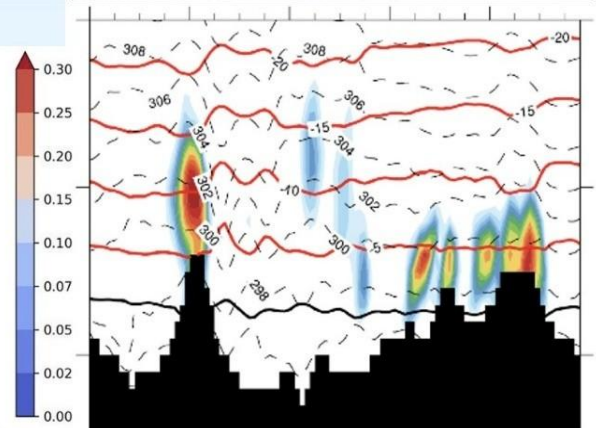
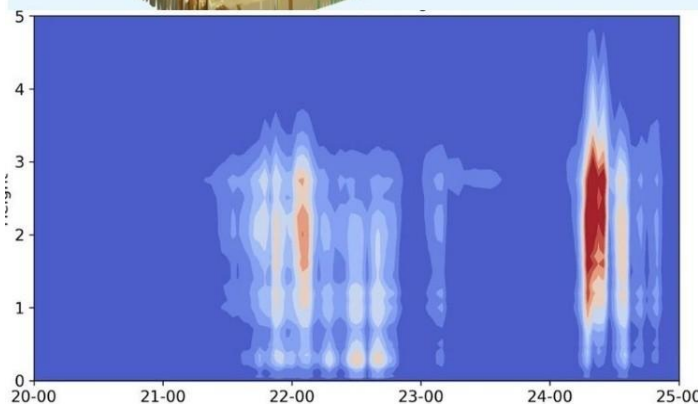
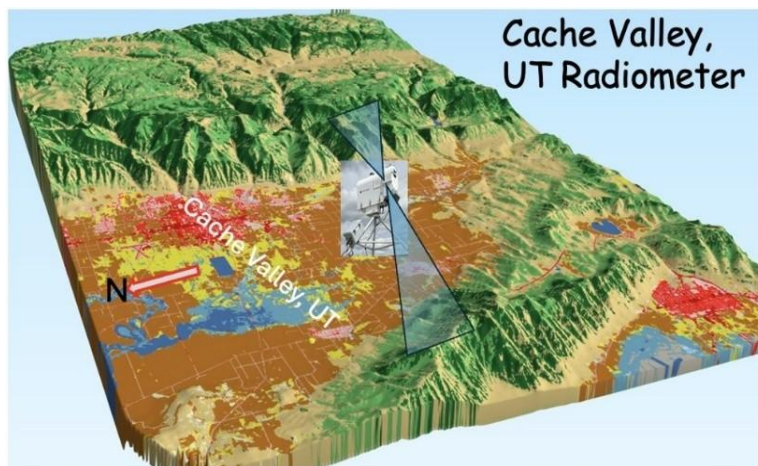


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VOLUME 57 Issue 1, 2025 WEATHER MODIFICATION ASSOCIATION



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OF WEATHER MODIFICATION FOR BENEFICIAL USES

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COVER PHOTO: Cover image: This JWM volume covers 1 year. The cover photo is courtesy of Binod Pokharel, and the radiometer belongs to the Utah Division of Water Resources at Cache Valley, UT., and Pokharel et al. as part of the technical submission titled, Evaluation of WRF Model Performance in Forecasting Supercooled Liquid Water Across the Uinta Mountains of Utah, presented herein.

THE WEATHER MODIFICATION ASSOCIATION

The Weather Modification Association was organized in 1950 to develop a better understanding of weather modification among program sponsors, the operators and members of the scientific community. In 1966, the first suggestion for a professional journal was proposed and Volume 1, Issue No. 1, of the Journal of Weather Modification was published in March 1969. This historic publication now includes 57 volumes (59 issues). Originally called the Weather Control Research Association, the name of the organization was changed to the Weather Modification Association in 1967. During its long history, the Association has:

- Pressed for sound research programs at state and federal levels.
- Promoted a better understanding of weather modification for beneficial use.
- Acted as a disseminating agent for literature.
- Provided extensive testimony before many federal, state and local committees and agencies in regard to all aspects of weather modification research and operations.
- Assumed an active role in the promotion of policy statements concerning all aspects of weather modification.
- Developed active positions on ethics, minimum standards for operations, and a strong certification program for operators and managers.
- Published the Journal of Weather Modification, the only professional journal in the world totally dedicated to the operational, societal, economic, environmental, legal and scientific aspects of weather modification.

The Journal is published annually. Its articles are related to weather modification research, operations, technology including instrumentation, with a historical emphasis on operations. Papers are always welcome for consideration in either the scientific papers, or technical notes and miscellaneous paper sections. The technical notes and miscellaneous section has technical notes and possibly information about the Journal, messages from the Weather Modification Association, 'In Memory' notes about people in the weather modification community, and member comments about relevant weather modification community topics. A nominal charge of \$100 per page or \$2700 USD per 3000 words plus extra charge for figures, tables, equations, and copyediting will be charged for each paper published in JWM's final double-column format. This fee is charged for all papers, foreign and domestic.

Additional information on the individual classes of membership can be found in the Articles of Incorporation found at <http://www.weathermodification.org>.

Applications for membership on a calendar year basis, as well as additional information, can be obtained by writing to WMA at the permanent address of the Association:

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MESSAGES

President's Message: It has been an honor to serve all of you during this past year. The Weather Modification Association is a growing organization that brings together people from a variety of career paths and scientific backgrounds. This includes students, professors, and others from the academic sphere, a number of both long-established corporations and more recent startups, and individuals with an interest in advancing the science and technology used in cloud seeding. The organization continues to develop in terms of its bylaws, membership structure, and community outreach, with a good number of changes taking place in 2025 and 2026. The WMA is international in scope and one of our goals is to grow this international reach to support scientific research and operational programs around the globe. There has also been a renewed focus on communicating complex scientific topics via a variety of different media, in a way that augments the understanding of these issues and supports critical thinking and decision making in the community at large. WMA members are strongly encouraged to present scientific research and developments from the field both at the annual conferences, and in the form of journal articles, as we continue to grow the collection of scientific knowledge in this field of work. This will allow for maximum benefit to the public, with the goal of wisely and carefully stewarding the natural resources we have been given.

David Yorty

President, Weather Modification Association 2025-2026

Editor's Message: The Journal of Weather Modification (JWM) Volume 57 includes 2 science papers, and the President's and Editor's messages. We continue to work toward increased paper submissions as our transition to the new platform nears completion. We are also working toward a refreshed vision for the journal that accommodates emerging communication platforms and outreach streams. This evolution is especially important as we face an aging membership, a transition toward shorter contributions, and a growing global need for potable water, water security, and sustainability.

The Journal of Weather Modification is an integral part of the WMA. It exists to document and facilitate interaction among operational, developmental, academic/research, and stakeholder communities within and beyond our organization. Proceeds from the JWM support WMA activities and help offset annual meeting costs. Each scientific article and technical note published in JWM receives 2 reviews and a unique DOI, ensuring global visibility and accessibility.

"Short" contributions, such as technical notes based on WMA meeting presentations or operational project reports adapted to the JWM format, are just as important as full scientific articles. We also welcome contributions emerging from newer communication and outreach platforms. The process for assigning DOIs to some of these newer formats is still being finalized, but we are committed to making it work. Our current publishing platform does have a streaming capability.

If you are considering a paper or topic-relevant submission, please contact the JWM Editor or any member of the Editorial Board to discuss its suitability. You may also visit our updated guidelines and submission page: <https://journalofweathermodification.scholasticahq.com/for-authors>. Click on submit the paper 'wigit'. Once done a popup menu appears and includes a choice between submitting a revised manuscript or a new submission. Submissions (including scientific articles, technical notes/short contributions, President's Messages, In Memoriam pieces, and outreach/communication topics) are accepted year-round through the journal's website. You may need to create an account on our new journal host. We now use an improved review and publication system hosted by Scholastica, which is fully active on the association's journal webpage. *Tom*

Dr. Thomas P. DeFelice, WMA-CO/CM

WMA JWM Editor, 2025-2026

SCIENCE PAPERS

Evaluation of WRF Model Performance in Forecasting Supercooled Liquid Water Across the Uinta Mountains of Utah

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⁴ Water Resources, Utah Department of Natural Resources Keywords: Radiometer, WRF Model, Supercooled Liquid Water, Utah <https://doi.org/10.54782/001c.159840>

ABSTRACT

This study evaluates the ability of a high resolution (2-km horizontal resolution) Weather Research and Forecast (WRF) model driven with North American Mesoscale (NAM) output to simulate cloud liquid water (LW) over the Uinta Mountains of Utah. Radiometer observations of LW (a critical ingredient for effective cloud seeding), are compared with modeled cloud conditions to better understand the ability of an operational WRF configuration to provide insight into impending cloud seeding conditions. The LW was measured on the southern and northern slopes of the Uinta range during the winters of 2019 and 2022, respectively. The WRF model's performance in forecasting LW was assessed by comparing it with the observed radiometer data. Results indicate that the model accurately predicted LW during major storms but exhibited discrepancies in magnitude, overestimating values on the southern slope and underestimating them on the northern slope. Statistical analysis revealed a bias score of 0.83 for 2019 and 1.06 for 2022, with a probability of detection of 0.74 and 0.70, respectively. This study demonstrates the value of the WRF model for supporting cloud-seeding operations while emphasizing the need for additional radiometer measurements to evaluate LW forecasts under very limited data availability. Because Utah's complex terrain and varying mountain orientations create strong spatial variability in LW, expanded observations are crucial for validating model output and improving forecasts through better selection of cloud-microphysics and boundary-layer schemes. While the findings provide useful guidance for optimizing precipitation-enhancement strategies in Utah's mountainous regions, WRF performance must be further assessed using longer-term LW datasets, as current forecasts show both positive and negative biases across the Uinta Range.

1. Introduction

Glaciogenic cloud seeding, a weather modification technique aimed at enhancing precipitation by seeding clouds with silver iodide (AgI), has garnered significant attention as a potential tool to address water scarcity and mitigate drought impacts in various regions worldwide (Pokharel et al. 2017; Rauber and Blanchard 2007; National Research Council 2003). This innovative approach holds promise for augmenting precipitation in mountainous areas, where water resources are vital for ecosystems, agriculture, and urban populations (Rauber and Blanchard 2007). Cloud seeding operations have a long history in Utah and across the Mountain West

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region of the United States (Breed et al. 2014); however, the scientific understanding of cloud seeding and meteorological intervention remains limited (Rauber et al. 2019; DeFelice 2018).

The history of glaciogenic cloud seeding stretches back several decades, with early experiments dating back to the mid-20th century (Cooper 1985). In the United States, Utah has been at the forefront of cloud seeding research and operational implementation, spearheading efforts to evaluate the effectiveness of cloud seeding as a water management strategy (Griffith et al. 2022). The state's arid climate and reliance on mountain snowpack for water supply make it an ideal testing ground for cloud seeding initiatives (Pokharel et al. 2021). Over the years, numerous cloud seeding projects have been conducted in Utah, utilizing various seeding techniques and targeting specific weather conditions to maximize precipitation enhancement (Pokharel et al. 2021).

Furthermore, there are widespread cloud seeding operations across the Mountain West region of the United States, encompassing states such as Colorado, Wyoming, Idaho, and Montana (Tessendorf et al. 2020; Friedrich et al. 2021; Pokharel and Geerts 2016; Breed et al. 2014; French et al. 2018). These initiatives, often conducted by water management agencies, research institutions, and private entities, aim to bolster snowpack levels, enhance water availability, and mitigate the impacts of drought on local communities and ecosystems (Rauber et al. 2019). The Mountain West's complex terrain and diverse meteorological conditions present unique challenges and opportunities for cloud seeding, prompting ongoing research and operational efforts to optimize seeding techniques and assess their efficacy in different geographic and climatic contexts (Rauber et al. 2019).

Glaciogenic cloud seeding, a technique designed to enhance precipitation by introducing additional ice nuclei into clouds, demonstrates high efficacy when abundant liquid water (LW) is present within clouds at temperatures below approximately -5°C (Pokharel et al. 2017; Pokharel and Geerts 2016). However, accurately measuring LW poses a significant challenge, particularly when considering larger areas, as point measurements may fail to represent the variability observed over complex terrain affected by wind, turbulence, and cloud dynamics (Hobbs and Rangno 1979). Furthermore, weather forecasting models encounter difficulties in simulating LW due to their inability to accurately capture boundary layer turbulence over mountainous regions, where air motion exhibits considerable variation (Kringelbotn et al. 2011). The selection of appropriate model schemes and boundary conditions further complicates LW forecasting, as certain physics schemes excel in temperature prediction while others perform better in forecasting precipitation and cloud water content (Bannister et al. 2020). Therefore, addressing these challenges in LW measurement and forecasting accuracy is crucial for optimizing the effectiveness of glaciogenic cloud seeding operations, particularly in regions characterized by complex terrain and dynamic meteorological conditions.

This study evaluates the presence of LW over the two sides (south and north) of the Uinta Mountain Range based on radiometer observation and compares the measurements with high resolution WRF model forecast data. This is the first model verification work of LW over the mountains in Utah. Continuous improvement of the model is essential, and observations play a critical role in this process. Observational datasets are used not only to evaluate model performance in forecasting LW, but also to identify systematic biases and inform improvements to model physics and parameterizations. Because accurate LW forecasts are crucial for cloud seeding operations and a dense observational network is not feasible across all of Utah, the model can be effectively utilized if the forecast accuracy meets the operational requirements for cloud seeding.

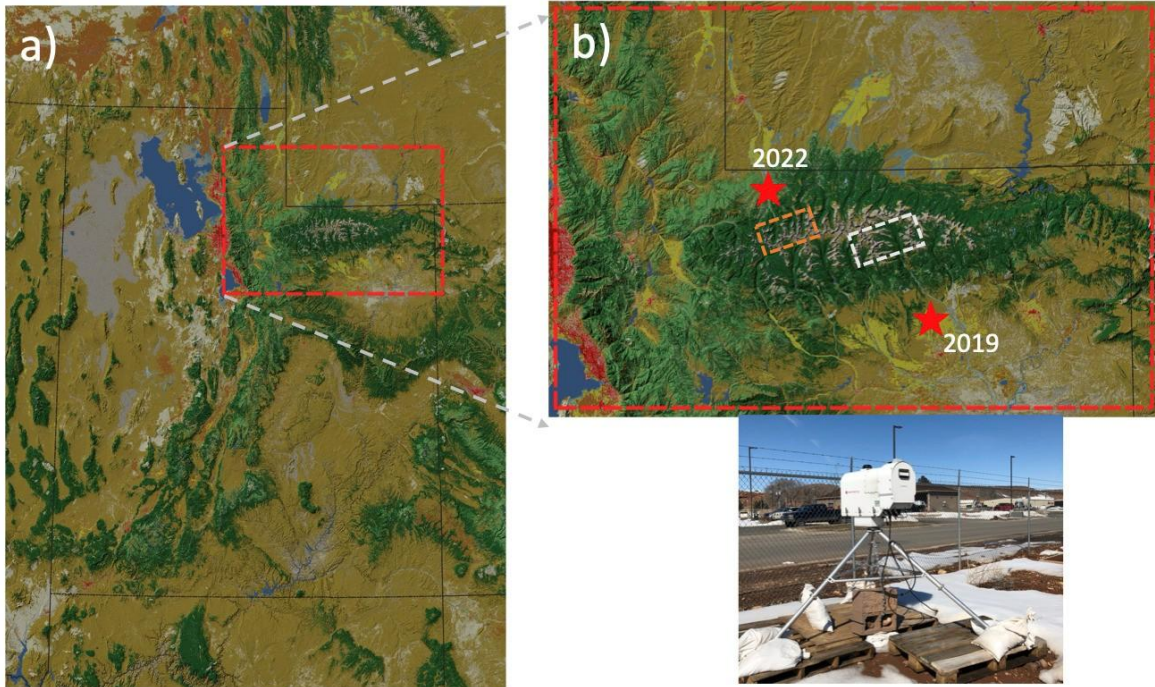


Figure 1. Land use and land cover map of Utah (a) and the Uinta Range (b), showing radiometer deployment locations in 2019 and 2022. The inset photo (2019) was taken at the Roosevelt, UT site. The white and yellow boxes in panel (b) denote the regions used to compute average liquid water path (LWP) from the WRF model for comparison with radiometer observations from 2019 and 2022, respectively.

2. Study Area, Data and Methods

This study focused on the Uinta Mountains, where a radiometer was employed to measure cloud LW, crucial for glaciogenic cloud seeding. Both the northern and southern sides of the Uinta range were targeted for cloud seeding, with LW measurements obtained for both sides, as illustrated in Figure 1.

The Utah Division of Water Resources (DWR) installed a radiometer in Roosevelt, Utah, to support operational cloud seeding activities over the Uinta Range during the winter of 2019 (January–March). In the winter of 2022 (January–May), the instrument was relocated to the northern side of the range, where it was operated at 20 degrees elevations targeting north and south directions. The radiometer also collected vertically pointing measurements to derive the vertical profiles of cloud LW. The data availability period is shown in Figure 2.

This is a unique dataset that includes vertically integrated liquid water path (LWP) observations from both the southern and northern sides of the Uinta Mountains. As most storms approach from the south, with a smaller number originating from the north, these observations provide valuable insight into the frequency and magnitude of LWP on both sides of the range. Although the measurements were not conducted simultaneously during the same winter season, the dataset enables a useful comparison of cloud liquid water characteristics across the two mountain flanks.

Radiometer data collected during both seasons underwent processing using Radiometrics software to produce final version (level 2) datasets, forming the foundation of analysis in this study. These datasets include measurements of both LWP and liquid water content profiles, offering valuable insights into cloud microphysical properties and their variations over the study area. Additionally, LWP was calculated using the liquid water profile data from the radiometer measurements to compare with existing LWP data derived from the Radiometrics

software. In addition to radiometer data, this study integrates forecast data from the Weather Research and Forecasting (WRF; Skamarock et al. 2008) model for the 2018/2019 and 2021/2022 winter seasons. These forecast data, aligned with the area covered by radiometer measurements, allow for a comprehensive analysis of cloud liquid water dynamics and the performance of the WRF model in simulating these phenomena. Although not directly related to the primary focus of this study, radiometer and forecast data from the 2018/2019 winter season were also utilized for comparative analysis to shape the final operational configuration of model physics; primarily planetary boundary layer and cloud microphysics. The results and analysis presented here further explore the ability of these “optimized” model physics configuration to capture cloud conditions over the added mountain ranges and the seasonally-unique large-scale synoptic patterns of the 2021/22 season. This comparative approach facilitates the evaluation of the WRF model’s performance in simulating cloud liquid water content across different years, providing valuable insights into the model’s reliability and predictive capabilities.

The WRF model is initialized by 12-km North American Mesoscale (NAM) output with 3-hourly lateral boundary conditions provided over an 84-hour (3.5 day) lead time. The model domain covers the entirety of Utah and into the surrounding states (see [Figure 1](#)) and initially (from 2019) operated at a 3 km horizontal resolution with 38 vertical levels; however, shortly after implementation in 2019 the model’s resolution was improved to 2 km horizontal grid spacing and 40 vertical levels. Alongside the implementation of the finer model resolution, the model’s physics options were optimized for cloud conditions during a multi-physics comparison phase using radiometer observations from the 2018/19 season. Many of the model physics options were selected to maintain consistency with the NCEP parent model’s configuration, as this minimizes confounding biases from parameterization designs. However, the primary focus of these comparisons was on cloud microphysics and boundary layer options, as these factor heavily into cloud conditions and boundary layer stability, both of which are critically important for cloud seeding decision-making. For this, we compared a collection of modeled forecast conditions against observations, particularly considering the LWP from radiometer measurements. Model physics configuration skill was assessed by comparing the timing and magnitude of the modeled vs observed presence of cloud liquid water to identify better performing model physics in capturing the timing, duration, and magnitude of cloud conditions. Based on the comparison, the Thompson graupel scheme (Thompson et al. 2008) was chosen for subsequent analyses for cloud microphysics, and MYNN 2.5 level TKE (Olson et al. 2019) for boundary layer physics. The comparison and subsequent refinement of model configurations led to improved WRF forecast performance, strengthening its applicability for operational cloud seeding guidance.

The vertically integrated LWP from the WRF model was averaged within the designated boxes for the two study periods from 2019 and 2022 as shown in [Figure 1b](#) and compared with the radiometer-measured LWP. Statistical methods were employed to evaluate the WRF’s performance in predicting the vertically integrated LWP during the two cloud seeding seasons. The methods used for evaluating the WRF LWP are detailed in [Tables 1](#) and [2](#).

3. Results

3.1. Vertical Profile of LW

The liquid water profile was measured targeting the Uinta Range from the southern side in 2019 and from northern side in 2022. [Figure 2](#) shows the February and March 2019 LW profiles measured from Roosevelt, Utah. The radiometer is pointing north to measure the profile of LW over the Uinta Mountains ([Figure 1](#)). Throughout February and March 2019, LW was frequently observed, coinciding with above-normal precipitation measured in Utah during that winter (result not shown). The majority of LW was observed below 3 km above ground level (agl), although in certain cases (early February in the upper panel and later March in the lower panel), LW was observed at higher level.

Table 1. Statistical and categorical indices for validation of WRF LWP forecast.

Variable	Statistics	Definition	Equation	Perfect score
Vertically Integrated liquid water path (LWP)	Bias Score (BIAS)	Measure of the overall forecast bias for continuous and probabilistic forecasts	$\frac{(A + B)}{(A + C)}$	0
	Probability of Detection (POD)	Measures the fraction of observed LWP events that were correctly predicted	$\frac{A}{(A + C)}$	1
	Accuracy (ACC)	Measures the fraction of forecasted events that were correct	$\frac{A + D}{(A + B + C + D)}$	1
	False Alarm Ratio (FAR)	Measures the fraction of observed no precipitation events that were correctly predicted	$\frac{B}{(A + B)}$	0
	Threat Score (TS)	Measures the fraction of observed and/or forecast events that were correctly predicted.	$\frac{A}{(A + B + C)}$	+1
	Heidke Skill Score (HSS)	Measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance	$\frac{(PC - E)}{(1 - E)}$	1

Where, A, B, C, and D in Equations 1 – 5 are defined in [Table 2](#). Further in Equation 6, PC is the proportion correct of forecast and E is the PC for correct random forecast. All of the above equations are adopted from Jolliffe and Stephenson (2012).

Table 2. Contingency table to define observed LWP categorical scores for the evaluation of WRF forecast with radiometer observation.

Event Observed			
Event Forecast		YES	NO
	YES	A	B
	NO	C	D

Where, A = Hit, B = False Alarm, C = Miss, D = Correct Negatives

Four months of data were collected and analyzed from January to April 2022. The radiometer, positioned on the northern side of the Uinta ([Figure 1](#)), captured LW profiles from 2022. [Figure 3](#) illustrates these profiles, indicating less frequent LW observed during the 2022 winter season. This reduced LW frequency is consistent with the anomalously low precipitation during the winter of 2021–2022, which was one of the driest winters on record in Utah (results not shown) and was characterized by less frequent storm activity.

Similarly to 2019, the northern side of the Uinta on 2022 primarily observed LW at lower levels (up to 3 km agl), with some higher-level LW in April. Storms with significant LW were sparse in January, with only two observed around January 21 and 24. February saw a few storms, with LW low in the first half but increasing in the second half. The radiometer experienced downtime during March, and although LW was low in the first week and towards the end of the month, some storms were observed. April witnessed several storms, with LW observed around April 5 and in the middle of the month, but a notable amount of LW was observed around April 23–24, indicating a potentially favorable seeding window.

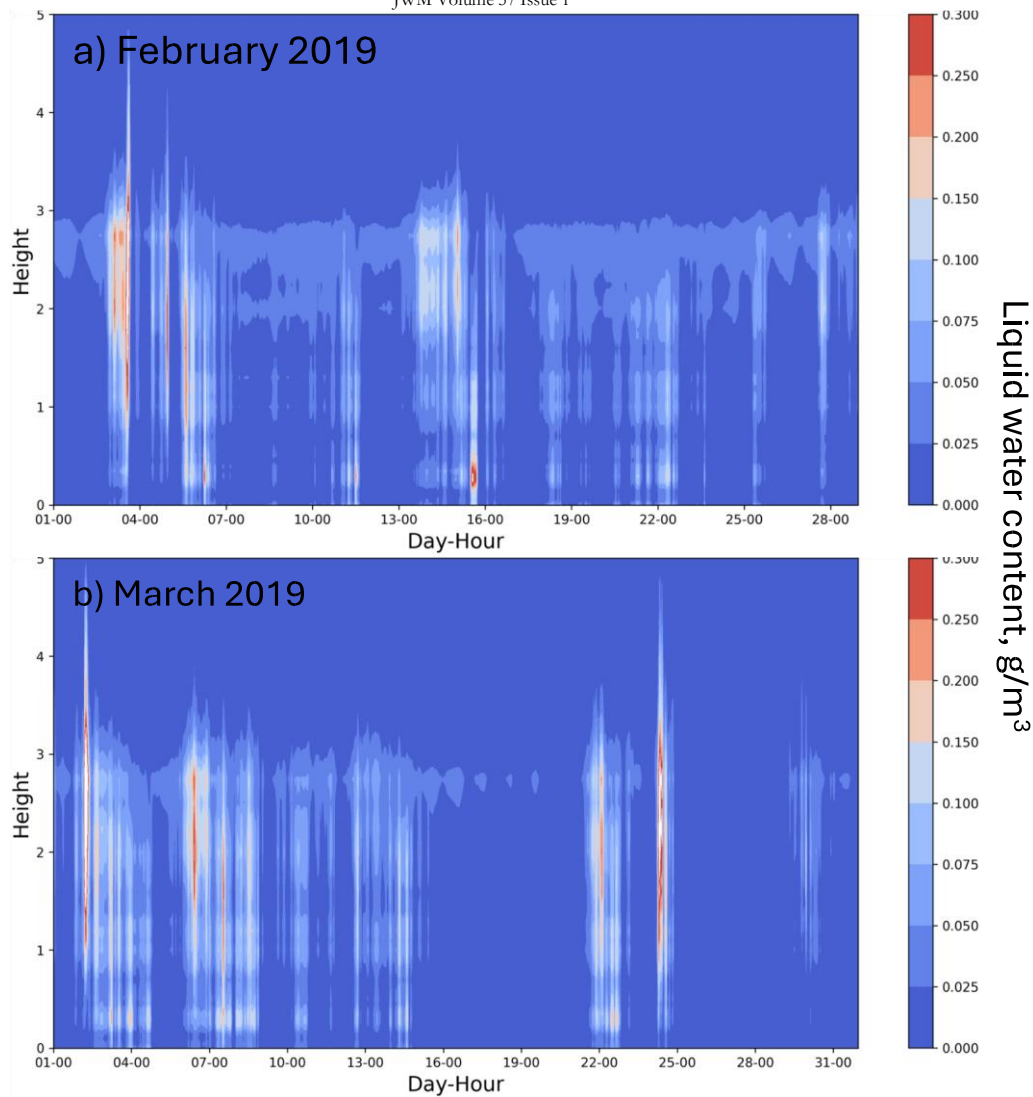


Figure 2. Radiometer measured LW profile from Roosevelt, UT during the winter of 2019. The upper panel (a) shows the measurement from 1 to 28 February and the lower panel (b) shows the measurement from 1 to 31 March 2019.

Further analysis of LW content and temperature profiles during selected storm events revealed notable atmospheric features (Figure 4). Two cases characterized by elevated LW values were analyzed to assess the corresponding vertical temperature structures measured by the radiometer. In early March (Figure 4a,b), elevated LW content was detected at higher altitudes, accompanied by a pronounced temperature inversion below 1 km. A similar pattern was observed on 24 March 2019 (Figure 4c,d), with high LW aloft and a distinct inversion layer below 1 km. In both cases, the maximum temperature occurred near 1 km, suggesting a stable layer below. Above this level, the atmosphere became increasingly unstable, likely facilitating convective development and the upward transport of moisture, resulting in enhanced LW content up to 3 km.

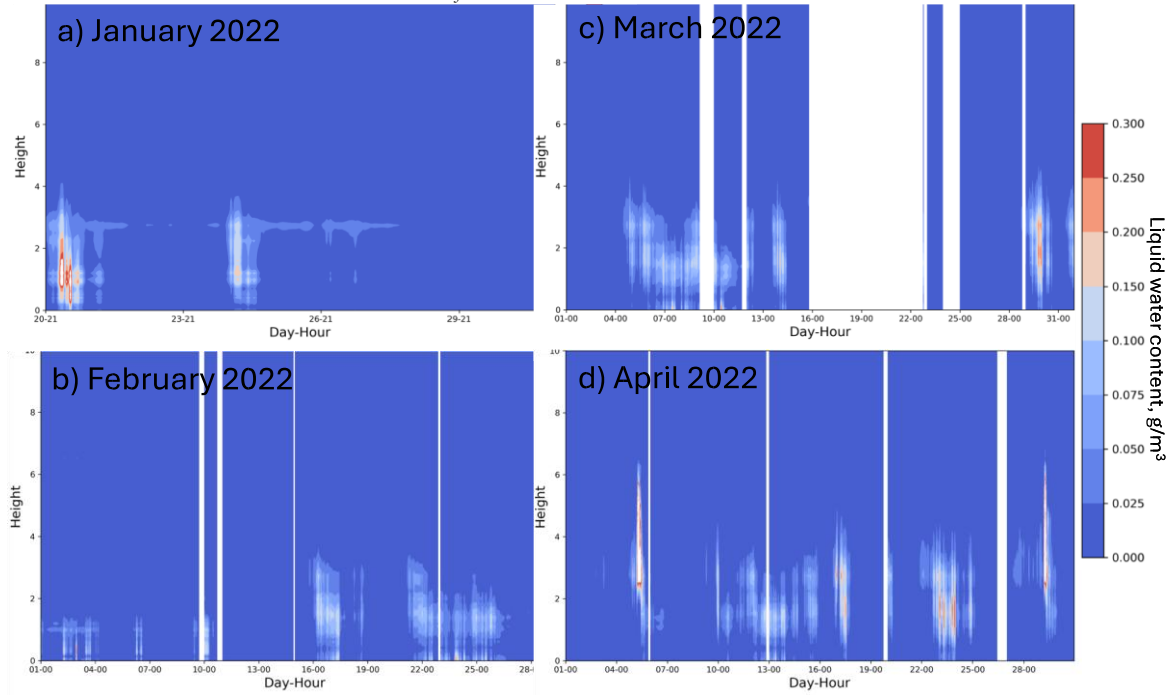


Figure 3. Radiometer measured LW profile from the Northern side of Uinta during the winter of 2022. The upper left panel a) shows the measurements from 1 to 31 January, b) shows the measurements from 1 to 28 February, c) shows the measurements from 1 to 31 March and d) shows the measurements from 1 to 30 April 2022.

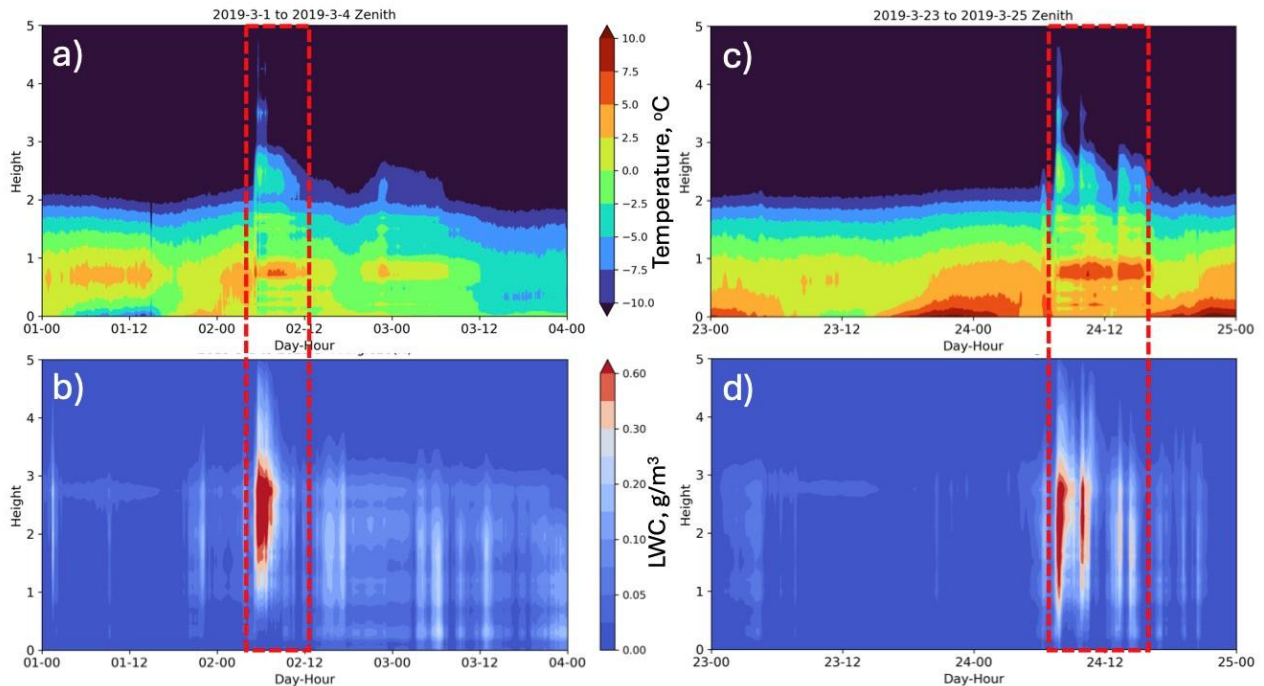


Figure 4. Radiometer measured temperature (upper panels) and LW (lower panels) profiles from 1 to 3 March 2019 (left panels, a) & b)) and 23 to 24 March 2019 (right panels, c) & d)). The box with red dashed line indicates the period of temperature inversion just below 1km agl.

3.2. WRF and Observed Liquid Water Path (LWP)

The WRF model has been employed to simulate cloud seeding operations in Utah since 2018. It is initialized four times a day using North American Mesoscale Modeling (NAM) forecast data. Both the radiometer and WRF provide LW profiles, albeit with significantly different data

frequencies. The radiometer offers profile data at a 20 degree elevation angle targeting the mountain. As it targets LW measurement over the Uinta range, we utilized profile LW data to calculate the LWP. Despite the radiometer data providing LWP, it contains unrealistically high values and biases that are impossible to eliminate. To validate the model data, realistic LWP data from observations must be obtained, achieved by calculating LWP from scratch using LW profile data through the Python programming language. The same technique is applied for WRF model LWP calculation.

Radiometer data frequency fluctuates from 2 to 5 minutes, whereas the WRF model provides broader spatial coverage but coarser data frequency. Thus, both measurements and models have limitations, but model data can be utilized if it aligns with observations. This section primarily focuses on comparing WRF model forecasts with observations, concentrating on LWP.

To align data frequency, radiometer LWP is interpolated (averaged) to 3-hourly data for comparison with model data. The comparison of LWP during February and March 2019 from observations and forecasts is depicted in [Figure 7](#). The model forecast accurately predicted LWP during major storms in February ([Figure 5a](#)); however, during periods of low LWP (2-21 February), the model underestimated compared to observations. Additionally, the model overpredicted in some instances, notably around the 19 February storm where observed values were considerably smaller. Similarly, the WRF model accurately captured major storms, predicting LWP at the correct times in March ([Figure 5b](#)). Notably, the model predicted smaller LWP during the earlier period (around 1-5 March, [Figure 5b](#)), but consistently overpredicted LWP compared to observations for most days, consistent with February. It's important to note that measurements and model data are from the southern slope of the Uinta range.

Further evaluation of WRF forecasts considered radiometer measurements from January to April 2022. The radiometer, targeting the northern slope of the mountains, was installed on January 20th, with data available from January 21st and for entire months thereafter. However, the instrument encountered some errors during measurements, resulting in gaps in observational data as seen white area in [Figure 3](#). LWP data from the radiometer and WRF model forecast are depicted in [Figure 6](#). In January ([Figure 6a](#)), observed values were significantly larger than WRF forecasts, although the model did predict LWP, albeit smaller values. The WRF forecast performed better in February ([Figure 6b](#)), with model values comparable to the observed LWP for the first half of the month. However, observed values surpassed model data in the second half of February, with the model failing to capture observed LWP after February 22nd. March ([Figure 6c](#)) displayed a similar trend to February's latter half, with observed LWP values surpassing WRF forecasts. In April ([Figure 6d](#)), the WRF model successfully captured all storms, with observed and forecasted LWP values largely aligned, though most radiometer values were larger than the forecast.

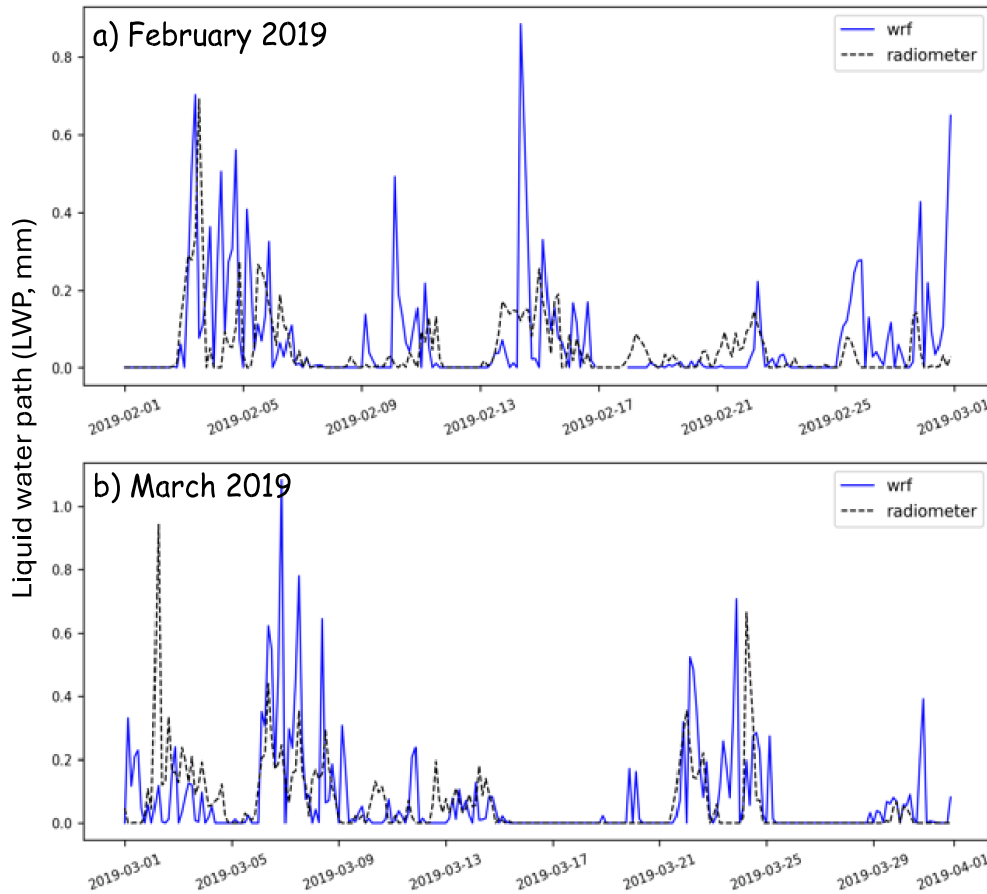


Figure 5. Three-hourly vertically integrated liquid water path (LWP) from radiometer measurements (dashed line) and WRF forecast (blue line) for the month of February (a – upper panel) and March (b – lower panel) of 2019.

3.3. Statistical Analysis

The observed and forecasted LWP values were compared using standard statistical metrics, as summarized in [Table 1](#). Daily averaged values from both observations and the Weather Research and Forecasting (WRF) model were used for analysis, as these statistical tools are most effective for daily datasets. An initial qualitative comparison categorized LWP detection under four conditions: a) both radiometer and WRF forecast showed LWP (yes, yes), b) neither WRF nor radiometer showed LWP (no, no), c) radiometer measured LWP but WRF did not forecast (yes, no), and d) radiometer did not measure LWP but WRF forecasted (no, yes) as given in [Table 2](#). The comparison for 2019 ([Table 3](#)) indicates that WRF predicted LWP on most days, correctly forecasting 31 events and missing 11. There were also four days when WRF falsely forecasted LWP in the absence of radiometer detection. In contrast, the 2022 results show a higher frequency of missed events by WRF when LWP was observed by the radiometer. It is important to note that Radiometrics did not calibrate the neural network for the correct location and elevation until February 10, 2022, which may have affected data quality prior to this date. Therefore, only data from February 11, 2022, onward were considered for comparison with observed data, particularly for the forecast verification results presented in the following section.

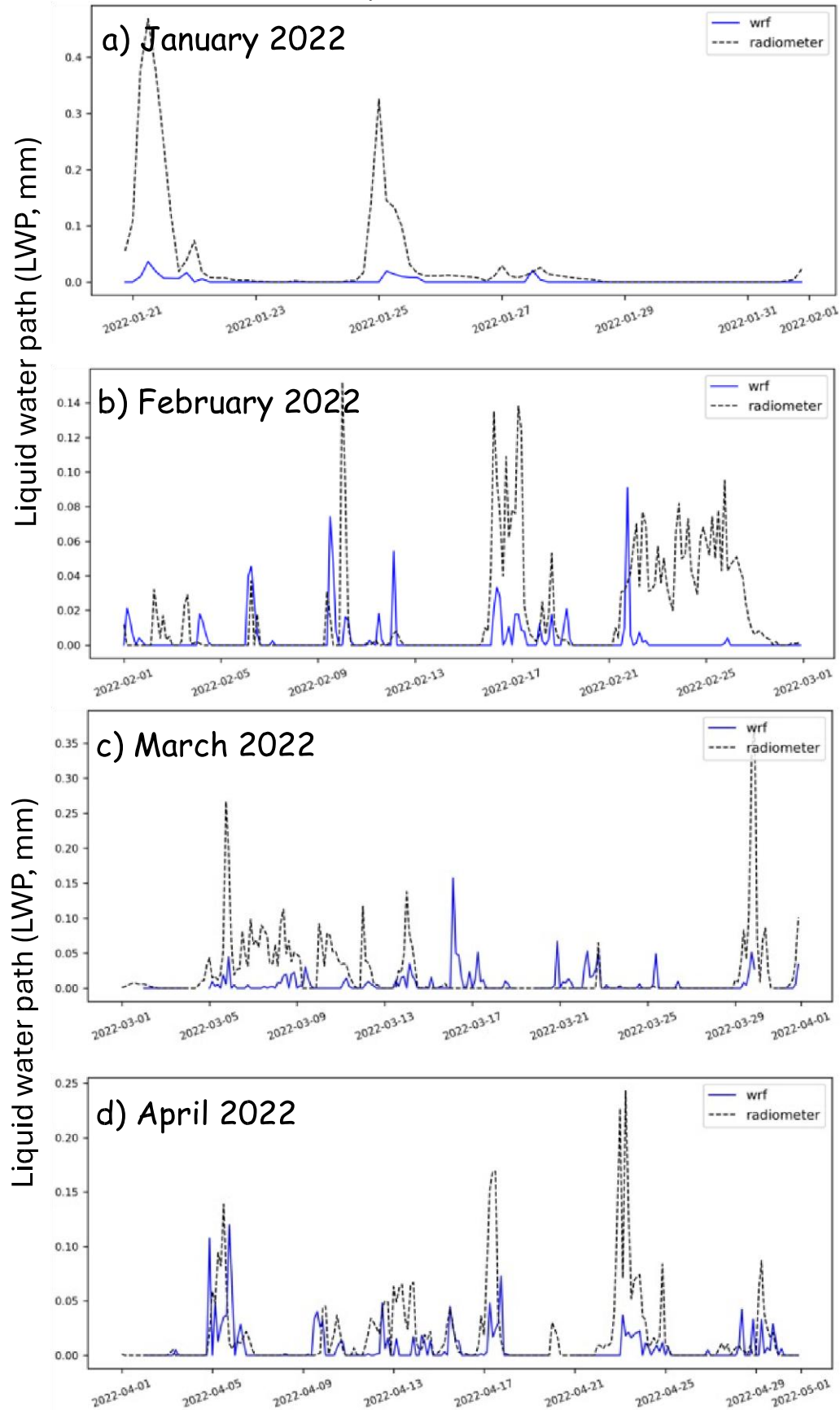


Figure 6. Three-hourly vertically integrated liquid water path (LWP) from radiometer measurements (dashed line) and WRF forecast (blue line) from January to April 2022. a) show the model and observed LWP for January (for the period from 21 to 31 January), b) for 1 to 28 February, c) for 1 to 31 March, and d) for 1 to 30 April 2022.

Table 3. Contingency table showing the number of events in which observed LWP exceeds 0 and is correctly forecasted by the WRF model, as well as cases of missed events and false alarms, for the periods 1 February–31 March 2019 and 11 February–30 April 2022. Row and column totals are included for each year.

year	Event Forecast (with total samples)	Event Observed (with total samples)	
		YES (42 in 2019 and 54 in 2022)	NO (28 in 2019 and 36 in 2022)
2019	YES (35)	A = 31	B = 4
	NO (35)	C = 11	D = 24
2022	YES (61)	A = 42	B = 19
	NO (29)	C = 12	D = 17

Table 4. Statistical indices calculated from observed and WRF forecasted LWP from the data from 2019 and 2018. The data used in this table are from February and March 2019 and 21 January to 30 April 2022.

Variable	Statistical Indices	Value	
		2019	2022
LWP	Bias Score (BIAS)	0.83	1.13
	Probability of Detection (POD)	0.74	0.78
	Accuracy (ACC)	0.79	0.66
	False Alarm Ratio (FAR)	0.11	0.31
	Threat Score (TS)	0.67	0.58
	HSS	0.57	0.26

Further evaluation using additional statistical metrics is presented in [Table 4](#). The WRF model exhibited a consistent bias score (0.8 in 2019 and 1.13 in 2022, ideal value is expected to be close to zero), and the probability of detection was 0.7 (ideal = 1). In contrast, the false alarm ratio remained low, at 0.1 in 2019 and 0.31 in 2022—close to the optimal value of zero in 2019 but higher in 2022. Moreover, the threat score (TS) and Heidke skill score (HSS)—for which values closer to one indicate better performance—are higher in 2019 than in 2022 ([Table 4](#)). This suggests that the model struggled more to forecast LWP during northerly flow conditions (2019 radiometer measurements) than during southerly flow conditions (2022 radiometer measurements). Nevertheless, these results indicate that although the model performs reasonably well in detecting the presence or absence of LWP, it has limitations in accurately predicting LWP magnitudes.

4. Discussion

The WRF forecast shows good to fair agreement with radiometer-derived LWP on both sides of the mountain range at the temporal scale. However, liquid water can vary substantially over complex mountainous terrain, where boundary-layer turbulence plays a critical role in LWP development, as previously observed over the mountains of Wyoming (Pokharel et al. 2014; Pokharel and Geerts 2016).

Two contrasting synoptic conditions produced distinct LWP distributions on the two sides of the mountain range, as shown in [Figure 7](#). The southwesterly flow during the 3 February 2019 case ([Fig. 7a](#)) transported abundant moisture and generated much higher LWP, whereas the northerly flow on 16 February 2022 ([Fig. 7b](#)) resulted in very low LWP on the northern side of the Uinta Mountains. However, the WRF forecasts were not fully consistent during these events. The model overestimated LWP in 2019 and underestimated LWP in 2022 relative to the radiometer observations (Figs. [5](#) and [6](#)). Similar overestimation of LWP by WRF compared to radiometer measurements was reported by Cossu et al. (2015) for Bern, Switzerland, during the summer of 2012. These results indicate that the WRF model continues to face challenges in accurately forecasting LWP magnitudes over complex terrain (Kringelbott Nygaard et al.

2011). Chen et al. (2015) demonstrated that assimilating satellite-derived cloud products into the WRF Data Assimilation (WRFDA) system significantly improves the forecasts of LWP, as well as upper-level wind and temperature. Despite these limitations, WRF remains highly valuable in regions with sparse observational coverage, providing important guidance for icing forecasts and cloud-seeding operations, particularly where in situ observations are limited. It should be noted that this study is limited to data from only two winter seasons, and the comparison of liquid water over the two sides of the mountain range does not cover the same time periods. Longer-term and more consistent LWP observations, along with corresponding WRF model outputs across multiple mountain regions, are therefore required to robustly validate and further improve the WRF model using observational data as continuous improvement of the model is essential, and observations play a critical role in this process. Observational datasets are used not only to evaluate model performance in forecasting LW, but also to identify systematic biases and inform improvements to model physics and parameterizations. Because accurate LW forecasts are crucial for cloud seeding operations and a dense observational network is not feasible across all of Utah, the model can be effectively utilized if the forecast accuracy meets the operational requirements for cloud seeding.

5. Conclusion and Recommendation

The WRF model has demonstrated its ability to forecast LWP based on radiometer measurements. This high-resolution operational forecast model provides valuable guidance for

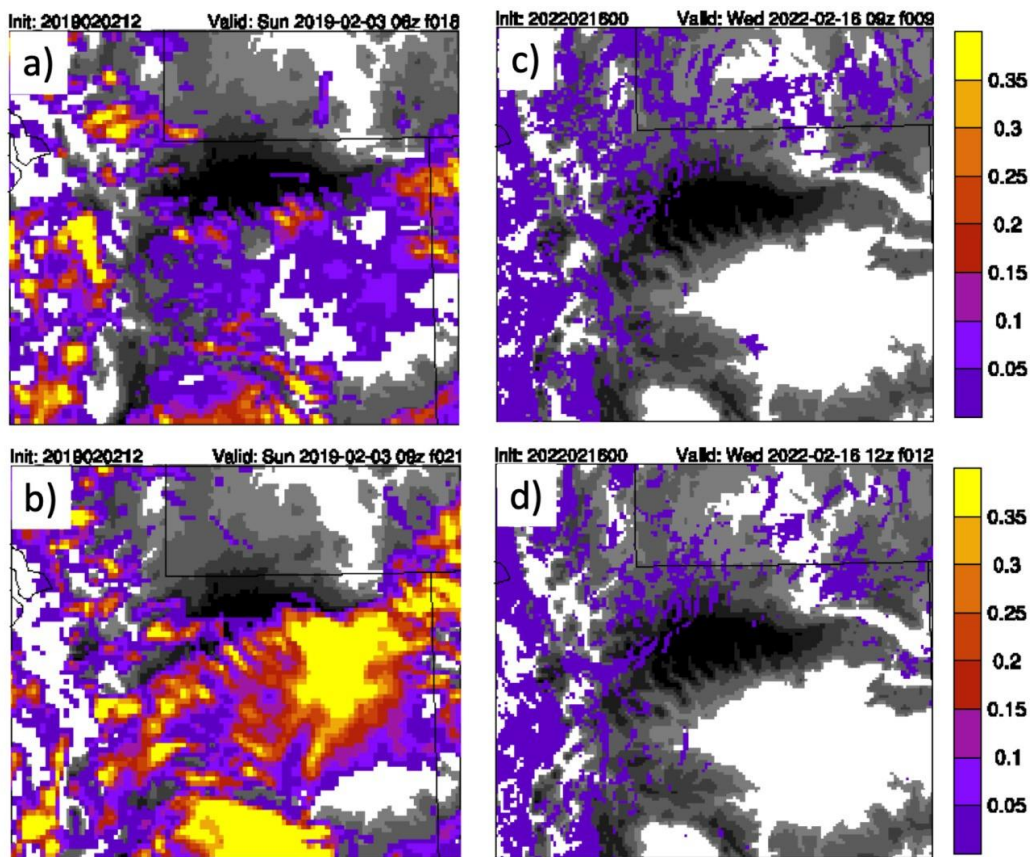


Figure 7. The left panel shows the WRF forecast of liquid water path (LWP) for (a) 06Z and (b) 09Z on 3 February 2019, based on the model run initialized at 12Z on 2 February 2019. The right panel shows the forecast of LWP for (c) 09Z and (d) 12Z on 16 February 2022, based on the model run initialized at 00Z on 16 February 2022. The high LWP observed in 2022 is associated with a southwesterly atmospheric river transporting moisture from the Pacific Ocean, whereas the low LWP in 2019 is linked to a cold air mass under northwesterly flow associated with a cutoff-low synoptic situation (synoptic condition is not shown here).

the Uinta Range, particularly aiding in future seeding operation planning, including the optimization of seeding generator arrays. While this study confirms the reliability of LWP forecasts, some discrepancies in magnitude were observed. Specifically, the WRF model tended to predict higher LWP values over the southern slope of the Uinta Mountains and lower values over the northern slope compared to radiometer observations. Expanding LWP measurements across different mountain ranges in Utah would support improved model testing and validation of various parameterization schemes. Furthermore, additional LWP observations would contribute to more accurate cloud seeding decisions. Future WRF simulations should be validated with increased observational data, particularly radiometer-derived LWP and temperature data. Additionally, comparing radiometer temperature profiles with observed soundings can aid in evaluating inversions.

Cloud seeding operations in Utah's mountainous regions have a long history, and accurately identifying suitable clouds is critical for achieving positive outcomes. Improvements to the seeding program can be made through scientific studies utilizing both model and observational data. The WRF model's ability to forecast liquid water in orographic clouds underscores its utility for seeding operations, emphasizing the importance of continued research and analysis in this field. Collaboration between the private sector (e.g., NAWC), government (e.g. Utah Division of Water Resources) and research groups (e.g. Utah State University) should persist for further research-to-operation advancements.

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Analyzing the Effects of Cloud Seeding on Hail Suppression: A Preliminary Analysis of Radar and WRF Model Data in Western North Dakota

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ABSTRACT

The effectiveness of cloud seeding for hail suppression is evaluated as conducted by the North Dakota Cloud Modification Project. A total of 88 Western North Dakota convective storm cases from 2016-2018 that include both seeded and unseeded storms are analyzed using a radar-based hail size retrieval algorithm. The algorithm determined hail sizes are compared to forecasted hail sizes derived from proximity sounding analysis from the Weather Research and Forecasting (WRF) model. Hail was placed into one of three bins: no hail, hail less than 2 inches in diameter, and hail greater than 2 inches in diameter. Model analysis includes two hail-centric indices, five severe weather indices, and the HAILCAST model. Results show strong agreement between forecasted and observed hail sizes in unseeded cases with 56 percent of cases matching hail size bins for both the forecast and radar-derived observation. In contrast, seeded storms showed less than 50 percent of cases had matching hail sizes. Rather, seeded cases consistently produced radar derived hail sizes smaller than forecasted hail sizes in 20.8 percent more cases than the unseeded category, indicating a hail suppression effect. The hail suppression is statistically significant at the 90 percent confidence level, with a p-value of 0.079. These findings support the potential of cloud seeding to mitigate hail damage and enhance agricultural resilience in Western North Dakota.

1. INTRODUCTION

Hailstorms are a frequent and damaging weather hazard in many parts of the world, particularly across the mid-latitudes. In the United States, hailstorms are more common than tornadoes, with substantial impacts on agriculture, property, and infrastructure (Lepore et al. 2018; Brown et al. 2015). Individual hailstorms can cause upwards of \$1 billion USD in damage (Sander et al. 2013). The risk is especially high in agricultural regions where hailstones are less likely to melt before reaching the ground.

Hail formation begins with a small aerosol particle known as an ice nucleus (Knopf and Alpert 2023). The ice nuclei initiates freezing, resulting in “embryos,” which are frozen particles that are smaller than 5 mm in diameter (Knight and Knight 1970; Federer et al. 1982; Allen et al. 2019). Embryos can be created when raindrops coalesce and then freeze as they enter the storm’s updraft, or when descending frozen precipitation (droplets or rimed graupel) is lofted back into the updraft. As the hail embryo travels through the updraft, water, either as vapor or supercooled liquid, collects via accretion or riming on the embryo, growing the hailstone. This process typically occurs between -10 °C and -25 °C (Nelson 1983). Many factors affect the hailstone trajectories within storms, including fall speed, updraft strength, updraft size, and horizontal wind shear. Ultimately, the longer a hailstone is in the storm’s growth region, the larger it grows (Nelson 1983; Dennis and Kumjian 2017). Such growth sometimes only stops when the storm’s maximum updraft can no longer support the hailstone’s weight.

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To mitigate hail damage, operational weather modification programs employ cloud seeding to introduce artificial ice nuclei to initiate earlier glaciation and alter hydrometeor development (Langerud and Moen 1998). Developing feeder cells that flank more mature cells in a multi-cellular thunderstorm often have high concentrations of supercooled liquid water which does not develop into ice until approximately -20°C (Smith et al. 1997). The slow development of ice allows the feeder cells time to evolve and/or merge with mature cells before precipitation starts. Hail embryos remain aloft throughout this process, thus allowing for significant hailstone growth. When the feeder cells are seeded, nucleation can begin at -5°C ; thereby, enabling precipitation formation to start earlier in the cell's life cycle and limiting hailstone development. Furthermore, cloud seeding produces more ice that results in a greater number of small hailstones as opposed to fewer large hailstones which may occur when seeding does not take place.

Synoptic-scale patterns support thunderstorm development that frequently produce hail in Western North Dakota (Frisby 1963). Therefore, Western North Dakota is a good location to study hail suppression due to its high hail frequency compared to the Upper Great Plains/Midwest region, particularly during June and July, when there is a localized maximum of cold fronts (Morgan et al. 1975). Furthermore, midlatitude cyclones are frequent in July in the Western North Dakota region (Zishka and Smith 1980). Midlatitude cyclones and cold fronts frequently initiate powerful thunderstorms, which increases hail frequency. Furthermore, geography is also important with Western North Dakota being 1000-2000 feet higher above sea level than Eastern North Dakota, which typically results in a lower freezing level. Having a lower freezing level provides less melt time for hail on descent which produces larger stones reaching the ground (Prein and Holland 2018). Furthermore, the semi-arid climate of Western North Dakota makes hail more likely due to increased evaporative cooling within the sub-cloud layer. This suggests that it is less likely that a hailstone will completely melt while falling (Syono and Takeda 1962).

Agriculture plays a central role in North Dakota's economy, consistently accounting for 20 percent, or more, of the state's economic base (Coon et al. 2014). The economic importance of agriculture makes the region particularly vulnerable to hail damage and can impact the livelihoods of many farmers. In fact, annual crop hail losses in North Dakota are estimated at \$299 million USD (Bangsund and Hodur 2019).

To mitigate hail losses, farmers began employing cloud seeding for hail suppression as early as the 1950s (Knowles 2020). While ground-based seeding methods were initially used, aircraft-based seeding became the preferred approach by the 1960s. The North Dakota Cloud Modification Project (NDCMP) was officially established in 1975 as a state-managed initiative (Smith et al. 1997) and has since conducted a yearly summer program. The NDCMP is run with anywhere between five and nine aircraft and two C-band radars in counties choosing to participate each year ([Figure 1](#)). The North Dakota Atmospheric Resource Board (NDARB) has designed the NDCMP to serve a dual purpose of suppressing hail and increasing rainfall (Langerud and Moen 1998). Operations are conducted to seed any cloud within the target area that meets established criteria so long as equipment and personnel are available.

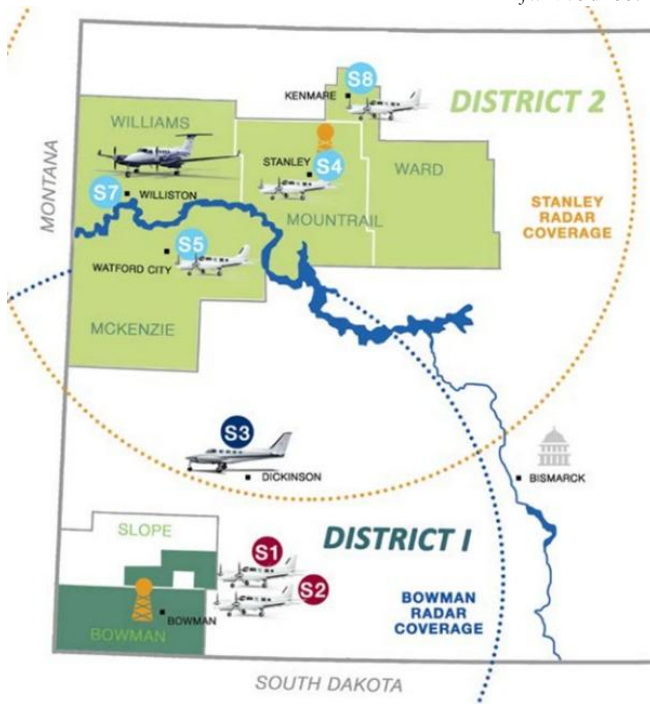


Figure 1. Map of the 2016 North Dakota Cloud Modification Project target area, including aircraft and radar locations. The shaded counties are those that chose to participate, and therefore where seeding took place (Fischer and Willette 2019).

Northern Great Plains precipitation usually forms as a result of cold cloud processes and tend to lack significant ice nuclei, so the NDCMP uses glaciogenic seeding materials, specifically silver iodide (AgI) and dry ice (frozen CO_2) (Smith et al. 1997; Langerud and Moen 1998). Hygroscopic seeding has been tested in North Dakota through the POLCAST campaigns with positive results for precipitation enhancement (Delene et al. 2011; Delene 2016); however, glaciogenic seeding is the only operational seeding method employed by NDCMP. Glaciogenic seeding material is dispersed at cloud base and directly injected into super-cool liquid water clouds near the -10°C level.

The remainder of the paper is organized as follows. Section 2 introduces the datasets, including radar hail diagnostics and WRF model configuration. Section 3 describes the data sets used and the methodology, including case classification, HRA output interpretation, and environmental characterization. Section 4 presents the results for individual cases and the aggregated seeded versus unseeded comparisons. Section 5 discusses the interpretation of the findings, uncertainties, and study limitations. Section 6 provides the conclusions and recommendations for future work.

2. DATA

There are three main approaches for obtaining surface hail data: numerical model simulations, ground-based observations, and empirical relationships or algorithms using remote sensing observations (Prein and Holland 2018). This study employs both radar-derived observations and numerical model simulations to better quantify the effect of cloud seeding for hail suppression.

2.1. RADAR DERIVED HAIL DATA

Dual-polarization radar data from the Department of Defense WSR-88D radar located in Minot, North Dakota, is used for case identification and incorporated into the hail detection algorithm to retrieve the observed hail size. The radar site is located at 48.39°N , -100.86°W at 455 m above sea level (Mohee 2008) and has been operational since 5 January 2001. This radar provides coverage across Western North Dakota, with a 120 km radius domain centered on the

radar site. Dual-polarimetric capabilities are critical for differentiating hydrometeor types and assessing hailstone diameter. The radar covers counties both within the cloud seeding target area and outside of the target area, so both seeded and unseeded storms regularly pass in range of the radar, making it a good choice for this project. Furthermore, while most storms in the project target area are seeded, occasionally there are exceptions, allowing for a more direct comparison between seeded and unseeded storms.

The Hail size Retrieval Algorithm (HRA) builds upon foundational work in hydrometeor identification. While the Hydrometeor Classification Algorithm (HCA) developed by Park et al. (2009) reliably distinguishes between rain and mixed-phase hydrometeors, it does not provide direct estimates of hail size. To overcome this, Ryzhkov et al. (2013) conducted a comprehensive threepart study culminating in the Hail Size Discrimination Algorithm (HSDA). The HSDA employs a fuzzy-logic approach that integrates radar reflectivity (Z), differential reflectivity (ZDR), and cross-correlation coefficient (ρ_{hv}) to differentiate between no hail, small hail (<1 in), large hail ($1-2$ in), and giant hail (>2 in). Building on the HSDA framework, the HRA was developed to refine hail size estimation and improve applicability to operational radar datasets. The HRA is utilized in this project to accurately determine radar indicated hail size. The HRA is composed of six vertical layers which compare the height of the radar sampling volume to freezing and melting layers. The polarimetric radar variables above are assessed within each layer to identify the hail size for each grid point within the domain. The grid spacing for these data points is 1 km times 1 km times 1 km.

2.2. MODEL DERIVED HAIL DATA

Among the modeling tools available, several methods have the ability to forecast hail size, including HailTrack (Brook et al. 2021) and HAILCAST, a one-dimensional hail growth algorithm integrated into the Weather Research and Forecasting (WRF) model (Adams-Selin and Ziegler 2016). This study utilizes the WRF HAILCAST feature to generate hail forecasts; however, these forecasts are not considered as a true observation. Ground-based observations include the use of hail pads, observer report networks, and/ or economic loss reports. The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) and the National Weather Service (NWS) both provide ground-based hail measurements. Most previous evaluations of the NDCMP have relied heavily on ground-based hail observations, which present several challenges (Jewell and Brimelow 2009; Johnson and Sugden 2014). The current network for observing hail is unreliable and the methods used for hail measurements frequently lack accuracy. In sparsely populated regions like Western North Dakota, hail reports are limited and emphasize only the largest hailstones observed. This practice raises concerns about the representativeness of the reported sizes; specifically, whether the reported size reflects the largest stone that fell, or if it accurately characterizes the entire storm event. Furthermore, because hail melts quickly after ground impact, delays in reporting can further compromise measurement accuracy. To address these limitations, this study uses a radar-based hail size retrieval algorithm to provide a more accurate measurement of hail size and distribution. This method doesn't eliminate all bias as the algorithm is not perfectly analogous to observations and there is a model element within the algorithm. Environmental input uncertainty could bias the HRA. Model associated errors include convective intensity biases, microphysical and other parametrization assumptions, horizontal and vertical grid resolution, and storm structure sensitivity. However, all data are treated consistently and objectively to minimize the effects.

By integrating these radar-derived observations with environmental analyses and model forecasts, this study develops a robust framework to assess the effectiveness of cloud seeding in reducing hail size during the NDCMP. The research objectives involve three main tasks:

1. Evaluate the forecasted hail size potential of convective storms using severe weather indices and WRF model output.
2. Compare the forecasted hail size with the radar-derived hail size estimates.

3. Assess the effectiveness of cloud seeding in reducing hail size using a combination of modeled and observed datasets.

Hail forecasts are generated using archived output from the Weather Research and Forecasting (WRF) model version 3.7. model. The model employs a triple-nested domain configuration, with horizontal grid spacing of 27 km, 9 km, and 3 km, respectively. The innermost domain (3 km) focuses on Western North Dakota, allowing for high-resolution representation of convective processes. [Figure 2](#) illustrates the location and size of each of the three domains.

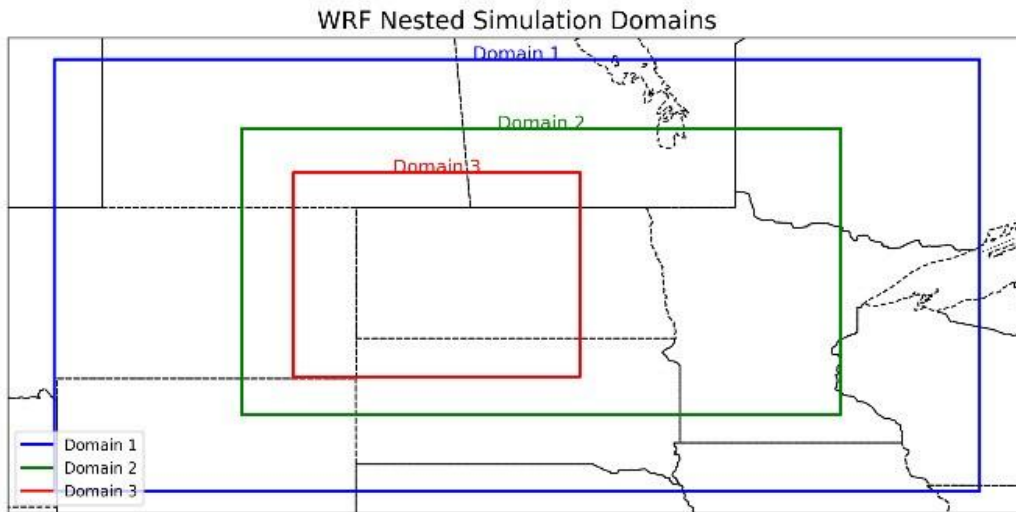


Figure 2. A map showing the three nested WRF domains with horizontal resolutions of 27km (Domain 1), 9km (Domain 2), 3km (Domain 3). Domain 3 is centered over Western North Dakota, which makes it particularly useful for this study.

The model includes 45 vertical levels and runs twice daily, initialized at 00Z and 12Z with North American Mesoscale (NAM) data, producing 48-hour forecasts with hourly output during the convective season (1 June–31 August) (Mullendore and Starzec 2016). The WRF setup is tailored for operational support for the NDCMP and includes the HAILCAST one-dimensional hail growth algorithm that can be used to estimate maximum hailstone size (Creighton et al. 2014).

This study uses output from the WRF Single-Moment 6-Class microphysics scheme (WSM6) simulation, which has shown robust performance for Great Plains hail-producing storms (e.g., Schwartz et al. 2009; Shafer et al. 2009). All key model parameterizations for Domain 3 are summarized in [Table 1](#).

Mullendore and Starzec (2016) conducted extensive testing of this particular WRF model configuration for use in Western North Dakota and found it sufficiently represented storms in the region.

Table 1. Summary of the key parameterizations used for Domain 3 of the WRF model simulation for this study.

Horizontal Grid Spacing	3 km
Vertical Levels	45
Microphysics	WSM6
Cumulus	Kain-Fritsch
Planetary Boundary Layer	YSU
Land Surface	Unified Noah
Longwave Radiation	RRTM
Shortwave Radiation	Dudhia

3. METHODOLOGY

This study follows a stepwise workflow to evaluate hail-size outcomes in seeded and unseeded storm cases in western North Dakota using radar derived hail diagnostics and WRF-based hail prediction. First, candidate storm events are identified and screened to retain cases where the modeled convection is comparable to radar-observed storms in timing and location. Second, radar data are used to diagnose hail-size categories for each case using the HRA framework. Third, the pre-storm environment is characterized using proximity soundings and key thermodynamic and kinematic parameters to document the background conditions for seeded and unseeded samples. Finally, results are summarized by comparing hail-size categories and related metrics between seeded and unseeded cases, followed by a discussion of uncertainty and limitations associated with radar hail sizing, model hail prediction, and case selection. A flowchart of the methodology along with detailed notes on each step is presented in [Figure 3](#), with further information below.

Storm case days are selected through a multi-step process that combines model diagnostics and WSR-88D radar observations in Minot. The process begins by examining HAILCAST output from the innermost domain to identify potential hail events. Any case with a HAILCAST signature in or near the edge of the study domain is considered a candidate day and moves forward in the selection process. For each candidate day, simulated composite reflectivity fields at 2 km above ground level (AGL) are subsequently examined over the designated study region. Only cases with convective events are retained for further analysis. A convective event is deemed present if at least one coherent storm structure with sustained reflectivity values equal to or exceeding 30 dBZ for a minimum duration of 15 minutes exists. In the verification phase, these simulated reflectivity fields are systematically compared against observed radar reflectivity data to assess spatial and temporal consistency. A case is retained for further analysis Only if the simulated convective system exhibits a comparable storm mode, intensity, and temporal evolution relative to the corresponding radar-observed event. Comparable events are identified as those in which the modeled and observed storms occurred within 3 hours and 200 km (~3 counties) of each other. Storm mode is identified as either supercell, squall line, or pop-up showers. If simulated reflectivity and radar data exhibit the same classification, the case is retained. Storm peak intensity between the model and radar are also compared. Maximum reflectivity needs to be within 5 dBZ of each other for the case to be retained. Examples of this case selection process are presented in Section 4.1.3. Though steps were taken to minimize biases in the selection process, biases such as operational decisions, radar range/ beam height/coverage differences across the domain, model domain-edge exclusions, missing data days or incomplete radar coverage, and preferential retention of cleaner cases due to “comparability” requirement are plausible for certain cases.

Radar-observed hail size is estimated using the HRA, which assigns integer values from 0 to 3 based on polarimetric radar variables. A value of 0 indicates no hail, 1 corresponds to hail less than 1 inch in diameter, 2 indicates hail between 1 and 2 inches, and 3 denotes hail exceeding 2 inches. For consistency with the forecast classification system, HRA values of 1 and 2 are combined into a single category representing hail smaller than 2 inches, resulting in three

observational categories: no hail, hail <2 inches, and hail >2 inches. These sizes represent the event-level maximum hailstone diameter within that grid cell.

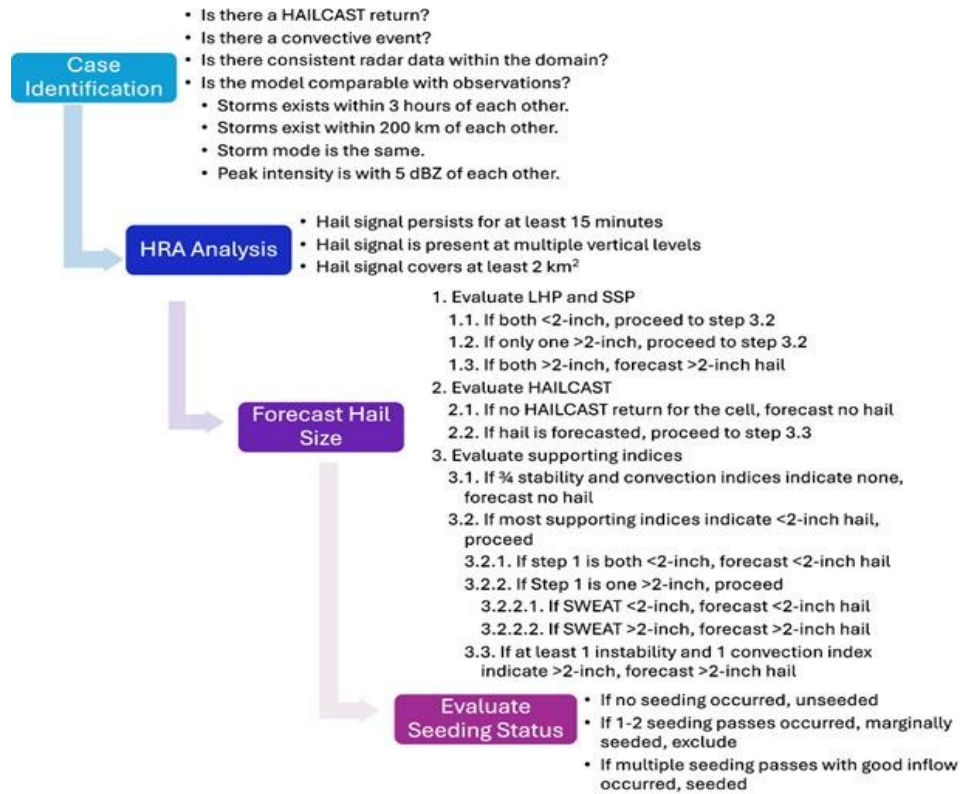


Figure 3. A flowchart showing the steps of the methodology in this study. The most important details from each step are summarized alongside the four main steps: Case Identification, HRA Analysis, Forecast Hail Size, and Evaluate Seeding Status. Additional details are provided below.

The HRA is applied to the four lowest constant altitude plan position indicators (CAPPIs), which are most representative of near-surface hail size. To minimize beam broadening effects and ensure radar quality, the analysis domain is limited to a 120 km radius from the WSR-88D radar site in Minot, North Dakota, following the guidelines of Ortega et al. (2016). A hail classification is accepted only if the detected signal satisfies three quality control criteria: (1) persistence for a minimum of 15 minutes, (2) presence across at least two vertical levels, and (3) spatial coverage exceeding 2 km². Examples illustrating the interpretation of HRA output are provided in Section 4.1.1.

Proximity sounding analysis is conducted using output from the WRF model. The proximity soundings are extracted either near the time the target storm entered the domain of the study, or within two hours of convective initiation if the storm developed within the domain. When choosing between the 00Z and 12Z model runs, the simulation closest to the convection initiation is used, provided that a minimum of 10 hours of model spinup time is achieved to ensure reliable boundary-layer development (Done et al. 2004). The location of the model proximity sounding is manually selected based on WRF-simulated maximum reflectivity, 2-m temperature, and 10-m wind speed and direction. The proximity sounding location is chosen as close to the storm as possible. The goal is to sample the near storm inflow environment as accurately as possible while avoiding localized storm-induced perturbations. To ensure environmental representativeness, the following criteria are applied:

- The sounding location must be outside of any convective influence.
- The sounding location must be outside of the outflow boundary.

- The sounding location must be in the inflow environment of the target cell.
- Examples of this case selection process are shown in section 4.1.4.

The forecasted hail size for each storm is estimated using a structured, multi-parameter approach that integrates environmental indices, model-based proximity soundings, and output from the HAILCAST module within the WRF model. This methodology is developed to address limitations found in previous hail studies that relied heavily on instability metrics, particularly the Convective Available Potential Energy (CAPE), to estimate the potential maximum size of hail produced by storms (e.g., Jewell and Brimelow 2009; López et al. 2001). While CAPE is widely used as an indicator of the buoyant energy available for convection (Blanchard 1998), its relationship to hail production is not always linear or predictive. For instance, Jewell and Brimelow (2009) found that in environments with high CAPE, hail stone size was often over predicted.

Accurate forecasting of hail requires consideration of both atmospheric instability and vertical wind shear, as these two factors jointly influence storm structure and updraft strength. Typically, the most severe hail events occur in a high-instability, high-shear environment which creates a rotating updraft (the “mesocyclone” of a supercell thunderstorm). Recognizing the limitations of using instability metrics alone, several studies have incorporated other convective parameters (e.g. Marcos et al. 2021) Johnson and Sugden (2014) examined two composite parameters that integrate both instability and wind shear to improve discrimination of hail size categories. Their analysis demonstrated that the Large Hail Parameter (LHP) and the Significant Severe Parameter (SSP) exhibit skill in distinguishing storms capable of producing large hailstones (greater than 2 inches in diameter) from those producing smaller hail (<2 inches). These composite indices are designed to capture the synergistic effects of buoyant energy and vertical wind shear, thereby enhancing predictive performance. In this study, both LHP and SSP are incorporated into the hail size forecasting methodology due to their demonstrated value in identifying environments conducive to severe hail.

Johnson and Sugden (2014) investigated LHP and SSP values across various hail size categories. They found considerable overlap in index values among the smaller hail size categories, particularly between >2 in. diameter hail and <1.25 in. hail. This overlap suggests that neither LHP nor SSP, when used independently, can reliably distinguish between specific hailstone diameters. However, there is minimal interquartile range separation when distinguishing between >2 in. and <1.25 in. hail. While some overlap remains, particularly in the SSP values, the combined use of LHP and SSP has been shown to enhance classification accuracy. When used together, these indices improve the ability to differentiate between storms producing hail greater than 2 inches in diameter and those producing smaller hail. Based on the findings of Johnson and Sugden (2014), this study adopts threshold values of LHP and SSP that are above the lower quartile values of 5.8 and 28926 respectively are used to classify a storm environment as supportive of hail greater than two inches. Cases falling below these thresholds were subjected to further analysis using additional indices and HAILCAST model output to refine the forecast classification.

To enhance the classification of forecasted hail size, this study incorporates output from the HAILCAST module within the WRF model. Although HAILCAST is based on a one-dimensional hail growth framework, it provides valuable insight into the potential for hail development within convective updrafts. Given the nonlinear and three-dimensional nature of convection, HAILCAST serves as a useful tool for assessing the potential for hail rather than determining its exact size. In cases where both the LHP and SSP values fall below their respective lower quartile threshold values, HAILCAST output is used to evaluate hail potential. If HAILCAST produces output for the target storm cell, the case is retained for further analysis, under the assumption that hail is possible but not expected to exceed 2-inches in diameter.

Conversely, if HAILCAST does not return any hail growth for the target cell, the storm is classified as having no hail potential.

In scenarios where only one of the two hail-centric indices (LHP or SSP) exceeds its threshold (the respective lower quartile value), HAILCAST is again used to refine the classification. If HAILCAST indicates no hail development, the case is marked as having no hail potential. If HAILCAST has indications of hail, a proximity sounding analysis is conducted to estimate the forecasted hail size. Specifically, the following severe weather indices are evaluated: Mixed-Layer CAPE (MLCAPE), Lifted Index (LI), 0–6 km bulk shear (SHR6), Bulk Richardson Number (BRN), and Severe Weather Threat Index (SWEAT).

These indices include both instability and shear parameters as both are necessary for hail production. Table 2 shows color-coded values of each of these variables to represent their likelihood of producing hail greater than 2 inches. Values highlighted in green are unlikely to produce hail, yellow highlights indicate an environment is likely to produce less than 2-inch diameter hail and a possibility of the environment being capable of producing greater than 2-inch diameter hail, and red highlights environments highly favorable to produce hail with a diameter greater than 2-inches. These threshold values are adapted from operational guidance provided by the National Weather Service and established literature.

Given the range of possible index combinations across individual storm cases, the final hail classification required some level of interpretive decisionmaking; however, a standardized set of rules is consistently applied to ensure methodological transparency and repeatability. If at least one instability index (MLCAPE or LI) and one convection-related index (SHR6 or BRN) exceed their red threshold values, the environment is classified as supportive of hail greater than 2 inches in diameter. Conversely, if at least three of these four indices fall within the green threshold range, the storm is classified as producing hail smaller than 2 inches. In cases where most index values are in the yellow range or do not meet either above criterion, the SWEAT index was used to resolve ambiguity. A red SWEAT value indicates potential for hail greater than 2 inches, while a yellow SWEAT value supports a forecast of less than 2-inch hail.

Hail	LHP	SSP	Instability	MLCAPE	LI	Convection	SHR6	BRN	Potential	SWEAT
<2 in.	0 to 5.8	0 to 28926	marginal	0 to 1000	0 to -3	none	0-35	0-10	none	0-300
>2 in.	5.8 & up	28926 & up	moderate	1000 to 2500	-3 to -6	multicell	20-35	45 & up	severe/ tornado	300 & up
			high/ extreme	2500 & up	-6 & down	supercell	35 & up	10-45		

Table 2. Threshold ranges for key severe weather indices used to assess hail size potential. Indices are divided categorically by hail indices (Large Hail Parameter and Significant Severe Parameter), instability indices (Mixed-Layer Convective Available Potential Energy and Lifted Index), convection indices (0-6 km shear and Bulk Richardson Number) and severe potential (SWEAT). Index values are color-coded to represent increasing likelihood of hail exceeding 2 inches in diameter: green indicates environments unlikely to support large hail, yellow indicates conditional support for hail greater than 2 inches, and red indicates high likelihood of hail exceeding 2 inches. Thresholds are based on guidance from the National Weather Service and prior literature.

After assessing both forecasted and observed hail sizes, each case is classified as unseeded, seeded, or marginally seeded based on cloud seeding activity. Classification relies on detailed flight logs and operational maps provided by the NDARB, which document aircraft tracks, seeding flare deployment, and inflow characteristics observed during the missions. Unseeded cases are characterized by the absence of seeding operations during the target storm's occurrence. Seeded cases involve multiple seeding passes conducted under consistent inflow conditions. Examples of this classification are presented in Section 4.1.2.

4. RESULTS

4.1 Storm Case Analysis

4.1.1. INTERPRETING THE HAIL SIZE RETRIEVAL ALGORITHM

Figure 4 illustrates a case from 12 June 2016 that exemplifies hail melting prior to surface impact. At 4 km altitude, red pixels in the HRA output indicate hailstones larger than 2 inches; however, these signatures diminish with decreasing altitude. By 2 km, only sparse returns remain, and at 1 km they are nearly absent, suggesting that melting prevented large hail from reaching the ground. This case is therefore classified as “no hail” at the surface.

In contrast, Figure 5 shows the HRA output for the 14 June 2018 case at 22:55Z, where a supercell located northwest of the radar site in Saskatchewan produced a strong and vertically continuous signature across all four CAPPIs. Red pixel coverage near the surface confirms that hail greater than 2 inches in diameter likely reached the ground. This case is classified as “greater than 2-inch hail.”

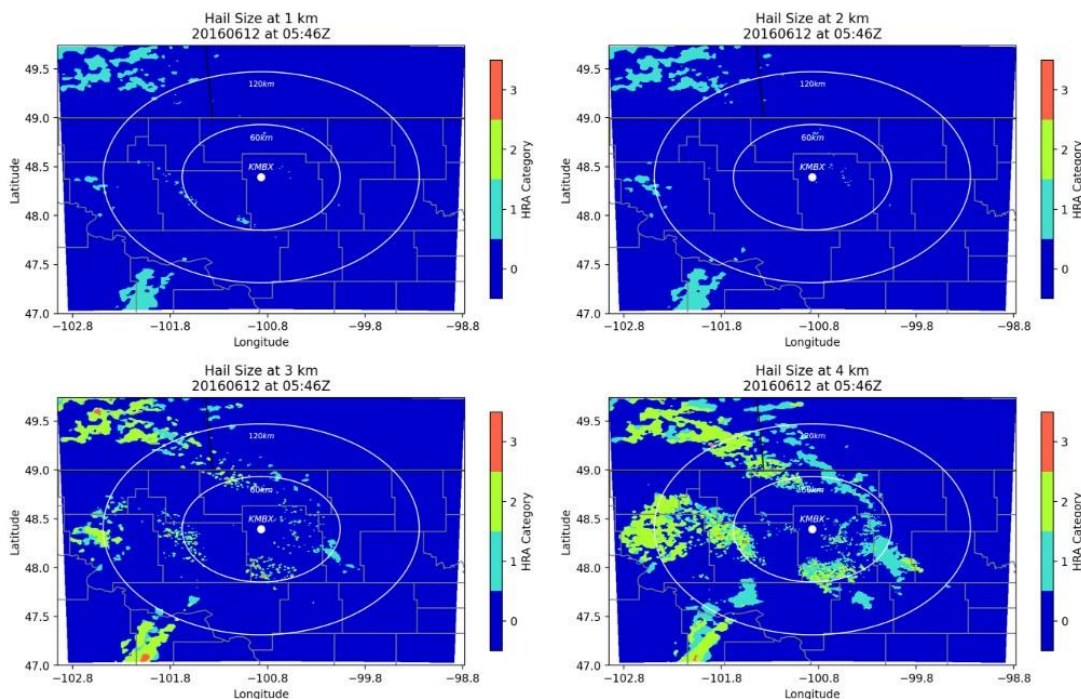


Figure 4. HRA output for 12 June 2016 at 05:46Z. HRA category 0 represents no hail, 1 is less than 1 in. diameter hail, 2 is 1-2 in. diameter hail, and 3 is greater than 2 in. diameter hail. This case shows a strong melting hail profile, especially in the convection due west of the radar site.

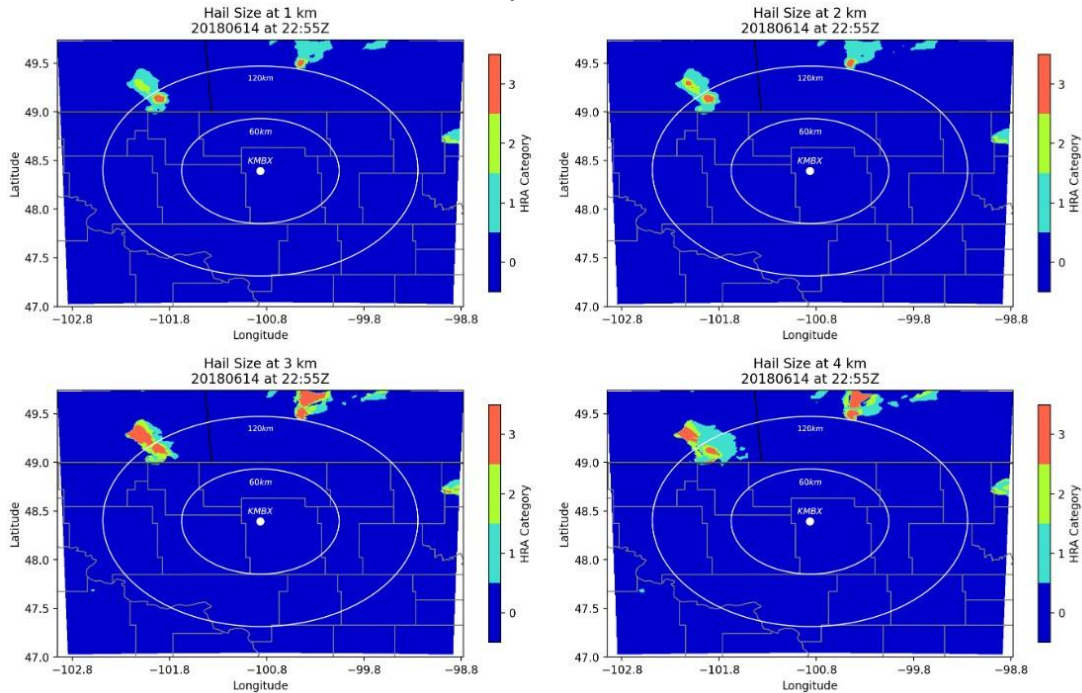


Figure 5. HRA output for 14 June 2018 at 22:55Z. HRA category 0 represents no hail, 1 is less than 1 in. diameter hail, 2 is 1-2 in. diameter hail, and 3 is greater than 2 in. diameter hail. The cell to the northwest of the radar site was determined to have produced greater than 2-inch diameter hail.

4.1.2. DETERMINING SEEDED AND UNSEEDED CASES

Storm seeding operations are identified using detailed pilot flight logs and maps provided by the NDARB. These records document aircraft tracks, flare deployment, and meteorological conditions encountered during flight. Storms are classified as “seeded” if multiple seeding passes were conducted under consistent inflow conditions and “unseeded” if no seeding occurred. Unseeded cases may be those which developed outside of the target seeding area or near the border where the effects of seeding would have occurred outside of the target area. Unsafe seeding conditions and suspension criteria for flash floods or tornadoes within the target area also contribute to unseeded cases. Additionally, some cases were weak enough that seeding was unlikely to have much impact. Of the 39 unseeded cases 14 originated outside of the target zone and 25 were inopportune or unsafe to seed within the target zone. Regardless of seeding status or origin location, the thermodynamic and kinematic profiles were similar across all cases. Cases with only one or two passes or insufficient inflow are designated as “marginally seeded” and excluded from final analysis. To identify which convective storms were seeded, flight operation forms and corresponding flight track maps from the NDCMP are analyzed for the summer seasons of 2016 through 2018. Out of 88 cases with sufficient model and radar data, 49 are confirmed to have been seeded based on documented seeding activities in the flight records.

Figure 6 shows radar reflectivity overlaid with the flight track of a seeding aircraft on 21 July 2018. During this 10-minute period, both burners of the aircraft were continuously active, and one burn-in-place flare was deployed. According to pilot reports, updraft speeds exceed 700 ft min^{-1} for approximately 40 minutes, supporting favorable conditions for seeding. The full flight path for this case is presented in Figure 7 where the double green lines indicate times when both burners were active for hail suppression and orange dots represent the activation of burn-in-place flares for the same purpose. This storm, actively targeted by the aircraft “Seed 5” along with other project aircraft, is classified as effectively seeded. The marginally seeded cases are those where only one or two seeding passes were completed due to either poor conditions or suspension criteria. Figure 8 shows a flight map from 13 June 2016 in which only a single short segment (marked by double green lines) involved active burner use. Pilot observations during

this mission indicated insufficient inflow to justify continued seeding activity. As a result, this storm did not meet the criteria for effective seeding and is excluded from the final analysis.

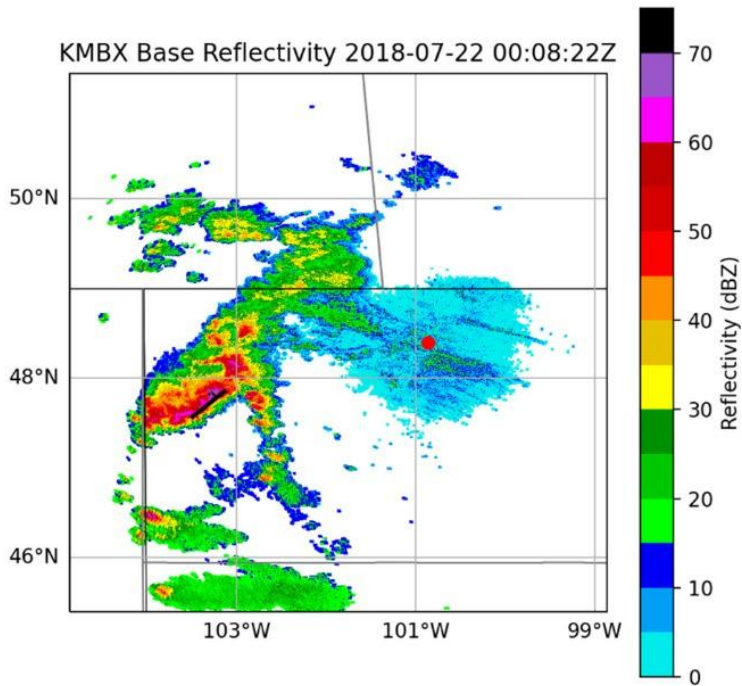


Figure 6. Minot, ND radar base reflectivity from 21 July 2018 at 00:08Z. Flight tracks from a seeding plane are overlaid for the 10-minute window from 00:00Z to 00:10Z as a solid black line. During this period, the plane was actively seeding at 7000 ft.

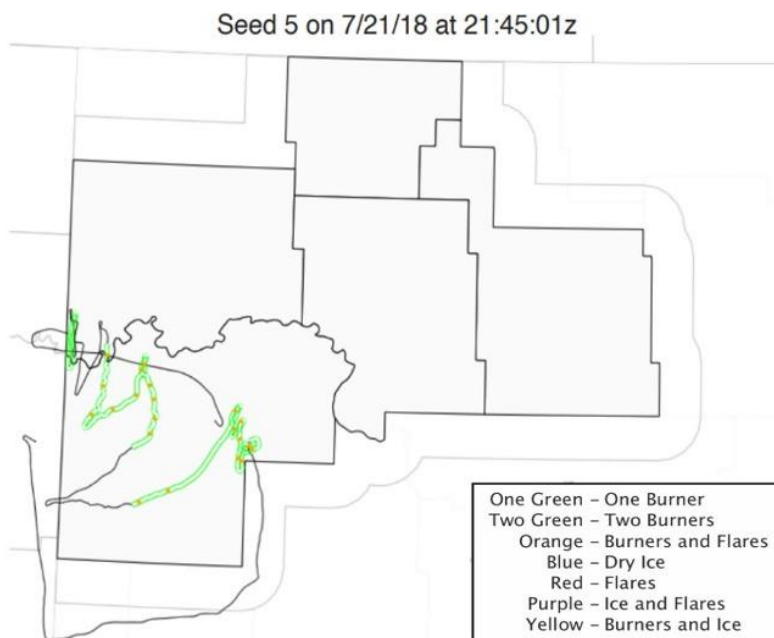


Figure 7. A map of Seed 5's flight on 21 July 2018. The black line represents flight tracks where no seeding material was dispensed, the double green lines indicate both burners were lit for hail suppression, and the orange dots represent burn in place flares that were ignited for hail suppression. This case was considered a seeded case for this study.

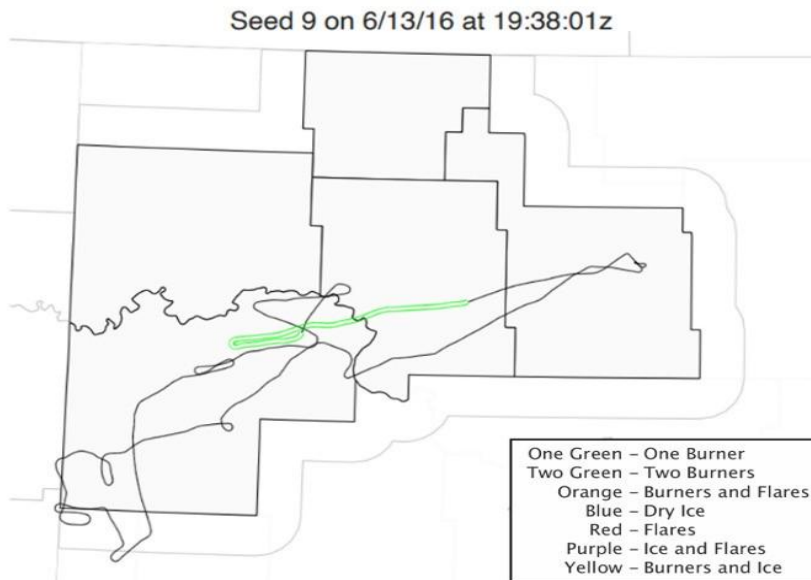


Figure 8. A map of Seed 9's flight on 13 June 2016. The black line represents flight tracks where no seeding material was dispensed, while the double green lines indicate both burners were lit for hail suppression. This case was marginally seeded and is therefore not considered usable for this study.

A total of 88 convective storm cases are analyzed over three summer seasons (2016–2018) in Western North Dakota. Of these, 49 cases are identified as effectively seeded, while 39 cases were classified as unseeded. Marginally seeded cases were excluded from the analysis to maintain a clear distinction between seeded and non-seeded events. Each case is evaluated using both forecasted hail size, derived from model-based indices and HAILCAST output, and radar-observed hail size from the HRA.

4.1.3. STORM CASE IDENTIFICATION

Figure 9 illustrates a representative storm case from 3 August 2018 which was marked as suitable for analysis. It presents HAILCAST output and corresponding model-simulated 2-km AGL reflectivity at 08Z, along with observed radar reflectivity data from 07:55Z. Although the observed storm formed two hours earlier than the model's forecasted convection initiation, the model accurately captured the storm's location, strength, and structure. Figure 10 presents similar diagnostics for the 4 August 2018 case, with model output at 21Z and radar observations at 01Z. In this case, the modeled storm initiated significantly earlier and is displaced considerably westward relative to the observed storm. Given the temporal and spatial mismatches between the simulated and observed storm evolution, this case was excluded from further analysis.

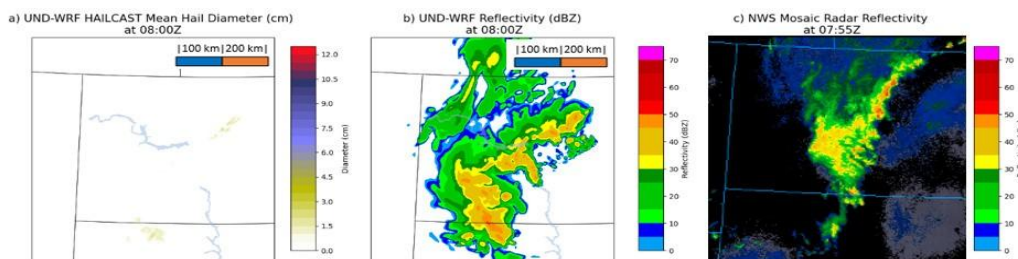


Figure 9. Panels for the 3 August 2018 case depict a) WRF HAILCAST, b) 2-km AGL Reflectivity from 08:00Z and c) NWS radar archive data from 07:55Z for 3 August 2018 case. Based on the spatial and temporal agreement between the model output and observed radar data, this case was deemed suitable for inclusion in the study.

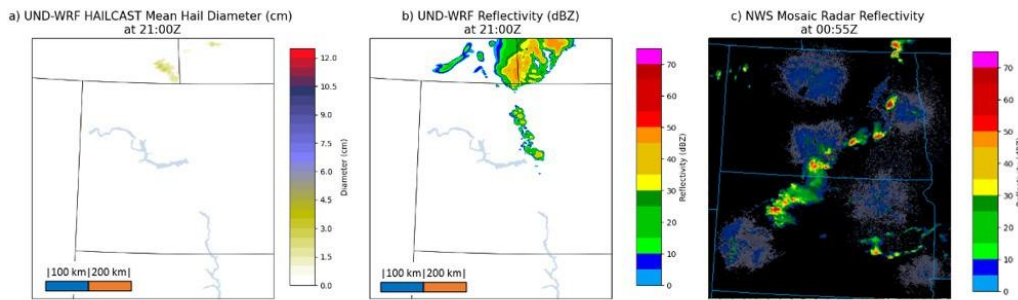


Figure 10. Panels for the 4 August 2018 case depict a) WRF HAILCAST output at 21:00Z, b) simulated 2-km AGL reflectivity at 21:00Z, and c) NWS radar reflectivity from 00:55Z. There are significant spatial and temporal discrepancies between the model simulation and observed radar data in this case, so it was not used.

4.1.4. PROXIMITY SOUNDING ANALYSIS

Figure 11 illustrates a representative example from 19 June 2017 at 19:00Z. Temperature, wind, and maximum reflectivity data are derived from the WRF model valid for 19 June 2017 at 19Z. The multicellular storm system is forecasted to move southeastward. The selected proximity sounding location (denoted by black “X”) is positioned downwind of the storm but sufficiently far from any convective influence to accurately represent the surrounding environment. A more complex case is shown in Figure 12 for 29 June 2017 at 19:00Z. In this case, multiple convective systems are present, including embedded convection to the southeast and a multicellular structure to the north. Due to the proximity to the edge of the model domain, the embedded system cannot be adequately sampled; therefore, the analysis focuses only on the northern system. The sounding location is strategically placed in a region with no convective influence and downwind of the target cells, satisfying all inflow criteria. For both of these cases the resulting proximity soundings are shown in Figures 11c and 12c respectively. This approach provides a consistent framework for characterizing pre-storm environmental conditions, enabling reliable comparison between forecast indices and observed hail outcomes across seeded and unseeded cases.

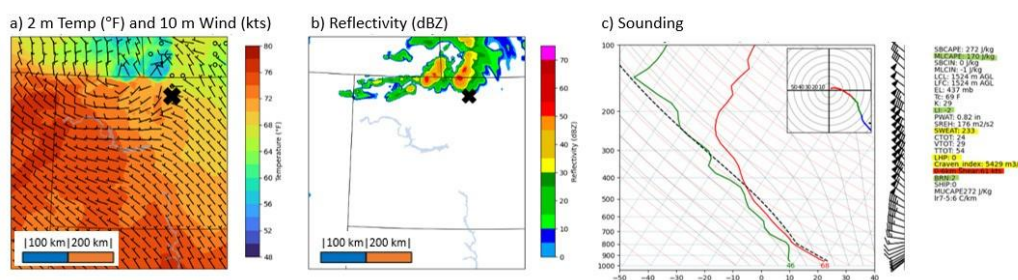


Figure 11. Panels for the 19 June 2017 case depict a) 2 m temperature and 10 m wind, b) maximum reflectivity, and c) proximity sounding charts from the WRF model for 19 June 2017 at 19:00Z. The black X indicates the location chosen for the proximity sounding.

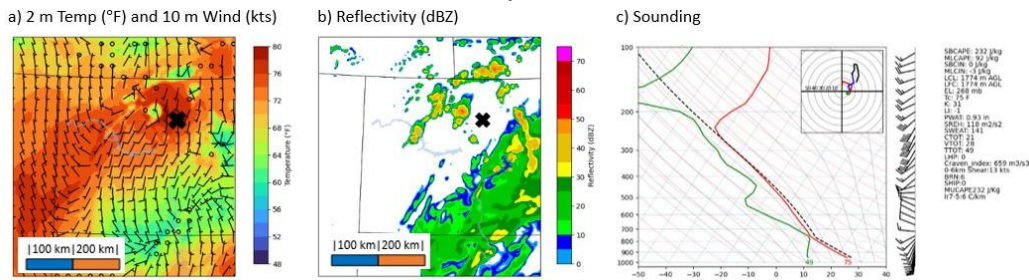


Figure 12. Panels for the 29 June 2017 case depict a) 2 m temperature and 10 m wind, b) maximum reflectivity, and c) proximity sounding charts from the WRF model for 29 June 2017 at 19:00Z. The black X indicates the location chosen for the proximity sounding.

4.2. Comparison of Forecasted and Observed Hail Sizes

A hail size distribution analysis is presented in Figure 13, comparing forecasted hail size (blank bars) with radar-indicated hail size (hatched bars) for both seeded (blue bars) and unseeded (green bars) cases. In unseeded cases, the forecasted and observed occurrences are relatively aligned across the three size categories. On the other hand, the seeded cases exhibit notable discrepancies; specifically, the forecasted occurrences of hail in the >2-inch diameter category significantly exceeds the observations. Additionally, there is a marked decrease in the forecasted cases with no hail compared to actual observations. In Section 4.2, we compare the distribution of radar-derived hail categories between seeded and unseeded cases. We observe a shift toward smaller hail categories in the seeded sample. This pattern is consistent with a reduction in larger hail-category occurrence in seeded cases; however, because the analysis is observational and verification data are limited, the result should be interpreted as an association rather than a causal estimate of seeding impact. Despite the notable shift to smaller observed hail than what was forecasted in the none and >2-inch diameter categories for seeded cases, the <2-inch diameter category has nearly identical counts of forecasted and observed hail size. This pattern likely reflects hail suppression, whereby seeded storms that would have produced >2-inch hail instead yielded hailstones in the <2-inch threshold and storms that could have produced <2-inch hail resulted in no hail. There is a shift to one bin smaller for radar-observed hail compared to the forecasted size based on environment.

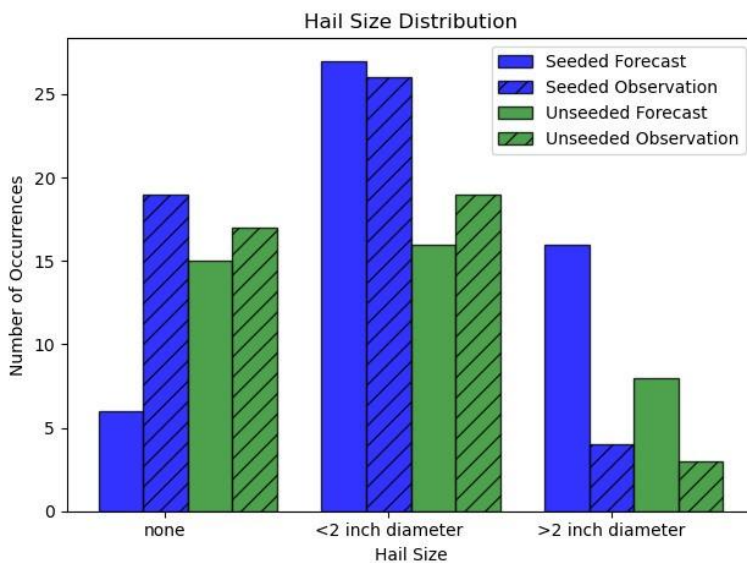


Figure 13. Hail size distribution for forecasted and observed hail categories in seeded (blue bars) and unseeded (green bars) cases. Blank bars are forecasts, while hatched bars are observations from the HRA. There are 88 total cases included: 39 unseeded and 49 seeded. Unseeded cases align well, however the seeded cases show marked differences between number of forecasted cases and number of observed cases in the none and >2 inch diameter bins.

To further explore the distribution of forecasted and observed hail sizes within the <2-inch diameter seeded category, Figure 14 provides heat maps for both unseeded (Figure 14a) and seeded (Figure 14b) storm cases. Unlike Figure 13, which presents the total counts of cases per category, Figure 14 offers a more nuanced comparison by matching forecasted and observed hail diameters for individual cases. By focusing on individual cases, deeper insights into the discrepancies observed in the larger size categories are gained as well as a better understanding of the performance of the hail size retrieval algorithm during hail events. These maps visualize the match between forecasted hail size (x-axis) and observed hail size (y-axis) on a case-by-case basis. For unseeded storms, most cases cluster along the diagonal from topleft to bottom-right, reflecting strong agreement between forecasted and observed hail sizes. Notably, only two unseeded cases involved both forecasted and observed hail exceeding 2 inches, consistent with the expectation that most high-potential hailstorms are targeted for seeding. In seeded cases, the distribution shifts. Many cases still fall along the diagonal, including a pronounced concentration in the center cell, representing <2-inch hail that is both forecasted and observed. However, the next most populated cells demonstrate a shift towards the upper right corner, where observations are smaller than forecasts. This convergence supports the idea that seeded storms often produce smaller hail than forecasted, with suppression lowering hail size into the sub-severe range. The wide bin range for the <2-inch category (from pea-sized to golf-ball-sized) likely contributes to the clustering in the center. To improve the accuracy of hail size forecasting, a more refined method could enhance the differentiation of effective seeding outcomes, thereby leading to better predictive capabilities for hail events.

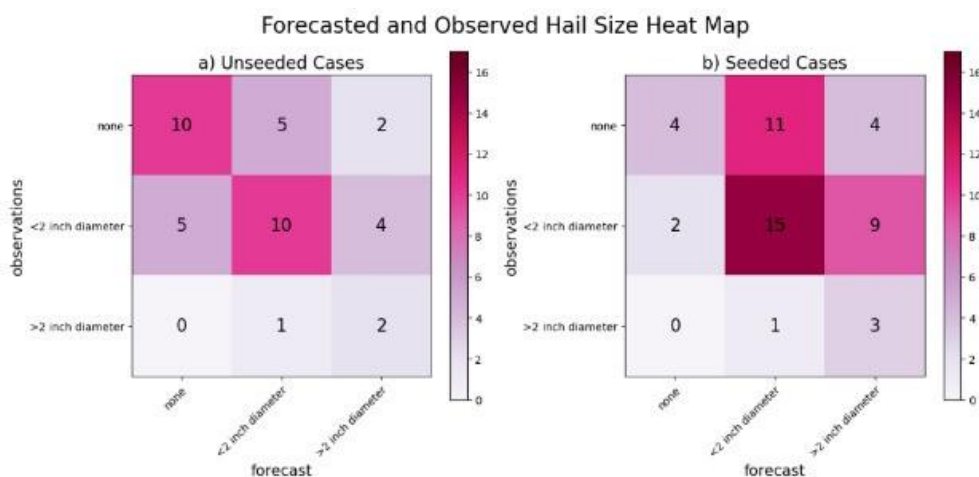


Figure 14. Heat maps for a) 39 unseeded and b) 49 seeded cases. Counts of each bin size for forecasts and observations are compared. While unseeded cases show agreement between forecasted and observed size with the center diagonal being most populated, seeded cases demonstrate a shift towards the top right corner, indicating smaller observed hail than forecasted.

4.3 Hail Forecast Verification and Seeding Effectiveness

While Figures 13 and 14 characterize size distribution, they do not directly assess seeding effectiveness. To address this gap, a contingency table analysis is employed to evaluate the total effectiveness of the seeding operations. This method allows for a detailed comparison of forecasted and observed outcomes across different scenarios, facilitating a clearer understanding of how seeding influences hail size predictions. Figure 15 illustrates the ratio of hits, misses, and false alarms for both seeded and unseeded case days. A “hit” is defined as a case where the observed hail size matches the forecasted size. A “miss” occurs when the observed hail size is larger than forecasted, and a “false alarm” is when the forecasted size is larger than observed. Among the 39 unseeded cases, 56.4% are classified as hits, 28.2% as false alarms, and 15.4% as misses. This distribution indicates that the majority of forecasts accurately predict observed hail sizes. In contrast, the 49 seeded cases demonstrate a notable increase in the false alarm ratio. The hit percentage drops to 44.9%, while the false alarm percentage rises

to 49.0%, and the miss percentage decreases to 6.1%. These findings reflect the impact of seeded cases in the analysis sample: in many cases, hail sizes were forecasted to be larger than what was ultimately observed, leading to a higher proportion of false alarms.

To gain further insight into how forecast performance varied across hail size categories, a bin-specific breakdown of hits, false alarms, and misses is conducted for both unseeded and seeded cases. This analysis is presented in Figure 16, which breaks down the results based on forecasted size bins for both unseeded (Figure 16a) and seeded (Figure 16b) cases. An additional category, “null,” is included to present each category on a 100% scale. Figure 16a shows the results for the 39 unseeded cases. In the no-hail and <2-inch bins, hits dominate, indicating strong agreement between forecasted and observed outcomes. However, in the >2-inch bin, there are unexpectedly

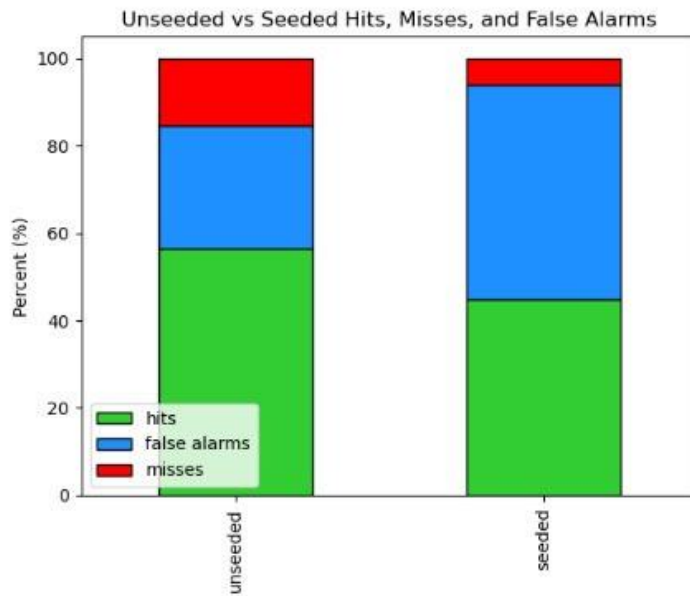


Figure 15. The number of a) unseeded and b) seeded cases that were either hits (green), false alarms (blue), or misses (red), divided by the total number of cases (39 unseeded and 49 seeded), to obtain the percentage of each possible scenario that occurred. The seeded cases exhibit an expanded false alarm region compared to the unseeded cases, suggesting effective cloud seeding.

more false alarms than hits. This over forecasting tendency may be attributed to biases in the WRF model, which has previously been shown to overestimate storm severity and convective strength in the Northern Plains (Mullendore and Starzec 2016). Figure 16b displays the results for the 49 seeded cases, which reveal a notable expansion in false alarms compared to the unseeded group. Specifically, in the <2-inch diameter bin, there is a 9.63% increase in false alarms, while the >2-inch diameter bin shows an 11.15% increase. These increases suggest a total 20.78% success rate for seeding operations.

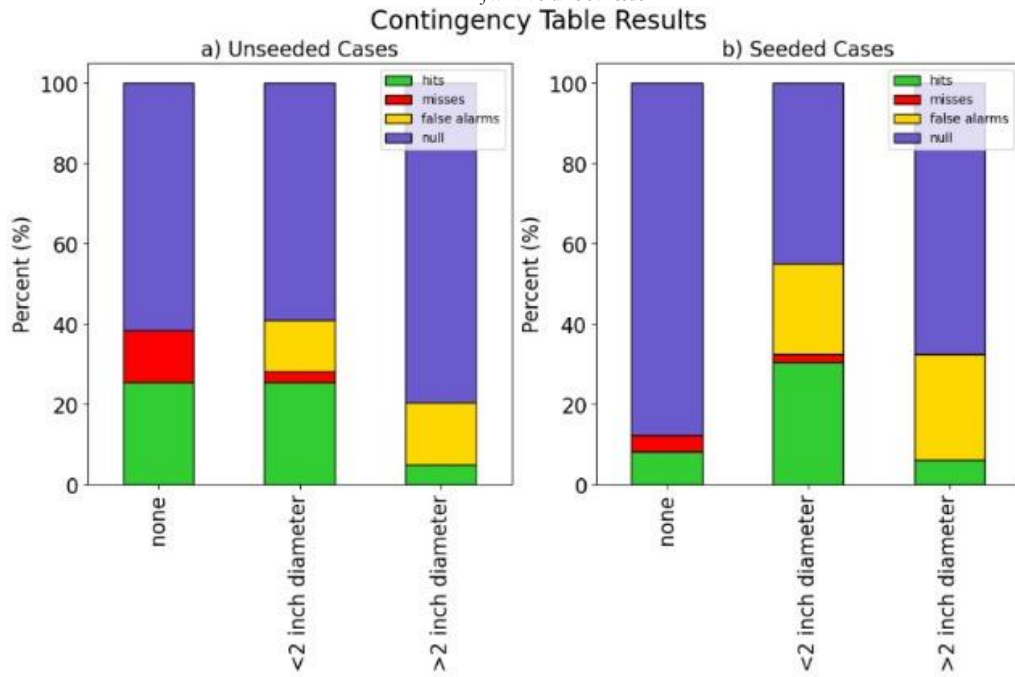


Figure 16. The number of a) unseeded and b) seeded cases that were either hits (green), misses (red), false alarms (yellow), or null (purple) divided by the total number of cases (39 unseeded and 49 seeded) to obtain the percentage of each possible scenario that occurred. This is then split into hail diameter size bins. The seeded cases show a 20.8% increase in false alarms compared to the unseeded cases which can be attributed to successful cloud seeding.

5. DISCUSSION

This study provides a quantitative assessment of hail suppression during the NDCMP, leveraging a novel integration of WRF model forecasts, hailcentric indices, and radar-based hail size retrievals. Analysis of 88 convective storms from 2016 to 2018 reveals a distinction between seeded and unseeded cases. Unseeded storms demonstrate strong agreement between forecasted and observed hail sizes, supporting the reliability of the forecasting framework under natural conditions. In contrast, seeded storms frequently produce smaller hail sizes than predicted, with a notable shift of cases from the >2-inch category into the <2-inch range or resulting in no hail, consistent with the expected impacts of seeding interventions. The analysis indicates a cloud seeding success rate of approximately 20.8 percent.

To assess whether the seeded vs. unseeded differences could be explained by environmental sampling, MLCAPE and 0–6 km bulk shear are compared across both groups (Figure 17). Both the raw counts (Figure 17a and b) and probability distribution functions (PDFs) (Figure 17c and d) are presented. The distributions for MLCAPE largely overlap; however, the PDF for 0–6 km wind shear is offset between seeded and unseeded cases. The seeded PDF shows a peak at lower shear values than the unseeded cases. Three seeded cases fall into the 0–5 ms^{-1} shear category, while no unseeded cases are in this bin, which likely skews the seeded curve lower. Table 3 presents other statistics for the same variables. Seeded cases show higher CAPE and lower wind shear than unseeded cases on average, but the differences are marginal. Though the values aren't identical between the seeded and unseeded cases, there is substantial overlap, indicating thermodynamic and kinematic conditions are comparable overall; thus, the observed shift toward smaller hail and the expansion of false alarms in seeded cases are unlikely to be artifacts of environmental bias.

Previous studies of the North Dakota Cloud Modification Project (Miller and Fuhs 1987; Smith et al. 1997; Knowles 2020) report 41–45% effectiveness of cloud seeding; however, it is important to recognize that these earlier estimates are derived from reductions in insurance

claims, an economic metric fundamentally different from the present study's focus on quantifying physical changes in hail size using combined radar and model diagnostics. This difference highlights an important hypothesis: although only 21 percent of storm cases in this study showed evidence of hail suppression, these particular cases might represent the most severe hail events that account for a disproportionately large share of historical financial losses. As such, effective seeding in these high-impact cases could still drive the higher economic benefits reported in prior work. Further research is needed to investigate the characteristics of successfully seeded storms and to determine whether the physical suppression rates

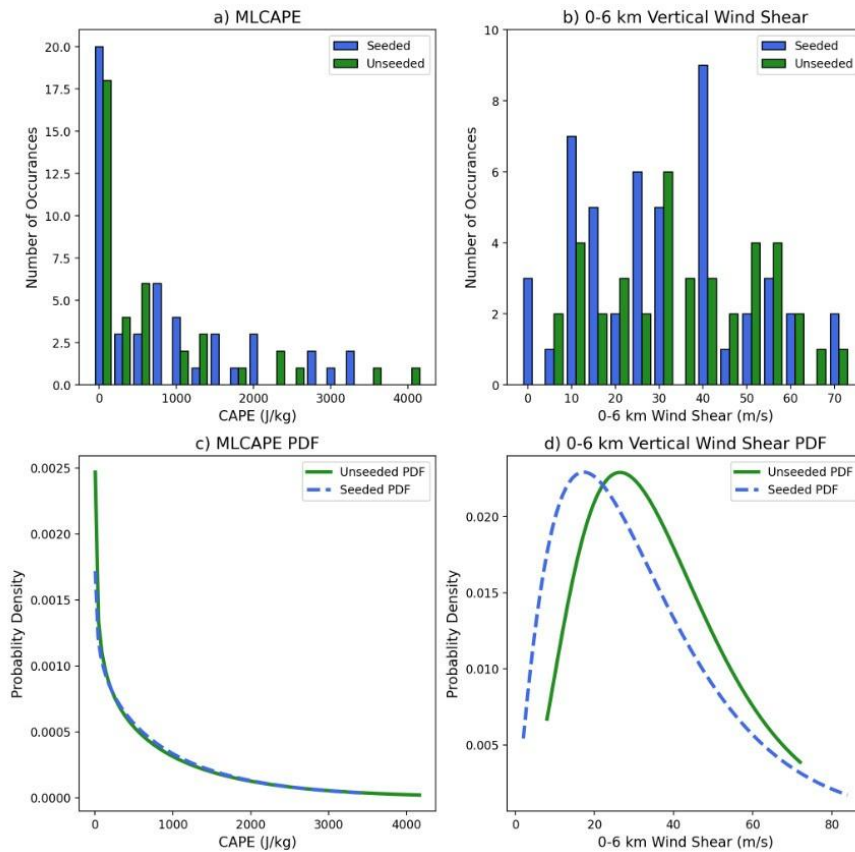


Figure 17. A comparison of a) MLCAPE and b) 0-6 km vertical wind shear for each case included in this study. Probability Distribution Functions (PDFs) using a gamma distribution for c) MLCAPE and d) 0-6 km vertical wind shear are also shown. No substantial differences exist between the seeded (blue) and unseeded (green) cases for MLCAPE; however, unseeded cases exhibit stronger wind shear.

Table 3. Statistics for Mixed-Layer Convective Available Potential Energy (MLCAPE) and 0-6 km vertical wind shear for seeded and unseeded cases. Mean, standard deviation, median, 25th and 75th percentiles were all calculated for the 49 seeded and 39 unseeded cases. The column on the right shows the percentage of cases above the key threshold for that parameter. Thresholds are 20 knot wind shear and 100 J kg⁻¹ MLCAPE. There is substantial overlap between the seeded and unseeded cases for both variables.

	Number of Cases	Mean	Standard Deviation	Median	25 th Percentile	75 th Percentile	% Cases above key threshold
MLCAPE - Seeded	49	888.8	973.4	641.0	106.0	1253.0	34.7%
MLCAPE - Unseeded	39	731.7	1035.1	274.0	0.0	1072.5	28.2%
0-6 km Wind Shear - Seeded	49	32.5	19.5	30.0	17.0	44.0	67.3%
0-6 km Wind Shear - Unseeded	39	37.1	17.8	37.0	22.5	52.5	76.9%

identified here align with economic loss reductions, or if discrepancies arise from methodological differences between physical and economic assessments.

Although 20.78 percent success is not particularly high, it highlights the need for operational cloud seeding programs. Bangsund and Hodur (2019) found an annual benefit of \$6.9 million USD in North Dakota counties with a seeding program, which equates to \$3.00 USD per planted acre. Each cloud seeding mission has the potential for success, which contributes to the overall financial benefit. This is of particular importance in hail-prone regions such as North Dakota.

One of the primary challenges in this study is the relatively large forecast bin size, which limits categorization of hail diameter to only three classifications: none, less than 2-inches, and greater than 2-inches. This binary approach presents a significant limitation, as the HRA can differentiate between hail sizes less than 1 inch and those between 1 and 2 inches in diameter. Furthermore, uncertainties are introduced with such large bin sizes due to the stark difference between the smallest and largest hail stone included in the bin. Introducing additional forecast parameters could minimize uncertainties and enhance the model's ability to effectively distinguish between hail sizes, particularly between those less than 1 inch and those ranging from 1 to 2 inches. This change in forecast could help produce results which align more closely with previous studies. Additionally, a predicted-sounding approach (e.g., model-based "virtual" soundings along the storm inflow, as in Marcos et al. 2021) is a valuable enhancement to pursue in future analyses to better align environmental characterization with storm timing and to support hail size estimation.

Another challenge identified by this study is the limited number of cases. Identifying trends with limited cases allows for some uncertainties to develop. This study would significantly benefit from the inclusion of additional cases to elucidate emerging trends. This study currently relies on data collected from three summers' worth of storms, resulting in a total of 88 usable cases. These cases were systematically categorized based on whether they were seeded or remained unseeded, creating a dataset with 39 unseeded storms and 49 seeded storms. While this dataset provides a foundation for identifying initial trends, incorporating more cases would enhance the statistical significance of the findings. More cases would allow for the identification of more certain trends. The NDCMP has been operational for over 40 years, collecting a wealth of data during this time. This extensive historical dataset holds the potential to significantly strengthen the current study, providing clearer insights into the behaviors and impacts of both seeded and unseeded storms. Utilizing these data could lead to more robust conclusions and better-informed storm management strategies.

6. CONCLUSIONS

This study has focused on three key objectives: (1) evaluating the maximum potential hail size of summertime storms, (2) comparing the forecasted hail size with outputs from the radar-based algorithm, and (3) assessing the effectiveness of cloud seeding for hail suppression during the NDCMP by examining both seeded and unseeded cases.

An integrated approach was employed, combining high-resolution WRF model output, including proximity soundings, severe weather indices, and HAILCAST simulations, with polarimetric radar-based hail size retrievals using the HRA. Given its demonstrated skill, the WRF model was confidently employed to provide the environmental context for hail size predictions and to serve as input for the HRA analyses.

The HRA was used to obtain radar-indicated observed hail size and then compared to forecasts generated by the WRF model to evaluate the effectiveness of hail suppression operations conducted during the NDCMP. Both the forecasts and observations were categorized based on hailstone diameter into three classes: no hail, hail less than 2-inch diameter, and hail greater than 2-inch diameter. A contingency table framework was used to evaluate forecasting skill and seeding impacts by classifying each case as either a miss (when the forecast is less than the

observations), a hit (when the forecast equals the observations), or a false alarm (when the forecast is greater than the observations) Contingency analysis showed that while hits (matching forecasts and observations) comprised 56.4 percent of unseeded cases, they declined to 44.9 percent in seeded cases. Concurrently, false alarms, where forecasts predict larger hail than observed, rise from 28.2 percent in unseeded storms to 49.0 percent in seeded storms, indicating that seeding operations likely reduced hail sizes below forecast expectations. This translates to an estimated seeding effectiveness of ~20.8 percent, based on the increase in false alarms attributable to successful hail suppression.

While this physical measure of success is lower than the 41–45 percent reductions inferred from historical insurance loss analyses, it highlights key differences in metrics: this study provides a direct quantification of changes in hailstone size, whereas previous studies captured broader economic impacts that may disproportionately reflect the mitigation of high-damage events. It is plausible that the subset of storms effectively suppressed by seeding, though representing ~21 percent of all cases, are those most likely to have caused substantial economic losses.

Analysis of statistical significance showed a p-value of 0.079. This indicates that the results are not statistically significant at the conventional 0.05 threshold, meaning the null hypothesis cannot be rejected with high confidence. However, the p-value is relatively close to 0.05, suggesting a possible trend toward significance that might warrant further investigation. This could imply that the observed effect is real but that the current study lacked sufficient statistical power—perhaps due to a small sample size—to detect it conclusively. While the result does not provide strong evidence against the null hypothesis, it may still hold practical or theoretical relevance, and replication with a larger dataset could help clarify whether the effect is robust. At the less conventional 90 percent confidence interval, results from this study do demonstrate statistical significance.

In summary, this study demonstrates that integrating model-based diagnostics with advanced radar retrieval algorithms offers a robust framework for physically quantifying hail suppression effects of operational cloud seeding. The findings reaffirm the value of cloud seeding programs in reducing hail sizes and support continued investment in such efforts, especially in hailprone agricultural regions like Western North Dakota. Despite several challenges, particularly the broad bin sizes for hail classification and the limited number of cases, successful cloud seeding was observed 21 percent of the time, indicating that it is a valuable program in Western North Dakota. Future work expanding the dataset to include more years of storms will provide clearer quantification of the effects of cloud seeding for hail suppression. New methods of forecasting maximum hail diameter will allow for a closer analysis of success/failure of seeding efforts.

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