Insurance Institute for Business & Home Safety®

IBHS CHARACTERISTICS OF SEVERE HAIL FIELD PROGRAM

NOVEMBER 2014

Introduction

2014 marked the third year of the Insurance Institute for Business & Home Safety's (IBHS) field program to measure characteristics of hailstones. The program began in 2012 as an effort to understand the characteristics of natural hailstones for use in laboratory production of hailstones. These data are vital to creating realistic hail that can be used in laboratory studies looking at the response of building materials and systems to hail impacts. Additionally, deployments have been designed to provide ground truth data to improve radar algorithms used for detecting and mapping of hail impact areas. Improved mapping of hail impact areas and the characterization of hail sizes within those areas are vital to understanding exposure, risk, and loss mitigation strategies.

Program History

Beginning in 2012, IBHS has conducted an annual field program to measure hailstones in-situ and to evaluate their hardness property. A unique piece of field instrumentation – the hailstone compressive force device – was developed in 2012 to perform compressive strength testing of hailstones in a field setting. This work is discussed in detail in Brown et al. (2012), Giammanco and Brown (2013), and Giammanco and Brown (2014). These studies appear to be the first known work to quantify the relative strength of hail using in-situ measurements. Measurements of the major and minor diameters and mass were made and each measured stone was photographically cataloged.

A database of more than 2500 measured and tested hailstones – the largest database of its kind – has been created. The sizes of measured hailstones range from 0.07 to 4.1 inches, with an average size of 0.8 inches. The measurements made during the field program have been used extensively to guide and validate laboratory development of artificial hailstones. The comparison between laboratory hailstones and field measurements is described in detail by Giammanco and Brown (2013) and Giammanco and Brown (2014) (*see IBHS Technical Report IBHS-RC04-2013*). Creation of laboratory hailstones with varying size, density and hardness characteristics allows for investigation of variations in damage states. These data also provide a general understanding of the material properties of natural hail, which are necessary to effectively understand and model impact mechanics and the response of impacted materials (e.g. asphalt shingles). The ultimate goal of the laboratory efforts is to produce vulnerability curves that predict hail damage as a function of the characteristics of natural hail and the characteristics of various building materials.

The pilot program in 2012 featured one measurement team and a single data collection mission. This effort was expanded in 2013 to include two teams and multiple missions. This significantly increased the database and allowed the hailfall swath of targeted thunderstorms to be effectively documented. This sampling strategy was employed again in 2014, with the inclusion of a third measurement team during the second of three missions. This strategy allowed for more detailed comparisons between storm types (e.g. supercell, squall line, multicell) and the storm environment in which each parent thunderstorm was embedded. Effort was also placed on accurately documenting the hail size distribution at each measurement location.

In 2013, a deployable camera probe was used in an attempt to gain information on the evolution of hailfall within a thunderstorm, the influence of wind on hailstones, and to provide footage of falling hail for communication and outreach purposes. This system did not prove effective in extracting information about the size of falling hail and was ineffective during periods of heavy rainfall, which often accompanies hail.

Design & Methodology

Hail Impact Disdrometers

In an effort to fill this measurement gap, two rapidly deployable prototype hail impact disdrometer probes were developed by IBHS scientists and technicians in 2014 to capture a time history of hail size distributions. The two hail impact disdrometer probes, shown in Figure 1, are able to sense impacts of falling hail and can be deployed in 2-minutes or less. Through empirical relationships, the size distribution of the falling hail can be extracted from the sensor signals. The IBHS type "A" probe was based on a design described in Lane et al. (2006) and used at the Kennedy Space Center for hail detection. It uses a single piezo-electric disk to detect falling hail and/or rain (Mikhaylovskaya 1964; Joss and Waldvogel 1967; Kinnell 1972). The IBHS type "B" probe was developed as a modified version of the Lane et al. (2006) probe, with a different surface area configuration. It uses multiple piezo-electric disks (one on each face) to sense the impact of falling hail and/or rain. The probes have an integrated GPS module for position and time synchronization. While similar sensors are commercially available, they are generally not rapidly deployable in a research setting, not rugged enough to withstand repeated exposure to large hail, and are more expensive than the IBHS systems. During the 2014 field phase, eight successful hail impact disdrometer deployments were made in advance of approaching thunderstorms. The field program will continue in 2015, and a pilot program has been approved to develop the platform for integration into existing fixed weather observing stations.

Figure 1: Photograph of the two prototype hail impact disdrometers (0102B-left, 0101A-right) deployed during the 2014 field phase.

Collaborative Research

High-resolution ground observations of hailstones and their physical characteristics are of substantial meteorological value – they will be instrumental in improving radar-based hail identification and sizing algorithms. Radar data characteristics that better define the edges of damaging hail swaths, help tune parameter thresholds, and inform the selection of data characteristics that are used in calculations that serve as the foundation for radar-based hail detection, can be evaluated with ground-based observations. In addition, high-resolution numerical model simulations of hailstorms are a promising avenue for not only understanding the influence of environmental and storm characteristics on hail, but also for future predictions of hail threats. Understanding how observable radar signatures associated with meteorological features relate to the location of large hail at the surface in a wide variety of environments could aid in reconstructing hail swaths, particularly in the absence of good low-level radar coverage. Comparison of simulated hail swaths generated using a suite of newly developed metrics, with ground observations from the field program, will allow for development of optimal methods for using numerical weather prediction models to forecast the threat of hail.

In 2014, IBHS entered into a research partnership with Dr. Matthew Kumjian, Assistant Professor of Meteorology at Penn State University, to investigate polarimetric radar detection of hail and storm-scale model simulations of hail-producing thunderstorms. Dr. Kumjian participated in the field phase of the project in 2014 and is fostering student participation in analysis work and future field phases. The primary objectives of this partnership are to:

- Correlate data from the new dual-polarization radar network with ground measurements to improve hail detection and discrimination of hail size.
- Construct detailed hail swaths based on field observations to facilitate improved numerical weather prediction of hail risk.
- Explore the feasibility of improving forecasts of hail threat and risk using numerical weather prediction models, potentially opening the door to future forecast-based mitigation of losses.

This collaborative research program will expedite the transition of research findings to operational use within the weather enterprise. Improved radar detection of hail will lead to significant improvements in radar-derived hail swaths, which are routinely used throughout the insurance industry to characterize damaging hail events.

Analysis

2014 Field Measurement Campaign

The 2014 field phase took place in May and June with three separate data collection missions. The first two missions focused on high spatial resolution hailstone characteristics measurements and limited impact disdrometer probe deployments. The third mission focused only on impact disdrometer probe deployments. Data were collected during ten "in-operation" days (IOPs) across the Great Plains of the United States with more than 1600 hailstone measurements. The number of hailstones measured in 2014 exceeded the existing database from 2012-2013 by more than 600 hailstones. The 2014 field phase illustrated the benefit of multiple measurement teams and experienced field personnel. It is believed the IBHS hail measurement database is now the largest collection of research-grade hail measurements (measurements extending beyond only the maximum diameter) assembled to date.

The objectives of the 2014 hail measurement program included:

- Collect quality spatial resolution hail measurements along the cross-swath axis
- Document representative hail size distributions for each measurement location
- Collect photographic documentation of the distribution of hail at each measurement location
- Measure an intermediate hailstone dimension, in addition to major and minor diameters
- Collect compressive strength measurements of large hail (> 1 in.)
- Collect pilot hail impact disdrometer probe measurements
- Evaluate the measurement differences between two hail impact disdrometer probe prototypes
- Evaluate the ability of the hail impact disdrometer probe to function as an adaptive deployable observing network or fixed platform sensor

Table 1: 2014 Field Measurement Summaries for each Parent Thunderstorm Sampled

ID	Location	Date	Sample size	Maximum Diameter (in.)	Mean Diameter (in.)	Maximum Compressive Stress (psi)	Mean Compressive Stress (psi)	Hail cross-swath axis (mi)
1A	Holliday, TX	5/7/14	6	1.14	0.8	1242	n/a	2
1B	Lakeside City, TX	5/7/14	54	0.9	0.56	382	159	n/a
1C	Waurika, OK	5/7/14	239	2.25	1.04	n/a	n/a	6
2A	Latham, KS	5/10/14	71	0.90	0.51	418	96	3
2B*	Beaumont, KS	5/10/14	279	0.94	0.75	702	107	4
3A*	Greensburg, KS	5/11/14	113	0.95	0.55	460	140	n/a
3B	Larned, KS	5/11/14	46	1.03	0.71	242	127	4
4A	Oconto, NE	6/3/14	95	1.35	0.67	2550	409	5
4B	Broken Bow, NE	6/3/14	228	2.66	1.01	2958	173	6
5A	Hay Springs, NE	6/4/14	273	1.14	0.61	2506	146	8
6A-1*	Punkin Center, CO	6/5/14	125	1.01	0.49	1978	138	3
7A	Lakin, KS	6/6/14	107	1.48	0.85	170	78	3

**indicates associated impact disdromemeter probe deployment*

Analysis

Hail Measurement Summary

Data from missions #1 and #2 were collected on a total of seven IOPs from 12 different parent thunderstorms. Figure 2 provides a map of all measurement and disdrometer probe locations during 2014. Table 1 provides a summary of hail measurements from each parent thunderstorm. The cross-swath distance in Table 1 was estimated using field observations, radar information, and notes taken by the measurement teams. The average cross-swath distance was 4 miles (~ 6 km). The hail size distribution ranged from 0.1 in. to a maximum diameter of 2.6 in. The compressive strength distribution ranged from stones which were too slushy to test and could not effectively support a load (< 10 psi) to a maximum of nearly 3000 psi. The average value of 136 psi was slightly higher than the previous two-year mean (104 psi). When compared to laboratory hailstones manufactured and at IBHS using water with different mixtures of dissolved CO_2, mean values were similar. Laboratory stones manufactured using compacted crushed ice were the only stones that on average were stronger than the average natural hailstone contained in the database (for more detailed laboratory comparisons please *see Technical Report IBHS-RC04-2013*).

Experimental Polarimetric Radar Detection of Hail Case Study: 7 May 2014

The two field measurement teams were successful in documenting the hail swath of a high-precipitation supercell thunderstorm which produced a large volume of hail exceeding 1.5 inches on 7 May 2014 near Waurika, Oklahoma. Hailstones were measured at 12 different locations within the hail swath. The northern and southern extents of hailfall were also documented by the teams. These ground truth data were compared against two experimental polarimetric-based hail detection schemes using data from the Fredrick, Oklahoma WSR-88D radar (KFDR). The two experimental products were evaluated for their ability to produce an accurate swath of hailfall.

The first experimental product (Figure 3) uses a blend of conventional radar reflectivity (measures of the intensity of falling precipitation) and differential reflectivity (ZDR, difference between the reflectivity of the two different polarized pulses). Within each radial bin in a defined time window, this experimental product counts the number of occurrences where conventional reflectivity values are greater than 50 dB at the lowest radar tilt (0.5°) and ZDR

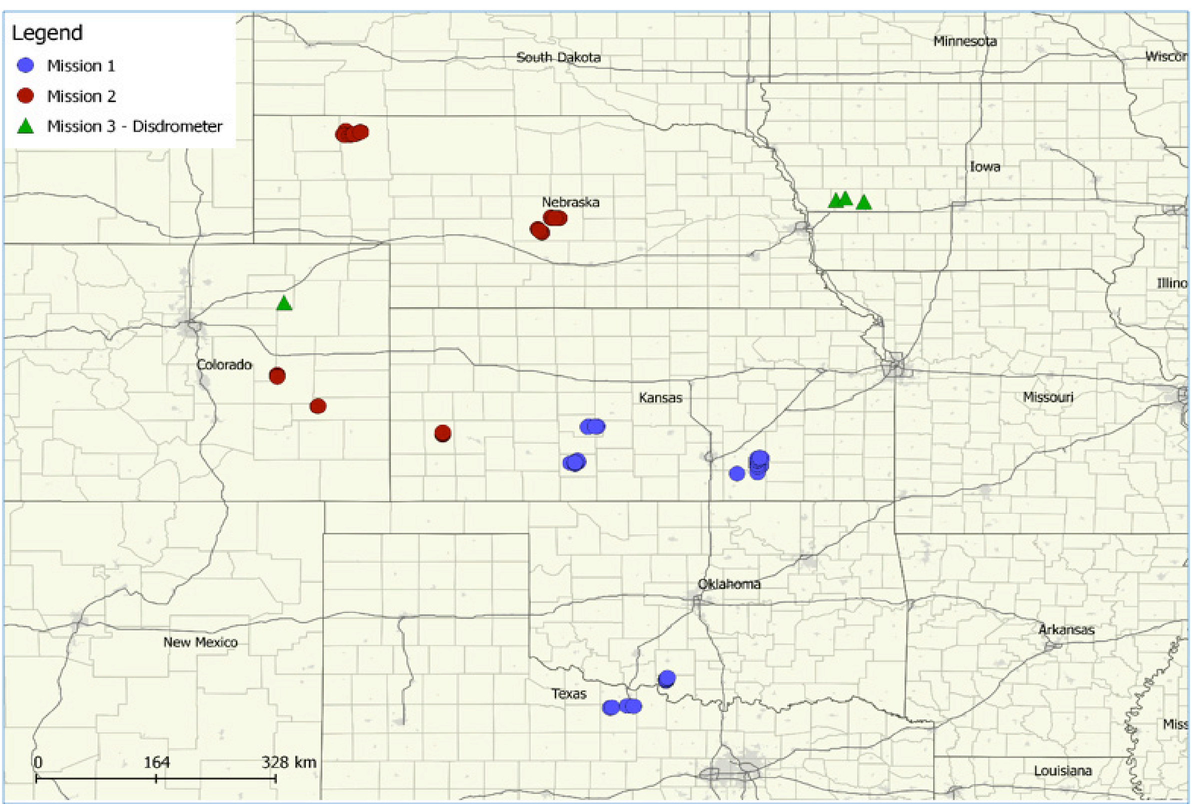

Figure 2: 2014 measurement locations for mission #1 (blue), mission #2 (red) and mission 3 impact disdrometer probe deployments (green). Probe deployments for mission #1 and #2 are co-located with measurement locations.

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values are less than 0; both conditions must be met for a count to register. Negative ZDR values are typically associated with more spherical or tumbling targets (e.g. hailstones; raindrops typically have a positive ZDR). The number of occurrences in each radial bin within the time window is used to produce the estimated swath. As shown in Figure 3, the non-dimensional quantity was effective in capturing the spatial extent of the hail swath. Higher values are associated with a larger number of occurrences, in which the dual-pol information suggested hail should be present within the time window. Locations of larger concentrations of hail at the ground observed by the field teams were in qualitative agreement with the non-dimensional quantity.

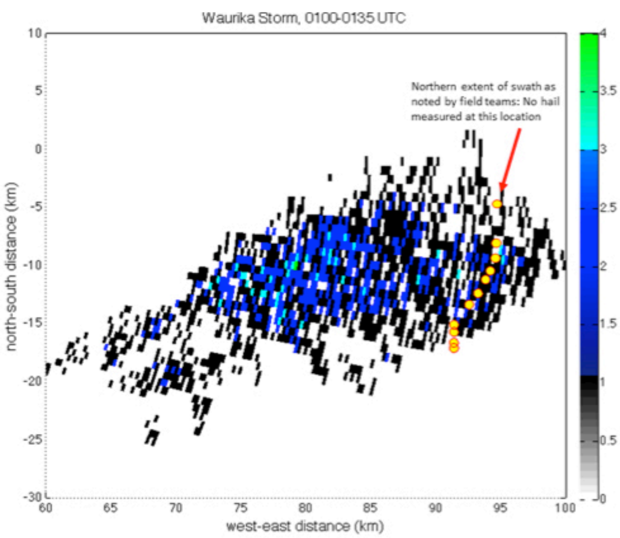

Figure 3: Experimental polarimetric radar-based hail swath from 7 May 2014 near Waurika, Oklahoma. The color scale represents the number of occurrences where the horizontal reflectivity exceeded 50 dBZ and the ZDR was 0 or less. Field team hail observation locations are shown in yellow. Hailstones were not physically measured by the field teams at the northern-most observation location. Data are courtesy of Dr. Matthew Kumjian, Penn State University.

The second product evaluated uses a derived quantity known as hail differential reflectivity (HDR) which is a combination of the reflectivity from the horizontally polarized radar pulse and ZDR (Bringi et al. 1984; Aydin et al. 1986). HDR represents only the hail portion of the reflectivity signal, by filtering out the influence of liquid raindrops. The hail swath is generated using the maximum value of HDR for each grid point over a defined temporal window. This product was effective in defining the spatial extent of hailfall as shown in Figure 4. Higher values theoretically should correlate to a larger concentration of hail and/or larger hailstone sizes. More work is needed to distinguish this relationship. For this particular case, higher values in the product did not spatially correlate well with the maximum sizes measured by the field teams, but higher product values were reasonably aligned with larger hail concentrations observed.

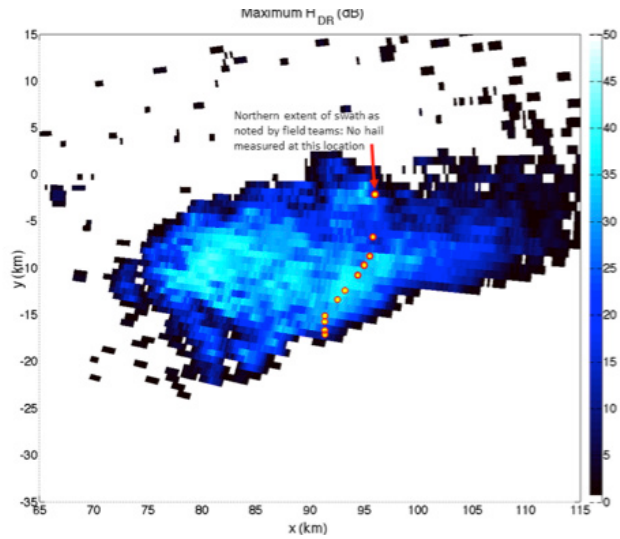

Figure 4: Experimental KFDR polarimetric HDR based hail swath from 7 May 2014 near Waurika, Oklahoma. The color-scale refers to the value of HDR (dB). Higher values are hypothesized to represent a larger confidence in the presence of hail. Field team observation locations are shown in yellow. Hailstones were not physically measured by the field teams at the northern-most observation location. Data are courtesy of Dr. Matthew Kumjian, Penn State University.

The two experimental products shown here were effective in capturing the spatial extent of hail and showed promise in describing the concentration of hail at the ground. Additional cases from 2014 are being studied to evaluate the performance of these two products. More work is needed to validate non-operational hail size discrimination algorithms, such as that developed by Ryzhkov et al. (2013). Both the size and spatial concentration of hail are needed to properly characterize hail events and evaluate their damage potential.

Deployment of Hail Disdrometers

During the 2014 field phase, it proved difficult to accomplish both hail measurement objectives and probe deployments. The two functions required different thunderstorm targeting and maneuvering strategies, therefore only a limited number of cases were obtained. Eight hail impact disdrometer probe deployments were made, resulting in three quality cases in which hail approaching 1 inch was measured at the deployment site. The two probes were typically collocated for sensitivity comparisons. Given a single deployment location, the margin for error was quite small given the lead time required to safely deploy the instruments and exit the area before the target thunderstorm reached the site.

Analysis

The experience gained will guide the development of an adaptive and deployable network of probes. Teams were also able to evaluate the probes for use as a fixed instrument on existing surface weather observing stations. To improve the IBHS platform for both roles, additional development is needed to process the raw sensor information into meaningful near real-time hail impact concentrations. Currently, the probes only collect raw sensor data which are post-processed after deployments are completed. Field measurements of hail by the measurement teams and laboratory testing are being used to develop signal analysis tools that will allow hail size discrimination algorithms to be developed.

As development continues, the platforms will be able to provide an estimate of hail size distributions and concentration by volume. The probes will also offer additional ground-truth observations of hail for comparison with polarimetric radar hail detection products. For engineering applications, these data will allow for accurate event simulations in the IBHS Research Center large test chamber using the full-scale hail propulsion system.

Disdrometer Case Study: 5 June 2014

The probe deployment on 5 June 2014 was one of the most successful with both probes deployed into a thunderstorm near Punkin Center, Colorado that produced a large volume of small hail with two distinct pulses in hailfall. The processed data from both probes are shown in Figure 5 as impacts per minute. The magnitude of the impacts are presented as percentage of the full-scale range of the instrument and are grouped into magnitude bins (size and kinetic energy relationships to translate these bins into hail characteristics are currently in development). For probe 0102B which features multiple impact sensors, the number of impacts per minute on each face of the device was averaged together to provide a single value of impact concentrations per minute for the comparison. As shown in Figure 5, sporadic hail began to fall as soon as the probes were deployed. Two distinct periods of small hail with relatively large concentrations (~10-20 impacts per minute) were evident. However, there are differences in the representation between the two probes. Each probe does resolve the relative lull in hailfall between 23:20 and 23:26 UTC, which is well correlated with radar reflectivity and differential reflectivity trends. Probe 0101A indicated a high impact concentration beginning at 23:22 UTC through the end of the record in the lowest magnitude group. It is believed the probe was actually resolving a high concentration of large rain drops in the lowest magnitude group (> 80 impacts per minute). The impact probes were effective in capturing the fine-scale structure within the hail swath. Radar data indicated the storm was evolving quickly as it passed over the probe locations with several pulses in intensity, which were well captured by the two distinct peaks and local minima in hailfall observed by the probes. It is likely this particular storm did not produce a continuous swath of hail but sporadic "streaks" which were well described by Changnon (1970). The data records from the probes also showed how hailfall can evolve and change on very small times scales less than the time operational National

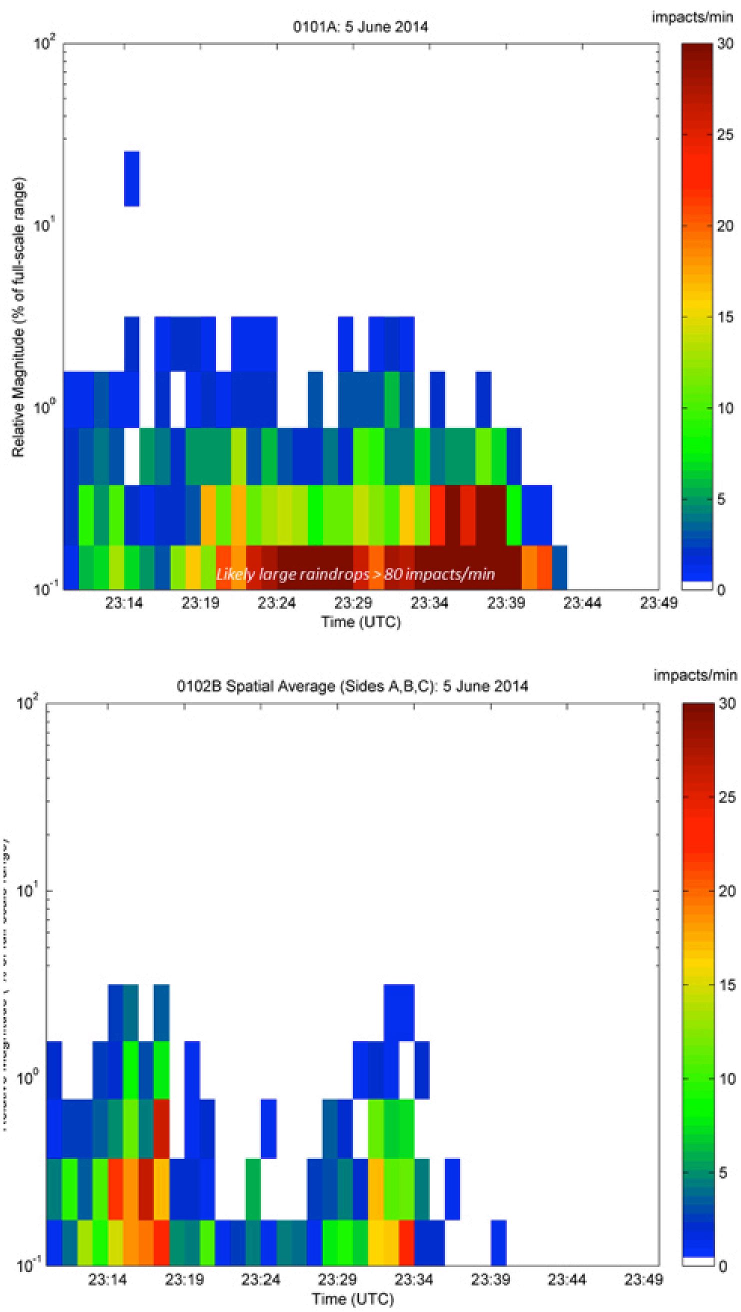

Figure 5: Impact concentrations per minute observed by probe 0101A (top) and 0102B (bottom) on 5 June 2014. The y-axis represents the relative-size of hail and/or large rain drops.

Conclusions

Weather Service radars can complete their volume scans (~ 5-8 minutes).

The maximum size measured by the field teams at the site was nearly 1 in. with an average size of nearly 0.5 in. The differing sensitivities between the two probes were anticipated given the different configuration of the probe designs. It is unclear where exactly the threshold between large rain drops and hail lies, but further sensitivity testing in strictly rainfall environments and in the laboratory will help identify this. Other differences are likely related to the random nature of hail and the larger surface area of probe 0102B compared to 0101A. It was encouraging to observe a similar structure in the evolution of the precipitation pattern and good correlation with the radar observations.

Summary

The 2014 field phase of the IBHS hail field program was successful in accomplishing the measurement objectives. The use of multiple field measurements teams allowed for a large number of hailstones to be measured, which more than doubled the existing IBHS hail database. The complete hail database will continue to be used to evaluate laboratory manufacturing of hailstones for impact testing. The dataset still lacks a large sample size of compressive strength measurements for hailstones with diameters larger than 1.5 inches.

Individual cases were successful in capturing the spatial extent of the hail swath, which is instrumental in evaluating experimental radar hail detection schemes. The first case in which new experimental products were evaluated showed promise. The program was also successful in evaluating the ability to rapidly deploy hail impact disdrometer probes in the path of hail-producing thunderstorms. Continued work is needed to evaluate the differences between the two prototypes and develop the hail size estimation algorithms. This work will allow the design of impact disdrometers to be adapted for a deployable network used in targeted research or for fixed platform use.

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