

Comments on “Unusually Long Duration, Multiple-Doppler Radar Observations of a Front in a Convective Boundary Layer”

DAVID M. SCHULTZ

Division of Atmospheric Sciences, Department of Physical Sciences, University of Helsinki, and Finnish Meteorological Institute, Helsinki, Finland

(Manuscript received 1 March 2007, in final form 19 April 2007)

ABSTRACT

Stonitsch and Markowski perform multiple-Doppler radar analyses of a cold front over Oklahoma and Kansas. Despite their interesting results, their explanations include a number of misconceptions about cold fronts. These misconceptions include the proper interpretation of the frontogenesis function, the role of entrainment versus differential surface sensible heat flux toward weakening the virtual potential temperature gradient across a cold front, a separation of the wind shift from the virtual potential temperature gradient, and the factors that affect the motion of the cold front.

1. Introduction

In their paper detailing multiple-Doppler radar analyses of a cold front over Oklahoma and Kansas during four separate deployments over an 8-h period, Stonitsch and Markowski (2007, hereafter SM) tarnish their otherwise interesting study with misconceptions of the kinematics and dynamics of cold fronts. These misconceptions include those arising from the frontogenesis function (section 2), the processes that affect the strength of cold fronts (section 3), a separation between the virtual potential temperature gradient and wind shift associated with the cold front (section 4), and the factors that affect the motion of cold fronts (section 5).

2. Interpretation of frontogenesis

During deployment 2 (1915–2030 UTC 3 June 2002), SM (their Figs. 12c,d and 13) observed weakening of the virtual potential temperature gradient across the front. SM (p. 109) write, “Throughout deployment 2, positive, albeit weak, frontogenetic forcing was ob-

served along the front despite weakening deformation . . . One must therefore conclude that the weakening baroclinity was brought about by frontolytic differential diabatic heating . . .” In this statement, SM misinterpret the frontogenesis function. The traditional form presented in SM [their (6)] is an adiabatic Lagrangian quantity that calculates the change in the magnitude of the virtual potential temperature gradient following the motion of air parcels. Thus, even weakening fronts may exhibit positive frontogenesis due to deformation and convergence as air parcels in the warm sector approach the virtual potential temperature gradient associated with the front. To derive a form of the frontogenesis function to measure the weakening of a front directly, one would need to calculate a quasi-Lagrangian (front following) form where the vector wind in the traditional derivation is replaced by the front-relative flow. Few people have evaluated such a formulation in observed fronts, in part owing to the difficulty in constructing a motion vector for the front that may vary along its length. Nevertheless, such a formulation is the proper way to assess quantitatively the changing intensity of the front in a frame of reference moving with the front. Moreover, that weakness does not diminish the usefulness of the traditional form of the frontogenesis function as a measure of the presence of a frontal zone or its vertical circulation, as has

Corresponding author address: Dr. David M. Schultz, Finnish Meteorological Institute, Erik Palménin Aukio 1, P.O. Box 503, FI-00101, Helsinki, Finland.
E-mail: david.schultz@fmi.fi

been employed by numerous authors in the past. *Thus, the traditional form of frontogenesis [SM, their (6)] is not suited for evaluating the changing intensity of the frontal zone in a front-following framework.*

3. Role of differential surface sensible heat flux versus entrainment into the frontal zone

Fronts are a result of competing processes maintaining the front and weakening the front. As the frontogenetic deformation maintaining the front weakens during deployment 2, previously active frontolytic processes dominate. SM suggest that differential sensible heat flux (i.e., heating of the cold postfrontal air by the warm ground) is that frontolytic process. This effect almost always is frontolytic, as cold air behind the cold front replaces the warm air (which tends to overlie warm ground). SM have not computed whether the time and space scales for the sensible heat flux and resultant turbulent mixing would be adequate to explain the observed frontolysis. Therefore, quantitative evidence for this mechanism is lacking in this case.

Unfortunately, SM omit the one process that is likely playing a rather significant role in the boundary layer: entrainment within the frontal zone. Although quantifying this effect is not simple, previous studies have indicated entrainment and the resulting mixing to be a significant, if not the most significant, frontolytic process affecting the strength of fronts (e.g., Sanders 1955, 1999b; Blumen and Piper 1999; Piper and Lundquist 2004). 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, a result surmised by Sanders (1955) in his calculated trajectory (his Fig. 13). In the presence of a thermally insulated lower boundary where surface heat fluxes are zero, superadiabatic lapse rates and mixing in the postfrontal air result. Such entrainment of warm prefrontal air into the frontal zone, and the subsequent mixing, weakens the virtual potential temperature gradient within the frontal zone. Although quantifying this effect is not simple, SM neglect this entrainment process in their possible explanations for the observed weakening.

In their reply to these comments, Markowski and Stonitsch (2008, their Fig. 2b) provide a graph of the horizontal distribution of buoyancy flux, arguing that this distribution is the correct sign to explain the observed frontolysis. Such evidence, unfortunately, does not demonstrate what process (e.g., differential sensible heat flux or entrainment) was responsible for weaken-

ing the virtual potential temperature gradient (or even if the magnitude of the buoyancy flux is sufficient to explain the weakening), as both processes would be measured with such data. *In the absence of such calculations, SM have not demonstrated that sensible heat flux was the likely cause of the observed frontolysis, and entrainment into the frontal zone cannot be dismissed.*

4. Separation of the wind shift from temperature gradient

The question of why the front weakens is best viewed through the offsetting of frontogenetic and frontolytic processes. When the frontogenetic deformation and convergence is less than the frontolytic effects of mixing and differential diabatic heating (computed in a front-following framework, section 2), the front weakens. During deployment 2, the front weakened, although whether this is due to decreasing deformation is not known. One way in which frontolysis can dominate is by the wind shift (usually associated with the vorticity) separating from the virtual potential temperature gradient (e.g., Schultz 2004, 2005).

During 1915–2145 UTC, air with virtual potential temperature less than 317 K, formerly found in the analysis domain, is no longer found within the analysis domain, although the wind shift is (Fig. 12 in SM). Clearly, the small domain, necessitated by the multiple-Doppler analysis, precludes an analysis over a larger domain where a separation of the wind shift from the virtual potential temperature gradient might have been apparent.

Moreover, defining the front as the maximum in the magnitude of the horizontal velocity gradient tensor (section 3b in SM) implicitly forces an interpretation on the front as an object rather than a process. The danger in this interpretation is the possible effect of not recognizing the processes that regulate frontogenesis. As discussed in Sanders (1967, 1999a), the separation of the wind shift from the temperature gradient weakens the front. There are many possible processes that separate the wind shift from the temperature gradient, as reviewed by Schultz (2005). In the absence of more thorough analysis on the SM front, what separates the wind shift from the virtual potential temperature gradient in the present case is not known. If such a separation were occurring, it would be consistent with the weakening of the virtual potential temperature gradient across the front observed by SM. Whatever the reason, *consideration of the virtual potential temperature gradient and wind shift as independent entities each with their own behavior should not be discounted.*

5. What controls the speed and direction of motion of a front?

Another misconception SM have about fronts is what controls their speed of motion. During deployments 2 and 3, the cold front slowed its equatorward progression, then moved poleward as a warm front. On p. 109, SM state, "The motion of the front slowed throughout deployment 2, perhaps in response to the weakening density gradient across the front." Unfortunately, peer-reviewed literature supporting such a relationship between the cross-front density gradient and the speed of cold fronts does not exist. Indeed, a casual survey of classic cold-frontal literature indicates that the speed and direction of motion of cold fronts are not related to the cross-frontal density difference—both extremely strong, but nearly stationary, cold fronts and weak, but fast-moving, cold fronts can exist.

The speed of a density current is related to its temperature difference, although, in this paper, I do not wish to debate whether cold fronts are density currents. That issue is discussed in Smith and Reeder (1988). Furthermore, whether intense cold fronts are dynamically, or just morphologically, similar to density currents awaits further research (Snyder and Keyser 1996), so the debate has not been resolved yet.

In the SM case, the wind field after 1915 UTC begins to change as the component of the wind speed toward the front in the cold air decreases (their Fig. 10), a factor likely associated with the weakening of the frontogenetical deformation field (or the separation of the density gradient from the wind shift, as discussed in section 4) and the eventual weakening of the front. This changing wind direction appears to be associated with a reorganization of the flow associated with the cyclogenesis in Colorado in the region outside the dual-Doppler domain studied by SM. The slowing down of the front during deployment 2 is likely caused by the reversal of the flow in response to the change in the pressure gradient, a concept apparently related to an earlier statement in SM (p. 96) attributing the poleward progression of the front during deployment 3 "to pressure falls associated with the amplification of a Rocky Mountain lee trough to the west." Thus, for the two reasons discussed in this section, the inability of the front-normal density gradient to explain frontal motion in general and the reorganization of the flow specifically in this case, *the weakening density gradient across the front*

likely has little to do with the frontal speed and its direction of motion in this case.

6. Conclusions

To conclude, I disagree with SM on some of their possible interpretations of their case found throughout their paper and the conclusions section, including some misconceptions they have of fronts in general. These misconceptions include the proper interpretation of the frontogenesis function, the role of entrainment in weakening the virtual potential temperature gradient across a cold front, a separation of the wind shift from the virtual potential temperature gradient, and the factors that affect the motion of a cold front.

REFERENCES

- Blumen, W., and M. Piper, 1999: The frontal width problem. *J. Atmos. Sci.*, **56**, 3167–3172.
- Keyser, D., and R. A. Anthes, 1982: The influence of planetary boundary layer physics on frontal structure in the Hoskins-Bretherton horizontal shear model. *J. Atmos. Sci.*, **39**, 1783–1802.
- Markowski, P. M., and J. R. Stonitsch, 2007: Reply. *Mon. Wea. Rev.*, **135**, 4240–4246.
- Piper, M., and J. K. Lundquist, 2004: Surface layer turbulence measurements during a frontal passage. *J. Atmos. Sci.*, **61**, 1768–1780.
- Sanders, F., 1955: An investigation of the structure and dynamics of an intense surface frontal zone. *J. Meteor.*, **12**, 542–552.
- , 1967: Frontal structure and the dynamics of frontogenesis. Final Report to the National Science Foundation, Grant GP-1508, 10 pp. with 10 appendixes.
- , 1999a: A proposed method of surface map analysis. *Mon. Wea. Rev.*, **127**, 945–955.
- , 1999b: A short-lived cold front in the southwestern United States. *Mon. Wea. Rev.*, **127**, 2395–2403.
- Schultz, D. M., 2004: Cold fronts with and without prefrontal wind shifts in the central United States. *Mon. Wea. Rev.*, **132**, 2040–2053.
- , 2005: A review of cold fronts with prefrontal troughs and wind shifts. *Mon. Wea. Rev.*, **133**, 2449–2472.
- Smith, R. K., and M. J. Reeder, 1988: On the movement and low-level structure of cold fronts. *Mon. Wea. Rev.*, **116**, 1927–1944.
- Snyder, C., and D. Keyser, 1996: The coupling of fronts and the boundary layer. Preprints, *Seventh Conf. on Mesoscale Processes*, Reading, United Kingdom, Amer. Meteor. Soc., 520–522.
- Stonitsch, J. R., and P. M. Markowski, 2007: Unusually long duration, multiple-Doppler radar observations of a front in a convective boundary layer. *Mon. Wea. Rev.*, **135**, 93–117.
- Xu, Q., and W. Gu, 2002: Semigeostrophic frontal boundary layer. *Bound.-Layer Meteor.*, **104**, 99–110.