Perspectives on Fred Sanders's Research on Cold Fronts

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ABSTRACT

One characteristic of Fred Sanders's research is his ability to take a topic that is believed to be well understood by the research community and show that interesting research problems still exist. Among Sanders's considerable contributions to synoptic meteorology, those concerned with surface cold fronts have been especially influential. After a brief historical review of fronts and frontal analysis, this paper presents three stages in Sanders's career when he performed research on the structure, dynamics, and analysis of surface cold fronts. First, his 1955 paper "An Investigation of the Structure and Dynamics of an Intense Surface Frontal Zone" was the first study to discuss quantitatively the dynamics of a surface cold front. In the 1960s, Sanders and his students further examined the structure of cold fronts, resulting in the unpublished 1967 report to the National Science Foundation "Frontal Structure and the Dynamics of Frontogenesis." For a third time in his career, Sanders published several papers in the 1990s and 2000s, revisiting the structure and dynamics of cold fronts. His 1967 and 1990s/2000s work raises the question of the origin and dynamics of the surface pressure trough and/or wind shift that sometimes precedes the temperature gradient (hereafter called a prefrontal trough or prefrontal wind shift, respectively). Sanders showed that the relationship between this prefrontal feature and the temperature gradient is fundamental to the strength of the front. When the wind shift is coincident with the temperature gradient, frontogenesis, or strengthening of the front, results; when the wind shift lies ahead of the temperature gradient, frontolysis, or weakening of the front, results. A number of proposed mechanisms for the formation of prefrontal troughs and prefrontal wind shifts exist. Consequently, much research remains to be performed on these topics.

"Fronts are a real and important feature of our environment, and an effort should be made to better understand them. We hope that this investigation is a contribution in that direction."

— Sanders (1967, p. 4.3)

1 Introduction

Synoptic meteorology has had a reputation of being less rigorous than other disciplines (e.g., Reed 2003, p. 2), perhaps rightly so in some instances. But, Fred Sanders and his colleagues Dick Reed and Chester Newton, provided legitimacy to our discipline by merging the application of dynamics and quantitative diagnosis with the study of observed weather systems (e.g., Gyakum et al. 1999). Besides his contributions as a teacher and mentor to many, Fred Sanders made fundamental contributions to synoptic meteorology in the structure, dynamics, and analysis of surface cold fronts. Sanders's research illustrates one of his characteristics that I find most inspiring: the ability to take a weather phenomenon that is considered solved by the research community and to show that compelling research problems still exist.

Any study of a cold front, whether it be an idealized simulation or an observational analysis, inevitably will be compared to Sanders (1955), "An Investigation of the Structure and Dynamics of an Intense Surface Frontal Zone." Sanders (1955) was the first, the simplest, and I would argue, still the best, quantitative study of the structure and dynamics of a cold front. Based on Sanders's 1954 Ph.D. thesis, this paper has influenced numerous synoptic and mesoscale meteorologists, theoreticians, and modelers by illustrating the archetype classical cold front. One who was so influenced was Daniel Keyser. Specifically, a goal of Keyser's Ph.D. thesis, eventually published as Keyser and Anthes (1982), was to reproduce the intense, low-level updraft at the leading edge of Sanders's (1955) cold front in a primitive-equation model starting with idealized initial conditions (D. Keyser 2003, personal communication).

Sanders (1955) serves as a launching point for further studies of cold fronts, a topic to which Sanders would return at two later times in his career (the 1960s and the 1990s/2000s). In the 1960s, Sanders and his students showed that the pressure trough and wind shift in some fronts lay

ahead of the temperature gradient in the warm air, rather than coincident as in zero- and first-order discontinuity models of fronts (e.g., Petterssen 1933; Godson 1951; Saucier 1955, 109; Bluestein 1993, 240–248). Such features are hereafter called *prefrontal troughs* or *prefrontal wind shifts*. This body of research by Sanders and his students was consolidated into a report to the National Science Foundation entitled "Frontal Structure and the Dynamics of Frontogenesis," softbound within a distinctive, dark red cover (Sanders 1967). This report has become a sought-after cult classic among some meteorologists. Although some material eventually appeared in print (Sanders 1983), this report remains largely unpublished.

Later, in the 1990s and 2000s, as an outgrowth of his long-standing criticism of the quality of operational frontal analyses and the lack of operational surface isotherm analysis (Sanders and Doswell 1995; Sanders 1999a; Sanders and Hoffman 2002; Sanders 2005), Sanders revisited these issues of the nonsimultaneity of the temperature gradient and wind shift by presenting analyses of more nonclassical cold fronts (Sanders 1999b; Sanders and Kessler 1999).

The purpose of this paper is to collect and review some aspects of cold-frontal structure, evolution, and dynamics in the context of Sanders's work. Other papers in this volume that discuss other aspects of surface fronts are Emanuel (2007) for arctic fronts as potential-vorticity fronts, Bluestein (2007) for fronts and other surface boundaries in the southern Plains, and Bosart (2007) for coastal fronts, cold-air damming, and cool-season fronts adjacent to the eastern slopes of the Rocky Mountains. Sanders's contributions to surface frontal analysis are discussed in more detail by Hoffman (2007) and Kessler (2007).

In section 2 of this paper, Sanders's career-spanning research on surface cold fronts is put into perspective by briefly reviewing the history of frontal research. In section 3, the structure, kinematics, frontogenesis, and dynamics of a classical cold front is reviewed, from the work of Sanders (1955) and others. Section 4 reviews Sanders's (1967) further analyses of cold fronts, whereas section 5 reviews Sanders's 1990s/2000s work. Section 6 concludes this paper with a discussion of the implications for cold fronts from the perspective of two dichotomies: theory versus observations, and research versus operations.

2 Cold fronts: Changing paradigms

"Since the first exposition by the Norwegian school of the concept of atmospheric fronts, the attitude of meteorologists towards fronts has gone from great enthusiasm through disappointment to the present air of confusion, consisting of acceptance with little understanding."

— Sanders (1967, p. 1.1)

Discontinuities in surface wind, temperature, and pressure, features we now recognize as fronts, have long been observed. Ficker (1923), Gold (1935), Bergeron (1959), Taljaard et al. (1961), Kutzbach (1979, section 6.7), Davies (1997), Newton and Rodebush Newton (1999), and Volkert (1999) have presented historical reviews of early frontal research. Surprisingly, the basic vertical structure of a cold front was advanced by Loomis as early as 1841 (Fig. 1). Unfortunately, Loomis's (1841) schematic made little impact at the time because the role of baroclinicity in midlatitude cyclones and fronts was not seriously discussed until the late 1800s (Kutzbach 1979, p. 30). Other early frontal studies included Bjerknes (1917) and others by his colleagues, who collectively became known as the Norwegian School (Friedman 1989, 92–94, 122–137, 158–178). Their work culminated in the conceptual model of extratropical cyclone structure and evolution known as the Norwegian cyclone model (Bjerknes 1919; Bjerknes and Solberg 1922; Bergeron 1937; Godske et al. 1957, section 14.3).

By applying the principles of physics and mathematics to the atmosphere, as well as employing detailed observational analysis from a dense network of surface stations over Norway, the Norwegian cyclone model synthesized and built upon earlier work to create a compact modern theory for cyclogenesis and frontogenesis. The Norwegian cyclone model has been quite successful in providing a common language to facilitate communication among scientists, forecasters, and the public. Even today, the Norwegian cyclone model serves as a first step in describing the structure and evolution of midlatitude cyclones (e.g., Wallace and Hobbs 1977, 126–127; Carlson 1991, chapter 10).

2a Interest wanes in frontal research

"Sometimes I wonder whatever happened to fronts?" — Sanders (1967, p. 5.1)

Between the two World Wars, the Norwegian cyclone model achieved a worldwide following, a period Ball (1960, p. 51) refers to as the "front-happy years." Ball's assertion is supported by Gold's (1935) detailed 51-page article documenting the state of frontal thinking during this period. After World War II, however, the discipline of frontal structure and dynamics waned. As Taljaard et al. (1961, p. 28) stated, "A perusal of the titles of the more than 100 articles in the *Compendium* [*of Meteorology*] would leave the uninitiated reader with the impression that there are no such things as fronts and air masses," despite the *Compendium* being "a survey of the current state of meteorology" (Malone 1951, p. v). Similarly, Sanders's quote above lamented the lack of interest in fronts. He continued, "fronts have passed through a sort of Dark Age of neglect in which only a loyal few worried very much about them" (Sanders 1967, p. 5.1).

Perhaps one impetus for the waning interest in frontal research, as noted by Kirk (1966), Sanders (1967), and Hoskins (1982), was the changing view of fronts as the result of cyclogenesis via the Charney (1947) and Eady (1949) paradigms for baroclinic instability, rather than the seat of the instability as originally envisioned by Bjerknes and Solberg (1922). Reed (2003, p. 3) noted that he and Sanders were "kindred spirits" during their days at MIT in the 1950s because, "it seemed obvious to us—and we were not alone in this view—that fronts often strengthened during cyclogenesis rather than providing sharp preexisting thermal discontinuities on which cyclones formed." The driving force behind cyclogenesis was the upper-level short-wave trough, and early observational evidence for the importance of positive vorticity advection aloft in cyclogenesis came from Petterssen (1955) and Petterssen et al. (1955), and was later supported by Sanders (1987) and Sanders and Auciello (1989) for explosively developing cyclones over the North Atlantic Ocean.

Another possible reason that interest in fronts waned was that, unlike other atmospheric features, a uniform definition of a front could not be agreed upon by meteorologists (e.g., Sanders and Doswell 1995; Sanders 1999a). This point becomes even more apparent when viewed in the context of exercises comparing the range of interpretations of the atmosphere by subjective analyses among different analysts (e.g., Vincent and Borenstein 1980; Uccellini et al. 1992). Such exercises may have frustrated meteorologists by the perceived unscientific nature of frontal research. Or, perhaps,

the inactivity in frontal research may be a result of the attitude epitomized by Shapiro et al. (1985, p. 1168): "one can say that surface fronts are presently considered one of the better understood and predictable of mesoscale atmospheric phenomena."

During the initial heyday of mesoscale meteorology in the 1980s, it appeared a renewed interest in fronts would develop with the rise of mesoscale modeling (Keyser and Uccellini 1987), mesoscale instabilities (e.g., frontal cyclogenesis, conditional symmetric instability), and a cornucopia of field programs (e.g., GALE, FRONTS, ERICA, STORM-FEST, FASTEX), but this interest was short-lived. For a second time in the history of modern meteorology, interest declined in frontal research. This second decline can be measured by participation at the eleven Conferences on Mesoscale Processes from 1983 to 2005 when the number of presentations on fronts declined from a high of 32 (21% of the total number of presentations) in 1990 to 6 (2.5%) in 2005 (Fig. 2).

2b Operational frontal-analysis methods change

". . . the practice of frontal analysis of surface data spread virtually everywhere outside the tropics, despite disappointment in cyclone behavior which often deviated substantially from the Norwegian rules." — Sanders (1983, p. 177)

In the operational forecasting environment, fronts encountered a different fate, but the outcome was the same—eventual disillusionment. The acceptance of the Norwegian cyclone model by the U.S. Weather Bureau (Namias 1983; Newton and Rodebush Newton 1999) led to the Weather Bureau abandoning surface isobar and isotherm analyses in favor of the now-familiar station model and frontal notations on its operational weather maps.

> The most striking change in the new map is the substitution of symbols indicating position and movements of air masses for the old familiar concentric ellipses of isobars and isotherms of weather maps in use until now. Isobars are still present, but more widely distributed, so that the map is much less striped-up with these curving lines. — *Science* (1941)

Thus, the Norwegian frontal analysis supplanted operational isotherm analysis in 1941. Over fifty years later, Fred Sanders became the leading figure in arguing that the inability to trust the Norwegian frontal analyses resulted from omitting the isotherms on analyses that were presumably constructed based on those very same unanalyzed isotherms! What was gained by this change in 1941 was a more compact description of the present weather using the conceptual model of the Norwegian cyclone. Unfortunately, the Norwegian analysis methods injected greater subjectivity into the analysis of weather maps. In addition, the meteorological community failed to evolve their frontal-analysis techniques given new advances, new meteorological structures and phenomena, and the growing emphasis on mesoscale analysis (e.g., Kocin et al. 1991). [At least two attempted proposals for revised analysis conventions did not become generally accepted (Colby and Seitter 1987; Young and Fritsch 1989).] Some attempts at automating surface isotherm analysis (e.g., Renard and Clarke 1965; Clarke and Renard 1966; Huber-Pock and Kress 1989; and others reviewed in Table 1 in Hewson 1998) may have failed because the horizontal grid spacing of the datasets at the time was too coarse. Later attempts with higher-resolution datasets by Hewson (1998) and McCann and Whistler (2001), however, have been much more successful. Along with the increasing automation in the forecast office, some have reported that map-analysis skills have atrophied or have been lost entirely (e.g., Bosart 1989, 2003; Mass 1991; Sanders and Doswell 1995; McIntyre 1999). In this environment, Sanders and Doswell (1995) made a call for returning to operational isotherm analyses.

The waning scientific interest in frontal research and the reduction in operational isotherm analyses have left the atmospheric science community clinging to an outdated and sometimes incorrect caricature of fronts that evolved from the Norwegian cyclone model, a state not too dissimilar from the period when Sanders (1955) was written (Reed 2003, p. 3). Despite the abundant evidence that fronts are more complicated than those presented by the Norwegian cyclone model, these caricatures of frontal structure and dynamics persist. Many authors have argued that scientific and forecasting progress has been inhibited sometimes by the success of the Norwegian cyclone model (e.g., Sutcliffe 1952; P. Williams 1972; Schwerdtfeger 1981, p. 505; Hoskins 1983, pp. 1 and

14; Mass 1991; Schultz and Trapp 2003, section 7). For example, some surface analysts identify the north–south-oriented boundary equatorward of a surface cyclone as a cold front, even if this feature is only a dryline or a lee trough without a significant temperature gradient (e.g., Hobbs et al. 1990, 1996; Sanders and Doswell 1995; Sanders 1999a). The crusade against the caricaturization of fronts and the deterioration of surface analysis techniques has one of its most outspoken proponents in Fred Sanders (Hoffman 2007).

To counter this caricaturization, we present the properties of cold fronts as derived from examples that Fred Sanders has published. In the next section, we begin with the archetypal example of a cold front: Sanders (1955).

3 Sanders (1955): The archetypal cold front

"If we are to learn anything about fronts, we must at least be sure our research is done on 'real' fronts, and not just regions where someone has drawn a line on a weather map."

— Sanders (1967, p. 1.2)

Keyser (1986) reviewed the characteristics of surface cold fronts from three observational studies: Sanders (1955), Ogura and Portis (1982), and Shapiro (1982). These three cases represented simple cases from which to build dynamical conceptual models. These three fronts, however, all occurred over the central Plains of the United States, all were characterized by weak or nonexistent cyclogenesis (e.g., Fig. 3a), and two of them (Sanders and Shapiro) produced little, if any, precipitation. Thus, generalizing from these three cases requires caution. Patterned after the conclusions in Sanders (1955, p. 552), Keyser (1986, p. 230) identified common structural aspects from the above three studies. Below, we examine the evidence for these conclusions and, where applicable, extend them to cold fronts in general.

- **Fronts are strongest at the surface and weaken rapidly with altitude.** As shown in Sanders (1955), the horizontal gradient of potential temperature was strongest near the surface and weakened upward (Fig. 3b). Neglecting diabatic effects, Sanders (1955) showed

that frontogenesis in this cross section could be expressed as the sum of two terms: confluence and tilting (Fig. 4). He showed that confluence dominated near the Earth's surface (Fig. 4a), where the tilting term was small owing to the horizontal gradients of vertical motion being small (Fig. 4b). Farther aloft, tilting was strongly frontogenetical in the warm air directly above the surface front and strongly frontolytical within the frontal zone (Fig. 4b). Above the surface within the frontal zone, frontolysis by tilting dominated the frontogenesis by confluence (Figs. 4b,c), explaining the weakening of the frontal zone away from the ground. Later observational (e.g., Ogura and Portis 1982; Shapiro 1984) and modeling studies (e.g., Hoskins and Bretherton 1972; Keyser et al. 1978; Rutledge 1989; Koch et al. 1995; Thompson and Williams 1997) have confirmed this basic tenet of Sanders (1955), although the release of latent heat in the updraft may offset the frontolysis by tilting (e.g., Rao 1966; Palmén and Newton 1969, p. 261; Bond and Fleagle 1985; Orlanski et al. 1985; Koch et al. 1995; Bryan and Fritsch 2000; Locatelli et al. 2002; Colle 2003).

- **A narrow plume of rising warm air exists above the surface frontal position.** Sanders (1955) calculated an upward vertical motion exceeding 0.25 m s^{-1} at a height of 1 km above the nose of the front (Fig. 3c). Subsequent direct measurements of updraft plumes of precipitating cold fronts (e.g., Browning and Harrold 1970; Carbone 1982) and other nonprecipitating cold fronts (e.g., Young and Johnson 1984; Shapiro 1984; Shapiro et al. 1985; Bond and Shapiro 1991; Ralph et al. 1999; Neiman et al. 2001) indicate the updrafts of cold fronts can be as strong as several m s^{-1}. Dry, inviscid, idealized, two-dimensional cold fronts (e.g., Hoskins and Bretherton 1972) do not capture such magnitudes or the strong vertical gradients of vertical motion. The addition of Ekman pumping by Blumen (1980) into the analytic solutions of Hoskins and Bretherton (1972) produced greater, but still insufficient, vertical motion and a maximum in the midtroposphere rather than in the lowest few km. The solutions to these two inviscid semigeostrophic models were calculated only to the time when the surface front collapsed (mathematically, the temperature gradient at the surface becomes infinite). To obtain updraft plumes similar to those observed above, idealized models of

fronts can be formulated in one of three ways: (i) numerical solution of a primitive-equation model (e.g., Keyser and Anthes 1982, 1986), (ii) numerical solution of a semigeostrophic model including viscosity (e.g., Xu et al. 1998; Xu and Gu 2002), or (iii) analytical solution beyond collapse of an inviscid semigeostrophic model using Lagrangian potential-vorticity conservation (e.g., Cullen 1983; Cullen and Purser 1984; Purser and Cullen 1987; Cho and Koshyk 1989; Koshyk and Cho 1992). The third approach produces a strong vertical gradient of vertical motion after the frontal collapse, but the frontal and wind structures appear unrealistic because the effects of boundary layer and surface friction are neglected. These results, as well as results published by others, showed that the strength of the vertical motion plume at the leading edge of modeled cold fronts was very sensitive to the formulation of the boundary layer (e.g., Blumen and Wu 1983; Thompson and Williams 1997; Chen et al. 1997; Chen and Bishop 1999) and the lower boundary conditions (e.g., Xu et al. 1998; Gu and Xu 2000; Xu and Gu 2002).

Keyser and Anthes (1982) found that the frictional convergence at the surface cold front was a consequence of the depletion of the along-front momentum by the downward turbulent flux of momentum to the surface. The depletion of momentum caused the winds to become subgeostrophic, deviate towards the pressure trough/front, and generate inflow towards the front, producing the updraft. The strength of the updraft and its acceleration with height above the ground can be explained by the presence of low-level, near-neutral static stability, as noted by Browning (1990) and Bond and Shapiro (1991). The vertical isentropes at the leading edge of the front explain how such strong updrafts can be generated in the presence of otherwise stable prefrontal soundings. These results were supported by observations of cold fronts showing the importance of friction to the strength of the updraft (e.g., Browning and Harrold 1970; Bond and Fleagle 1985; Fleagle and Nuss 1985; Fleagle et al. 1988; Chen and Bishop 1999; Yu and Bond 2002).[1]

[1]Two caveats to this section require stating. First, the maximum vertical motion observed at the nose of cold fronts and the minimum horizontal scale across the front are sensitive to the resolution of the data. This resolution dependence may explain partially why the vertical motion at the leading edge of the Sanders (1955) front is an order

- **The frontal zone, a region of statically stable stratification, tilts rearward over the colder postfrontal air.** Sanders (1955) showed that air parcels originating in the prefrontal environment near the Earth's surface entered the front, experienced an increasing horizontal temperature gradient, and then were transported aloft in the updraft and rearward into the frontal zone (e.g., trajectory ABCD in Fig. 4c). This rearward tilt of cold-frontal zones (Fig. 3b) is due to the cross-frontal vertical shear of the direct ageostrophic circulation tilting the isentropes rearward with height (R. T. Williams 1972). Specifically, the rear-to-front ageostrophic flow near the surface and the front-to-rear ageostrophic flow aloft tilts the frontal zone rearward with height (see also Bluestein 1993, 337–338). In the absence of the ageostrophic circulation, quasigeostrophic frontogenesis would produce unrealistic vertical fronts (Stone 1966; Williams and Plotkin 1968; Williams 1968). In addition, the postfrontal subsidence may be responsible for maintaining the static stability of the frontal zone (e.g., Keyser and Anthes 1982, p. 1798; Ogura and Portis 1982, 2781–2782). Longwave radiation from the tops of postfrontal stratocumulus clouds may also enhance the stability of the frontal zone, as reviewed by Keyser (1986, 231–232). Although the overwhelming majority of published cross sections through cold fronts show rearward-tilting frontal zones, some fronts tilt forward, as discussed by Schultz and Steenburgh (1999), Parker (1999), van Delden (1999), Stoelinga et al. (2002), and Schultz (2005).

- **Warm air is entrained into the frontal zone near the ground.** Because near-surface air-parcel trajectories from the warm air were ingested into the frontal zone, Sanders (1955) appears to be the first to note that the front was not a material boundary. Later, others

of magnitude smaller than more recent, direct measurements through cold fronts. What controls the minimum scale of fronts remains an unanswered question (e.g., Emanuel 1985a; Boyd 1992). Whereas previous large-scale, idealized model simulations of dry cold fronts did not develop gravity-current-like fronts (e.g., Hoskins and Bretherton 1972; Gall et al. 1987; Snyder et al. 1993), simulations of dry cold fronts by Snyder and Keyser (1996) and Chen and Bishop (1999) showed that a gravity-current-like leading edge could be produced, given sufficient resolution.

Second, it is important to distinguish between precipitating and nonprecipitating fronts. The addition of moisture to idealized cold-frontal simulations results in narrower ascent plumes with stronger vertical motions (e.g., Sawyer 1956; Hsie et al. 1984; Mak and Bannon 1984; Bannon and Mak 1984; Emanuel 1985b; Thorpe and Emanuel 1985). Also, because of the strong vertical motions that could be produced by the leading edge of the cold outflow from a precipitation system, much stronger vertical motions could be possible on even smaller scales.

came to the same conclusion (e.g., Ligda and Bigler 1958; German 1959; Brundidge 1965; Blumen 1980; Young and Johnson 1984; Shapiro 1984; Smith and Reeder 1988; Schultz and Mass 1993; Miller et al. 1996; Parker 1999). Despite this evidence, some textbooks still claim that fronts are nearly material surfaces (e.g., Wallace and Hobbs 1977, 116–117).

Determining whether a front is a material surface comprises two issues. First, consider an adiabatic front. In the absence of mixing, Smith and Reeder (1988) note that some fronts may move along at the advective speed of the cold air and, hence, be considered material surfaces. Yet other fronts, such as those in the presence of along-front warm advection, may move at a speed faster than the advective speed—in other words, propagation is occurring. Smith and Reeder (1988, p. 1940) say, "In essence, the frontal zone, centered on the position of the maximum surface temperature gradient, advances principally because of the differential alongfront temperature advection in the presence of an alongfront temperature gradient as noted by Gidel (1978)." [See also Sanders (1999a).] Such fronts cannot be characterized as material surfaces. Thus, whether or not a front is a material surface may depend on other factors such as the along-front temperature gradient.

Second, because of the no-slip condition at the Earth's surface, prefrontal air parcels with zero horizontal velocity are overtaken by a moving front (e.g., Xu and Gu 2002, 104–105). For this reason, fronts cannot be considered material surfaces. It is this near-surface entrainment that leads to the next characteristic of cold fronts.

- **The postfrontal boundary layer is well-mixed or slightly unstable.** There are two possible explanations for the well-mixed or slightly unstable postfrontal boundary layer. The first mechanism was proposed by Sanders (1955) and Clarke (1961), who argued that fluxes from the ground in their cases were sufficient to yield this well-mixed postfrontal environment. Subsequent circulations in the planetary boundary layer were then essential for transporting this heat vertically (e.g., Fleagle et al. 1988; Chen et al. 1997). Alternatively, the second mechanism is as follows. The idealized cold-front simulations of Keyser and Anthes (1982)

and Xu and Gu (2002) showed that cold advection, in conjunction with a no-slip lower boundary condition, results in near-surface warm prefrontal air passing into the frontal zone by entrainment. In the presence of a thermally insulated lower boundary where surface heat fluxes are zero, superadiabatic lapse rates in the postfrontal air result. Upward turbulent heat transport then produces the postfrontal neutral stratification, a mechanism earlier proposed by Brundidge (1965). This second mechanism likely operates in general, whereas the first mechanism becomes nonnegligible under conditions of strong surface heat fluxes. Specifically, mesoscale model simulations of the Sanders (1955) cold front showed that the surface fluxes were not needed to reproduce this well-mixed layer (Schultz and Roebber 2007).

- **The prefrontal boundary layer is weakly stable.** Relative to the postfrontal boundary layer, the prefrontal boundary layer was weakly stable in the three cases examined by Keyser (1986). This statement does not generalize well to other cold fronts, however, as there can be a tremendous range in the static stability of the prefrontal environment. For example, rope clouds associated with cold fronts (e.g., Cochran et al. 1970; Shaughnessy and Wann 1973; Janes et al. 1976; Woods 1983; Seitter and Muench 1985; Shapiro et al. 1985; Bond and Shapiro 1991) are typically associated with prefrontal soundings characterized by surface-based, shallow moist-neutral layers topped by strong inversions and dry air aloft owing to large-scale subsidence (e.g., Shaughnessy and Wann 1973; Woods 1983). Even vertical motions of several m s^{-1} within the shallow moist layer cannot penetrate the inversion, thus limiting the depth of the rope cloud. The appearance of prefrontal boundary layers over the North Pacific Ocean that were nearly moist neutral and saturated (e.g., Bond and Fleagle 1988) may explain the prevalence for rope clouds over the oceans. In contrast, cold fronts moving into deeper surface-based moist layers with substantially weaker capping inversions may lead to deep moist convection (e.g., Koch 1984; Dorian et al. 1988; Bluestein 2007).

Previous research results support the above generalizations of many of the structural aspects of cold fronts. In addition, textbook illustrations of cold fronts show a discontinuity (or near-

discontinuity) in temperature, a simultaneous wind shift, and coincident pressure trough with a surface cold-frontal passage, a feature predicted from zero- and first-order discontinuity theory (e.g., Petterssen 1933; Godson 1951; Saucier 1955, 109; Bluestein 1993, 240–248). [In this regard, Schultz (2004, his Fig. 9) and Schultz and Roebber (2007, their Fig. 2b) showed that the front studied by Sanders (1955) may not be as classical as previously believed. A mesoscale model simulation of the Sanders (1955) cold front presented by Schultz and Roebber (2007) also reveals some potentially interesting aspects of this cold front that deviate from Sanders's (1955) original analysis.] Not all cold fronts, however, may feature the simultaneity of the temperature decrease, wind shift, and pressure trough, as is demonstrated in the next two sections.

4 Sanders (1967): Further studies of cold fronts

"Fronts do not just suddenly exist. They form, go through intensifications and weakenings, become diffuse and finally indistinguishable." — Sanders (1967, p. 4.8)

Sanders resumed his analyses of surface fronts in the 1960s. The National Science Foundation awarded Sanders $117 200 over four years to perform a "description of typical frontal structure in the three-dimensional fields of temperature and wind, diagnosis of the fields of vertical motion and divergence associated with fronts, study of the frontogenetical and frontolytical processes, and study of the effects of friction" (Sanders 1967, p. 1). His 1967 report was principally a collection of ten appendices, comprising excerpts from student theses and papers presented at conferences. The first four appendices analyzed cases of surface cold fronts over Texas and Oklahoma, and these appendices are summarized below; the remaining six appendices dealt with upper-level fronts and other projects unrelated to fronts and are not discussed here.

4a "Detailed analysis of an intense surface cold front" by Jon Plotkin (S.M. thesis, August 1965)

This section presented an analysis of the Texas cold front of 20–21 January 1959 using standard synoptic surface data. One-hour temperature drops associated with this cold front ranged from

18°C (33°F) at Mineral Wells to 3°C (6°F) farther equatorward at Galveston. The changes in the wind consisted of two generally separate features: a change in direction, followed by an increase in speed. The wind shift preceded the temperature drop by as much as an hour at some stations. The temperature drop accompanied, or was close to, the increase in wind speed, with the pressure trough occurring in the warm air.

Confluence was the strongest frontogenetical process acting on the front. The front would inevitably weaken, however, owing to the convergence at the wind shift not being coincident with the temperature gradient, along with the frontolytical effect of turbulence. Indeed, divergence quickly followed the frontal passage and the front weakened as it moved equatorward. This conclusion would become a common theme for Sanders: when the temperature gradient and wind shift were coincident, the front would undergo frontogenesis, but when the wind shift preceded the temperature gradient, the front would undergo frontolysis (Fig. 5). This sentiment echoed that of Petterssen (1936, p. 21) who proposed the following rules, "(a) Fronts that move towards a trough increase in intensity. (b) Fronts that leave a trough dissolve." Sanders's conclusions were tentative, however, owing to the hourly reporting of the stations and the lack of simultaneous pressure, temperature, and wind data from stations. These limitations were remedied in the next appendix.

4b "Detailed analysis of an intense surface cold front" by Fred Sanders and Jon Plotkin (paper delivered at meeting of the American Meteorological Society, Denver, Colorado, 25 January 1966)

During the 1960s, the National Severe Storms Laboratory beta network (Kessler 1964, 1965) covered south-central Oklahoma with a surface observing station spacing of 16–24 km. This network provided Sanders the opportunity to acquire high temporal- and spatial-resolution data in the region where strong cold fronts were relatively common. Some of the material from this appendix was later published in Sanders (1983).

On 23 March 1965, a cold front moved through the network. The time between the temperature break and the wind shift ranged from –1 to 34 minutes (Fig. 6). A composite of the time series at individual stations during the frontal passage showed that the average temperature drop of

1.4°C (2.5°F) in one minute occurred around the same time as the wind strengthened (Fig. 7). Within nine minutes after the initial temperature drop, the temperature had decreased an average of 7.2°C (13°F). Assuming a two-dimensional and steady-state front, the maximum vorticity and convergence lay ahead of the maximum temperature gradient and frontogenesis by about 1 km (Fig. 8). This appendix abruptly ended, leaving the next appendix to expand on this event in more detail.

4c "Analysis of mesoscale frontogenesis and deformation fields" by R. Throop Bergh (S.M. thesis, May 1967)

Additional analysis of the 23 March 1965 cold front, along with two more fronts (24 March 1964 and 24 April 1965), included horizontal maps of the divergence, vorticity, axes of dilatation, resultant deformation, and frontogenesis at the time the fronts were in the mesonetwork (e.g., Fig. 9). For these three events, there was no correlation between the strength of the temperature (density) gradient and the frontal speed, as might be expected if the fronts behaved as density currents (e.g., Seitter 1986). Even with the small spacing of the network, most wind shifts occurred less than 5 minutes before the temperature decrease, although for at least one station this value was as large as 34 minutes. Despite the huge rates of frontogenesis calculated [0.45°C km^{-1} h^{-1} or 1.5°F (n mi)$^{-1}$ h^{-1}] (e.g., Fig. 9), all three fronts maintained a nearly constant intensity as they moved through the network, suggesting a balance existed between deformation frontogenesis and turbulent frontolysis.

4d "Mesoscale analysis of complex cold front based on surface and tower data" by William T. Sommers (S.M. thesis, July 1967)

The final analysis of a surface cold front in Sanders (1967) was performed on the front of 8–9 June 1966. This case differed from the others in that the front appeared to undergo three hours of frontolysis. No large frontolytical deformation was present because of the near coincidence of the temperature decrease and the wind shift. Thus, diabatic turbulent processes must have been acting to weaken the front. Data from a 444.6-m (1458.5-foot) tower showed that the leading edge of the front, as defined by the wind change, was vertical or forward-tilting below 44.5 m (146 feet)

AGL, but rearward-tilting with height above.

5 Sanders at the turn of the millenium

"Routine analysis does not stop with consideration of the temperature field."

— Sanders (1999a, p. 954)

In 1995, Sanders coauthored a critique of current surface analysis techniques with Chuck Doswell (Sanders and Doswell 1995). Returning once again to his roots by trying to raise the quality of operational surface analysis, Sanders was poised to revisit the topic of fronts once again. Three more papers (Sanders 1999a,b, 2005) advanced Sanders's agenda of bringing more science into surface map analysis and are discussed below. A fourth paper (Sanders and Kessler 1999) on interesting frontal passages in rural Oklahoma is discussed in more detail by Kessler (2007). A fifth paper (Sanders and Hoffman 2002) describes a climatology of surface baroclinic zones and is discussed by Hoffman (2007).

Sanders (1999a) "A Proposed Method of Surface Map Analysis" picks up where Sanders and Doswell (1995) left off. Sanders (1999a) presented instances of where operationally constructed surface maps bore little resemblance to the actual surface frontal positions. In order to deal with the frequent absence of a relationship between analyzed fronts and surface potential temperature gradients, Sanders (1999a) proposed analysis notation for three features: nonfrontal baroclinic zones, fronts, and baroclinic troughs. These features would be distinguished by the magnitude of the surface potential temperature gradient and the existence of a cyclonic wind shift: fronts would possess both, nonfrontal baroclinic zones would possess only the magnitude of the surface potential temperature gradient, and baroclinic troughs would possess only the cyclonic wind shift.

Because many fronts are associated with a prefrontal wind shift and pressure trough (see Schultz 2005 for a review), Sanders (1999a) proposed a process by which such a prefrontal feature would occur. Quasigeostrophically, in the presence of an along-front temperature gradient, the speed of movement of the pressure trough would exceed the advective speed of the isotherms in the front by several m s^{-1}; thus the pressure trough would be propagating relative to the flow. This process,

however, has not been rigorously evaluated for observational cases (Schultz 2005).

Sanders (1999b), "A Short-Lived Cold Front in the Southwestern United States", analyzed a cold front in the southwestern United States on 26–27 March 1991. [Sanders spotted this case, interestingly, during the Surface Analysis Workshop at the National Meteorological Center (Uccellini et al. 1992).] He found that, during the day, clear skies on the warm side of the front and cloudy skies on the cold side intensified the cross-front temperature gradient, resulting in an ageostrophic secondary circulation that produced convergence at the front and led to further intensification. Although there was a 6-h period where the temperature drop, pressure trough, and wind shift were coincident, eventually, the pressure trough and wind shift traveled eastward at 17.2 m s^{-1}, which was faster than the 11.8 m s^{-1} advective speed of the surface isotherms. This arrangement resulted in nonsimultaneity of the wind shift and the temperature gradient, leading to mixing within the frontal zone being unopposed by any frontogenetical process and the eventual weakening of the front.

Sanders (2005), "Real Front or Baroclinic Trough?", examined surface analyses prepared by the Hydrometeorological Prediction Center between 7 February and 29 March 2002. Sanders (2005) found about 50% of the analyzed fronts were associated with baroclinic zones meeting his criteria of at least 8°C per 220 km. He used this statistic to argue for a better distinction on operational surface analyses between fronts and baroclinic troughs—the difference between the two being "a substantial temperature change at the time of the cyclonic wind shift" (Sanders 2005, p. 650).

6 Conclusion

"This complexity should not be cause for despair! It is what is there and to deny it cannot benefit forecast accuracy." — Sanders (1999a, p. 947)

Fred Sanders contributed much to the understanding and analysis of surface fronts. With an eye towards reducing the overreliance on the Norwegian cyclone model, Sanders (1955) performed quantitative calculations investigating the dynamics of a surface cold front over the south-central United States. With access to high-resolution data from the National Severe Storms Laboratory

beta network, further research by Sanders and his students, culminating in Sanders (1967), raised the issue of the importance of the relationship between the temperature gradient and the wind field to surface frontogenesis. Sanders (1967) and Sanders's (1999a) classification scheme provided some basic terminology and the groundwork for my review of prefrontal troughs and wind shifts (Schultz 2005). Although such prefrontal features had been discussed previously in the literature by people other than Sanders, an extensive review of them had not been performed. To my knowledge, Sanders (1999b) was apparently the first to document the regional evolution of a surface cold front and its associated prefrontal features over the southwestern United States, if not over the western United States. Recently, Sanders's outspoken presentations at Cyclone Workshops (e.g., Gyakum et al. 1999), AMS conferences, and the symposium in his honor have been his attempt to revive these issues of surface analysis and show the complexities of fronts differing from the Norwegian cyclone model. Fred Sanders is nothing if not persistent.

Shapiro et al. (1999), building upon earlier ideas by Bergeron (1959), Doswell et al. (1981), and Hoskins (1983), argued that scientific inquiry progresses most effectively when a synergy between theory, observation, and diagnosis occurs to produce physical understanding expressed in the form of conceptual models (Fig. 10). One example of what happens when the elements of this schematic figure work in harmony is illustrated at the beginning of this paper: Sanders (1955) calculated frontogenesis diagnostics on observations of a cold front, which subsequently inspired the numerical experiments of Keyser and Anthes (1982) to advance the knowledge of the structure and dynamics of the leading edge of cold fronts. A counterexample of what happens when links become severed from each other was also presented in section 2. Specifically, the Norwegian cyclone model concept of cold fronts became nearly impervious to modification by new scientific results (theory, observations, and diagnosis) because people failed to appreciate the rich spectrum of cold fronts possible in the real atmosphere and how that spectrum deviated from the reigning Norwegian paradigm.[2] Thus, these new results were not reconciled with the conceptual models with sufficient veracity to modify the

[2]How such a process works in science in general is discussed in more detail by Kuhn (1970, especially chapters 6–8).

paradigm. Other examples exist where previous researchers have noted the limitations in extending their modeling research because of inadequate verifying observations of cold fronts (e.g., Keyser 1986; Keyser and Pecnick 1987; Blumen 1997). Thus, the inattention to fronts and frontal research has stymied more rapid progress because of the lack of links between theory, observations, and diagnosis. This paper hopes to start a dialog on reconnecting theory, observation, and diagnosis to conceptual models for cold fronts.

The literature is rife with alternative structures and evolutions of cold fronts that are often observed by operational forecasters and analysts, but have not been placed in a dynamical context. There are opportunities to expand the knowledge reviewed in this paper into the operational sector. Ultimately, this argument leads to the inevitable conclusion that forecaster training and manual analysis of the data is important to improved understanding of the atmosphere. Beyond his talents as a scientist, teacher, and mentor, Fred Sanders has also been an outspoken advocate for forecaster education and surface analysis (e.g., Sanders and Doswell 1995; Sanders 1999a). Intuitive forecasters [i.e., forecasters who construct their conceptual understanding on the basis of dynamic visual images, as defined by Pliske et al. (2004)] are good at incorporating a variety of information into the hypothesis-formation and hypothesis-testing stages of forecasting (e.g., Roebber et al. 2004). Thus, providing improved conceptual models of cold-frontal processes and dynamics leads to improved forecasting skill for intuitive forecasters. Consequently, effective forecaster education, along with an emphasis on weather-analysis skills, are required for the best forecasters to excel in their talents (e.g., Doswell et al. 1981; Bosart 2003; Doswell 2004).

"We trust that this paper will not be the last nor most comprehensive to report on these structures . . . ." — Sanders and Kessler (1999, p. 1132)

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Figure 1: Cross section through what would later be called a cold front (Loomis 1841).

Figure 2: Presentations (oral and poster) given at the American Meteorological Society Conferences on Mesoscale Processes from 1983 to 2005 with the phrase "front/frontogenesis/frontal/baroclinic zone" in the title: number of these "frontal" presentations (solid line with squares), total number of presentations at the conference (solid line with circles), and percentage of these "frontal" presentations out of the total number of presentations (thick red line). Locations of the conferences are listed along the bottom of the figure.

Figure 3: 0330 UTC 18 April 1953: boundaries of frontal zone (thick solid lines). (a) Surface chart: sea level pressure (thin solid lines every 6 hPa). Plotted reports follow conventional station model. Dashed line E–N indicates position of vertical cross section in (b) and (c). (b) Cross section through cold front along E–N in (a): potential temperature (thin solid lines every 5 K) and horizontal wind component normal to cross section (dashed lines every 10 m s^{-1}; positive values represent flow into the plane of the cross section). (c) Cross section through cold front along E–N in (a): horizontal divergence (light solid lines in units of 10^{-5} s^{-1}) and vertical velocity (dashed lines every 5 cm s^{-1}). Distance between adjacent letters on horizontal axis is 100 km. (Sanders 1955, Figs. 2, 9, 10).

Figure 4: Cross section through cold front along E–N in Fig. 3a on 0330 UTC 18 April 1953: boundaries of frontal zone (thick solid lines). Units are °C (100 km)$^{-1}$ (3 h)$^{-1}$. (a) Confluence frontogenesis; (b) tilting frontogenesis; (c) sum of (a) and (b). (Sanders 1955, Figs. 11, 12, 13).

Figure 5: Schematic of frontogenetical and frontolytical scenarios. Surface temperatures (solid lines every 10°F) and surface winds (one pennant, full barb, and half barb denote 25, 5, 2.5 m s^{-1}, respectively). (Sanders 1967, Fig. 2.9).

Figure 6: Difference (solid lines every 3 minutes) between the time of the temperature drop and the time of the start of the wind shift for the cold front on 23 March 1965. Number in parentheses represents difference between the time of the start of the wind shift and the increase in the wind speed (Sanders 1967, Fig. 2.13).

Figure 7: Average temperature (numbers along top line in °F) and wind (one pennant, full barb, and half barb denote 0.5, 1, 5 m s^{-1}, respectively) at each station in the network relative to the time of the temperature drop (t=0) for the cold front on 23 March 1965. (Sanders 1967, Fig. 2.14).

Figure 8: Average confluent frontogenesis [top row, solid line, °F (n mi)$^{-1}$ h^{-1}], temperature gradient [second row, dashed line, °F (n mi)$^{-1}$], convergence (third row, solid line, h^{-1}), and vorticity (bottom row, solid line, h^{-1}). (Sanders 1967, Fig. 2.15).

Figure 9: Cold front on 23 March 1965: (a) surface winds (one pennant, full barb, and half barb denote 25, 5, 2.5 m s^{-1}, respectively); (b) divergence (solid lines every 15×10^{-4} s^{-1}); (c) vorticity (solid lines every 15×10^{-4} s^{-1}); (d) isotherms (solid lines every 5°F) and direction of axes of dilatation; (e) absolute magnitude of the resultant deformation (solid lines every 15×10^{-4} s^{-1}); (f) confluent frontogenesis [solid lines every 0.5°F (n mi)$^{-1}$ h^{-1}]. (Sanders 1967, Fig. 3.8).

Figure 10: Physical understanding and conceptual representation through the union of theory, diagnosis, and observation (Shapiro et al. 1999, Fig. 1).