TORNADO DEBRIS CHARACTERISTICS AND TRAJECTORIES DURING THE 27 APRIL 2011 SUPER OUTBREAK AS DETERMINED USING SOCIAL MEDIA DATA

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A Facebook page of over 1700 lost-and-found objects from a historic tornado outbreak provided the raw material for a unique study, which establishes a new distance record for tornado debris.

On 27 April 2011, a tornado outbreak of historic proportions ravaged Alabama and surrounding states. On that one day, more than 120 tornadoes, including four that were rated as a 5 on the Enhanced Fujita (EF) scale (NOAA 2012a), caused 315 deaths (Storm Prediction Center 2012) and over 2400 injuries (NOAA 2012a). This made 27 April 2011 the deadliest single tornado day since 1932 (NOAA 2012b). Severe weather experts could cite only the 3–4 April 1974 Super Outbreak as comparable in terms of number and intensity of tornadoes (Corfidi et al. 2010; Doswell et al. 2012; Simmons and Sutter 2012). However, the 1974 Super Outbreak extended from Alabama to Canada, with six F5 tornadoes in Alabama, Kentucky, Indiana, and Ohio. In contrast, on 27 April 2011, all four EF-5 tornadoes occurred within a far more concentrated area, from eastern Mississippi through northern Alabama to extreme southern Tennessee and extreme northwest Georgia. As in 1974, tornadoes during the 2011 Super Outbreak struck a number of populated areas, such as Tuscaloosa and Birmingham, Alabama, with devastating direct hits to smaller cities and towns, such as Smithville, Mississippi; Cullman, Hackleburg, and Phil Campbell, Alabama; and Ringgold, Georgia (Fig. 1).

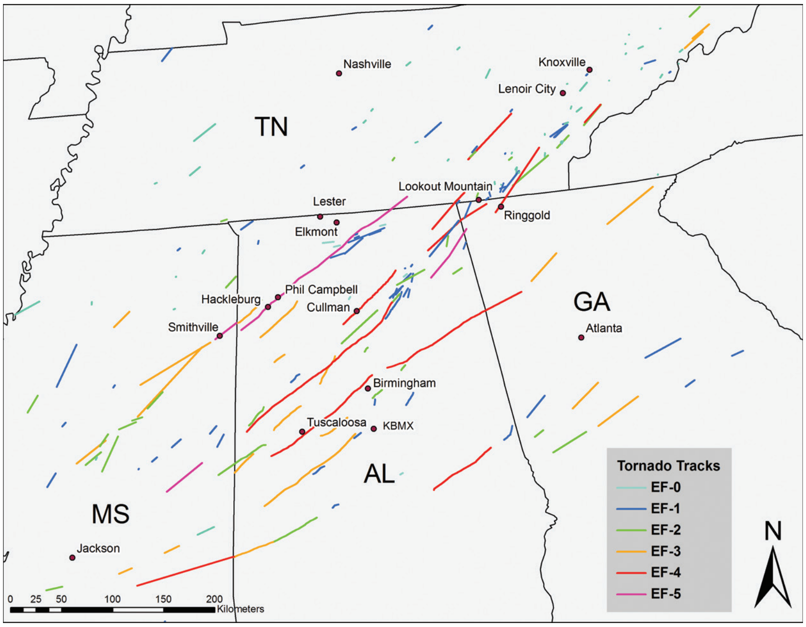

FIG. 1. Tornado tracks across the southeast United States on 27–28 Apr 2011 by EF scale.

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FIG. 2. A remarkable story of tornado debris recovery and return from the 27 Apr 2011 outbreak. A month after the outbreak, Dan Morris of Russellville, AL (about 10 miles from Phil Campbell), found a 5-ft-tall metal sign on his property. This was no ordinary sign, as it turned out; it held a special place in the hearts of residents of Smithville, MS, roughly 80 km (50 air miles) southwest of Russellville. The sign portrayed a photograph of an important member of the Smithville community, band member Lee Frederick, who passed away from bone cancer in 1998. The sign hung above the bleachers of the Smithville High School football stadium until the tornado destroyed much of Smithville, including the school and its football stadium (Ortiz 2011). A picture of the sign was uploaded to Patty Bullion's Facebook page and identified by a member of Frederick's family the next day. In this photograph, Dan and Tammy Morris return the sign to Lee's parents, Jerry and Patsy Frederick. [Photo from Ortiz (2011).]

The debris caused by this outbreak attracted public attention because of several items that took remarkable flights up and through the storms on 27 April (Cross 2011; Ortiz 2011). Many items were identified by their owners and then returned to them, thanks to the power and reach of social media (Fig. 2). Patty Bullion, a resident of Lester in extreme northern Alabama, created a Facebook page entitled "Pictures and Documents found after the April 27, 2011 Tornadoes" less than two days after the outbreak to help tornado victims recover prized items that had been lost because of the tornadoes (Harmon 2011). Via the Facebook equivalent of word of mouth, her effort expanded from items Bullion found in her yard to items found across Alabama and neighboring states that were scanned and uploaded onto her page (Fig. 3). By the first anniversary of the outbreak, when Bullion finally removed her Facebook page, nearly 100,000 Facebook users had "liked" her page. Of greater significance, more than 1700 tornado-blown items had been reunited with their owners, with an efficiency inconceivable in the pre-Internet, pre-Facebook era (Bonvillian 2012). It was possibly the most comprehensive recovery-and-return effort in American weather-disaster history.

In the months following the outbreak, we became interested in the possibility of deriving scientific data from this unusual social media page of lost-and-found objects. All previous studies of tornado debris (Anderson 1985; Peterson 1993; Snow et al. 1995; Magsig and Snow 1998) have been based on small numbers of objects, from a few dozen (Magsig and Snow 1998) to no more than 163 (Snow et al. 1995), and in some cases based on decades-old historical accounts (Snow et al. 1995). Furthermore, this antecedent research was performed generally before very high-resolution trajectory analyses using numerical weather prediction model output were available, and before social media existed to provide a source of observations related to meteorological phenomena (Hyvärinen and Saltikoff 2010; Blair and Leighton 2012). In short, the April 2011 outbreak offered the possibility to study tornado debris using twenty-first-century capabilities.

Therefore, with Bullion's knowledge, we accessed her Facebook page and gleaned publicly available information about lost-and-found objects, in particular

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the beginning and ending locations of the lost-and-found items. This allowed us to transform information from a socially valuable Facebook page into a scientifically useful database. In the end, we were able to gather reliable information about beginning and ending locations for 934 lost-and-found items, roughly half of the total. Our results extend our knowledge of how objects are transported by tornadic thunderstorms, and also how the flight trajectories of these objects relate to the background wind flow.

In this article, we explain this transformation process from social media posts to scientific data, and then discuss the results gained from it with regard to the flight trajectories of tornado debris during the 27 April 2011 Super Outbreak.

DATA AND METHODOLOGY.

Collection of data. We obtained information on the debris items by viewing each of the 1716 objects that were returned to their owners through the "Pictures and Documents found after the April 27, 2011 Tornadoes" Facebook page. The process by which tornado debris became Facebook-viewable images was as follows. First, someone would have to find the item and then either digitally photograph or scan it. The finder would then post the image and the location where it was found (with varying degrees of detail) on the "Pictures and Documents found after the April 27, 2011 Tornadoes" Facebook page. In most cases, someone would recognize a name on a document or face in a picture and put the original owner in contact with the item's finder. Unfortunately, many of the objects found and posted were not returned because the original owner could not be identified. (There were also likely tens or hundreds of thousands of items that were picked up by the tornadoes and deposited in areas where they were not found, or that may have been found and discarded by people who were unaware of Bullion's page.) As each item was returned, the picture was moved by Bullion into online photo albums of returned objects.

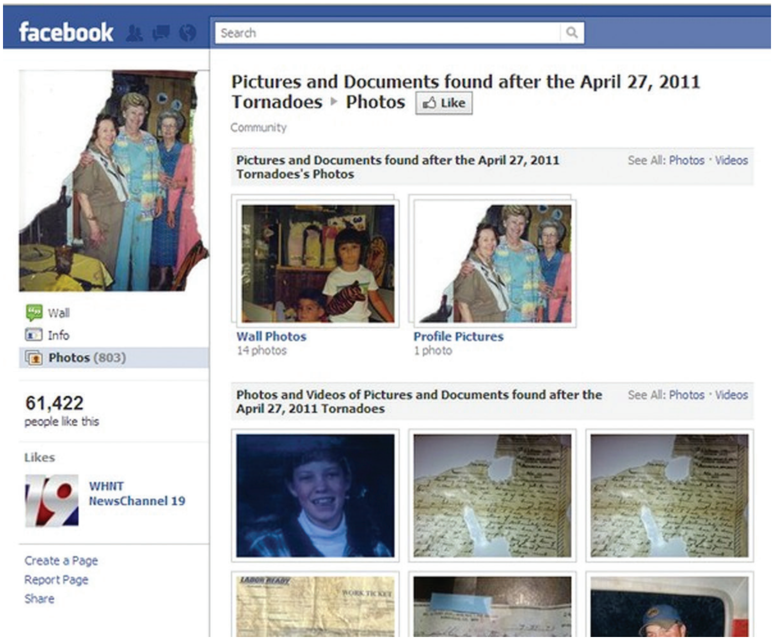


Fig. 3. Screen capture of Patty Bullion's "Pictures and Documents found after the April 27, 2011 Tornadoes" Facebook page.

Quality control and analysis of data. Our analysis began at this stage. We retained in our database only items that were both returned to their original owners and placed in the online albums of returned objects. Using the publicly available information on Bullion's Facebook page for each of the returned items, we then recorded the location (city, county, and state) of each item's takeoff and landing point. The takeoff point was determined in several ways. In most cases, the object was returned to a town or city that was struck by a tornado (e.g., Phil Campbell, Alabama, or Smithville, Mississippi), and it was highly likely that the object originated from that town or city. Many return locations were towns small enough that the object's original location could be narrowed to a region of a few square kilometers. In other cases, the location of the item's owner was identified via comments on the Facebook page. (We intentionally did not contact finders or owners of items for additional information out of respect for the privacy of tornado victims.) We excluded from further analysis items for which it was difficult to conclusively determine the takeoff or landing point because of a lack of precise and/or accurate information. This left a total of 934 items with reliable takeoff and landing points.

For each of the 934 items, the latitude and longitude of takeoff and landing were recorded. We chose a point within the tornado path through each community to represent the coordinates of the takeoff location. In roughly 5% of cases, only the county of takeoff *or* landing was available. In these few cases, the latitude and longitude of the county seat were used. For each item, the straight line distance between the starting and ending points was calculated, along

TABLE 1. The distribution of 934 reports of paper, light, and heavy debris as a function of tornado EF-scale for 27 Apr 2011.

EF scale	Heavy	Light	Paper	All types
EF0	1	0	0	1
EF1	0	0	0	0
EF2	0	0	2	2
EF3	0	1	39	40
EF4	2	5	190	197
EF5	9	12	673	694
Total	12	18	904	934

with the azimuth (measured in degrees with 0° as true north). The debris were classified into three groups based on weight (Table 1) after Anderson (1985) and Snow et al. (1995): 1) paper (such as photographs or receipts), 2) light (less than 0.45 kg or 1 pound), and 3) heavy (greater than 0.45 kg). In addition, the EF scale of the tornado that generated each piece of debris was recorded by examining the tornado tracks and the latitude and longitude of the takeoff point. This task was complicated by the proximity of tornado tracks to each other during this very concentrated outbreak. We estimate that the 934 items were generated by at least 15, and possibly 20, different tornadoes in Mississippi, Alabama, Georgia, and Tennessee. In a few cases (e.g., Cordova, Alabama) tornadoes struck the same location in both the morning and afternoon of 27 April 2011; however, in these few cases (estimated at fewer than 2% of the database) only the EF scale of the afternoon tornado was used.

HYSPLIT methodology. To assess the potential paths that a paper or light object may have traveled, an online version of the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (see http://ready.arl.noaa.gov/HYSPLIT.php and http://ready.arl.noaa.gov) was used. We simulated debris trajectories using a point-source release and forward trajectory framework. Point-source releases were chosen for several locations that experienced catastrophic tornadic damage (e.g., Phil Campbell, Alabama). HYSPLIT was initialized with data from the 1200 UTC 27 Apr 2011 run of the 12-km North American Mesoscale Model (NAM). NAM soundings and convective available potential energy (CAPE) values were very similar to observations for the afternoon and evening of 27 April. The forward trajectories were specified for 27 April 2011 at times nearest to the tornadic event by location (e.g., 2000, 2100 UTC). Each trajectory was initialized at altitudes of 3, 4.5, and 6 km above ground level (AGL). These release heights were chosen to account for the variability in rapid vertical displacement of lightweight debris from a tornado that would be absent in model vertical velocity fields due to coarse grid spacing. These heights are consistent with the 5.5- to 6.5-km peak heights for debris lofting estimated by Forbes (2012) for EF-4 and EF-5 tornadoes during this outbreak. In addition, dual-polarization radar data gathered during several of the tornadoes indicated that these release heights were consistent with the altitudes of the observed debris plumes (Schultz et al. 2012a,b). The array of items consisted of differing weights, distances traveled, and azimuth angles from the source location.

It should be noted that HYSPLIT would likely perform poorly predicting the path of heavier debris items, as the model was originally designed to simulate pollutant dispersion for air quality purposes. However, paper objects (e.g., photographs, certificates) would likely be sufficiently modeled via HYSPLIT because of their larger surface area-to-

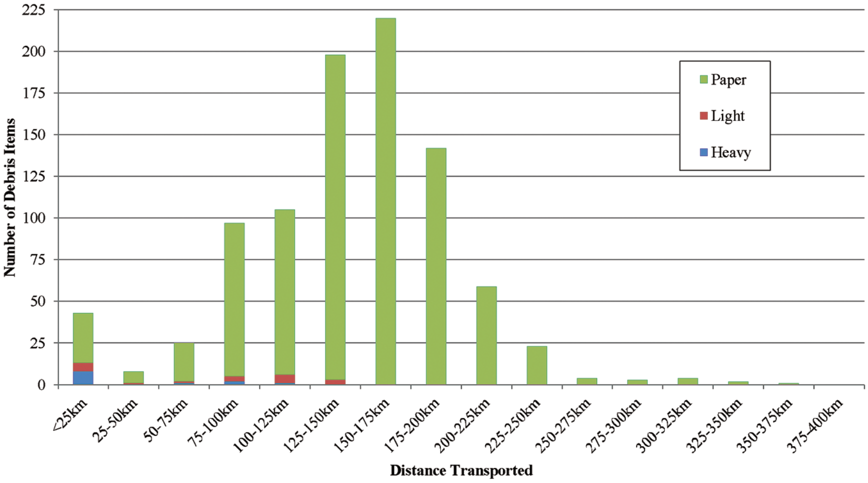


FIG. 4. Plot of number of debris reports as a function of type and distance for 27 Apr 2011. Debris categorized as paper, light (weighing less than 0.45 kg or 1 lb.), and heavy (weighing more than 0.45 kg or 1 lb.). Total number of reports plotted: 934. The farthest transported item traveled: 353 km. No light or heavy items in the database were transported more than 144 km.

weight ratio. Admittedly, HYSPLIT cannot resolve storm-scale motions. But given the high CAPE values on 27 April 2011 and the relationship between CAPE and thunderstorm vertical velocity [$w_{max} = (2*CAPE)^{0.5}$], these lightweight objects could reach levels where the upper-level background flow would dominate within minutes.

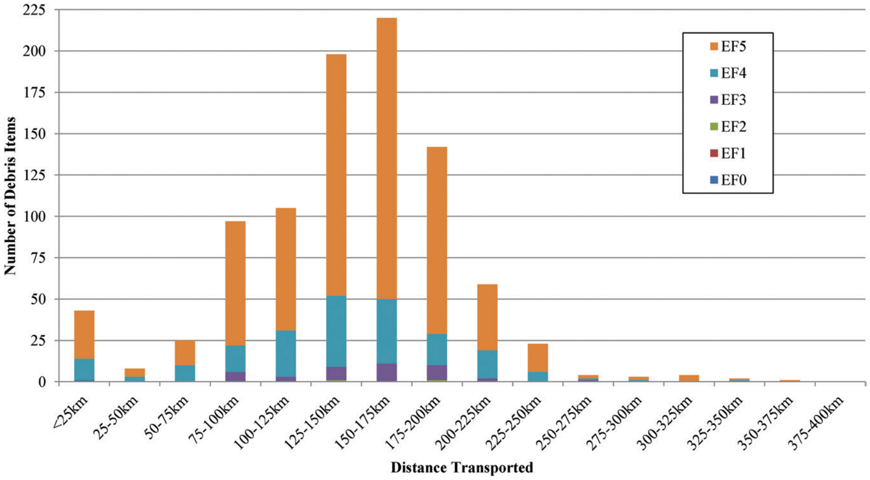


Fig. 5. Plot of number of debris reports as a function of EF scale and distance for 27 Apr 2011.

RESULTS.

Distribution. Because of the larger size and novel characteristics of the database used, the distribution of tornadic debris in this study is unique and provides additional insights in comparison to previous studies. We first analyzed the distribution of debris by transport distance and weight (Fig. 4). Given the particular emotional value of photographs and the ease with which they can be scanned, uploaded, and identified on Facebook, we anticipated that photographs would represent a large percentage of the overall database. The results in Fig. 4 confirm that the "paper" debris category, comprised mostly of photographs, does largely outnumber both the "light" and "heavy" classifications for the 934 articles of debris in this study.

The overall distribution of debris by distance in Fig. 4 differs significantly from the results of Anderson (1985) and Snow et al. (1995). These previous debris studies found a spike in debris fallout less than 30 km from the source, followed by a general decay in number of debris items with greater distance. These studies found an inverse relationship between weight and distance traveled (i.e., heavy items fall closer to the origin than light items.) Although numbers of heavy and light objects are limited, Fig. 4 does demonstrate this tendency for 27 April 2011. The distribution suggests that most heavy debris items fell out within 25 km of the source, while all light debris fell within 144 km of the source. The longest transport distance of any heavy object was 107 km; this was a windbreaker jacket found in Elkmont, Alabama, and returned to its owner from Hackleburg, Alabama. The longest transported item traveled 353 km from its point of origin. This item, a photograph, was found in Lenoir City, Tennessee, and returned to its owner from Phil Campbell, Alabama.

Figure 4 does show a local maximum for transport distance of less than 25 km as indicated in previous studies. However, in contrast to previous studies, our distribution yields a much higher peak for distances of 125–200 km. The mode of the overall distribution is from 150 to 175 km. These differences are likely caused by the large percentage of light and easily transported photographs, the much larger size of our dataset, the extremely violent nature of the 27 April tornadoes, and the strength of upper-level winds. For example, for a fall speed of ~1 m s^{-1} characteristic of paper debris (Magsig and Snow 1998) objects would reach the ground from an altitude of 3 km in about an hour. Given the 3-km wind speeds on 27 April of approximately 35 m s^{-1}, this would translate to a trajectory of about 125 km—and even farther for objects lofted higher and/or into stronger winds. Thus, the results in Fig. 4 comport with back-of-the-envelope estimates for debris trajectory distances during this outbreak.

The outbreak on 27 April 2011 was by no means typical, and, as expected, the distribution of debris items by their respective tornado's classification using the EF scale is also atypical of previous studies. Figure 5 shows the same distribution as Fig. 4, except as a function of EF scale. The majority of recovered debris (74.3%) originated from EF-5 tornadoes. This differs from Snow et al. (1995), who found only 10% of items from F5 tornadoes. The explanation for this disparity appears to be that our database includes more EF-5 tornadoes than Snow et al. (1995), despite the fact that Snow et al.'s study covered a time period that is longer than our study's time period by a factor of 43,830. This further highlights the exceptional nature of the 27 April 2011 outbreak. The object that traveled

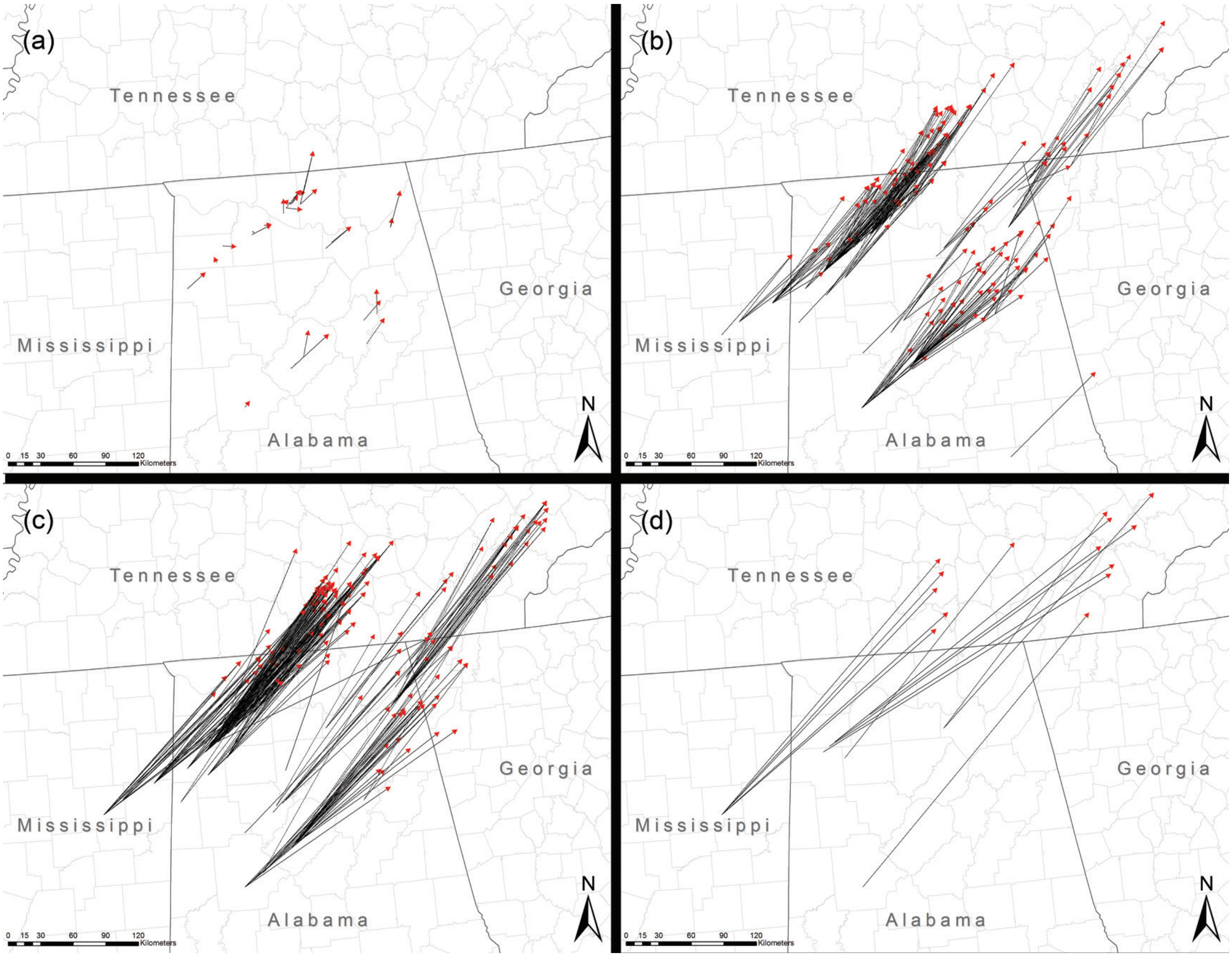


Fig. 6. Tracks of debris objects that traveled (a) <50, (b) 50–150, (c) 150–250, and (d) >250 km.

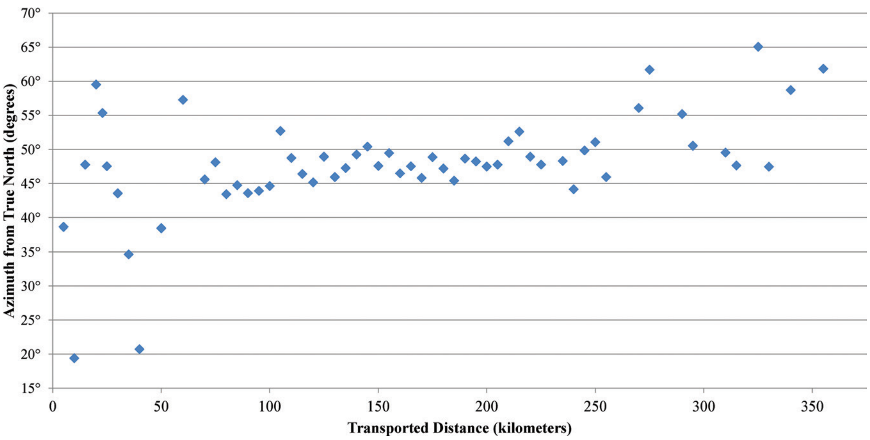


Fig. 7. Average azimuth of debris trajectories for every 5 km indicating the general trend of greater azimuth angle with distance. For reference, the average tornado track vector was 57° from the north.

the longest distance (353 km) was lofted by the EF-5 Hackleburg/Phil Campbell tornado.

The data in Table 1 show the 934 items of debris as a function of EF scale and classified weight. No items remained in our dataset that were lofted by an EF-1 tornado, and very few originated from an EF-0 or EF-2 tornado. In fact, 99.7% of all debris in the dataset originated from strong and violent EF-3 or greater tornadoes. This can be attributed, in part, to the large number of EF-4 and EF-5 tornadoes that occurred on 27 April and the much higher amounts of damage that these violent tornadoes produce. In our database, 56% of debris originated from the violent EF-5 Hackleburg/Phil Campbell tornado.

Tornado track vectors and HYSPLIT trajectories.

Snow et al. (1995) found that a concentrated area of debris fell within 10° and 35° to the left of the "storm direction," defined as the direction of the line tangent to the beginning portion of the tornado track. With a larger dataset, we are able to expand on these previous findings. Figure 6 geospatially demonstrates the azimuthal pattern of trajectories by distance, assuming in the absence of other information a linear path for each object. The azimuth of each trajectory from true north was analyzed and plotted in Fig. 7. The results depicted in this figure suggest that debris fallout tended to be oriented southwest to northeast. Debris trajectories within 50 km of the origin were more varied in azimuth than debris lofted longer distances. Beyond 50 km from the origin, the overall orientation the debris trajectories had was an average azimuth of 47° from north. This places the majority of debris trajectories roughly 10° to the left of the average tornado track vector, which was 57° from north. This is consistent with recent dual polarimetric radar research (e.g., Schultz et al. 2012b; Bodine et al. 2013) on tornado debris signatures (TDS), which are typically found to the left of the ground track of the tornado. Analysis yielded a trend of greater azimuth from true north with greater transport distance, as demonstrated in Figs. 6 and 7.

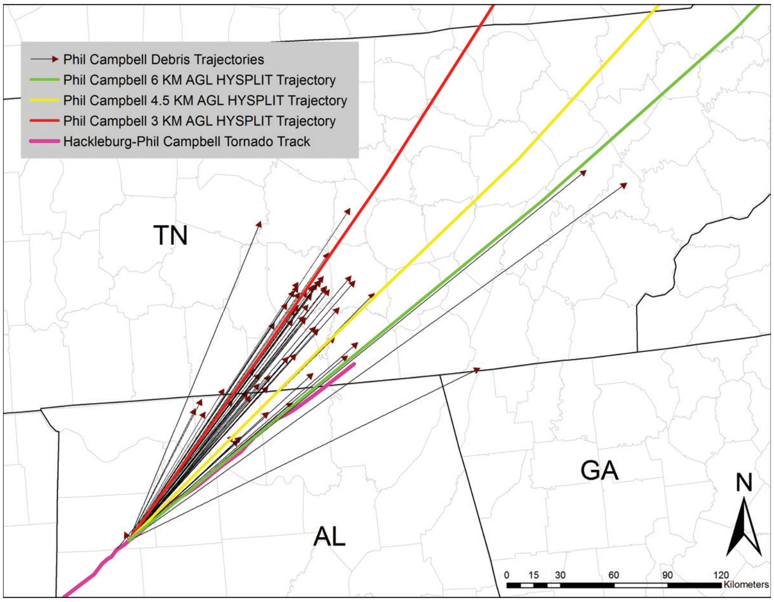


Fig. 8. Trajectories of debris originating from Phil Campbell, AL, with overlaid 3-, 4.5-, and 6-km AGL HYSPLIT trajectories initialized at 2000 UTC 27 Apr 2011.

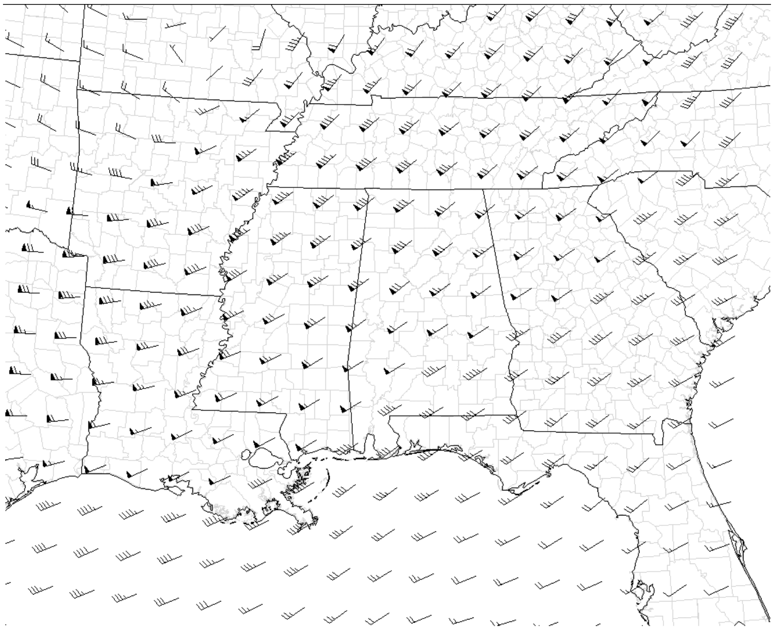


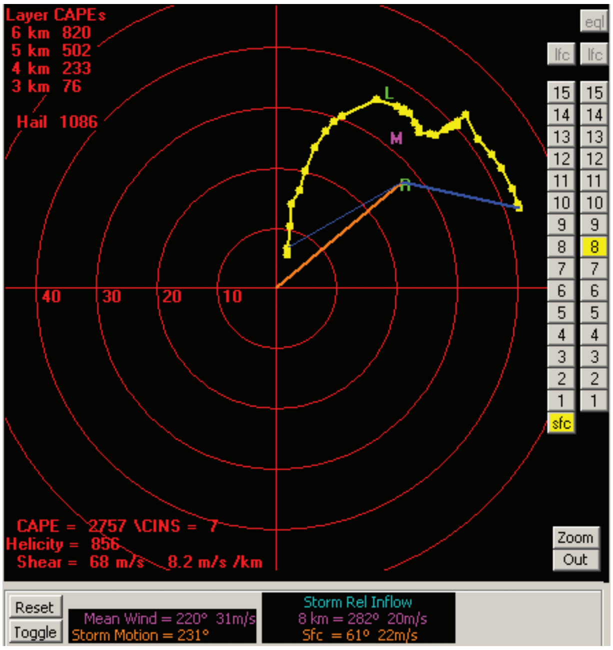
Fig. 9. 400–700-hPa mean wind vector from the 27 Apr 2011 2100 UTC Rapid Update Cycle (RUC) 211 grid initialization.

Trajectory analysis results using HYSPLIT (Fig. 8) indicate a clockwise turning of debris trajectories with higher initialization height. When overlaid on the Hackleburg/Phil Campbell tornado track and associated debris trajectories, the 3-km-height initialized HYSPLIT matches the azimuth angle for the majority of debris. The noticeable difference in azimuth angle for longer trajectories is better demonstrated with the higher 6-km HYSPLIT initialization. Ensemble runs of HYSPLIT (not shown) also indicate that initializations at lower altitudes are very unlikely to generate right-of-tornado-path trajectories. This leads to the conclusion that debris items traveling longer distances were also lofted higher by the tornado. The outlier, a photograph that traveled from Phil Campbell, Alabama, to Lookout Mountain, Tennessee, has a large azimuth angle of 70.9° and is, perhaps, anomalous in that it was lofted much higher than other debris.

The relationship between debris height and trajectory distance is further supported by an analysis of the midlevel wind flow on 27 April 2011. The 400–700-hPa mean wind vector (Fig. 9) indicates winds consistent with the concentrated band of debris trajectories to the left of the average tornado track vector. The increased azimuth angle from north of longer trajectories can be explained through the pattern of veering wind with height (Fig. 10). Likely, debris transported long distances were lofted higher within the parent storm, maintaining a higher altitude in an environment with winds from a more west-southwesterly direction than lower-level winds. We infer in these cases that the trajectory will be largely determined by the high-altitude winds because these objects presumably spend more time at these altitudes than in ascent or descent.

CONCLUSIONS. Our work documents the trajectories of nearly 1,000 objects lofted by the 27 April 2011 tornado outbreak. As such, it is the most comprehensive and detailed study of tornado debris to date. It follows the recommendations of Hyvärinen and Saltikoff (2010) regarding the utility of social media, especially for the study of mesoscale phenomena, when large sample size and limited amounts of erroneous data are available.

Our results indicate that objects lofted by tornadoes can travel even farther than previously thought. Examination of tornado debris travel by Snow et al. (1995) found only two objects that traveled over 217 km between 1871 and 1990, a period of 120 years. In contrast, our study found 44 items that traveled a comparable distance or greater in a single day. Two objects from Phil Campbell, Alabama, were found in the general vicinity of Knoxville, Tennessee, both traveling farther than the longest previously documented tornado debris trajectory of 335 km (Snow et al. 1995).



Layer CAPEs
6 km 820
5 km 502
4 km 233
3 km 76
Hail 1086

CAPE = 2757 \CINS = 7
Helicity = 856
Shear = 68 m/s 8.2 m/s /km

Mean Wind = 220° 31m/s
Storm Motion = 231°

Storm Rel Inflow
8 km = 282° 20m/s
Sfc = 61° 22m/s

Fig. 10. Hodograph from the Birmingham (AL) National Weather Service Office (KBMX) for 0000 UTC 28 Apr 2011, generated using archived data from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/).

Trajectories based on the takeoff and landing points of lost-and-found objects revealed that most debris was deposited 10° to the left of the average tornado track vector. However, objects that traveled the longest distance were found approximately 5° to the right of the average tornado track vector. Our results thus confirm and extend the results of Snow et al. (1995) using a much larger database. In particular, we confirmed Snow et al.'s results that the majority of tornado debris objects fall to the left of the average tornado track vector. In contrast to Snow et al.'s results, however, the debris that traveled the farthest in our study was found to the right of the average tornado track vector, rather than to the left. We surmise that this is due to the longest traveled objects being the objects that were lofted highest by the tornadic supercells.

Our inference that changes in azimuth are related to the altitude that tornado debris objects were lofted is based on high-resolution trajectory analysis. To our knowledge, our research is the first to use high-resolution numerical trajectory analysis to determine the travel of tornado debris. [Magsig and Snow (1998) used one sounding and terminal fall speed estimates to calculate debris trajectories.] Trajectories from HYSPLIT provided an excellent fit for the longest traveled objects for a release point altitude of 6 km, whereas HYSPLIT trajectories using a release point altitude of 3 km correlated well with observed debris trajectories for objects that traveled shorter distances (Fig. 8). This conclusion advances beyond the conjectures of Snow et al. (1995), who were unable to determine the height to which objects were lofted. Our estimates of the altitude of debris lofting are also consistent with emerging radar analysis of this outbreak.

Conducting meteorological research with social media data revealed both pros and cons with this source of information. The use of social media allowed us to construct a database of tornado debris travel an order of magnitude larger than any others previously constructed. Several negative aspects were also revealed during the course of our research, however. Comparison of our Table 1 to Table 1 in Snow et al. (1995) reveals that our dataset contains considerably more paper items and fewer heavy and light items. As Bullion's site was designed primarily to return photographs, there was a bias toward these paper objects. Furthermore, personal checks, a prime source of tornado debris information in the past, were not posted on the Facebook page because of privacy concerns. Another downside is that the Facebook page was taken down just one year after the event, while previous sources of tornado debris information (Grazulis 1993; Snow et al. 1995) used sources with far more permanence, such as newspaper accounts.

Future work on tornado debris may benefit from a coordinated study using dual-polarization radar as a basis to locate items. While tornadoes exact a terrible toll on the communities they strike, we hope that this research can transform some of this suffering into an increased understanding of tornadic thunderstorms and the debris that they transport. In particular, if in the future a tornado lofts radioactive or biological items, it will be of the utmost importance to know where the debris will land. We hope that our work better establishes our scientific understanding of this underappreciated tornado hazard.

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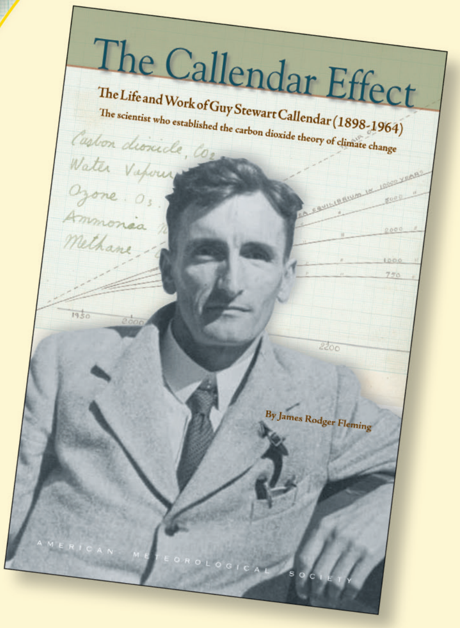

The Callendar Effect

The Life and Work of Guy Stewart Callendar (1898–1964)

The scientist who established the carbon dioxide theory of climate change

By James Rodger Fleming

AMERICAN METEOROLOGICAL SOCIETY

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