CORRESPONDENCE

Reply to "Comments on 'Double Impact: When Both Tornadoes and Flash Floods Threaten the Same Place at the Same Time'"

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1. Introduction

We greatly appreciate the comments by Bunkers and Doswell (2016, hereafter BD16) on our earlier paper (Nielsen et al. 2015, hereafter N15). Such commentary allows for continued and open advancement of the scientific body of research on concurrent, collocated tornado and flash flood (referred to here as TORFF) events. BD16 discuss the importance that storm motion can have in TORFF events, especially when it comes to high-precipitation (HP; Moller et al. 1994; Smith et al. 2001) supercells; investigate the details of slow-moving tornado-producing storms; and clarify the relationships between convective available potential energy (CAPE), precipitation efficiency, and rainfall rate. While we agree in principle with all the comments made by BD16, there are some important points of discussion that we would like to bring forward.

First, the authors would like to clarify the scope and purpose of the research enumerated in N15. Before any potentially dangerous weather phenomena can be thoroughly investigated, it must first be identified as something that is a problem and fundamental questions must be answered. For example, how prevalent are the events in question? What are their climatological characteristics? What is the most common storm mode associated with such events? In the case of concurrent tornado and flash flood events, this foundational type of analysis had not been done for events that were exactly collocated, that is, what we defined as TORFF events. The purpose of N15 was to establish a baseline of knowledge about TORFF events. Specifically, it sought to "[start] the topic of conversation" (N15, p. 1689) on TORFF events by establishing the prevalence, through the warning intersection and event verification identification strategies; the regional distribution; the most common storm modes, through the radar analysis; the general large-scale meteorological characteristics, through the full-field and local standardized anomaly analyses; the discussion of complicated communication implications; and providing a case list of "verified" TORFF events for the scientific community.[1] Certainly, as BD16 point out, there is more that some readers "would like to have seen" (BD16) and, accordingly, more the authors would like to have included; however, practical constraints on manuscript length and cohesiveness limited the depth of the initial article.

The authors are currently working to expand the scientific body of knowledge on TORFF events, including some of the storm-scale aspects specifically raised by BD16. Work is ongoing to expand the TORFF identification strategies to include various spatial buffers around flash flood observations, in an effort to complete the knowledge of TORFF event prevalence outside the initial conservative definition. Additionally, the authors are in the process of using additional statistical methods, including principal component analysis (PCA; Mercer

[1] The authors would like to take this opportunity to correct the listed radar classification of case 15 in N15. "Tropical" was mistakenly listed for case 15 in the appendix instead of the actual classification of "synoptic." This, in turn, led to the counts of each radar-based classification in Table 3 of N15 being slightly incorrect. A corrected version of the table is presented here.

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TABLE 1. Breakdown of radar-based TORFF event classifications for the 68 identified events. Corrected from Table 3 of Nielsen et al. (2015).

	Training	Nontraining	Total
MCS	6	9	15
Transitioning	13	3	16
Discrete	6	9	15
Synoptic	—	—	14
Tropical	—	—	6
Other	—	—	2

et al. 2012; Peters and Schumacher 2014), to further discern the specific synoptic-to-mesoscale characteristics of these events. Some of the authors are also examining, through observations and modeling, the influence of storm motion and meso-β-scale vortices on the extreme precipitation accumulations associated with TORFF events. Last, a real-time TORFF warning identification website has been created that identifies tornado and flash flood warning overlaps within 30 min of one another (available online at http://schumacher.atmos.colostate.edu/weather/TORFF_rt/).

The main body of this reply will present further discussion on the aspects of storm motion as it relates to TORFF events with comments on the points that were brought up by BD16.

2. TORFF storm motion

BD16 correctly call attention to the importance of storm motion for producing locally heavy precipitation accumulations (e.g., Doswell et al. 1996). The authors would like to note that the sentence in N15 brought up by BD16 regarding supercells being fast moving [i.e., ‘‘For instance, tornadoes are associated with surface-based convection (e.g., Nowotarski et al. 2011) and fast convective cell motions, while flash floods can be caused by both surface-based and elevated convection and usually need slow cell motions or ‘‘echo training’’ to cause large rainfall accumulations’’ (N15, p. 1675)] was being used as a rhetorical device in the introduction to generally enumerate differences between tornado and flash flood producing storms, but the authors regret any confusion caused by these general statements without further clarification. However, the authors do agree that more attention to this matter is warranted and welcome the additional opportunity to discuss it here.

Although not explicitly discussed in N15, within the ‘‘discrete’’ radar classification (see Table 1) there were TORFF events identified that fit the specific storm mode discussed by BD16 (i.e., slow-moving, HP supercells). Specifically, ‘‘the events characterized as nontraining discrete include verified TORFF events that were the results of discrete clusters of individual thunderstorms or in some cases a single thunderstorm’’ (N15, p. 1677). Furthermore, TORFF events that were caused by a single storm within this classification were labeled as ‘‘discrete isolated’’ in the appendix of N15. The ‘‘nontraining discrete’’ classification contains TORFF events similar to the ‘‘supercell system(s)’’ described in BD16, and the discrete isolated category contains TORFF events (i.e., cases 23, 40, and 52 in Table A1 of N15) originating from one discrete slow-moving HP supercell. The ‘‘discrete’’ moniker was chosen, compared to ‘‘supercell’’ for example, for the category name to create a simple classification system, since many slight variations on storm mode were observed. However, the authors understand that the lack of specificity in the name could have led to the belief that such events were not considered or identified by the TORFF verification criteria chosen.

As previously mentioned, the authors completely agree that additional information about the storm motion of TORFF events is valuable to both the scientific and forecasting communities. Utilizing the same local standardized anomaly (LSA) method used in N15, LSAs of the mean storm level wind speed from 850 to 500 hPa were calculated for all tornado-only (TOR) events and the list of verified TORFF events. The results of the additional mean storm-level wind speed and the original LSA analysis are presented in the third row of Table 2. The results show that mean wind speeds are anomalously high for TORFF events, and, further, TORFF events have anomalously *higher* mean wind speeds than TOR events. This is not completely surprising, given that U_{500}, V_{500}, U_{850}, and V_{850} are also anomalously high (see Table 2) for TORFF events. These results do not *necessarily* inform about the hodograph shape of TORFF events, so we cannot compare to the three examples shown in BD16 directly. However, given that TORFF events have higher mean wind speeds than TOR events, the cell motions of TORFF events would be generally expected to be higher compared to TOR events. Additionally, there does not seem to be any obvious reason that TORFF events with overall stronger winds would be any more likely to have the hodographs described in the three examples in BD16 (i.e., large looping hodographs) than TOR events, especially since the meridional wind is anomalously high at all levels for TORFF events (Table 2). Thus, in a bulk sense, TORFF events are not simply characterized by slower storm motions than tornado-only events, and other factors must be involved.

Although mean wind speed does not seem to be a completely unique factor in discriminating TORFF from TOR events, in some instances or regions, it

TABLE 2. Results of the mean local standardized anomalies calculated in this study. The TORFF row depicts the mean anomaly from the sample of all identified TORFF cases (68 cases) compared to the climatological environment. The TORFF–TOR row represents the difference of mean local standardized anomalies between identified cases producing simultaneous collocated tornadoes and flash floods and those that produced only tornadoes (1622 cases over the 2008–13 period) (positive values indicate that TORFF events were more positively anomalous). Anomaly differences statistically significantly different from zero ($\alpha = 0.05$) are depicted in boldface; differences significant at 90% but not 95% confidence are italicized. Reproduced from Table 4 of N15, but modified to include the calculation of the mean wind magnitude in the third row, where UV_{850}, UV_{700}, and UV_{500} represent the wind speeds at 850, 700, and 500 hPa, respectively.

	U_{10}	U_{80}	U_{850}	U_{500}	V_{10}	V_{80}	V_{850}	V_{500}	V_{850_10}	V_{500_10}
TORFF	**−0.44**	**−0.31**	**0.64**	**0.55**	**1.11**	**1.12**	**1.59**	**1.40**	**1.66**	**1.03**
TORFF–TOR	**−0.46**	**−0.36**	0.24	0.11	**0.53**	**0.57**	**0.85**	**0.60**	**0.96**	**0.39**
	ω_{850}	T2M	Q2M	Q_{850}	Q_{500}	MSLP	PWAT	CAPE	SOILW	WAA
TORFF	**−2.37**	**0.41**	**1.62**	**1.54**	**0.87**	**−1.63**	**1.54**	**3.81**	**5.22**	**1.27**
TORFF–TOR	**−1.25**	0.07	**0.46**	**0.53**	0.19	**−0.58**	**0.51**	1.28	*1.18*	**0.82**
	$(UV_{850} + UV_{700} + UV_{500})/3$									
TOR	**0.72**									
TORFF	**1.63**									
TORFF–TOR	**0.90**									

undoubtedly plays a larger role than other environmental factors. One possible cause for the difference between the LSA results and the three examples discussed in BD16 is that the examples presented in BD16 are not representative of the regional distribution of TORFF events described in N15. The three events mentioned in BD16 occurred in Bennington, Kansas; Superior, Nebraska; and near Corpus Christi, Texas, which are all outside or just within the one spatial standard deviation of warning intersections presented in Fig. 6 and east of the main cluster of verified events in Fig. 7 of N15. Additionally, all of these events occurred in the central plains with no example given for the Mississippi valley or southeastern United States, where the TORFF geographic maximum exists. Smith et al. (2012) show, specifically in their Fig. 10, the percentage of tornadic storms caused by specific storm modes throughout the contiguous United States. This figure highlights the importance of discrete and clustered right-moving supercells in the central plains, while showing how embedded, linear tornadic modes [i.e., their quasi-linear convective system (QLCS), line right mover, and line marginal] become more common in the Mississippi and Ohio valleys. Accordingly, the storm motion of the latter might be more correctly predicted using other methods (e.g., Corfidi et al. 1996; Corfidi 2003) than hodographs alone (e.g., Bunkers et al. 2000). Thompson et al. (2012) also noted in their section 3a that ‘‘Differences in low-level and deep-layer vertical shear (e.g., effective storm relative helicity and effective bulk wind difference, respectively) between right mover and QLCS environments were too small to be of practical utility in an operational forecasting environment, despite statistical significance in the difference of the means (e.g., Potvin et al. 2010)’’ (p. 1142). This illustrates another complication in determining the storm motion of various tornadic-producing modes, since distinguishing the environmental shear and helicity characteristics of each mode is itself difficult. Whereas storm motion estimates for right-moving supercells may be reasonable in certain regions (e.g., the central plains), other methods for estimating storm motions may be needed in other regions where TORFFs are more prevalent and are more frequently caused by more linear storm modes.

Finally, the authors would like to discuss potential issues utilizing the Bunkers et al. (2000) method (i.e., the Bunkers method) on predicting the storm motion of HP supercells. HP supercells, as BD16 discuss, ‘‘can be especially conducive’’ for producing TORFF events. Predicting the storm motion of HP supercells, even when using the Bunkers et al. (2000), method can be challenging. Ramsay and Doswell (2005) point out that, ‘‘Despite the high relative accuracy of the Bunkers scheme on the average, there were times when it produced large errors ($>10\,\mathrm{m\,s^{-1}}$). These errors suggest that supercell storm motion is determined by more than just the mean wind and the vertical wind shear. In fact, we found that most of the large errors in the Bunkers scheme were associated with either high-precipitation (HP) supercells, or supercells that eventually evolved into bow echoes’’ (p. 968). Further, Ramsay and Doswell (2005) go on to note that, ‘‘Other studies have shown that HP supercells tend to develop and move along preexisting thermal boundaries, including old outflow boundaries and stationary fronts (Maddox et al. 1980; Zehr and Purdom 1982; Moller et al. 1990; Guyer 2002; Sills et al. 2004), which can have orientations promoting movement by propagation that would be quite different from those based on the hodograph alone'' (p. 968). This reinforces the idea that the usual forecast methods do not represent the storm motion of HP supercells as well as other supercell modes. Evidence of this can be seen in the three examples presented in BD16, where storm motion is overestimated using the Bunkers method, albeit not to the magnitude ($>10\,\mathrm{m\,s^{-1}}$) seen in Ramsay and Doswell (2005). Additionally, the previously quoted influence that boundaries can have on the motion of HP supercells that might not be represented by a hodograph alone, has been shown to be very important in the 31 May–1 June 2013 El Reno, Oklahoma, event (e.g., Bluestein et al. 2015; Schumacher 2015). BD16 illustrated how using a combination of the hodograph properties and the mesoscale forcing for ascent was required to diagnose the storm motion of the Bennington supercell[2] on 28 May 2013. In this case, the initiation and storm motion were heavily influenced by colliding boundaries. We share and endorse BD16's view that when monitoring the potential for both tornadoes and flash flooding, forecasters must closely monitor the storm motion characteristics that might be inferred from the hodograph properties, along with other mechanisms that may cause storm propagation of a different direction or speed.

3. Summary

Although not discussed in detail here, the authors agree with the comments made by BD16 regarding the relationships between precipitation efficiency, CAPE, and rainfall rate. We may have unintentionally implied a stronger connection, especially regarding precipitation efficiency, than actually exists in the meteorological characteristics identified in N15 for TORFF events.

Further, the authors welcome the points enumerated by BD16 commenting on the storm motion characteristics of TORFF events and agree with the concepts that were presented, but caution the broad interpretation and application of their conclusions to all TORFF events. Similar to the three example TORFF events discussed in BD16, the original list of TORFF ''verified'' events contained HP supercells and supercell clusters that were included in our meteorological analysis. Using this verified dataset of TORFF events, an LSA analysis (identical to the one performed in N15) of the mean wind speed revealed that TORFF events had statistically significant *higher* mean wind speeds than TOR events (Table 2). Storm motion is undoubtedly an important contributing factor in some TORFF events in certain regions, such as the central plains, where the three examples in BD16 were taken; however, it does not appear to be the only factor that differentiates TORFF events from TOR events. Additionally, TORFF events can occur from many different storm modes and, thusly, require corresponding methods of storm motion evaluation and identifying the appropriate method/storm mode ahead of time can be particularly complicated. Further, as described in Ramsay and Doswell (2005), the typical methods of predicting the storm motion of HP supercells (e.g., Bunkers et al. 2000) may not perform as well and could potentially misinform forecasters. In the end, the points brought up in BD16 illustrate some important aspects of TORFF events but do not distinctly differentiate them from TOR events. There are multiple, compounding factors involved in differentiating TORFF from TOR events, and we look forward to continuing research that examines both the detailed atmospheric processes and the complicated forecasting and warning scenarios.

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[2] This case would not have met the very strict criteria used in N15 for being a ''verified'' TORFF event. However, the reports were very nearby.

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