FINAL REPORT

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Type of Project (Partners or Cooperative): Partner

Project Title: GOES-R Partner Project: Identifying Plowable Hailstorms on the Front Range of Colorado using GOES-R Imagery, Dual Polarization Radar Data, and Total Lightning Information

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SECTION 1: SUMMARY OF PROJECT OBJECTIVES

The **overarching goal** of collaborative work between CU and the WFO is to find predictors from operational products that can be used to identify, observe, and forecast plowable hail events within the area operated by the Colorado forecasting offices. This information can be used to issue significant weather statements for road and airport management.

The **specific objectives** of this work are i) identifying the strength and weaknesses of GOES-R convection-related products that are most useful to identify thunderstorms that might produce large hail accumulations, ii) integrating GOES-R products with information from ground-based lightning and radar networks into a merged product, iii) evaluating if the merged product verifies with observed plowable hail events and provides useful guidance to forecasters for these events, and iv) familiarizing forecasters with new guidance of plowable hail events and students with weather forecasting operations. *We solely focus on events that occurred in 2016. 10 storms were cataloged during the summer of 2016, nine in the Colorado front range and one located in Omaha, Nebraska. Currently we have 10 reports with reported accumulations of more than 2.5 cm at the surface, and eight more events without community reported depth, but with estimated accumulation above 2.5 cm based on social media pictures. We have four reports of hail accumulation greater than 10 cm, all occurring on either July 29th or August 29th, 2016.*

SECTION 2: PROJECT ACCOMPLISHMENTS AND FINDINGS

Obj. 1: Analyze GOES-R proxy products to find predictors of plowable hail

We used the six derived GOES products that are available from the NWS archived data to analyze their usefulness to identify and forecast thunderstorms with large hail accumulations on the ground. Note that the GLM proxy data were received by the product PI directly with 60 second temporal resolution. While Skin Temperature and Precipitable Water might be useful in general, the data restrictions (no data are reported for T < -37degC and PW > 2.6 inches) make them currently not useful. The temporal resolution of one hour is inadequate for thunderstorm applications, providing at most three unique data points prior to and leading up to the hail event. Even though very limited data exists, cloud top height and lifted index may at the very least provide information about these accumulation events by indicating the cloud properties prior to the time of the event. The temporal resolution of GLM Flash Extent Density proxy data is every minute and provides valuable information. ProbSevere, with a time resolution of 5 minutes, is a product available to forecasters that uses multiple data inputs to gauge the probability of severe weather in the immediate future. The ProbSevere product is useful to forecasters because it provides an easy to read output that allows for quick synthesis of data for time-sensitive forecasting. The readout on AWIPS II for ProbSevere gives the following sub-products as well as the probability of severe weather as stated above: Most Unstable CAPE (MUCAPE), Estimated Bulk Shear (EBS), Vertical Growth Rate and Glaciation Rate. Due to upgrades to the AWIPS II archiving and analysis process, specifically using the Weather Emulator System (WES), the ProbSevere data set was not available until 29 July. Consequently, only the 29 July and 29 August events included data from the ProbSevere products. For the hail events on 29 July and 29 August ProbSevere correctly forecasted severe weather for both events, calculating 100% probability for the July event and 88% probability for the August event. The individual products MUCAPE and EBS may be useful in determining the environment needed for plowable hail cases, but the limitation of having ProbSevere data for only two events does not allow for a robust analysis of it's utility for these events.. The growth rate products did not provide enough detail to be useful, as their values were either not reported or were static throughout the storm. Although ProbSevere correctly forecasted severe weather for the 29 July and 29 August events it does not provide specific information to help identify large hail production in thunderstorms and related hail accumulations on the surface, i.e., there is no difference in ProbSevere between thunderstorms with and without large hail accumulations.

Table 1: List with GOES-R products and their usefulness to identify thunderstorms with large hail accumulations at the surface.

GOES R Product	**Utility**	**Temporal Resolution**	**Usefulness**
GLM Proxy Data	Data is not constrained	1 Minute	Likely Useful
ProbSevere	Data is not constrained	5 Minute	Possibly Useful
Cloud Top Height	Data is not constrained	1 hour	Possibly Useful
Lifted Index	Data is not constrained	1 hour	Possibly Useful
Skin Temperature	Data does not report below -37 deg C	1 hour	Not Useful
Precipitable Water	Data does not report above 2.6 inches	1 hour	Not Useful

Obj. 2: Merge GOES-R proxy products with ground-based observations

AWIPS II is a weather forecasting display and analysis package in use at National Weather Service (NWS) forecast offices throughout the United States. AWIPS II merges satellite, radar, and lightning data. AWIPS II is theoretically capable of merging the following GOES-R proxy products: GLM Flash Extent Density, ProbSevere, Convective Initiation, Cloud Top Phase, Cloud Top Height, Lifted Index, Skin Temperature and Precipitable Water. However, only GLM, ProbSevere, Lifted Index, Skin Temperature, and Precipitable Water data are currently available through AWIPS II. Analysis of all 2016 plowable hail cases showed that the radar-based hail accumulation maps align well with large hail accumulation reports. We recommend that the NWS includes the dual-polarization radar-based hail accumulation maps into the AWIPS II system. This product has a high temporal and spatial resolution as well as a good horizontal texture to identify areas of deep hail accumulations. Due to the coarsity in time, space and for some products in texture, the utility of GOES-R proxy data needs to be further evaluated once the products are available at higher temporal and spatial resolution. As of now, GOES-R proxy data available through AWIPS II provide little useful information due to poor spatial and temporal resolution of rapid hail production leading to large hail accumulation on the surface.

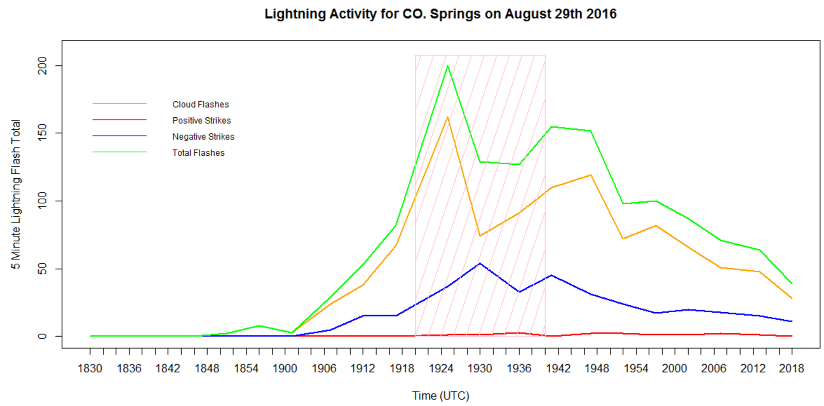

Figure 1 Lightning Flash and Strike Totals for 29 August 2016. The shaded box indicates the duration of the hail event as derived from reports and radar.

Earth Network Total Lightning 5-Minute data were used in evaluating the lightning activity for each archived event. This information can be potentially merged with the GOES-R GLM proxy products to improve lightning information for individual thunderstorm. The 5-minute data include Cloud Flash count, Positive Strike count, and Negative Strike count. Most events saw a large spike in lightning activity prior to the hail accumulation. *Figure 1* presents a typical pattern seen prior to the hail event. Cloud Flash Count appears to be the most distinguishable product as both the positive and negative strike counts lend irregular variation and may themselves not be very useful to forecasters. For those events that did not see a spike in lightning activity prior to the event, it is likely that the storm had already reached a mature stage of development prior to the accumulating hailfall.

Initial analysis of the Flash Extent Density GLM proxy product shows a peak in Flash Extend Density at the time of the hail event (*Figure 2*). Spatial analysis shows the peak is located over the reported location (*Figure 3*). As more events are analyzed this signature will be either confirmed or refuted.

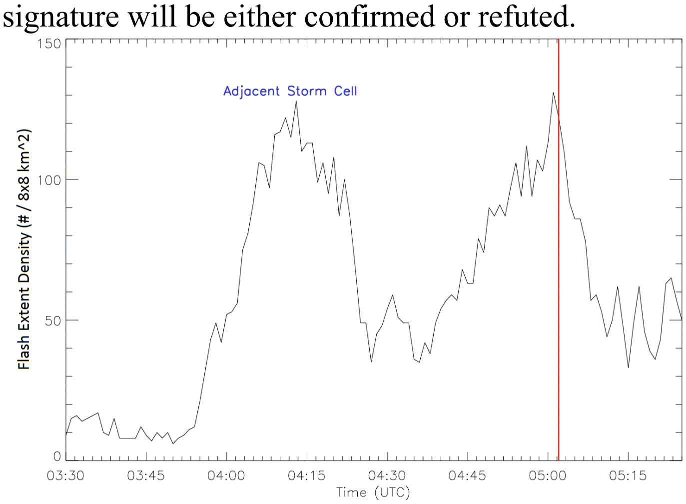

Figure 2 Flash Extent Density for the event on 5 June 2015. The red line indicates the time of the reported hail event.

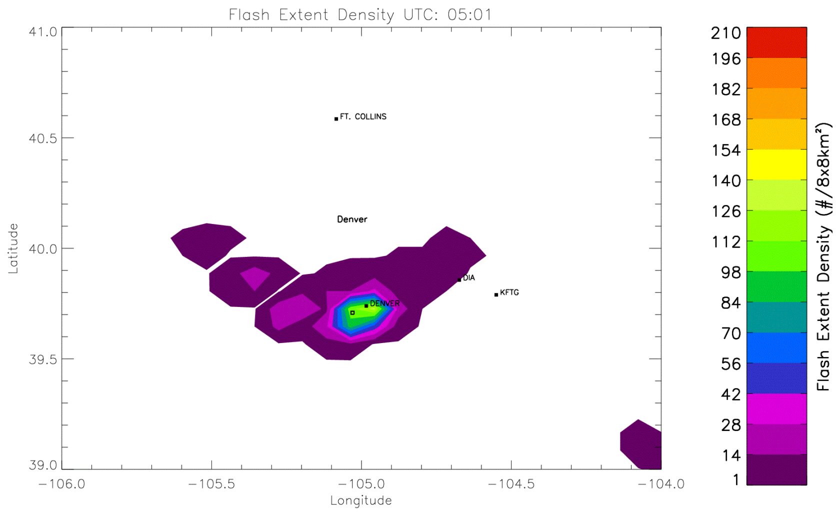

Figure 3. Flash Extent Density on 5 June 2015 at 5:01 UTC.
The black box indicates the location of the hail accumulation report.

Obj. 3: Testing the merged product for nowcasting applications and verifying plowable hail events

Hail depth verification: In collaboration with the NWS WFO in Boulder, we have established a verified database of hail depth in thunderstorms across the United States with emphasis on Colorado dating back to 2013. Note that prior to 2013, most operational radar sites did not have dual-polarization capacity, therefore, this project focuses on events that occurred after the dual-polarization operational radar upgrade. In April 2016, we started a pilot project to verify hail depth in Colorado, where we asked the general public, news agencies, trained spotters, and transportation authorities to report on hail depth and areal coverage using Facebook, Twitter, NWS storm reports, and Email (http://clouds.colorado.edu/deephail; https://twitter.com/hashtag/deephail?src=hash). As of June 2016, we have already received over 26 reports with pictures, videos, and drone footage to verify the location, time, depth, and areal coverage of hail accumulations. Hail depth reporting is now part of the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) reporting system and the weather service has developed hail depth report forms (https://docs.google.com/forms/d/1BXAf-mM_dTDSFOS866kkKkAB-GgbFY_EQ_5TuXr6Y60/viewform). In order to find unique characteristics in the radar, satellite, and lightning products, we cataloged the events into three categories: few hailstones on the ground (considered to be null cases since no hail reports are difficult to communicate), labeled as trace, hail accumulations that would impact driving with hail depth < 2.5 cm, labeled as moderate, and hail accumulations with depth > 2.5 cm, labeled as high. (Fig. 4). In order to verify the radar-based hail and graupel accumulations maps, we will use the reported heights for all events.

Testing merged products: During the 2016 hail depth pilot project, we have run the radar analysis algorithms developed by Kalina et al. (2016) for all major events in a real-time simulation mode generating plots for the thunderstorms with deep hail accumulation reports. Robinson Wallace, the graduate student funded through this project, has already optimized Kalina's algorithms to be applicable in real-time. He applied an automated quality control and particle identification algorithm for radar Level 2 and Level 3 data in polar coordinates, optimized Kalina's research-focused analysis algorithms to be applicable in real-time, and developed code to merge Level 2 and Level 3 radar data with lightning data.

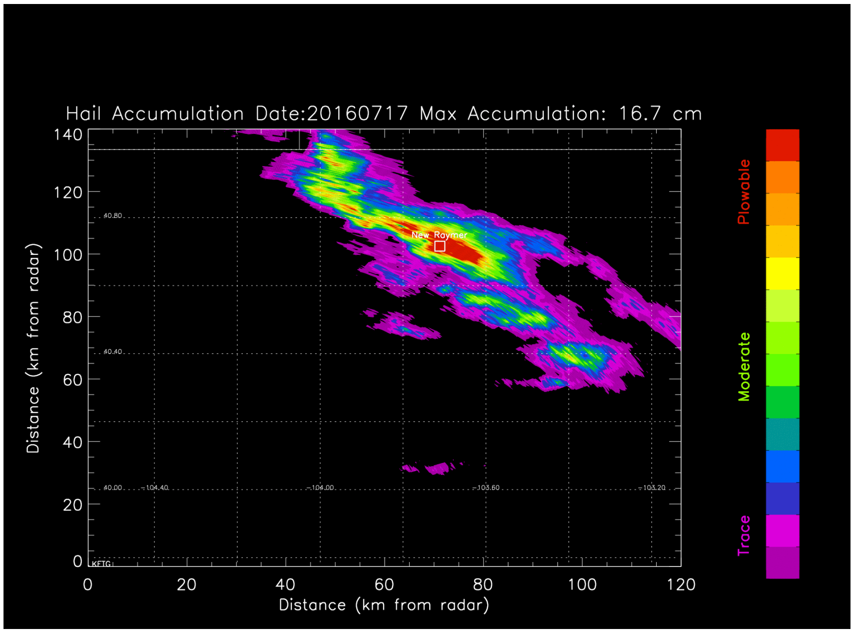

Figure 4 Hail accumulation map as provided by merged products for the event on July 17th 2016

In addition, the NWS has archived all AWIPS II products for thunderstorms with hail depth reports. Currently we have about 18 hail depth reports with more than 2.5 cm in hail accumulations at the surface, which occurred over 10 days. For each case, we are able to combine the data as shown in the examples above. We are currently working on calculating quantitative measures for statistical analysis of radar parameters, such as centroids (center of mass of the plot), from horizontal and vertical maps of the radar variables. Running algorithms in a semi real-time mode prior to the start of this project allows us to analyze large numbers of hail events in a timely manner with the statistical analysis allowing us to add more parameters that can be compared to large number of storms. The algorithms are designed to easily add new radar parameters or other observations.

Obj. 4: Provide guidance and training for forecasters and familiarize students with weather forecasting operations

Since the GOES-R proxy data does not provide sufficient resolution to identify large hail accumulations, we are unable to provide any guidance to operationalforecasters. However, the NWS office in Boulder has and will continue to have a close collaboration with PIs at CU so that we can eventually provide forecaster training once the fundamental products are available through AWIPS II.

Robinson Wallace has spent a lot of his time at the NWS and has maintained a close rapport with NWS forecasters during and after the plowable hail events. He has also learned advantages and limitations of the AWIPS II system and will continue to do so.

SECTION 3: BENEFTS AND LESSONS LEARNED: OPERATIONAL PARTNER PERSPECTIVE

Benefits:

1. **Real-time hail accumulation maps would be beneficial to NWS operations:** A radar-based real-time hail accumulation map, one of the outcomes of this study, would be very useful to National Weather Service forecasters in several ways. Currently, forecasters use rain and snow accumulation and hail size maps to help issue advisories and warnings. However, there are currently no available products that help forecasters determine the amount of hail that has fallen. If forecasters are able to identify where large amounts of hail have fallen in real time, then they can add informative statements to Severe Thunderstorm Warnings, or Significant Weather Advisories (for non-severe thunderstorms) alerting the public and our partners about this hazard. Alerting the public and NWS partners that roads are ice or hail covered would be a significant societal benefit.
2. **Continue to strengthen the working relationship between NWS Boulder and University of Colorado, Department of Atmospheric and Oceanic Sciences:** This may lead to additional projects in the future.
3. **Better understanding on how to collect and review data from past weather events**: The AWIPS II archiving and playback/reviewing features are relatively new. New software for the Weather Event Simulator (WES) created challenges for reviewing cases during the partnership. The challenges were overcome during this study, and an end result is that NWS Boulder will now be able to view future cases and help other NWS offices do the same. The partnership will make it easier for NWS Boulder to collect and review data for future storms.

Lessons Learned

1. **Using Flash Extent Density to help identify large hail accumulations**: A peak in Flash Extent Density was observed prior to most events where hail occurred. This piece of information combined with radar data can help forecasters with their confidence that large amounts of hail have fallen, have not fallen, or about to fall. In addition, Flash Extent Density can help forecasters identify large hail accumulations where radar data are poor due to beam blockage or distance from the radar, such as the Estes Park case on June 6th, 2016.
2. **GOES-R proxy data in its current form presents great challenges to operational usage**: GOES-R proxy data do not provide the spatial or temporal resolution necessary to identify large hail accumulations at this time. When the GOES-R data are available sometime in 2017, it could be useful to identify thunderstorms that are producing large hail accumulations.
3. **Better understanding of hail accumulating thunderstorm types**: A wide range of thunderstorm types produced accumulating hail during the 2016 convective season. Strong supercell thunderstorms with hailstones larger than 5 cm in diameter produced accumulating hail over the plains of northeast Colorado. In addition, sub-severe

thunderstorms, with hail diameter less than 2.5 cm moved across the Denver metropolitan area May 26th producing accumulating hail. By collecting data from hail accumulating thunderstorms during the 2016 convective season, the NWS learned hail accumulating thunderstorms come in "different shapes and sizes."

SECTION4: BENEFITS AND LESSONS LEARNED: UNIVERSITY PARTNER PERSEPCTIVE

Benefits:

1. **Better understanding of the forecasting problem:** The collaboration with the NWS helps us to get a better understanding of forecasting problems and how data, products, and information are being used and displayed at the NWS. While we initially thought of developing our own analysis software, we came to the conclusion to better include everything into the AWIPS II framework.
2. **Better understanding of research-to-operations**: In addition, the graduate student has been exposed to operational forecasting and to how his research might be best incorporated into an operational setting.
3. **Utilizing large reporting resource of the NSW to verify and quantify deep hail cases**: Most importantly, the NWS assists in verifying hail depths and, therefore, provides a fundamentally important piece to our research. NWS is able to reach out to a large number of people and also has a better infrastructure to collecting and tracking severe weather reports – something that would have been impossible for CU.

Lessons learned and suggestions:

1. **Innovative research needs to fit pragmatic approaches**: Most of the research conducted at the university needs to be innovative and cutting edge in order to fulfill requirements for Masters or PhD theses, publication in peer-reviewed journals, or scientific proposals. On the other hand, NWS is looking for products that they can incorporate into everyday operations. Some of the results from this research resulted in new hypotheses that need to be further tested and evaluated in an operational environment before NWS forecasters use them. Who is filling this gap? Now that our research produced its first results, how can we test then work to implement this new capability in an operational environment? How can the NWS directly benefit from our results?
2. **Data availability:** There is a large mismatch between what is required from the solicitation and what is realistically available at the NWS. Over the last year, the NWS has committed large efforts to provide us with GOES-R proxy data but apparently the NWS does not have access to the latest products and their solicited resolution. For instance, the NWS does not have access to all GOES-R proxy data and products; GOES-R proxy data comes at 1 hour resolution (useless for tracking the evolution of microphysical processes in thunderstorms), some of the data are restricted (e.g., skin temperature is not reported below -37degC so we are unable to detect high/cold cloud tops; precipitable water is constrained to < 2.6 inches, which makes it impossible to detect areas of high PW content in thunderstorms). The coarse resolution and the data constraints strongly influenced the quality of the research. Once we connected with the product-PIs, e.g., to get the GLM proxy data, we received unconstrained data at one minute resolution. In the case of the GOES-R

research, we recommend someone makes sure that the highest quality data are to the NWS. Also, there does not seem to be a GOES-R proxy data archive where research data can be downloaded.

3. **Where do we go from here**? Now that we have conducted this research, it is not clear where we go from here. As mentioned under comment #1, there is a lot of work to be done to cross the gap between research result to an operational product. Also the total amount of the grant ($20k) is a small to conduct any serious research. The university can certainly use the result to apply for grant money but it will most likely not meet NWS needs. There is no clear pathway on how to proceed with the partner project beyond the initial seed money.

SECTION 5: PUBLICATIONS AND PRESENTATIONS

Wallace, R.: "Plowable Hail Prediction Methods Using Radar and Lightning Observational Products". 10th Earth Science & Space Science Poster Conference, November 2016.

Wallace, R.: "Plowable Hail Prediction Methods Using Radar and Lightning Observational Products" 20-page paper and a 45-minute talk for the ATOC second comprehensive exam in Spring 2017.

Friedrich, K., R. Wallace R., B. Meier, N. Rydell, W. Deierling, E. Kalina, B. Motta, P. Schlatter, 2017: Deep hail accumulations from thunderstorms. *Bull. Americ. Soc*. (in preparation).

Forecasters will be trained on the findings from this partnership project at National Weather Service Boulder's 2017 spring convective workshop, with a goal of better identifying storms that may product accumulating hail and an improvement in impact messaging to NWS partners and the general public when they occur.

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

The collaboration between CU and the NWS helps gain a better understanding of forecasting problems, how data and products are being used and displayed at the NWS, and what products are absolutely necessary to advance in identifying plowable hail events. While we initially thought of developing our own analysis software, we came to the conclusion to better include everything into the AWIPS II framework. In addition, the graduate student is exposed to operational forecasting and to how his research might be best incorporated into an operational setting. Most importantly, the NWS assists in verifying hail depths and, therefore, provides a fundamentally important piece to our research. In addition, NWS is able to reach out to a large number of people and also has a better infrastructure to collecting and tracking severe weather reports – something that would have been impossible for CU. The 2016 hail depth pilot project provides us with information about the frequency and distribution of thunderstorms with large hail accumulations, which were limited prior to this project. Although hail accumulations map are currently not available, the reports, which arrive mainly via twitter in real-time, can be related to observations and products that are available through AWIPS II. The post-processed data (e.g., hail accumulation maps) in relation to the reports, help us to understand the nature of this phenomenon.

Through this partnership project, the NWS was able to reach out to partners in the media and to CoCoRaHS regarding these high impact events. CU and NWS worked together to develop social media content and a form that is used to document accumulating hailfalls. They also used social media to solicit photos and reports of accumulating hail, and received many such reports throughout the period of study. The NWS also was able to archive satellite, radar, numerical weather prediction output, and upper air data for all accumulating hail cases analyzed.

CU and NWS will continue to collaborate on that topic. However, the partner proposal helped us understanding better the data availability through AWIPS II and how new products can be implemented into the forecast system. It also helped developing a hail accumulation data base for 2016.