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Supporting fire weather forecasting through a tool to identify convective outflows in numerical weather prediction models

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Introduction

Thunderstorm downdrafts can cause abrupt changes in surface winds that dramatically impact wildfire spread rate, direction, and intensity. These thunderstorm-induced changes in fire behavior can pose a significant danger to firefighters and have been implicated in a number of fatal fires. To assist fire weather forecasting, a tool to objectively identify convective outflow boundaries in high-resolution numerical weather prediction (NWP) model output has been developed. The tool works with both deterministic and probabilistic forecasts and has initially been applied to output from: (i) the High-Resolution Rapid Refresh (HRRR) (Benjamin *et al.* 2016) system and (ii) the National Center for Atmospheric Research (NCAR) ensemble (Schwartz *et al.* 2015), both of which employ the Weather Research and Forecasting (WRF) Model (Skamarock *et al.* 2008).

Methodology

Gust front characteristics

When the rain-cooled air of a thunderstorm downdraft strikes the earth's surface it spreads laterally away from the downdraft and often results in a sharp discontinuity in wind, pressure, temperature, and relative humidity between the downdraft air and the ambient surface air. This boundary is called a gust front, as winds in the rain-cooled air are usually stronger than the undisturbed air, and the boundary acts like a small-scale cold front. Therefore, diagnostic variables capable of detecting gust fronts are similar to those associated with cold fronts. Three variables used to construct the tool are (i) frontogenesis; (ii) hourly vector wind difference; and (iii) potential temperature (θ) gradient. Frontogenesis is a mathematical description of the processes that can create a front and is mainly how winds act to increase a temperature contrast.

Gust front tool

The tool has two application modes. In the first, it diagnoses and plots selected meteorological fields to identify potential gust fronts. In the second, the tool determines discrete edges from the gradients in such fields using the Multiple-Directional Non-Maximum Suppression (MDNMS) method (Sun and Vallotton 2009) using various filters based on threshold criteria to focus on convective outflow environments. An initial version of the tool has been applied to convective events over both simple and complex terrain and with and without wildfire activity. The

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following cases are discussed here: (1) Great Plains gust front— 3 July 2017 (simple terrain, no fire), (2) Colorado mountain gust front— 7 May 2017 (complex terrain, no fire).

Results and discussion

3 July 2017 case

On 3 July 2017 a mesoscale convective system on the Oklahoma-Kansas border produced a strong gust front that moved southeast. Figures 1(a) and 1(b) show the observations from Gage, OK (passage at approximately 2300 UTC 3 July), marked GAG in Figure 2. Wind gusts in excess of 29 m s^{-1}, temperature falls of 14 ºC, pressure rises of 7 hPa, and large increases in relative humidity accompanied the gust front's passage at Gage. This strong, classical gust front over flat terrain is a good first test for the tool.

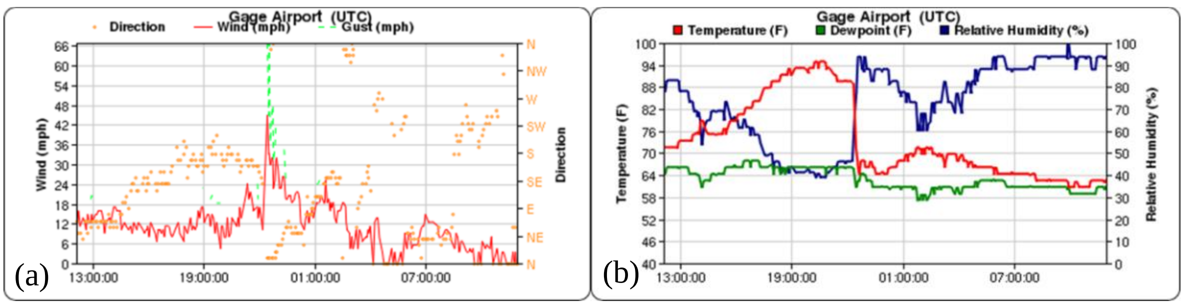

Figure 1: Surface observations from 1200 UTC 3 July – 1200 UTC 4 July 2017 from Gage, OK. (a) Wind speed, direction, and gust. (b) Temperature, dewpoint temperature, and relative humidity.

Figure 2 shows tool-diagnosed fields at 0100 UTC 4 July based on the 4-h HRRR forecast (2100 UTC 3 July initialization) for 2-m temperature and 10-m winds. Figure 2(a) presents the one-hour surface vector wind difference (shaded). Many areas exhibit significant one-hour wind differences. In Figure (2b) the tool employs the surface frontogenesis function and shows a much sharper analysis of the forecast gust front zone.

From the NCAR ensemble 24-h forecast valid 0000 UTC 4 July, Figure 3 shows three members' frontogenesis fields. The frontogenesis maxima (green-red shading) imply gust front boundaries. Figure 4 shows the tool's MDNMS capability applied to the θ-gradient field and illustrates its determination of discrete boundaries. These types of products can alert fire weather forecasters to potential gust fronts.

Figure 5a shows a paintball plot of all the gust fronts in the 10-member ensemble identified by MDNMS applying the θ-gradient analysis. Results from each member are assigned a different color. As might be expected, the ensemble members produce a wide range of gust front solutions. These ensemble results can be combined into an ensemble-based probability of a gust front within 40 km of a given point (Figure 5b). Red-shaded regions are where all ten members produced a gust front within 40 km of that point at 0000 UTC 4 July 2017.

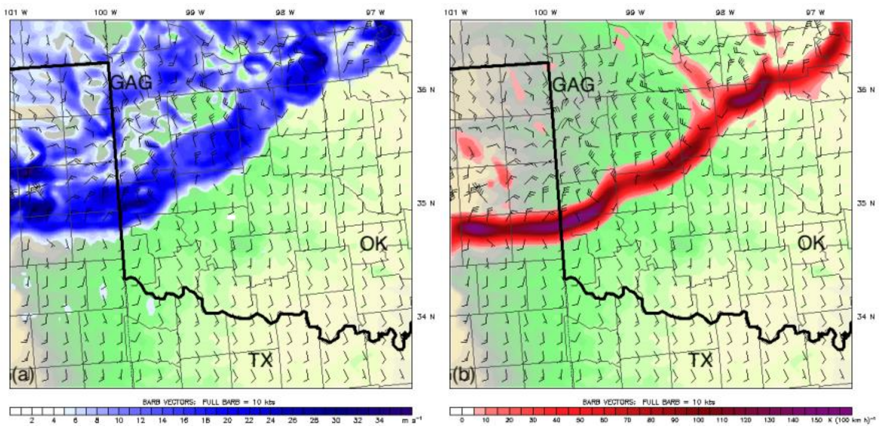

Figure 2. Outflow boundary fields diagnosed from the HRRR forecast valid 0100 UTC 4 July 2017 (2100 UTC 3 July initialization). Instantaneous surface wind field (full barb= 5 m s^{-1}) also shown. (a) One-hour vector wind difference (m s^{-1}) (shaded, scale at bottom). (b) Surface frontogenesis (K 100 km^{-1} h^{-1}) (shaded, scale at bottom).

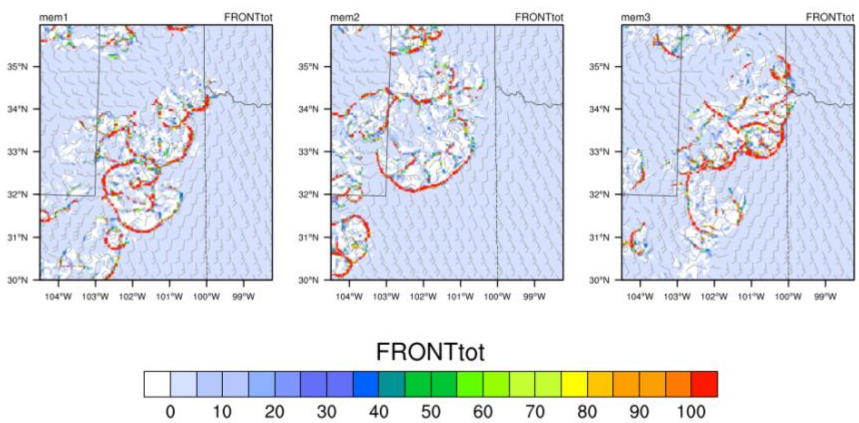

Figure 3. Surface frontogenesis field (K 100 km^{-1} h^{-1}) (shaded, scale at bottom) in 24-h forecast from three members of the NCAR ensemble (valid: 0000 UTC 4 July 2017) in northern TX/southwestern OK. Instantaneous surface wind field (full barb= 5 m s^{-1}) also plotted.

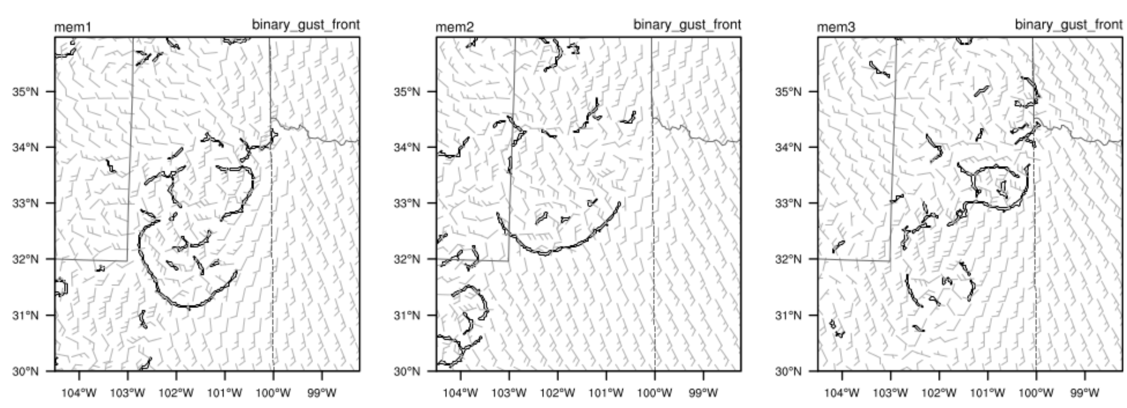

Figure 4. Gust front tool MDNMS-identified outflow boundaries in members of the NCAR ensemble for the 24-h forecast valid 0000 UTC 4 July 2017. Instantaneous surface wind field (full barb= 5 m s^{-1}) also plotted.

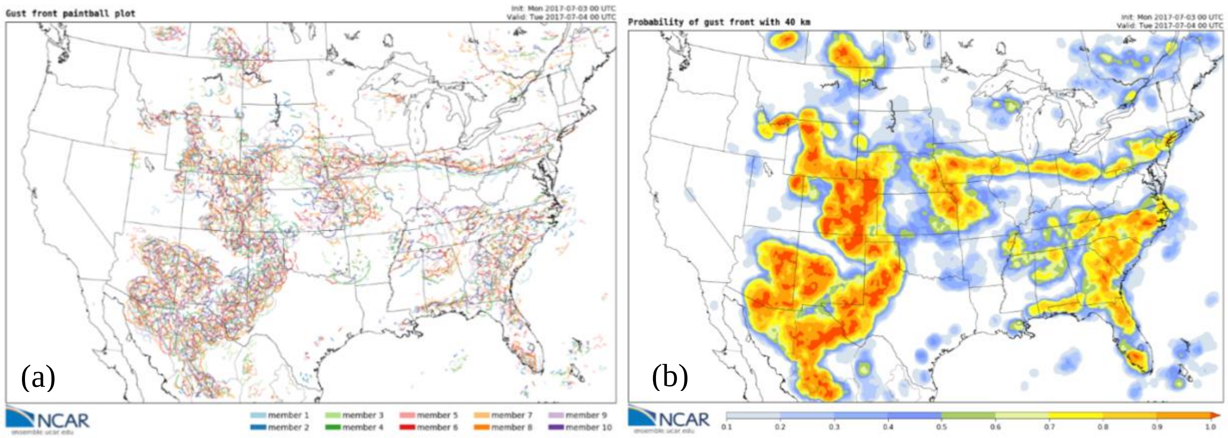

Figure 5. (a) Gust front tool MDNMS-identified outflow boundaries in the 10-member NCAR ensemble for the 24-h forecast valid 0000 UTC 4 July 2017. (b) Probabilities of gust fronts within 40 km of a given point based on gust front tool MDNMS-identified outflow boundaries in the 10-member NCAR ensemble for the 24-h forecast valid 0000 UTC 4 July 2017. Probabilities shaded, scale at bottom (0–1; 0%–100%). The MDNMS method was applied to the WRF forecast surface θ-gradient fields.

7 May 2017 case

On 7 May 2017 a NW–SE-oriented line of convection developed along the Continental Divide in the Colorado Rockies and produced a long-lived, eastward-propagating outflow boundary. Figure 6 shows surface time series from Boulder, CO where a 23 m s^{-1} wind gust (Figure 6(a)) was accompanied by an abrupt 12 ^{o}C temperature decrease (Figure 6(b)).

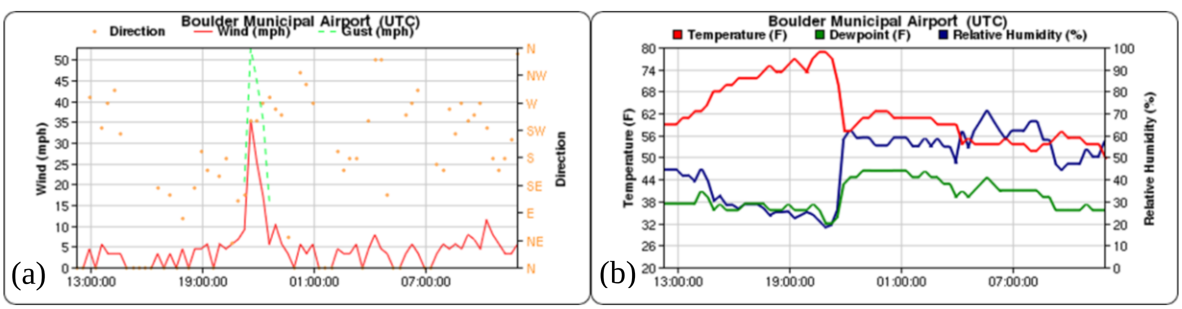

Figure 6. Surface observations from 1200 UTC 7 May – 1200 UTC 8 May 2017 from Boulder, CO. (a) Wind speed, direction, and gust. (b) Temperature, dewpoint temperature, and relative humidity.

The HRRR forecast produced two waves of convection. Figure 7 shows the tool's hourly vector wind difference and surface frontogenesis fields for 2000 UTC (forecast hour 4, 1600 UTC initialization). One outflow boundary moved east over the Plains ("A"), while a second was over the complex topography ("B") to the west. The HRRR thus can simulate gust fronts in complex mountain topography and the tool can reveal them.

The MDNMS tool (Figure 8) shows the identified boundaries in the NCAR ensemble at 2200 UTC 7 May 2017 (22-h forecast). The first and third members (left and right panels) have long and coherent outflow boundaries east of the mountain convective initiation region, similar in mode to that observed.

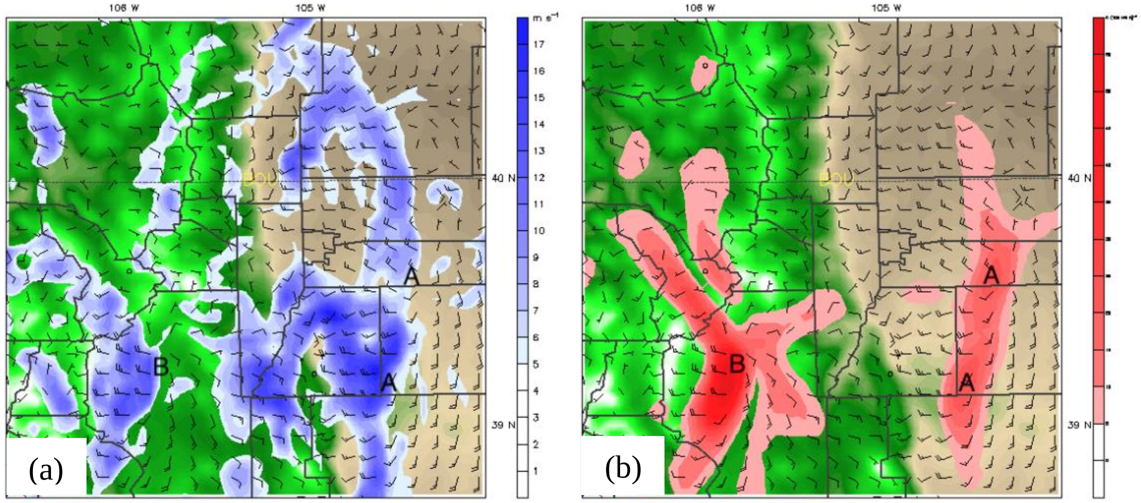

Figure 7. Outflow boundary tool output from the 4-h HRRR forecast valid 2000 UTC 7 May 2017. Terrain is shaded with brown indicating plains and green the mountains. County outlines are shown. Instantaneous surface wind field (full barb= 5 m s^{-1}) also shown. "A" and "B" mark locations of boundaries. (a) One-hour vector wind difference (sfc) (m s^{-1}) (shaded, scale to right). (b) Surface frontogenesis (K 100 km^{-1} h^{-1}) (shaded, scale to right).

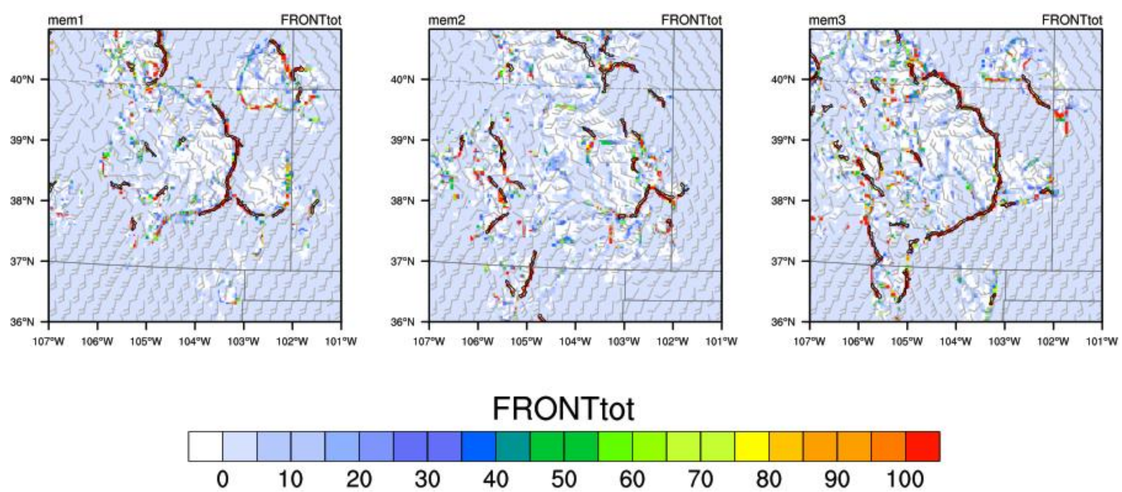

Figure 8. Convective outflow boundaries identified by MDNMS method (black outlines) from three members of the NCAR ensemble, forecast hour 22 from 0000 UTC 7 May 2017 initialization. Surface winds (full barb= 5 m s^{-1}) and surface frontogenesis (shaded, scale at bottom: K 100 km^{-1} h^{-1}) shown.

Summary

For wildland fire forecasting applications, an initial version of a tool for objectively identifying gust fronts in NWP model forecasts has been developed. It operates in both deterministic and ensemble model configurations. The tool can reveal forecast gust front locations based on wind shifts, frontogenetic zones, and potential temperature gradients and furthermore can objectively determine boundaries using the Multiple-Directional Non-Maximum Suppression technique. As the tool is model-reliant, we note that a basic limitation on its performance is the accuracy of the underlying NWP model forecast. The tool is also dependent on the NWP model's ability to predict gust fronts which is (among other things) a function of grid spacing. The 3-km HRRR seems well suited for this task. Refinement of the tool is continuing, particularly for complex terrain regions. Experimental real-time plots of the tool are available at http://www2.mmm.ucar.edu/prod/rt/pages/jfsp.html

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