A Proposed Method of Surface Map Analysis

FREDERICK SANDERS

Marblehead, Massachusetts

(Manuscript received 6 November 1997, in final form 22 June 1998)

ABSTRACT

Present surface frontal analyses suffer from the defect that frontal positions are typically not collocated with zones of intense temperature contrast. Further, individuals typically do not agree as to the existence, type, and location of fronts.

The author argues that the lack of a surface temperature analysis is mainly responsible for these flaws, and it is proposed that such analysis, preferably of potential temperature in regions of variable terrain elevation, become part of routine procedure. Such an analysis will reveal nonfrontal baroclinic zones of considerable intensity. Most cold fronts, except the strongest ones, are denoted as baroclinic troughs, propagating eastward in the prevailing westerly flow. It is argued that when a meridional cold front exists in the presence of even a small meridional temperature gradient, the wind shift should propagate away from the intense surface temperature gradient, which then weakens. An explanation is provided, based on quasigeostrophic theory. It follows that fronts are short-lived phenomena.

1. Introduction

Particular interest in surface map analysis was prompted by a workshop at the National Meteorological Center (NMC; now the National Centers for Environmental Prediction) in 1991, as reported by Uccellini et al. (1992). This workshop was a response to a widespread perception that the quality of surface analyses prepared by the center was often poor, especially with regard to frontal analysis. As reported by Sanders and Doswell (1995), the workshop participants (all highly experienced in synoptic analysis) were unable to agree on the frontal analysis for a sample case judged to be of ‘‘average difficulty,’’ despite the provision of three-hour continuity and access to observations and analyses of all kinds. In a study of about six weeks of National Weather Service (NWS) analyses, it was found that most of the time zones of strong temperature contrast did not coincide with analyzed frontal positions. Some examples are provided by Sanders and Doswell (1995).

These two undesirable characteristics, lack of agreement as to frontal existence and position and lack of coincidence between fronts and the surface temperature field, have at their source the lack of temperature analysis at the surface. Similar characteristics and flaws are noted in analyses from other operational centers and from the research community. It is not only an NWS problem. The lack of surface isotherms is curious because the surface is the only standard level at which temperature analysis is not carried out, despite the enormous database with a density of coverage in space and time that is at least an order of magnitude greater than that afforded by the rawinsonde network at upper levels. It may be due to the following admonition in the textbook by Petterssen (1940), much used for many years. ‘‘The temperature observed near the surface of the earth is often neither representative [of the air mass] 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. Of such influences we mention insolation, outgoing nocturnal radiation, conduction of heat to and from the surface of the earth, evaporation and condensation, etc.’’ The second edition of this text (1956) neither repeats nor disavows these sentiments, and it is perhaps no wonder that surface isotherms are rarely attempted.

There is an unstated inference that in order to be significant a temperature contrast must extend through some minimum depth (so that it represents conditions in the ‘‘free atmosphere’’). The initial statement of frontal concepts (Bjerknes 1919), however, places surface temperature contrast in a central position. Moreover, our present understanding of the development of a front and ageostrophic circulation (Hoskins and Bretherton 1972) offers no reason to discount conditions near the surface, the only level where a collapse toward temperature discontinuity is likely to occur. Elementary hydrostatic

---

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

considerations indicate that strength of contrast can overcome shallowness so far as the unbalanced pressure field resulting from development of the baroclinic zone is concerned.

In practice, strong contrasts are often discounted as being ‘‘just due to land–sea differences or to the presence of sloping terrain,’’ but the associated land- and sea-breeze circulations and mountain and valley breezes are unquestionably important. So far as heat transfer across the ground–air interface is concerned, there is no reason to discount the results of this process, for how else are air masses made? Where more clearly than at the surface might one expect temperature gradients due to horizontal variations of heat flux to appear?

Similarly, in convective situations relative coolness in surface temperatures is often regarded as ‘‘just due to outflow from existing or former thunderstorm activity.’’ But the boundaries of such outflow regions are regarded in some areas as favored regions for the initiation of new deep convection.

In summary, we look askance at any assertion starting with ‘‘just.’’ There is no reason to discount the surface temperature field and every reason to insist on its analysis and serious consideration. Surface temperature analysis is the major addition characterizing this proposed method of surface analysis.

2. Surface temperature analysis

We recommend that surface potential temperature, rather than ordinary temperature, be analyzed, as an attempt to account for differences in station elevation. On average, at higher elevations, ordinary temperature is lower and potential temperature is higher, but variation in the latter is less extreme. Analysis of equivalent (or wet bulb) potential temperature would show stronger contrasts owing to the variation of water vapor content, but this variation adds little to density contrast, however important it may be in forecasting deep convection (Sanders and Doswell 1995). Therefore, we do not recommend it. Use of virtual (potential) temperature, on the other hand, would represent density with increased accuracy and would be desirable, but has not been attempted here.

The horizontal gradient of temperature near the ground can often, but not always, be inferred from the gradient along the ground, as shown schematically in Fig. 1. When the surface boundary layer is well mixed, as during daytime in the absence of a thick layer of cloud, the isentropic surfaces are vertical and the two gradients are identical, as in Fig. 1a. When stratification is present, however, as at night with clear skies, the gradients are not generally the same and may be in opposite directions, as shown in Figs. 1b and 1c. When the stratification is moderate, in Fig. 1b the horizontal gradient is in the same sense as the gradient along the ground but is not as intense. With strong stratification, when the slope of the isentropes approaches the slope of the terrain as in Fig. 1c, the direction of the horizontal gradient may be opposite to that of the gradient along the ground. In these nocturnal cases, this coincidence is lost, although no advantage accrues to the analysis of any other thermodynamic variable. A sounding is necessary to determine the structure of the horizontal gradient. On the whole, though, the advantage of potential temperature is considerable, at night as well as during the day.

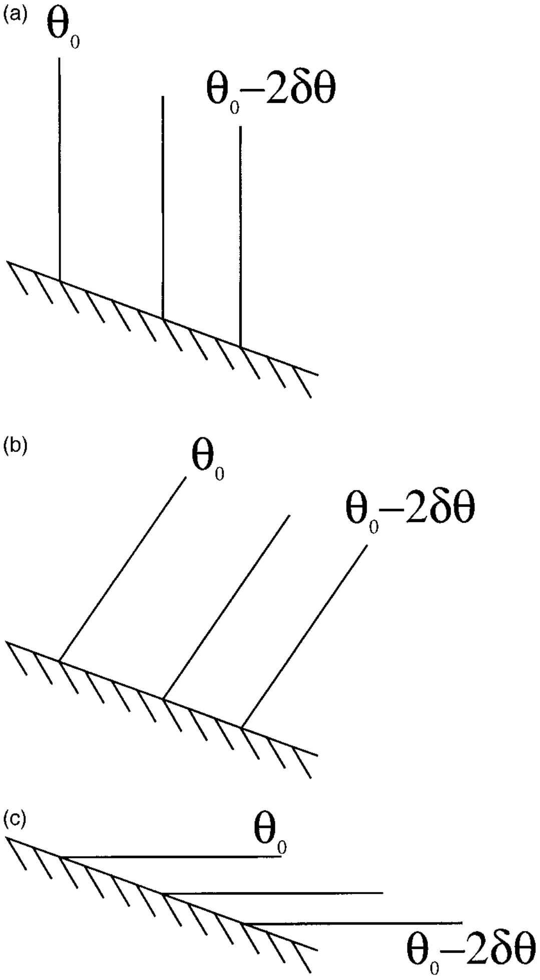

FIG. 1. Schematic vertical cross section of potential temperature over sloping terrain (a) for a well-mixed boundary layer, (b) for moderate stratification, and (c) for strong stratification.

To obtain potential temperature from routine observations, Poisson's equation can be used if surface pressure is given. If only the sea level pressure or altimeter setting is provided, as is the case with the majority of Meteorological Terminal Aerodrome Forecast (METAR) stations, the approximate surface pressure can be retrieved hypsometrically from the station elevation and the reported surface temperature, and then Poisson's equation can be applied as before.

An easily obtained approximation to the potential temperature can be obtained directly from the station elevation. Since the dry-adiabatic (isentropic) lapse rate is very nearly 1°C per 100 m, and since the average elevation of the 1000-mb surface (to which potential temperature is referred) is approximately 100 m, the potential temperature can be estimated simply by adding to the surface temperature 1°C for each 100 m by which the station elevation exceeds 100 m when sea level pressure is 1016 mb, and temperature is not far removed from the Standard Atmosphere value. For stations at sea level, 1°C is subtracted from the observed temperature, while for the highest station in the United States (Leadville, Colorado, at 3096 m) the correction is +30°C.

Either of these approximations to potential temperature will be in error if the height of the 1000-mb surface is not 100 m. It will vary about 100 m for each 7.5 mb that the sea level pressure departs from 1016 mb, so the error is usually not large. The correction will be positive when the pressure is lower than the standard level and negative when it is higher.

3. Features of the analysis

A number of such analyses have been prepared routinely over North America. Zones of enhanced gradient are arbitrarily denoted as moderate when a difference of 8°C occurs over a distance of no more than 220 km (2° of latitude). It is considered strong when such a difference occurs over a distance of no more than 110 km (1° of latitude). Gradients of this magnitude are relatively rare at any upper level, although they are sometimes seen (e.g., Sanders et al. 1991).

At the surface, on the other hand, many strong zones appear, only rarely coincident with an analyzed front. Cursory examination of 72 analyses of surface potential temperature, mainly from February and March 1998, show a range from 1 to 10 strong baroclinic zones, elongated in the direction of the isotherms but often no more than 200 km long, embedded within moderate zones of much greater length. Limited study of them shows that many are short lived, some being characteristic of daytime, while others are nocturnal. Many are associated with a response in the wind field, some are frontal and others land and sea breezes, and mountain and valley winds, as well as a variety of topographically induced phenomena. This complexity should not be cause for despair! It is what is there and to deny it cannot benefit forecast accuracy. Indeed, it is hard to see how forecast accuracy can be improved by suppression of these features in the interest of some ''synoptic-scale'' field of temperature. In limited experience, it seems that egregious ''busts'' of forecast temperature often involve some zone of strong contrast, incorrectly predicted and not even seen in the analysis.

When such analyses are examined, two additional kinds of structure are apparent in addition to traditional fronts. These are 1) nonfrontal baroclinic zones and 2) baroclinic troughs.

The first of these are zones not accompanied by a significant cyclonic wind shift at their warm edges. They prompt one to consider frontogenesis as a two-stage process. First, a substantial temperature gradient is produced, predominantly it seems by horizontal variation of heating or cooling due to surface heat flux, although advection by large-scale wind fields with deformation also plays a role. Then, the gradient near the warm edge of the zone is strengthened by convergent ageostrophic flow, apparently by the process described by Hoskins and Bretherton (1972). In this process there is a positive feedback between the strengthening gradient and the ageostrophic circulation arising in response to thermal-wind imbalance. The result is a collapse of the temperature contrast toward discontinuity.

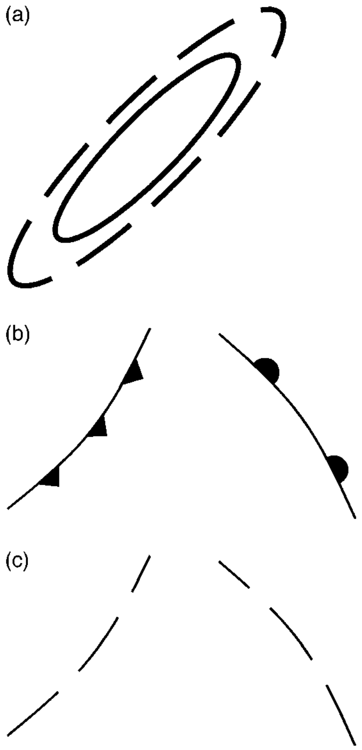

FIG. 2. Notation for features of proposed analysis method; (a) nonfrontal baroclinic zone, with solid line indicating a strong zone and dashed line a moderate zone (see text); (b) conventional cold and warm fronts; (c) baroclinic troughs.

Even though the collapse has not occurred and there is little disturbance in the wind field, nonfrontal baroclinic zones are important in forecasting merely because of their presence. Further, they are likely locations for subsequent frontal collapse, since the rate of frontogenesis is exponential, being proportional to the gradient itself. These zones should be marked, perhaps as indicated in Fig. 2a, in which moderate and strong zones are enclosed by heavy dashed and solid lines, respectively.

4. An analysis procedure

In practice the isentropes are drawn at intervals of 4°C and the moderate and strong baroclinic zones are determined by scanning the positions of the isotherms. It is unusual in measuring gradients to specify a temperature difference and vary the corresponding distance rather than the other way around. The choice of 8°C is arbitrary and cannot be determined from a priori physical reasoning. Rather, it is guided by experience, with the observation that a smaller difference would produce yet more baroclinic structure and more details in the temperature analysis. The substantial number of qualifying zones, as noted above, produces as much detail as this analyst is prepared to deal with. Further experience may suggest a somewhat smaller difference, to accommodate relatively weak fronts that appear to be significant features. Such a reduced difference, however, would have to be applied everywhere, to avoid complicating the rules.

If a considerable wind shift coincides with the warm edge of a baroclinic zone, then the structure is regarded as a front. The traditional frontal notation is appropriate, as shown in Fig. 2b.

The second new type of notation occurs when there is a pressure trough and wind shift, but associated with an insufficient temperature contrast. If we accept the above criterion for moderate baroclinic zones, then this amount of contrast must be absent. Again, experience may suggest that a smaller contrast could qualify as a front. In current practice, though, the great majority of imputed cold fronts fail the suggested gradient criterion, or even a much weaker one. Forecast discussions sometimes announce the passage of a cold front but then add that there will be little temperature change. Such a self-contradictory practice should be avoided.

It seems preferable to refer to these structures as baroclinic troughs and to use the ‘‘trof’’ notation to show them on the map, as in Fig. 2c. The wind shift line may have a number of characteristics usually attributed to fronts. They may well mark the boundary between air streams from different regions, as described by Cohen and Kreitzberg (1997), but the presence of such a boundary is evidently not a sufficient condition for a significant temperature (and density) contrast, as required by the frontal concept. There may be a change of weather across the wind shift line, with cloudy and rainy conditions ahead of it and clearing conditions behind it. This is hardly the sharp line of showers along the wind shift described by Bjerknes (1919) and Bjerknes and Solberg (1921).

Moreover, if there is a temperature gradient *along* the line, as is typically the case, then warm advection ahead of the line and cold advection to the rear connotes ascent ahead and subsidence behind, according to quasigeostrophic theory. It may well occur that the day prior to the wind shift is warmer than the day following it, but this says nothing about the presence of an intense contrast along the shift itself.

Examination of hourly reports rarely yields an unambiguous indication of when a front might have passed in an instance like this, and individuals will disagree as to the hour of passage, returning to one of the flaws that motivated this revision of analysis method. The maximum hourly vector wind shift should designate the trof.

Further, a line of cloud or precipitation in satellite or radar imagery is often taken to signify the presence of a front. But more than a single mechanism can produce line structure. These images, moreover, display much more such structure than could be accounted for by any reasonable frontal analysis.

5. Propagation of surface troughs

Detailed analysis shows instances in which a front meeting the criteria outlined above dissolves, with the wind shift advancing eastward more rapidly than the band of intense temperature gradient. This type of development is illustrated schematically in Fig. 3. In Fig. 3a a cyclone is associated with an intensifying quasistationary front to the northeast, along which it travels [hence confirming Bjerknes’s (1919) denoting of this feature as a ‘‘steering line’’]. There is little temperature gradient in the warm air, and the component of geostrophic flow normal to the front is approximately zero. Somewhat later, as in Fig. 3b, the cyclone has moved northeastward and the wind shift to the south, left in its wake, has begun to move toward the east as a baroclinic trough, while the zone of temperature gradient becomes a weakening nonfrontal baroclinic zone.

Quasigeostrophic theory indicates why this should happen. Both the wind shift line and the band of strong temperature gradient move east with the westerly components normal to these features, very nearly the same because of their proximity. The wind shift (and pressure trough), however, will *propagate* eastward relative to the flow, because of low-level convergence to the east and divergence to the west of the trough line. This propagation speed, which is not shared by the zone of temperature gradient, accounts for the more rapid advance of the trough and the ultimate dissipation of the front.

The speed of propagation can be obtained from the version of quasigeostrophic theory given by Sanders (1971). His formula for the eastward rate of propagation of a cyclone center at the surface (taken to be the 1000-mb level) yields his Fig. 10, showing the propagation speed as a function of the two-dimensional wavelength, L, and a, the magnitude of the meridional temperature gradient. If a north–south trough is regarded as a cyclone with an infinitely long meridional wavelength, the propagation speeds in Fig. 10 are doubled. We choose a value of his ‘‘vorticity-stability parameter’’ equal to typical atmospheric values, obtaining the present Fig. 4., where zonal wavelengths no larger than 4000 km and meridional temperature gradients no larger than 1°C per 100 km are considered.

If we identify the wavelength with the distance between upstream and downstream ridges of high pressure, we see that appreciable propagation speeds can be expected for even modest values of the meridional tem-

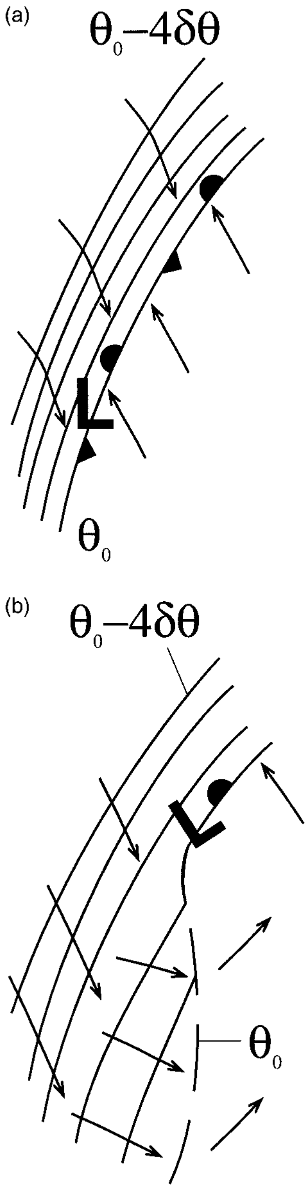

FIG. 3. Evolution of a front; (a) newly formed steering line and (b) wind shift propagating away from weakening temperature contrast. See text.

perature gradient. It follows that the wind shift and the intense temperature gradient can be expected to separate quite promptly. Thus, the existence of a cold front is likely to be a transient matter, forming quickly and dissipating after a short life. An example of this behavior will be presented in a subsequent paper.

This application of quasigeostrophic theory does not apply to the front itself, which is a mesoscale feature in the ageostrophic transverse circulation. The front, however, can be regarded as embedded in a synoptic-scale pressure trough, to which quasigeostrophic analysis can be applied.

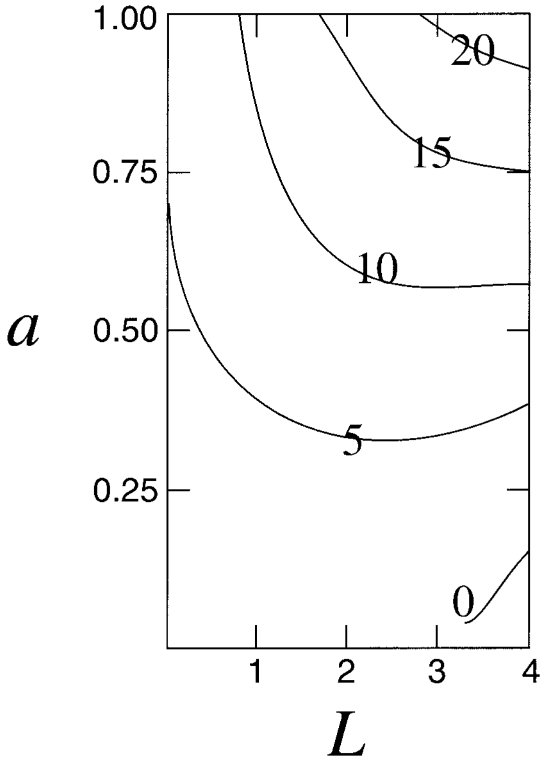

FIG. 4. Eastward propagation speed (m s^{-1}), of a surface trough as a function of wavelength, *L*, in km, and meridional temperature gradient, *a*, in °C per 100 km. [Adapted from Sanders (1971), Fig. 10.]

In summary, the largest modification of present methodology suggested here is the addition of surface potential temperature. This will show that most of the cold fronts now routinely analyzed lack the kind of temperature contrast contemplated by Bjerknes (1919) and are better regarded as baroclinic troughs. This distinction will reserve frontal identity for the really strong examples that occur from time to time and will emphasize their importance in daily weather forecasting.

6. Some examples

Examples of this technique have been prepared for an area covering most of North America for a week in 1991. Results will form the basis for a future paper. Maps were also prepared for the western two-thirds of North America for March 1997 and February and March 1998, and for the eastern two-thirds in March 1998, while the author was visiting the Department of Atmospheric Science at The University of Arizona. The plotted maps show surface potential temperature, wind, sea level pressure, and present weather in standard format.

An effort was made to use all stations providing observations in METAR code, plus observations from ships and buoys in adjacent marine sectors. All maps were for 1800 UTC, when the surface boundary layer is most likely to be well mixed. Analysis at other times

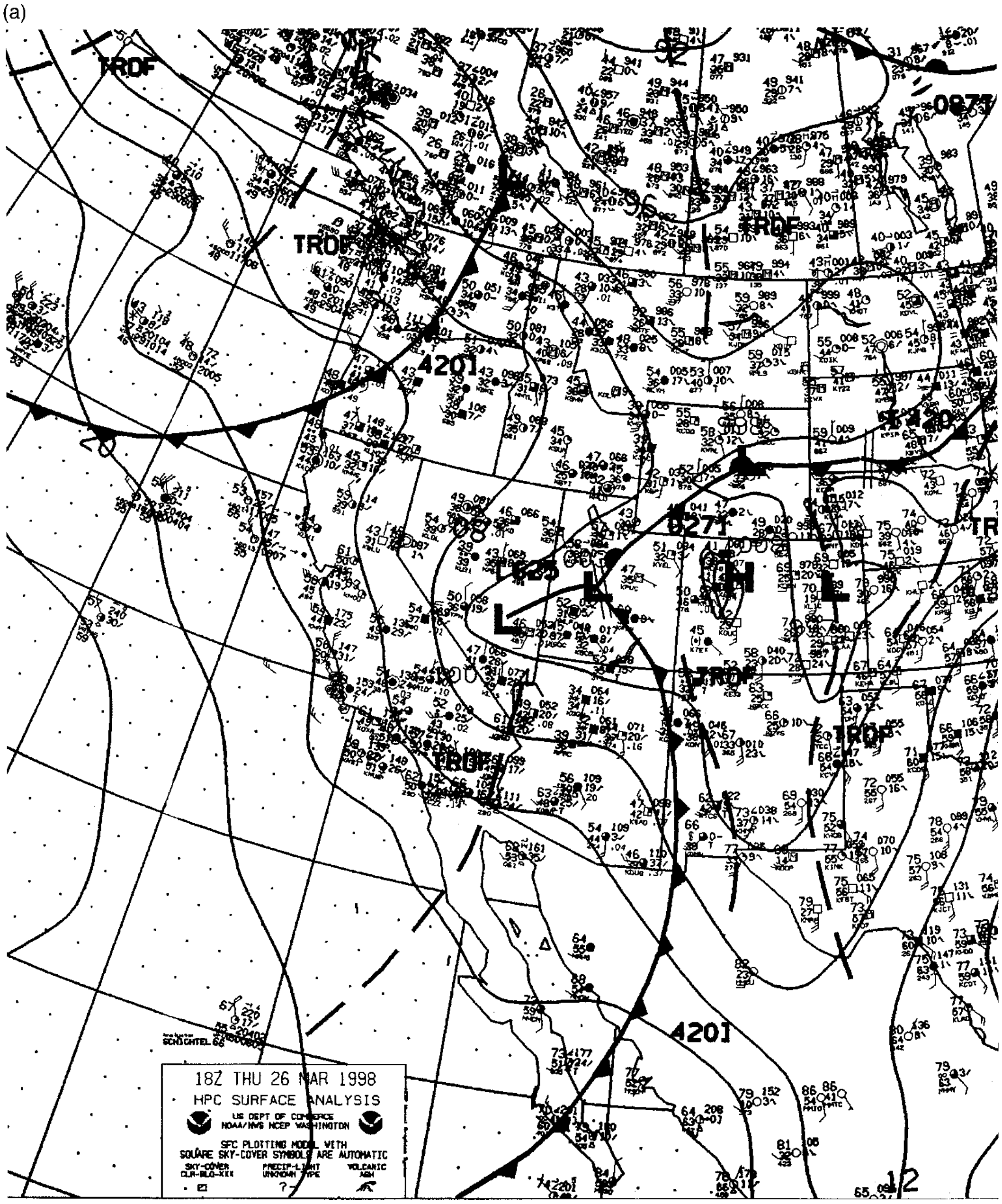

FIG. 5. Surface analyses for the western two-thirds of the United States and southern Canada at 1800 UTC 26 March 1998. (a) NWS analysis of isobars, fronts and pressure centers and with conventional station plotting model; (b) proposed analysis with station plots showing wind, surface potential temperature and present weather phenomena.

is beyond the scope of the present paper. North American maps prepared by the NWS were consulted for comparison and for providing some additional data.

When a set of isotherms had been manually completed, zones of moderate and strong gradient were identified, as described above. Then a set of isobars was prepared at intervals of 4 mb. From these isobars and the observed winds the positions of significant trough lines were determined. These were compared with the isotherms to identify fronts, frontless baroclinic zones, and baroclinic troughs. No attempt was made to maintain continuity from day to day.

The day selected for examination of the western two-thirds of North America was 26 March 1998, for which the NWS analysis appears in Fig. 5a, while the proposed analysis is seen in Fig. 5b. The NWS analysis shows isobars, conventional fronts, and trofs, while the features of the proposed analysis are moderate and strong baroclinic zones (excluding some small moderate ones of little importance), fronts, and baroclinic troughs.

(b)

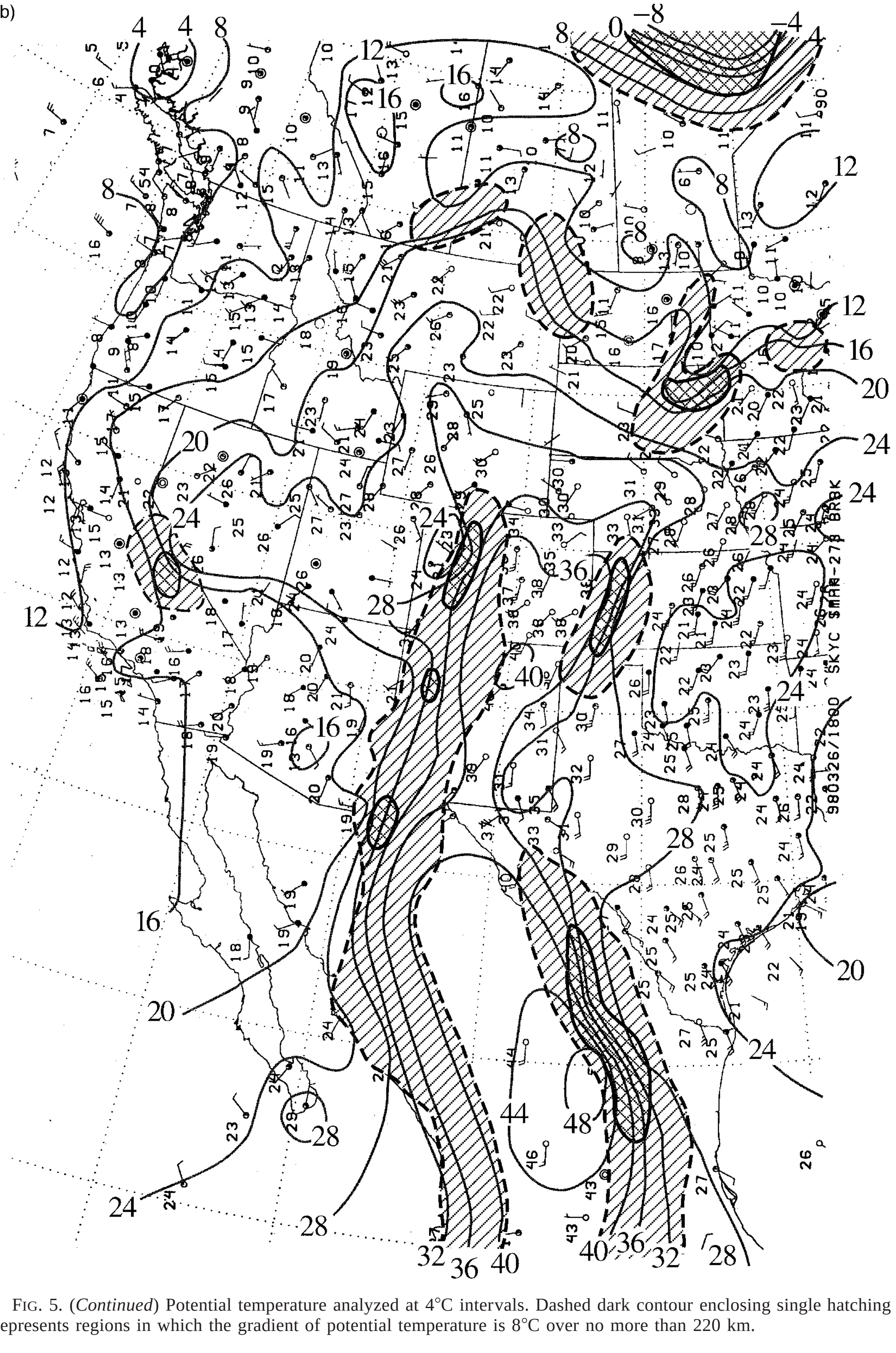

FIG. 5. (*Continued*) Potential temperature analyzed at 4°C intervals. Dashed dark contour enclosing single hatching represents regions in which the gradient of potential temperature is 8°C over no more than 220 km.

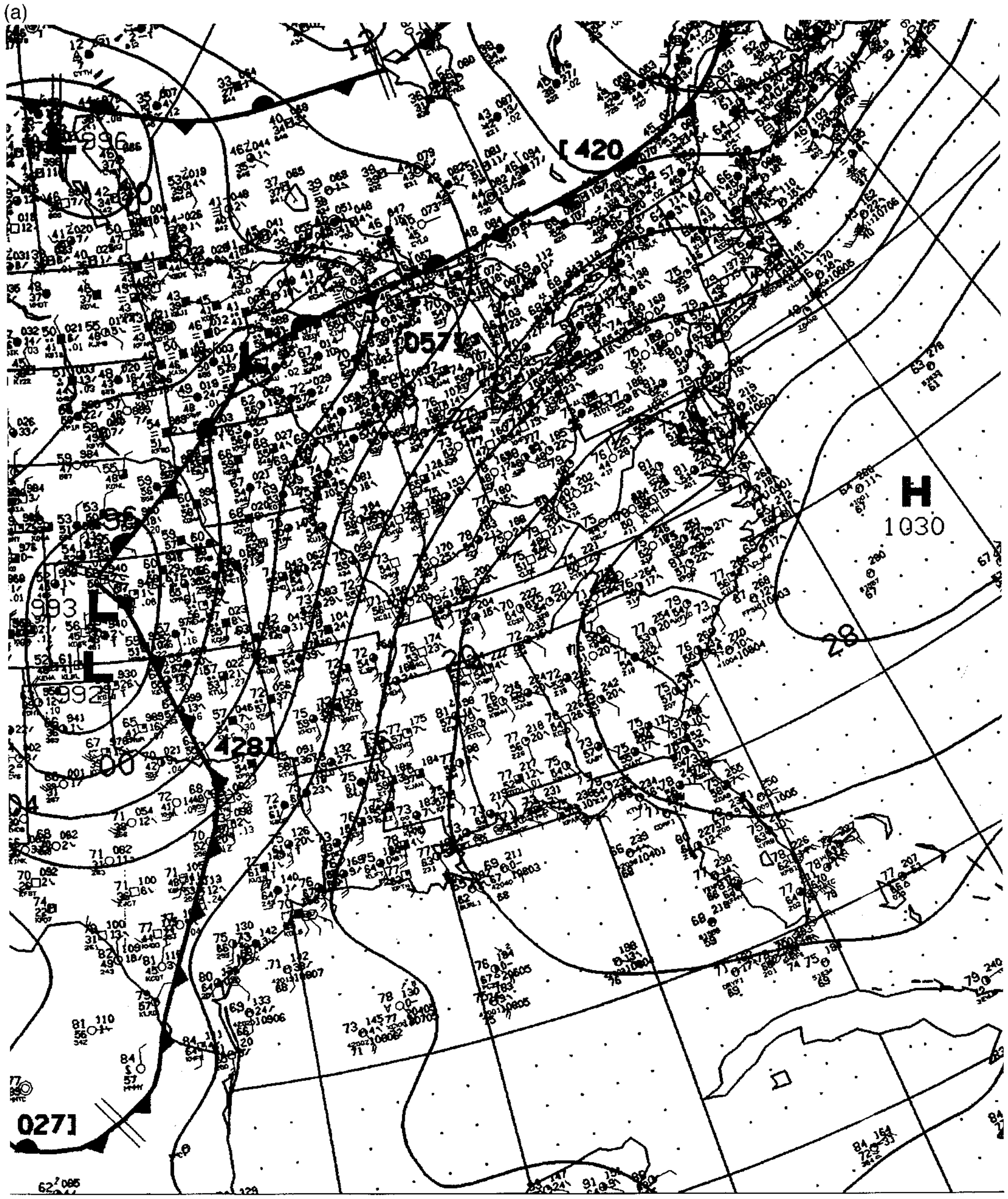

FIG. 6. Same as Fig. 5 but for the eastern two-thirds of the United States and southern Canada at 1800 UTC 27 March 1998. Solid dark contour enclosing cross hatching represents regions in which the gradient of potential temperature is 8°C over no more than 110 km.

Comparing the analyses in Fig. 5, we see good agreement of the proposed with the NWS analysis of a quasi-stationary front from northwestern Ontario to northeastern Saskatchewan. It lies near the southern edge of a strong baroclinic zone. The NWS cold front entering Washington and Oregon from the Pacific Ocean, on the other hand, shows no substantial temperature contrast aside from a small moderate patch in Oregon. Although the wind shift is not pronounced, the proposed analysis shows it as a baroclinic trough.

There is an ill-defined region of low pressure in the NWS analysis, with centers in Colorado, Utah, and Nevada, and with a cold front from northwestern Mexico through the mountains and then extending as a quasi-stationary system across the northern plains to a weak low center in Minnesota. This system is associated in the proposed analysis with a band of moderate to strong temperature contrasts with its warm edge through New Mexico and Colorado. Northeastward from there the temperature contrast is insufficient for frontal desig-

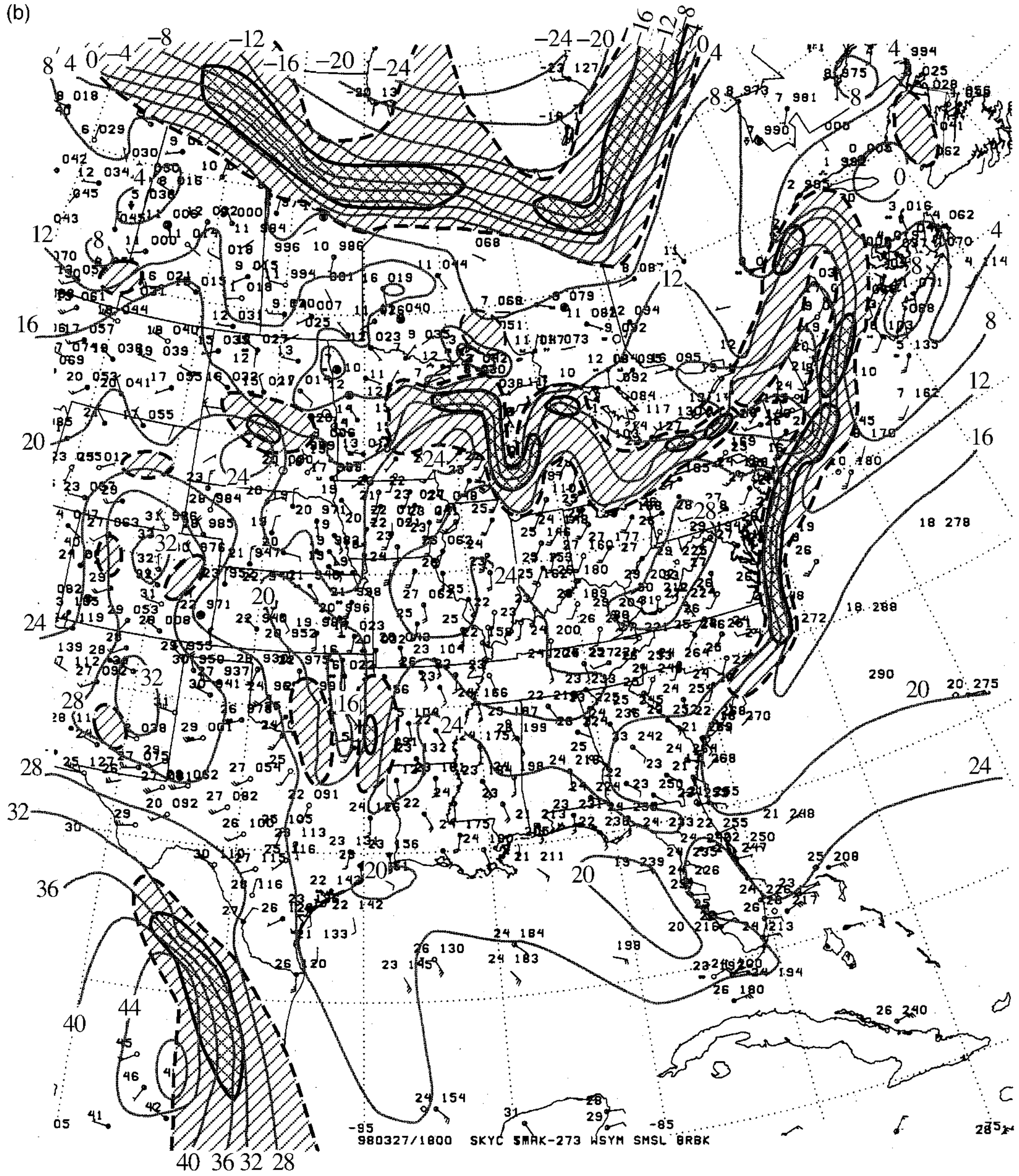

FIG. 6. (*Continued*)

nation except in two small patches of moderate gradient near the last-noted low center.

Various trofs in the NWS analysis show only very weak or no wind shift and do not appear in the revised analysis. The latter, however, does show three prominent baroclinic zones, one in central California and two along the eastern and western flanks of the Mexican plateau, the former extending northward to Texas north of the Rio Grande. In all cases, the strong gradient coincides with a strong gradient of land elevation. They are the western slopes of the Sierra Nevada in California and the Sierra Madre Oriental and Occidental in Mexico. Potential temperatures are higher at higher elevations. The former of the Mexican zones appears to show a cyclonic wind shift (although scarcity of observations precludes confident analysis) so it is shown as a front. The others are frontless baroclinic zones. An elongated moderate zone suggests linkage of the New Mexico cold front and the Occidental baroclinic zone, but the absence of observations in northwestern Mexico makes analysis impossible.

Examining the situation a day later in the eastern two-thirds of the United States and southern Canada (Fig. 6), we see the quasi-stationary front in Canada now extended to Quebec (Fig. 6a), in good agreement with the proposed analysis along the warm edge of moderate to strong gradient in Fig. 6b. Ahead of cyclogenesis in western Kansas there is a pronounced flow of very warm air from the Gulf of Mexico to the east coast of the United States. In the NWS analysis, this flow is bounded on the west and north by a frontal system, quasi stationary except south of Kansas, where the cold front from New Mexico (Fig. 5a) has progressed to eastern Texas. This system finds little support in the temperature analysis, except for small patches of strong gradient in Oklahoma and near the weak low center now on the Minnesota–Wisconsin border, as seen in Fig. 6b.

The contrast in Oklahoma results from dramatic 24-h cooling, evidently by evaporation from rain, in the southerly flow ahead of what must be denoted a warm front rather than a cold front. Elsewhere the system is shown in the proposed analysis as a baroclinic trough or is not shown where the wind shift was not pronounced. Comparison of Figs. 5b and 6b shows that the wind shift in the southwest has propagated through the ridge of maximum potential temperatures at high elevations and now lies east of it, although temperatures in the warm ridge in New Mexico have dropped as much as 10°C over the 24-h period.

Elsewhere in Fig. 6b, there are other topographically associated strong baroclinic zones. The zone along the Sierra Madre Oriental is much as it was the day before, but its northern extension to the Rio Grande has dissipated. The unusually warm air mass has advanced to the Great Lakes and the East Coast. In all coastal regions small, narrow, and strong baroclinic zones have developed, because the Great Lakes and the Atlantic have not participated in the warming. Some of this structure would not have been noticed were it not for observations from buoys in Lakes Superior, Michigan, and Huron, as well as in the coastal waters of the western Atlantic. Although there may be coastal breezes from the water, the available observational network does not show them, so they are left in the proposed analysis as strong nonfrontal baroclinic zones. It is noteworthy, however, that a few days later the cold air over the Gulf of Maine arrived unexpectedly at Boston, producing a maximum temperature there of only about 7°C in contrast to the forecast in the morning paper (on 2 April) that called for 24°C! The NWS analysis does not acknowledge these land–water contrasts (Fig. 6a).

We urge adoption of this method of surface map analysis, at least over the continents, where contrasts are large and observations are abundant. It should not be difficult to obtain consensus on the existence and location of significant features. The extensive cloudiness and precipitation ahead of baroclinic troughs is better explained by ‘‘Q-G thinking’’ than by the Norwegian cold front model, which prescribes precipitation only in a narrow band of ascent to the rear of the surface position of the front. This latter structure will in fact be observed when the wind shift and temperature field indicate the presence of a front.

7. Concluding discussion

The proposed analysis method will eliminate the vast majority of cold fronts whose poor fit to the Norwegian model is ascribed to their weakness. The denoting of nonfrontal baroclinic zones is a new aspect, which should be of immediate importance in short-term temperature forecasting.

The major change from present practice is the addition of a surface temperature analysis, the absence of which, to date, seems wrongheaded. Use of potential temperature, while having its own limitation, seems an improvement, especially when the surface boundary layer is well mixed, in regions of substantially variable elevation. With automated processing of data, the determination of potential temperature and plotting of the maps should not be a problem, even in the pressured operational setting. At the moment there does not seem to be a satisfactory algorithm that will produce an analysis fitting the observations closely enough to reveal the features of interest. Any amount of smoothing will tend to eliminate the very strong gradients we seek to identify. Because of the mesoscale character of features of interest, all observations should be used, and cluttering may require the preparation of regional analyses of less than a continental or global scale. As matters now stand, addition of this analysis would put a significant additional burden on the analysts, but the development of a suitable automated algorithm would not seem a particularly difficult task. Even given this desirable development, the interpretation of features would probably continue to require more attention than is now given to surface analysis, but this is a plus, not a minus!

Routine analysis does not stop with consideration of the temperature field. In particular, fields of wind and moisture deserve attention but are beyond the scope of this paper.

Acknowledgments. The author is grateful to the Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, for providing materials and facilities, and to Professor Steven L. Mullen and Michael Leutold, of the Department of Atmospheric Science, The University of Arizona, for arranging and providing the NWS maps and the potential-temperature maps during 1997–98. He is also grateful to Professors Lance F. Bosart and Peter V. Hobbs, and to Dr. Richard Rotunno for comments on the penultimate version of the paper, and to the reviewers of the present version. The effects of these comments were salutary.

REFERENCES

Bjerknes, J., 1919: On the structure of moving cyclones. *Geof. Publ.,* **1,** 1–9.

——, and H. Solberg, 1921: Meterological conditions for the formation of rain. *Geof. Publ.,* **2,** 1–62.

Cohen, R. A., and C. W. Kreitzberg, 1997: Airstream boundaries in numerical weather simulations. *Mon. Wea. Rev.*, **125,** 168–183.

Hoskins, B. J., and F. P. Bretherton, 1972: Atmospheric frontogenesis models: Mathematical formulation and solution. *J. Atmos. Sci.*, **29,** 11–37.

Petterssen, S., 1940: *Weather Analysis and Forecasting.* 1st ed. McGraw-Hill, 503 pp.

——, 1956: *Weather Analysis and Forecasting.* 2d ed. Vol. 1. McGraw-Hill, 286 pp.

Sanders, F., 1971: Analytic solutions of the quasi-geostrophic omega and vorticity equations for a structurally simple model of disturbances in the baroclinic westerlies. *Mon. Wea. Rev.*, **99,** 393–407.

——, and C. A. Doswell III, 1995: A case for detailed surface analysis. *Bull. Amer. Meteor. Soc.*, **76,** 505–521.

——, L. F. Bosart, and C.-C. Lai, 1991: Initiation and evolution of an intense upper-level front. *Mon. Wea. Rev.*, **119,** 2832–2851.

Uccellini, L. W., S. F. Corfidi, N. W. Junker, P. J. Kocin, and D. A. Olson, 1992: Report on the surface analysis workshop at the National Meteorological Center 25–28 March 1991. *Bull. Amer. Meteor. Soc.*, **73,** 459–471.