

## Research Article

# Predicting Microbursts in the Northeastern U.S. Using Lightning Flash Rates and Simple Radar Parameters

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Convective storms that produce microburst winds are difficult to predict because the strong surface winds arise in a short time period. Previous research suggests that timing and patterns in cloud height, echo top height, vertical integrated liquid (VIL), intracloud (IC) lightning, and cloud-to-ground (CG) lightning may identify and predict microbursts. Eleven quasi-cellular microburst cases and eight non-microburst severe wind cases were identified from New York, Pennsylvania, and New Jersey between 2012 and 2016. Total lightning data (IC + CG) were obtained from Vaisala's National Lightning Detection Network (NLDN), and radar parameters were obtained from the Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN) software. Values of VIL, echo top height, and cloud height were tracked through time along with total lightning strikes within a 15 km radius of the storm center. These parameters were plotted with respect to their mean and standard deviation for the 45 minutes leading up to event occurrence. Six of eleven cases featured peaks in total and IC lightning within 25 minutes prior to the microburst. These were the only variables among those examined to peak more than half the time for either the microburst cases or the null cases. The results suggest that microbursts behave somewhat differently than severe wind events, particularly in terms of lightning and VIL timing. The results dispute previous research that suggests that microbursts are highly predictable by the behavior of lightning and radar parameters.

## 1. Introduction

Microbursts are strong winds exhibiting a divergent damage pattern across an area 4 km wide or less [1]. Although dry microbursts (reflectivity <35 dBZ) are possible in other climates, all observed microbursts in the Northeast U.S. are wet microbursts, produced by rapid changes in thunderstorm environments. They present a serious hazard to life and property. Prediction of microburst winds is difficult owing to the rapid lifecycle associated with many convective storms. Such storms can produce intense downbursts, usually >5 minutes in duration, with limited warning. Previous studies [2–4] have suggested that microbursts might be predicted by changes in radar parameters and/or lightning frequency. However, these studies have focused on only a handful of cases, mostly in the southern U.S. Microbursts have not been extensively studied in the Northeast U.S., such that the validity of these earlier findings remains a question for the Northeast. Furthermore, other studies have

not compared microburst-producing storms with non-microburst storms that produced wind damage to determine the likelihood of microburst false alarms.

Thunderstorm downdrafts occur in response of the concentration and/or phase changes of water. This generates negative buoyancy in convective environments. In the presence of steep ambient lapse rates or continued diabatic cooling, the air maintains its negative buoyancy while descending. With large amounts of negative buoyancy, microbursts spreading out at the ground can be produced [5].

Microburst formation is often attributed to hail core collapse, and the cooling of midlevel air caused by the rapid melting of hail and subsequent evaporative cooling is associated with many microbursts because it can rapidly generate large negative buoyancy [5–7]. Thunderstorm collapse occurs when a storm's downdraft overtakes the updraft, causing mixed-phase precipitation particles to fall out of the cloud. The rapidly descending downdraft is capable of creating a microburst, or strong diverging winds at

the surface [8]. Not all downdrafts associated with collapsing thunderstorms produce microbursts, and not all thunderstorms that produce microbursts decay rapidly following the microburst. High reflectivities ( $>50$  dBZ) must be above the melting level ( $-10^{\circ}\text{C}$ ) for the downdraft to be strong enough to create a microburst. Microbursts are unlikely with storms that exhibit high reflectivities below the melting level [3]. Lightning production often increases as the updraft strengthens, particularly between  $0^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ , suggesting that lightning peaks may be important predictors of microburst events [9].

Goodman et al. [2] discovered lightning indicators of a microburst in Alabama that resulted in  $>15\text{ m}\cdot\text{s}^{-1}$  winds. A peak, followed by a sharp decrease, in the intracloud (IC) lightning flash rate occurred six minutes before thunderstorm collapse and the subsequent microburst event. An abrupt increase in cloud-to-ground (CG) lightning activity occurred five minutes before the microburst, directly after the peak in IC lightning. Williams et al. [3], examining several microbursts also in Alabama, similarly found that a peak in IC lightning preceded a peak in CG lightning, both of which occurred before the microburst. Kane [4] studied one downburst in Massachusetts and found that five-minute CG lightning peaked just a few minutes before the downburst. Metzger and Nuss [10] examined lightning activity associated with wind, hail, and mixed severe reports. They found that wind-type lightning jumps were characterized by increasing CG strike rates and either increasing (12 of 18 cases) or steady or decreasing (6 of 18 cases) IC flash rates.

Other signatures of a vigorous updraft, such as peaks in vertical integrated liquid (VIL), cloud height, and echo top height, may presage microburst development. Strong updrafts allocate low-level moisture into a storm, where the moisture then condenses and freezes when lifted above the melting level, creating graupel and hail. Hail is associated with high values of VIL [11]. VIL is sensitive to reflectivity, such that higher reflectivity values ( $>40$  dBZ, and especially  $>50$  dBZ) are associated with higher VIL [12]. Reflectivity values above 55 dBZ are often contaminated by hail, and VIL is typically capped near this value, assuming that hail is present above this value and not all reflectivity is produced by liquid water.

Echo top height is defined as the height of the radar beam at which a certain reflectivity threshold is exceeded [13]. A reflectivity threshold  $>18$  dBZ is typically considered the minimum threshold for echo top height of a given storm cell [14]. High echo top heights indicate that hail is likely present throughout a storm, especially in the “charging zone” between  $0^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$  [9]. Convective storms with strong updrafts cause greater hail production and higher echo top heights. Vigorous updraft signatures are precursors to thunderstorm collapse, possible microburst development, and damaging outflow winds.

Tall cloud heights are also suggestive of a vigorous updraft. In order for a convective cloud to grow, the updraft must ingest and lift moisture. The stronger the updraft, the higher the moisture that can be lifted, resulting in higher cloud heights. The 0 dBZ reflectivity echo can be used as a proxy for cloud height [2].

Peak values of IC lightning flashes, VIL, echo top heights, and cloud heights about six minutes before the outflow imply a strong updraft in a convective storm [2]. The six-minute prediction interval for a strong updraft is reflective of a convective storm’s lifecycle. In a convective storm, peaks in updraft strength are rapidly followed by the downdraft becoming dominant [3]. CG lightning forms as particles rapidly descend, collide, and build up charge as a result of a storm’s downdraft [15]. A sharp decrease in IC lightning activity and increases in cloud-to-ground (CG) lightning strikes indicate the downdraft is overcoming the updraft.

In this study, we examine quasi-cellular microbursts and a collection of non-microburst quasi-cellular severe wind events in the Northeast U.S. from 2012 to 2016 to determine how well peaks in various radar and lightning parameters perform in predicting microburst occurrence.

## 2. Data and Methodology

Quasi-cellular microburst cases during the years 2012–2016 were identified through the National Centers for Environmental Information (NCEI) Storm Events Database [16]. Reports of thunderstorm winds  $>36\text{ m}\cdot\text{s}^{-1}$  (70 kt), with a summary indicating a National Weather Service- (NWS-) confirmed microburst, were recorded. Level II Next Generation Weather Radar (NEXRAD) data were acquired to determine whether the microburst was quasi-cellular. Quasi-cellular storms included isolated cells, small clusters of cells, and cells that later merged with larger convective features. In addition, the quasi-cellular storm center had to be easily tracked to be included in this study.

A second dataset consisting of non-microburst-producing wind damage reports from the NCEI SED was included for comparison with the microburst events. High wind events were chosen rather than ordinary thunderstorms because most days on which quasi-cellular microbursts occur feature widespread wind damage. Thus, a primary forecast challenge on these days is determining whether a given thunderstorm cell will produce “ordinary” wind damage or microburst wind damage. Quasi-cellular events that produced reported wind speeds  $\geq 26\text{ m/s}$  (50 kt) were selected from the microburst days. These events were subject to the same storm tracking and lightning analyses as the microburst events.

The radar data were processed by the Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN) system [17], to track the storm centroid. TITAN also produced estimates of vertical integrated liquid (VIL), cloud top height (0 dBZ), and echo top height (18 dBZ). TITAN was run for reflectivity thresholds every 5 dBZ from 30 dBZ to 50 dBZ and for hail caps of 53 dBZ and 56 dBZ. The results in this paper are presented for the 45 dBZ/56 dBZ runs, which produced the most reliable tracks in some cases where cells were clustered or merged with linear features. Others have preferred to use a slightly lower threshold of 40 dBZ [14, 18, 19], but these studies were primarily interested in heavy precipitation and flash flooding, while the present study is more interested in tracking high reflectivity cores that produced severe weather.

Reflectivity centroids from the TITAN output were ingested into the GR2Analyst software (Gibson Ridge) and compared with the Level II NEXRAD data to identify the complex and simple track numbers associated with each microburst-producing storm. The VIL, echo top height, and cloud height values for each verified storm cell center along the microburst-producing storm track were plotted with time, and trends were distinguished by plotting time-series graphs of each parameter.

Lightning data (IC and CG) were obtained from Vaisala's National Lightning Detection Network [20, 21] for the period from 2012 to 2016 across most of Pennsylvania, New Jersey, and New York (see Figure 1 for a general map of the study area; all but the eastern half of Long Island was included). Detection efficiency (DE) for NLDN cloud-to-ground (CG) lightning was found to be approximately 90–95% from 2002 to 2012 [22], and following an upgrade to the network, it improved to over 95% since 2013 [23]. Prior to 2013, the NLDN had a cloud-to-cloud (CC) lightning, or intracloud (IC) lightning, and DE of 15%–25%. Following the upgrade in 2013, this DE increased to about 50% [23, 24].

Lightning data were paired with the reflectivity centroids to determine lightning flash rates for each microburst-producing storm. Total lightning strikes within 15 km of each reflectivity centroid from TITAN were aggregated and assumed to be related to the storm cell that produced the microburst. One-minute and five-minute flash rates were computed for IC, CG, and total (IC + CG) lightning.

All of the lightning and radar parameters, including the null datasets, were examined using standard  $Z$ -scores. The  $Z$ -score normalizes the deviations in a dataset from the mean with the standard deviation of the said data. This manipulates a dataset towards zero mean and unit variance, allowing for equal comparisons across data with multiple scales, and indicates how far each point is from the mean. Deviations of lightning data greater than  $2\sigma$ , or two times the standard deviation, were found to detect severe weather with a high probability of detection (POD), and a low false alarm rate (FAR) [25]. These large increases in lightning activity have been termed “lightning jumps” [25, 26]. For consistency, and to analyze local maxima of values in a dataset relative to the time of a microburst, the radar parameter deviations were also standardized to identify large deviations from the mean.

The mean and standard deviations for all datasets were calculated over data for 45 minutes before a microburst occurred and then employed over the entire 60-minute time period. Deviations from the total, cloud-to-ground, and intracloud datasets were plotted together, as well as plots of VIL, echo top, and cloud top. In addition,  $2\sigma$ ,  $1\sigma$ ,  $-1\sigma$ , and  $-2\sigma$ , as well as the time of the microburst, were highlighted to examine any changes in the datasets. A “peak” in a parameter is considered to be the maximum data value exceeding  $2\sigma$  at any time during the 60-minute time period examined for each event.

A separate analysis was performed using the “ $2\sigma$ ” algorithm from the study of Schultz et al. [25]. Detected large increases in lightning activity have been termed “lightning jumps” [25, 26]. The “ $2\sigma$ ” algorithm introduces a minimum lightning flash threshold of 10 flashes per minute, to decrease

the number of lightning jump false alarms. The average minute flash rate is then calculated between two time steps (two minutes in our case) where the threshold is exceeded. For each averaged flash rate, the standard deviation is calculated from the previous five averaged lightning observations (or 10 minutes prior), not including the time being investigated. The calculated standard deviation is doubled and becomes the “jump threshold,” where the averaged flash rates that exceed the jump threshold is a “lightning jump.” This algorithm creates a moving lightning jump threshold, rather than a static threshold over a total time period [25]. We follow the original paper in comparing total lightning using this algorithm, as it performed the best in the original paper.

### 3. Results

The procedures above yielded 11 quasi-cellular microburst cases to be examined. The 11 microburst cases were spread across Pennsylvania and New York, with local maxima in the Mohawk River Valley and Hudson River Valley of New York and the Valley and Ridge region of Pennsylvania (Table 1 and circle points in Figure 2). It appears that orography may play a role in producing microbursts in the Northeastern U.S. A twelfth case (not shown) was located along the northern shore of central Long Island, but its track ran east of the available lightning data. This case was excluded from the analyses. No microburst cases meeting the case selection criteria were found in New Jersey during the period for which lightning data were available.

The eight null cases do not show a strong preference for complex topography (Table 2 and triangle points in Figure 2), and they are scattered across New York and Pennsylvania. They generally occurred earlier in the day than the microbursts (Tables 1 and 2) and produced weaker winds.

The total lightning data from storm cells associated with microbursts indicated that total lightning peaked within 20 minutes before the microburst in five of eleven cases and within 25 minutes before the microburst in six of eleven cases (Figures 3–5 and Table 3). CG lightning peaked within 25 minutes before the microburst in five of eleven cases, and IC lightning peaked within 25 minutes before the microburst in six of the eleven cases. About one-third of the time, lightning peaked after the microburst. The mean lead time for total and CG lightning peaks was about 8 to 10 minutes, and for IC lightning peaks, it was about 14 minutes.

Using instead the Schultz  $2\sigma$  algorithm (Figures 6 and 7), four of the eleven cases (20140708NY, 20150623, 20150630, and 20160616) met the lightning jump threshold for total lightning, and three others (20120724, 20140703, and 20150612) equaled or closely approached the threshold. For the null cases (Figure 8), only the 20150612 case saw the time rate of change in flash rate exceeding the lightning jump threshold.

The radar parameters were found to be less significant than the lightning parameters, often just barely exceeding the  $2\sigma$  threshold used to determine whether a particular value had peaked (Figures 9–11 and Table 3). The radar parameter peaks had shorter mean lead times than the



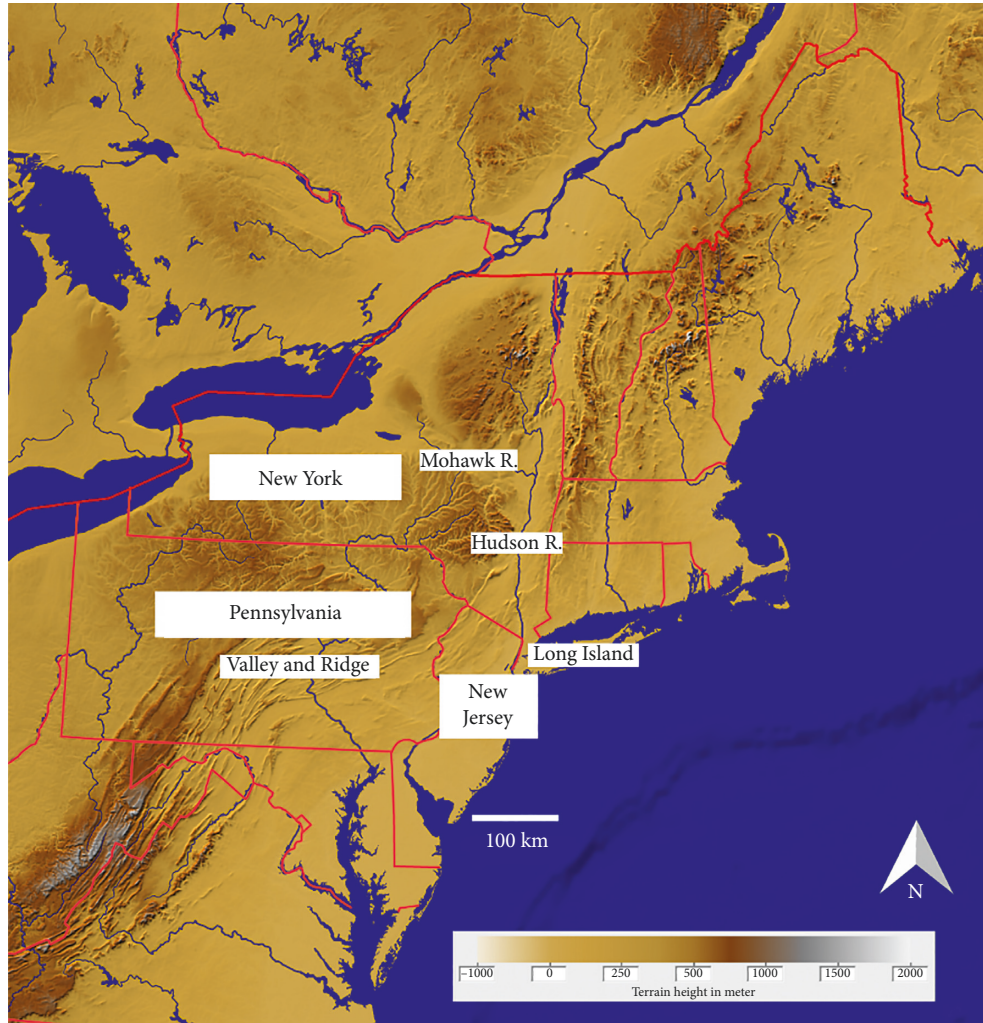


FIGURE 1: General map of the study area, highlighting key locations.

TABLE 1: List of microbursts examined in this study.

Case	Date	Time (UTC)	Latitude (°)	Longitude (°)	Wind speed (m/s)
1	7/24/2012	04:12	43.13	-75.32	49
2	6/24/2013	22:08	42.658	-73.726	45
3	7/3/2014	19:55	42.8842	-75.2009	45
4	7/8/2014NY	23:10	43.31	-75.29	43
5	7/8/2014PA	22:52	40.46	-76.98	43
6	6/12/2015	21:05	41.66	-74.19	45
7	6/23/2015	16:35	40.9068	-77.4522	36
8	6/30/2015	18:35	40.6631	-75.5153	36
9	8/3/2015	23:33	42.9344	-74.6262	43
10	6/16/2016	18:55	39.938	-78.6537	36
11	7/1/2016	20:17	42.802	-73.9144	40

lightning parameters, particularly VIL, with a mean lead time of about four minutes. VIL peaked within 25 minutes of the microburst in four of the eleven cases. Three of those peaks were within six minutes of the microburst. Cloud tops peaked after the microburst in three of the eleven cases and did not peak before the microburst. Echo tops peaked within 25 minutes of the microburst in two of the eleven cases, one with 2-minute lead time and the other with 17-minute lead

time. VIL thus appears to be the most useful predictor of the radar parameters, yet it peaks before the microburst less than half the time.

The mean lightning lead times for the null events were similar to those for the microburst events, but the individual values are either far before the severe wind event or after it occurred (Figures 12 and 13 and Table 4). Total lightning peaked within 25 minutes before the severe wind event only



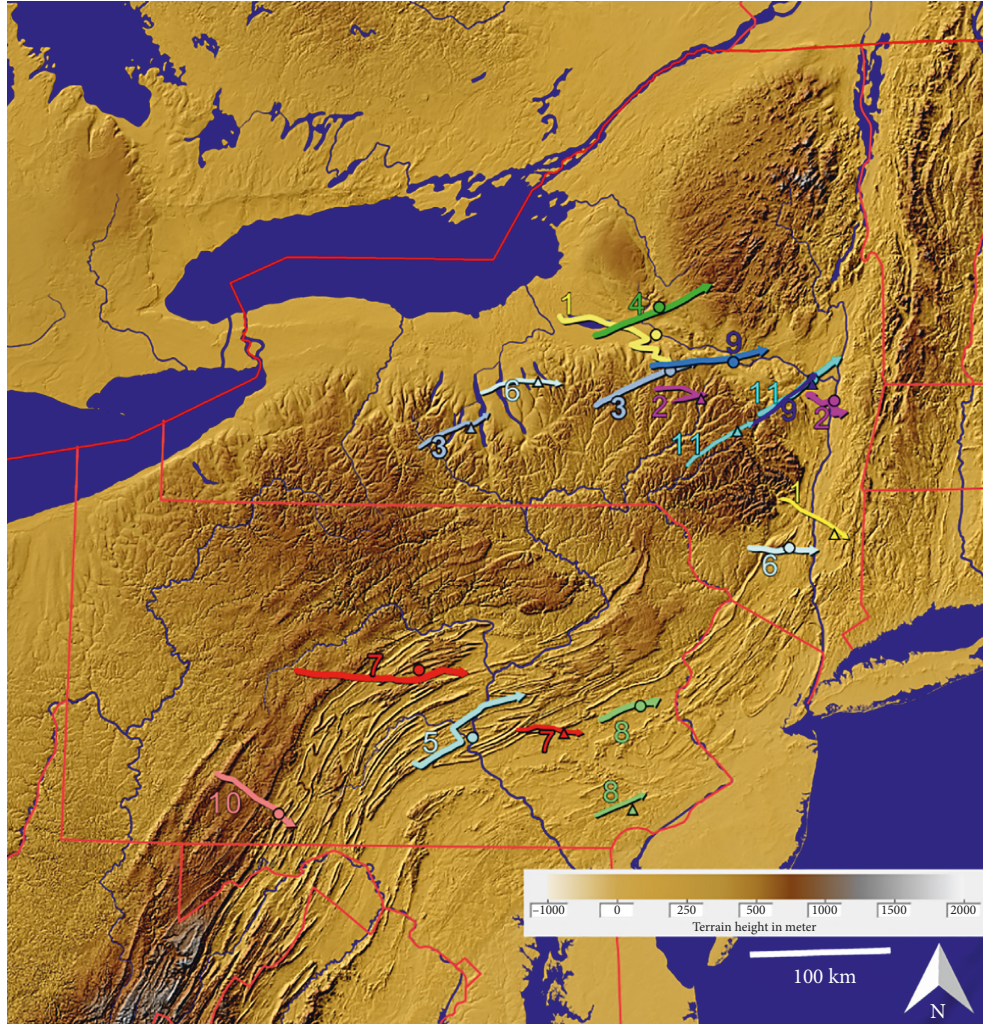


FIGURE 2: Terrain map of the eleven quasi-cellular microburst storm tracks (lines) and locations (circles) and the eight quasi-cellular null event storm tracks (lines) and locations (triangles).

TABLE 2: List of null severe wind events examined in this study.

Case	Date	Time (UTC)	Latitude (°)	Longitude (°)	Wind speed (m/s)
1	7/24/2012	20:29	41.7747	-73.768	31
2	6/24/2013	19:28	42.7	-74.93	26
3	7/3/2014	17:50	42.52	-77.00	26
6	6/12/2015	19:15	42.83	-76.40	33
7	6/23/2015	20:12	40.4917	-76.185	27
8	6/30/2015	19:17	39.979	-75.5917	27
9	8/3/2015	19:00	42.7801	-73.9222	26
11	7/1/2016	18:42	42.4813	-74.6101	26

once, and IC lightning peaked within 25 minutes before the severe wind event in three of eight cases. Neither total nor IC lightning had a single peak within 10 minutes of the null event. CG lightning, on the contrary, showed some predictive capability, with four cases peaking within 25 minutes of the null events; three of these cases peaked within 10 minutes.

For the radar parameters of the null events, the mean lead times were close to the time of the microburst Figures 14 and 15. Except for echo tops, the majority of the  $2\sigma$  maxima in the radar parameters were after the severe wind event:

three of eight events for cloud tops and six of eight events for VIL “peaked” after the event. For the three cases where the positive lead time was small, this may be indicative of small errors in the reported timing of the events. It could also indicate some microphysical processes amplifying liquid water in the cloud after evacuating a large gust of entrained dry air. For VIL and cloud tops, none of the eight events saw a  $2\sigma$  maximum within 25 minutes before the event. Echo tops showed the best potential as a predictor, with two of the eight events maximized at greater than  $2\sigma$  within ten

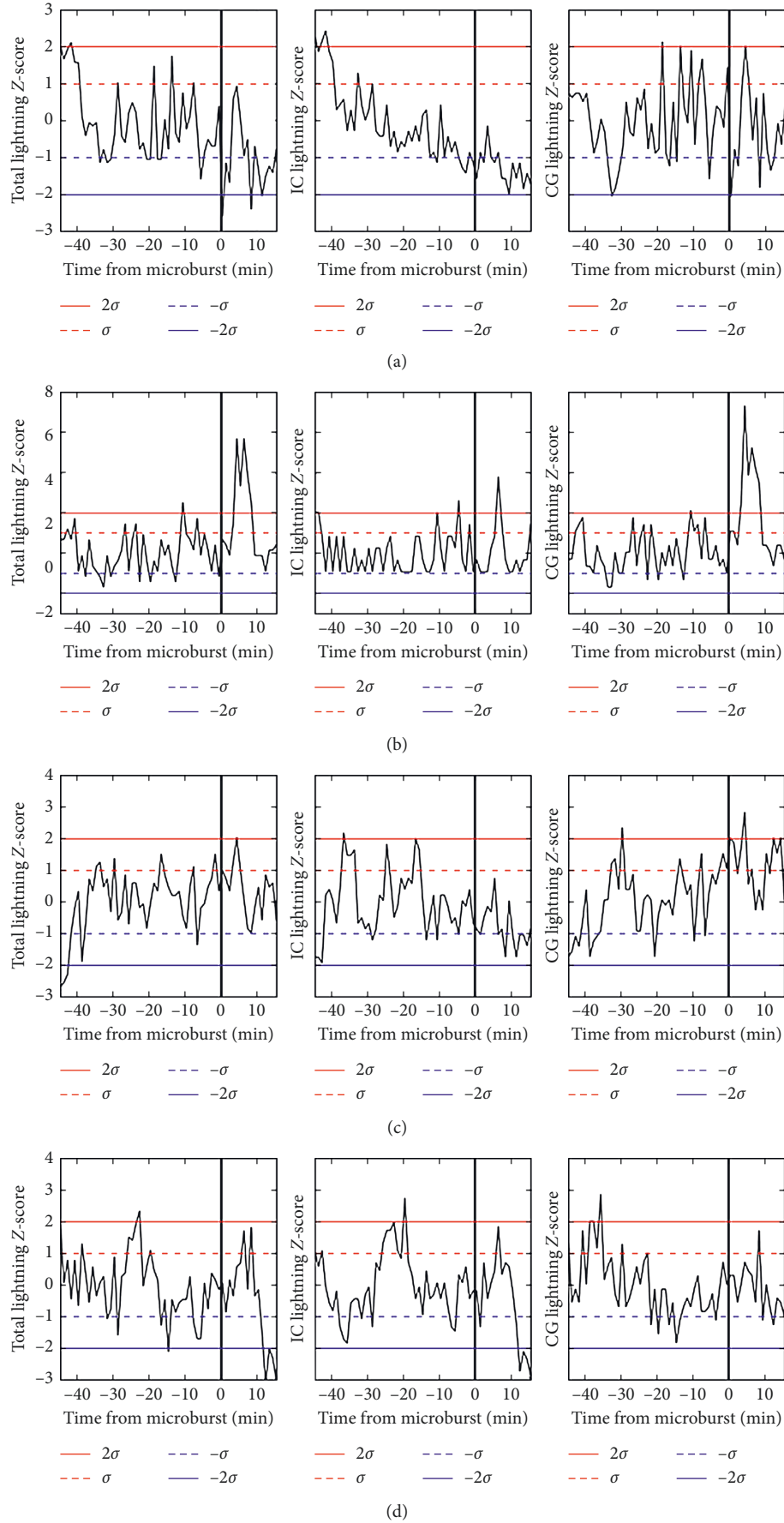


FIGURE 3: Plots of total lightning, IC lightning, and CG lightning for the first four microburst cases. (a) 20120724 microburst. (b) 20130624 microburst. (c) 20140703 microburst. (d) 20140708NY microburst.

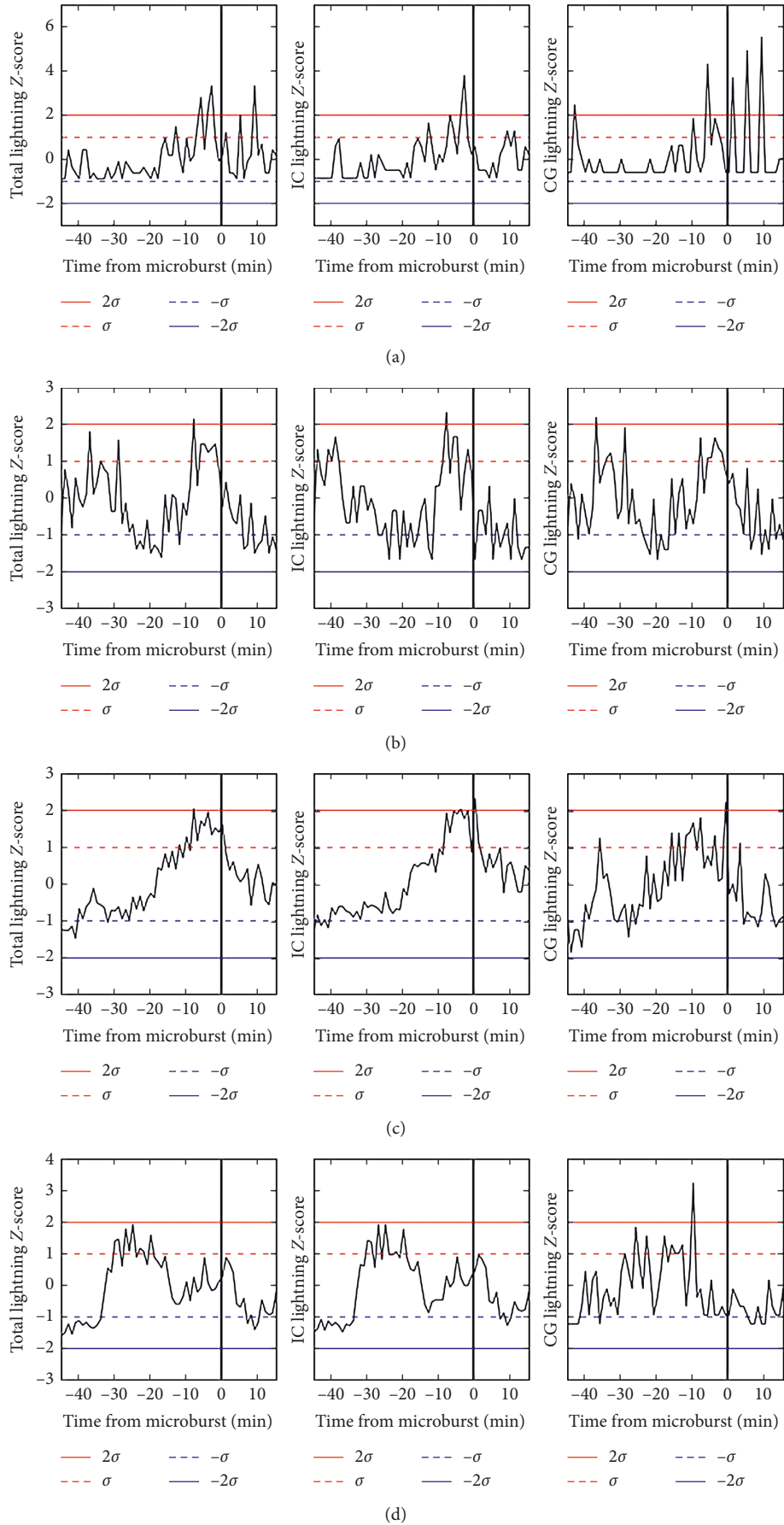


FIGURE 4: As in Figure 3, except for the next four cases. (a) 20140708PA microburst. (b) 20150612 microburst. (c) 20150623 microburst. (d) 20150630 microburst.



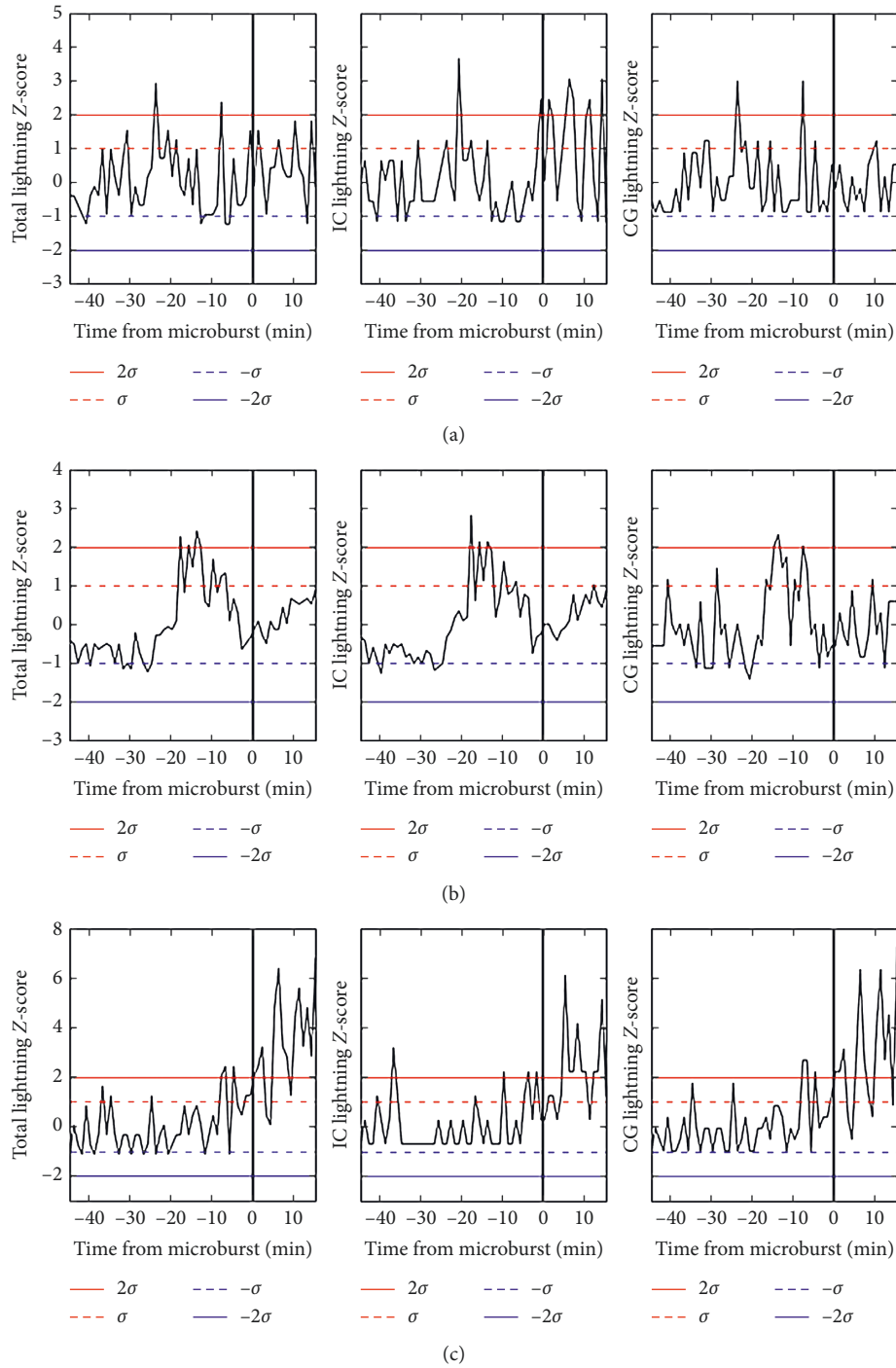


FIGURE 5: As in Figure 3, except for the last three cases. (a) 20150803 microburst. (b) 20160616 microburst. (c) 20160701 microburst.

minutes of the event. In short, trends in radar parameters for the null events show little predictive capability, as many of the maxima fall short of the  $2\sigma$  maximum, and many of the  $2\sigma$  maxima, especially for VIL, happen after the event.

#### 4. Discussion

Previous studies [2, 3] have linked microburst formation to the development of downdraft dominance. Downdraft

dominance is characterized by an increase in intracloud (IC) lightning, followed by a peak and sharp decrease in IC flashes. Peaks in IC lightning flashes were found to occur six minutes prior to outflow winds for a case in Alabama [3]. Thus, we hypothesize that IC lightning activity is related to a storm's microphysical and convective states before thunderstorm collapse. IC lightning forms in the temperature region between  $0^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ , where ice, graupel particles, and supercooled water are produced.

TABLE 3: Time of  $2\sigma$  maxima of each parameter with respect to the microburst.

Date	Total ltng. (minutes)	CC (minutes)	CG (minutes)	VIL (minutes)	Cloud top (minutes)	Echo top (minutes)
20120724	-42	-42	-20	N/A	N/A	N/A
20130624	+4	+6	+4	+2	+2	N/A
20140703	+4	-41	+5	-14	N/A	N/A
20140708NY	-23	-20	-36	-1	N/A	-17
20140708PA	-3	-3	+9	-5	N/A	N/A
20150612	-8	-8	-37	-42	N/A	N/A
20150623	-6	0	-1	N/A	+15	N/A
20150630	N/A	N/A	-10	0	N/A	N/A
20150803	-8	-21	-8	+12	N/A	N/A
20160616	-14	-18	-14	N/A	N/A	N/A
20160701	+15	+5	+15	+15	N/A	-2
Mean/SD	-8.1/15.9	-15.2/16.8	-14.2/17.4	-4.1/17.8	10.7/7.5	-9.5/10.6

Negative numbers indicate before the microburst, and positive numbers indicate after the microburst. N/A indicates maximum value was less than  $2\sigma$ .

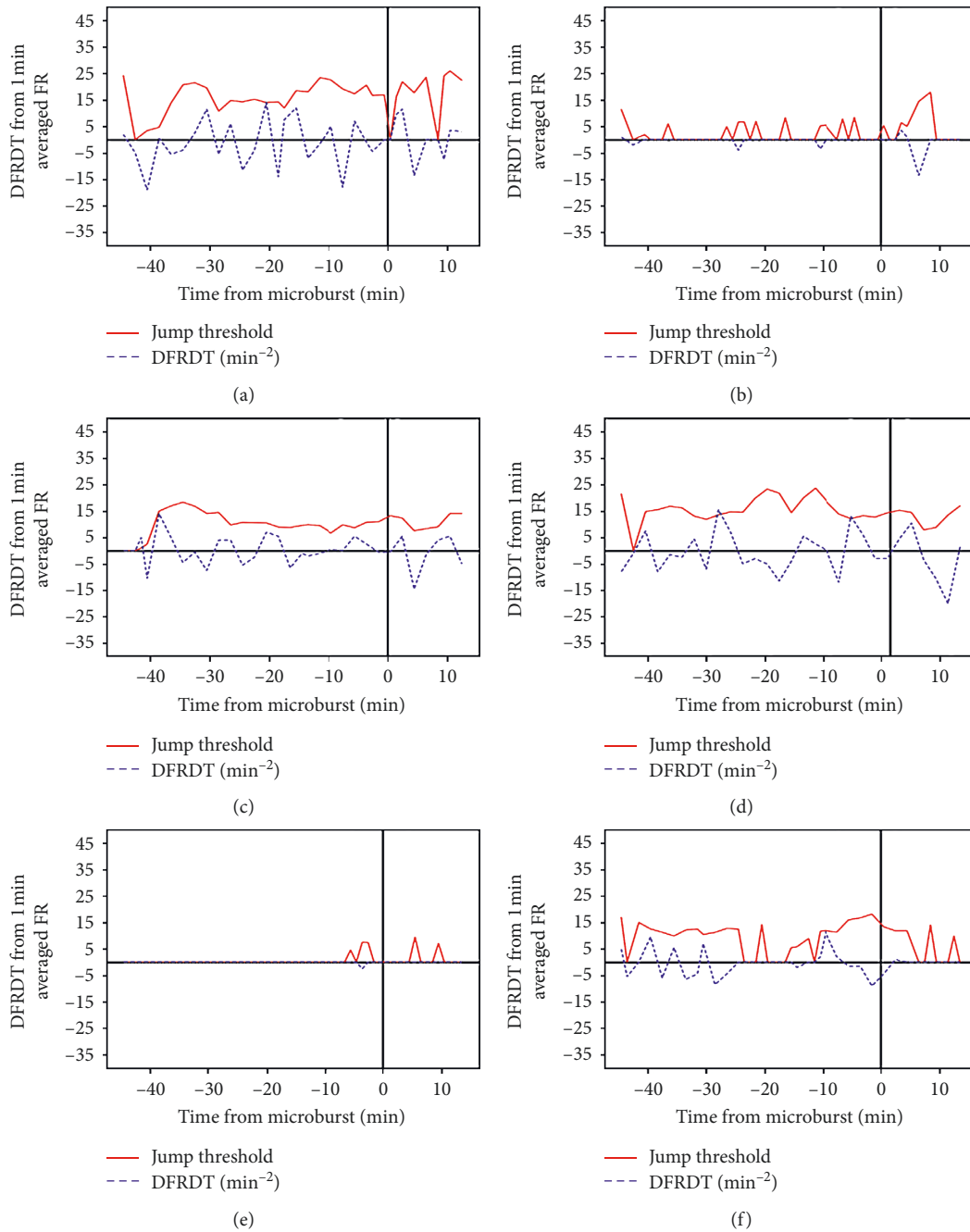


FIGURE 6: Continued.

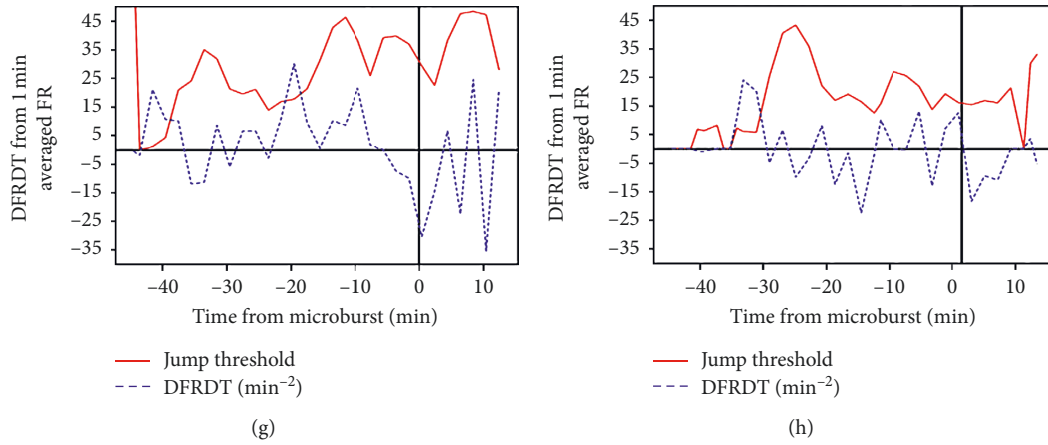


FIGURE 6: Plots of total lightning jumps using the  $2\sigma$  analysis of Schultz et al. [25] for the first eight microburst cases. (a) 20120724 total lightning. (b) 20130624 total lightning. (c) 20140703 total lightning. (d) 20140708NY total lightning. (e) 20140708PA total lightning. (f) 20150612 total lightning. (g) 20150623 total lightning. (h) 20150630 total lightning.

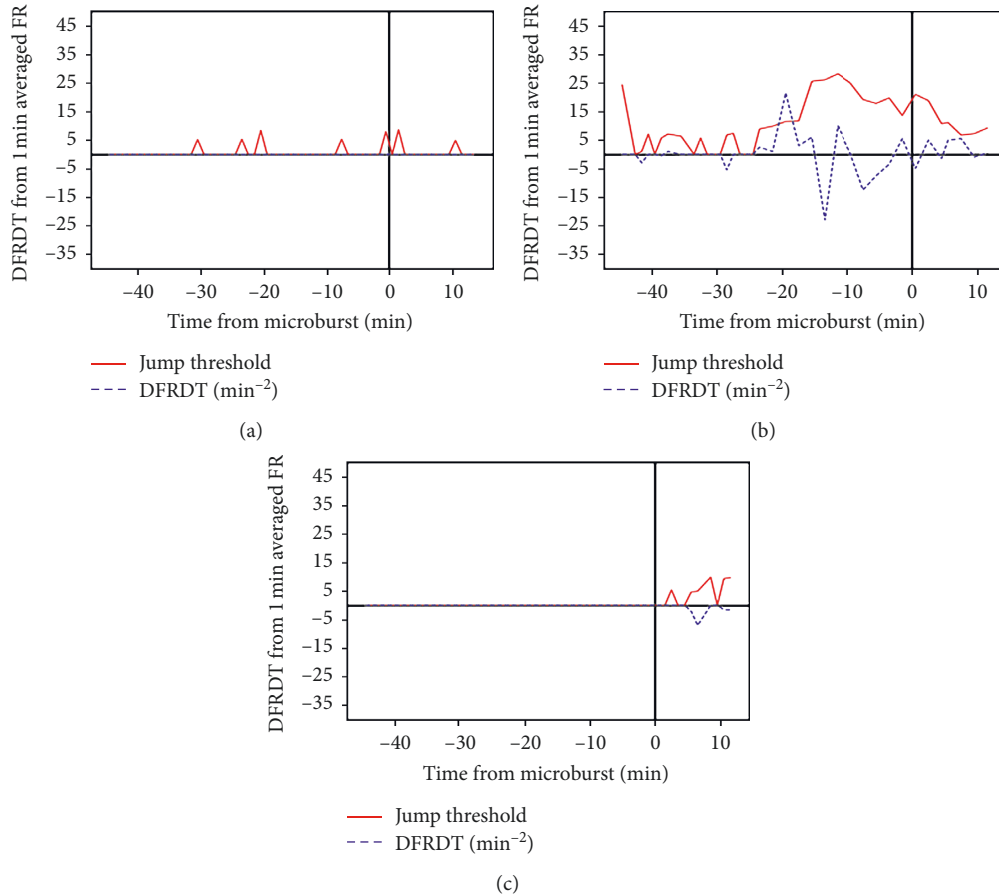


FIGURE 7: As in Figure 6, but for the last three microburst cases. (a) 20150803 total lightning. (b) 20160616 total lightning. (c) 20160701 total lightning.

Collisions between particles cause noninductive charging and the release of electricity in the form of IC flashes [9]. In order for a saturated  $0^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$  region to exist, a vigorous, deep updraft must be present to ingest water vapor into the storm. A peak in IC lightning activity indicates a

vigorous updraft that extends into this  $0^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$  layer, an indicator of imminent thunderstorm collapse, and a possible microburst. In the present study, IC lightning was found to peak and rapidly decline as much as 41 minutes before microburst occurrence, suggesting that perhaps



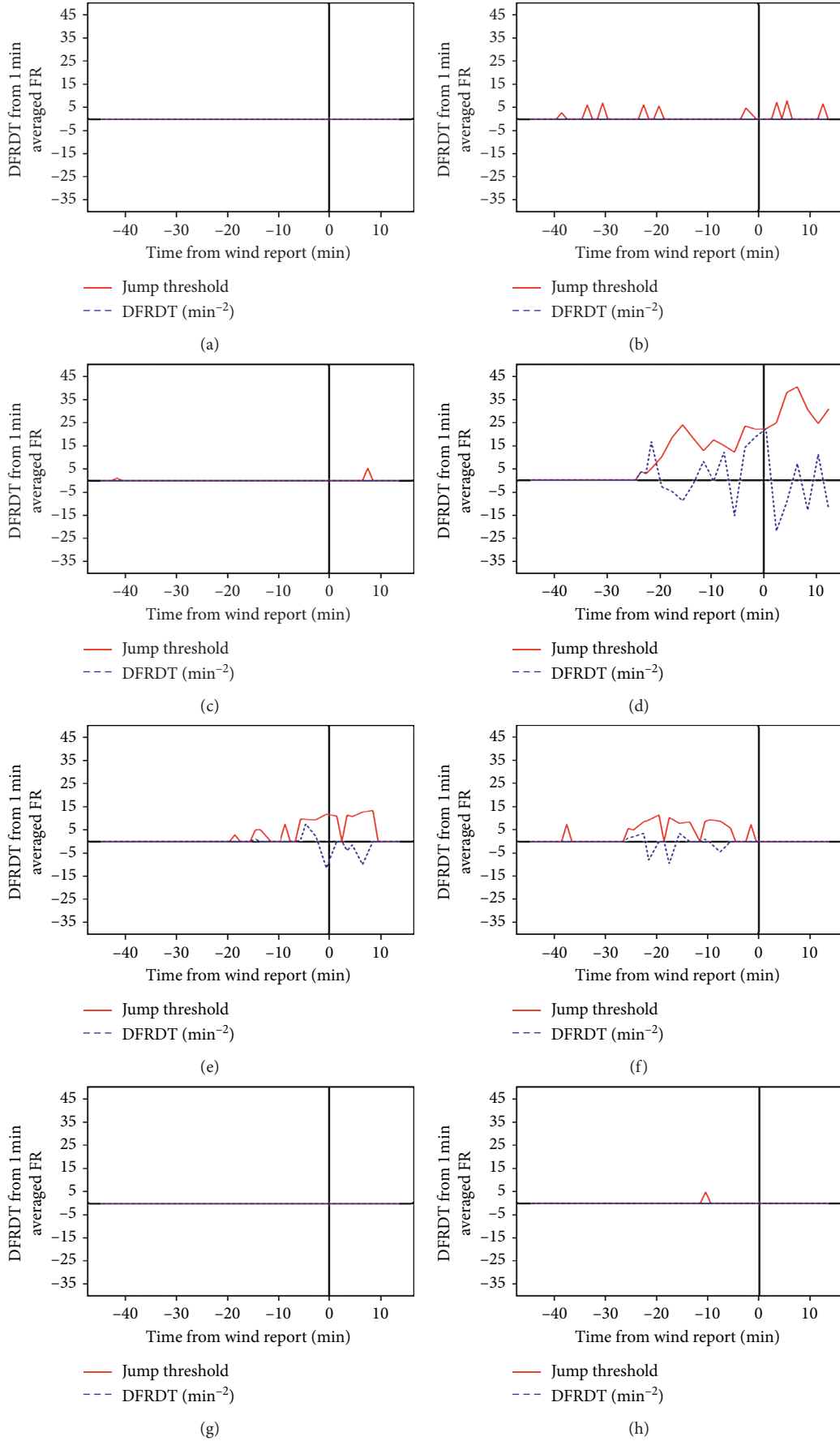


FIGURE 8: Plots of total lightning using the Schultz et al. [25]  $2\sigma$  analysis for the eight null cases. (a) 20120724 total lightning. (b) 20130624 total lightning. (c) 20140703 total lightning. (d) 20150612 total lightning. (e) 20150623 total lightning. (f) 20150630 total lightning. (g) 20150803 total lightning. (h) 20160701 total lightning.

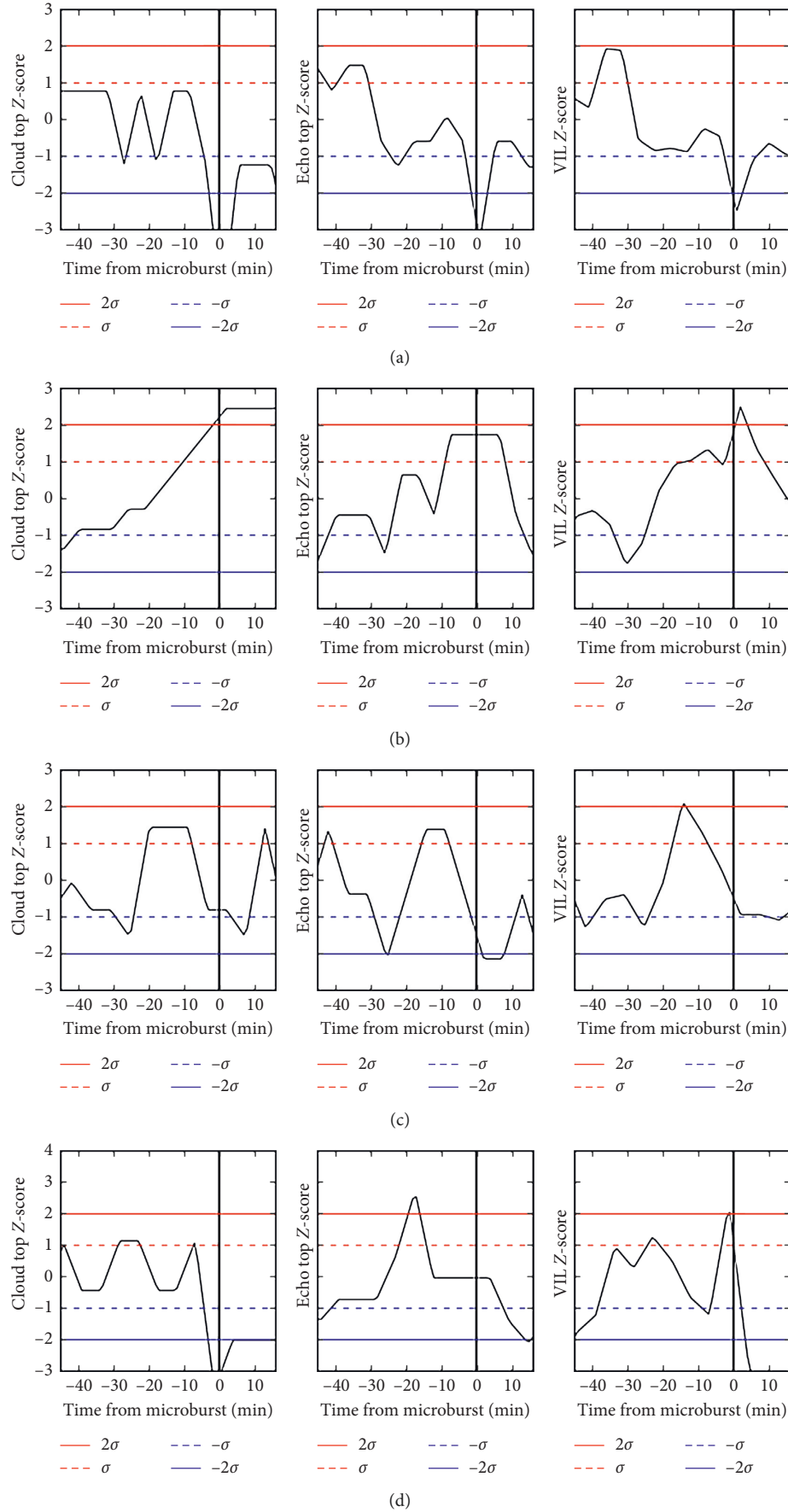


FIGURE 9: Radar parameters—cloud top, echo top, and VIL—for the first four microburst cases. (a) 20120724 microburst. (b) 20130624 microburst. (c) 20140703 microburst. (d) 20140708NY microburst.

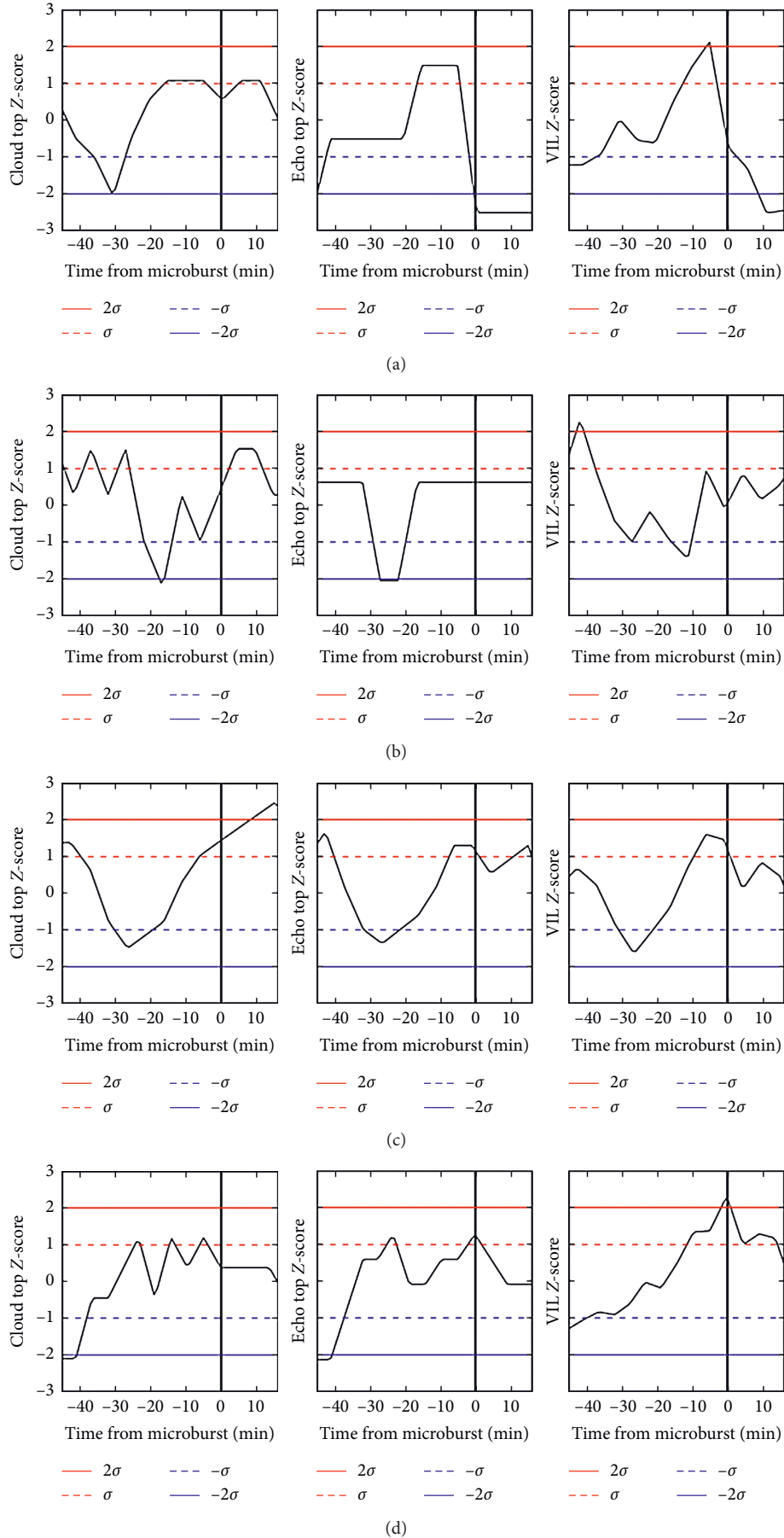


FIGURE 10: As in Figure 9, except for the next four cases. (a) 20140708PA microburst. (b) 20150612 microburst. (c) 20150623 microburst. (d) 20150630 microburst.



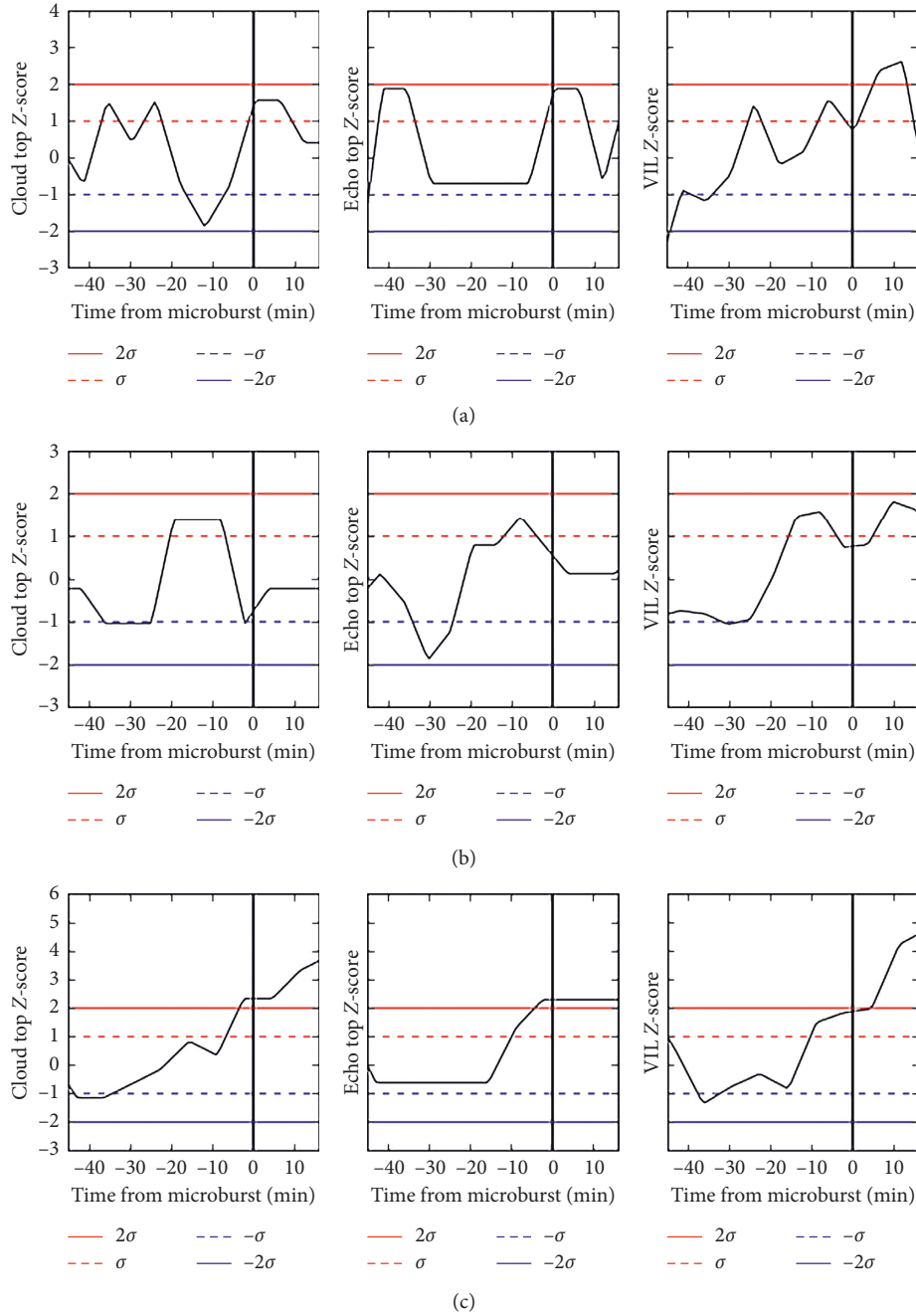


FIGURE 11: As in Figure 9, except for the last three cases. (a) 20150803 microburst. (b) 20160616 microburst. (c) 20160701 microburst.

another mechanism is generating IC lightning peaks in some of these cases. IC lightning was found to peak within 25 minutes before the microburst in six of eleven microburst cases but only in one of eight null cases. This suggests that the process of downdraft dominance is more common in microbursts than in severe wind events, and detection of a peak in IC lightning in real time may distinguish potential microburst scenarios from less dangerous, ordinary severe wind events.

The transition from strong updraft to strong downdraft is accompanied by a transition in lightning from IC to CG lightning [2]. CG lightning forms as particles rapidly

descend, collide, and build up charge as a result of a storm's downdraft [15]. A sharp decrease in IC lightning activity and increases in cloud-to-ground (CG) lightning strikes indicate the downdraft is overcoming the updraft. Kane [4] found that increasing CG lightning occurred about 10 minutes before a downburst in the northeast. In the present study, peaks in IC and CG lightning did not behave as consistently as the literature might suggest. Rather than a transition from an IC lightning peak to a CG lightning peak, in three microburst cases, CG lightning presaged the IC lightning, and in three more microburst cases, their peaks occurred during the same five-minute window.

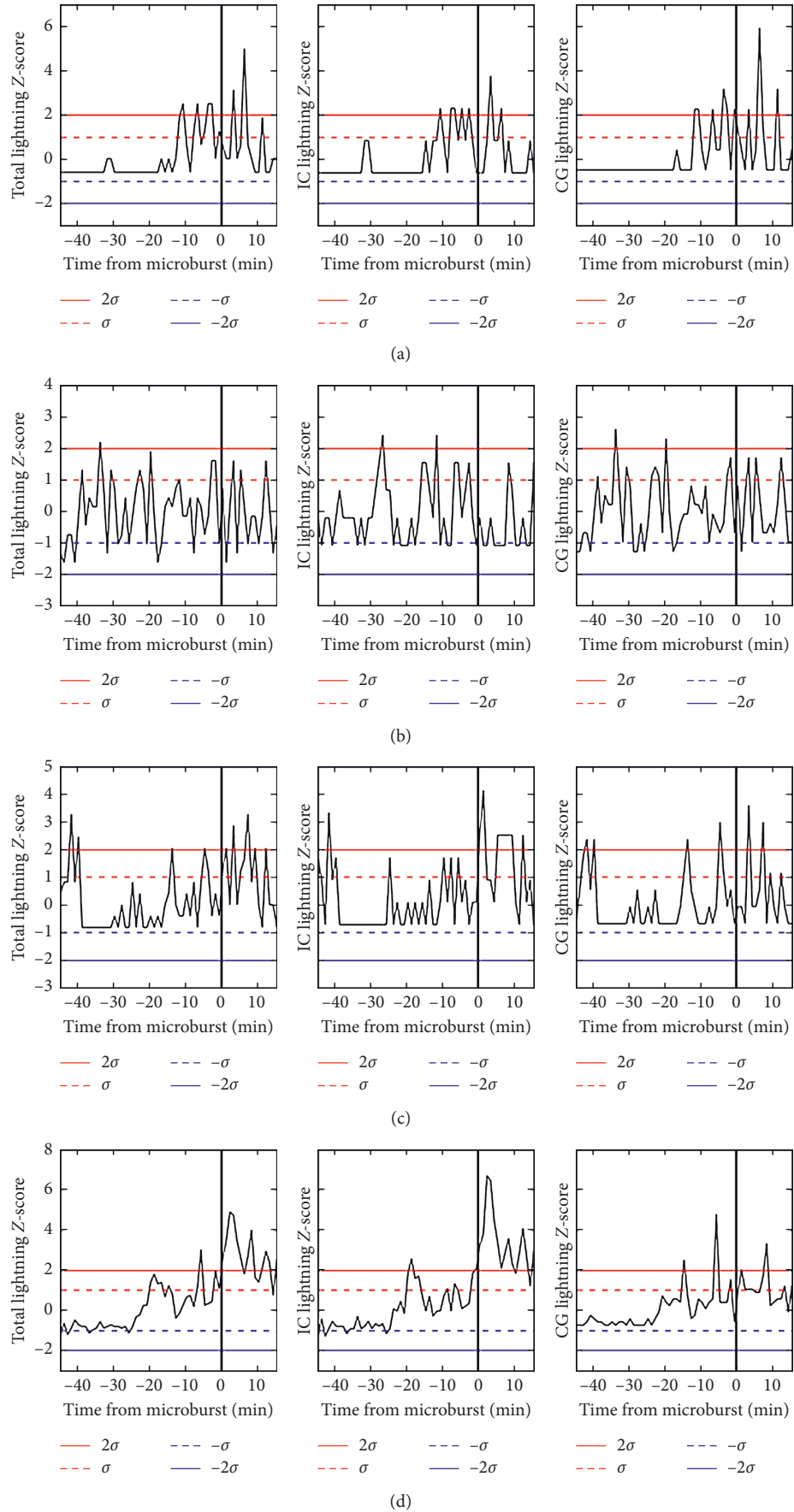


FIGURE 12: Plots of total lightning, IC lightning, and CG lightning for the first four severe wind cases. (a) 20120724 null. (b) 20130624 null. (c) 20140703 null. (d) 20150612 null.

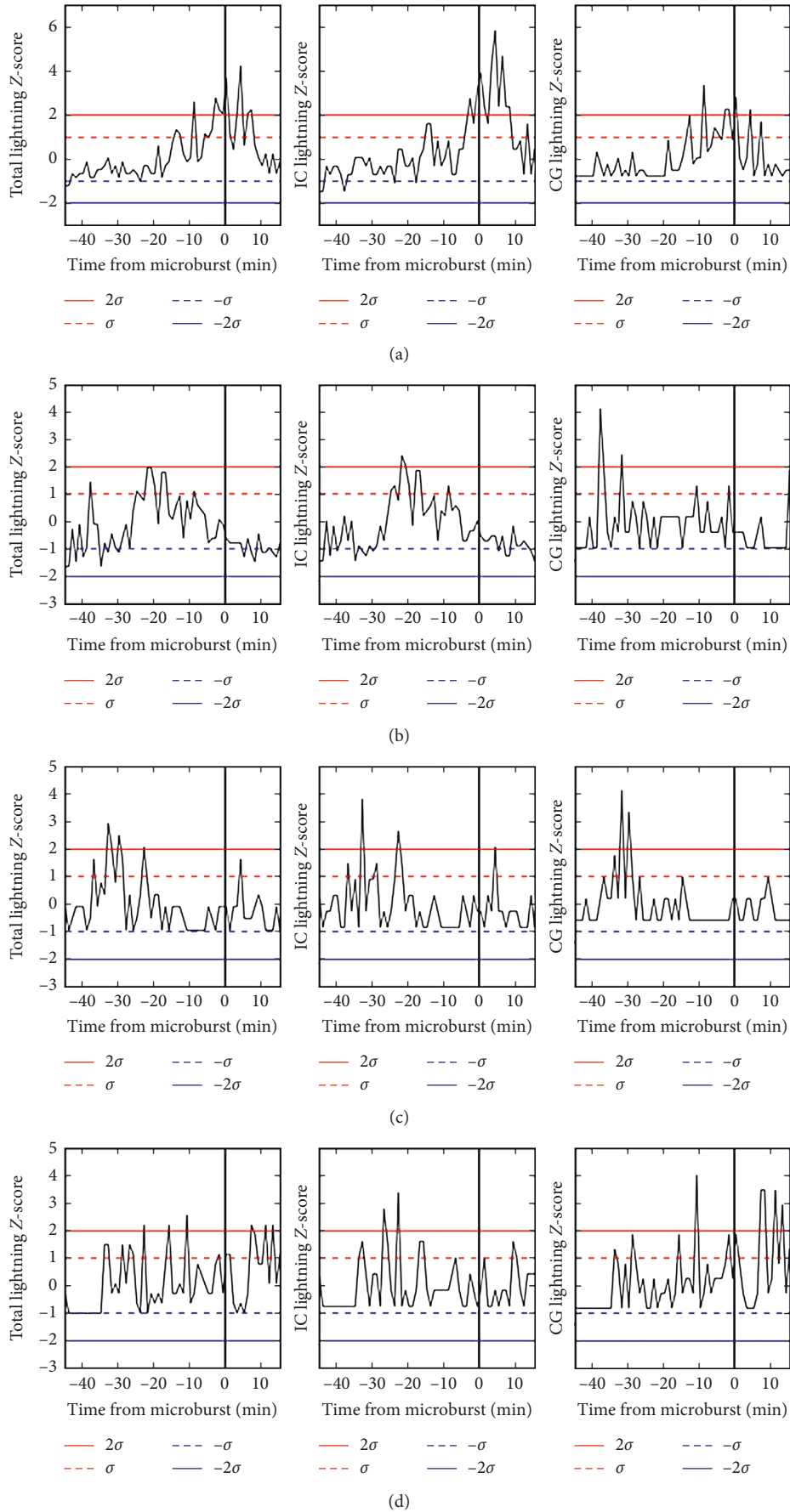


FIGURE 13: As in Figure 12, but for the last four severe wind cases. (a) 20150623 null. (b) 20150630 null. (c) 20150803 null. (d) 20160701 null.



TABLE 4: Time of  $2\sigma$  maxima of each parameter with respect to the severe wind report.

Date	Total ltng. (minutes)	CC (minutes)	CG (minutes)	VIL (minutes)	Cloud top (minutes)	Echo top (minutes)
20120724	+6	+3	+6	+1	N/A	N/A
20130624	-34	-12	-34	+13	+13	N/A
20140703	+7	+1	+3	+1	N/A	0
20150612	+2	+2	-6	+6	N/A	N/A
20150623	+4	+4	-9	N/A	N/A	N/A
20150630	-21	-22	-2	+5	+6	N/A
20150803	-33	-33	-32	-31	+15	-5
20160701	-11	-23	-23	+15	-31	-3
Mean/SD	-8.4/18.1	-10.0/14.5	-10.6/14.9	1.4/15.3	-3.3/24.4	-2.7/2.5

Negative numbers indicate before the report, and positive numbers indicate after the report. N/A indicates maximum value was less than  $2\sigma$ .

Metzger and Nuss [10] found that severe wind events tend to be characterized by increasing CG strike rates. However, in eight of eleven microburst cases in the present study, CG lightning was decreasing or steady at the time of the microburst. They also found that IC lightning was increasing in two-thirds of wind cases and decreasing or steady in one-third of wind cases. This ratio was lower in the present study, with six cases increasing and five cases decreasing or steady. The severe wind events from the present study contained five of eight events with increasing CG lightning and four of eight events with increasing IC lightning. It appears that decreasing CG lightning behavior may distinguish microbursts from many more ordinary severe wind events.

Metzger and Nuss [10] also examined radar parameters (VIL, VIL density, and 55 dBZ height) and determined that two of these parameters must decrease by a certain threshold for severe wind events. For microbursts in the present study, VIL and echo tops were decreasing for six of twelve cases, while cloud top height was increasing for six of twelve cases. The behavior of echo tops was quite different in the severe wind cases, where they were found to be decreasing at the time of the event for six of eight cases. VIL was decreasing for four of the eight cases, and cloud tops were increasing for four of the eight cases. In short, our study suggests that the particular radar parameters' behavior is too erratic to make robust conclusions.

Five out of eleven microburst cases and five out of eight null cases had more CG lightning strikes than IC lightning flashes (Tables 5 and 6). The null events did not all fall on the same day as the microbursts, suggesting that there can be appreciable differences in the IC:CG ratio from storm to storm. The analysis of the IC:CG ratio is complicated by the very different DEs of IC and CG lightning by the Vaisala network. In reality, IC lightning is likely much more common than these data suggest, owing to its 50% DE. Correcting for this deficiency would likely lower the IC:CG ratios appreciably. Severe storms have been found to typically have higher IC flash rates than CG lightning strikes [27]. However, Boccippio et al. [28] found anomalously low ratios of IC:CG flashes around the Appalachian Mountains. This anomaly has been attributed to differences in storm morphology over the Appalachian Mountains and elevation differences [28]. Murray and Colle [29] further discuss how convection is favored on the leeward side of the

TABLE 5: Summary of IC:CG and CG+:CG- ratios for microburst events.

Date	IC:CG	CG+:CG-
20120724	0.67	0.29
20130624	0.25	0.19
20140703	0.87	0.66
20140708NY	2.01	0.88
20140708PA	2.07	0.67
20150612	0.32	1.39
20150623	1.69	2.36
20150630	8.16	1.34
20150803	0.94	1.20
20160616	3.63	0.60
20160701	0.34	1.04

TABLE 6: Summary of IC:CG and CG+:CG- ratios for null severe wind events.

Date	IC:CG	CG+:CG-
20120724	0.64	0.22
20130624	0.25	0.19
20140703	1.03	1.19
20150612	2.79	0.81
20150623	1.80	1.39
20150630	4.66	2.38
20150803	2.10	0.39
20160701	0.65	1.16

Appalachians in the evening, when the majority of microburst and null cases occurred.

Five microburst cases and four null cases had more CG+ lightning than CG- lightning. Three dates—20150623, 20150630, and 20160701—had more CG+ lightning for both the null case and the microburst case. In general, CG+:CG- lightning ratios were closer to one than IC:CG ratios. This disputes the results of previous studies. For example, Carey et al. [30] found that the eastern United States sees predominantly negative lightning nearby severe weather (large hail and tornadoes) regions more often than in other regions of the country.

## 5. Conclusion

This study examined quasi-cellular microburst activity and concurrent wind damage events in the Northeast U.S.,

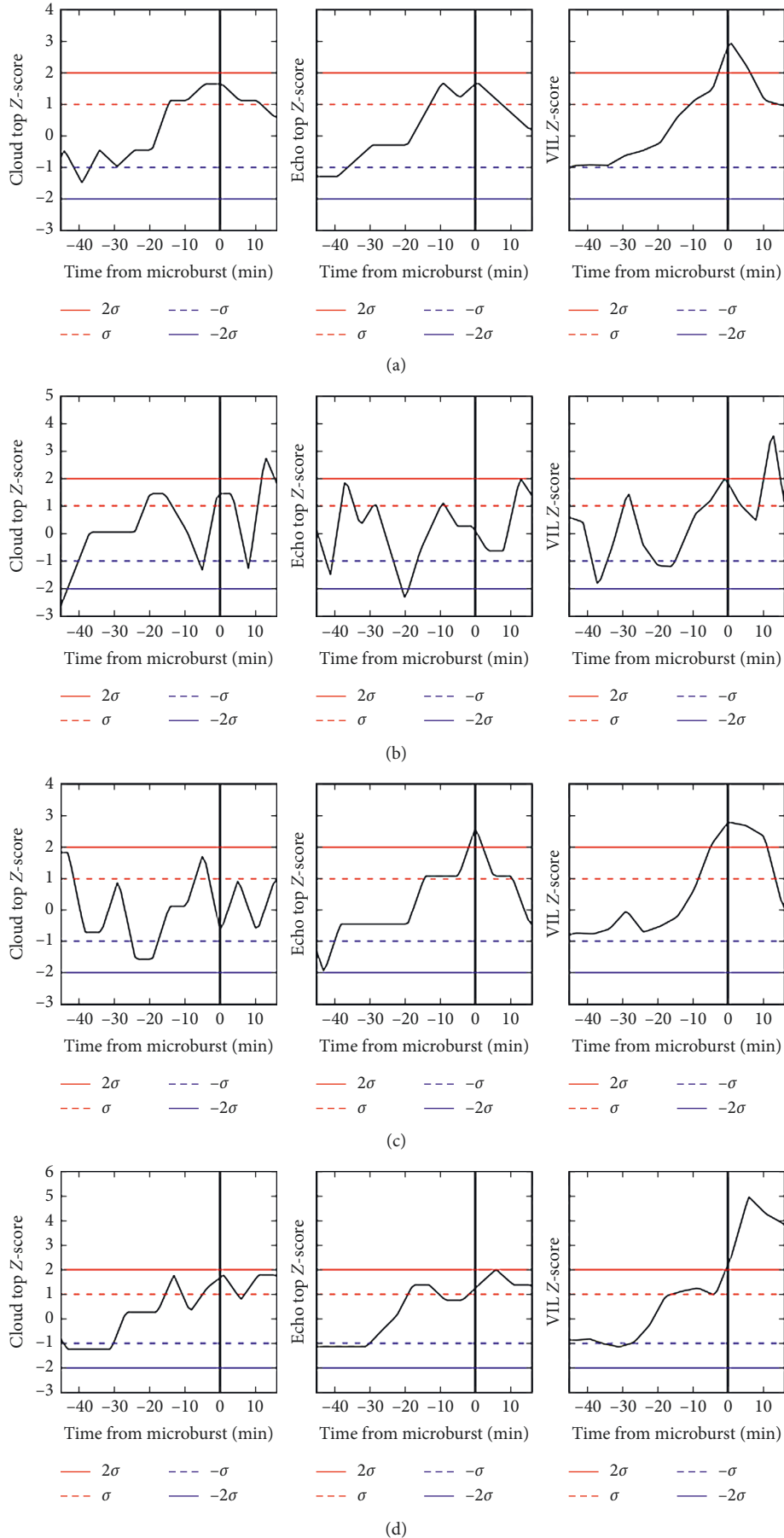


FIGURE 14: Radar parameters—cloud top, echo top, and VIL—for the first four severe wind cases. (a) 20120724 null. (b) 20130624 null. (c) 20140703 null. (d) 20150612 null.

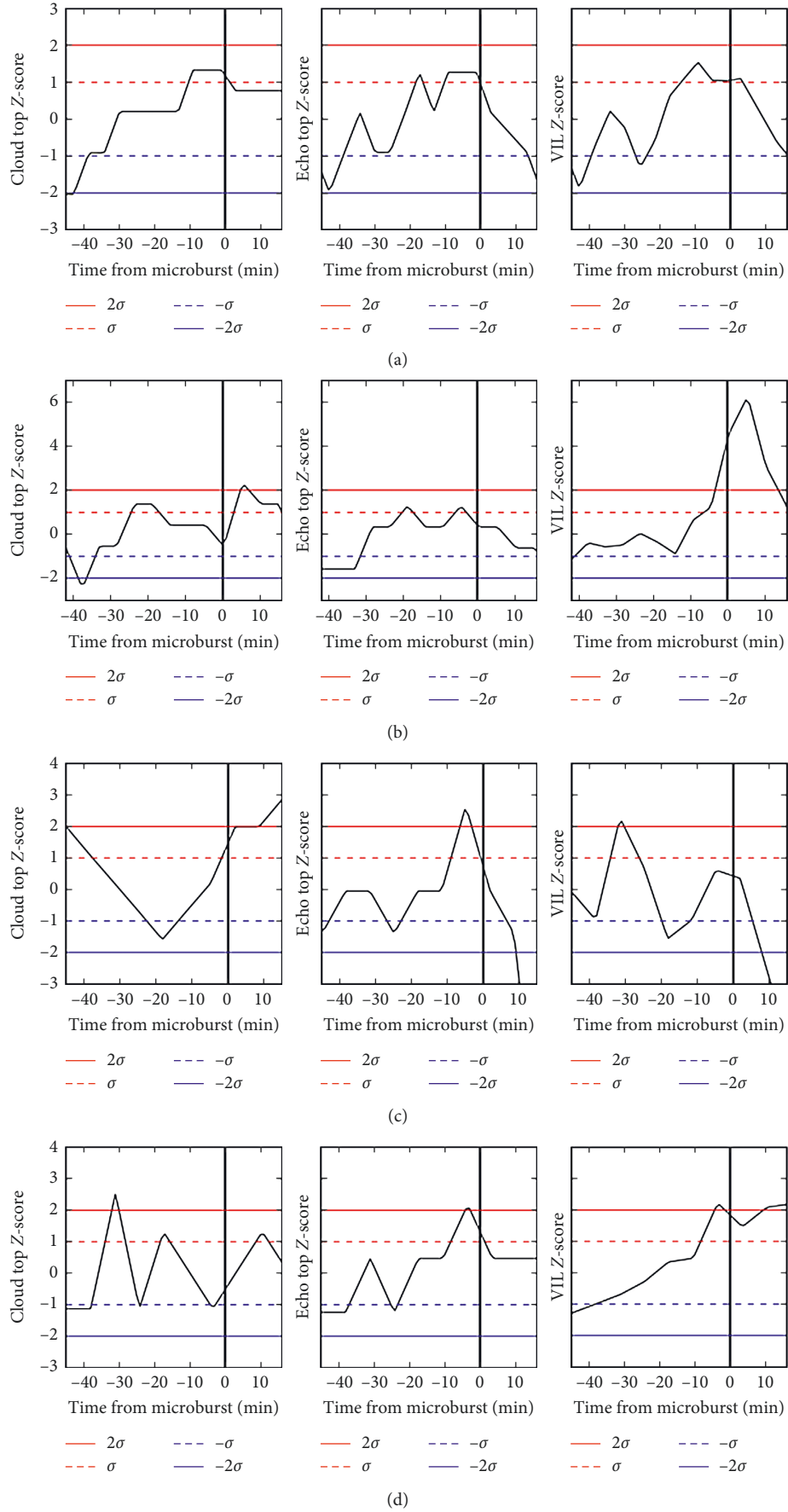


FIGURE 15: As in Figure 14, but for the last four severe wind cases. (a) 20150623 null. (b) 20150630 null. (c) 20150803 null. (d) 20160701 null.

seeking precursor signals for microbursts in the radar and lightning data and looking to determine the likelihood of false alarms. Standard deviations relative to the mean of the 45 minutes prior to microburst or severe wind report were used to determine whether lightning and radar parameters peaked prior to microburst or wind damage occurrence. Total lightning was the best-performing variable, with six of eleven cases showing a peak within 25 minutes before the microburst. IC lightning peaked within 25 minutes before the microburst six times, and CG lightning peaked within this same time window five times. The  $2\sigma$  requirement for a “peak” eliminated echo top and cloud top from consideration most of the time. VIL peaked at the time of the microburst or within fifteen minutes before the microburst in four of eleven cases. The null events showed erratic lightning behavior, with no peaks within 10 minutes of the microburst for either total or IC lightning. CG lightning provided some predictive values for the null cases, peaking within eleven minutes of the severe wind report in four of eight cases. VIL often peaked after the wind damage (six of eight cases). As in the microburst cases, cloud top and echo top were eliminated from more than half the cases as they failed to produce a  $2\sigma$  peak. The “ $2\sigma$ ” algorithm from Schultz et al. [25] was adopted, and lightning jumps were less common than using a static  $2\sigma$ , with only three microburst cases and one wind case experiencing a lightning jump before the event.

While the overall mean of these variables suggests that the variables peak with several minutes of lead time to predict microbursts, there is a large amount of variability about the mean. The results call some findings of previous studies into question, at least for the region of study. First, there was wide variability in the timing of lightning and radar parameter microburst peaks, spanning nearly the entire 60-minute window examined in this study. Relying on peaks in the parameters alone may generate early, false warnings in some cases and may cause late warnings or no warning at all in other cases. Second, previous studies have suggested that IC lightning peaks preceded CG lightning peaks. This was true for less than half of the cases in this study. Instead, CG peaks preceded IC peaks in three cases, and the two peaked nearly simultaneously in three other cases. And finally, peaks had been observed in the Southeast U.S. in cloud height and echo tops prior to declines in these parameters. In the present study, echo tops and cloud height were typically constant before declining, leading to a lack of  $2\sigma$  peaks.

The results of this study offer important implications for weather forecasters. Radar parameters are less consistent than lightning as short-term predictors of microburst activity, although the timing of peaks in VIL seems to discriminate fairly well between microburst and null events. In some portions of the Northeast U.S., beam blockage becomes an issue, limiting the availability of radar data. Lightning as a forecast and verification tool may provide insight into where radar data are absent, but the inconsistency of lightning peak timing relative to microburst time complicates the use of lightning data in the absence of radar data.

## Data Availability

The radar and TITAN data used to support the findings of this study are available from the corresponding author upon request. The lightning data may be obtained directly from Vaisala.

## Disclosure

Amanda L. Burke is currently at the Department of Atmospheric and Geographic Sciences, University of Oklahoma, 120 David L Boren Blvd., Norman, OK, USA. This work was presented at the 29<sup>th</sup> Conference on Severe Local Storms in Stowe, Vermont.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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