially the temperature, which often headlines public weather messages. Surface isotherms, moreover, are typically included in forecast maps appearing in the media.

The neglect of surface temperature analysis probably has its origin in the perception, exemplified by Petterssen (1940, p. 7), that "[surface temperature] is often neither representative nor conservative. It is not representative because of many local or orographic influences, and it is not conservative on account of the preponderance of nonadiabatic irreversible processes in the air close to the earth's surface."

The apparent meaning of representative in Petterssen's view is that the quantity in question is "characteristic of an entire air mass or a large portion thereof." Although the concept of a broad air mass with nearly uniform properties in middle and high latitudes is no longer taken literally by most analysts, "representative" clearly refers to some large scale, perhaps the scale of migratory cyclones and anticyclones. Since we are now much concerned with the mesoscale, however, the concept needs rethinking. What formerly was considered nonrepresentative may be viewed now as representative of a *mesoscale* system. Local and orographic influences are strongly influential on mesoscale structure and thus are now thought to be processes to be diagnosed rather than disregarded. The conservative character of a variable is not a requirement for its analysis. Pressure, temperature at upper levels, clouds, and precipitation are not conserved following the air motion, of course, but are analyzed widely nevertheless. The bases for declining

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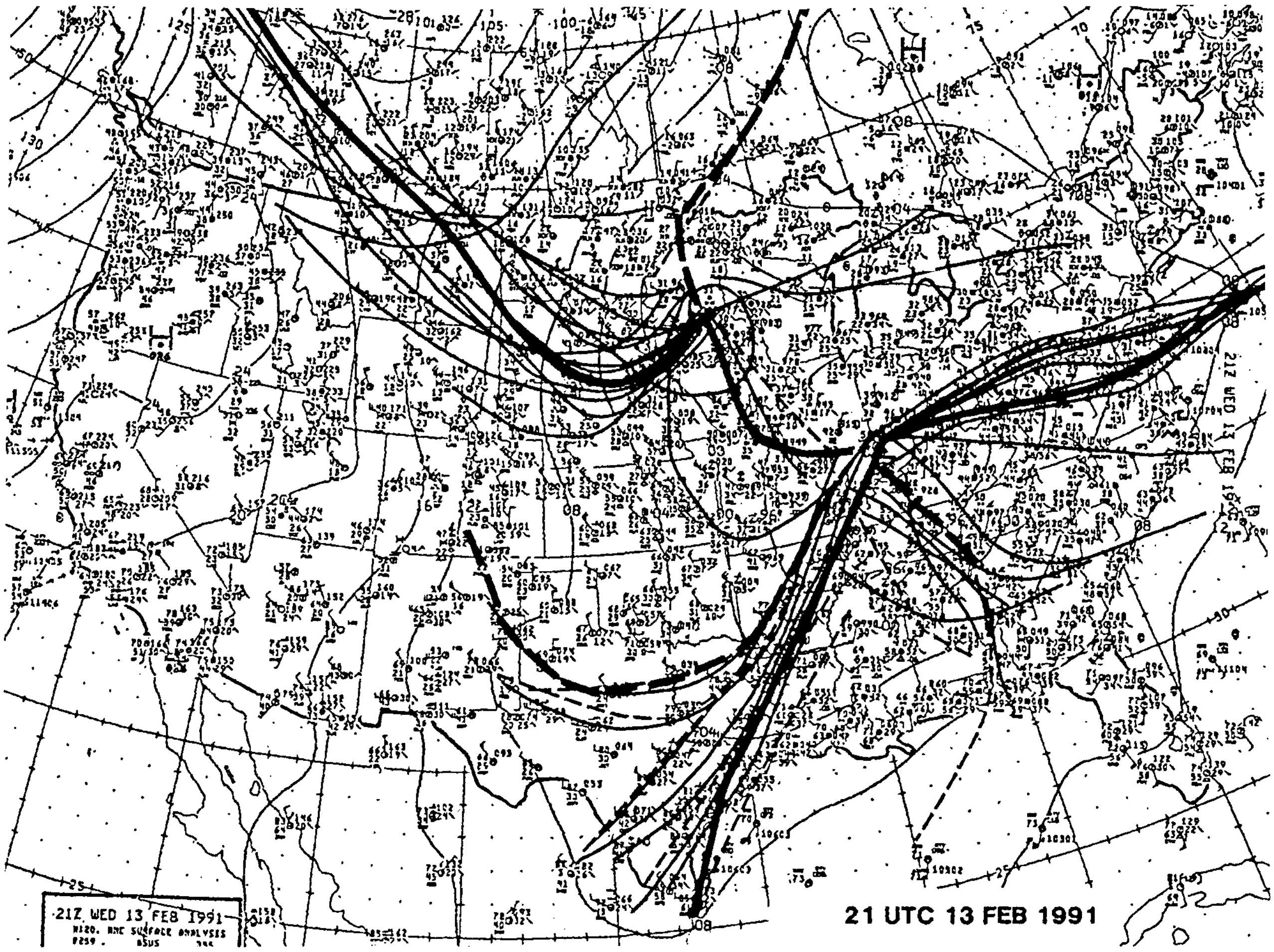

FIG. 1. NMC North American surface data plot for 2100 UTC 13 February 1991, with fronts and troughs as analyzed by workshop participants (from Uccellini et al. 1992; used with permission).

to deal with surface temperature analyses, therefore, do not now seem to be valid.

We acknowledge, on the other hand, the value in analysis of elements that are conservative for adiabatic conditions. In regions of significantly variable surface elevation, use of potential temperature enables a distinction to be made between diabatic heating or cooling and adiabatic temperature changes resulting from flow along the slope of the terrain. Similarly, the analysis of specific humidity or mixing ratio enables the analyst to distinguish between the effects of true gains or losses of water vapor by the air parcel and the relatively modest changes in dewpoint that occur solely due to changes in parcel elevation.[1] Computation of potential temperature and, say, mixing ratio is quite simple today. Thus, we feel that (i) good reasons no longer exist for not tapping the rich vein of information in the surface thermodynamic and moisture observations and (ii) doing appropriate analyses will add precision and utility to surface analyses. In particular, we will describe benefits expected to result from two classes of applications.

2. Surface feature analysis

A composite of the independent frontal analyses prepared during the 1991 workshop (Uccellini et al. 1992) by each of the assembled experts appears in Fig. 1. The wide range of positions determined by individuals (including the operational NMC analysis shown by the heavy lines) reflects the present state of confusion even in a region of dense data coverage. Some, but by no means all, analyzed fronts in Fig. 1 lie near the warm boundary of a zone of strong surface temperature contrast (the primary determinant of density contrast), evidently showing that not all the partici-

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[1] Of course, in regions with little or no variation in surface elevation, the difference between temperature and potential temperature (or dewpoint and mixing ratio) becomes moot.

pants viewed the thermal contrast as adequate. It appears that other, indirect means of identifying fronts (including wind shifts, pressure troughs and tendency contrasts, dewpoints, and clouds and precipitation) were being used. But these various indirect indications are weighted differently by different individuals, leading to a plethora of frontal positions. Similar disagreement between the frontal analyses produced simultaneously at a number of weather centers was demonstrated by Renard and Clarke (1965) for a hemispheric case in 1964, so the problem is not a new one.

Present guidelines for frontal analysis, as quoted from *NWS Forecasting Handbook No. 1* (1979) by Uccellini et al. (1992), refer to "vertical consistency" as an important guideline. This consideration evidently serves the goal of inferring the flow aloft from the surface analysis, by assuring vertical consistency between surface fronts and upper-level baroclinic zones/jets. Hence, strong horizontal contrasts of surface temperature are discounted sometimes on the basis that they are too shallow to have an impact on the structure aloft. We believe that these guidelines are not now appropriate, given the present and prospective database. The analysis of the flow aloft, based on aircraft, satellite, and profiler observations, in addition to rawinsondes, no longer depends on the surface frontal analysis.

Details of the surface temperature pattern within the boundary layer nevertheless are important in themselves. Indeed, Sanders (1955) showed that an intense surface front in the central United States weakened substantially immediately above the surface. This typical structure was explained by Hoskins and Bretherton (1972), who showed analytically the dynamical importance of a surface boundary. Only at the surface, where the reinforcement of confluent geostrophic frontogenesis by the accompanying ageostrophic flow is not opposed by the frontolytic effect of the vertical circulation, can the temperature gradient develop toward discontinuity in finite time. It appears that processes other than geostrophic confluence that tend to strengthen horizontal temperature (thus density) contrasts, specifically diabatic and frictional ones, also will tend to produce discontinuities in this way only at or very near the surface. The importance of surface temperature analysis is thus reinforced.

The 1979 guidelines also refer to "continuity, [and] persistence." We take this to mean that the analyzed front should appear on a number of consecutive maps at 3-h intervals, preferably constituting a life history of days. Theory and close observation, however, indicate that the timescale of significant frontogenesis can be *hours* rather than days. We do not wish to reject continuity of the gradient as a criterion but we wish to deemphasize its importance, especially on timescales less than 12 h.

Finally, the 1979 guidelines refer to "the evidence of satellite pictures," but the imagery, while effective for locating cyclone centers, especially at sea, rarely indicates specifically the position of a front and generally displays much more banded structure than could be explained by any reasonable number of fronts. Satellite imagery certainly can be helpful but it also can obfuscate the analysis, and its information should not be the primary driver in frontal analysis, except perhaps in the absence of all other supporting data.

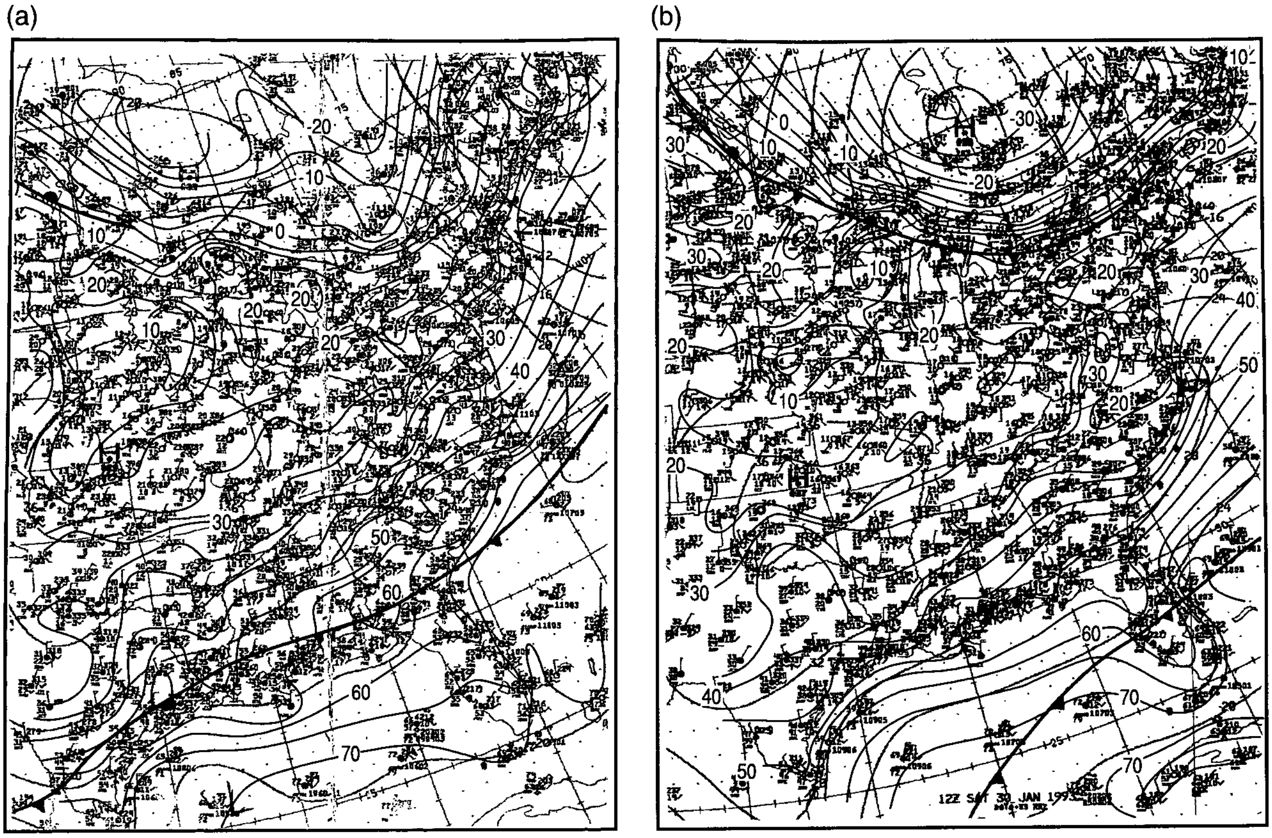
We choose to stand by the classical definition of a true front as a density "discontinuity," reflected in the surface data as a strong thermal gradient, with the front located by convention on the warm side of the gradient zone. The main point is that we wish to characterize boundaries as *nonfrontal* if there is *not* an associated strong thermal gradient.

At times, the surface boundary layer in which surface observations are taken is, indeed, not representative of the deep troposphere above. Whereas features characterized by deep tropospheric baroclinity typically are well reflected in the surface data, this is not always the case. Basically, we are advocating using *surface data* to guide the *surface analysis.* If features extending through much of the troposphere are reflected in the surface data, then they should be depicted. However, if they do *not* show up clearly in the surface observations, then we think that those features should not be added to the surface analysis simply because they are present aloft.

a. Current operational analyses

To provide some experience in surface temperature analysis and to see the extent to which current operational frontal analysis is consistent with it, we added isotherms to NMC surface maps. We chose to examine these not because we believe the NMC frontal analyses to be uniquely unsatisfactory but rather because they are most readily and widely available. It is our experience that an extensive series of analyses from nearly any other source, whether it is an operational center, a research laboratory, or a university department, typically will show comparable characteristics.

Specifically, isotherms at intervals of 5°F were added to the North American surface analyses received on DIFAX (digital facsimile circuit) at or near 0000 and 1200 UTC, from 20 January to 5 March 1993. Analyzed fronts often corresponded with strong analyzed temperature gradients, but many were not so supported and many regions of strong gradient were not denoted.



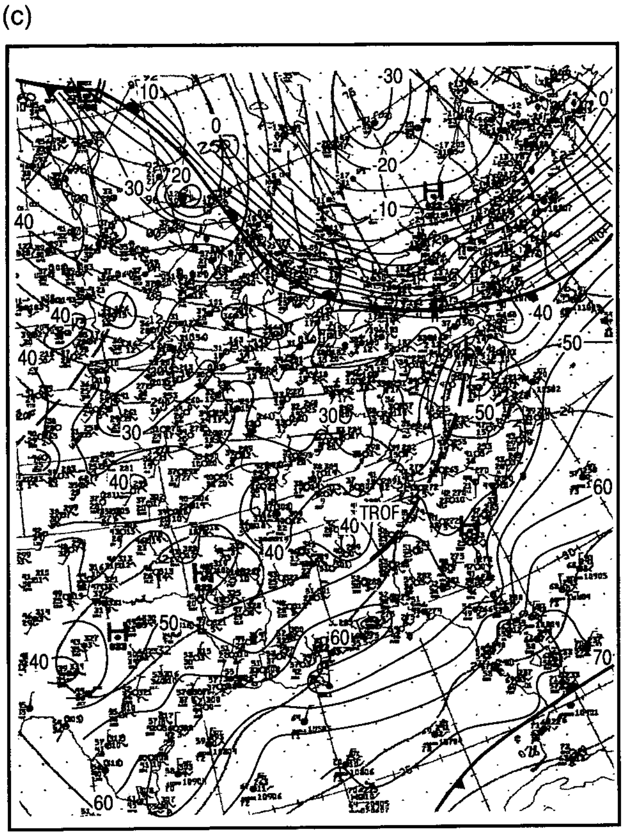


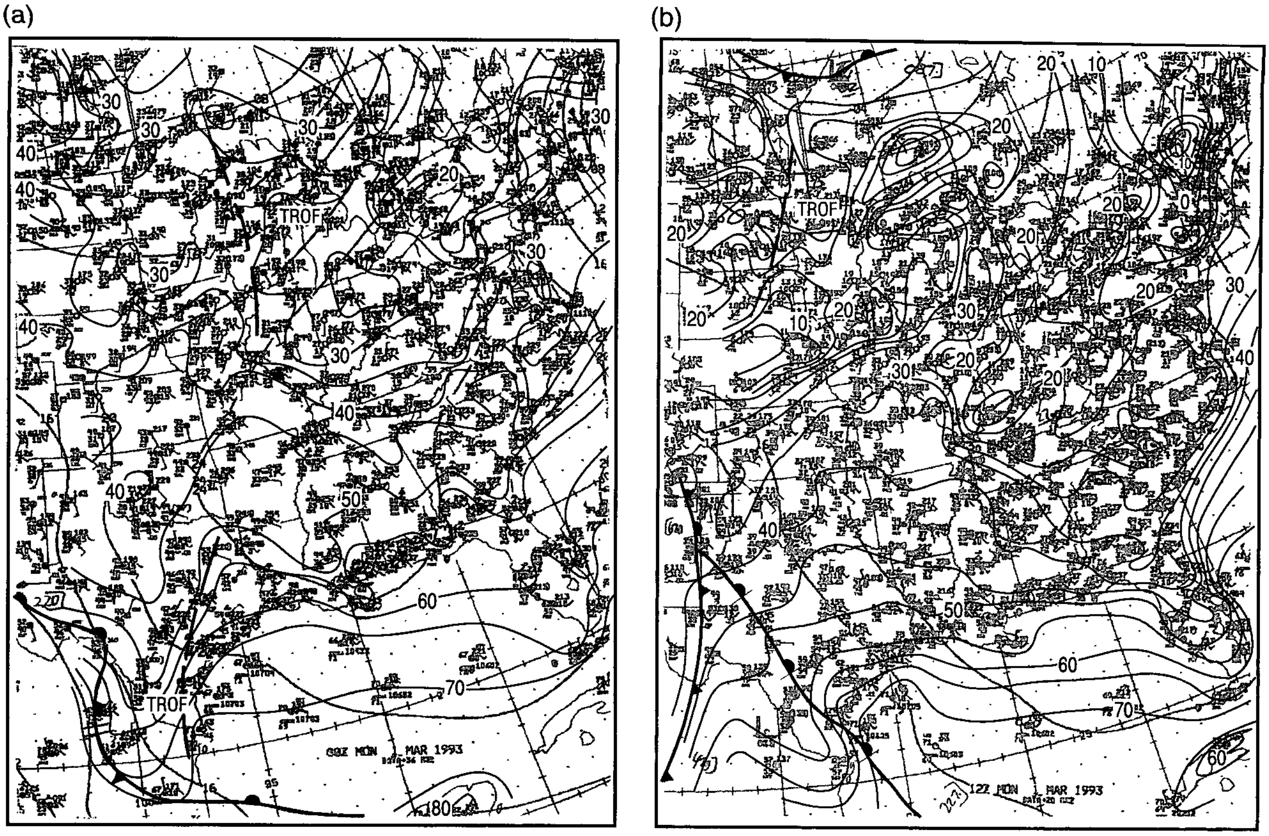
FIG. 2. NMC surface analyses with isotherms added for (a) 0000 UTC, (b) 1200 UTC 30 January, and (c) 0000 UTC 31 January 1993.

The case shown in Fig. 2 displays an intense gradient north of the Great Lakes that is not recognized as a front initially (Fig. 2a). By the next chart (Fig. 2b), 12 h later, this front is added to the chart in the proper position at the leading edge (i.e., the warm side) of the zone of thermal contrast. To the southeast, the front offshore over the Atlantic matches the isotherms satisfactorily in Fig. 2a, but just north of the Gulf Coast the analyzed front lies in a region of weak gradient from southern Georgia to eastern Texas, avoiding relatively strong gradients to the north and offshore. The analyzed front moves southward 800–1100 km during the next 24 h (Figs. 2b,c), while the isotherms move only 250 km or less.

A case of little correspondence between fronts and isotherms shows a trough of cool air in the lower Rio Grande valley (Fig. 3a), warming slowly, as first an analyzed warm front (Figs. 3a,b) and then an analyzed cold/occluded front (Fig. 3c) appear to pass through it with little effect. A strong gradient near the Texas Gulf Coast is first denoted as a trough ("trof"), then by nothing, and finally by a cold front as a new low forms in southeastern Texas. The warm front extending southward from this low runs through a region of homogeneous air over the Gulf. Although this is an extreme example, it is not an isolated one.

No other fronts were analyzed on these maps, except for a cold front in central Canada (Figs. 3b,c)

(a) (b)



(c)

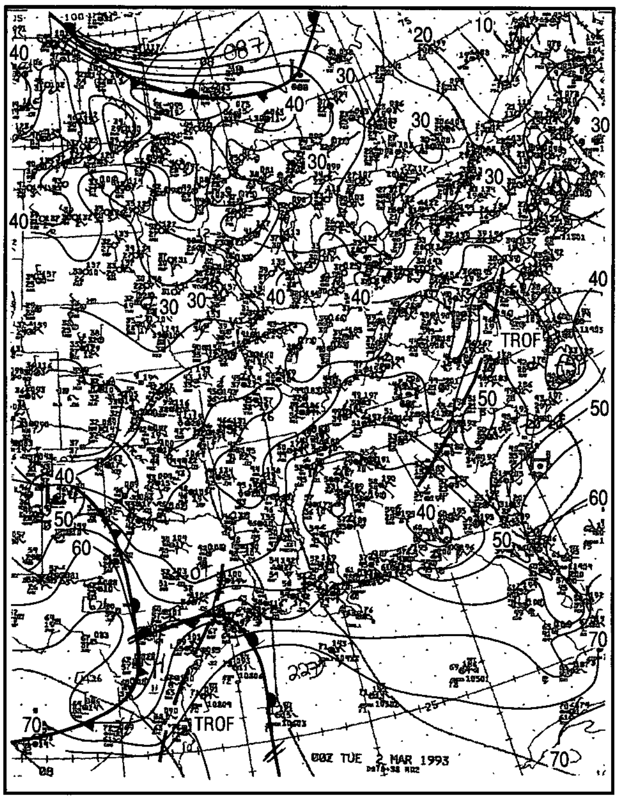


FIG. 3. Same as Fig. 2 but for (a) 0000 and (b) 1200 UTC 1 March, and (c) 0000 UTC 2 March 1993.

analyzed slightly to the south of its associated thermal gradient. There is, however, a persistent moderate (0000 UTC)-to-strong (1200 UTC) contrast between the cold air along the East Coast from the Carolinas to Florida and the relatively warm air over the Gulf Stream (itself substantially colder than the sea surface). There is also a systematic contrast between colder air over Nebraska, Iowa, Illinois, and Indiana and warmer air to the south. This zone, notably stronger at the end of the night than shortly after sunset, persists for at least 24 h (Figs. 3a–c) before dissipating (Fig. 3c). Further, there is a moderate-to-strong gradient south of a pool of cold air centered in northern Maine and southern Quebec, also varying diurnally. Why should these contrasts not be considered as important as traditional fronts?

b. The source of the problem

We believe that the root of the problem of frontal analysis is reliance on the indirect indications listed above, and it is our assertion that they are an improper basis for frontal analysis. Let us consider them individually.

1) PRESSURE TROUGH

Meteorological textbooks show that if a front constitutes a zero-order discontinuity in temperature while sloping upward toward the colder air, then it must be accompanied by a first-order discontinuity in pressure. Any isobar crossing the front must display a "kink" in the sense of a sharp trough, according to this simple theory.

On maps, however, we typically see extended zones of relatively strong temperature gradient rather than discontinuities. That is to say, the temperature can be regarded as showing first-order discontinuities at the boundaries of a frontal zone, with the front depicted by convention at the warm edge. Godson (1951) showed that in this case there is a *second-order* discontinuity in pressure at the front. In practical terms, the requirement is that an isobar crossing the frontal zone of strong gradient must be curved more sharply in the sense of cyclonic geostrophic flow, or less sharply in the anticyclonic sense, within the zone than without. The frontal zone may lie in a trough or perhaps in a flat spot within a ridge. On the other hand, many troughs on surface maps have no relationship to zones of strong temperature contrast.

2) Surface pressure tendency

Although pressure tendencies at the surface are influenced hydrostatically by low-level temperature changes, pressure changes do not imply the presence of a surface front. Surface pressure change is a secondary characteristic of moving or changing thermal gradients, derived primarily from the movement of the implied pressure trough. It is possible that the isallobaric accelerations associated with pressure changes would generate frontogenetical surface flows that could strengthen a weak thermal gradient, but in such a case the front should be identified by the isotherms, not the pressure tendencies themselves. Tendencies might have value in rendering more precise the location of a cold front already located approximately from an analysis of the temperature field, provided it is clear that the pressure rise is associated with the temperature drop.

3) Wind shifts

Wind shifts are another secondary characteristic of zones of strong temperature gradient, contingent on the extent to which the wind responds to the pressure trough. It often appears, however, that one or more wind shifts precede the zone of temperature contrast in cold fronts, as illustrated in the above examples. Although the nature of these prefrontal shifts is not firmly established, it is clear that a wind shift alone cannot be a reliable basis for locating fronts. For a cold front situation in which the wind at a surface observation site has just shifted but the temperature has scarcely begun to fall, however, the shift *can* add precision to the frontal location.

Lines of wind shifts with no proximity to bands of strong temperature contrast, moreover, appear relatively often on surface charts (Doswell 1982). The origins of such lines are not typically well known and they may arise from more than one source. The widespread practice of analyzing fronts along such wind shifts is not appropriate. Such lines, including prefrontal wind shifts, should be denoted in some manner to distinguish them from true fronts and other surface boundaries.

4) Dewpoint differences

Although dewpoint variation has a slight effect on density gradient, it sometimes is regarded as a characteristic of fronts. That is, warm air is sometimes systematically moister, or systematically drier, than cold air. Even in these cases, though, it is not even a secondary characteristic as pressure and wind fields are, since the latter can be derived from the fundamentally important temperature field through the assumption, as above, that discontinuities are present. Moisture is quasi-independent of temperature, so its distribution cannot be inferred in any way from the thermal field, or vice versa. At best, dewpoint could be regarded as a *tertiary* characteristic, perhaps used like wind shift and pressure rise to refine the position of a cold front defined primarily by the temperature field. The dryline (discussed below) is an example of a distinctly nonfrontal moisture discontinuity.

5) Clouds and precipitation

If the connection between dewpoints and fronts is tenuous, the association of clouds and precipitation with fronts is even more so. We know of no consistent connection between fronts determined from the surface temperature field and attendant weather, the popular association reflected in the media notwithstanding. The problem is that these phenomena are not uniquely located with respect to zones of thermal contrast. Precipitation is found sometimes only on the cold side of the zone, sometimes just on the warm side, and sometimes well out into the warmer air. On occasions when the air is very dry, there may be no precipitation at all and few if any clouds, anywhere near the zone. The occurrence of cloud lines along fronts is rather sporadic at best, and it is not always the case that such cloud lines are located specifically on the warm side of the zone of thermal contrast. Thus, there is no justification for locating a frontal zone solely on the basis of these weather elements.

c. A proposed methodology

Accordingly, it is proposed that in routine analysis the entry of frontal symbology be delayed and that first a close analysis be made of the field of surface temperature (or potential temperature, in regions with notable variations in elevation). This idea certainly is not altogether new, as Renard and Clarke (1965) and Clarke and Renard (1966) have described experiments in automated calculation of first and second derivatives of the potential temperature field on constant-pressure surfaces as a basis for determination of frontal analysis at upper levels over the Northern Hemisphere. Unfortunately, they avoided use of the surface observations because of "nonrepresentativeness." We believe a similar technique, measuring only first derivatives, could be applied profitably to identify surface fronts using the abundant surface temperature data. Over North America, the hourly surface observations should be an adequate basis for determination of horizontal gradient in terms of differences over about 100 km.

1) North American surface analysis

We have performed a North American surface analysis, the first example of which is shown in Fig. 4. The regions of intense gradient show maxima reaching about 10 K $(100\text{ km})^{-1}$, five times the maxima found by Renard and Clarke (1965). There are at least two reasons for this: 1) surface observations are more dense than the sounding network, and 2) there are dynamical reasons to expect surface boundaries to be more intense than those aloft, as discussed in section 2. The NMC operational frontal analysis is added. Of the three NMC-analyzed cold fronts, the zonally oriented one shows relatively good agreement with the temperature gradient, although it lies north of the warm boundary of the baroclinic zone initially. Note, however, that the front is weaker and less continuous at 1200 (Figs. 4b, 4d) than at 0000 UTC (Figs. 4a, 4c), mainly because of a strong diurnal temperature cycle in the warm air. At 1200 UTC on 26 March the patch of strong gradient centered near northeastern Colorado forms in situ as a result of strong nocturnal cooling of the warm air immediately after 0000 UTC and is independent of the front 12 h earlier and later.

The more meridionally oriented cold front shows poor agreement with the temperature field. The warm edge of some regions of strong gradient lies along the front at some places and times, but weak gradient accompanies much of it. For example, relatively good agreement between the analyzed front and the thermal gradient is centered near the Four Corners region at 1200 UTC on 26 March. The strong gradient is seen on the intermediate 3-h series of maps (not shown) to move slowly to the NNE, reaching western Colorado by 0000 UTC on 27 March. The analyzed front, on the other hand, moves far to the east during this interval.

The very strong band of gradient in central New Mexico at 0000 UTC on 27 March is shown by the same 3-h intermediate maps to form rapidly in southern Arizona about 6 h earlier, well to the west of the analyzed front. The band then moves rapidly eastward, almost but not quite overtaking the NMC-analyzed front by 0000 UTC. At 1200 UTC on 27 March, there is no sign of the strong gradient of 12 h earlier, and the NMC cold front may have been analyzed mainly on the basis of dewpoint contrasts.

The intense gradient east of the lower Rio Grande valley at 0000 UTC on both days is an important diurnally varying feature responsible for the particularly strong surface winds along the Texas Gulf Coast at that time. The air with a trajectory recently over the Gulf of Mexico does not share the intense heating of air farther inland, the phenomenon being akin to a sea breeze. It is reasonable to recognize the warm boundary of this zone of contrast as a front, even though it dissipates at night. If the wind shift at the warm edge were sufficiently sharp, there would be general agreement that it constitutes a "sea-breeze front."

All nonfrontal features should be denoted in some way that distinguishes them from true fronts. We have discussed some of the features in the data that are nonfrontal, like wind shift lines not accompanied by thermal gradients. In section 3, we describe the dryline and what distinguishes it from a true front, as well as some guidelines for distinguishing convective outflow boundaries from fronts (although this distinction can become quite blurry).

The problem of feature analysis over the data-sparse oceans is not easily resolved. The sea surface temperature field strongly influences the surface boundary layer in which surface observations are taken over the oceans. Oceanic surface analysis often may not reveal deep tropospheric structures that might be identified readily in operational numerical model diagnostic fields and/or analyses above the surface. This apparent discordance is, we believe, an acceptable result of using surface *data* to drive surface *analyses,* irrespective of the anguish this might cause some.

2) Frontal analysis

To draw attention to prominent features of the field for the benefit of meteorologists and clients, frontal notation could be added to the completed temperature analysis, at the warm boundary of bands of sufficient strength and longevity. The quantitative limits of sufficiency might be obtained by experience, and we are not prepared to impose such limits arbitrarily here, but any reasonable choice would be an improvement on current examples that bear no consistent relationship to the temperature field. When a zone of strong gradient is attributable to a single observation, and no other information is available, it seems best not to

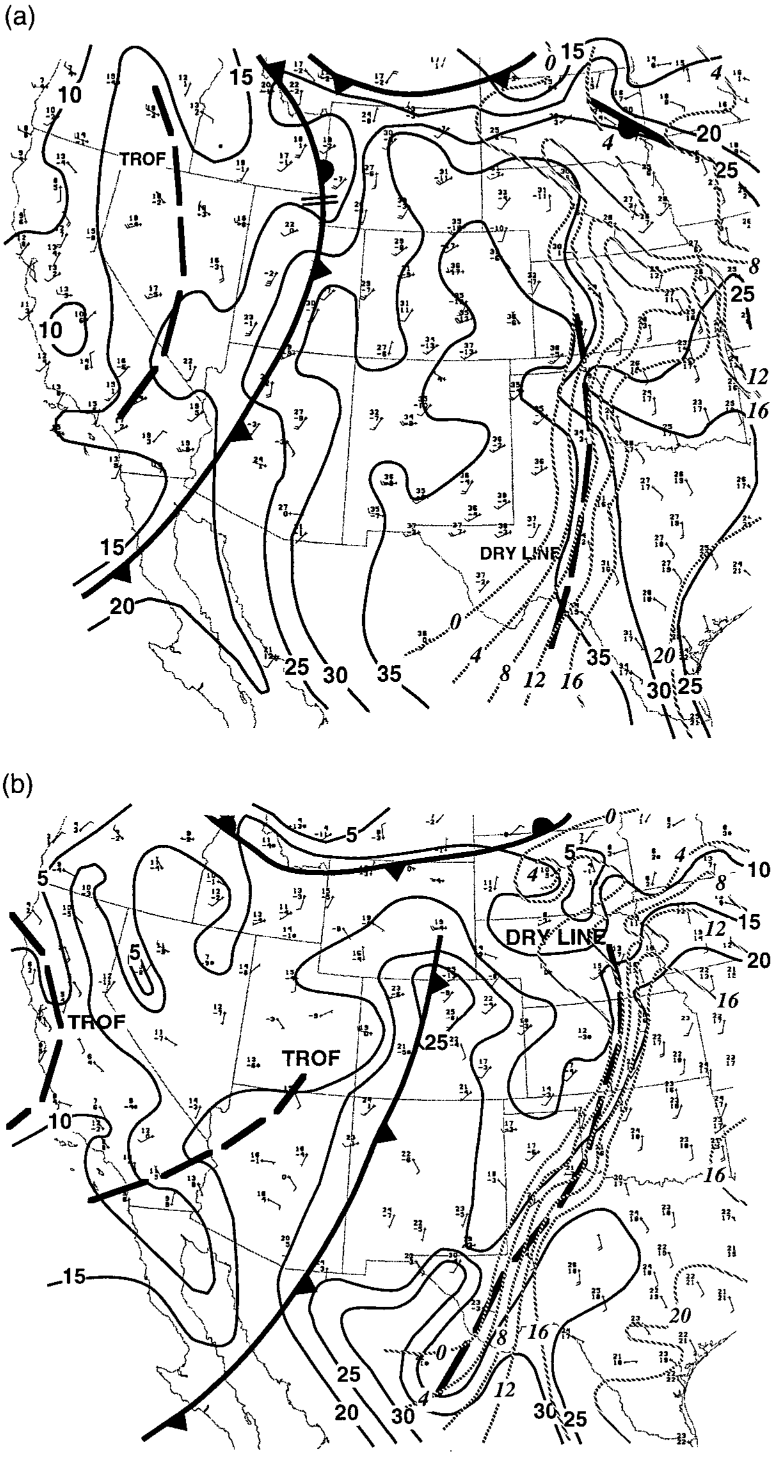


FIG. 4a,b. Station plots of surface potential temperature (°C) and wind (standard notation) with 4°C isotherms (solid) for (a) 0000 and (b) 1200 UTC 26 March. Features (i.e., fronts and trofs) identified by NMC are indicated with standard notation. Solid lines are isentropes at intervals of 5°C, and hatched lines are isodrosotherms at intervals of 4°C, starting at 0°C.

denote it a front, because the extent of the feature may be meters rather than 10s or 100s of kilometers.

Persistent zones of strong potential temperature contrast in Fig. 4 lie along the western slopes of the Sierra Nevada in California and of the Sierra Madre Occidental in Mexico. These reflect the vertical stratification as well as horizontal contrast, and it is not obvious how they should best be represented. The problem is that the vertical gradient of potential temperature does not imply the potential for developing frontal circulations that the horizontal gradient does. Without some way of observing or estimating the stratification, the two contributions to the observed surface gradient cannot be separated. During the daytime, it sometimes can be assumed that the layer from the lower to the higher elevation is well mixed, in which case the variation along the sloping surface also represents horizontal variation.

d. Frontogenetical calculations

The component of geostrophic flow normal to the isotherms is important in diagnosis of vertical motion, with temperature fields in general via quasi-geostrophic theory, and with 2D frontal temperature fields in particular via semigeostrophic theory. Thus, measurements of this component's gradient normal to the isotherms can be made via finite differences. Confluent variation of this component across the core of a band of strong gradient, for example, would imply further (frontogenetical) strengthening and a thermally direct ageostrophic circulation (with warmer air rising relative to colder). Even when frontal intensity remains relatively constant with time, some confluence accompanied by a direct thermal circulation is probably necessary to maintain it against the dissipative effects of mixing. Direct diagnosis of frontogenesis might well be useful in surface analysis, since surface data are at relatively high resolution, even compared to fine-mesh operational numerical models of the near future, given that considerable smoothing is associated with initialization and data assimilation in such models.

An example of the possible effect of a frontogenetical circulation is illustrated in Fig. 5 for the case of a flash flood in Kentucky described by Kirkpatrick (1992). Note that the definition of the Petterssen frontogenesis function involves the magnitude of the thermal gradient, so that the seemingly straightforward frontogenesis calculations tend to show contours more or less coincident with the front itself. We believe it is more illuminating to consider the component of flow normal to the thermal gradient and the magnitude of the thermal gradient separately. Hence, Fig. 5 has been done to reflect this belief. A relatively weak frontal temperature gradient along the Kentucky–Tennessee border at the start of the 24-h period of particularly heavy rainfall strengthens by a factor of 2 by the end, while moving slowly to the south. The geostrophic confluence seen along the relevant part of the frontal zone is more than enough to account for the strengthening. The flooding rain fell in an elliptical band with the long axis parallel to the zone and somewhat to the north of it. The displacement is probably the consequence of the frontal zone's northward tilt, whereby ascent produces precipitation on the north side of the zone. The frontal diagnosis might have been used to modify the short-term nested grid model precipitation forecast (not shown), which showed an elongated maximum somewhat too far to the north and too weak by a factor of about 3.

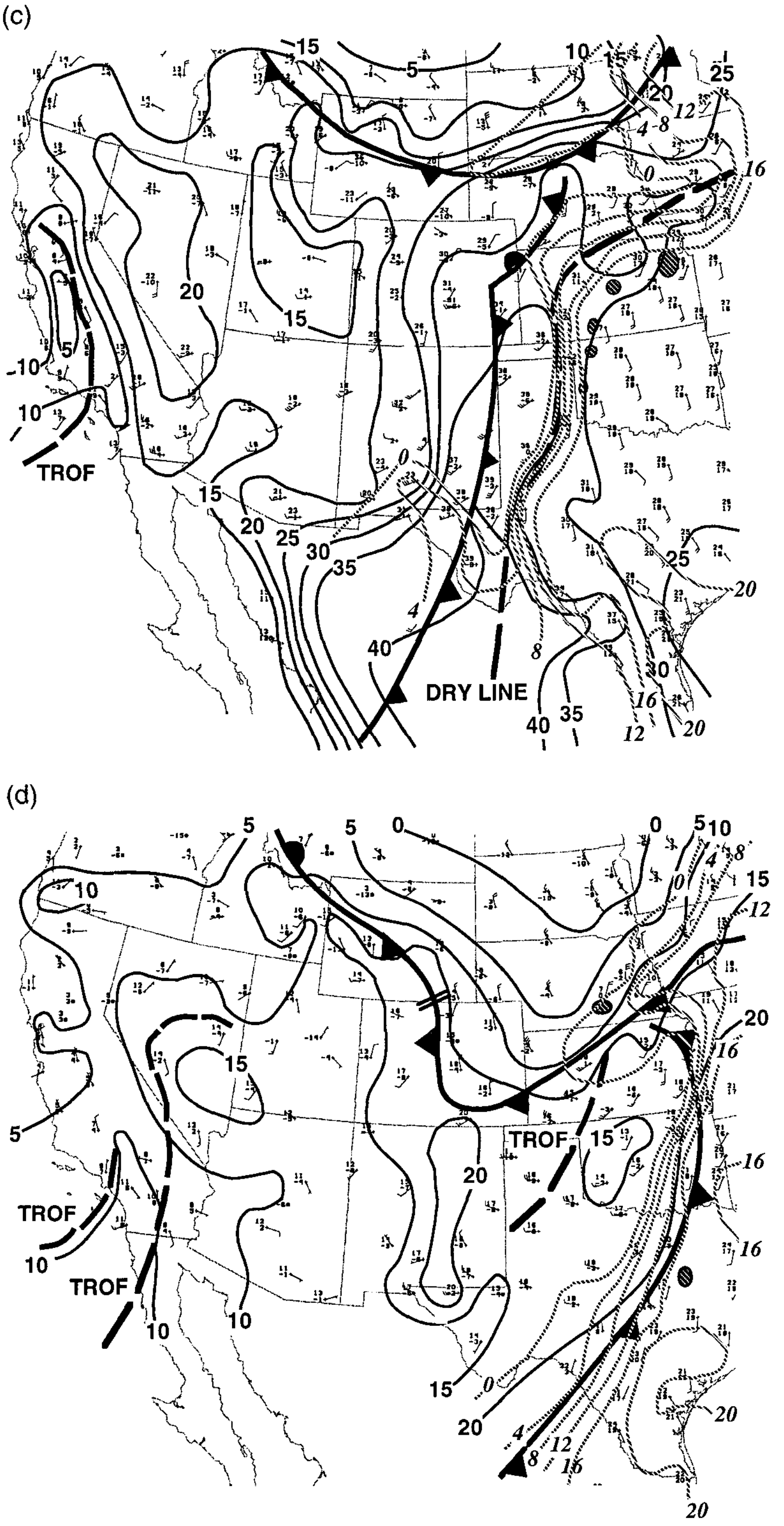


FIG. 4c,d. As in Fig. 4a,b except for (c) 0000 and (d) 1200 UTC 27 March 1991. Hatched areas are Video Integrator and Processor level 5 (VIP-5) (see Burgess and Lemon 1990, p. 626) echoes (51–57 dBZ) as reported on the radar summary charts 25 min before map times.

3. Analysis for prediction of deep convection

The value of a careful surface analysis in forecasting deep convection with roots in the boundary layer is especially great, because the features that influence the development of convective storms are often on the "subsynoptic" scale (i.e., well below the capability of the twice-daily rawinsonde network to resolve). Even with the new observing technology beginning to be available, no data source today other than the routine surface observations offers sufficient spatial coverage and temporal resolution to resolve sub-synoptic-scale features with reliability.

The hourly surface observations permit the detection and tracking of thermal plumes associated with conditional instability and of the important details of the moisture pattern that permits deep convection. Examples appear in Figs. 4b,c, and Figs. 6 and 7. A number of examples of association can be seen between small-scale features of the thermal and moisture fields and strong convective radar echoes or reports of thunder. When the two fields are combined to produce the distribution of temperature of parcels lifted to saturation and then to 500 mb (Hales and Doswell 1982), this form of wet-bulb potential temperature is useful in diagnosis of deep convection. The "surface-lifted index," which is the excess or deficit of this temperature relative to the ambient 500-mb temperature (Sanders 1986), is a measure of parcel buoyancy, a well-recognized ingredient for thunderstorm activity (e.g., Johns and Doswell 1992). Examples of these quantities appear in Figs. 6c,d and 7c,d.

The surface observations also allow analysis of initiating mechanisms that permit parcels to reach their level of free convection. These mechanisms (even for convection based in air above the boundary layer) often are detectable via convergence along various boundaries that can be seen in the surface data, including fronts (as discussed above), drylines, outflow boundaries, nonfrontal windshift lines, and pressure troughs. Some of these deserve special attention here.

a. The dryline

A dryline is a surface boundary between dry and moist air, such as the examples seen in Figs. 4, 6, and 7. In North America this boundary, which has been studied extensively by Schaefer (1974a,b), can be viewed in a broad sense as the result of the terrain rising to the west from the Mississippi Valley intersecting the top of the moist layer created by poleward flow off the Gulf of Mexico. A typical pair of soundings across the dryline is shown in Fig. 8. The large moisture difference at the surface almost disappears above an elevation of about 1.5 km, while the boundary meets the surface at this time (Fig. 5c) at the slightly lower elevation of about 1 km. Thus, horizontal moisture contrasts exist through a layer only about 500 m thick.

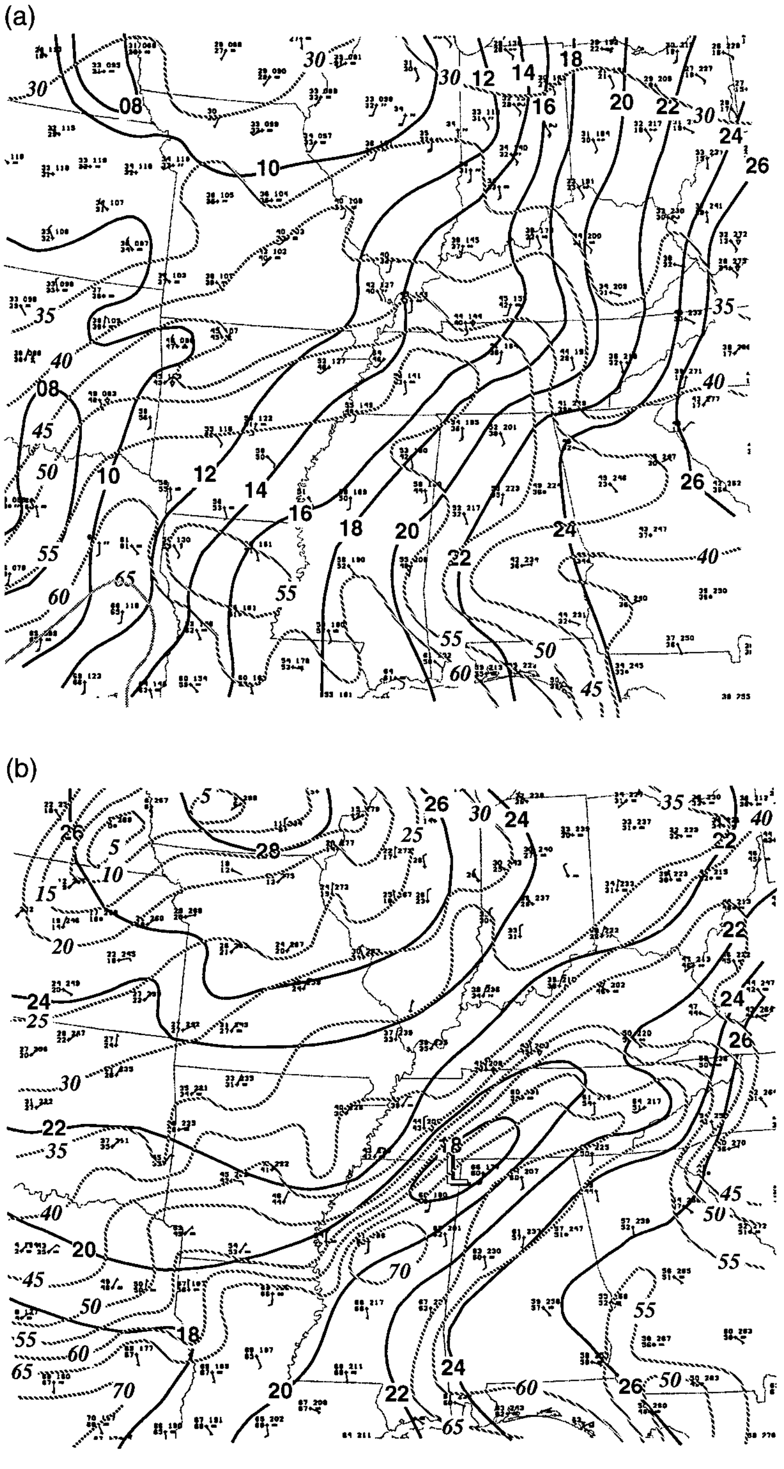


Fig. 5a,b. (a) Sea level isobars at intervals of 2 mb (dark lines) and surface isotherms at intervals of 5°F (hatched lines) for 1200 UTC 13 February 1989; (b) as in (a) but for 14 February.

To the west of this surface boundary lies the rain shadow of the Rockies, with high terrain and dry conditions. The persistent lack of moisture during much of the year here favors a deep daytime boundary layer with a high-amplitude diurnal cycle and with well-mixed conditions extending to near 500 mb during the afternoon (Fig. 8a). On the other side of the surface dryline, low-level moisture is high, tending to reduce the amplitude of the diurnal heating and cooling cycle (Fig. 8b). The result is a boundary separating dry air to

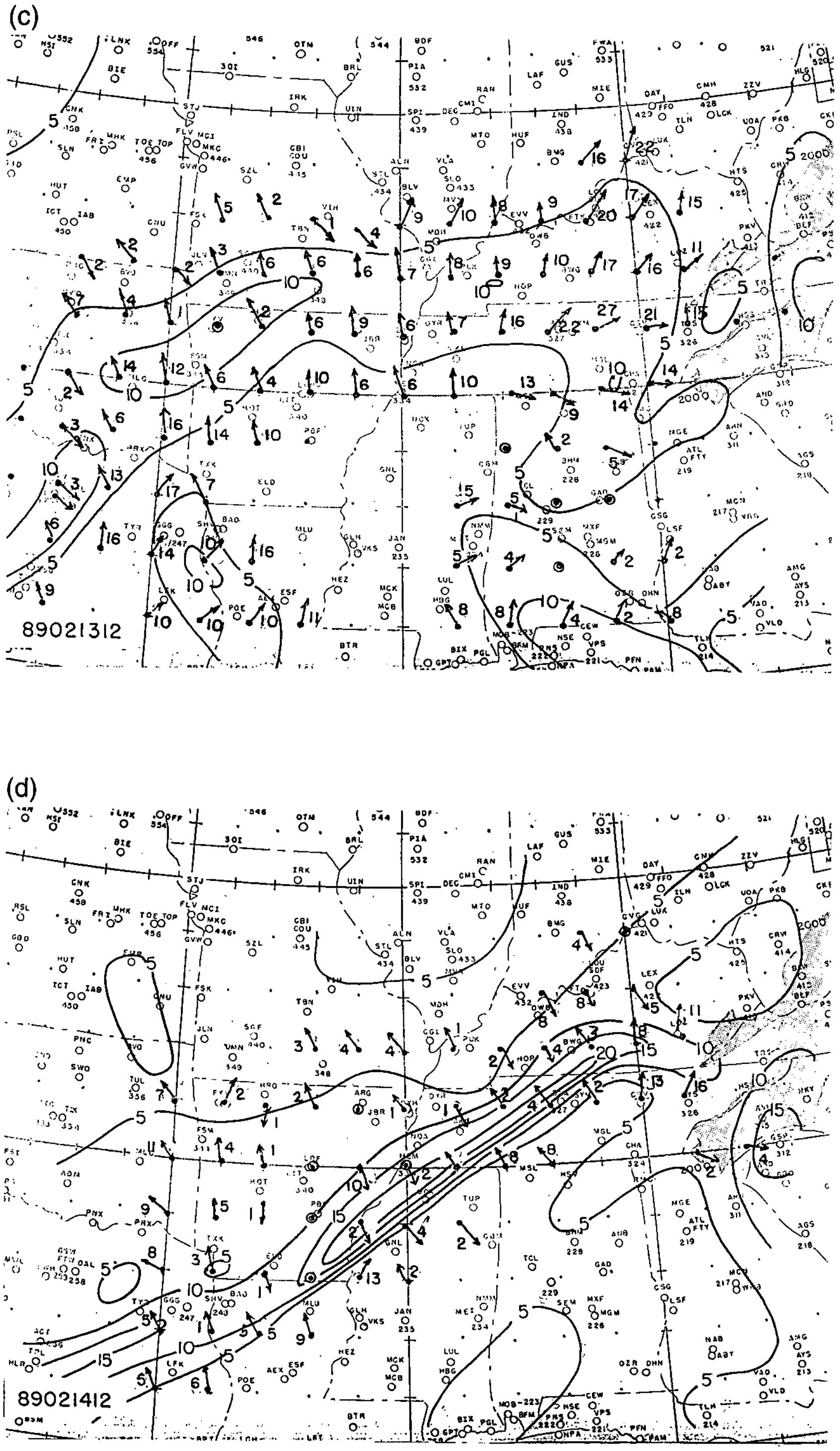


FIG. 5c,d. (c) Isopleths of the horizontal temperature difference (°F) across the front over a distance of 110 km (arrows indicate the sense of the geostrophic flow normal to the isotherms and the plotted number near each arrow is the magnitude of that geostrophic flow component in m s^{-1}, at 1200 UTC 13 February); (d) as in (c) but for 14 February.

the west, which is relatively hot during the day and cool during the night, from moist air on the east side, in which the diurnal temperature change is comparatively small. Thus, there is a diurnal reversal of the surface potential temperature gradient, as seen in Figs. 4, 6a, and 7a. As a contribution to density, the water vapor in the moist air counteracts the temperature difference during the day, increasing the virtual temperature on the cool, moist side of the boundary relative to that on the warm, dry side. This effect, however, *enhances* the density contrast at night.

Prediction of convection is more closely related to equivalent (or wet bulb) potential temperature than to surface density contrasts. A useful parameter is the surface-lifted temperature mentioned above, which has a one-to-one relationship to the other measures of equivalent potential temperature, provided the lifted air reaches saturation before arriving at the reference level. This is almost always the case when the reference level is 500 mb. Any of these quantities that are conserved for adiabatic processes typically do not show a diurnal reversal, as seen in Figs. 6c and 7c. In Fig. 8, surface-lifted parcel temperatures are slightly lower at Amarillo, Texas (AMA), than at Norman, Oklahoma (OUN), even at 0000 UTC (1800 local time), despite the high surface potential temperature there. As usual, deep convection is always favored in the moist air.

The dryline has long been known as a favored site for the initiation of convection (Rhea 1966). A frontal circulation is neither a likely nor an attractive explanation, however, because the initiation occurs mainly in the late afternoon, when the horizontal contrasts along the dryline are relatively small and the dry air is warmer. A typical direct frontal circulation, moreover, would then place ascent in dry air and descent in the moist air, unfavorable for convection.

Other explanations have been offered. Schaefer (1975) has proposed that if warm, dry air and cool, moist air (with the same virtual temperature) are mixed, the virtual temperature will be slightly higher in

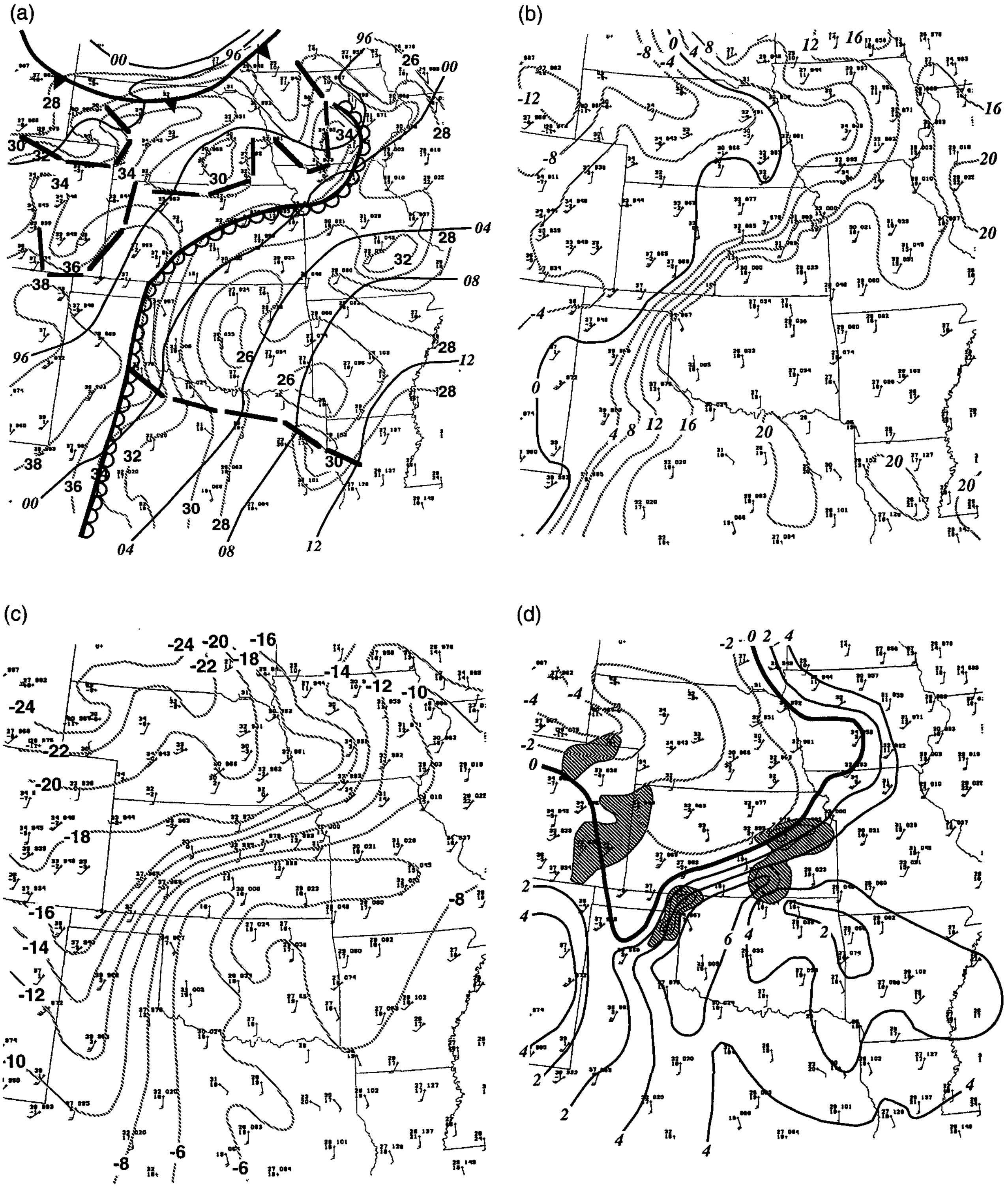


FIG. 6. Detailed surface analysis for 2100 UTC (1500 CST) 26 March 1991. (a) Surface potential isotherms (hatched lines) at intervals of 2°C and sea level isobars (solid lines) at intervals of 4 mb, labeled with tens and units digits; cold front denoted with standard symbols and a heavy solid line, the heavy scalloped line denotes the dryline, and nonfrontal features (e.g., outflow boundaries) are denoted by heavy dashed lines. (b) Surface isodrosotherms at intervals of 4°C. (c) Isotherms of surface air lifted to 500 mb, at intervals of 2°C. (d) Isotherms of the difference, ambient 500 mb minus lifted surface air, at intervals of 2°C (negative solid, zero heavy solid, and positive hatched lines). Hatching indicates area covered by echoes of intensity VIP-1 (minimum detectable signal equals 30 dB*Z*), VIP-3 (41–45 dB*Z*), and VIP-5 from the radar summary chart for 2035 UTC.

the mixing zone than that of either air parcel initially, so that buoyant ascent might be anticipated. Lilly and Gal-Chen (1990) point out, however, that the specific heats of the two air samples are different, as well, due to the difference in the water vapor contents. If this factor is taken into account, then the density of the mixture would be slightly *higher* in the above example, so that very slight descent would be favored in the mixed region, but the effect is deemed negligible. Thus, the precise mechanism promoting vertical motion at the dryline is unknown at present.

Nevertheless, drylines often exhibit confluent surface flow and typically this confluence is indicative of horizontal convergence on the scale of the surface observations. An example is seen in Figs. 4b and 7, in which the line of intense echoes from western Oklahoma to central Kansas developed along a confluent (inferred to be convergent) portion of the dryline. The large intense echo in eastern Kansas appeared near a portion of the dryline moving north in southerly flow without confluence. (The isolated strong echo in western Kansas in Fig. 4c formed at high levels in dry air and was shallow and short lived.) In Figs. 4d and 7, where the analyzed front really has the character of a dryline, the intense radar echo in eastern Texas is part of an extensive line that had developed during the night along the strong moisture gradient.

b. Convective outflow boundaries

The analysis procedure proposed in section 2c often is useful in delineating the boundaries of cool moist outflow from convective storms. Examples are seen in Figs. 4c and 7. In NMC analyses these are sometimes denoted as "outflow boundaries" but also sometimes as squall lines, "trofs," or fronts. When the convection is strong and persistent, the growing area of outflow influences more surface stations. In cases like the Johnstown, Pennsylvania, flash flood event (Maddox et al. 1979; Hoxit et al. 1978), many convective cells contribute to the outflow, and it shows up clearly in an analysis of temperature and moisture.

When only one or two stations are affected (as in Fig. 4c—eastern Kansas) the situation is comparable to the isolated extrema in temperature discussed above. Most such observations will not persist for more than an hour or so at a given station. Even so, the timescale of convective events makes it important to recognize what is going on, and features of this sort may serve as foci for continuing or redeveloping convection. The convection in eastern Kansas in Figs. 4c and 6 continued through the night and evolved into the large area of thunderstorms seen in Fig. 7. The case described by Kennedy et al. (1993) appears to be an example in which a detailed surface temperature analysis might have offered some additional insights into the developing convective situation (Doswell 1995), although the available details do not permit a completely unambiguous interpretation.

Convective outflow normally is cooler than the surrounding air, and while its *relative* humidity can be quite high, its *absolute* humidity is usually lower than that of the surrounding "unprocessed" surface air. Note in Fig. 7 that the cool outflow had formed an extensive line of moderately strong temperature gradient running across the northern half of Illinois and into Missouri. In the region of thunderstorm activity, the dewpoints were somewhat lower than they might otherwise have been, even though the air approached saturation.

The surface winds observed in convective outflow can be from a variety of directions, since the surface flow in convective events can be complex and is undersampled even by the standard surface network, as is likely the case in Fig. 7. Owing to the short time and space scales of convection, it is inappropriate to infer an approach to geostrophic balance, except perhaps in the persistent outflows of mesoscale convective systems, and then only after they have existed for many hours. The typical outflow is characterized by high pressure, from both hydrostatic and nonhydrostatic contributions. This results in the so-called bubble high or mesohigh associated with the region covered by outflow (Magor 1959; Fujita 1963; Doswell 1982). Small-scale but intense irregularities in the pressure field in this region also can include a "wake depression" (Fujita 1955). Figure 7 offers examples: a wake depression in northern Iowa, and mesohighs in southwestern Wisconsin and northeastern Missouri–western Illinois.[2]

The air within an outflow boundary does not remain unmodified. If convection ceases and the clouds clear off, the thermodynamic difference between old outflow and the surrounding air can decrease substantially within a few hours. Moreover, in an ongoing system, the surface boundary near the *active* convection (which may cover less than 10% of the total affected area) tends to be more distinct than in the other regions influenced by outflow. The oldest outflow tends to lose its clear difference from the surroundings. Thus, an outflow boundary can be quite pronounced near its leading edge and may not be detectable on its trailing edge. It is common to analyze

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[2] Note that not all the observations used for analysis were present in the digital dataset available to plot the observations in our figures. Hence, some of the features analyzed may not appear to be supported by the observations.

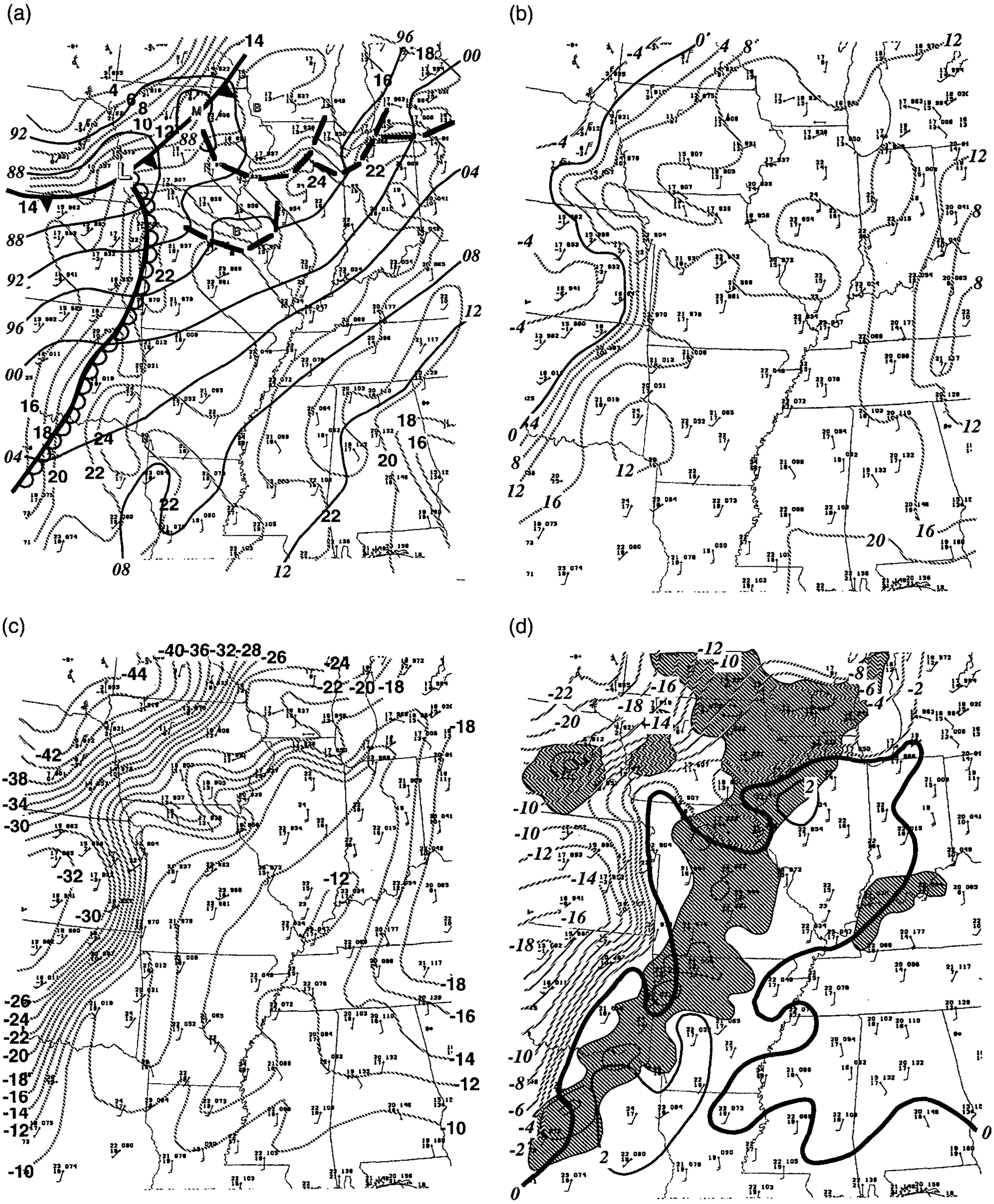

FIG. 7. Same as Fig. 6 but for 1200 UTC (0600 CST) 27 March 1991. In (d) the echoes are from the radar summary chart for 1235 UTC. The letter M denotes the location of a mesoscale wake depression, while B denotes the location of mesoscale bubble high pressure centers.

the boundary to reflect this nature. In Fig. 7 there is no distinct northwestern boundary to the thunderstorm outflow air.

Given the occurrence of convection near a front, it may be difficult at times to distinguish between the outflow and the front, at least for a time when they are close together. Generally, the air behind an outflow boundary will show signs of "recovering" to the previous ambient conditions, as just noted. Alternatively, the outflow air may have an intermediate temperature that provides notable contrasts with both the warmest and the coldest air. In those cases, the front is obviously a separate entity, as generally shown in Fig. 7. When there is no recovery, or when the synoptic-scale baroclinity is weak, on the other hand, the strong temperature contrast at the outflow boundary may *become* the effective front.

c. Nonfrontal wind shift lines

The presence of nonfrontal wind shifts in association with convection has been recognized for many years (Newton 1950; Fulks 1951; House 1959). Many fronts are preceded by wind shifts, and these have been recognized as important in convective forecasting for a long time (e.g., House 1963). Note that one should distinguish a nonfrontal *convective* line from a wind shift line that precedes convective development; it is the latter that is of concern here. At times the front is the convectively significant boundary, and at other times it is the prefrontal wind shift line. Garratt et al. (1985) have observed that the prefrontal "transition zone" (in their terminology) can be characterized by a number of "change lines" (again, their terminology). The physical processes producing them have not been comprehensively explained, and if there are a number of such lines ahead of the true front, each one might well have a different origin. In the absence of detailed studies of these prefrontal change lines we choose not to speculate about their origins. Despite the lack of a universally accepted explanation, there can be no doubt that the actual complexity of the structure ahead of a true cold front needs to be recognized and tracked as potentially significant for convective forecasting. Sometimes these change lines can undergo significant frontogenesis and they may *become* the locus of the thermal gradient (i.e., the front), as described by Hanstrum et al. (1990). Simply placing the analyzed cold front at the leading wind shift line is a serious oversimplification.

4. Feasibility and notation

The proposed method of temperature and moisture analysis and diagnosis may seem too time consuming in some operational forecasting situations but it could be facilitated by an automated analysis, provided an adequate one is available. A procedure of the type developed by Miller and Benjamin (1988) or something comparable (see, e.g., Kocin et al. 1991 or Doswell 1992) applied on a workstation might be feasible. Our proposed method of including thermal (and moisture, where appropriate) analyses would not only go a long way toward solving a long-persisting analysis inconsistency but would at the same time make explicit some important features of the surface thermal field that frequently are ignored but are quite important when using the surface analysis for forecasting.

This approach really represents a radical departure from the traditional way of looking at fronts as the surface manifestation of baroclinic zones extending through the entire troposphere (Bjerknes 1932; Bjerknes and Palmén 1937; Crocker et al. 1947;

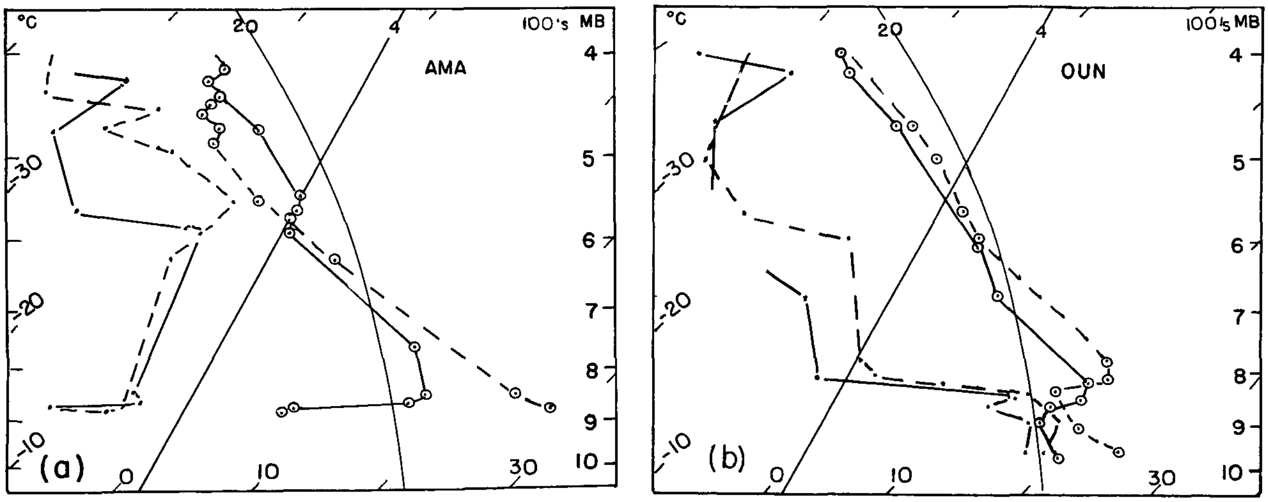

FIG. 8. Skew T–log$p$ plots showing temperature and dewpoint sounding profiles for 1200 UTC (0600 CST) 26 March (solid) and 0000 UTC 27 March (1800 CST 26 March) 1991 (dashed) at (a) AMA, in dry air, and (b) OUN, in moist air. Thin lines in background are reference dry and saturated adiabats and isopleths of saturation mixing ratio.

Palmén 1951). Instead, it focuses on the detailed structure of the surface boundary layer, which does not always correspond to deep tropospheric baroclinity. Numerous research analyses and modeling studies have addressed various aspects of this structure (e.g., Ookouchi et al. 1984; Shapiro et al. 1985; Abbs and Piekle 1986; Mass et al. 1986; Zhang and Fritsch 1986; Wilson and Schreiber 1986; Segal et al. 1989; Arritt et al. 1992; Ulrickson 1992; Huang and Raman 1992). We believe it is just this structure that needs greater attention than it now receives in synoptic analysis.

If, as we have indicated, the careful analysis of surface observations is important to the task of forecasting, then doing a detailed surface analysis and diagnosis is an indispensable part of forecasting. Time simply *must* be found to accomplish this end. This task is particularly pertinent to the problem of forecasting deep convection. We believe it is not feasible to attempt forecasting convection without a commitment to do regular, detailed surface analyses designed to depict the pertinent structures and their evolution. The evolution is especially important, so unquestioning adherence to "continuity" may blind the analyst to important changes in structure occurring during short intervals. Some changes occur so rapidly that 6-h, or sometimes even 3-h, analyses may not suffice.

A continuing source of difficulty is the *notation* used in depicting features of interest on the surface chart. As already seen, many features on a surface chart were not included in the original frontal notation, and the introduction of the trof and squall line in the NMC analyses seems to have produced more ambiguity than clarification. In the absence of a clearly superior alternative, the proposal by Young and Fritsch (1989) seems reasonable for denoting various types of boundaries, but we choose not to make specific recommendations at this time. Perhaps more experimentation and discussion could lead to a consensus on notation. The object ought to be to distinguish features on the chart according to their mechanism of origin. This capability should be matched to the analysis task. Doing detailed analysis of surface features *without* taking account of changes on an appropriate timescale (perhaps even hourly for some purposes, in some situations) is not possible.

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