The relationships between temperature gradient and wind during cold frontal passages in the eastern United States: a numerical modeling study

Robert Conrick, 1* Nathan L. Curtis, 2 Paul W. Staten 2 and Cody Kirkpatrick 2

1 Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA
2 Department of Geological Sciences, Indiana University, Bloomington, IN, USA

Abstract

Cold frontal passages are a common occurrence throughout the eastern United States. Previous observational research showed the surprising result that there is only a very weak, statistically nonsignificant relationship between a cold front’s maximum 2-min sustained wind and the across-front temperature gradient. By using the WRF-ARW model to simulate eight cold fronts, we re-examine the relationship between temperature gradient and wind near the surface, and provide additional analysis. Results confirm previous observational research that found no relationship between wind speed and cross-frontal temperature gradient. The agreement between studies suggests that the lack of relationship may be physical and not a result of undersampling.

Keywords: cold front; front; wind; temperature gradient; correlation

1. Introduction

Midlatitude cyclones and their associated cold fronts are among the most common meteorological events in the eastern United States. With many events occurring each year, these systems were among the first atmospheric phenomena studied. Early cyclone models outlined characteristics of the midlatitude cyclone and associated cold front (Bjerknes, 1919; Bjerknes and Solberg, 1922; Henry, 1922; Godske et al., 1957), and are frequently cited in modern discussions of cyclogenesis. With such a long history of study, cold fronts have received wide attention with many theories describing their movement and behavior (see Smith and Reeder, 1988) for an in-depth discussion of several theories of frontal motion).

Early cyclone models often describe cold fronts as discontinuities between air masses. Sharp gradients in temperature, moisture, precipitation, and wind direction are well-documented (e.g. Brundidge, 1965; Shapiro, 1984; Moore, 1985; Crook, 1987; Smith and Reeder, 1988; Mass and Schultz, 1993; Sanders, 1999; Schultz, 2004; Zhang et al., 2009; Payer et al., 2011; Sinclair et al., 2012; Sinclair, 2013; Clark and Parker, 2014). However, relatively little research is available on the relationships between these quantities – in particular between temperature gradient and wind – along the cold-frontal interface.

Frontal theory offers two important hypotheses regarding the relationship between temperature gradients, wind, and wind gradients. First, the speed of cold frontal propagation – in the absence of convection – should depend on wind speeds immediately following and normal to the cold front (Bluestein, 1993). Assuming cold fronts have characteristics similar to density currents, then the speed of frontal propagation will partially depend upon the virtual potential temperature gradient across the front (Simpson, 1987) due to the temperature/density gradient at the frontal interface promoting an across-front pressure gradient force (PGF). Sinclair and Keyser (2015) showed that cold fronts can exhibit dynamical regimes similar to density currents if simulated at high resolution with a modern Planetary Boundary Layer (PBL) scheme, and further concluded that in such simulations, PGF dominates force balances at the frontal interface. This framework provides a possible link between temperature gradient and wind speed at the frontal interface.

The second theory presented is based on the two-dimensional frontogenetical function. For an idealized cold front oriented in the north–south direction, this function simplifies to:

\[ F = \frac{1}{|\nabla \theta|} \frac{\partial \theta}{\partial x} \left( \frac{1}{C_p \frac{\rho_0}{\rho}} \right) K \left( \frac{\partial Q}{\partial t} \right) - \left( \frac{\partial u}{\partial x} \frac{\partial \theta}{\partial x} \right) \]

(Bluestein, 1993), where terms follow convention. Frontogenesis thus depends on the strength of the temperature gradient and the front-normal wind gradient. Therefore, one can expect coincident gradients in wind and temperature at the cold frontal interface. Moreover, the temperature gradient at any point along a cold front should, by definition, point toward warm air and be normal to isotherms along the front. Considering these viewpoints, it is expected that the temperature gradient at any point along a cold front should point in the direction of frontal motion, with strong wind and wind...
gradients associated with strong cold front temperature gradients.

Strong wind and wind gradients associated with cold fronts are directly and indirectly documented on numerous occasions (Shapiro, 1984; Smith and Reeder, 1988; Friedrich et al., 2008; Ma et al., 2010; Sinclair et al., 2012). Shapiro (1984) observed a cold front as it passed over an instrument tower in Colorado – finding temperature gradients overlapped front-normal wind gradients along the frontal interface (see his Figure 3). Sanders (1999) observed a temperature gradient of 18 °C per 100 km that coincided with damaging wind gusts ranging from 22 to 31 m s⁻¹. Pryor et al. (2014), however, showed only weak relationships exist between a cold front’s temperature gradient and maximum 2-min observed wind. Pryor et al. (2014) analyzes the ‘scale and intensity’ of extreme wind in the eastern United States. Among many results presented, they discuss the relationship between temperature gradient and wind observed along 35 cold fronts between January 2012 and September 2013. Their analysis reveals a weak positive trend, but no statistically significant relationship. We choose to verify and expand upon their results in part to address the following: (1) data are chosen from surface observing stations, which are often separated by more than 100 km – thus a gradient through several stations may not be representative of what occurs along the frontal interface; (2) the calculation of temperature gradients at only 1200 UTC; (3) only wind speed – not direction or gradient – is considered. We address these points by using high-resolution simulations to spatially and temporally increase the amount of data along the frontal interface. Furthermore, we consider wind gradients due to their connection to frontogenesis, and include the direction of wind relative to temperature gradient in order to provide a complete analysis.

Our aim is to investigate the relationships between horizontal temperature gradients (dT), wind (Wind), and wind gradients (dWind) at the frontal interface. Beyond better understanding cold fronts, our work provides insight into sensible weather quantities, which may prove useful for short-term forecasting and understanding surface weather.

This article is structured as follows. Section 2 describes model configuration, methodology, and data filtering. Section 3 presents results/relationships found in the model output. Section 4 offers concluding remarks.

2. Methods

2.1. Cold front cases and model configuration

We identified eight midlatitude cyclones based on the location and orientation of their associated cold fronts (Table 1). We selected cyclones that approximately followed the structure common to the eastern United States and outlined in Bjerknes (1919) in which the cold front extends from the center of low pressure in a southwestward direction. The National Oceanic and Atmospheric Administration Weather Prediction Center (WPC) Daily Weather Maps were used to identify cold fronts which occurred between April 2012 and December 2013 – chosen to overlap with many of the fronts analyzed in Pryor et al. (2014). We chose a particular cyclone if the cold front: (1) traveled, in part, from west-to-east across the model domain; (2) impacted the majority of the eastern United States; (3) remained mostly unoccluded while over the domain; and (4) exhibited a sufficiently large temperature gradient. This fourth criterion was achieved by choosing the eight fronts with the largest temperature gradients that met the other criteria.

The Advanced Weather Research and Forecasting Model version 3.5 (WRF-ARW; Skamarock et al., 2005) is used to simulate all cases. We integrate the model over a domain extending from approximately 105° to 66°W (Figure 1; similar to Pryor et al. (2014)) with a horizontal grid spacing of 2 km and 31 vertical levels. The Noah land-surface model (Ek et al., 2003) is used with high-resolution 30-s topography data. Initial and boundary conditions are from the North American Mesoscale (NAM) Model (Janjić et al., 2005) 40-km analysis. Boundary conditions are updated every 6 h from the corresponding NAM forecast. Other model parameters include the Goddard Microphysics Scheme (Tao et al., 2003), the Dudhia longwave radiation scheme (Dudhia, 1989), and the Mellor-Yamada-Janjić (Janjić, 2002) planetary boundary layer/surface layer schemes. No cumulus scheme is used. Simulation durations are outlined in Table 1.

### Table 1. A listing of cold front cases, including model initialization time, length of simulation, and maximum analyzed dT value.

| Case                      | Start time, UTC | Duration, h | Maximum dT, °C km⁻¹ |
|---------------------------|----------------|-------------|---------------------|
| 14 April 2012             | 1200           | 84          | 3.4564 (LMH)        |
| 10 March 2013             | 0000           | 84          | 2.5088 (LMH)        |
| 10 April 2013             | 0000           | 72          | 5.0622 (SFC)        |
| 17 April 2013             | 1200           | 57          | 5.0240 (LMH)        |
| 22 April 2013             | 1200           | 84          | 2.9360 (LMH)        |
| 12 June 2013              | 0000           | 84          | 2.5932 (LMH)        |
| 04 October 2013           | 1200           | 84          | 1.6788 (LMH)        |
| 04 December 2013          | 0000           | 72          | 1.8742 (LMH)        |

2.2. Data filtering and processing

We process data at 1 h increments starting at forecast hour 02 and ending at the last hour of simulation. Near-surface temperature gradients (dT), wind (Wind), and wind gradients (dWind) are the fields of interest for this study. ‘Near-surface’ refers to either the surface (SFC) or the lowest model height (LMH). We define ‘Wind’ as the magnitude of the vector consisting of the u– and v-component wind at a particular level and location. The horizontal gradient is defined as

\[
\nabla F = \frac{\partial F}{\partial x} + \frac{\partial F}{\partial y} \hat{J} \tag{1}
\]
where $F$ is a scalar field in the $x$-$y$ plane. The gradient is calculated using a central difference for interior points ($dx = 4$ km). To isolate cold fronts from the model output and remove data affected by other processes (e.g., moist convection), we apply data filters, including gradient thresholds, edge detection, and a terrain filter, to the $dT$ fields. An example of a filtered $dT$ field can be found in Figure 1. For a full description of data filters applied, see Appendix S2, Supporting Information. Filtered data were inspected manually, and only hours with a clearly detected cold front were chosen (SFC $n = 212$; LMH $n = 222$). Because surface temperature (2-m) and wind (10-m) are computed in the surface- and boundary-layer parameterization schemes, we consider $dT$, Wind, and $dWind$ at the surface and LMH – thus giving attention to parameterized surface data and

Figure 1. The model domain for all simulations, including the filtered $dT$ field (black dots) of hour 26, 17 April 2013. The inset shows directions of all $dT$ points - the bold line corresponds to the direction of the point of maximum $dT$ (red box on map).

Table 2. Correlation coefficients ($r^2$), normalized regression coefficients ($b$), and $p$ values for the results outlined in Section 3, including 100-km regional averaging. Relationships are organized by model level (surface [SFC] or lowest model height [LMH]) and by the dependent variable being compared to temperature gradient ($dT$).

| Level  | Independent variable | Dependent variable | $r^2/b$ | $p$ | $r^2_{\text{regional}}/b_{\text{regional}}$ | $p_{\text{regional}}$ |
|--------|----------------------|--------------------|---------|-----|--------------------------------|---------------------|
| SFC    | $dT$                 | Wind               | 0.2084 / 0.44 ± 0.35 | <0.001 | 0.3487 / 12.6 ± 4.39 | <0.001 |
|        | $dWind$              |                    | 0.1415 / 0.36 ± 0.07 | <0.001 | 0.0317 / 3.80 ± 0.46 | 0.0094 |
|        | $dT$-parallel $Wind$ |                    | 0.2061 / 0.43 ± 0.34 | <0.001 | 0.1528 / 8.34 ± 4.79 | <0.001 |
|        | $dT$-normal $Wind$   |                    | 0.0608 / 0.24 ± 0.26 | 0.003  | 0.1801 / 7.84 ± 5.32 | <0.001 |
|        | $dT$-parallel $dWind$|                    | 0.1314 / 0.35 ± 0.07 | <0.001 | 0.0231 / 3.24 ± 0.40 | 0.0270 |
|        | $dT$-normal $dWind$  |                    | 0.0424 / 0.20 ± 0.04 | 0.003  | 0.0137 / 2.50 ± 0.37 | 0.0894 |
| LMH    | $dT$                 | Wind               | 0.1951 / 0.41 ± 0.33 | <0.001 | 0.3170 / 11.4 ± 4.49 | <0.001 |
|        | $dWind$              |                    | 0.1062 / 0.30 ± 0.06 | <0.001 | 0.0430 / 4.21 ± 0.48 | 0.0019 |
|        | $dT$-parallel $Wind$ |                    | 0.0971 / 0.29 ± 0.29 | <0.001 | 0.1801 / 8.61 ± 4.64 | <0.001 |
|        | $dT$-normal $Wind$   |                    | 0.1303 / 0.34 ± 0.29 | <0.001 | 0.1077 / 6.65 ± 5.36 | <0.001 |
|        | $dT$-parallel $dWind$|                    | 0.0450 / 0.20 ± 0.05 | 0.002  | 0.0285 / 3.43 ± 0.41 | 0.0117 |
|        | $dT$-normal $dWind$  |                    | 0.0817 / 0.27 ± 0.05 | <0.001 | 0.0225 / 3.04 ± 0.41 | 0.0253 |
less-parameterized LMH data. Our chief interest is identifying correlations between these quantities, therefore we perform linear regression to determine whether relationships exist. Correlation coefficients ($r^2$) and normalized regression coefficients (with uncertainty bounds derived from a $t$-statistic) are computed as metrics of relationship strength.

3. Results and discussion

We calculate two sets of correlations (dT vs Wind; dT vs dWind) at the surface and LMH. In these analyses, the point of maximum dT in the domain is chosen with collocated Wind or dWind selected for each 1-h increment of each model run (i.e. dT is the independent variable; henceforth referred to as the dT-Wind analysis).

Assuming that the direction of the dT vector is primarily oriented across the front (Appendix S2 presents a qualitative look at dT direction), then components of Wind and dWind are examined to assess whether their across-front (dT-parallel) or along-front (dT-normal) components exhibit a stronger relationship. Directions are computed by projecting the Wind vector onto the dT vector: the projection itself is dT-parallel and the normal component is dT-normal. While it is hypothesized that dT-parallel wind will be better correlated, we include dT-normal wind to present a complete argument. Correlations, regression coefficients, and $p$ values are listed in Table 2.

Correlations between dT and Wind are low at both the surface ($r^2 = 0.2084$; Figure 2(a)) and LMH ($r^2 = 0.1951$; Figure 2(b)). When dT is correlated...
Temperature gradient and wind relationships of cold fronts

Figure 3. Scatterplots of $dT$ vs. $dWind$. The left column shows surface relationships and the right column shows LMH relationships. Regression lines, regression coefficients ($b$), and correlation coefficients ($r^2$) are displayed.

with $dWind$, results are similar (SFC $r^2 = 0.1415$; LMH $r^2 = 0.1062$; Figure 3(a) and (b), respectively). Associated $p$ values suggest significance ($p < 0.05$), however low correlation coefficients imply that no strong linear relationships exist between $dT$ and Wind or $dT$ and $dWind$. An examination of Figures 2 and 3 confirm no obvious relationship among the data. It is possible, however, that either the along-front or across-front component of the wind is correlated with the temperature gradient, even if the wind speed is not. To investigate this possibility, we consider the parallel and normal components of Wind and $dWind$ relative to $dT$ in order to determine whether correlations are stronger in the across-front ($dT$-parallel) or along-front ($dT$-normal) directions. At the surface and LMH, the correlations between $dT$ and $dT$-parallel Wind is also weak (SFC $r^2 = 0.2061$ and LMH $r^2 = 0.0971$; $p < 0.05$ for both; Figure 2(c) and (d), respectively). For relationships between $dT$ and $dT$-normal Wind, correlations are the weakest observed (Figure 2(e) and (f)). Correlations between $dT$ and components of $dWind$ are similarly weak with $r^2 > 0.0424$. For all regressions, regression coefficients are also computed. However, the substantial overlap in uncertainty bounds across all regressions implies that the regression slopes do not significantly differ. All correlations and regression coefficients are summarized in Table 2 and displayed on Figures 2 and 3.

A natural question to ask is whether inspecting a region along the front, rather than one grid point, will
lead to better sampling. Thus, we inspect an average of 
\( dT \), Wind, and \( dW \) over a 100 km region centered on the
points of greatest \( dT \) for each hour. While results are
similar to those presented earlier, correlations between
\( dT \) and Wind magnitude increase – possibly due to
including many points with \( dT \) similar in magnitude to
the point of maximum \( dT \), but with stronger Wind. We
summarize the results in Table 2.

The results of these analyses show that while trends
are positive for all comparisons, no strong correlations
exist between \( dT \), Wind, and \( dW \). The conclusion
applies for both the surface and the LMH, and indicates
that the magnitude of \( dT \) is not a reliable indicator of
the magnitude of near-surface Wind or \( dW \) observed
along a cold front. These results are consistent with
previous studies.

4. Conclusion

This study builds on previous observational work on
relationships that exist between temperature gradient
and wind observed during cold frontal passages. Eight
carefully selected cold front cases that impacted the
eastern United States are simulated. We use linear
regression to examine potential correlations between
near-surface temperature gradients, wind, and wind
gradients. Scatterplots of these variables exhibit no
obvious linear or nonlinear relationship. Low correla-
tion coefficients, coupled with statistically indistinct
regression coefficients, indicate a lack of strong
relationships.

The results of the \( dT \)-Wind analysis imply that the
influence of near-surface temperature gradients on wind
or wind gradients observed during frontal passage is
likely negligible (all \( r^2 \leq 0.2084 \)). These findings are
counter to theory presented in Section 1, but agree with
results of Pryor et al. (2014). These weak relationships
may be physical – rather than the result of analysis
or undersampling – and it is likely the case that other
mechanisms exist which accelerate air along/across
cold fronts. Future work could focus on these mecha-
nisms. For instance, near-surface wind may be more
closely related to synoptic than near-surface condi-
tions. Furthermore, boundary layer friction may play
a role by lessening the impact of frontogenesis. We
reiterate that the agreement between observations and
simulations is of great importance to understanding
these results, and conclude that cold fronts with strong
temperature gradients will not necessarily yield strong
near-surface wind.

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Supporting information

The following supporting information is available:
Appendix S1. Data filtering
Appendix S2. Inspection of the direction of temperature gradi-

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R. Conrick et al.
