# **COMET Partners Project Final Report**

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# Section 1: Summary of Project Objectives

The overall objective of this project was to expand upon a real-time system that predicts specific characteristics of high-impact convective precipitation systems. This system is based on a meteorological feature-specific prediction approach. Weather forecasters often use a "feature-specific" conceptual approach throughout their forecast process when predicting specific meteorological phenomena and the hazardous conditions associated with them, such as hurricanes or thunderstorms. This approach can be used across the wide spectrum of weather events ranging from very short-term/small-scale predictions (e.g., tornado warnings with lead times on the order of 15 minutes) to long-range/planetary-scale predictions (e.g., week two forecasts of blocking patterns). Forecasters often identify features in the observed data, characterize important aspects of those features, and track those features throughout their temporal evolution. The prediction of such features is often accomplished by continuing this process via analysis and diagnosis of the output from numerical weather prediction models and/or some sort of extrapolation of the feature along its current observed track.

While today's high-resolution operational and experimental numerical weather prediction models can provide valuable forecast information, they also contribute substantially to the volume of data available to the forecaster. In addition, there is little information related to forecast uncertainty available to the forecaster that is relevant to these high-resolution models. The overall objective of this project was to develop a feature-specific prediction system to provide guidance related to the characteristics of forcing for vertical motion associated with convective weather systems predicted by such high-resolution numerical models. The goal of this research is to eventually provide relevant guidance regarding high-impact weather events that can be quickly obtained in a manner that is consistent with the conceptual approach that many forecasters use in their day-to-day forecast process.

The *feature-specific prediction* approach involves identifying and characterizing predicted meteorological "features" of interest as well as the meteorological "forcing" associated with them, tracking the features over time, applying appropriate statistical models, and evaluating the resulting predictions. This project focused primarily on feature-specific analysis procedures to identify, characterize, and classify surface frontal boundaries in numerical model forecast output. The results of this work are expected to allow further development of probabilistic models to predict the temporal evolution of the convective precipitation weather systems and provide quantifiable information regarding forecast uncertainty of such systems.

In order to expand the existing prediction system, an automated procedure for identifying surface-based fronts was developed and incorporated into the real-time prediction system. This prediction system consisted of a daily run of the WRF model at 4.25 km grid spacing over a domain that covers the eastern 2/3 of the contiguous 48 U.S. states. The overall goal of this work was to incorporate automated analyses of larger-scale forcing for vertical motion, such as surface fronts, relating the characteristics of this forcing to precipitating weather systems in the daily Purdue WRF model output. To meet this objective, Purdue researchers worked to create an objective frontal locating algorithm. The general approach taken to develop this algorithm involved identifying the surface front by its thermal characteristics, particularly by the gradients in the surface equivalent potential temperature.

### Section 2: Project Accomplishments and Findings

#### **Objective Frontal Locating Algorithm**

Kim Hoogewind, the Purdue University graduate student who worked on this project, has made several major accomplishments during the year-long period of the project. Kim has developed and tested an objective frontal analysis procedure, advancing a method that was first proposed by Renard and Clarke (1965). Their mathematical formulation, known as the thermal front parameter (TFP), was designed to work with gridded datasets and utilizes finite-differencing techniques to evaluate spatial derivatives of a scalar thermal field to mathematically identify the warm side of the thermal gradient was first. The TFP is defined as

$$\text{TFP} = \frac{-\nabla |\nabla \tau| \cdot \nabla \tau}{|\nabla \tau|} \qquad \qquad \text{Eq. 1}$$

where  $\tau$  represents some thermal variable and  $\nabla$  (del) represents the operator of the horizontal gradient. Mathematically,  $\frac{\nabla \tau}{|\nabla \tau|}$  represents a unit vector in the direction of  $\nabla \tau$ . Thus, the TFP describes the change of  $\nabla |\nabla \tau|$  in the direction of  $\frac{\nabla \tau}{|\nabla \tau|}$ , or in other words, the scalar result of the equation describes the "gradient of the magnitude of the thermal gradient resolved into the direction of the thermal gradient" (Hewson 1998). Where the vector  $\nabla |\nabla \tau|$  and  $\frac{\nabla \tau}{|\nabla \tau|}$  are pointing in opposite directions, their dot product will be negative. When a negative sign is applied, as in Eq. (1), the dot product will instead be maximized. Figure 1, adapted from McCann and Whistler (2001) and Hewson (1998), effectively displays the meaning of this formulation in a very conceptual manner. Contours through maximum values in this field, above some defined threshold, will then indicate the location of the warm edge of a potential front.



Figure 1: This schematic depicts the attributes of the TFP for an idealized straight cold front. The direction and magnitude of the vectors  $\nabla \tau$  and  $\nabla |\nabla \tau|$  are shown in the center, and the opposite sign of the magnitude of their dot product is displayed in the schematic beneath. The area where the dot product is maximized (along the leading edge of the frontal zone), a potential frontal boundary may exist. Adapted from McCann and Whistler (2001) and Hewson (1998).

An alternative way to interpret the TFP parameter exists within natural coordinates. Natural coordinates are often used within fluid mechanics and are based on a set of orthogonal unit vectors  $\hat{s}$ ,  $\hat{n}$ , and  $\hat{k}$  (Hewson 1998; Glickman 2000). This coordinate system is essentially a rotated Cartesian coordinate system based upon the orientation of the flow. The horizontal coordinates (*s*,*n*) are defined by the direction of the flow at each point within the fluid. This coordinate transformation may easily be extended to the application of thermal gradients, and in particular, fronts. Using this design, the TFP formulation may be interpreted as

$$\text{TFP} = -\nabla |\nabla \tau| \cdot \hat{\mathbf{n}} = -\frac{\partial^2 \tau}{\partial \mathbf{n}^2}$$
 Eq. 2

where  $\hat{n}$  is the unit vector normal to the thermal gradient. While the orientation of the field is not known a priori, for all practical purposes,  $\hat{n}$  may be considered equivalent to the unit vector  $\frac{\nabla \tau}{|\nabla \tau|}$ . It may be interpreted as the vector in the cross-front direction ( $\hat{n}$ ), and  $\hat{s}$  represents the along-front direction, so that the formulation represents the typical first-order natural coordinate system. In effect, the TFP may

be realized as the second derivative of  $\tau$  in the direction of the unit vector  $\hat{n}\left(-\frac{\partial^2 \tau}{\partial n^2}\right)$ . Equations 1 and 2 are simply two different representations of the same mathematical formulation.

Most techniques utilize a variation of the Renard and Clarke thermal front parameter to identify the warm side of a thermal boundary within numerical weather prediction output or reanalysis data. Fronts are depicted as a simple boundary on the warm edge of a strong thermal gradient as deduced by the contour of maximum TFP values that satisfy certain masking and threshold criteria. However, while this follows conventional frontal depiction, fronts are essentially transition zones between two airmasses and might benefit from being depicted as such rather than a definitive boundary. Additionally, information about the thermal gradient itself, particularly its intensity, may be displayed graphically for interpretation. Following this notion, the task thus requires the isolation of the thermal gradient where the gradient is changing most rapidly. To accomplish this, additional steps beyond the calculation of the TFP need to be undertaken as the TFP itself only identifies one side of a strong thermal gradient. In accordance with this concept, the goal then becomes to identify both sides of the most strongly changing thermal gradient. The following describes the methodology of this type of approach.

To begin, the calculation of the TFP is still a necessary component of the methodology, however, a slight deviation from the original TFP formulation will be used in this study. Following McCann and Whistler (2001); the thermal gradient vector will not be normalized to create a unit vector. This un-normalized version of the TFP is defined as

$$TFP = -\nabla |\nabla \tau| \cdot \nabla \tau \qquad \text{Eq. 3}$$

As in McCann and Whistler (2001), the purpose for using the un-normalized version of the TFP will enhance the sensitivity to the thermal gradient, otherwise the premise remains the same as the original TFP formulation. Going forward, all references to the TFP parameter will refer to the definition supplied by Eq.3.

The thermal front locator (TFL) employed by Huber-Pock and Kress (1981), may be used to identify each edge of the thermal gradient. Theoretically, this could be deduced by identifying the maximum and minimum of the TFP values via calculation of the gradient of the TFP in the direction of the thermal gradient (see Fig. 2). This function takes the derivative of the TFP in the direction of the thermal gradient, which may be interpreted as the third derivative of the thermal variable in the direction of the thermal gradient. This approach is not uncommon: the TFL of Huber-Pock and Kress (1981) is similar to the MM $\theta$  function defined in Renard and Clarke (1967) and the locating function of Hewson (1998); it is also identical to the GGG $\tau$  function of Creswick (1967). It should be noted, though, that these studies used the zero isopleths of this defined field only to locate the warm side of the thermal gradient.

The TFL in this study will be formulated using the un-normalized TFL, and is defined as follows:

$$TFL = \nabla(-\nabla|\nabla\tau| \cdot \nabla\tau) \cdot \nabla\tau = \nabla(TFP) \cdot \nabla\tau = 0.$$
 Eq. 4

The zero values would mathematically define the points at which the maximum and minimum TFP values lie; these are the points in which bound the desired thermal gradient (again, refer to Fig. 2). To isolate this thermal gradient, a masking variable must be applied to obtain the zone of strongest gradient. To accomplish this, only the thermal gradient which occurs where TFL values are greater than

zero will be displayed. Additionally, the zero isopleths of this field lies within an area defined by positive values of TFP will be shown to discriminate which side of the thermal gradient is the warm edge.



Figure 2. This schematic describes the distribution of (a) the thermal variable  $(\tau)$ , (b) the magnitude of the thermal gradient, (c)  $TFP(\tau)$ , and (d)  $TFL(\tau)$ . The red dashed line depicts the warm side of the thermal gradient and is located by a zero value of TFL where the TFP is maximized. For the cold boundary of the thermal gradient, indicated by the blue dashed line, the TFL is zero where the TFP is minimized.

Within the literature, several different thermal parameters have been used within the TFP

formulation: low-level thickness values, low-level temperature, potential temperature, equivalent potential temperature, and wet-bulb potential temperature to name a few. The selection of a thermal variable wholly relies upon the type of boundary that is desired to be detected. Each of the many variables used for the objective location of frontal boundaries have their own strengths and weaknesses.

Low-level thickness parameters, while robust in that it takes into account a vertically averaged temperature, are dependent on the vertical temperature structure within the layer. Thus, if the layer is too "thick" and a front is shallow, the frontal boundary may be overshot and consequently masked out. Such was the case with most warm fronts when this type of thermal parameter was used; essentially, they were not represented. Since cold fronts slope toward cold air with height, or more technically toward the more statically stable air (Stoelinga et al. 2002), the frontal boundary should be nearer the surface. However, this thermal front parameter would more than likely maximize somewhere in between the two levels used for the thickness evaluation, and thus would not indicate the true location of the surface front. Although results for moderate to strong cold fronts had been very promising, it had likely been for the wrong reasons. Because of their steeper slopes, cold front locations using a TFP formulated with a thickness parameter may appear nearer their observed locations; the location of fronts that have less inclination (more slanted), however, would be ambiguous. Results for warm fronts and weaker cold fronts have proven poor. For these reason, low-level thickness as an input parameter into the objective front algorithm have been rejected.

Potential temperature ( $\theta$ ) as a thermal variable would identify a boundary solely in a temperature field as advocated by Sanders (1999). No previous work with objective frontal techniques made an attempt to use virtual potential temperature within the TFP formulation. Virtual potential temperature ( $\theta_v$ ) is a measure of atmospheric density which would conform to the more formal definition of a front as "the interface or transition zone between two air masses of different density" (Glickman 2000). In this regard, though, experimentation with  $\theta_v$  have shown very similar results to that of  $\theta$ .

Past research has favored the use of equivalent potential temperature (or nearly equivalently wet-bulb potential temperature), within the TFP framework which takes into account both temperature and moisture. Through experimentation,  $\theta_e$  does identify distinct boundaries and generally has a much stronger signal than any of the other variables tested. This is true particularly in the summer months, when frontal boundaries are typically associated with weaker temperature gradients, but more pronounced moisture contrasts. When moisture and thermal gradients are coincident, the TFP measure provides a superior performance as compared to simply potential temperature alone. However, with this lies a caveat in that gradients of equivalent potential temperature may result from pure moisture contrasts only. While this may be particularly useful in identifying dryline boundaries, it may hinder the efforts to identify synoptic fronts that may not conform to the definition in which is typically adopted for identifying fronts (i.e. pure thermal gradients). This study has decided to use  $\theta_e$  as the thermal variable of choice, despite its aforementioned shortcoming. The variable clearly identifies air mass boundaries, and its stronger signal provides a more robust way of boundary identification. Additional investigation of the identified thermal zone with this variable may reveal which type of boundary is depicted, and work on this matter will be discussed in the last section of this report.

It is common for the thermal front parameter to be computed on fixed levels (e.g. pressure levels); these levels vary, but all are generally near the top of or above the boundary layer. The reasoning is that boundary layer processes may partially mask the synoptic front nearer the ground; diurnal variations in temperature are much more evident within the boundary layer than the free atmosphere above it. While using levels such as 900 mb or 850 mb are well suited for this purpose, the frontal position at the surface may be dislocated, particularly in the case where the frontal boundary has a shallow slope. In the case of a more vertical slope (e.g. cold fronts), this measure may provide useful results.

However, only examining levels that are sufficiently far from the surface is somewhat

counterintuitive to traditional methods of frontal analysis, where fronts are defined to be located along the leading edge of surface temperature/dew point gradients that are visualized through inspection of surface data (Dept. of Commerce 2006). It is the contention that while boundary layer processes may somewhat hinder fronts, there should still be some aspect of a front discernible at or near the surface (Sanders and Doswell 1995). Therefore, the surface (or near surface) thermal characteristics should be the primary basis for identification of the surface frontal boundary, especially since boundaries nearer the surface play an integral role in convective initiation (Bluestein 2008).

A terrain following coordinate is desired in these situations. While many compute values of TFP on fixed levels (e.g. pressure levels), issues involving terrain can result. Within data from the experimental daily Purdue WRF model, the frontal zone is identified within the lowest 30 mb layer. Six pressure depth layers (PDLY) of 30 mb extend to 180 mb AGL and may be defined in post-processed model output. Nearly all of the operational models (i.e. GFS, NAM, RUC) have PDLY defined in their output. While these 30 mb averaged variables suit the purpose of identifying surface fronts and the extent of the front within the approximate depth of the boundary layer, for the purpose of identifying the extent of the front beyond 180 mb AGL, it is insufficient. This concern is currently being addressed and will be referred to in the Discussion section. This approach was chosen as it maintains the robustness of an integrated layer, but avoids a "too thick" layer as to "smear" out or overshoot a frontal zone. This new method also provides a means of visualizing the vertical coherence of the frontal zone so as to view the front in its true 3-dimensional structure.

The TFP parameter is sensitive to the amount of smoothing applied to the thermal fields, and the amount of smoothing applied depends on the grid spacing of the data to be examined. A movingaverage Gaussian filter with normally distributed weights seems to work well for this purpose. The weight (w) given to a grid point that lies within the location that is encompassed by the moving average is governed by the following relationship

$$w = \exp[-D^2]$$
 Eq. 5

where D is the ratio of distance from a point to the target point and the standard deviation of the normal distribution. The degree of filtering that is requested (i.e. number of passes) is specified by an integer, and will determine the standard deviation. The integer represents the number of grid increments from crest to crest of the wave that will have the response (theoretically) of 1/e = 0.3679.

For data of 30-40 km grid spacing, 10 passes of the Gaussian filter seemed reasonable. For very fine scale resolution (~4 km), an initial smoothing of the thermal field requires 100 passes to sufficiently damp out the high frequency thermal and moisture fields.

### **Application to Convective Mode Prediction**

#### **Factors Affecting Storm Organization**

Historically, vertical wind shear and buoyancy have been considered strong discriminators when it came to distinguishing between anticipated convective mode types, supported by both numerical and observational studies. The general findings from both observational and numerical studies have suggested that the determination of convective mode is strongly established by the magnitude of deep layer wind shear given sufficient CAPE, particularly between strong and weak shear. Thus, operational forecasters will often examine the magnitude of the vector wind difference over a deep layer, usually taken to be 0-6 km AGL, to determine the likely mode of convection as it exerts the greatest influence on storm type. Fig.3 shows the typical magnitudes of the 0-6 km vector wind difference as related to convective mode, taken from Markowski and Richardson (2010). It should be noted, however, that moderate to strong magnitudes of wind shear indicate that some overlap between multicell and supercell modes exist, thus mode may be more difficult to determine by shear magnitude alone in this regime.





One caveat of this approach to convective mode prediction lies within the neglected role of synoptic and/or mesoscale forcing mechanisms upon convection initiation and evolution. Often times, convection is initiated about synoptic boundaries such as a cold front or dryline. Persistent forcing due to a front can have a large impact on both the initiation and evolution of convection (Jewett and Wilhelmson 2006). In a study of the severe squall lines along the dryline in Oklahoma by Bluestein and Jain (1985), it was theorized that the orientation of the 0-6 km vertical wind shear vector (i.e. the vector wind difference over a deep layer) with respect to the initiation. This may be of importance, particularly when the deep-layer shear magnitude lies within the overlap area of the moderate to high regime and convective mode may be difficult to determine beforehand.

Many numerical studies (Weisman et al. 1988; Bluestein and Weisman 2000; James et al. 2005;

Parker 2007 a,b) and observational studies (French and Park 2008; Dial et al. 2010) have shown that the relationship between the orientation deep-layer shear vector with respect to the initiating boundary is indeed influential upon the subsequent mode of convection, particularly within a few hours of initiation. While the definition of "deep-layer" shear vector may vary between studies (see Table 1 for a summary), the general consensus between studies maintains that the orientation of the shear vector may have skill in determining convective mode.

Table 1: Layer used to compute shear vector from different studies.

\*Dial et al. (2010) used the 2-6 km vector wind difference when storm tops were expected to be less than 9 km AGL and 2-8 km shear when storm tops expected to be greater than 9 km AGL. These layers are also felt to be important with regard to precipitation distribution due to storm-relative flow and shear as these layers represent approximately 70-80% of cloud depth where most of the mass is concentrated.

Study	Layer
Weisman, Klemp, and Rotunno (1988)	0-5 km AGL
Bluestein and Weisman (2000)	Above 1.7 km AGL
James et al. (2005)	"deep-layer"
Parker (2007 a,b)	"deep-layer"
French and Parker (2008)	0-6 km AGL
Dial et al. (2010)	0-6 km; 2-6 km or 2-8 km AGL*

In the context of the orientation of the shear vector with respect to the initiating boundary, results from these studies have categorized the orientation (perpendicular, oblique, and parallel) and related this to the subsequent influence upon storm mode via storm interaction. For perpendicular orientations, it has been shown that storms initiated can remain discrete for a few hours before generally growing upscale into a linear system. Parallel orientations of the shear vector with the boundary generally result in linear systems, while oblique (~45°) orientations favor more discrete storms the initiate along the boundary. This relationship, along with other factors such as the magnitude of the linear forcing due to the boundary, may provide insight into the anticipated mode of convection should it form. It should be noted that this relationship is only applied to cold fronts, drylines, and prefrontal troughs and wind shifts. Fig. 4 depicts the conceptual model for the perpendicular and parallel orientations of the shear vector with respect to the initiating boundary.



Figure 4. Conceptual model proposed by Dial et al. (2010). The orientation of the shear vector with respect to the boundary in (a) is more parallel resulting in upscale linear growth and in (b) is more obliquely oriented, favoring discrete modes.

## Quantifying the Orientation of the Deep-Layer Shear Vector with Respect to the Frontal Boundary

A method to quantify the angle that the deep-layer shear vector creates upon its intersection with the frontal boundary (not zone) has been developed. The angle that the shear vector creates with the surface frontal boundary ideally may be examined by the angle created when the shear vector intersects the ridge line (maxima) of the TFP parameter. However, the angle a vector creates with a scalar field is not as straightforward to identify. An alternative course of action can exploit the relationship between the TFP field, the thermal gradient vector, and the shear vector. The premise for the technique relies upon the relationship between the thermal gradient vector ( $\nabla \tau$ ) and the shear vector ( $\nabla v_{shear}$ ), where is  $\nabla \tau$  is presumed to be orthogonal everywhere to the contour of TFP maxima as depicted in Fig. 5. This should be intuitive as the TFP is defined by the change of the thermal gradient in the direction of the thermal gradient itself.



*Figure 5. The thermal gradient vector is expected to be orthogonal to the frontal boundary (TFP maxima) as depicted above for an idealized straight cold front with no along front gradient.* 

The method utilizes vector mathematics, beginning with the dot product definition

$$\vec{V}_{shear} \cdot \vec{\nabla \tau} = \left| \vec{V} \right| \left| \vec{\nabla \tau} \right| \cos \alpha \qquad \qquad \text{Eq. 6}$$

Taking this formulation and performing some algebra, the equation may be rearranged to calculate the angle ( $\alpha$ ) between the two vectors

$$\alpha = \cos^{-1} \left( \frac{\vec{V}_{shear} \cdot \vec{\nabla \tau}}{|\vec{V}_{shear}| |\vec{\nabla \tau}|} \right)$$
Eq. 7

A simple conversion from radians to degrees will result in the angle between the shear vector and thermal gradient vector. While this process is fairly straightforward, an additional step needs to be taken as this angle is defined between  $\vec{V}_{shear}$  and  $\vec{\nabla \tau}$ , and not between  $\vec{V}_{shear}$  and the frontal boundary. As a result, the final step in this process requires the calculated angle to be subtracted from 90°, as  $\vec{\nabla \tau}$  is presumed to be orthogonal to the front. This method is intended to be applied to those frontal segments identified as either a cold front or a dryline as suggested by previous research. Fig. 6 a-c depicts the common orientation of the shear vector with the frontal boundary and their association with  $\vec{\nabla \tau}$ .



Figure 6. The relationship between the contour of TFP maxima,  $\nabla \vec{\tau}$ , and  $\vec{V}_{shear}$  for a combination of ideal orientations: (a) the relationship between  $\vec{V}_{shear}$  and the TFP maxima is shown to be perpendicular when  $\vec{V}_{shear}$  and  $\nabla \vec{\tau}$  are parallel (b) as in (a) but for a shear vector that is oriented parallel to the TFP maxima contour, but perpendicular to  $\nabla \vec{\tau}$ , and (c) as in (a) but for a shear vector that is oriented that is oriented obliquely (~45°) to both the TFP maxima contour and  $\nabla \vec{\tau}$ .

### **Case Study**

The application of the above procedures will be shown and evaluated via a case study of severe weather from this past spring. On April 14, 2011, first day of a 3-day severe weather outbreak, convection erupted along a dryline between 2000 UTC and 2100 UTC (and eventually a cold front upon its overtaking of the dryline), and produced over 300 reports of severe weather (Fig. 7). A moderate risk for severe weather was forecast by the Storm Prediction Center for eastern Oklahoma and into western Arkansas as outlined in each of the Convective Outlooks for that day. The analyzed frontal positions by the Hydrometerological Prediction Center (HPC) are shown in Fig. 8.



Figure 7. Storm reports for April 14, 2011.



*Figure 8. Surface frontal positions valid at 2100 UTC on April 14, 2011 as analyzed by the Hydrometeorological Prediction Center (HPC)* 

The dryline was anticipated to be the boundary of interest for initiating convection. The orientation of the shear vectors with the dryline was noted in the following excerpt from SPC Mesoscale Discussion #0425 on April 14, 2011, which shows the applicability of this general rule of thumb (SPC Mesoscale Discussion Archive 2011):

### STG ORTHOGONAL COMPONENT OF MEAN WIND AND DEEP-SHEAR VECTORS...RELATIVE TO DRYLINE...INDICATES STORMS CAN REMAIN DISCRETE FOR AT LEAST A FEW HOURS AFTER INITIATION.

Figure 9a shows the national 2 km Radar mosaic for the continental US at 2100 UTC. As can be seen, storms are initiating along the dryline and appear to be fairly discrete in nature. Nearly three hours later at about 0000 UTC (Fig. 9b), the line appears to be filling in, as would be anticipated from examination of the angle of the shear vector.



*Figure 9. 2 km mosaic of 0.5° Doppler radar reflectivity for the CONUS at (a) 2104 UTC and (b) 0002 UTC.* 

To evaluate the efficacy of the outlined methodology of automated frontal zone and the calculation of the shear vector angle with the frontal boundary, the 00Z run of the 4.25 km Purdue WRF will be utilized. Due to an unforeseen matter with archiving the data, the lowest 30mb PDLY level was not archived. Therefore, the frontal calculations will be made at the 850 mb level rather than in the lowest 30 mb layer; this should not hinder the location of the cold front and dryline a great deal. The frontal zones as identified by out outlined methodology are depicted in Fig. 10. A general likeness can be made when comparing this output with the HPC surface analysis.

Because initiation occurred near central Oklahoma, the frontal locations and shear vectors will be examined in that area. In Fig. 11, the TFP parameter and the contour of the zero value of TFL are depicted. Overlaid are the 0-6 km shear vectors and the angle (in degrees) that it makes when intersecting the frontal boundary. As can be seen, along the dryline boundary that initiated the convection, the angle the shear vector made with the boundary varied between 70° and approximately 90°.



Figure 10. The  $\theta_e$  frontal zones at 850 mb valid at 2100 Z.

Lastly, Fig. 12 depicts the frontal zone and the zero isopleth of the TFL field that illustrates which edge of the thermal gradient is the warm edge. Also shown are the shear vectors, and the angle they create when crossing the frontal boundary.



Figure 11. Shown are magnitudes of the TFP parameter, the zero isopleths of TFL, the 0-6 km shear vector, and the angle the shear vector creates when crossing the frontal boundary.



Figure 12. The objectively identified frontal zone, contour of zero in the TFL field, 0-6 km shear vectors, and the angle between the shear vector and the thermal gradient in the vicinity of the frontal zone.

### **Discussion and Future Work**

For the most part, the application of the TFP and TFL has produced acceptable results when attempting to locate cold or warm fronts, and a general comparison with manual analyses has proved this. However, it has been noted early on (e.g. Kirk 1965; Clarke and Renard 1966) that the method will not perform adequately in the vicinity of occluded fronts, in area of significant curvature (i.e. thermal ridges), and during the case when a notable along front thermal gradient exists. This also is very noticeable at the location where frontal boundaries join. Additional work will need to be done to take these issues into account.

Work is underway to refine the procedure which calculates the angle between the shear vector and the frontal zone. Only small changes will need to be made to evaluate this angle where the TFL parameter is equal to zero, and thus will represent the true angle of the shear vector at identified frontal boundary.

Methods to type the identified boundaries are currently being evaluated. A formulation to calculate the instantaneous frontal speed has been applied in several instances in the literature (Hewson 1998; McCann and Whistler 2001; Kašpar 2002; Jenkner et al. 2010). The equation for the instantaneous speed of the front is as such:

$$s = \vec{V} \cdot \frac{\nabla |\nabla \tau|}{|\nabla |\nabla \tau||}.$$
 Eq. 8

The formulation uses the component of the horizontal wind (V) perpendicular to the frontal zone and into the direction of the colder air, thus suggesting that the front may move at the advective speed of the air behind it (i.e. the frontal boundary acts as a passive scalar). Similarly, Jenkner et al. (2010) define their formulation for frontal motion as

$$s = \vec{V} \cdot \frac{\nabla TFP}{|\nabla TFP|}.$$
 Eq. 9

This measure may be somewhat suspect for the purpose of labeling the frontal movement, however it does provide an efficient method for typing fronts (McCann and Whistler 2001, Jenkner et al. 2010). Positive speeds denotes where a front is moving toward the warm air, or in other words, a cold front. The opposite is true as well, where negative values for the frontal speed would identify a frontal boundary as a warm front.

The dryline is a geographically tied phenomena, and while it does occur in other parts of the world such as Australia, Spain, eastern China, and India (e.g. Schaefer 1986; Markowski and Richardson 2010), a survey of the literature suggests that the phenomena is studied primarily in regards to its existence in the United States. The dryline will be considered a special type of front within this framework. Deemed a mesoscale boundary (Glickman 2000, Hoch and Markowski 2005), the dryline is generally confined to the lower levels (i.e. the boundary layer) and separates a cooler, more moist air mass from a warmer, dry air mass. The dryline is a particularly important boundary to identify as it can serve as a mechanism for convective initiation (e.g. Schaefer 1986); it may be detected in moisture fields such as dew point temperature, mixing ratios, and both by equivalent potential temperature and virtual potential temperature fields. Prior work has made no attempt to address the typing of such boundaries as distinct from other fronts, likely due to the fact that it is geographically tied and most objective frontal studies have been carried out in Europe in areas of complex terrain which requires the frontal calculations to be calculated upon elevated levels that are distant from the surface.

A simple method for determining the existence of a dryline as opposed to a cold frontal boundary may be applied in the afternoon hours, particularly within the time frame of 1800 UTC to 0000 UTC. Exploiting the common characteristic that the "dry" side of the dryline boundary is typically of a higher temperature than the "moist" side, the relationship between the temperature gradient vector and the moisture gradient vector would be such that a simple operation of the dot product could be utilized. If the boundary is indeed a dryline, the scalar result of the dot product between these two vectors would be a negative number as a result of the angle between the two vectors would be larger than 90°. Evaluation of this method is still underway.

To examine fronts which extend above the boundary layer, or exist in the upper levels, a vertical interpolation has been made to from pressure coordinates to sigma coordinates, which are also terrain following (Phillips 1957). Sigma levels are defined by the ratio of the pressure of the level and

the pressure at the surface

$$\sigma = \frac{p}{p_s}$$
 Eq. 10

This will allow for the frontal algorithm to be calculated in layers throughout the depth of the atmosphere and to examine the vertical structure and slope of the frontal zone.

Future work with frontal identification aims to utilize the Baldwin Object-Oriented Identification Algorithm (BOOIA) (Baldwin et al. 2005; Carley et al. 2010). This will allow the attributes of the identified frontal "objects" to be quantified, such as the area encompassing the frontal zone, the eccentricity of the identified zone, the orientation, and lengths of the major and minor axes. Also, meteorological quantities associated with the frontal zone may be identified and quantified. Examples of such quantities include but are not limited to: the magnitude of the thermal gradient, the bulk-shear magnitude, magnitude of the relative vorticity, instability measure (e.g. CAPE, convective instability, mid-level lapse rates), CIN, searching in the vertical for forcings for vertical ascent (e.g. QG omega, Q-vector convergence, differential PVA), and mean convergence in the lowest 90 mb.

## Section 3: Benefits and Lessons Learned: Operational Partner Perspective

Kim Hoogewind gave an office seminar to our forecast staff providing background information and operational applications for the Thermal Front Parameter developed for output in the local WRF model run at Purdue University. Following the presentation, real-time output from their 1km model runs were made available to our office via their website. Testing of the utility of this parameter in operational forecasting was done during the convective season this year. Forecasters were asked to begin looking at this parameter as part of their mesoscale analysis to see if any benefits could be gained by associating the magnitude of this parameter with favorable areas for convective development along a frontal boundary. While no specific cases were documented, informal comments from forecasters suggest promising results for incorporating this parameter into the forecast process by combining it with other parameters already used in forecasting convection. Future work includes incorporating the code into our own local WRF model and begin formal documentation of cases where the parameter proves beneficial to operational forecasting.

# Section 4: Benefits and Lessons Learned: University Partner Perspective.

Purdue University students benefited by the availability of the daily, real-time WRF model runs that were executed at Purdue. Students utilized this output in their own weather analysis and forecasting (forecast contests and class weather briefings) and benefited by gaining exposure to real-time highresolution NWP model output. The archive of numerous WRF forecasts was also beneficial in the development of the Euclidean-distance based forecast verification approach, and is expected to continue to have value in future development of new verification techniques and value-added forecasting products. Kim Hoogewind, the graduate student supported by this project, also benefited through the process of developing and implementing the automated frontal analysis procedures, interacting with the operational forecasters, and performing the background research necessary to accomplish the tasks throughout this project. Her master's thesis will primarily involve the work performed during this project. The algorithm developed here will also be utilized in follow-on research involving the analysis of downscaled climate simulations to determine the accuracy of the WRF model's frontal positions in a  $\sim 20$  year springtime dataset that has been generated during a separate NSF-funded collaborative project. The majority of this Partners project has involved the development of the frontal analysis algorithm, we expect that future collaborative work with IWX, AWC, EMC, and other interested NWS partners will result in improved numerical guidance for operational forecasters across the NWS.

### **Section 5: Presentations and Publications**

Hoogewind, K. A. and M. E. Baldwin, 2010: A proposed method for objectively identifying and characterizing surface fronts. Poster for 35th National Weather Association Annual Meeting, Tucson, AZ, October 2-7, 2010, P1.9.

Hoogewind, K. A. 2011: A method to objectively identify frontal zones. Presentation to IWX, March 2011

Baldwin, M.E., 2011: Feature-specific analysis and prediction. Presentation to AWC, July 2011

## Section 6: Summary of University/Operational Partner Interactions and Roles

Purdue researchers (Prof. Mike Baldwin and Kim Hoogewind) visited the Syracuse, IN NWS office in order to collaborate with NWS partners and discuss project plans with NWS researchers and other interested staff. In March 2011, the preliminary algorithm code (GEMPAK scripts) was transferred to the IWX office for evaluation by the operational forecasters. PI Baldwin and Hoogewind also visited the Aviation Weather Center in July 2011 to participate in the Aviation Weather Testbed, give a presentation related to this project, and discuss transfer of this research into the operations at AWC. Purdue researchers maintained daily, real-time WRF model runs that included diagnostic output from the automated frontal analysis. Web pages were also developed to include side-by-side comparisons of daily WRF model forecasts and observed analyses using NEXRAD, RTMA, and RUC analysis fields. These web pages were used to routinely evaluate the performance of the prediction system.

Project Roles:

Michael Baldwin (Purdue University) – PI: project manager, algorithm development, forecast system evaluation, real-time WRF model system implementation and maintenance

Kim Hoogewind (Purdue University) – graduate student researcher: frontal analysis and deep-layer shear/front orientation algorithm development, web product development

Jeffrey Logsdon (NWS/IWX) : forecast system evaluation

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