

Synoptic Frontal Analysis: Time for a Reassessment?

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Abstract

For over a half-century, the Bergen School conceptual model of cyclone structure and development has dominated the practice of synoptic meteorology, especially regarding the techniques by which surface synoptic charts are analyzed. Although the Norwegian paradigm captures some of the essential features of cyclone evolution, research and practical application over the last 60-odd years have revealed significant deficiencies, several of which are discussed in this paper. The Bergen model has also been applied in regions and under conditions quite unlike those for which the model was originally developed. Knowledge of these problems by many in the research and operational communities has had little impact on the manner in which synoptic charts are analyzed or the way the subject is described in many textbooks. Deficiencies in the underlying conceptual model of cyclone development have been compounded by a lack of consistent and well-defined procedures for defining fronts and for analyzing surface synoptic charts. Several examples of confusing and inconsistent surface analyses are presented in this paper.

To resolve these problems, the meteorological community should follow a two-pronged approach. First, the research and operational insights gained over the last half-century should be combined with recent numerical modeling and observational studies to establish improved conceptual models of cyclone evolution. Second, a clear and consistent methodology for analyzing synoptic charts should be devised. Several possible approaches for implementing these suggestions are presented in this paper.

1. Introduction

Nearly 70 years ago, the Bergen School of meteorologists in a series of celebrated papers (e.g., Bjerknes 1919; Bjerknes and Solberg 1922) proposed a conceptual model of the structure and evolution of midlatitude synoptic-scale cyclones. This conceptual model and associated analysis techniques were destined to dominate synoptic meteorology and operational forecasting to this date. During the past half-century, synoptic meteorologists, using a variety of observing, analysis, and theoretical tools unavailable to the Bergen researchers, have rapidly expanded knowledge of the dynamics and structural development of midlatitude cyclones. This new knowledge has revealed that although the Norwegian model captures many important aspects of cyclone evolution, some significant modifications to the model are required. Unfortunately, a comprehensive conceptual model integrating the insights gained over the past half-century does not exist, and synoptic analysis techniques have not

evolved in parallel with the increased understanding of cyclone structure and dynamics. Operational and research meteorologists often interpret observational data through the Bergen School viewpoint, incorrectly forcing "non-classic" developments into the Bergen School mold and not exploring obvious discrepancies with the Norwegian cyclone model.

Another area of concern is the often inconsistent and illogical application of classical Norwegian frontal symbols (the familiar combinations of triangles and semicircles) in operational and research synoptic analyses. These frontal symbols are frequently applied to mesoscale and synoptic-scale features not encompassed in the original Norwegian cyclone model. For example, the Norwegian frontal symbols are used not only for synoptic fronts with deep baroclinicity in the lower troposphere, but shallow boundary layer features as well. A regular user of National Meteorological Center (NMC) operational 3-hourly surface analyses will note many examples of complex, unphysical frontal analyses that lack continuity in time and are inconsistent with Norwegian analysis conventions. Section 5 presents some examples of such problem analyses.

This paper briefly reviews the history of synoptic application of the Bergen School ideas, notes the deficiencies that have become apparent in over a half-century of research and operational forecasting, describes some attempts to rectify the situation, provides several examples of problematic and inconsistent application of the Norwegian analysis techniques, and discusses some potential approaches towards addressing these problems. The author hopes that this paper will stimulate a lively and constructive debate on the analysis techniques used by the synoptic community. It is not meant as a vehicle for criticism of operational analysts, who labor under the handicaps of severe time restraints, often inadequate data, and aging conceptual models and analysis techniques.

2. Frontal analysis based on the Norwegian cyclone model

Although many components of the Bergen School cyclone model were known prior to World War I (see

Kutzbach 1979 for an excellent review), the Bergen meteorologists (such as V. and J. Bjerknes, and H. Solberg) must be credited with establishing a comprehensive conceptual model of cyclone development that could stand the test of operational application. Many of their essential ideas, summarized in Bjerknes and Solberg (1922), are still found in the majority of introductory textbooks used today. Figure 1 presents their classic conception of the horizontal and vertical structure of a wave cyclone, with its warm and cold fronts and intervening warm sector. The vertical structures in the figure were mainly derived from "indirect aerology," whereby features above the surface were inferred from cloud observations and surface data.

Probably the Bergen School's most important contribution lay in their proposed life cycle for midlatitude cyclones (Fig. 2). They suggested that cyclones develop from infinitesimal perturbations on a preexisting polar front, which marks a boundary separating tropical and polar air masses. This perturbation amplifies into a wave cyclone with cold, polar air pressing southward along the cold front and warm, tropical air thrusting poleward with the warm front. Since the cold front advances more rapidly than the warm front recedes, the warm sector progressively narrows. The region in which warm sector air is lifted off the surface by the colliding fronts is said to be occluded. If the two fronts first contact some distance south the cyclone center, a seclusion of the trapped warm sector air occurs. Bjerknes and Solberg proposed two types of occlusions (cold and warm) depending on the relative temperatures of the cold air on the two sides of the warm sector.

Although the Norwegian cyclone model was accepted quickly in Europe, it was not until the mid-1930s that the United States Weather Bureau applied this conceptual model and its attendant analysis procedures operationally (Bates 1989). But, once accepted, it has held ascendancy with tenacious force, even as contradictory information has mounted. Clearly, simple conceptual models are extremely difficult to modify or replace once they have received wide acceptance; individuals often resist or ignore

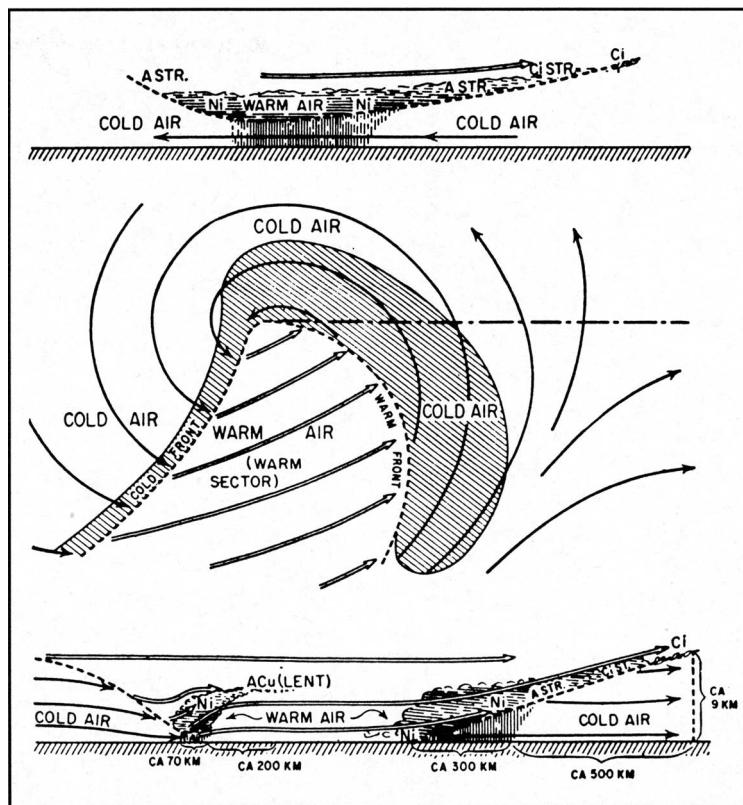


FIG. 1. Structure of an unoccluded midlatitude cyclone as presented by Bjerknes and Solberg (1922).

challenges to such models, even in the light of conflicting information. In the next section, we review some problems with the Norwegian cyclone model that have become apparent during the past 70 years.

3. The need for amendment of the Norwegian conceptual model

Observational and numerical studies completed during the past several decades have revealed that the structure and evolution of midlatitude cyclones often differ substantially from the ideal picture suggested by the Bergen School. For example, it is now clear that their depiction of cyclones growing from infinitesimal perturbations on preexisting, globe-girding polar fronts is generally not correct. Rather, observational,¹ theoretical (e.g., Eady 1949; Charney 1947) and numerical modeling studies (e.g., Phillips 1956; Hoskins and West 1979; Schar 1989) have revealed that cyclones only require a zone of baroclinicity for development, and that the process of cyclone evolution itself can sharpen diffuse temperature gradients into intense frontal zones.² Thus, in general, cyclogenesis and

¹See Reed (1990) for an overview of the evolution of thought on cyclone development during this century.

²It should be noted that waves and small scale disturbances can form on preexisting, well-defined frontal boundaries.

frontogenesis must be seen as inseparable processes. It can be argued that the implicit separation of these processes in the Norwegian cyclone model has been to the detriment of the discipline, since it has drawn meteorologists' attention away from the fact that fronts are the result of the motion fields associated with baroclinic disturbances. Too much emphasis has been given to fronts and the weather associated with them.

Another apparent deficiency with the classical model is that one of its major components — the warm front — is often weak and limited in horizontal extent, especially for mature and dying systems (e.g., Wallace and Hobbs 1977; Hoskins and West 1979). Furthermore, it is often not possible to identify a distinct warm front in satellite imagery (Anderson et al. 1974).

The Norwegian cyclone model often appears unrealistic regarding the evolution of occluded fronts. Most textbooks and papers on the subject repeat the basic Bjerknes and Solberg paradigm, namely, that occluded fronts form when cold fronts overtake warm fronts during cyclone development and that occluded fronts come in two varieties, warm and cold, depending on the relative temperatures of the air on the eastern and western sides of a system. However, several investigators have noted that the formation of an occluded front from the collision of cold and warm fronts is generally undocumented and that occluded fronts can form in other ways. For example, Wallace and Hobbs (1977) suggest that occluded fronts are essentially new fronts that grow northward from the junction of warm and cold fronts. Penner (1955) notes that "cases of true occluded fronts as in the classical model are extremely rare over North America and adjacent regions ... an occluded front which can actually be verified by aerological data is one of the rarer meteorological phenomena." Palmen (1951) notes that many of the cyclones analyzed as occluded on surface charts never go through a real process of occlusion. Classical Norwegian cyclone evolution also does not include the process which is now known as "instant occlusion," whereby comma cloud features join with open waves to produce apparently mature occluded systems over a short span of time.

Not only is the classic occlusion process difficult to document, but, in addition, a variety of observational studies have shown that ideal occluded frontal structures are rarely observed in their entirety. Frequently one or more of the frontal components of the Bergen School occluded front model are missing, and in other cases "non-classical" frontal structures and mesoscale features are observed. For example, Kreitzberg (1968) noted that old and new occlusions have different structures, with younger occlusions split between lower-tropospheric fronts and associated secondary

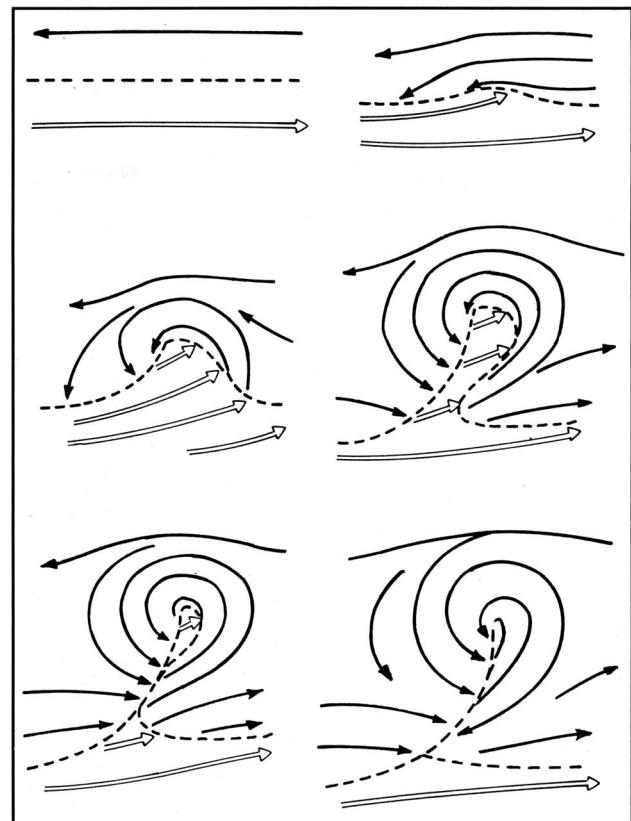


FIG. 2. Life cycle of a midlatitude cyclone as presented by Bjerknes and Solberg (1922).

cold surges aloft. In a series of observational studies (see Houze et al. 1976; Hobbs 1978), a variety of non-classical structures were found to be associated with occlusions passing over the Washington coast.

During the past several decades, several investigators (e.g., Reed 1979) have noted the existence of cyclogenesis on the cold air side of major frontal bands; this phenomenon is not included in the Norwegian model of cyclogenesis. These disturbances usually begin as relatively small (~500-1000 km) comma-shaped regions of enhanced convection and sometimes grow into disturbances indistinguishable from the usual synoptic scale cyclones. It is frequently observed that when a comma-cloud, and its associated short-wave aloft, approaches a preexisting baroclinic zone, cyclogenesis is initiated. This process, an example of Petterssen Type B cyclogenesis (Petterssen and Smebye 1971), was never a part of the original Norwegian cyclone model.

The Bergen School model lacks a description of upper tropospheric structures as well as the interaction between upper level disturbances and low-level development. Upper level fronts and the relationship between upper level short waves and individual cyclones was never a part of the classic paradigm. These deficiencies are hardly surprising considering

that during the first third of this century little upper air data was available. To be fair, it must be noted that as upper air data became more plentiful in the 1930s and 1940s, several of the Bergen researchers recognized the importance of upper level features in cyclogenesis (Bjerknes 1937; Bjerknes and Palmen 1937; Bjerknes and Holmboe 1944). Even today, a time in which the basic structure of upper level fronts is well-known (see Keyser and Shapiro 1986, for an excellent review), a clear understanding of upper level frontal evolution within the context of cyclone development does not exist.

4. Attempts at creating improved conceptual models and analysis techniques

During the past 70 years, meteorologists have followed two main routes in their attempts to improve upon the Bergen School model. One approach has endeavored to modify and improve the model while retaining its essential frontal "flavor," in which most weather is traced to vertical motions forced by frontal surfaces. The other approach (e.g., quasi and semi-geostrophic diagnosis, isentropic potential vorticity, jet streaks) has been basically dynamical in perspective. Although impressive gains have been made in following both of these approaches, it is sobering to note that today there is still no comprehensive picture of the three-dimensional structure and evolution of midlatitude cyclones that draws together the collective insights of the past 70 years. With large numbers of unconnected ideas regarding frontal structure and development floating around, the old dependable Norwegian cyclone model has remained in ascendancy. In this section, we will briefly review some of the findings of the above two approaches as they pertain to the establishment of a comprehensive conceptual model for midlatitude cyclone evolution.

a. The frontal approach

Eliassen and Kleinschmidt (1957), Browning and Harrold (1969), Carlson (1980), and Browning (1985), among others, have attempted to define the three-dimensional airflow through cyclones using relative-flow isentropic analyses. Their studies have suggested that the airflow may be conceptualized as a series of "conveyor belts." A warm conveyor belt begins at low-levels in the warm sector in front of the cold front and climbs anticyclonically above the warm front while a cold conveyor belt descends westward north of the warm front. Although perhaps a useful conceptual tool, this approach suffers from several deficiencies. For example, it assumes system transla-

tion without change of speed and shape, or equivalently that streamlines and trajectories are identical in storm-relative coordinates; this assumption is not appropriate for the period of rapid development of cyclonic systems. Moist-adiabatic motion is assumed. Furthermore, it is not clear whether the motion fields on a handful of isentropic levels (typically three) adequately describe complex three dimensional motions through synoptic systems.

During the past several decades, further complication and confusion regarding the structure and evolution of fronts have resulted from the anafront, katafront, trowal, and split cold front models, each of which appears to be applicable in differing locations and at varying times in the life cycle of cyclonic systems. The first delineation of the differences between anafronts (descending cold and ascending warm air streams) and katafronts (descent on both sides of the front, with stronger subsidence on the "warm" side) was made by Bergeron (1937). He suggested that anafronts are more prevalent in younger cyclones, and katafronts more likely in older occluded systems. Miles (1962) and Browning and Monk (1982) proposed a related frontal structure, commonly known as the split cold front model. In this model, the boundary between low θ_e air aloft, produced by subsidence, and higher θ_e air in the warm sector is labeled an upper level cold front, with an additional cold front lagging behind at low levels. Several Canadian meteorologists (e.g., Penner 1955; Galloway 1960) have proposed an alternative convention for analyzing occlusions. In their analysis method, the base of the warm air aloft is projected to the surface and analyzed as a "trowal." They suggested that the trowal is often more significant meteorologically than the weak occluded front left at the surface. Recently, Hobbs et al. (1990) proposed a conceptual model of cold fronts aloft, incorporating the warm occlusion and split cold frontal models. In this model a cold-frontal surface in the midtroposphere is followed by a sharp drop in θ_e , a surface trough lags the upper level feature, and a zone of potentially-unstable, high θ_e air connects the two components.

Recent observational studies of cyclogenesis over the western Atlantic (e.g., Neiman et al. 1990; Shapiro and Keyser 1990), using aircraft, dropsondes and other new observing technologies, have suggested a structure and evolution substantially different from the classic Norwegian conceptual model. For example, Fig. 3 presents 920-mb temperature, geopotential height, and frontal analysis of a cyclone over the eastern Atlantic at approximately 1200 UTC 27 January 1988 (Shapiro and Keyser 1990). This analysis makes use of both conventional observations as well as aircraft and dropsonde data. Note how the cold front projects northward towards the warm front at

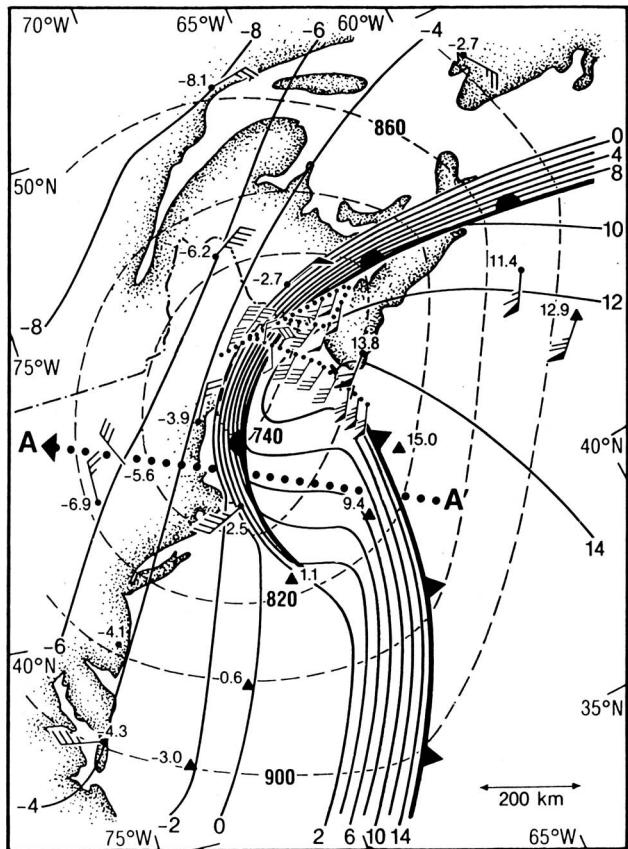


FIG. 3. 920-mb temperature ($^{\circ}$ C, solid lines) and geopotential height (m, dashed line) analyses for approximately 1200 UTC 27 January 1988 from Shapiro and Keyser (1990). Dropsonde locations are indicated by solid triangles.

nearly a right angle; this frontal geometry has been called the "T-bone" pattern. The cold front in this figure is analyzed to weaken ("fracture") as it approaches the warm front. An important deviation from classical structure is the lack of any occluded front; rather the warm front is analyzed to extend through the low; not unlike a "bent-back" or "retrograde" occlusion (Bergeron 1937; Petterssen 1956). The cold front appears to propagate normal to the warm front, but never catches up with the warm front as in the Bergen School model.

The generality of this fractured-cold front, T-bone model is uncertain. Such structures have only been documented over the ocean; over land, cold fronts are generally not fractured. Occluded fronts have been observed over land. Furthermore, the strong low-level baroclinicity that extends through and beyond the low center (analyzed as a warm front in Fig. 3) is usually not apparent over land. It could well be that lesser surface friction and larger heat fluxes over water have major effects on the structural evolution of cyclones, at least in the lower troposphere. Thus, the structures found over the western Atlantic (such as in Fig. 3) may not be truly general, being the result of a specific

geographic area with unique elements such as the intense advection of cold continental air over the warm water of the Gulf Stream.

It should be noted that semi-geostrophic models using idealized basic states and realistic primitive equation simulations have duplicated several of the non-classical structures and evolutions described above. For example, Kuo et al. (1990) simulated the evolution of the explosive QE II storm over the western Atlantic using the NCAR/Penn. State (MM4) mesoscale primitive equation model. The sea-level temperatures and pressures for this simulation suggest the "bent-back" warm front and "T-bone" configuration noted above. The non-linear, semi-geostrophic simulation (adiabatic, no friction) of Schar (1989), starting with a highly idealized initial state, produced a similar structural development.

b. The dynamical approach

An alternative perspective that has developed during the past 40 years examines the dynamical relationships between fields as synoptic systems evolve and is less concerned with the definition and movement of specific structural (e.g., frontal) elements. Under this approach, frontal development and the resulting vertical motions are seen as only one component of the evolution of baroclinic systems. The dominant dynamical method during the past 40 years has been quasi-geostrophic analysis, which relates fields of vertical motion, vorticity, temperature and horizontal winds in a physically consistent way (see Holton 1979). For example, using the quasi-geostrophic approach, upward motion is related to quantities such as horizontal vorticity advection rather than the geometry and flow patterns associated with a frontal zone. More recently, the more accurate semi-geostrophic theory has been applied to understand the structure and evolution of fronts (e.g., Hoskins and Bretherton 1972) and the evolution of cyclonic systems (e.g., Hoskins and West 1979).

Another dynamical approach makes use of the vertical circulations attendant with limited regions of strong winds, i.e., jet streaks (see Uccellini et al. 1987, for an example). This perspective, although intuitively satisfying, is limited to situations with relatively simple geometries and is essentially identical to the quasi-geostrophic approach for uncurved flow. Another diagnostic technique makes use of isentropic potential vorticity (see Hoskins et al. 1985 for a comprehensive review). By noting the evolution and interaction of upper and lower tropospheric potential vorticity centers, insight is gained into the development of cyclonic systems.

Although these dynamical approaches can provide an “explanation” for the structure of baroclinic distur-

bances and attendant significant weather features (e.g., areas of large upward motion and heavy precipitation), they can be obscure to the layman and their application is limited to the scales for which they are dynamically relevant and for which appropriate data sets are available. All of the above dynamical approaches are constrained by the resolution of the analyzed fields which they require. This limitation is not as severe for the frontal approach since important features (e.g., a narrow cold front) can sometimes be positioned subjectively (e.g., by examining time series at a single station or a satellite image) even though the analyzed fields on a horizontal surface cannot properly represent them.

In summary, synoptic meteorologists are faced with a confusing array of different and often contradictory conceptual models and approaches regarding the structure and evolution of cyclonic systems and their attendant fronts. Are some aspects of the proposed structural models simply incorrect, or do they represent cyclone structures applicable only in specific geographical areas or particular stages in cyclone development? Is it better to drop fronts completely and consider only the dynamical relationships between basic fields? Certainly, there is a need for an updated, comprehensive, and unifying conceptual model of the development of cyclones throughout their life cycle, or at least information on how development varies with changing environmental and geographical conditions.

5. Deficiencies of current surface analysis techniques

An examination of operational or retrospective surface analyses reveals a number of disturbing deficiencies. Problems begin with analyzing and interpreting atmospheric evolution using a conceptual model (the Norwegian cyclone model) that apparently does not properly represent, in several ways, the development of midlatitude cyclones. It is noteworthy that over the oceans, where conventional data is sparse, cyclones are nearly always analyzed in terms of classic Norwegian structures and evolution, while over land, where observational data are relatively abundant, analysts are often compelled to draw complex and non-classic structures (although they seem to fight this tendency whenever possible). Is it reasonable that meteorologists apply the Norwegian cyclone model, developed over a relatively small region on the eastern terminus of an ocean, to a worldwide domain in which topography and surface conditions vary greatly?

The problems with current analysis techniques are not confined to a limited, misused, or deficient conceptual model. Temporal continuity is often lacking in

surface analyses, as fronts move back and forth and transform from one type to another for apparently little reason. Perhaps equally serious is the inconsistent use of the familiar palette of symbols established by the meteorological patriarchs of Bergen. An examination of a large number of NMC operational surface analyses reveals that the familiar frontal symbols are used in a variety of ways:

- For cyclone-related frontal zones extending through a considerable portion of the lower troposphere (generally consistent with the Norwegian cyclone model).
- For relatively shallow topographically-induced features, such as the boundary of cold air damming, coastal fronts, lee troughs and temperature discontinuities created by high mountain barriers (such as the Rockies).
- For shallow zones of temperature contrast produced by discontinuities in surface properties or cloudiness. For example, the often large temperature contrasts across synoptic snow boundaries are sometimes graced with a Norwegian frontal symbol (usually a stationary front).

Several additional examples could be provided. As a result of this varied use of frontal symbols, a viewer of a surface synoptic chart is often uncertain as to the true meaning of analyzed boundaries. When frontal symbols are used indiscriminately and excessively, maps can become a writhing mass of confused and often intersecting lines that fail to provide a meaningful portrayal of lower tropospheric structures. Consider the following illustrative cases.

The National Meteorological Center (NMC) surface chart for 0000 UTC 13 November 1989 (Fig. 4) presents a complex pattern of fronts and troughs over the western U.S. A cold front near the U.S./Canadian border is about to intercept a double-waved frontal system, while a trough and another stationary front lie just to the south of this menagerie. It is hard to explain several of these fronts from the surface observations. Furthermore, at 850 mb (Fig. 5) the pattern appears relatively straightforward with a single baroclinic zone and low center over the northern U.S.

Figure 6 (a surface chart at 1200 UTC 6 December) presents a "double-decker" cyclone pattern over the Midwest. Both lows possess the "de rigueur" stubby warm front (often found in surface analyses) and the northern cyclone is analyzed as a mini-occlusion. Although two fronts are analyzed over the Great Plains, the northern one is generally not apparent in the wind field and is not associated with a pressure trough. It appears to separate a region of weak temperature gradient to the south from one of more rapid temperature decrease to the north. Some of the temperature

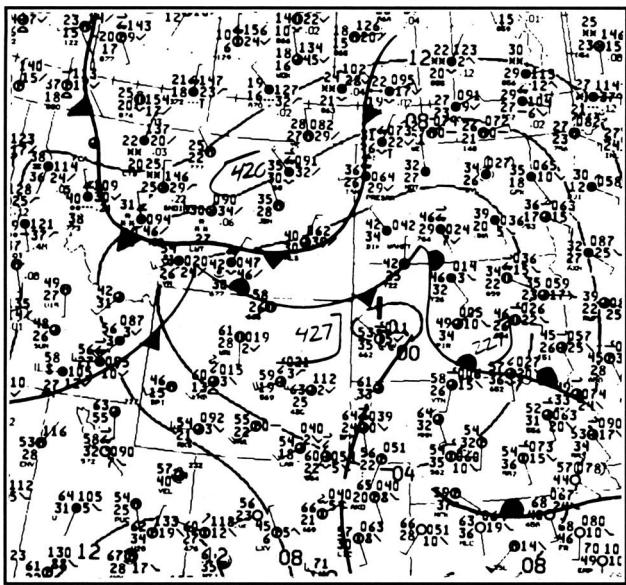


Fig. 4. National Meteorological Center (NMC) surface analysis for 0000 UTC 13 November 1989.

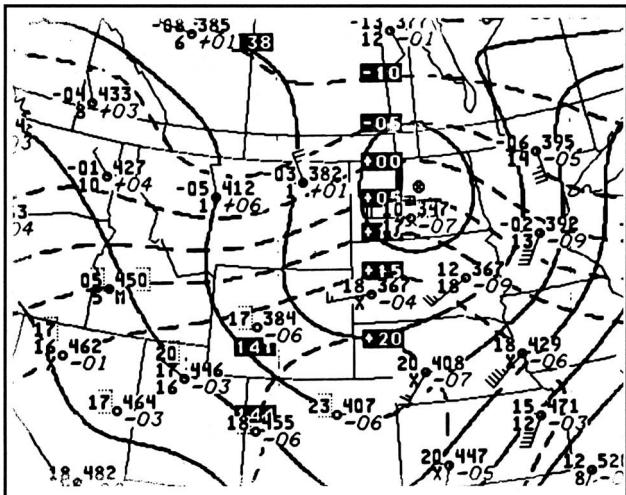


Fig. 5. NMC 850-mb analysis for 0000 UTC 13 November 1989.

contrast across the northern front undoubtedly results from a gradient in cloud cover across the front: clouds to the south and broken to clear skies to the north produce a large contrast in surface radiational cooling. However, as evident from the 850-mb analysis at this time (Fig. 7) the northern feature is clearly quite shallow and the southern front represents the true synoptic frontal boundary.

Figure 8 shows a particularly strange sequence over the southwest U.S. At 0600 UTC 5 March 1990 the NMC surface chart (Fig. 8a) shows a partially occluded frontal zone to the west of a cold/stationary/warm frontal complex that passes through a low over the Utah/Nevada border. Six hours later (Fig. 8b), the frontal complex associated with the low has transformed into a cold front that is intersected by a cold/

occluded front combination. To the west, a dying cold front is noted. In this case both temporal continuity and any conceivable conceptual model are violated.

The lack of temporal continuity is particularly noticeable with occluded fronts. On numerous occasions, the author has noted analyzed cold fronts turning into occluded fronts and back to cold fronts again. Only rarely do fronts drawn as occluded develop as a result of the classic Bergen School "catch-up" mechanism. The following egregious example illustrates some of these points.

At 0000 UTC 11 January 1990, an unoccluded 978-mb low center with both a cold and warm front is found near the Minnesota/Canadian border (Fig. 9a). (Another cold front and a trough approach but do not intersect the low center). Six hours later the system is analyzed as being occluded, with a stubby warm front shown several hundred km south of the low center (Fig. 9b). By 1200 UTC 11 January (Fig. 9c), the occluded frontal section has shrunk considerably, the short warm front has disappeared, and a stationary front now enters the low center from the east. By 0000 UTC 12 January (Fig. 9d), a warm front has reappeared, with a short stationary front a few degrees to the north. Clearly, this sequence diverges substantially from the classic Bergen School evolution and

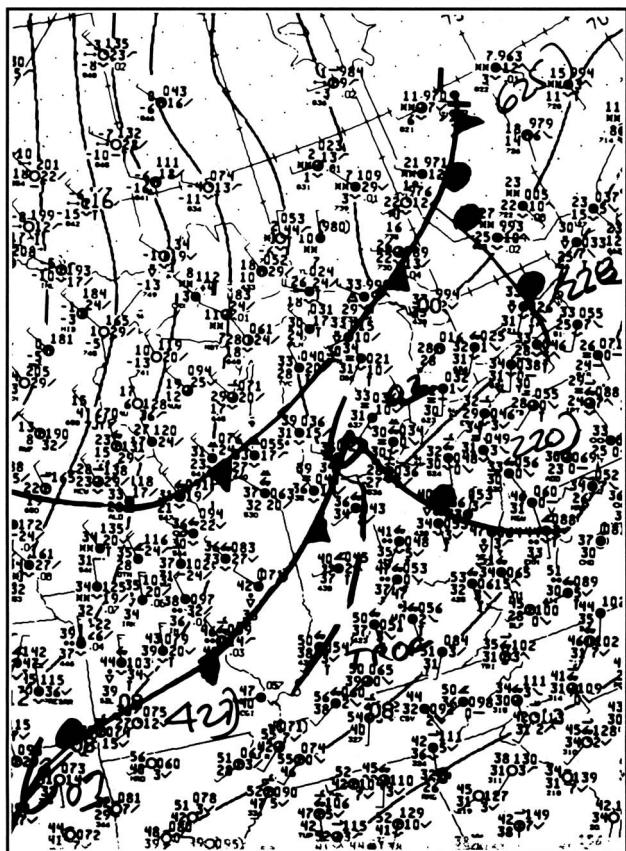


Fig. 6. NMC surface analysis for 1200 UTC 6 December 1989.

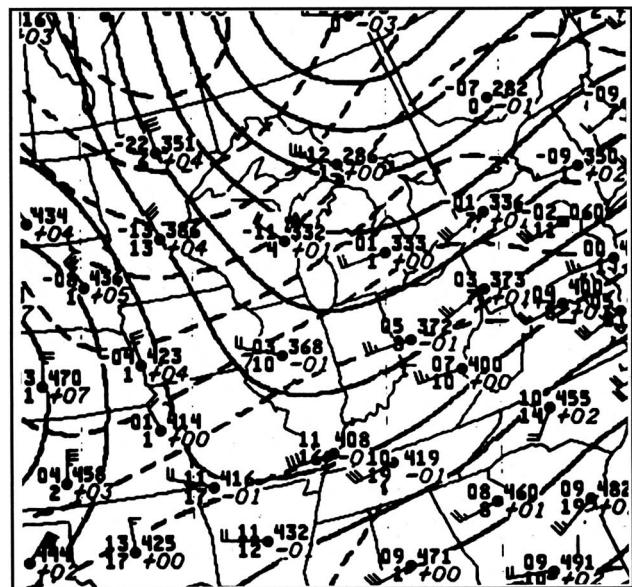
fronts (e.g., the stubby warm front) appear to come and go with little logic.

It is important to note that the above comments are not directed towards ridiculing operational analysts; rather, the above examples pose a challenge to the meteorological community to devise a superior and more consistent system of synoptic analysis. The above problems are not limited to NMC; similar difficulties can be found in the products of foreign operational centers as well as retrospective analyses done by the research community. For example, Fig. 10 shows a surface analysis from the European Meteorological Bulletin, produced by the West German Meteorological Service. Over the Atlantic the frontal analysis is simply and "classically" done. Over land, the story is quite different. For example, over the eastern section of the Soviet Union, there is a tangle of four fronts of varying natures that nearly intersect at a point.

Although the problems at NMC are not unique they are certainly compounded by the use of automated sea-level pressure analyses for the three-hourly North American charts (Bosart 1989). These analyses are often seriously in error over the ocean; and even over land, the computer-analyzed features do not capture structures that would be obvious to a human analyst. As a result, manually-analyzed frontal positions are frequently inconsistent with features of the machine sea-level pressure analyses.

6. Some approaches to the problem

Although this author does not claim to be able to



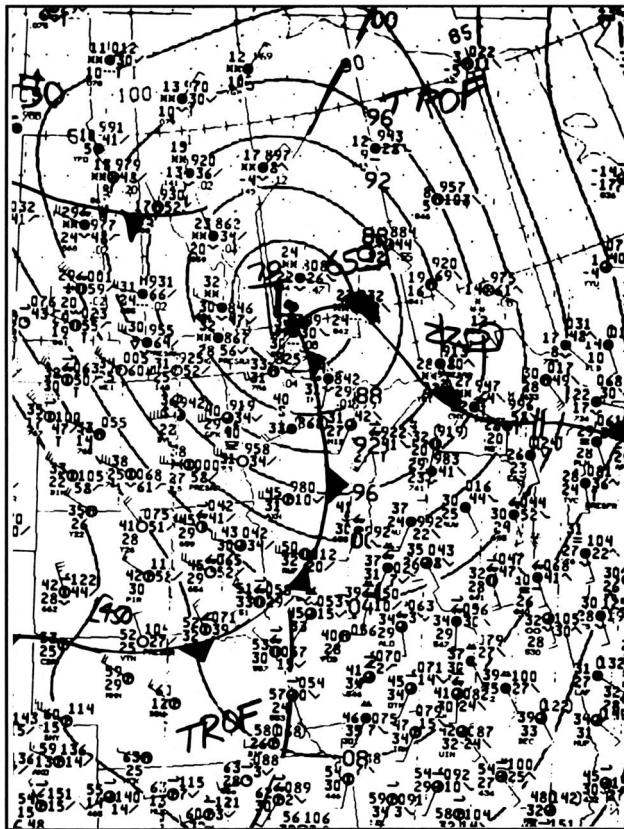


Fig. 9a. NMC surface analysis for 0000 UTC 11 January 1990.

regions and large-scale conditions. We have not clearly documented the evolution of occluded fronts, or even agree on their existence. As noted above, one cause of this unfortunate situation has been a large and confusing array of unconnected ideas regarding cyclone structure and development; as a result, there has been an excessive dependence on the aging Bergen School paradigm and its nearly unamended retention in textbooks. It also can be convincingly argued that limitations in meteorological observations (i.e., a coarse network of twice-daily radiosonde stations) has also circumscribed progress in this field.

The replacement or amendment of scientific paradigms must often wait until new data overwhelm old conceptual models. Such is the situation today with the Norwegian cyclone model. Numerical models are now capable of simulating cyclonic development with great fidelity and offer a powerful tool for diagnosing the detailed evolution of cyclone structures (see Keyser and Uccellini 1987). New observing platforms (e.g., profilers and NEXRAD) offer the potential for the continuous monitoring of cyclone development in sufficient temporal and spatial detail to describe adequately the evolution and structure of midlatitude cyclonic systems. Regional field experiments (such as the proposed winter STORM project or the recent ERICA field program) will make use of many of the

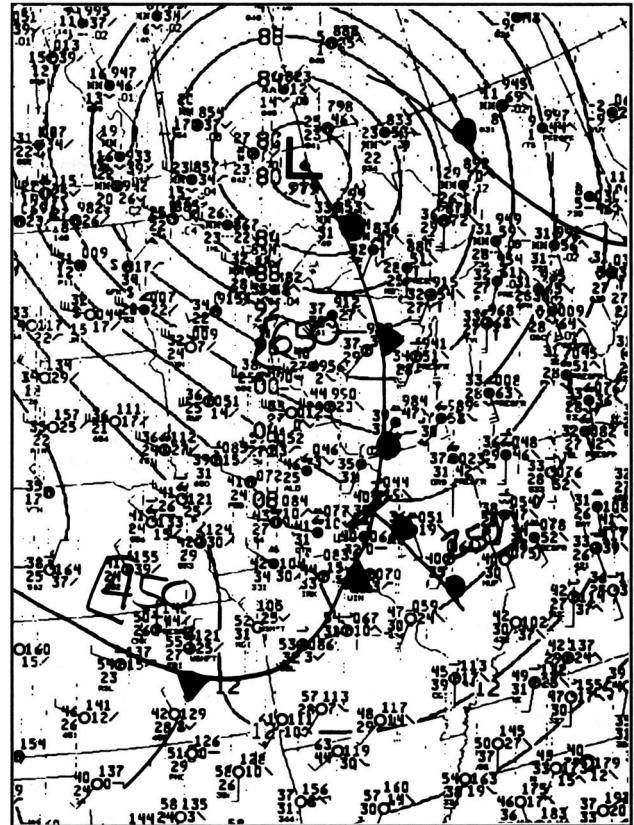


Fig. 9b. NMC surface analysis for 0600 UTC 11 January 1990.

new technologies in order to provide greatly enhanced descriptions of cyclone and frontal development.

In short, new observational datasets and ever more accurate numerical model simulations should be used to establish realistic conceptual models of cyclone evolution and to define how cyclone development is altered by varying environmental conditions (e.g., topography, surface conditions, large scale flow, etc.).

b. Establish a logical and consistent system for analyzing synoptic charts.

Once a comprehensive understanding of midlatitude cyclone evolution is achieved and corresponding conceptual models are established, logical and consistent techniques for analyzing and presenting synoptic charts must be developed. Since the surface synoptic chart has traditionally been the vehicle for displaying conceptual model symbolism, let us consider some possible approaches for analyzing and displaying these charts.

Approach 1) Present analyzed fields without frontal or other types of symbols.

Some people might argue that the real world is far more complex than any simple conceptual model, and therefore it is an exercise in deception to force a simplified model on observations. Such individuals would recommend that observations, analyzed fields

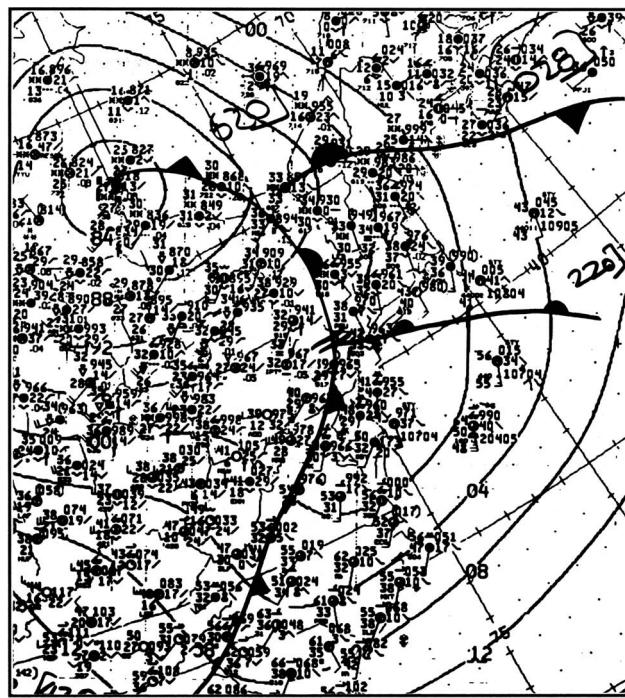
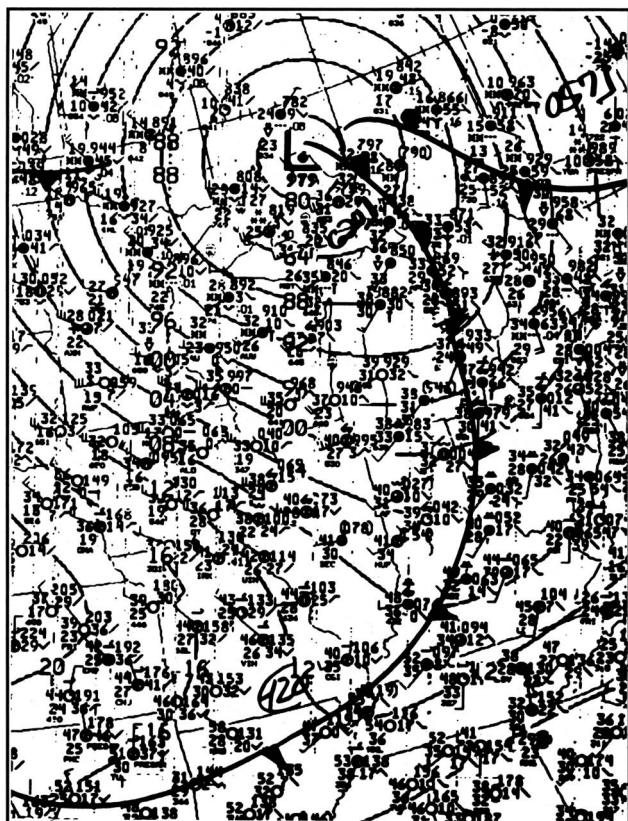


FIG. 9c (left). NMC surface analysis for 1200 UTC 11 January 1990; and Fig. 9d (above): surface analysis for 0000 UTC 12 January 1990.

(e.g., isotherms, isobars, isentropes), and perhaps some derived dynamical quantities (e.g., potential vorticity) speak for themselves. They would note that meteorologists appear to be content with numerical model output, which lacks any frontal symbolism, so why not do the same for observational data? Simple conceptual models might have been useful as tools for gaining insight into the flow aloft when upper level data was scarce, but today three-dimensional information is more readily available. Another advantage of removing frontal symbols is that fronts are not well-defined features. Baroclinicity in the atmosphere varies over a wide range; at what point should the appellation of front be used?

Although this position (no analyzed fronts) might hold the high ground of simplicity, there are arguments against it. Even with its obvious shortcomings, the classic Norwegian cyclone model and the analysis techniques that derive from it, do express some essential truths, one in particular being that many cyclones evolve in a rather similar way, i.e., as an amplifying wave in a region of substantial temperature gradient. This conclusion is evident from conventional observational data, satellite imagery, and numerical model output. Conceptual models can help organize a mountain of observations into a coherent picture and aid the visualization and interpretation of complex three-dimensional motions; they are particularly val-

uable in regions of limited conventional data (e.g., the oceans, where only satellite data and a few ship and aircraft reports might be available). Frontal symbols provide information about temporal changes (e.g., movement of cold and warm air masses) that would require more than one chart if only analyzed fields were shown. Another problem with the non-symbol approach is that automated analyzed fields may not be able to display or correctly position all the features of interest—such as a mesoscale front that is too narrow to be captured by the resolution of the synoptic network. Such a front might be clearly evident using other approaches, such as the analysis of a time series at a single station or from satellite imagery. Finally, one must consider the implications of dropping all frontal symbolism on the general public and media. Fronts are displayed prominently on TV weathercasts and newspaper weather maps and are simple, but useful, tools for communicating weather information to a lay audience. Would the public accept maps with only isotherms or other analyzed fields? Or would some sort of symbolism have to be retained for non-meteorologists?

A surface chart without fronts might consist of station models as well as sea-level isobars and isotherms. Figure 11 presents an illustrative example of such a chart for 1200 UTC 15 December 1987. The traditional NMC surface analysis for that time is shown

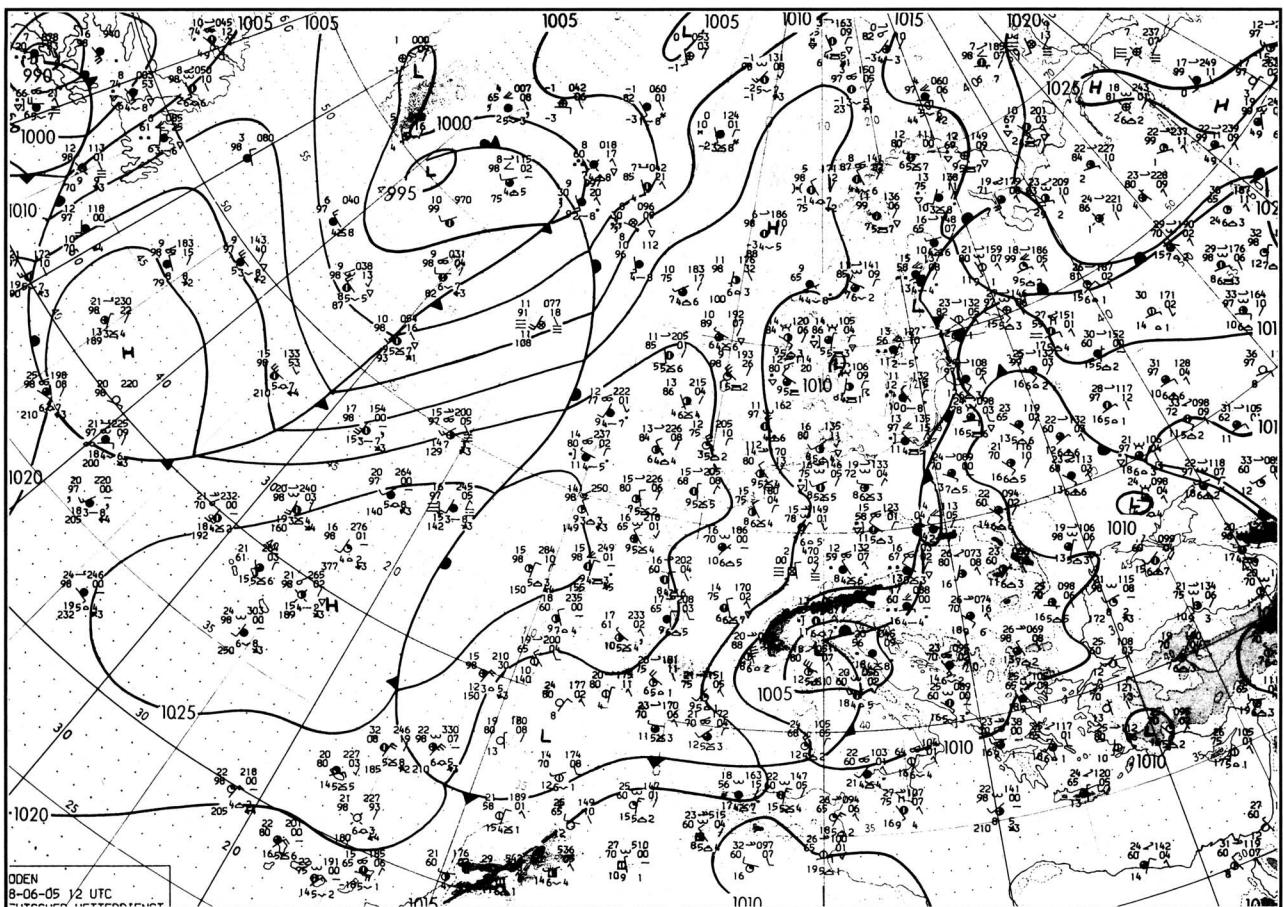


FIG. 10. West German Meteorological Service surface analysis for 1200 UTC 5 June 1988.

in Fig. 12. In the analysis-only chart (Fig. 11), the cold front and the boundary of the cold air damming are quite evident. Also apparent is a region of secluded warm air to the west of the Appalachians. This feature is not well analyzed in the NMC analysis, which indicates a mini warm front leading an occlusion.

Approach 2) Modify current analysis techniques to fit the improved paradigm.

The other extreme would retain the general approach to frontal analysis used today (i.e., station model, isobars, and frontal (or other) symbols on the surface chart) but greatly improve the clarity and consistency of the symbolism used. The following modifications and clarification of current practices would go a long way towards reducing the confusion evident in contemporary analyses:

1) The application of classic Norwegian frontal symbols should be restricted to surface-based fronts that extend through a considerable depth of the lower troposphere. The application of classical frontal symbols to deep synoptic fronts, shallow radiationally-forced regions of large temperature gradient, and windshift lines in polar lows, as is currently done, is a prime example of inconsistent and confusing usage.

2) Frontal symbols should only be used for features that fundamentally concern horizontal density (in reality, temperature) gradients. Frontal symbols should not be used for regions of moisture contrast alone.

3) A modified form of these symbols (or new symbols) could be used for shallow features, such as those associated with gust fronts, sea breezes, topographic damming, and boundary-layer processes. Young and Fritsch (1989) have suggested such a set of symbols for mesoscale analysis.

4) The analyses must be consistent in time, i.e., temporal continuity should be upheld.

An attempt to create a surface chart following these rules is found in Fig. 13. Note that a secluded area of warm air is more clearly indicated than in the operational NMC analysis and the leading edge of the shallow cold air damming is marked by the symbolism proposed in Young and Fritsch (1989), i.e., by perpendicular bars on the shallow, topographically-forced sections.

There are many possible creative variations on the above approach. For example, instead of the classic frontal symbols (with all their considerable baggage) a range of symbols for generic types of transitions (e.g.,

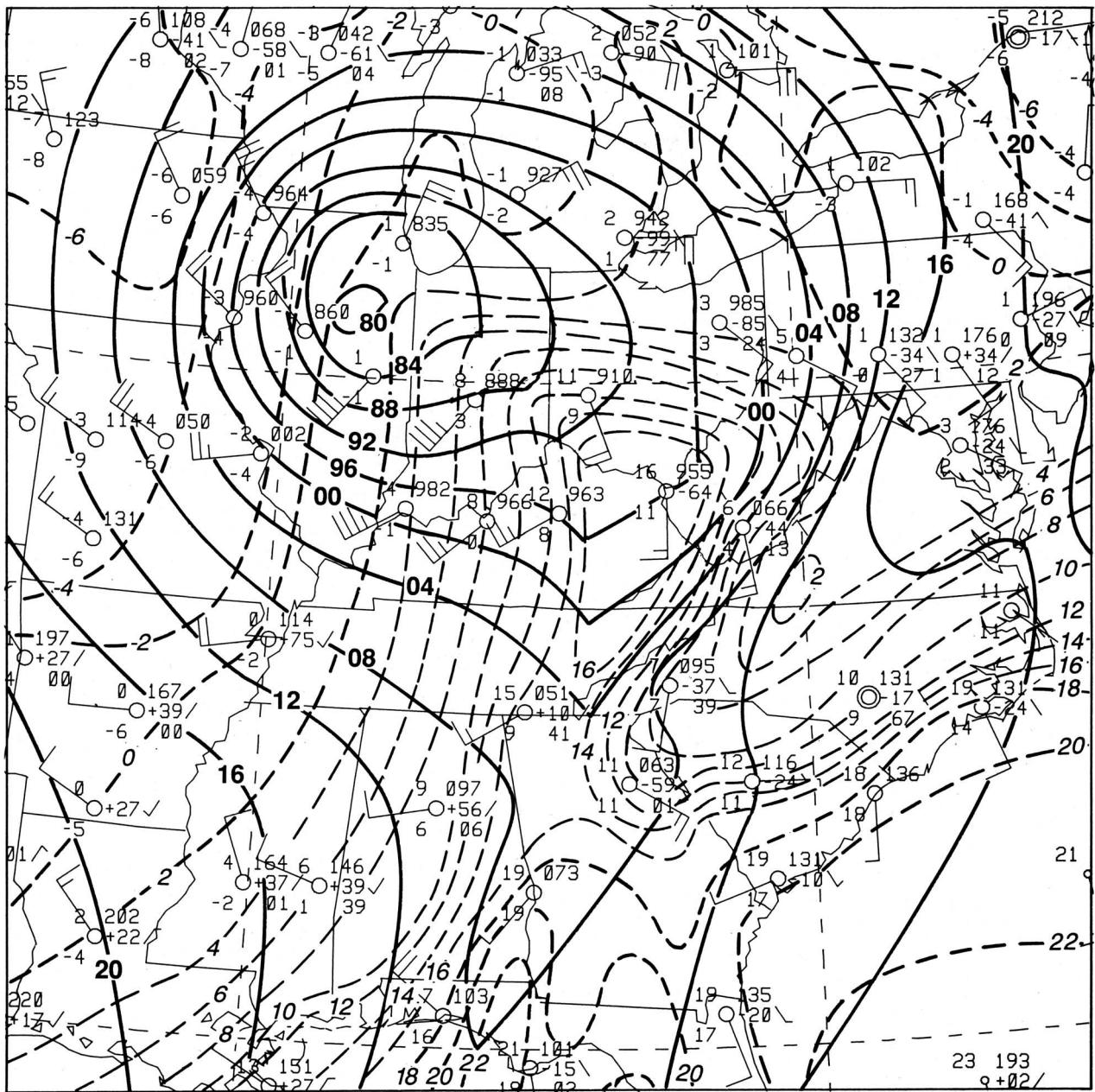


FIG. 11. Surface chart following approach 1 (see text) for 1200 UTC 15 December 1987. Solid lines are isobars (4-mb interval) and dashed lines represent isotherms (2°C interval). Temperatures on the station models are in °C. Note that there are far more observations than indicated by the displayed station models.

wind-shift lines, pressure troughs, lines of changes in gradients) at the surface or aloft could be created. Whatever set of symbols is accepted, consistent and logical usage will be the key to success.

Approach 3) Present analyzed fields and use frontal (or other) symbols only for features that cannot be represented in the analyses.

One of the most serious problems possessed by the first approach (no symbols) is that automated analyzed fields will inevitably miss or improperly represent some small-scale features that are quite evident to human analysts. Furthermore, even manual analyses

might not be able to clearly represent some small scale features. A compromise approach would address this problem by using frontal (or other) symbols to indicate features that are unresolved or improperly positioned by the analyzed fields.³ A possible problem with this approach is that boundaries (or symbols) might come and go on the display as their intensity and horizontal scale varied. Furthermore, a generally-

³This approach was independently suggested to the author by Professors Fred Sanders and Richard Reed.

acceptable criterion for making the decision to display a feature would have to be developed.

A major question not addressed so far is whether upper level features, such as middle or upper tropospheric fronts, should be noted on synoptic charts. In addition, it is often observed that important synoptic features (e.g., a warm front) can be obscured at the surface by a thin veneer of cold air at low levels. Should important upper level features that are not clearly evident in surface fields (e.g., temperature) be noted in some way? An example of this approach is the Canadian trowal model (Penner 1955), in which the base of the upper level cold front associated with an occlusion is indicated at the surface.

No matter which approach is taken, it is difficult to underestimate the obstacles in the way of modifying the Norwegian analysis methodology. It has dominated so long because of its simplicity and easy application; any new methodology or set of symbols must be limited in scope and straightforward enough to allow easy learning and use.

c. The unrealized potential of modern technologies for the analysis and display of meteorological data

A major reason that a comprehensive conceptual model of cyclone development has been slow in coming and analysis techniques have not progressed significantly is because of a general inability to visualize the three-dimensional evolution of synoptic systems. The integration of large numbers of horizontal maps, cross sections, and soundings into a mental picture of the three-dimensional structural evolution of a cyclone is a daunting challenge that few can master. In regard to this problem, it is clear that meteorologists have not taken full advantage of the potential of modern technologies of communication, analysis, and

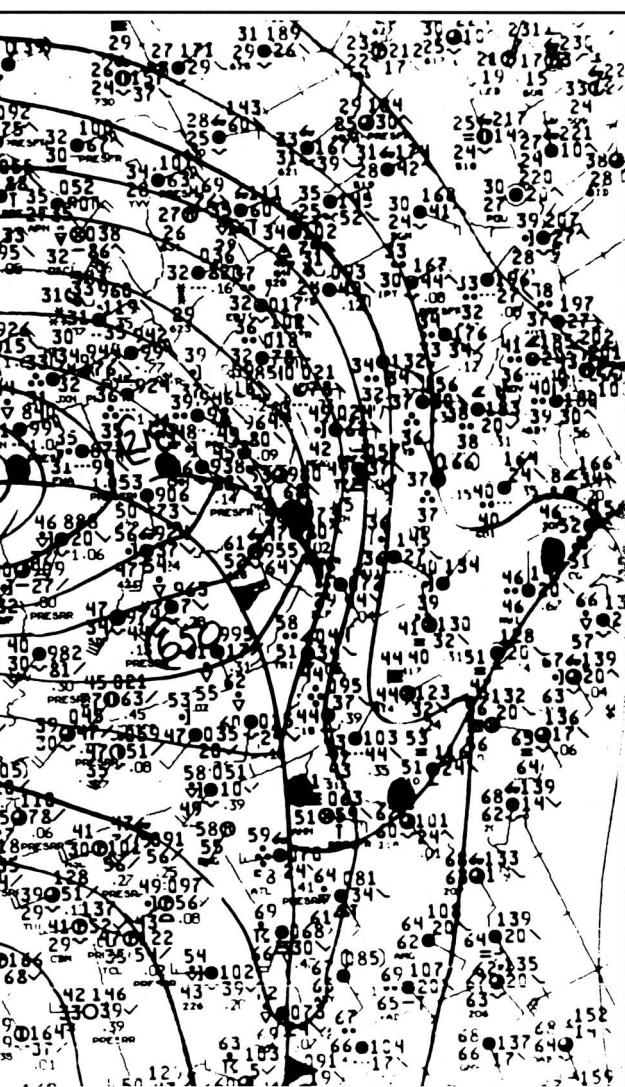


FIG. 12. National Meteorological Center surface chart for 1200 UTC 15 December 1987.

display. Synoptic charts are generally poor quality, monochrome products that have improved only marginally over the past 30 years. Meteorologists need to comprehend the three-dimensional evolution of highly complex systems; it is readily apparent that two-dimensional, one-color displays (either paper or electronics) are not able to present enough information even today and certainly will be inadequate in the upcoming era of increased observational data. Conventional modes of presentation fail to tap the exceptional ability of humans to grasp the subtleties of complex structures when they are presented in the form of three-dimensional images.

Fortunately, the technologies that promise to produce a flood of information also hold the potential for solving the problems of data management, analysis, and display. By adding color alone, meteorologists could comfortably add several fields (e.g., isotherms

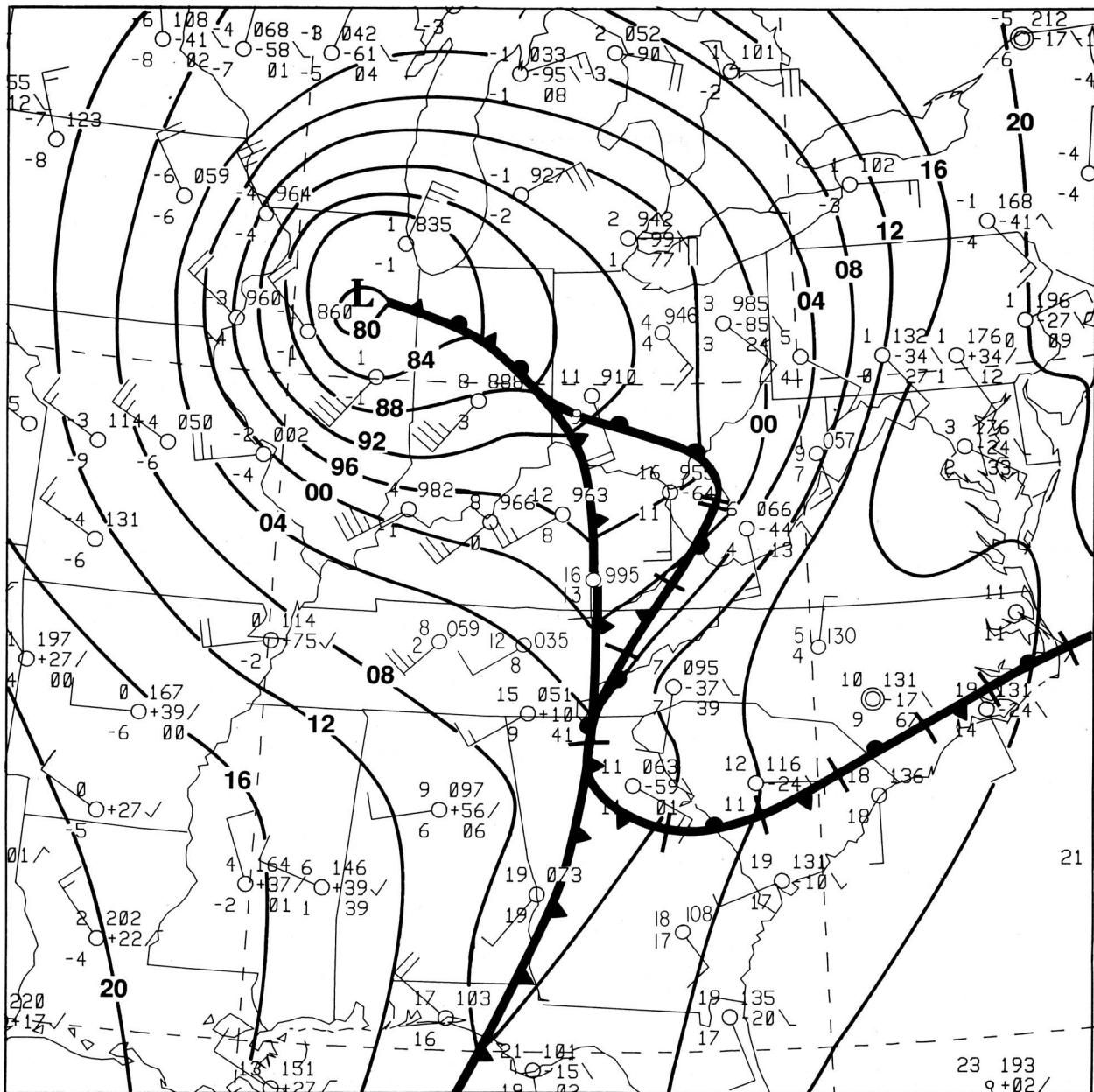


FIG. 13. Surface chart following approach 2 (see text) for 1200 UTC 15 December 1987.

at the surface) to synoptic charts. Three-dimensional graphics could allow the viewing of synoptic system structure from a variety of perspectives, and would provide insights that might never be attained using conventional displays (see Wilhelmson et al. 1989; Schiavone and Papathomas 1990). Many of the software and hardware tools that will allow the solution of the display/visualization problem exist today and some progress in their application has been made (e.g., Mcdas and Profs interactive systems); unfortunately, the dispersal of such capabilities within the research and operational communities has been slow and uncoordinated.

7. Summary and conclusions

For over a half-century, the Bergen School conceptual model of cyclone structure and development has dominated the practice of synoptic meteorology, particularly in the manner in which surface synoptic charts have been analyzed. Although the Norwegian paradigm captures several of the essential features of cyclone evolution, research and operational experience over the last 70-odd years has revealed significant deficiencies. For example, it is now clear that cyclone development does not require preexisting, extensive polar fronts; rather, only a zone of baroclin-

icity is mandatory for development, with the process of cyclone evolution itself sharpening diffuse temperature gradients into intense frontal zones. Warm fronts, a major component of the Norwegian cyclone model, are often weak or limited in extent. Classical Norwegian cyclone evolution also does not include the process of "instant occlusion," whereby comma cloud features join with open waves to produce apparently mature occluded systems over a short span of time. Finally, not only is the classic "catch-up" occlusion process difficult to document, but in addition, a variety of observational studies have shown that ideal occluded front structures rarely are observed in their entirety. Although these and other deficiencies are known to many in the research and operational communities, this knowledge has had little impact on the manner in which synoptic charts are analyzed or even the way the subject is described in textbooks.

During the past 70 years, meteorologists have followed two main routes in an attempt to improve upon the Bergen School model. One approach has attempted to modify and improve the Norwegian conceptual model, while retaining its essential frontal "flavor," in which most weather is traced to vertical motions forced by frontal surfaces. The other approach has been basically dynamical in perspective. Although impressive gains have been made following both of these approaches, a comprehensive picture of the three-dimensional structure and evolution of mid-latitude cyclones that draws together the collective insights of the past 70 years does not yet exist. Meteorologists are faced with a confusing array of unconnected ideas regarding cyclone structure and development, and thus the old dependable Norwegian cyclone model has remained in ascendancy.

Problems with the underlying conceptual model of cyclone development have been compounded by a lack of consistent and well-defined procedures for the analysis of surface synoptic charts. For example, classic frontal symbols are frequently applied to mesoscale and synoptic-scale features not encompassed in the original Norwegian cyclone model. Bergen-style frontal symbols are not only used for fronts with baroclinicity extending through a significant portion of the lower troposphere, but also for shallow boundary layer features such as those produced by cloud and snow boundaries.

To resolve the above problems, the meteorological community should follow a two-pronged approach. First, the research and operational insights gained over the last half-century should be combined with more recent numerical modeling and observational studies (making use of new technologies such as Doppler radar, dropsondes, aircraft, and profilers) to establish an amended, and more general, conceptual

model of cyclone evolution. An important tool will be advanced analysis and display technologies that will provide a three-dimensional view of cyclone evolution. It may well turn out that cyclone development is highly variable, depending on surface conditions, topography, and other factors. Second, a clear and consistent methodology of analyzing synoptic charts should be devised. Several possible approaches are discussed in section 6.

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