# Defining a Severe Weather Event

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ABSTRACT

Weather radar observations were used to create a definition for a severe weather 'event.' Radar reflectivity was used as a proxy for storm strength. Contours of maximum radar reflectivity above a critical threshold were grouped into clusters forming a single event according to distance and minimum area thresholds. Results indicate that the current insurance industry standard catastrophe event definition neglects sparely populated areas that are impacted by the same systems that are responsible for declared catastrophes. The use of an objective definition derived from radar data can better deliniate the geographic and temporal extent of catastrophe events for use in insurance applications. Two examples of such events are shown using a proposed radar-based method.

# 1. Introduction

Defining what constitutes a single severe weather event is an issue of critical important to insurers and reinsurers. When an insurer issues a policy it assumes a liability up to an agreed coverage limit from a single event. If the insured suffers a loss above the prescribed limit, the insurer's liability is capped. However, if the insured suffers losses from two separate occurrences within a short period it effectively enjoys double the coverage. If no clear definition of an event exists in advance, a protracted legal struggle can follow in which large sums of money are at risk. A well-known example of such an ambiguity is the loss of the World Trade Center on 11 September 2001. The leaseholder of the World Trade Center claimed that the loss the twin towers constituted two separate "occurrences" whereas the insurers maintained that the day's events constituted a single attack from a coordinated group (Hiles 2007).

From the perspective of weather losses, a similar situation can be imagined wherein a single geographic area suffers losses on consecutive days from severe thunderstorms. Do these two (or more) thunderstorms in a short period of time constitute two (or more) separate events or one weather system? In order for an insurance company to offload its severe weather exposure to a reinsurer or catastrophe bond market, it is important to create an objective method to resolve this question.

The current industry standard trigger for the payment of reinsurance policies is to use a catastrophe definition provided by a neutral third party, such as the Property Claim Services (PCS) unit from Insurance Services Office, Inc. (ISO). PCS defines a catastrophe as a high-impact event that causes at least $25 million of insured losses. For each catastrophe event, PCS manually drafts and issues a summary of estimated insured property losses, impacted states, and dates included. In this paper we propose an objective method to define the spatial and temporal extent of catastrophe events caused by warm-season severe weather that can be coupled with reported losses for use in reinsurance bonds and policies.

In order to be accessible to the end user, a severe weather event definition must be:

- Objective —based on easily measured, quantifiable metrics
- Automated —evaluated daily with no human intervention
- Simple —easily understood by the customer
- Of well-defined scope —clear in what is and is not included

There are several potential sources of meteorological information to use in crafting a severe weather event definition. Potential definitions could be based on active and passive satellite sensors, ground-based radar, lightning strikes, spotter reports, weather advisories, and model-derived quantities. In order to satisfy the above requirements we choose to craft our event definition based on publicly available weather radar data. The general public is very familiar with weather radar as they are exposed to radar images on a daily basis. In the modern computing era the average consumer has instant access to weather radar images through their computers and phones. We seek to utilize the public's existing familiarity to build an objective event definition.

The choice of radar data for use in defining a severe weather event has several advantages. Radar provides an objective measure of storm strength and location. Detailed geographic and temporal information can be derived for individual storm cells. Derived hail and rainfall products are also available for future use. Modern Weather Surveillance Radar - 1988 Doppler (WSR-88D) data is available back to 1992 to develop a full climatology. Unfortunately radar reflectivity is not directly connected with storm damage. Weaker storm systems, especially those occurring during the winter associated with frontal cyclones, can still cause extensive damage yet not show up as severe on radar.

While the public may be unfamiliar with the details of how meteorological radars work, anyone can identify a thunderstorm on a radar image. Courtesy of color scaling of radar reflectivity, consumers simply look for the warm colors in a radar image. Similarly by thresholding for a minimum critical maximum composite reflectivity (MCR) we will isolate only the strongest updrafts. By then associating the selected radar echoes on the basis of Euclidian distance we identify geographic areas as being impacted by distinct events.

In Section 2 we discuss the source and processing of the weather radar data. We develop and objective event definition in Section 3 and present two case studies comparing our definition to PCS in Section 4. Finally our results and conclusions are discussed in Section 5.

## 2. Data processing

As we are seeking to develop an event definition that can track systems across the continental United States of America (CONUS), we require radar data with continental coverage. For our purposes we use the National Mosaic and Quantitative Precipitation Estimates (NMQ) system from the National Severe Storms Laboratory (NSSL) as a source of radar data mosaicked over the CONUS. NMQ data is provided on a 0.01° Cartesian grid which corresponds to roughly 1 km spatial resolution with 5 minute temporal resolution. Raw radar data is sourced from a national network (Fig. 1) of WSR-88D, Terminal Doppler Weather Radar (TDWR), and Canadian radars (Crum and Alberty 1993; Turnbull et al. 1989; Joe and Lapczak 2002). The raw radar data is then projected onto a 3D Cartesian grid and mosaicked following the methodology of Zhang et al. (2005). NSSL provides the radar data on the NMQ domain that is divided into eight adjoining tiles (Fig. 1). Before processing the radar data we first stitch together the eight tiles into one large CONUS domain.

During preliminary development of our event definition, it became clear that the NMQ radar data is not free of quality control issues. Multiple cases of a speckled clutter pattern were found to contaminate the radar returns. An example from the KPIX radar in central California on 3 June 2009 is shown in Figure 2 where strong ($>$ 60 dbZ) echoes are found throughout the radars domain with the strongest along the periphery. The KPIX radar is operated by a commercial TV station (KPIX-TV) and is operationally ingested by NSSL per the request of the Monterey, CA forecast office of the National Weather Service to supplement WSR-88D coverage of the Russian River watershed northwest of San Francisco Bay (Hondl 2009).

Contamination like that shown in Figure 2 was not limited to the KPIX radar. Another example (not shown) was found in the Elko, NV, WSR-88D on 1 February 2011. In our event definition presented in Section 3 each of these speckles would be identified and processed as a separate feature. While ground clutter is a common problem with radar data, the strength and widespread distribution of these anomalies makes them especially troublesome. Accordingly, this contamination pattern must first be removed before processing. One possible technique for identifying contaminated time periods is the using an index based upon the non-zero composite reflectivity variance (Fig. 3). Due to its use of variance, this criterion is not sensitive to low-amplitude clutter. The removal of this clutter is left as an open issue for the radar processing experts at NSSL in the upstream data before including into the NMQ data.

## 3. Defining an event

For our purposes we seek to define severe weather events over the timescale of a day (from 1200 UTC to 1200 UTC) that corresponds with the same period used by the Storm Prediction Center to aggregate spotter reports. Using this time window, we calculate the MCR at any of the 5-minute intervals over the course of the day and use this MCR as a proxy for storm strength. An example of the MCR for 20 July 2009 is shown in Figure 4. To identify individual storm cells the MCR data is contoured in 5 dbZ increments and converted to polygons. A centroid, enclosed area, and unique identifying number (ID) are calculated and saved as attributes of each polygon. A minimum MCR threshold of $Z = 65$ dbZ was taken to be indicative of severe weather.

To combine individual cells into meso-alpha scale systems we iteratively merge cells within some to critical distance, $D$, to form events that share the same ID. If the centroids of two contours are within $D$ of each other, then we set their ID to the lower of the two values. This process is iterated until no IDs change. All clusters whose total enclosed area is below a minimum value, $A$, are neglected. If any cluster lies within $D$ of a cluster from the preceding day then those two clusters will share an ID. Examples of the results of this process with $D$ = 50-200 km and $A$ = 10 km$^2$ applied to 20 July 2009 are shown in Figure 5. Differing values of $D$ should be used based upon what features the user desires to capture. A value of $D$ = 100 km isolates the swaths of individual convective systems. A value of $D$ = 200 km isolates regional groups of storms with similar forcing characteristics.

In order to merge storm clusters that are associated with the same synoptic scale frontal cyclones, we can use analyzed frontal boundaries and treat them as pseudo-observations. This has the benefit of combining clusters that are associated with elongated frontal boundaries that drape across the continent. This is demonstrated for 20 July 2009 in Figure 6 using frontal analyses archived by the National Climatic Data Center. This technique successfully combines the storms associated with frontal boundaries while not drawing in isolated convection away from the front.

To focus on just the cores of the severe events and thus eliminate isolated cells on the periphery of a cluster, we employ a two-step merger (Fig. 7). For the first pass we merge clusters with $D$ = 100. With the local clusters formed (see Fig. 5b) we can then neglect as small clusters based upon our choice of $A$, 100 km$^2$ in this case. We then merge the remaining large clusters using $D$ = 200 km. This two-step process cleanly identifies just the hardest impacted area and makes provides us with the spatial limits of our event definition.

# 4. Case studies

## *a. 16 - 21 July 2009*

There were two PCS catastrophes related to severe weather in the Great Plains in mid-July 2009. The first event was declared 16 - 20 July 2009 with scattered damage in Texas and Oklahoma. The second, higher-impact event was declared for 20 - 21 July 2009 for just Colorado due to a severe hail storm that directly impacted the greater Denver area.

The July 2009 PCS events are presented in Figure 8 using the same two-step method as used to generate Figure 7. The time-series shown in Figure 8 was generated over a number of days and allows for carry-over of IDs between subsequent days. The outlined frontal boundaries are presented only for reference. By using the two-step process over a number of days we eliminate the need for manual frontal analyses as cells with common ancestry are combined into one event. By not using frontal boundaries we maximize objectivity and minimize dependence on extra data sources whose availability may be questionable in the future.

Both of the July 2009 PCS events are shown to be associated with the same stagnant frontal boundary draped across the CONUS. This is a very typical pattern that is commonly observed at mid-latitudes. The presence of persistent frontal boundaries minimizes the utility of frontal analyses in an event definition as the fronts tend to link together storm systems over very large distances.

The two-step method clearly links together the proper extent of convection over the Great Plains while still indicating separate, but significant, events such as the monsoon convection over Arizona on 17 July 2009, the diurnal convection over Florida on 19 July 2009, the weak frontal passage over Minnesota on 21 July 2009, and the cold front passage in the Northeast and Mid-Atlantic on 16 - 17 July 2009. However, there is less justification for separating the two discrete events declared by PCS. Both events were focused along the same stagnant frontal boundary and temporally overlapped by one day. The only synoptic difference between the two events was the involvement of a new cold front and upper-level trough coincident with the Colorado event.

The spatial extent of both PCS events seems to be biased to just states where densely populated areas were impacted. Severe thunderstorms caused widespread damage reports in the central and northern Great Plains, but were omitted from the PCS event as there was not much insured property damaged. However, these areas were clearly impacted by the same severe outbreak.

### *b. 10 - 16 May 2010*

The influence of stagnant frontal boundaries was also present during mid-May 2010 when there were two PCS catastrophes separated by a single quiet day. The first event on 10 May 2010 was declared for Kansas and Oklahoma. Two days later the second event was declared 12 - 16 May 2010 for Illinois, Maryland, Oklahoma, Pennsylvania, and Texas.

The radar summary presented in Figure 9, using the same technique as that in Section a, reveals that the two PCS events were focused along a common frontal boundary. On 11 May 2010 the quieter pattern barely allows the event ID in our technique to carry over between PCS events. This carry-over could easily be enable or disabled by tuning the minimum area threshold, $A$. Whether or not differentiating between the two PCS events is desired is subjective matter of preference left up to the user.

The non-contiguous geographic extent of the 12 - 16 May 2010 PCS event is questionable given the radar observations. Strong convection is observed along the entire frontal boundary across the eastern 2/3 of the CONUS. There appears to again be a sampling bias in the PCS geographic definition. Illinois, which was included, shows almost no MCR of $Z \geq 65$ dbZ. Conversely, many states that did see widespread MCR of $Z \geq 65$ dbZ were not included in the PCS event. Using radar observations we can better quantify the spatial coverage of several weather outbreaks and provide a more accurate geographic area for inclusion in catastrophe events.

The temporal limits of severe weather events are difficult to constrain, both in the start as previously discussed and in when to terminate the event. As is evident in Figure 9, strong convection remains across much of the South after the end of the PCS catastrophe declaration. The same stagnant frontal boundary remains draped across the CONUS for two weeks (not shown) until May 22 when a new front sweeps through the region and initiates a new PCS event in Colorado, Nebraska, South Dakota, and Wyoming. A potential temporal limit to the extent of an event remains a subjective question that requires a more intensive climatological study after an appropriate radar quality control algorithm is implemented.

## 5. Discussion and conclusions

An objective method to define warm-season severe weather events was developed using NMQ MCR data for the CONUS. A MCR threshold of $Z \geq 65$ dbZ was found to be optimal for warm-season severe weather events. Cold-season severe weather outbreaks, which often feature weak tornadoes forced by baroclinic systems, require a lower MCR threshold. Before processing the NMQ data, a careful quality control is needed to account for a small number of cases with strong and pervasive noise and clutter.

MCR contours were grouped according to the distance between their centroids to merge severe weather events. A critical distance of $D = 100$ km groups together echoes from mesoscale convective systems or swaths from long-lived supercells. A distance of $D = 200$ km effectively merges radar echoes associated with a meso-alpha scale weather system. Neglecting MCR clusters with a total area below a minimum threshold, $A$, eliminates isolated cells that are not large enough to have impacts that are significant to insurers or others with national interests. Systems were allowed to carry over their ID if there was any spatial overlap between immediately subsequent days.

If the end user would like to group together all events forced by nearly continuous frontal boundaries then the frontal analyses can be used as pseudo-observations using the same clustering technique. Using frontal boundaries as pseudo-observations results in connecting radar observations on a continental scale. These widespread events can persist for weeks due to weak frontal boundaries that stagnate across the continent. While this technique may successfully associate weather events into large-scale regime patterns, it is less effective at isolating outbreaks on daily timescales.

In order to include the full scale of severe weather outbreaks while neglecting outlying storms, we proposed an event definition that uses a two-step process to merge MCR contours associated with severe weather events. In the first step MCR contours of $Z \geq 65$ dbZ were grouped with a mesoscale choice of $D = 100$ km. Small clusters with $A < 100$ km$^2$ were neglected. The remaining larger clusters were then merged using $D = 200$ km. The resulting grouping successfully associated nearly continuous frontal systems while separated outbreaks separated by hundreds of kilometers. This two-step method could be further refined for use an objective alternative to current catastrophe event definitions used in the insurance industry. This method was demonstrated for two severe weather catastrophe events.

Using the two-step event definition we showed the two partially contemporary PCS catastrophe events of mid-July 2009 to be associated with the same stagnant frontal boundary. This suggests that two events could justifiably be combined. At the very least, the storms observed in the central Great Plains on 20 July 2009 should have been included in the PCS event that was limited to Colorado. Similarly the May 2010 PCS definition was shown to miss significant areas of the South and Appalachia that were impacted by severe weather. This example also raises the question of how long to continue to declare an event when a frontal boundary stagnates across the continent. The separation of the 10 May 2010 and 12 - 16 May 2010 PCS events by a single relatively quiet day calls focus to the importance of carefully selecting the minimum area threshold, $A$, to terminate events on quiet days.

*Acknowledgments.*

The authors would like to thank NSSL for providing the NMQ radar mosaics.

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# List of Figures

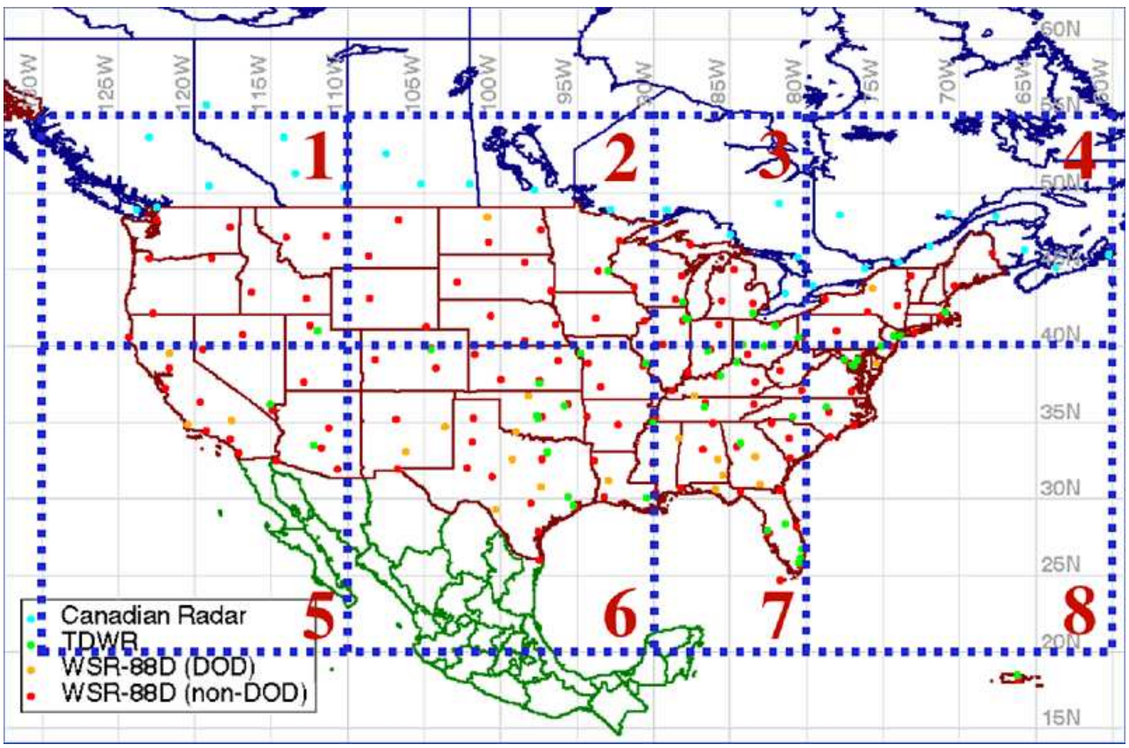


FIG. 1. The NMQ radar domain. The dots correspond to radar locations with the colors corresponding to the type of radar. Figure from QVS (2011).

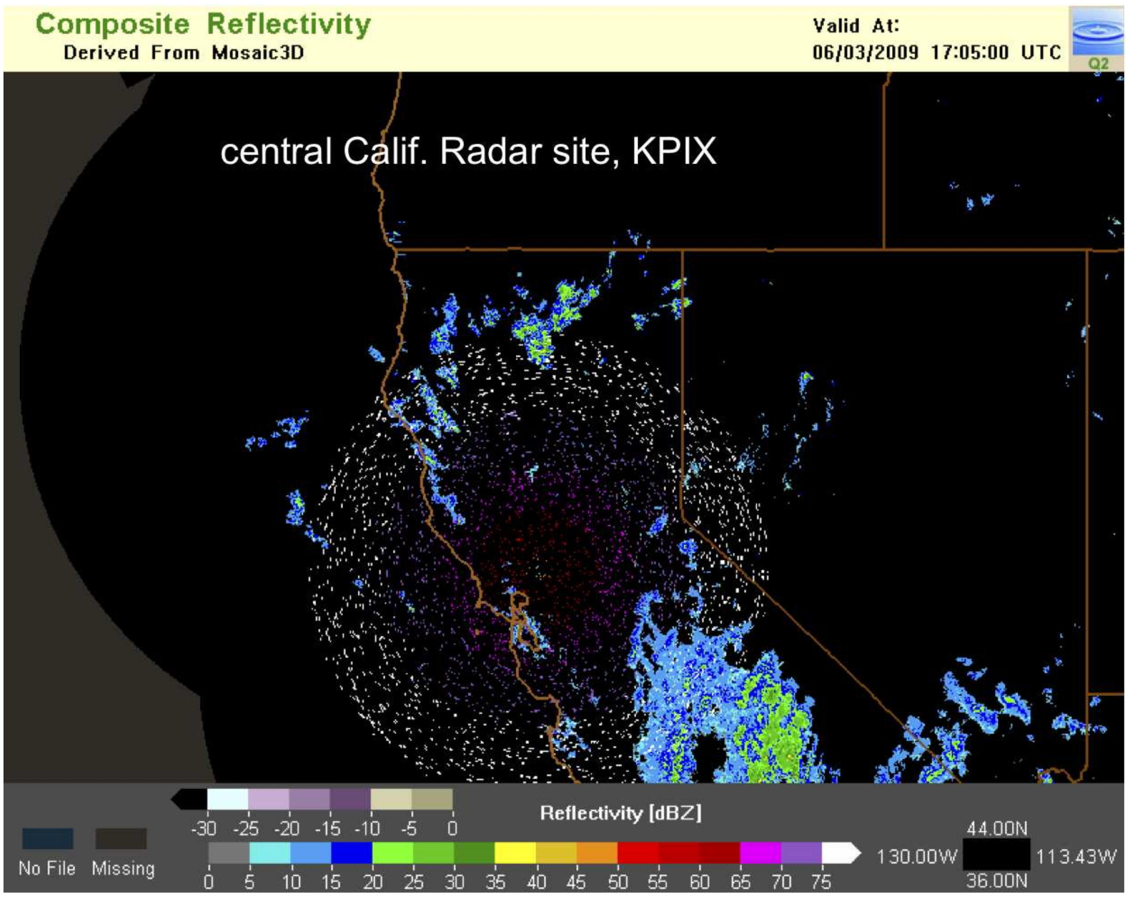


FIG. 2. Composite reflectivity from the KPIX radar showing an example of a speckled clutter pattern with very high reflectivity values.

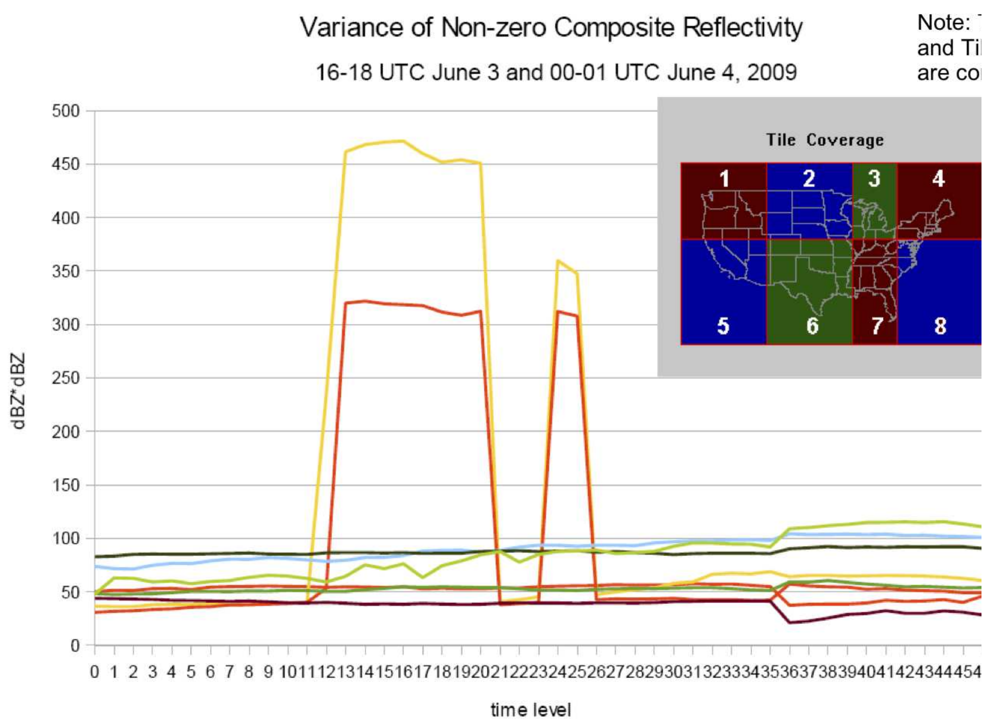


FIG. 3. Non-zero composite reflectivity variance for a contaminated period at the KPIX radar. The line color corresponds to the NMQ tiles.

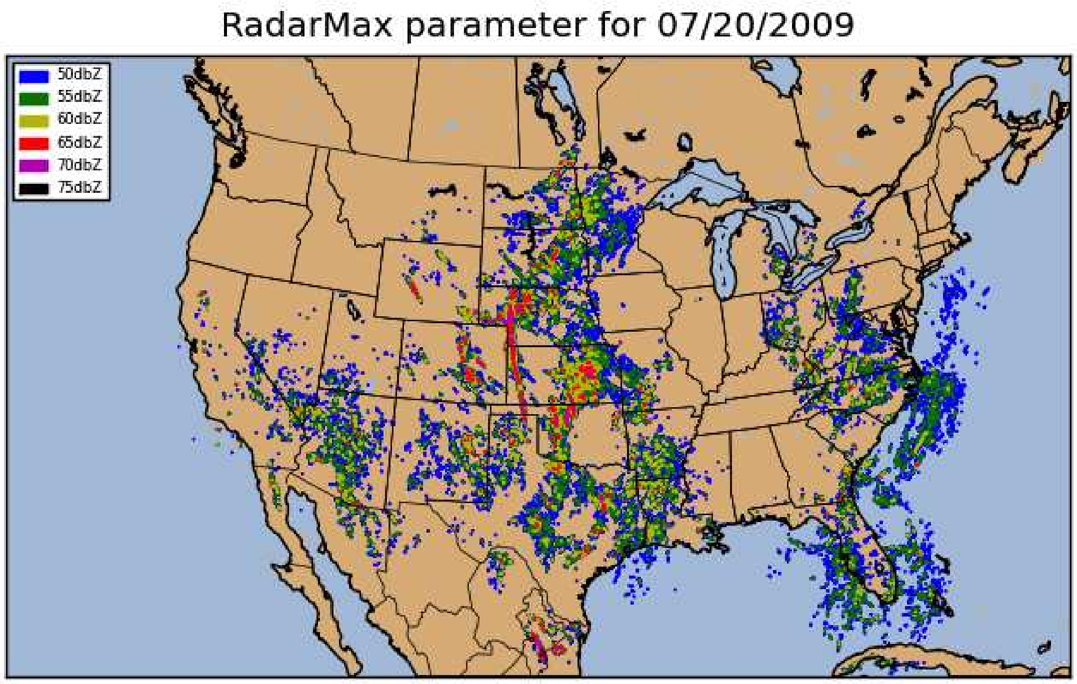


FIG. 4. The maximum composite reflectivity in the NMQ domain between 1200 UTC 20 July 2009 and 1200 UTC 21 July 2009. Values below 50 dbZ are neglected.

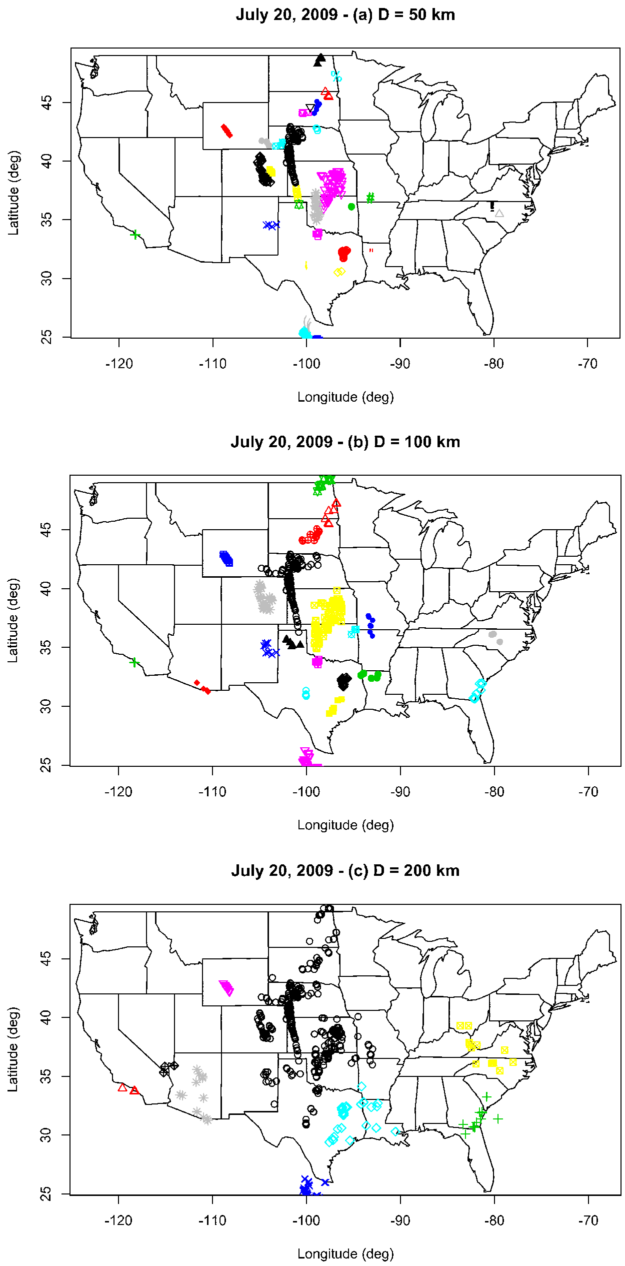


FIG. 5. Clusters of radar echoes with $Z \geq 65$ dbZ grouped using $D =$ (a) 50 km, (b) 100 km, and (c) 200 km. Clusters with areas $A < 10$ km$^2$ were omitted. Each point corresponds to the centroid of a contour.

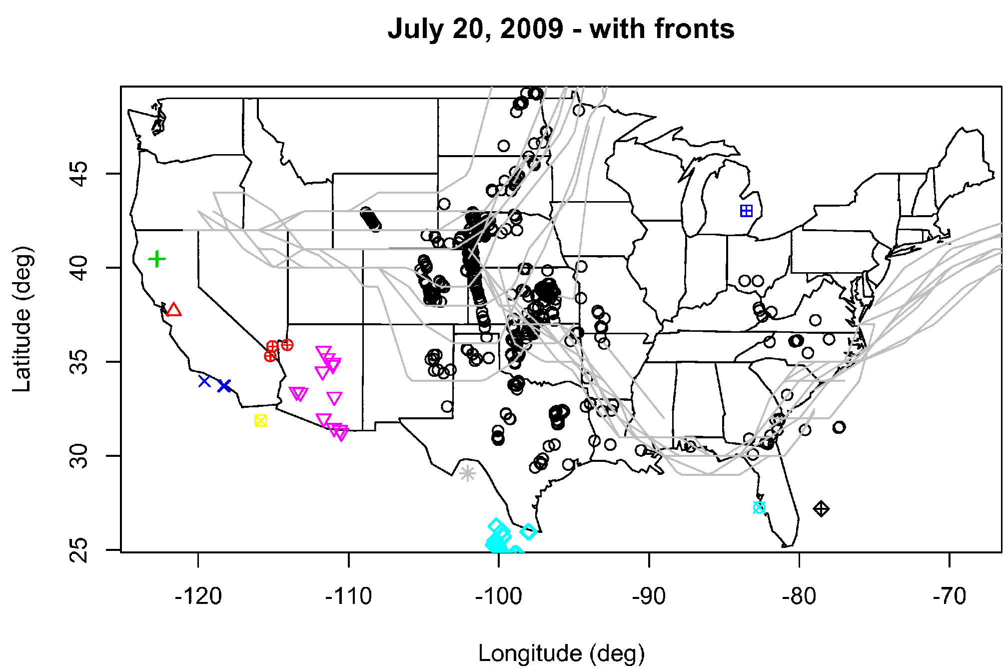


FIG. 6. Clusters grouped using $D = 200$ km and pseudo-observations from frontal boundaries. The location of frontal boundaries throughout the day are marked with the grey lines. No filtering based on a minimum echo size is used so as to demonstrate the ability of the method to not include extraneous echoes.

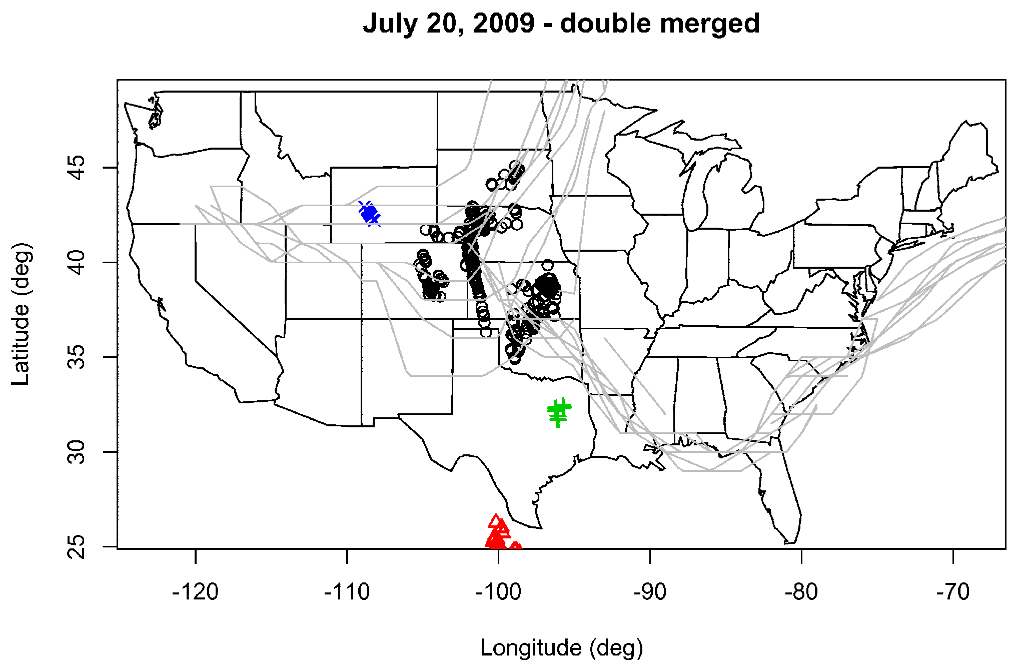


FIG. 7. Clusters grouped using $D$ = 100 km then $D$ = 200 km. Clusters with areas < 100 km$^2$ were omitted in between the two clustering passes. Each point corresponds to the centroid of a contour. The location of frontal boundaries throughout the day are marked with the grey lines for comparison to Figure 6.

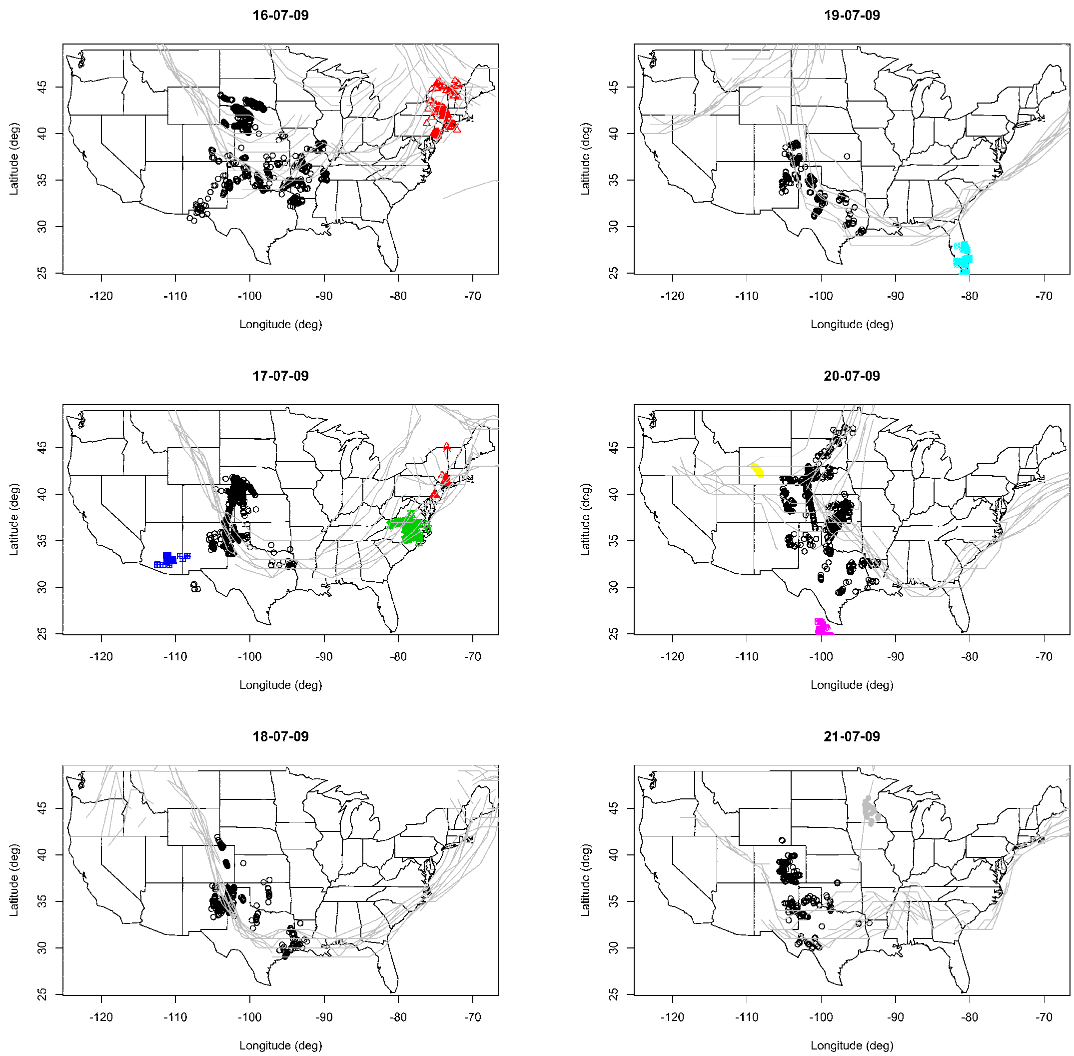


FIG. 8. The July 2009 event discussed in Section a using the two-step method as in Figure 7. Frontal boundaries are included for reference, but not used.

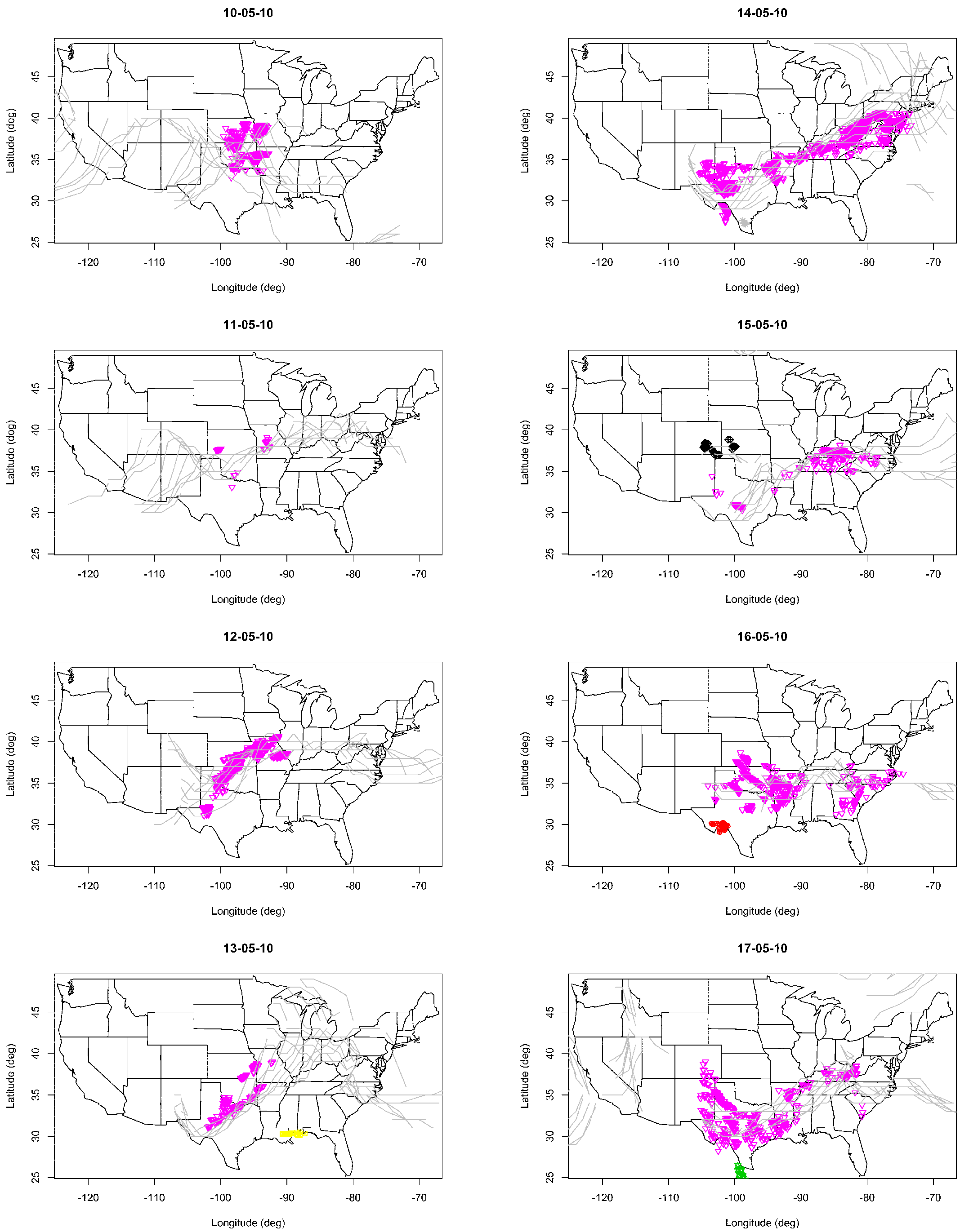


Fig. 9. The May 2010 event discussed in Section b using the two-step method as in Figure 7. Frontal boundaries are included for reference, but not used.