CORRESPONDENCE

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

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1. Introduction

Nielsen et al. (2015) studied the environments of concurrent, collocated tornado and flash flood (hereafter TORFF) events that occurred across the continental United States from 2008 to 2013. They found that TORFF events are difficult to distinguish from tornado events that do not produce flash flooding, although the TORFF environments tended to possess greater moisture and synoptic-scale forcing for ascent.

Although we agree with most of the content of the paper by Nielsen et al. (2015), one thing that they did not address was storm motion as it relates to these TORFF events; neither the mean wind nor any other proxy for storm or system motion was mentioned in their paper. Perhaps this omission was related to their statement that "tornadoes are associated with. . .fast convective cell motions" (p. 1675). Either way, this is an overgeneralization as there have been some notable tornadoes that occurred with relatively slow-moving storms (e.g., Maddox and Doswell 1982; Davies 1998; Wakimoto et al. 2004; Houston and Wilhelmson 2007; Wurman et al. 2013).

Another concern we have is that Nielsen et al. (2015, p. 1679) stated that "high CAPE values promote more vigorous ascent and more intense rainfall rates when compared to low CAPE values." Although this is generally correct, the unintended implication later on p. 1685 is that higher convective available potential energy (CAPE) equates to "higher rainfall production and precipitation efficiencies." However, this is not necessarily true, especially with respect to precipitation efficiency (e.g., Davis 2001).

Although these items are minor, we believe that in total they are sufficient to be addressed formally. Therefore, our goals in this comment are to 1) discuss the importance of storm (and supercell) motion in potentially helping to anticipate TORFF events; 2) provide examples contrary to the notion that tornadic storms are necessarily fast moving, as well as discuss briefly the characteristics of slow-moving tornadic supercell environments; and 3) clarify the relationship of CAPE with rainfall and precipitation efficiency.

2. Storm motion and heavy rainfall

One way to get locally heavy rainfall with any storm is slow storm motion (e.g., Doswell et al. 1996). A long-standing simple proxy for storm *cell* motion is the mean wind calculated over a representative layer (e.g., 0–6 km AGL or the depth of the storm). In addition, mesoscale convective *system* motion (Corfidi et al. 1996) also influences the potential for locally heavy rainfall. Therefore, at minimum we would like to have seen Nielsen et al. (2015) include these two variables as part of their environmental evaluation. It is possible that these could help discriminate between the TORFF events and the tornado events without flash flooding.

Previous studies have shown that supercells—including high-precipitation (HP) supercells[1] (Moller

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[1] HP supercells are defined by having substantial precipitation within the mesocyclone, but this does not necessarily mean that all of them are prolific rainfall producers.

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et al. 1994)—can be prolific rainfall producers and contain extreme rainfall rates (e.g., Smith et al. 2001; Hitchens and Brooks 2013), and it is clear that some of the storms from the Nielsen et al. (2015) dataset were supercells. Using the assumptions that advection and shear-induced propagation dominate supercell motion, a hodograph can be used to evaluate the possibility of slow-moving supercells (Rasmussen and Blanchard 1998; Bunkers et al. 2000; Ramsay and Doswell 2005). Accordingly, Zeitler and Bunkers (2005) provided an example in which a supercell produced an (enhanced Fujita scale) EF1[2] tornado and flash flooding, and the hodographs indicated slow supercell motions of around 5 $m\,s^{-1}$ (10 kt; refer to their Figs. 9–12).

Note that methods for estimating cell motions, including supercells, do not necessarily provide estimates of multicell storm *system* motions owing to various kinds of discrete propagation (Corfidi et al. 1996). The case of the infamous El Reno, Oklahoma, tornado on 31 May 2013 (Bluestein et al. 2015) began with a few discrete supercells, but after the major tornado of the day near El Reno, the situation evolved into a storm system including multiple HP supercells arranged in a line. These supercells were moving mostly parallel to that line, which was moving slowly southward. Thus, the individual cells were moving relatively fast, but they were "training" over the same area for an extended period. Only infrequently are the individual cells in a training situation supercells, but this is another way for TORFF events to occur.

Based on an informal literature review, we have found examples of other TORFF events that contained supercell storms. Three of these cases are presented below to show how it is possible to forecast slow-moving supercells, which has implications for flash flooding.

a. Superior, Nebraska, 22 June 2003 TORFF

The supercells of 22 June 2003 southeast of Hastings, Nebraska (Guyer and Ewald 2004; Wakimoto et al. 2004), resulted in a localized but intense TORFF event. There were at least two HP supercells that produced 10 tornadoes (2 EF2, 2 EF1, and 6 EF0) and flash flooding in two adjacent counties per *Storm Data*.[3] Flash flooding was reported within 20 min of the last tornado in one county and within 77 min of the last tornado in the other county. Individual supercells moved at 2–6 $m\,s^{-1}$ (4–12 kt) in both the northeast and southeast directions, while system motion was near zero, owing to discrete storm development/propagation.

The closest soundings were 167–185 km (90–100 n mi) to the northeast (Omaha, Nebraska; OAX) and southeast (Topeka, Kansas; TOP) of the supercells. The Fairbury, Nebraska (FBY), wind profiler was much closer at 28–37 km (15–20 n mi) away. Hodographs were developed for a composite of the 0000 UTC OAX/TOP soundings and a composite of the four 2100–0000 UTC FBY profiles to represent the environment as the storms were maturing. Despite the three locations being relatively far apart, the hodographs are quite similar (Fig. 1)—including the individual hodographs (not shown). The forecast supercell motion (Bunkers et al. 2000) was only 4–5 $m\,s^{-1}$ (8–10 kt) to the east for both hodographs, consistent with the envelope of observed supercell motions in this case. In addition, the low-level clockwise curvature of the hodographs resulted in 0–3 km AGL storm-relative helicity (SRH_3) of 250–300 $m^2\,s^{-2}$, which is quite favorable for tornadic supercells (e.g., Davies-Jones et al. 1990).

b. TORFF near Corpus Christi, Texas, 15 November 2001

In another example—north of Corpus Christi, Texas (CRP), up through New Braunfels, Texas—there were 17 tornadoes (9 EF1 and 8 EF0) during the afternoon and evening of 15 November 2001; flash flooding was on going throughout this period that was part of a 2-day event beginning on 14 November (*Storm Data*). Several supercells occurred and moved slowly, generally to the northeast.

The CRP sounding was released about 56–120 km (30–65 n mi) away from the southernmost storms. The observed hodograph (Fig. 2) exhibited a shear profile favorable for both slow-moving supercells capable of producing heavy rainfall (and ultimately flash flooding) and tornadoes. The supercells only moved at 3–5 $m\,s^{-1}$ (6–10 kt), similar to the forecast supercell motion. And although the midlevel winds were somewhat weak, the low-level winds were sufficiently strong to produce 180° of clockwise turning of the low-level shear vectors, and this resulted in SRH_3 of around 200 $m^2\,s^{-2}$. A similar hodograph and storm motions existed 24 h prior to this time (not shown).

c. Bennington, Kansas, 28 May 2013 TORFF

A nearly stationary HP supercell "system" produced tornadoes and flash flooding in north-central Kansas during the afternoon and early evening of 28 May 2013 (Wurman et al. 2013). Two tornadoes (EF3 and EF0) occurred, with the EF3 tornado lasting an hour; flash

[2] The Fujita scale transitioned to the enhanced Fujita scale on 1 February 2007 (Doswell et al. 2009).

[3] *Storm Data* is maintained by the National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center), and reports can be obtained online (http://www.ncdc.noaa.gov/IPS/sd/sd.html).

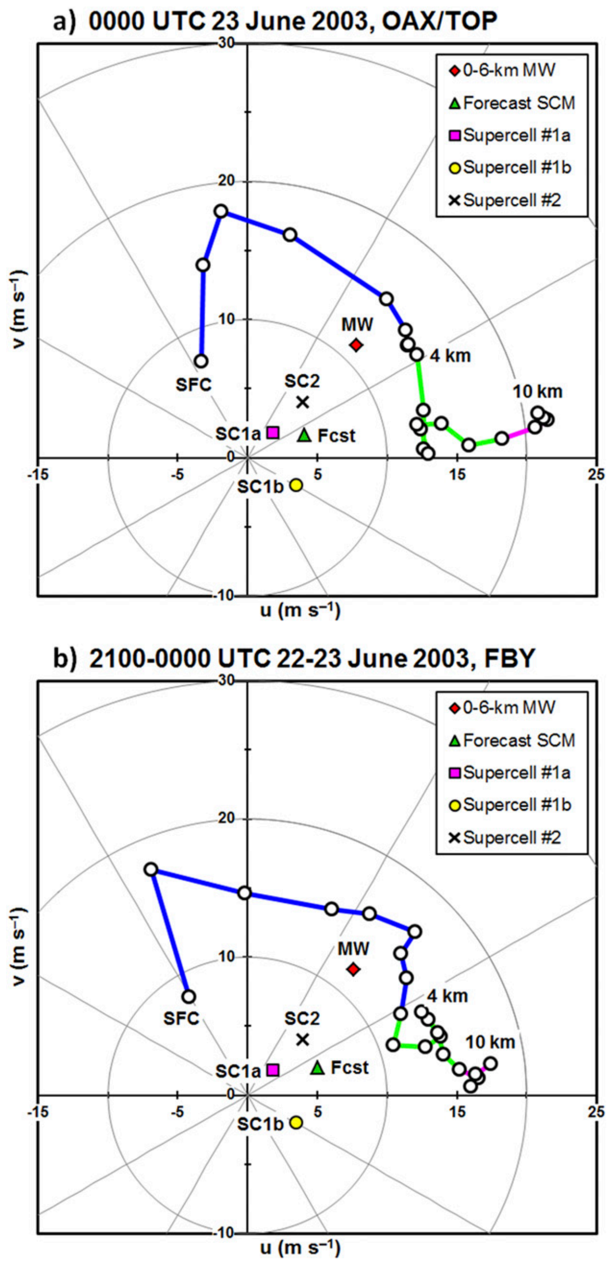

FIG. 1. Observed 0–10-km hodographs at (a) 0000 UTC 23 Jun 2003 using a composite of the OAX and TOP soundings and (b) the four hourly observations from 2100 to 0000 UTC 22–23 Jun 2003 using the FBY vertical wind profiler. The wind (m s^{-1}) is plotted with circles every 500 m; the 0–6-km mean wind (MW) is the equally weighted average of all 500-m-spaced points in this layer; the forecast supercell motion (SCM) was derived using the method in Bunkers et al. (2000); and observed supercell motions are plotted per the legend.

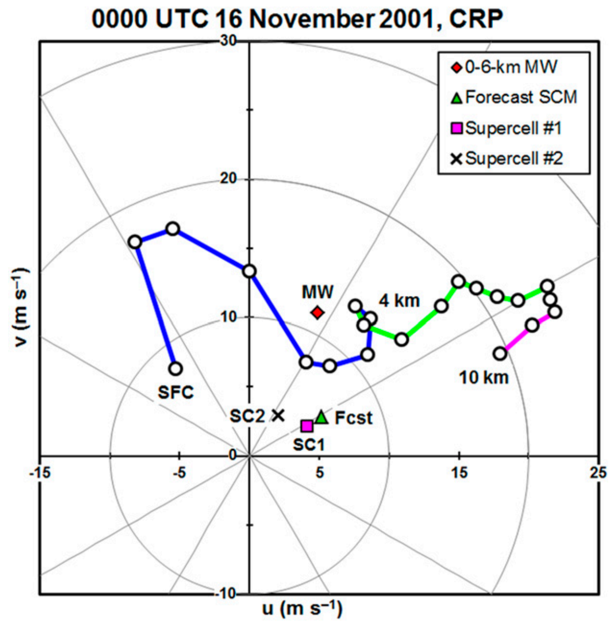

FIG. 2. As in Fig. 1, but at 0000 UTC 16 Nov 2001 at CRP.

flooding was reported 35 min after the EF3 tornado ended (*Storm Data*).

This HP supercell also exhibited discrete propagation (like the case discussed in section 2a), although early in its lifetime it was steady for about 45–60 min. During this time the storm motion was east-northeast at 5 m s^{-1} (10 kt), or 8 m s^{-1} (16 kt) slower than the forecast supercell motion based on the TOP hodograph (Fig. 3a, SC1a). During the next hour the supercell displayed considerable discrete propagation as feeder cells merged onto the southwest flank of the storm—slowing the system motion to near zero (Fig. 3a, SC1b). The value of SRH_3 ranged from 155 $m^2 s^{-2}$ (predicted motion) to 105–115 $m^2 s^{-2}$ (observed motions).

The TOP sounding was released about 176 km (95 n mi) east of the storm, and in this case did not represent the environment of the supercell adequately because of notable horizontal heterogeneity. To examine this further, the North American Regional Reanalysis (NARR) was used to plot the supercell motion across the area of interest. This shows that the predicted supercell motion was 6–7 m s^{-1} (12–14 kt) near the Bennington, Kansas, supercell (Fig. 3b), consistent with the early motion of the storm, noted above. The NARR-predicted supercell motion near TOP also was consistent with the sounding observation (cf. the hodograph to the NARR plot in Fig. 3), supporting the NARR's representativeness. Finally, 0–30 hPa AGL moisture convergence (MCon) was maximized just south of the Bennington supercell—along a boundary (not shown)—and most likely aided in the discrete storm propagation.

In summary, hodographs can be used to anticipate slow-moving supercells and, therefore, the potential for TORFF environments. This potential can be refined further through an understanding of the mesoscale

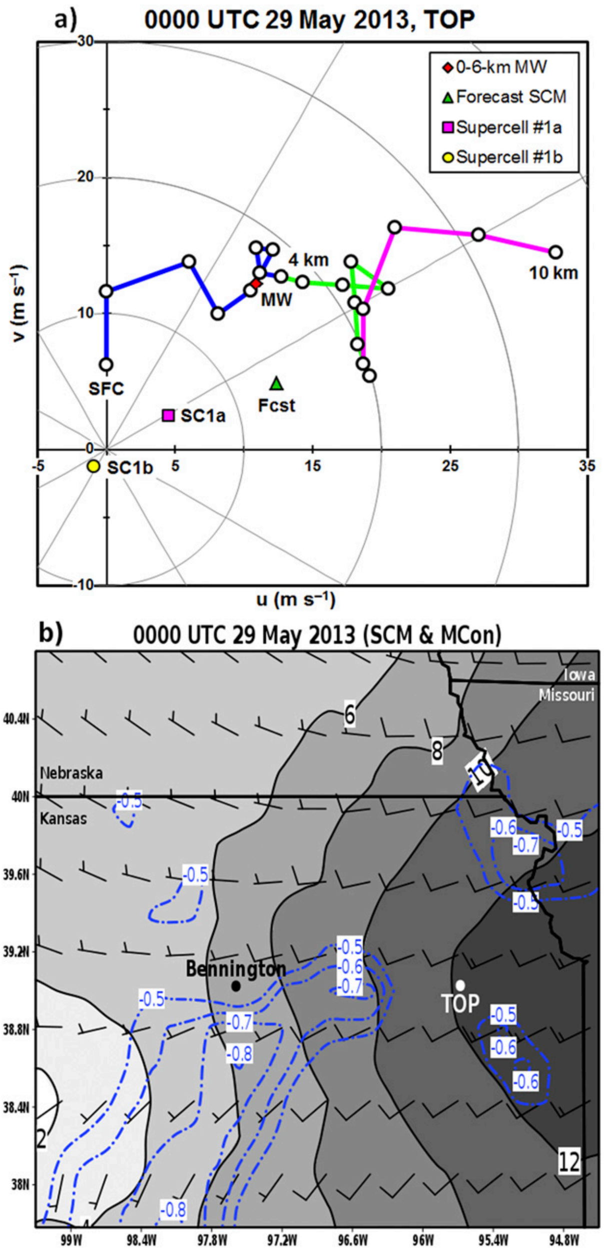

FIG. 3. (a) As in Fig. 1, but at 0000 UTC 29 May 2013 at TOP. (b) NARR forecast SCM (barbs and contours every $2\,\mathrm{m\,s^{-1}}$) and 0–30 hPa AGL MCon (blue dotted–dashed lines plotted for values $\leq -0.5 \times 10^6\,\mathrm{kg\,kg^{-1}\,s^{-1}}$). The hodograph in (a) corresponds to the location of TOP in (b), and the motion of SC1 in (a) was obtained from the supercell that occurred at Bennington in (b).

environment and airmass boundary locations. And even if supercells are not slow moving, they can produce extreme precipitation rates such that the existence of a supercell warrants attention for the potential of heavy rainfall and flash flooding, especially when supercells are HP and/or they train over the same area (e.g., Moller et al. 1994; Doswell et al. 1996; Rogash and Smith 2000; Smith et al. 2001). The El Reno supercell of 31 May 2013 (Bluestein et al. 2015) is a prime example of this and further underscores the importance of system motion (i.e., cell motion plus discrete propagation).

3. Slow-moving tornadoes

Tornadic storms do not always move rapidly, but many of the big tornado outbreaks do exhibit fast-moving storms (e.g., Fujita et al. 1970; Corfidi et al. 2010; Knupp et al. 2014). The typical setting for tornadic storms often features strong mid- to upper-level flow (e.g., Newton 1967; Uccellini 1990), and thus the attendant storms have a tendency to move relatively fast. However, other configurations of the environmental winds can produce vertical wind shear profiles that favor slow-moving storms and tornadoes (e.g., Belville et al. 1979; Doswell 1980; Chappell and Rodgers 1988; Jungbluth 1993; Davies 1998; Monteverdi et al. 2010).

Some noteworthy (EF2–EF5) slow-moving tornadoes occurred near 1) Grand Island, Nebraska, on 3 June 1980 (Maddox and Doswell 1982); 2) Jarrell, Texas, on 27 May 1997 (Houston and Wilhelmson 2007); 3) Superior, Nebraska, on 22 June 2003 (Wakimoto et al. 2004); and 4) Bennington, Kansas, on 28 May 2013 (Wurman et al. 2013). These tornado events were relatively small in scale compared to typical outbreaks, but nonetheless they illustrate environments that are conducive to slow-moving, significant tornadoes.

There are at least four environmental settings that lend themselves to slow-moving supercells and, thus, the possibility for slow-moving tornadoes. The first setup involves postfrontal upslope flow in the lee of the Rocky Mountains (Doswell 1980). The mean wind may be relatively weak in these scenarios, but the vertical wind shear is sufficient for supercells because of modest west-to-southwest flow aloft combined with east-to-southeast flow at the surface (e.g., Chappell and Rodgers 1988). A second configuration involves ''northwest flow aloft'' severe weather events (Johns 1984). Although this sometimes results in fast storm motions, under certain situations with a substantial southeast low-level flow, the mean wind can be fairly weak, but again the shear will be relatively strong (e.g., Fig. 4a). Yet a third setup occurs when the midlevel flow is fairly weak but the low-level jet stream (nocturnally and/or synoptically generated) elongates the hodograph to the northwest and rotates the 0–6 km AGL shear vector clockwise. This shifts the supercell motion closer to the origin and can result in an increasing threat of slow-moving supercells with time from the late afternoon through midevening (e.g., Fig. 4b; flash flood producing but not tornadic). Finally, a fourth environment that favors slow-moving

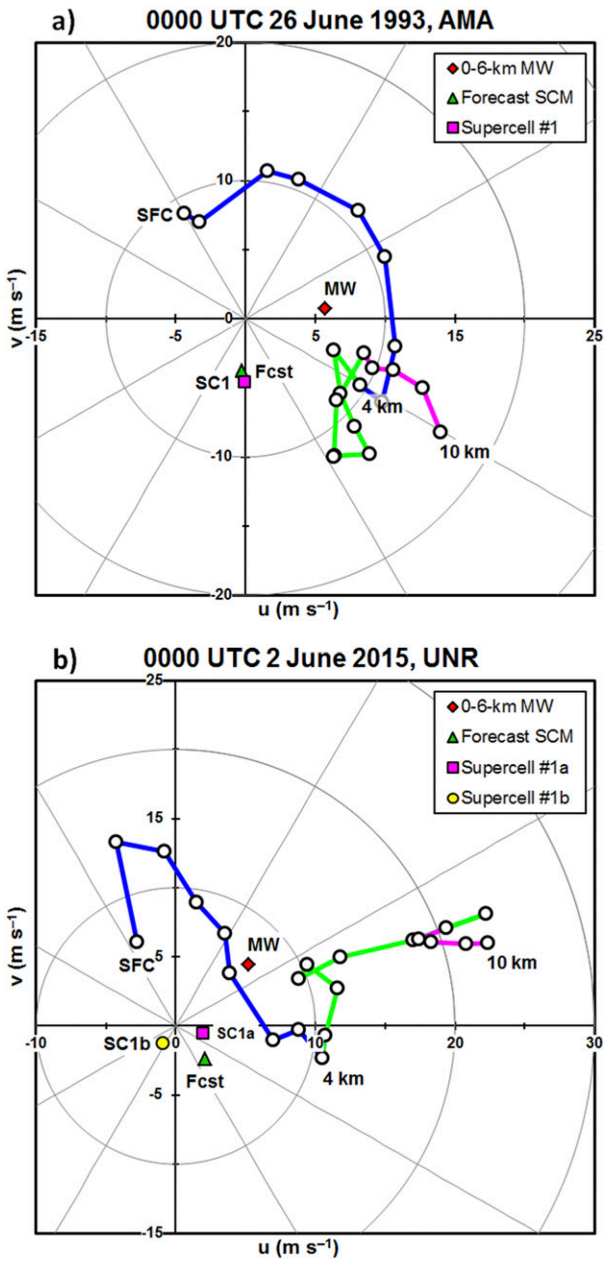

FIG. 4. As in Fig. 1, but at (a) 0000 UTC 26 Jun 1993 at Amarillo, Texas (AMA), and (b) 0000 UTC 2 Jun 2015 at Rapid City, South Dakota (UNR). The AMA case is described in Hotz et al. (1994) and was associated with an EF0 tornado and flash flooding, whereas the UNR case was associated with flash flooding but not a tornado.

tornadoes can occur with shear that is modestly sufficient for supercells and the storms propagate discretely along a boundary (Houston and Wilhelmson 2007). The preceding is not meant to represent an *exhaustive* list of environments that support slow-moving tornadoes, but rather indicates how the vertical wind shear profile may evolve to favor slow-moving tornadic supercells.

4. Precipitation efficiency and CAPE

There are several factors that regulate precipitation efficiency; these include wind speed, wind shear, warm cloud depth, cloud base, relative humidity, the buoyancy profile, and the size and number of convective elements (Fankhauser 1988; Doswell et al. 1996; Davis 2001). Regarding buoyancy, a narrow CAPE profile that creates a modest updraft helps prevent condensate loss high in the storm and out the anvil (Davis 2001). This profile keeps relatively more precipitation within the warm cloud to enhance collision–coalescence—a reason that low-centroid storms can have high precipitation efficiency. Such soundings are common with modest midlevel lapse rates and CAPE of 1500–2000 J kg^{-1} (versus steep midlevel lapse rates with drier environmental air aloft that result in large CAPE). Thus, large CAPE can be associated with low precipitation efficiency.

Despite a reduction in precipitation efficiency for some high-CAPE environments, precipitation efficiency may not be relevant in some supercellular situations except, for example, in cases of high-based convection (Doswell et al. 1996; Davis 2001). The fact that supercells can have such intense rainfall rates (e.g., Moller et al. 1994; Hitchens and Brooks 2013) may counter the effect of decreasing precipitation efficiency at high CAPE. However, for shorter-lived nonsupercells, precipitation efficiency can be a limiting factor in high-CAPE environments.

In addition to buoyancy, supercells have another source of vertical accelerations [i.e., the dynamic perturbation vertical pressure gradient force from the mesocyclone; Weisman and Klemp (1984)], augmenting the effect from buoyancy on the updrafts, resulting in very high rainfall rates even if at low efficiency (Doswell et al. 1996; Smith et al. 2001).

5. Summary

The following summary statements are based on the above comments regarding the Nielsen et al. (2015) paper:

- Hodographs can be used to assess the possibility of slow-moving supercells that may result in TORFF events (either individually or in conjunction with other storms). It also is possible that the mean wind (or more sophisticated estimates of convective system motion) may help identify TORFF environments.
- Slow-moving tornadoes are not uncommon and can occur under several environmental configurations.
- *Increasing* CAPE generally is associated with *reduced* precipitation efficiency; however, in the case

of supercells, their extreme rainfall rates tend to counteract this effect.

- HP supercells can be especially conducive to TORFF events, even when cell motion is relatively fast (owing to effects of discrete propagation and a slow system motion).

Severe storm forecasters would benefit by looking at hodographs and plan-view displays of predicted supercell motion to help increase situational awareness of these TORFF environments. Attention especially should be given to those situations when forecast cell motions are $<8\,\mathrm{m\,s^{-1}}$ (15 kt). Further, forecasters should be alert to situations where convective rain systems have movements that are very different from component cell motions, potentially creating a ''training'' situation.

In conclusion, Nielsen et al. (2015) closed by stating that ''Future work includes examining the storm-scale dynamics of individual TORFF events...,'' and we welcome that work as it relates to storm and system motion as well as HP supercells and convective mode.

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