

A STRUCTURED PROCESS FOR PREDICTION OF CONVECTION ASSOCIATED WITH SPLIT COLD FRONTS

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1. Introduction

A split cold front is a katafront characterized by cold, dry air that advances ahead of the surface cold front by several hundred kilometers, resulting in a warm occlusion structure (Browning 1985). A cold front aloft (CFA) as defined by Hobbs et al. (1990) is quite similar to the Browning model of a split front, but a pressure trough (typically a dryline, or “drytrough”) replaces the surface cold front. These nonclassical frontal systems are prolific producers of heavy precipitation and severe thunderstorms, since they act both to increase the potential instability and provide for the lifting mechanism (the associated frontal circulation) to release this instability (Locatelli et al. 1995).

It is demonstrated here that diagnosis of the structure of split cold fronts and cold fronts aloft can be achieved by applying a systematic procedure presented by Koch (2001) using only operationally available data and tools. This procedure consists of a synthesis of water vapor channel satellite imagery, isentropic and cross sectional analysis of mesoscale model fields, and thermal retrievals and other products obtained from WSR-88D radar and wind profiler data.

This structured process for identifying split cold fronts and CFAs is applied to the major severe weather and flash-flooding event of 21–23 January 1999. Records for the most tornadoes in any state on any day in January as well as the most tornadoes in a single day were broken in this event. More than \$1 billion in damage, 150 injuries, and 17 deaths across the southern United States resulted. Flash flooding, wind damage, large hail, and tornadoes accompanied multiple squall lines as they swept across the Southeast, and massive flooding affected the Ohio Valley from heavy perpetual rainfall aggravated by rapid snowmelt. Forecasters were well aware of the potential for a major severe weather and flash-flooding event. However, conventional analyses of severe storm environments, such as quasi-geostrophic analyses, failed to reveal the actual forcing mechanism for the severe mesoscale convective systems. WSR-88D product and Meso Eta model analyses reveal that the vast majority of the severe weather occurred in conjunction with two CFAs and their interactions rather than any surface features, “short waves,” or quasi-geostrophic forcing.

2. The Procedure for CFA Identification

Split cold fronts and CFAs may be easily identified with operationally available data – primarily water vapor imagery, diagnostic analysis of mesoscale model fields,

and derived products obtained from WSR-88D radar and wind profiler data. The following stepwise process is advocated for this purpose:

1. *Is there pronounced cold advection in the middle troposphere (~700 hPa) associated with a cloud band or rain band at least 200 km ahead of a surface trough or cold front? This feature is often most pronounced in the wet bulb potential temperature or theta-e field from a mesoscale model, but not easily seen in rawinsonde data.*
2. *Does the forecast vertical velocity field show a strong upward motion band associated with the cloud/rainband, and do vertical cross sections indicate that the upward motion band is part of a midlevel frontal transverse circulation?*
3. *Does the water vapor imagery show a pronounced dry wedge (slot) in association with strong isentropic descent diagnosed from model data?*
4. *Verification of the model forecast of a split cold front consists of whether the zero isodop in the radial velocity display from a WSR-88D radar shows a mid-level “backward S” pattern above a low-level “S” (this being indicative of cold overlying warm advection)*
5. *Use the thermal wind equation to retrieve split front geostrophic cold advection pattern from the wind profiler or radar VAD data (discussed below).*

3. Application to 21–23 January 1999 Case

The above procedure is now demonstrated with the 21–23 January 1999 event (though all the analyses cannot be shown here, missing analyses will be shown at the conference). A lee cyclone slowly propagated from southeastern Kansas at 0000 UTC 22 January to southeastern Missouri by 0600 UTC 23 January. The attendant frontal systems included a stationary front, a dryline in eastern Texas and Oklahoma during the first half of this event, and two surface cold fronts in the latter half. The severe weather was produced by two major mesoscale convective systems. First, an organized cluster of supercell thunderstorms in Arkansas (Fig. 1b) gradually transformed into a quasi-stationary complex of heavy rainstorms across eastern Arkansas northeastwards to the Ohio Valley (Fig. 1c). Thereafter, a squall line with accompanying large hail and damaging winds formed over the southern Mississippi Valley region (Fig. 1d). Analysis of the surface observations and the MesoEta model forecast fields both revealed that these mesoconvective systems were located several hundred kilometers ahead of the surface frontal systems throughout this event.

The various fronts aloft depicted in Fig. 1 were obtained from analysis of the model wet-bulb potential temperature (θ_w) and wind fields at 700 hPa (Fig. 2). The leading edge of the strong horizontal gradient of θ_w was defined as the CFA with the provision that lower values of θ_w were progressively advancing toward the ridge in θ_w . Two CFAs are analyzed on the 700-hPa maps. The model precipitation forecasts (not shown) portrayed a significant rainband along the first CFA, the result of potential instability generated by this CFA as it advected lower θ_w air over higher θ_w air near the surface. Convective Available Potential Instability (CAPE) increased in a narrow region just ahead of the first of the two CFAs over Arkansas at 0000 UTC 22 January as the CFA advanced ahead of the dryline. It was actually at this time that the tornadic activity rapidly developed across Arkansas and western Tennessee.

The southern half of the first CFA crept eastward while the northern half advanced to the northeast. At the same time, a second surge of low θ_w air from the high Mexican plateau began to enter western Texas.

This second CFA began to occlude with the first CFA by 1200 UTC 22 January. Rapid strengthening of the convection resulted across the southern Mississippi Valley region. Despite the dramatically greater horizontal gradient of θ_w associated with the second CFA (Fig. 2d), tornadoes were not generally produced by the thunderstorms accompanying it. Rather, the stronger vertical wind shear associated with this greatly enhanced horizontal thermal gradient provided a more ideal environment for the intense squall line. In fact, the 1000-500 hPa wind shear over Arkansas (not shown) increased from 40 m s^{-1} at 0000 UTC 22 January to more than 80 m s^{-1} by 0600 UTC 23 January, and also became more unidirectional in character. Thus, it is apparent that *the location and general nature of the mesoconvective systems that developed in this event are both well explained by the presence of the evolving frontal systems aloft and the accompanying vertical wind shear patterns.*

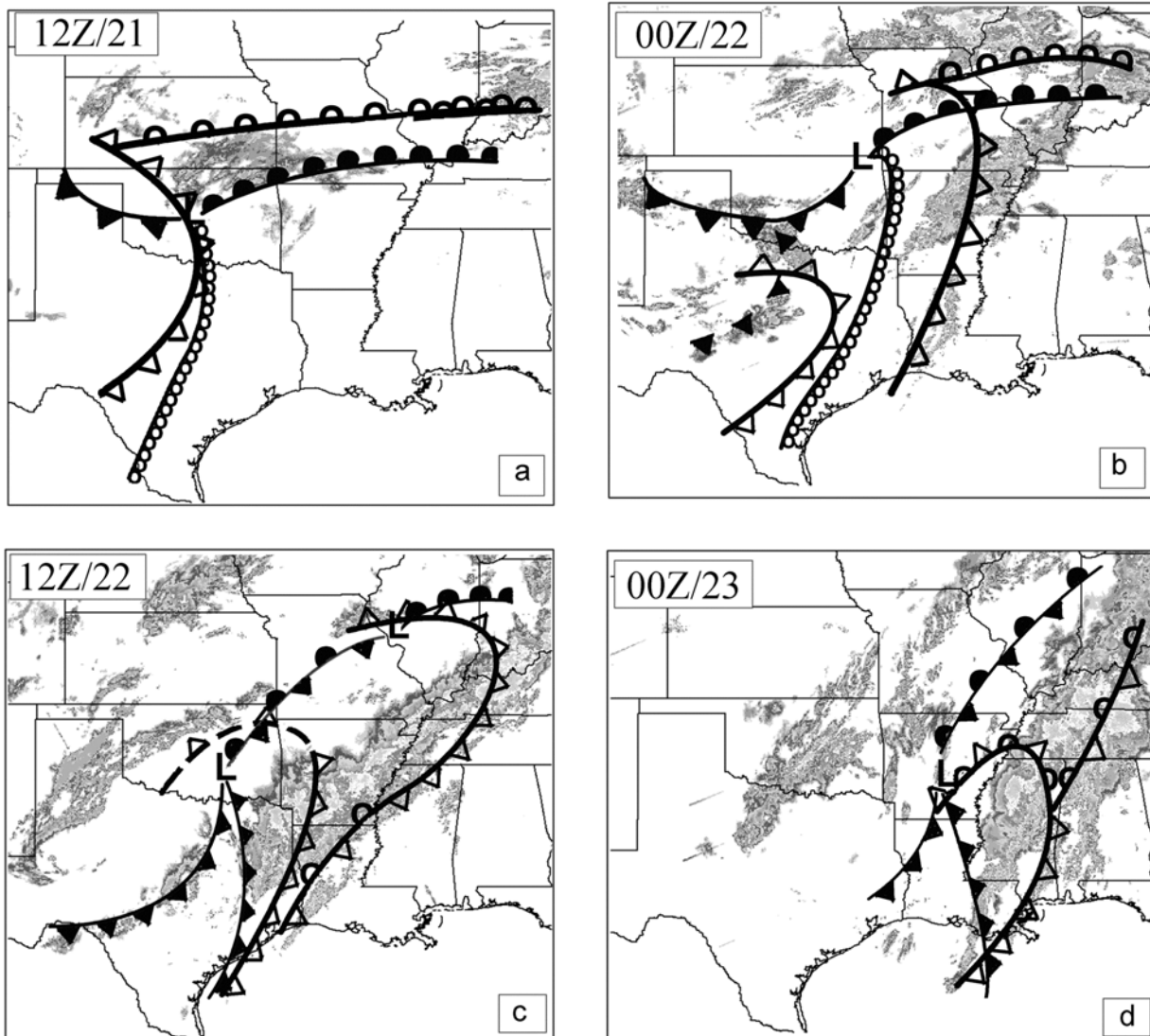


Fig. 1. Radar imagery overlaid with Meso Eta forecast surface fronts and fronts aloft at a) 1200 UTC 21 January, (b) 0000 UTC 22 January, (c) 1200 UTC 22 January, and (d) 0000 UTC 23 January 1999.

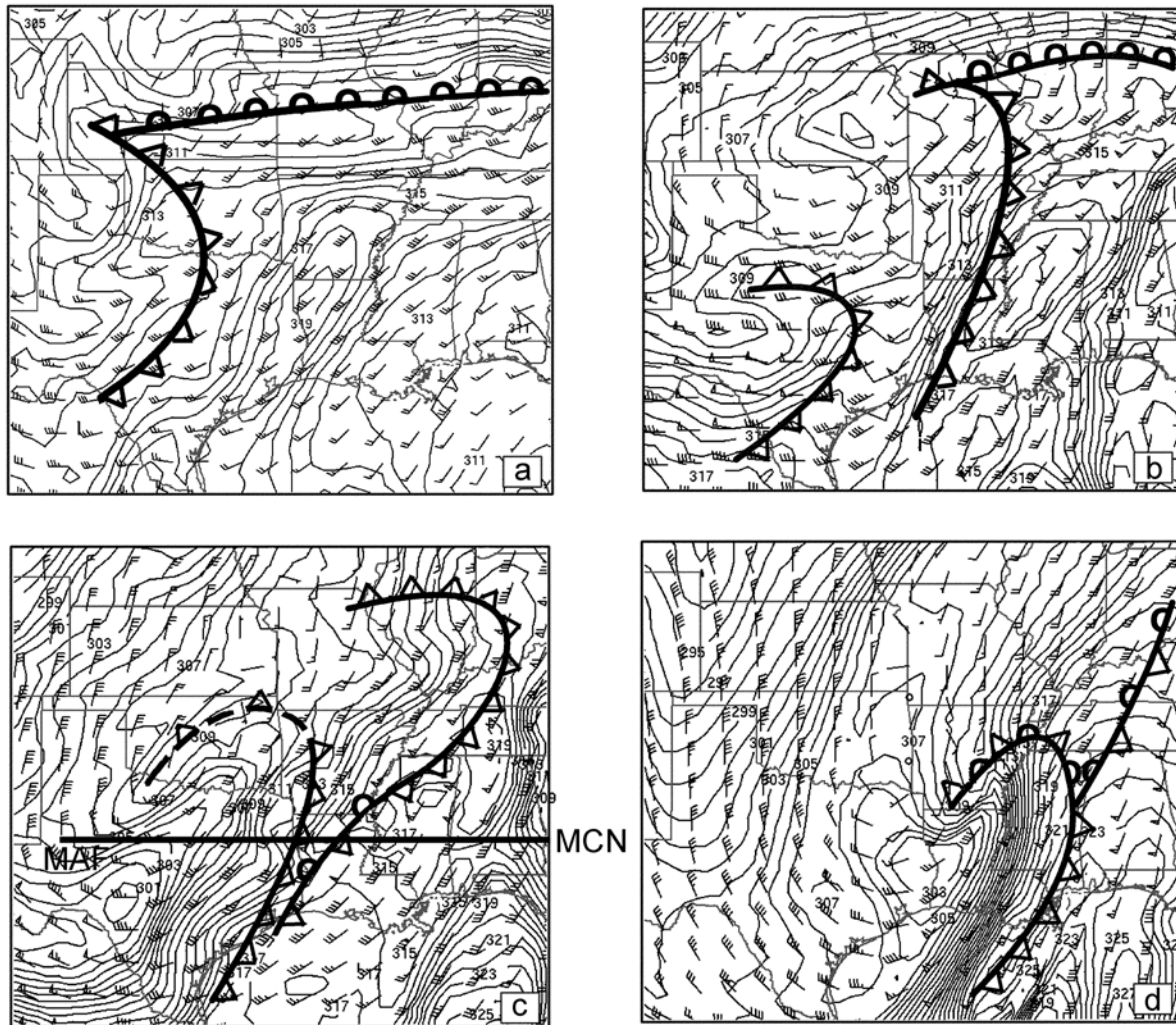


Fig. 2. MesoEta 700-hPa winds and wet-bulb potential temperature (1K isotherms) at same times as in Fig. 1.

Vertical cross sections from extreme west central Texas to central Georgia were prepared from the Meso Eta model forecast fields in order to investigate the structure and evolution of the CFAs and their relationship to the surface features. The CFAs can be easily identified at the leading edge of strong horizontal θ_e gradients (Fig. 3a) in the same positions as seen on the plan view of θ_w at 700 hPa (Fig. 2c). As the dry, cooler (lower θ_e) air behind the CFAs advanced over warm, moist air, potential instability ($\partial\theta_e/\partial z < 0$) was created. This instability is particularly strong underneath the nose of the CFA, whereas the instability associated with the surface cold fronts is relatively shallow and weak.

A similar cross section of front-relative circulation and relative humidity (Fig. 3b) shows two bands of strong rising motion, one along the leading edge of each of the CFAs. A thermally direct frontal circulation was associated with active frontogenesis along each CFA, with the rising branch of the circulation acting upon very moist air (shaded), much of which was also potentially unstable (Fig. 3a).

These figures strongly suggest that the CFAs were the dominant lifting mechanisms in this case. The relative humidity was maximized along or just ahead of the CFAs as moisture was lifted from lower levels. The push of dry air can be seen following the CFAs, which by definition aligns along the leading

edge of these dry surges. The surface cold fronts have less moisture, upward motion, and instability with which to work than the CFAs. Similar analyses conducted for the other model forecast times showed that the ascent and moisture associated with the CFAs increased with time, in agreement with the increasing magnitude and length of the squall line.

Potential temperature cross sections (Fig. 3c) displayed a clear tendency for the isentropes to slope upward behind the analyzed CFAs. Thus, the CFAs in this case were not mere "humidity fronts." Additionally, analyses of potential vorticity in these cross sections strongly suggested that a tropopause fold was present behind the westernmost CFA. This is not surprising, since as a midtropospheric front and its associated transverse circulation develop, the tropopause is driven downward along sloping isentropes, and a fold can develop. This fold brings down dry, stratospheric air behind the frontal zone. It is believed that this accentuated the moisture contrast across the mid-tropospheric front. Isentropic

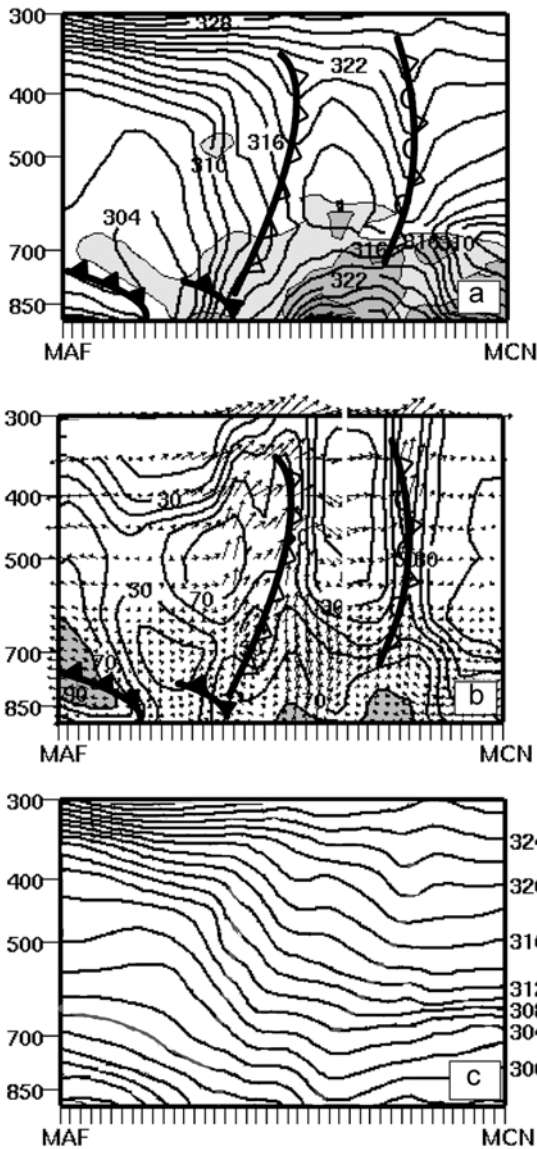


Fig. 3. Cross section (see Fig. 2) at 1200 UTC 22 January 1999 of a) equivalent potential temperature (thick lines, 2K) and potential instability (shaded), b) front-relative circulation and relative humidity (shaded above 80%), and c) potential temperature (2K isotherms). Dual CFAs are depicted with open frontal pips, and shallow surface cold fronts are shown by traditional symbols.

analysis showed strong cross-isobar flow indicating rapid descent did indeed occur in west Texas in association with the second CFA. Furthermore, this dry conveyor belt (Browning 1985) was very evident in water vapor imagery from GOES-8. The value of overlaying isentropic analyses on enhanced water vapor imagery to detect split cold fronts will be demonstrated at the conference.

4. Doppler Radar Analysis

Level II WSR-88D radar data can be used to easily detect the presence of split fronts and CFAs. The VAD Wind Profile (VWP) product, which is a time-height display of the mean horizontal winds using the Velocity-Azimuth Display (VAD) technique,

is well suited for detecting temporal changes in the vertical profile of winds. Geostrophic cold and warm advection can be inferred from backing and veering of winds with height, respectively. Temperature advection was calculated from the VWP layer-mean winds and retrieved temperature gradients using the geostrophic thermal wind equation, following the procedure described by Koch (2001). Analysis at Little Rock on 21 January showed strong cold advection in the ~ 2 - 4 km layer, in close proximity to where the Meso Eta model indicated the first CFA. Analyses performed as the strong squall line impacted Fort Rucker, Alabama (KEOX) suggested that the merged CFA maintained this squall line, since pronounced mid-level backing winds and cold advection from ~ 1.5 to 5 km were supporting a rear inflow jet. These results are in agreement with the assertion of Locatelli et al. (1995) that such rear inflow can be dynamically linked to the synoptic-scale cooling behind the nose of a CFA.

5. Conclusions

This paper has discussed how the structure of split cold fronts and CFAs can be understood in an operational setting by synthesizing water vapor channel satellite imagery, isentropic and cross sectional analysis of mesoscale model fields, and thermal retrievals and other products obtained from WSR-88D VAD Wind Profile (VWP) displays. These principles were demonstrated in the severe weather case of 21-23 January 1999, which involved two CFAs. This study demonstrates how readily available mesoscale model fields and observational data can detect the presence and vertical structure of an important class of mesoscale phenomena that can produce extreme weather events such as the one in this case.

6. References

- Browning, K.A., 1985: Conceptual models of precipitation systems. *Meteor. Mag.*, **114**, 293-319.
- Hobbs, P.V., J.D. Locatelli, and J.E. Martin, 1990: Cold fronts aloft and the forecasting of precipitation and severe weather east of the Rocky Mountains. *Wea. Forecasting*, **5**, 613-626.
- Koch, S. E., 2001: Real-time detection of cold fronts aloft and split fronts using mesoscale models and WSR-88D radar products. *Wea. and Forecasting*, **16**, 35-55.
- Locatelli, J.D., J.E. Martin, J.A. Castle, and P.V. Hobbs, 1995: Structure and evolution of winter cyclones in the central United States and their effects on the distribution of precipitation. Part III: The development of a squall line associated with weak cold frontogenesis aloft. *Mon. Wea. Rev.*, **123**, 2641-2662.