Evaluation of the Alberta Hail Suppression Project Using 2017 Radar Data

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M.S. Thesis Defense

University of North Dakota

Courtesy of
Darren Howard and Dan Gilbert

Courtesy of NWS Gaylord.

Project Motivation: Insurances Losses in Alberta

- **Two 1996 hailstorms caused a loss of $103 million CAD.**
- **In 2010, hailstorms caused loss of $400 million CAD.**
- **In 2012, storms with golf ball size hailstones resulted in almost half of damage claims across Canada, which totaled to about $552 million CAD.**

- Reference: Desjardins Insurance 2017

Hail damage in Vulcan County near Calgary.

Seeding Effectiveness Assessment of Previous Hail Suppression Projects

- **31% reduction in crop hail damage in North Dakota (1969-72) using crop hail insurance data.**
- **48% reduction in insurance loss cost value in Texas (1970-73) using crop hail insurance data.**
- **15.6% decrease in number of hailstones larger than 0.7 cm diameter in ANELFA project in France (1987) using hailpad.**

Hail Suppression Concept Hypothesis

🟢 symbol indicates the **Natural Hail Trajectory** which starts at a greater height in a region having naturally occurring ice nuclei.

🟡 symbol indicates the effect of **Beneficial Competition** on the hailstones which now travel to a greater height but are smaller in size because the supercooled liquid water is now distributed among the natural and artificial ice nuclei.

- 🟣 symbol indicates how the introduction of artificial ice nuclei at a lower level causes an **Early Rainout** of smaller precipitation particles forming at those heights having weaker updrafts.
- 🔵 symbol indicates the **Trajectory Lowering** of the hailstones,which now have a reduced size owing t reduced growth time as they are in a weaker updraft region.
- 🟠 symbol indicates the trajectory of hailstones which travel higher but are greater in number and smaller in size due to the **Promotion of Coalescence** among the natural and artificial ice nuclei.

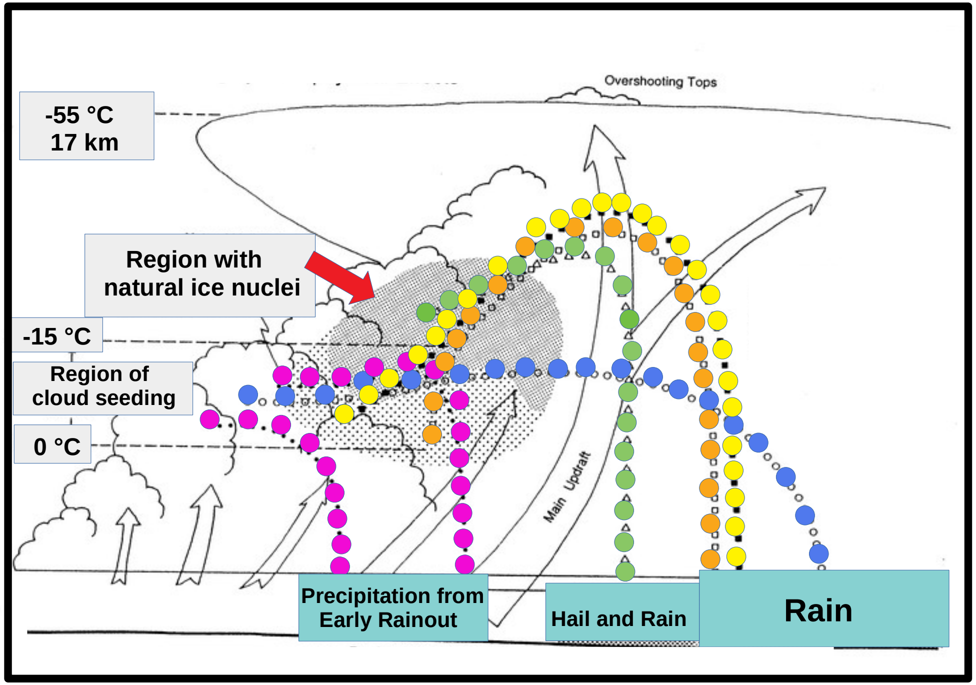
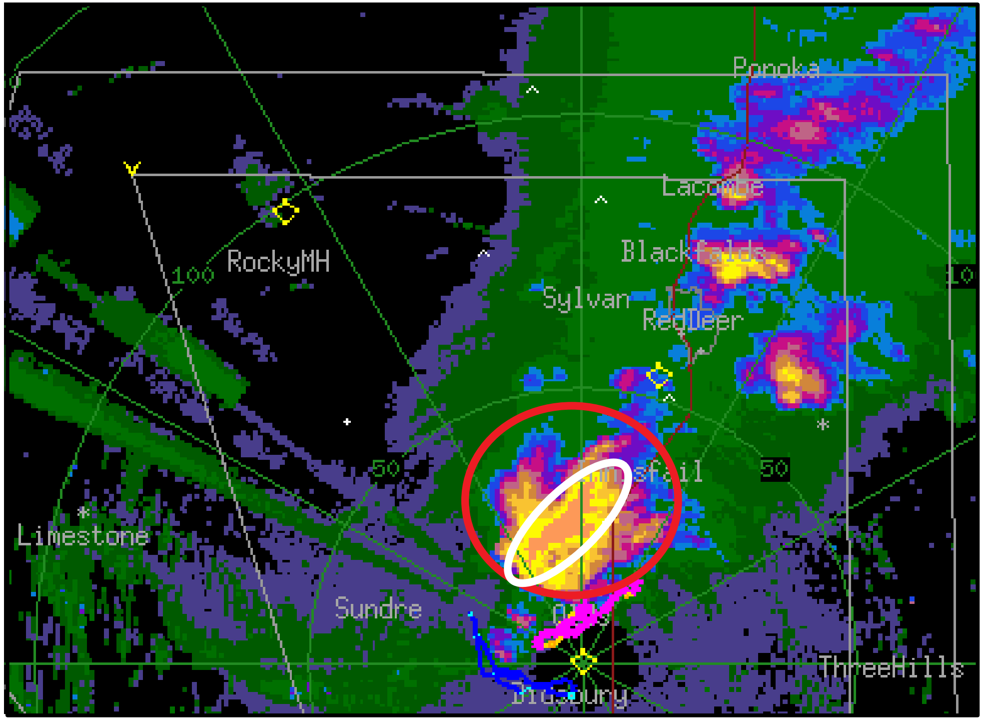


Photo Courtesy of Bruce Boe, Weather Modification International

Goals of the Alberta Hail Suppression Project

- **The Alberta Hail Suppression Project is designed to reduce property losses through,**
  - **Reduced size of hail, which then leads to**
    - **Reduced duration of damaging hail**
    - **Reduced area of damaging hail**



Measurable Outcomes of Cloud Seeding

- **Reduction in hailstone size.**
- **Reduction in very high reflectivity values during and after seeding.**
- **Reduction in Maximum Vertically Integrated Liquid (MaxVIL) during and after seeding.**

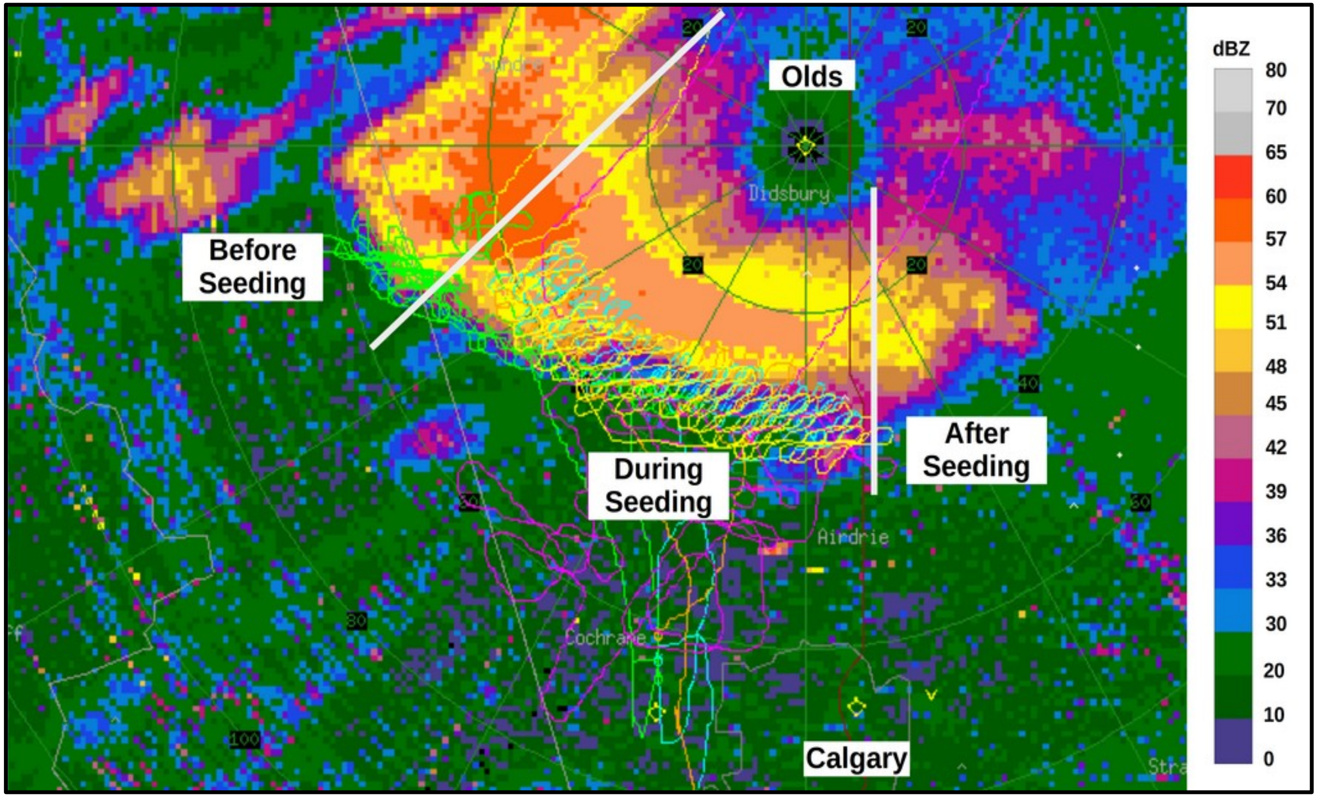


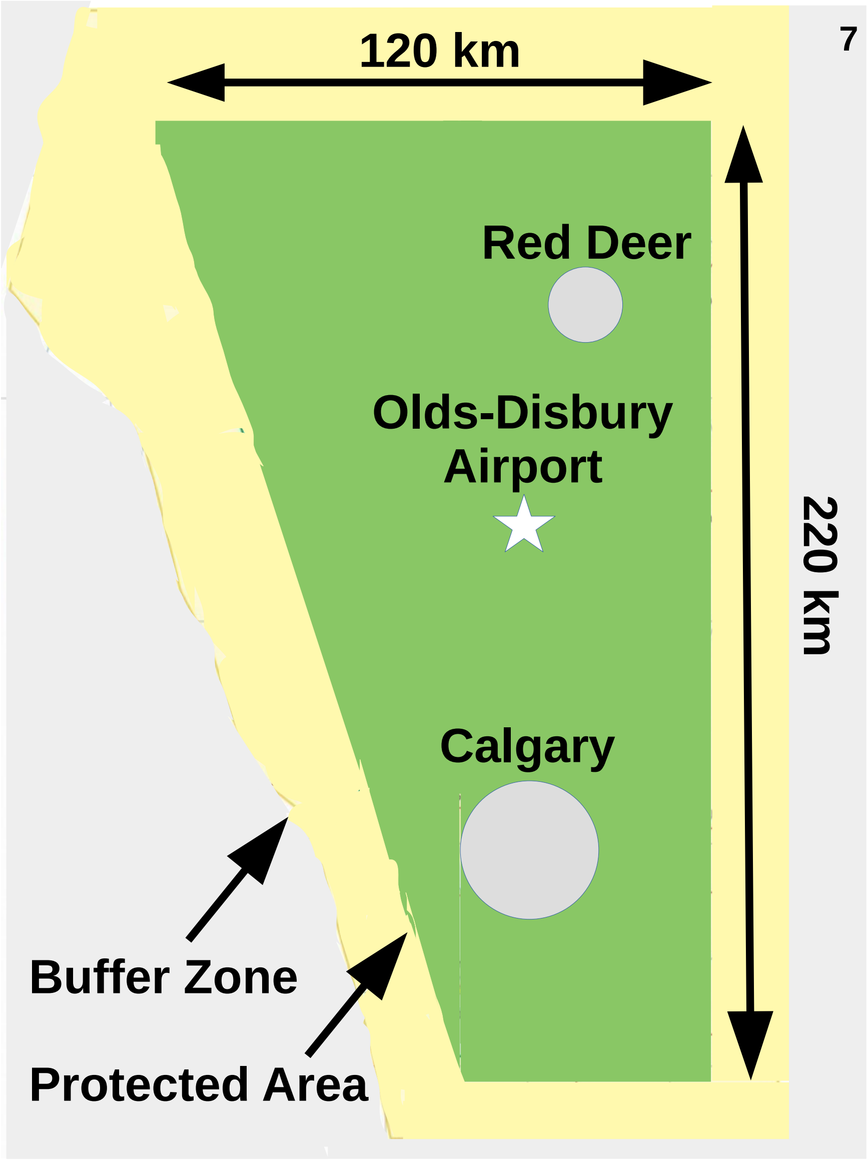
Image showing maximum composite radar reflectivity for the 13 July 2017 storm north of Calgary. The thin color lines on the south side of the storm denote seeding aircraft flight tracks. The white lines delineate different sections of the storm based on the cloud seeding operations.

- References:
- Donaldson 1961
- Auer 1972
- Krauss et al. 1998

Alberta Hail Suppression

- Seeding area has two parts, buffer zone (20,787 km^2) and protected area (23,174 km^2).
- The current project uses several (5) aircraft.
- The current project uses a C-band Doppler radar located at Olds-Didsbury Airport.
- The radar is operated with less than 4 minutes volume scans.

Courtesy of Alberta Hail Suppression Project Final Operations Report 2018.



Storm – TITAN Cell - Case

- **Storm**

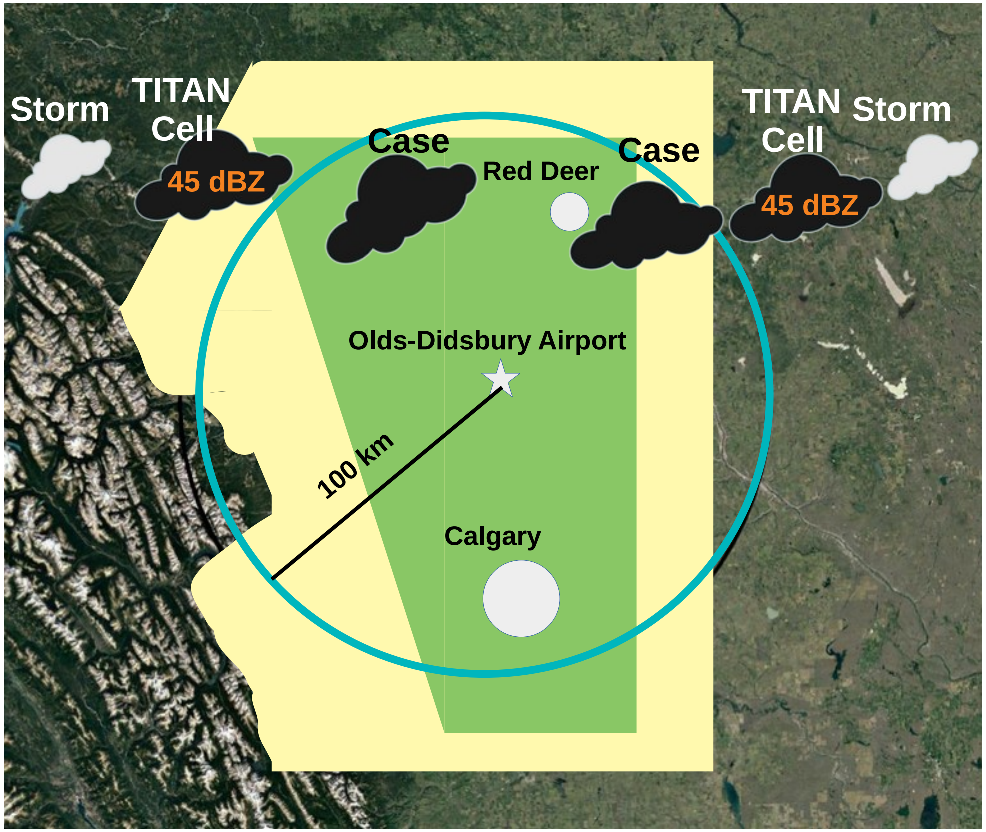
  Any area of convection.

- **TITAN Cell**

  Storm having 45 dBZ reflectivity volume greater than 10 km^3 above 4 km altitude.

- **Case**

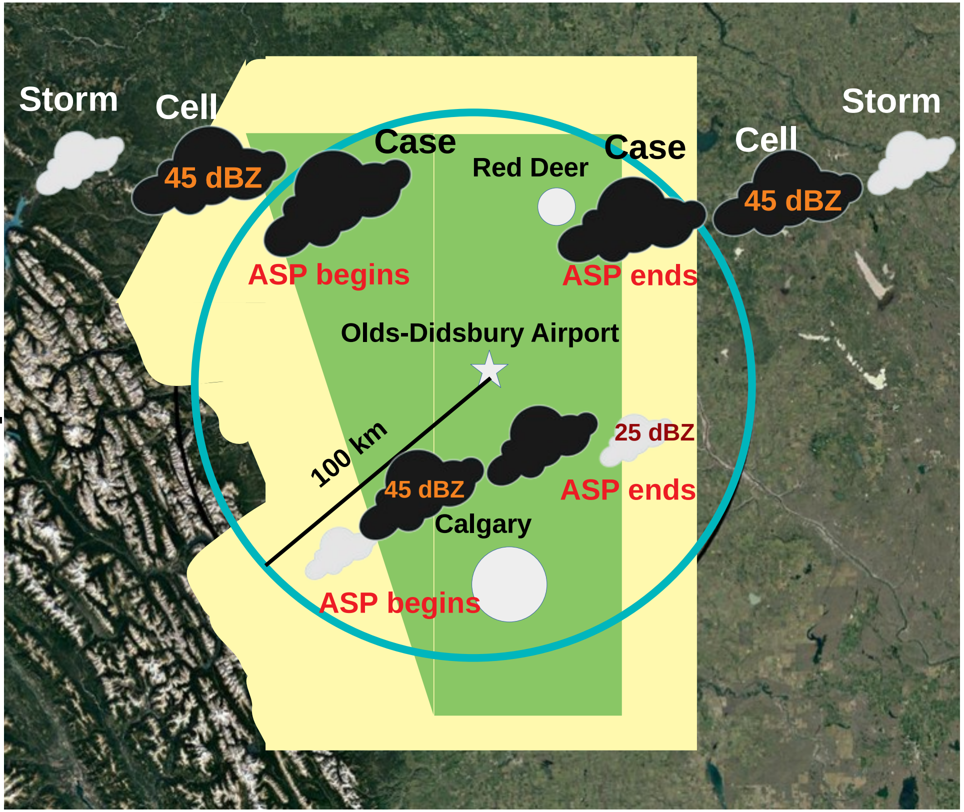
  TITAN Cell at a distance of 100 km or less from the radar.



- References: Gilbert et al. 2016

Overview of Active Storm Period

- **Active Storm Period (ASP)**
  - Length of time for which a case is studied.
  - Case stays inside 100 km radar ring.
  - Case has the potential to produce damaging hail.
- **ASP begins** when a cell becomes a case.
- **ASP ends with the earlier of the following two events**
  - Case moves more than 100 km away from the radar.
  - Case decays to 25 dBZ at the 4 km level.

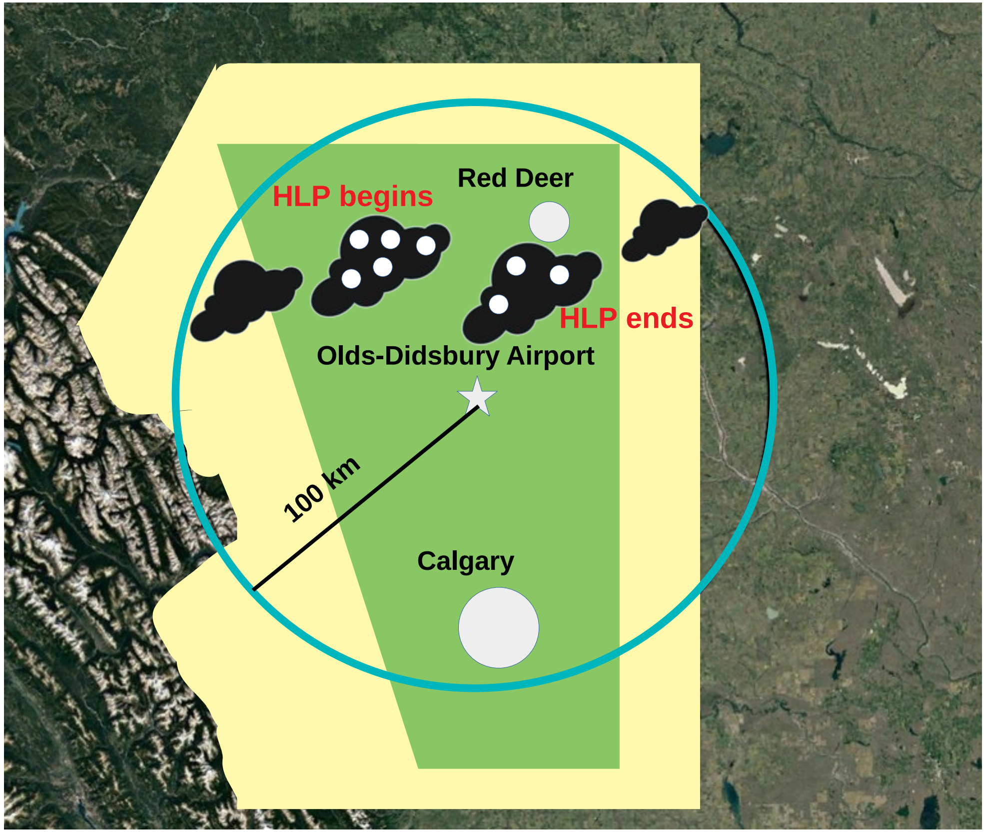


Overview of Hail Likelihood Period

- **Hail Likelihood Period (HLP)**
  - Length of time in the ASP during which case contains damaging hail.
    - Damaging hail is defined by the indicators

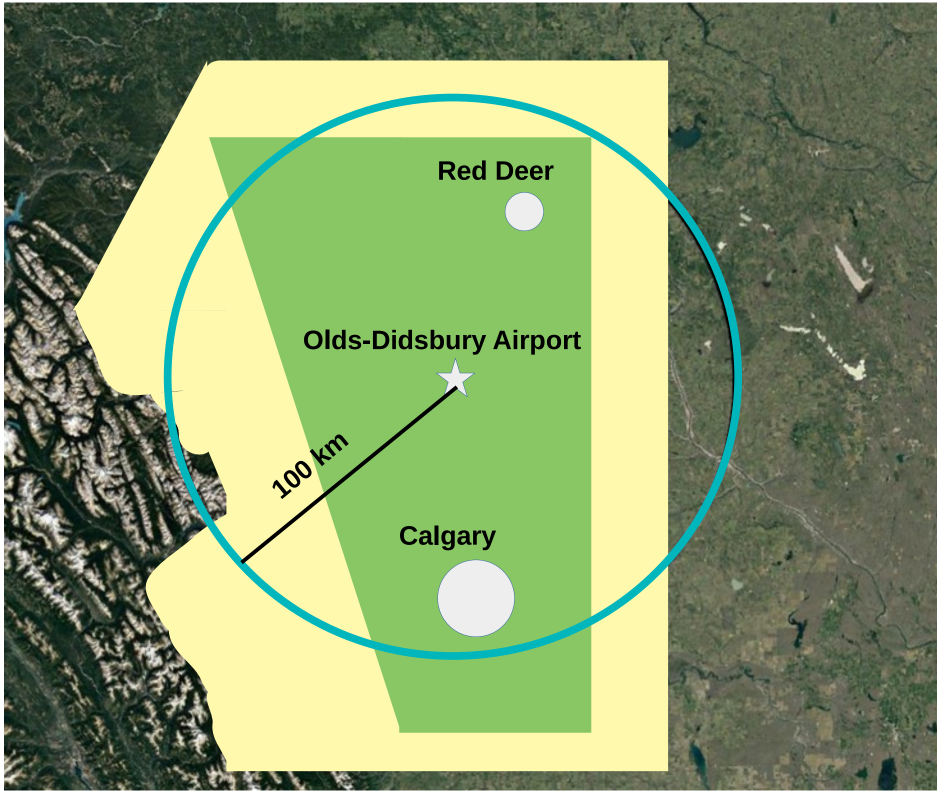
    1. Maximum Vertically Integrated Liquid (MaxVIL) ≥ 30 kg/m^2 (above melting layer)
    2. Storm Area ≥ 60 dBZ

  - There can be multiple HLPs in an ASP.



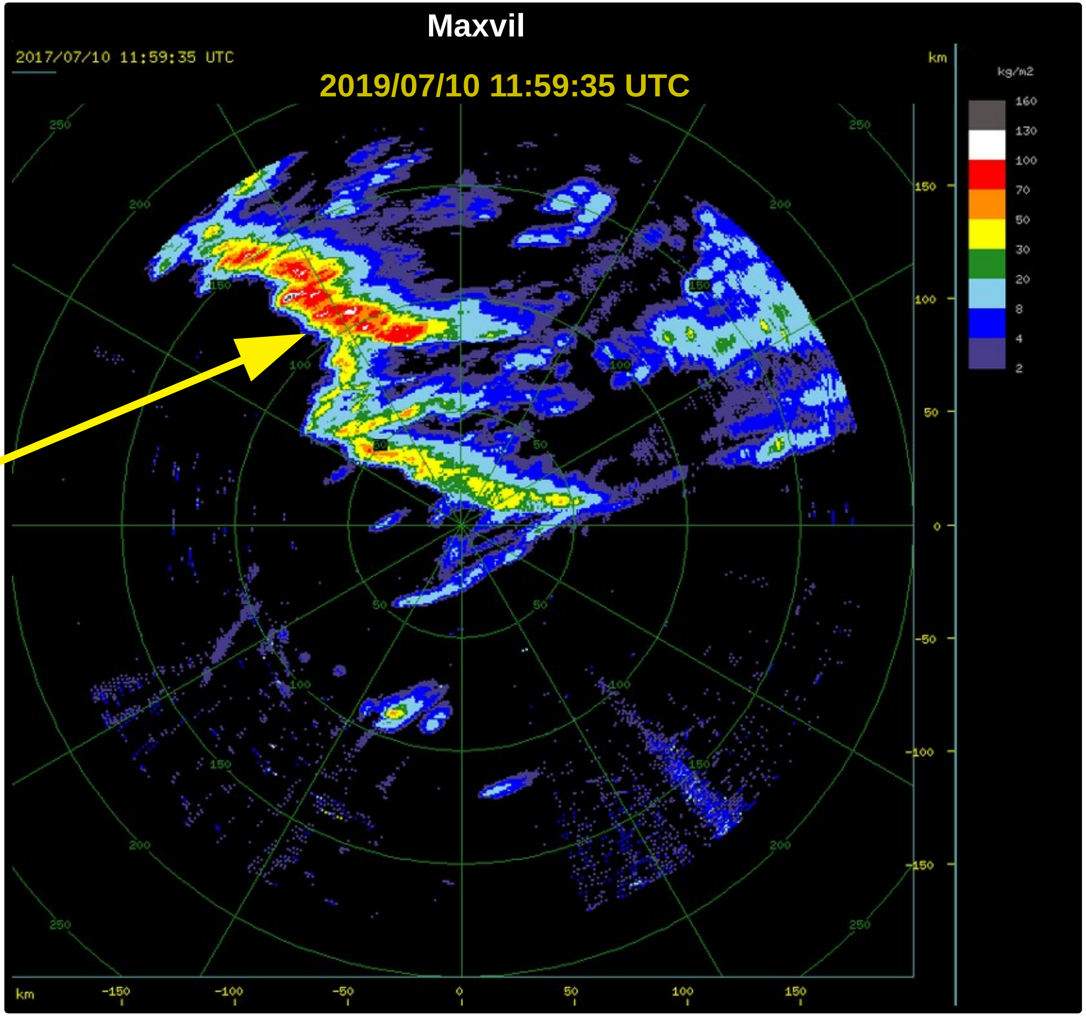
Target Categories

- **Seeded**
  - A target treated with more than 2 kg of seeding material and having at least 4 volume scans during the ASP.
- **Non-Seeded**
  - A target treated with 0 kg of seeding material but staying inside the ring for at least 4 volume scans during its ASP.
- **Non-Analyzed**
  - A target that is not in the seeded or non-seeded category. Includes attenuated cases and those passing over the radar cone of silence.



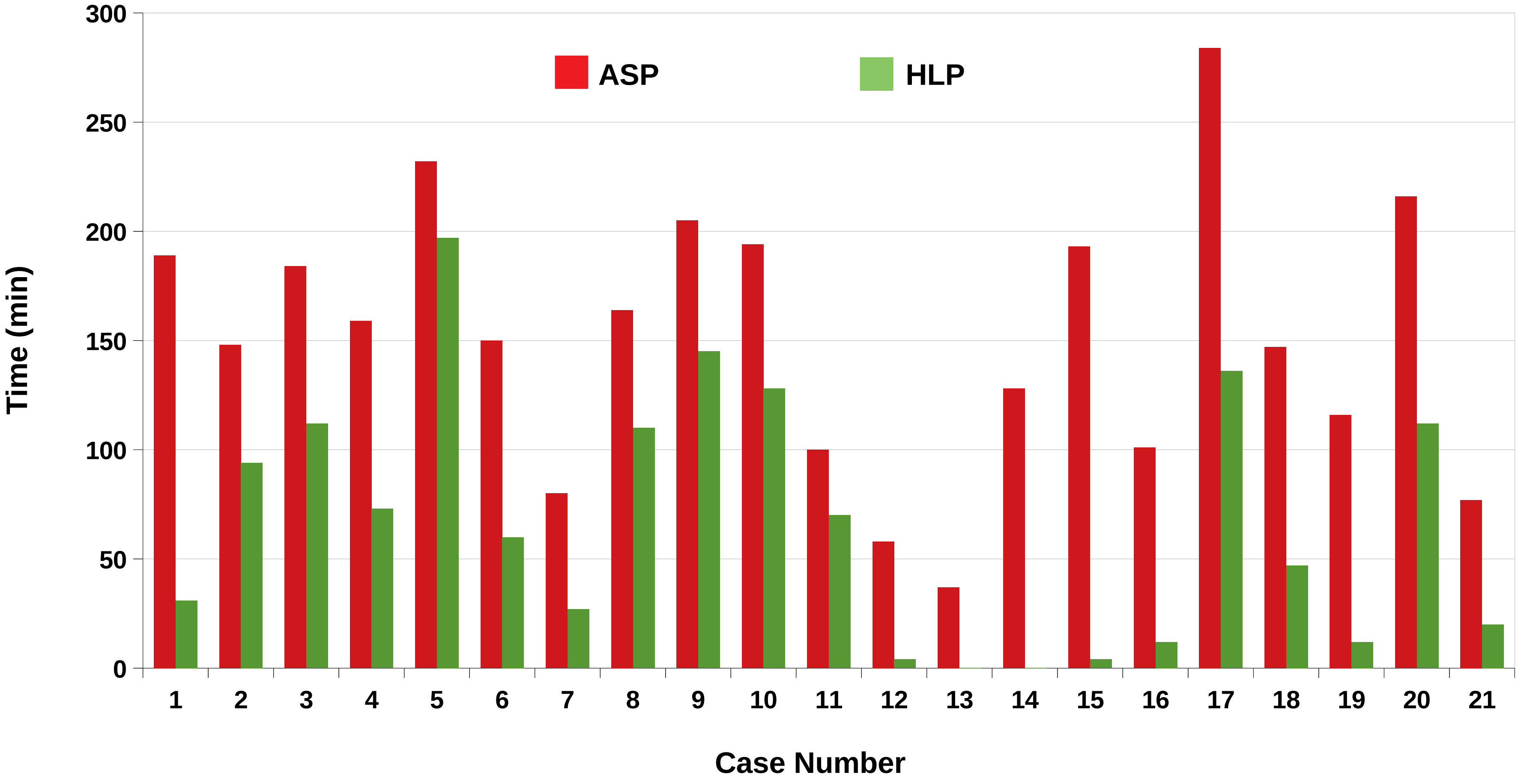
Case Selection

- **Alberta Hail Suppression Project annual reports used to make an initial list of seeding days and storm locations.**
- **TITAN used to identify seeded cells on the listed seeding days.**
  - **Cell track numbers used.**
  - **Flight and seeding flare tracks used for seeding start and end times.**

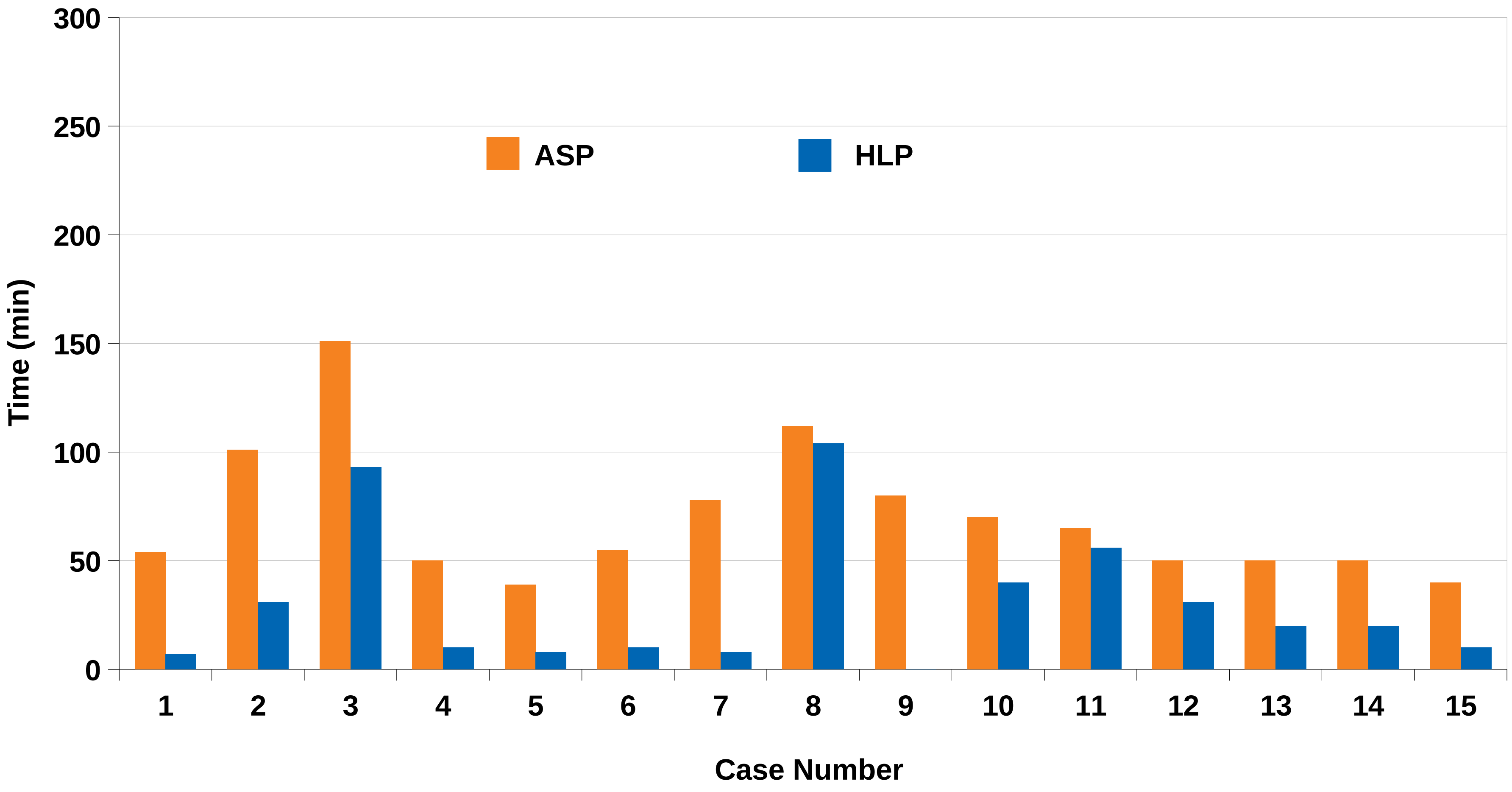


Maxvil is obtained from Vil from 12 Z on July 9 to 12 Z on July 10

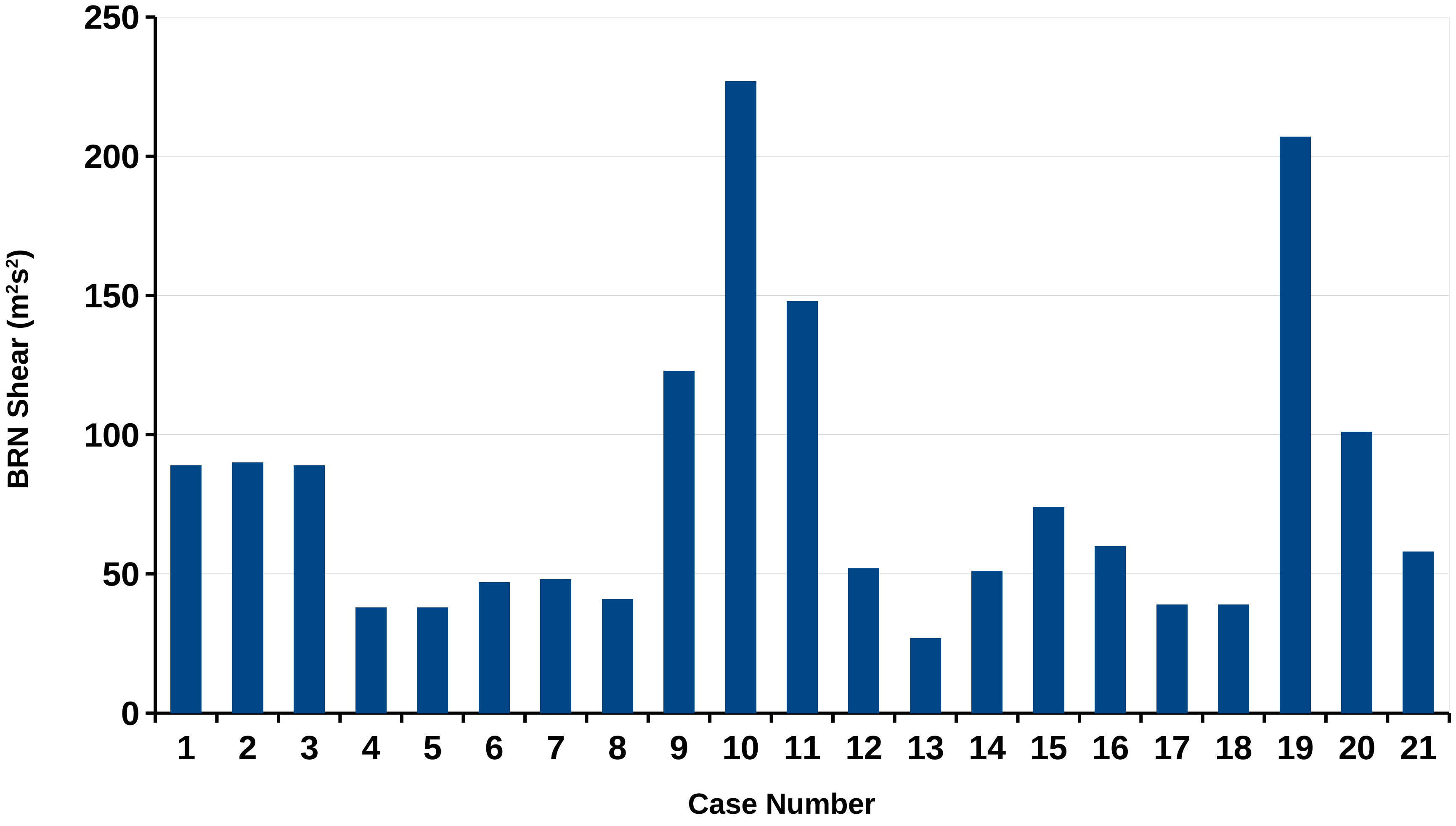
Seeded Cases Duration



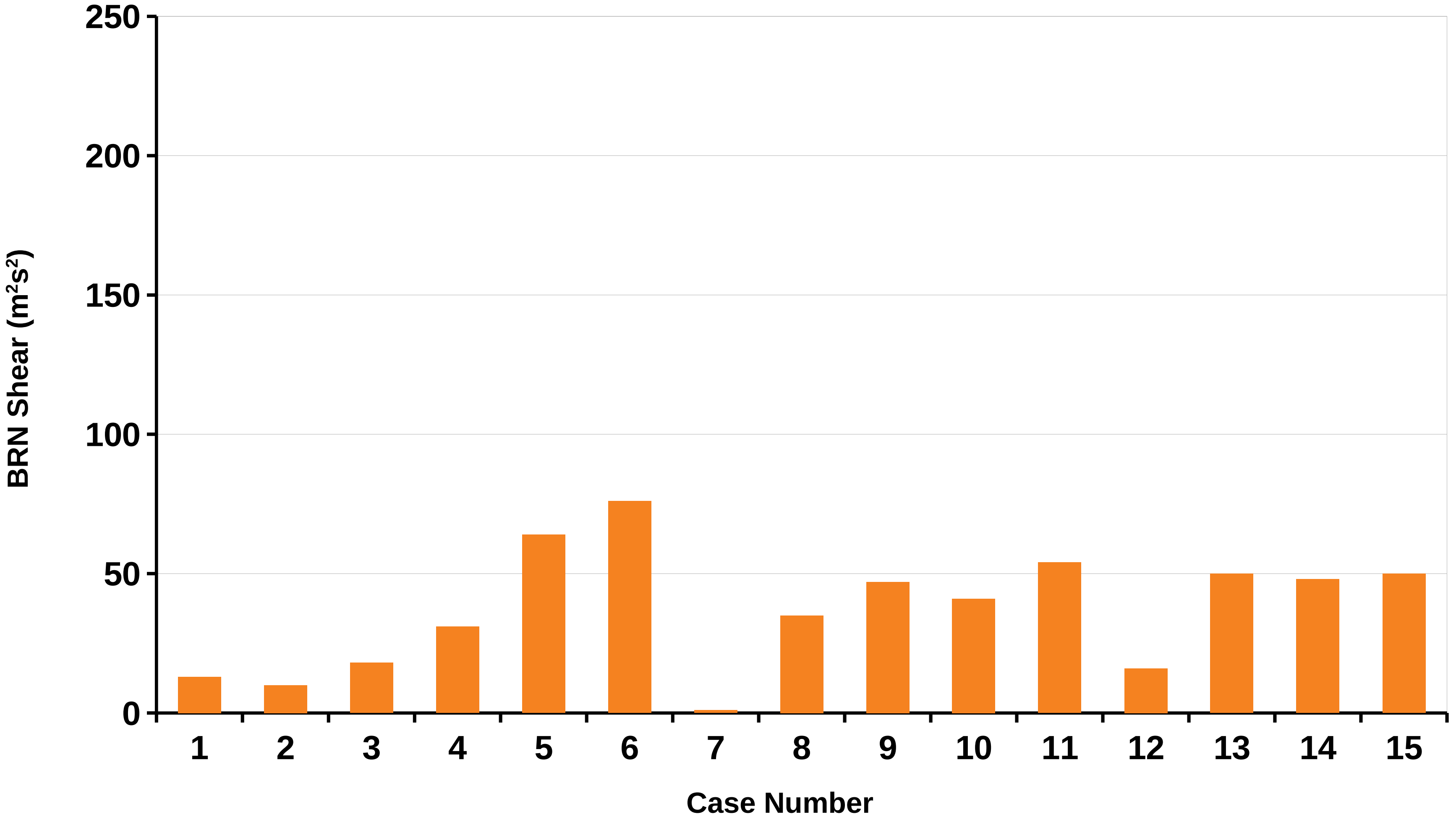
Non-Seeded Cases Duration



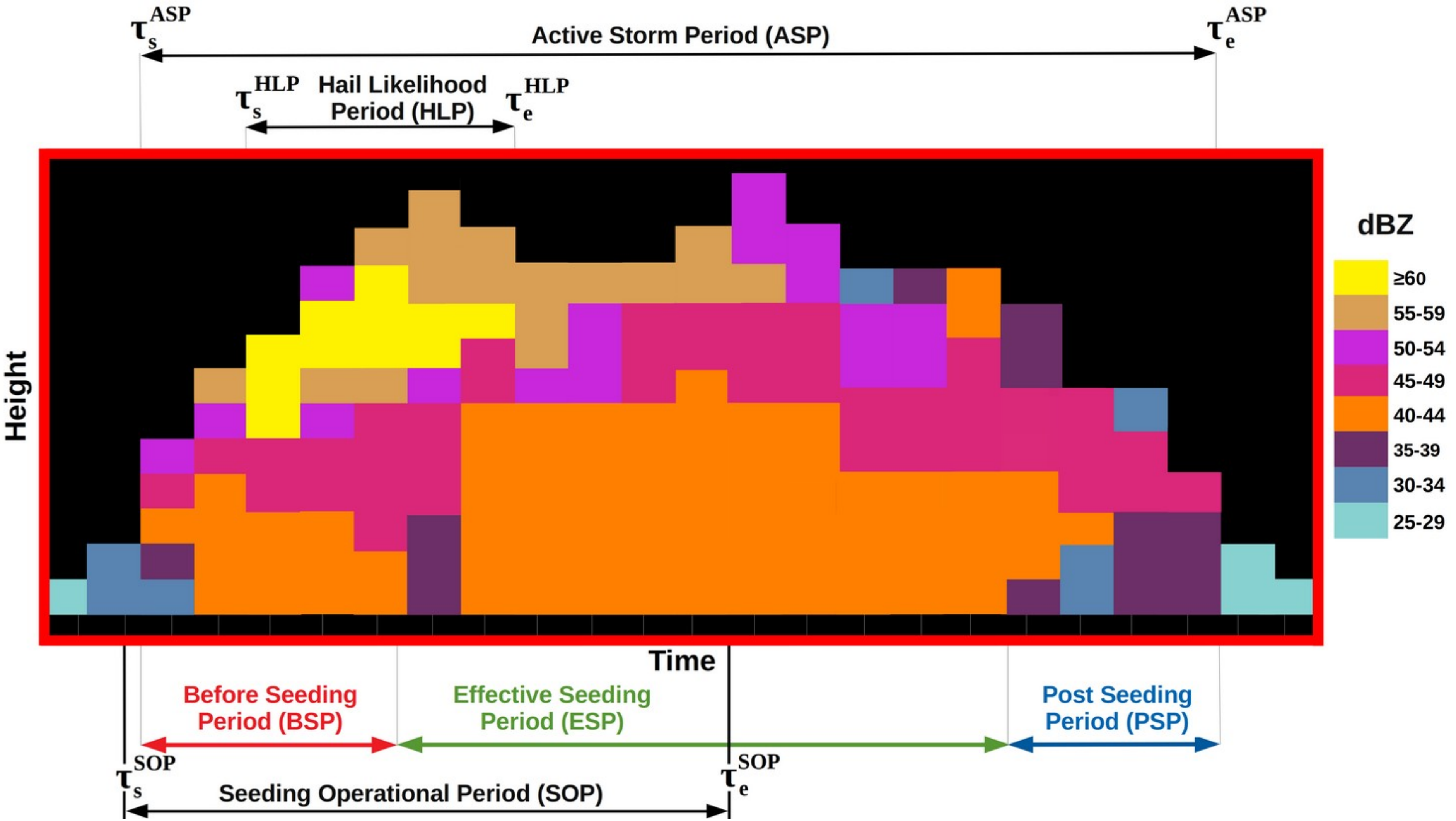
Seeded Cases Shear



Non-Seeded Cases Shear

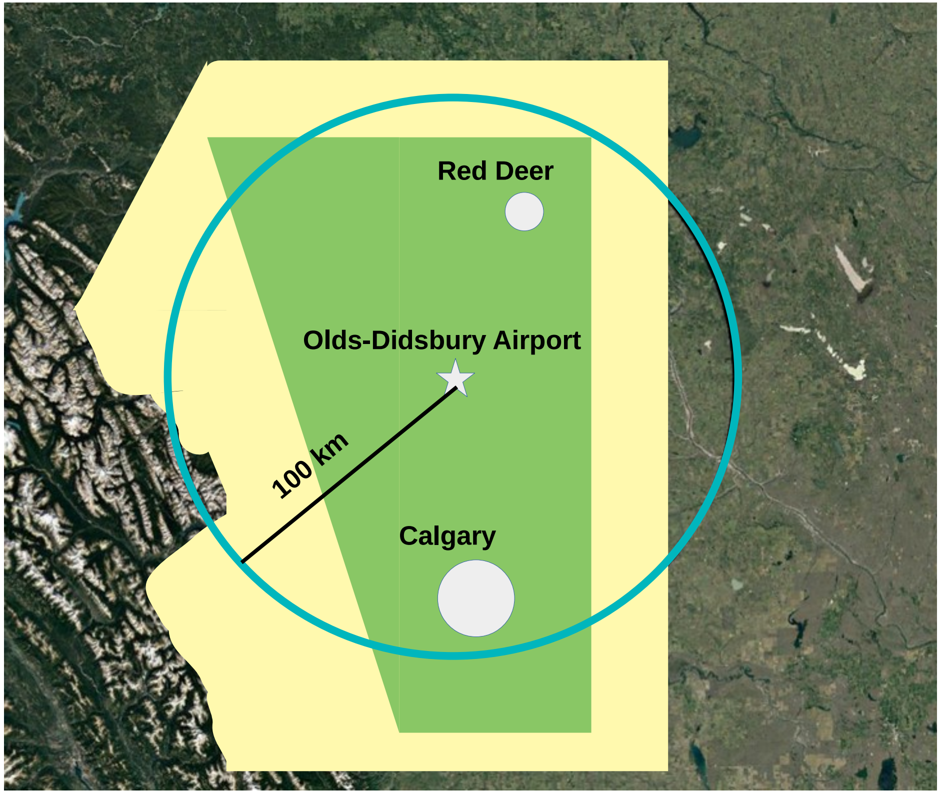


An Idealized Reflectivity of a Hailstorm



2017 Cases

- **Seeded (21 cases)**
  - A target treated with more than 2 kg of seeding material and staying inside the ring (ASP) for at least 4 volume scans **during both BSP and ESP.**
- **Non-Seeded (15 cases)**
  - A target treated with 0 kg of seeding material but staying inside the ring for at least 4 volume scans during its ASP.
- **Non-Analyzed (17 cases)**
  - A target that is not in the seeded or non-seeded category. Includes attenuated cases and those passing over the radar cone of silence.



Indicators Used

- Maximum Vertically Integrated Liquid (MaxVIL)
  - MaxVIL is a measure of the liquid water mass in a column over a height interval.

  - Derived using radar reflectivity.

  - VIL is defined as $\sum_{i+1}^{n}((3.44*10^{(-6)})*((Z_i+Z_{i+1})/2)^{(4/7)}*h)$ where,

    Z_i = radar reflectivity at lower edge of column

    Z_{i+1} = radar reflectivity at upper edge of column

    h = height of column
  - Maximum value of VIL within a TITAN cell is referred to as MaxVIL.

- Storm area greater than or equal to 60 dBZ.

References: US Department of Commerce 1991

General Formula of Seeding Effectiveness (SE)

Indicators → Hail Metrics → SE

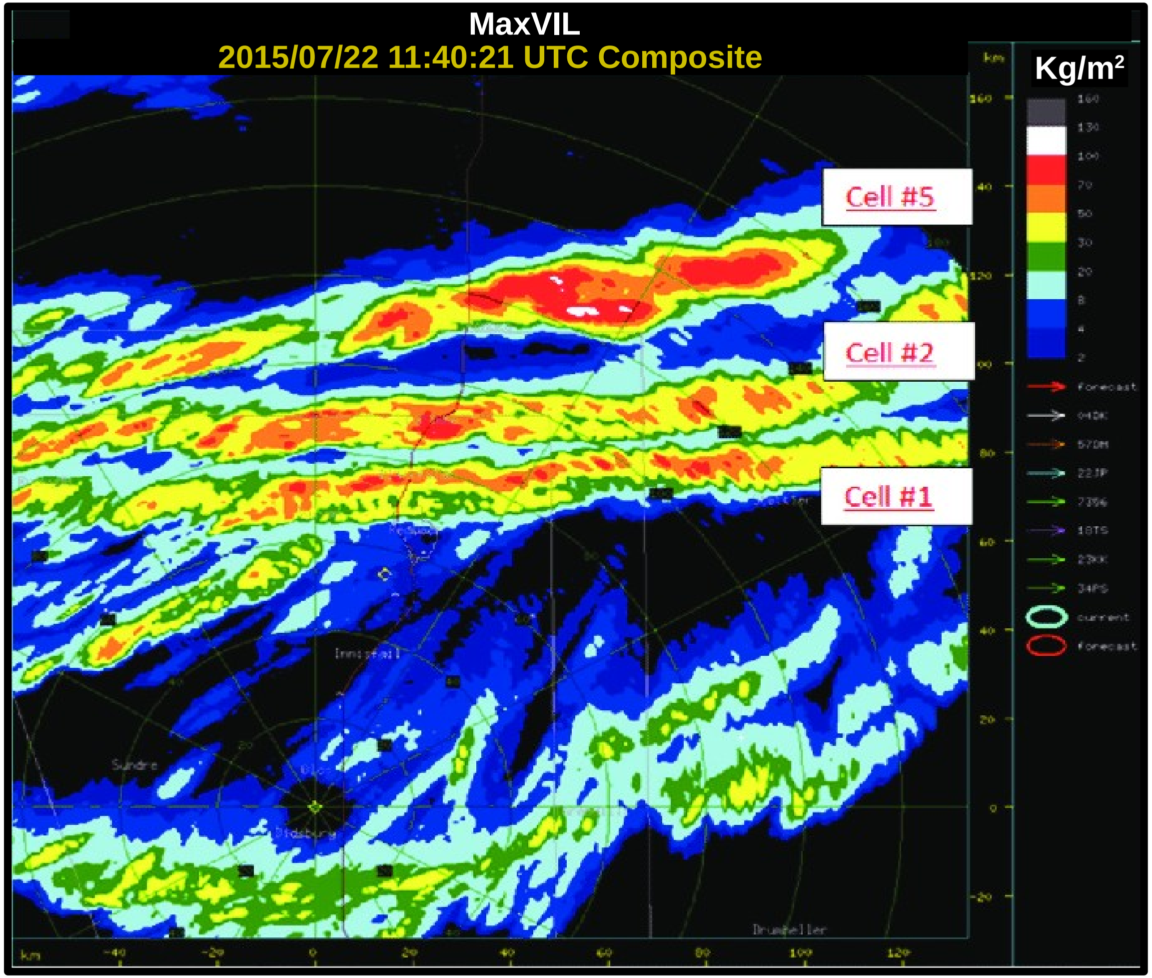
- **The Seeding Effectiveness (SE) is calculated using,**

$$SE = \frac{H_{BSP} - H_{ESP}}{H_{BSP}}$$

H_{BSP} **- Hail Metric Before Seeding**

H_{ESP} **- Hail Metric During Seeding**

- **Positive SE indicates hail reduction.**
- **SE can have a maximum value of 1.**
- **SE should be consistent across cases**



MaxVIL plots on 22 July 2015 for the Alberta Hail Project.

Seeding Effectiveness (SE): Indicators and Metrics

- **Average Hail Indicator (AHI)**
  (Mean of Indicators)
  1. MaxVIL (above melting layer)
  2. Area ≥ 60 dBZ

- **Hail Occurrence Ratio (HOR)**
  (How long do we have damaging hail ?)
  3. MaxVIL (above melting layer)
  4. Area ≥ 60 dBZ

- **Increasing Hail Ratio (IHR)**
  (How long do the indicators increase ?)
  5. MaxVIL (above melting layer)
  6. Area ≥ 60 dBZ

Average Hail Indicator (AHI) using MaxVIL

- **Seeding Effectiveness of each case is calculated using,**

$$SE_{AHI}^{MaxVIL} = \frac{\overline{AHI_{BSP}^{MaxVIL}} - \overline{AHI_{ESP}^{MaxVIL}}}{\overline{AHI_{BSP}^{MaxVIL}}}$$ **where,**

$\overline{AHI_{BSP}^{MaxVIL}}$ **= mean MaxVIL during the BSP**

$\overline{AHI_{ESP}^{MaxVIL}}$ **= mean MaxVIL during the ESP**

- **Shows the average change in the MaxVIL between BSP and ESP.**

Hail Occurrence Ratio (HOR) using MaxVIL

- HOR_{BSP}^{MaxVIL} = m/n where,

  m = number of volume scans during BSP having MaxVIL ≥ 30kg/m^2

  n = number of volume scans during BSP
- HOR_{ESP}^{MaxVIL} = p/q where,

  p = number of volume scans during ESP having MaxVIL ≥ 30kg/m^2

  q = number of volume scans during ESP
- Seeding Effectiveness of each case is calculated using,

$$SE_{HOR}^{MaxVIL} = \frac{HOR_{BSP}^{MaxVIL} - HOR_{ESP}^{MaxVIL}}{HOR_{BSP}^{MaxVIL}}$$

- Shows the average change in the time fraction for which damaging hail is present between the BSP and ESP.

Increasing Hail Ratio (IHR) using MaxVIL

- IHR_{BSP}^{MaxVIL} = i/j where,

  i = number of occurrences of MaxVIL increase during BSP

  j = number of volume scans during BSP
- IHR_{ESP}^{MaxVIL} = k/l where,

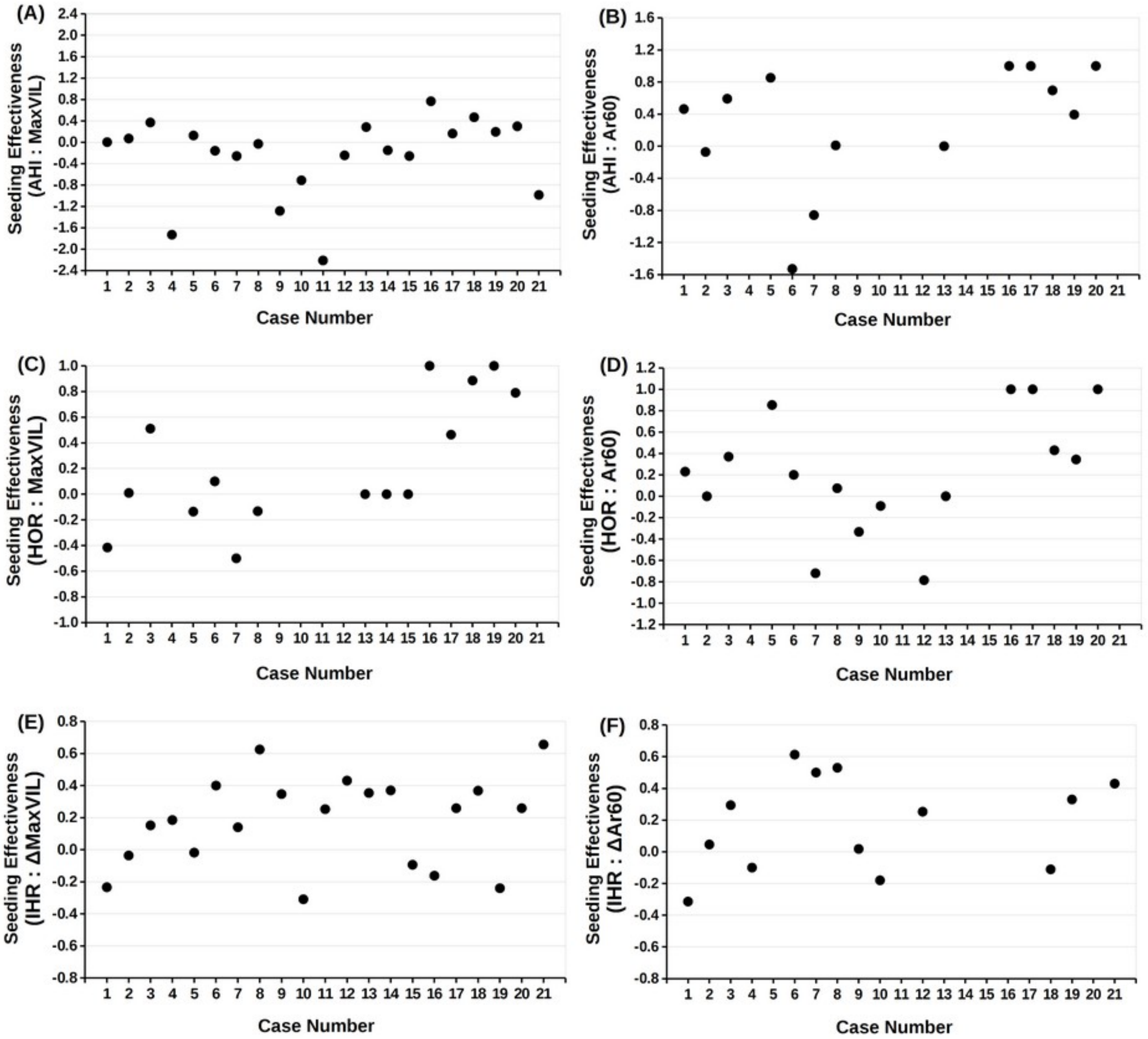
  k = number of occurrences of MaxVIL increase during ESP

  l = number of volume scans during ESP
- Seeding Effectiveness of each case is calculated using,

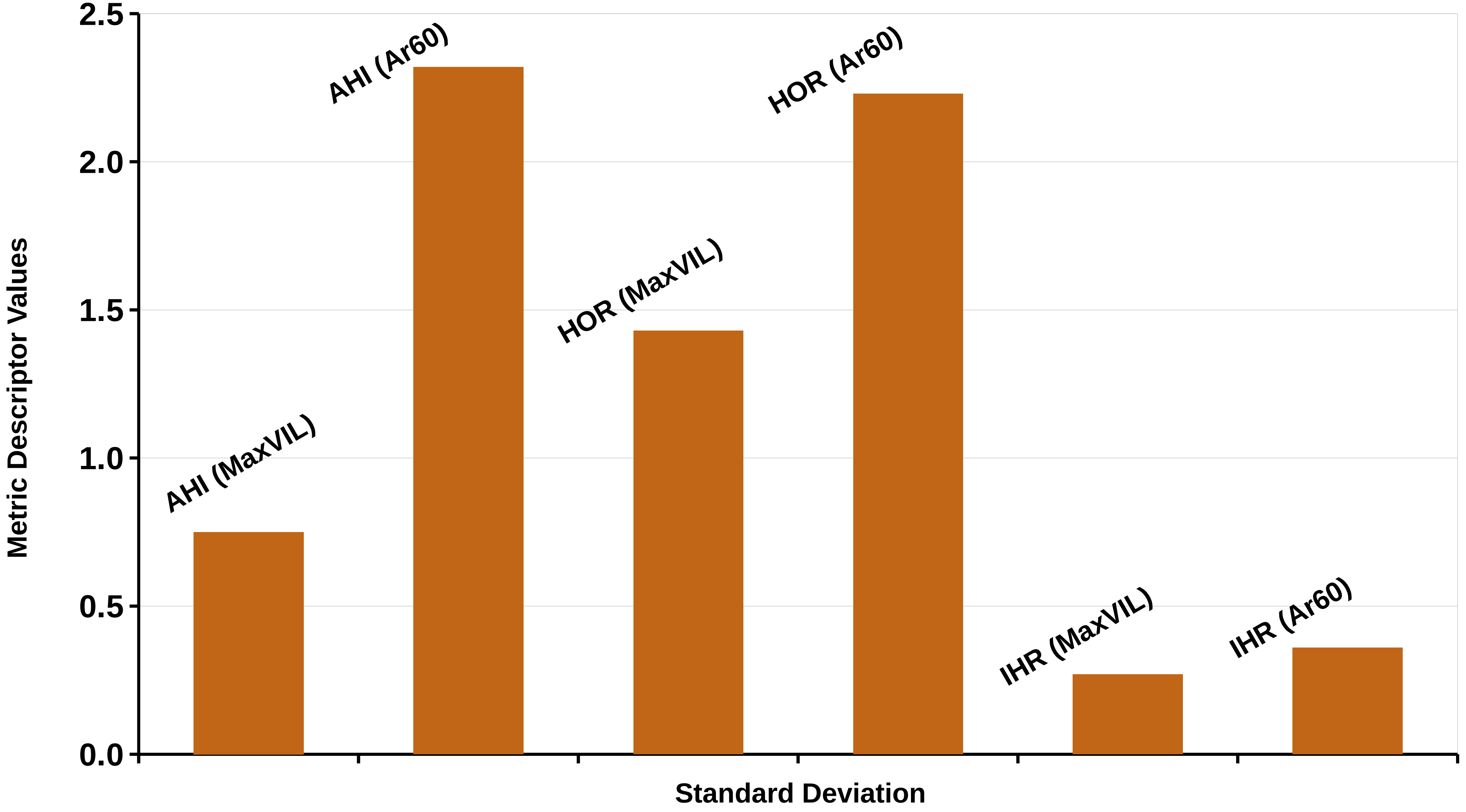
$$SE_{IHR}^{MaxVIL} = \frac{IHR_{BSP}^{MaxVIL} - IHR_{ESP}^{MaxVIL}}{IHR_{BSP}^{MaxVIL}}$$

- Shows the average change in the time fraction for which hailstones increase in size between the BSP and ESP.

SE of Seeded Cases



Standard Deviation of Seeding Effectiveness



Summary

Metric Name	Hail Indicator	Cases	Average SE
Average Hail Indicator	MaxVIL	21	-0.25
Average Hail Indicator	Ar60	21	-0.87
Hail Occurrence Ratio	MaxVIL	21	-0.21
Hail Occurrence Ratio	Ar60	21	-0.42
Increasing Hail Ratio	**ΔMaxVIL**	21	**+0.18**
Increasing Hail Ratio	**ΔAr60**	15	**+0.23**

Conclusion

- A 2 to 1 ratio of seeded versus non-seeded cases is found but the non-seeded cases have lower values of shear compared to the seeded cases.

- The Increasing Hail Ratio metric generating SE’s having lower variability across the 2017 seeded cases and hence show promise for future research.

- The low standard deviation metrics (IHR using MaxVIL and Ar60) have a positive SE; however, they are not statistically significant ($p>0.05$).

Future Work

- **Use same method and approach on data from the 2014-2020 period to obtain a statistically significant result.**
- **Include the Post Seeding Period (PSP) in the analysis.**

Acknowledgements

- **Committee Members** *(..forever in debt to your priceless advice !!)*
    - **Professor David Delene**
    - **Professor Andrew Detwiler**
    - **Professor Michael Poellot**

- **Weather Modification International (WMI)**
    - **Mr. Bruce Boe, Vice President of Meteorology, WMI**
    - **Mr. Daniel Gilbert, Chief Meteorologist, WMI**

- **Dr. Terry Krauss, Project Director, Alberta Severe Weather Management Society**

- **Faculty Members**

- **Friends and Colleagues**

- **Parents and Family**

References

- **Auer, A.H., 1972. Distribution of Graupel and Hail With Size. Monthly Weather Review 100, 325–328. https://doi.org/10.1175/1520-0493-100-05-0325**

- **Desjardins Insurance, 2017: Expensive and Deadly Hailstorm in Alberta I Desjardins Insurance. *desjardinsgeneralinsurance.com*,. https://www.desjardinsgeneralinsurance.com/blog/-/the-most-expensive-and-deadly-hailstorms-in-alberta-s-history (Accessed June 14, 2021).**

- **Donaldson, R.J., 1961. RADAR REFLECTIVITY PROFILES IN THUNDERSTORMS. Journal of the Atmospheric Sciences 18, 292–305. https://doi.org/10.1175/1520-0469(1961)018 <0292:RRPIT>2.0.CO;2**

- **Gilbert, D.B., Boe, B.A., Krauss, T.W., 2016. Twenty Seasons of Airborne Hail Suppression In Alberta, Canada. The Journal of Weather Modification 48, 68–92.**

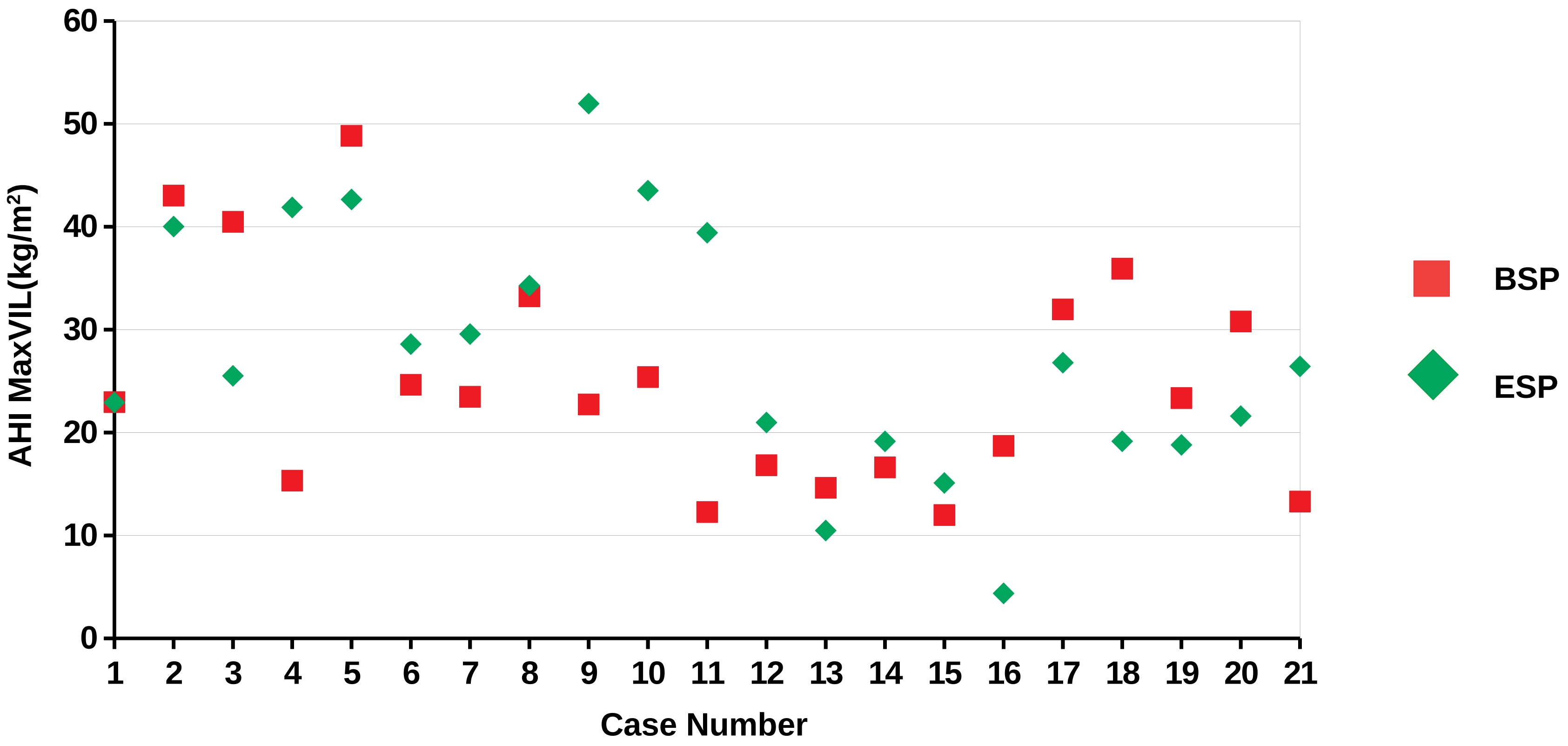
- **Krauss, T. W., R. E. Rinehart, J. L. Kollegger, and S. A. Kozak, 1998: *VIL As A Predictor of Hail in Alberta.* Amer. Meteor. Soc., 14th Conf. on Planned and Inadvertent Weather Modification,.**

- **US Department of Commerce, 1991: Doppler Radar Meteorological Observations Part c. *Federal Meteorological Handbook 1 11*, p. 105.**

Questions and Comments ??

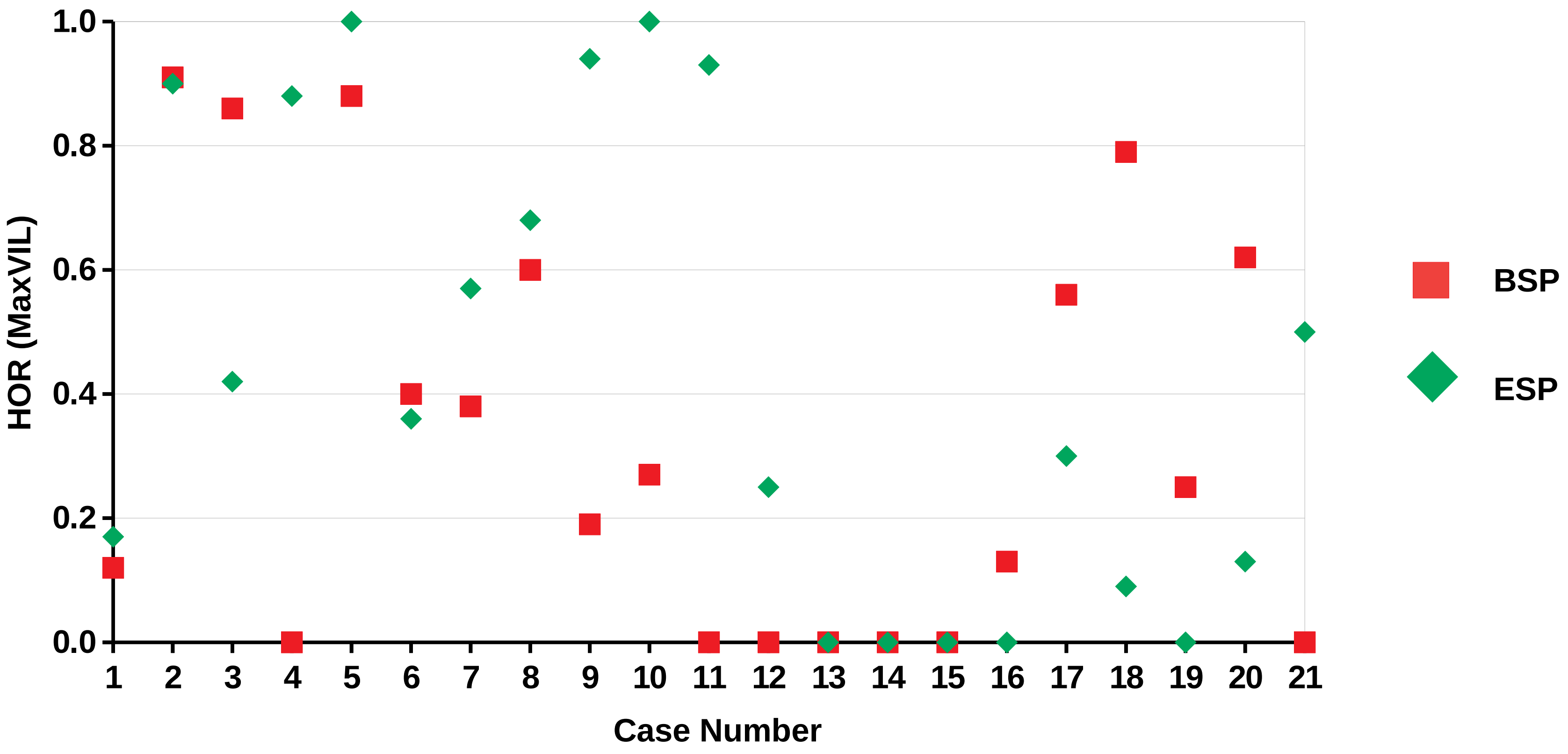
THE END

Seeding Effectiveness based on AHI (Max VIL)



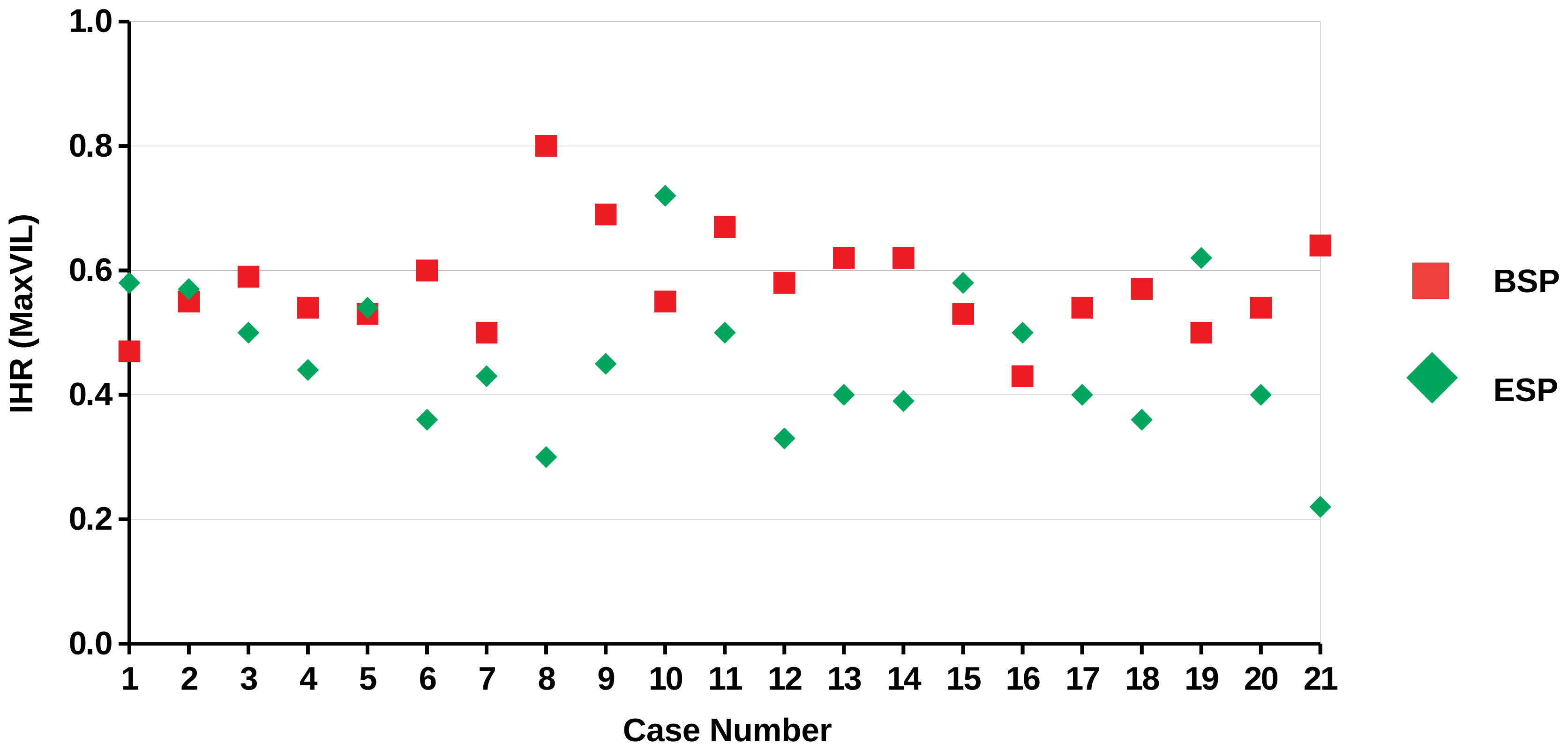
- **Result: Mean Max VIL is 25.07 kg/m^2 during the BSP and 27.77 kg/m^2 during the ESP.**

Seeding Effectiveness based on HOR (Max VIL)



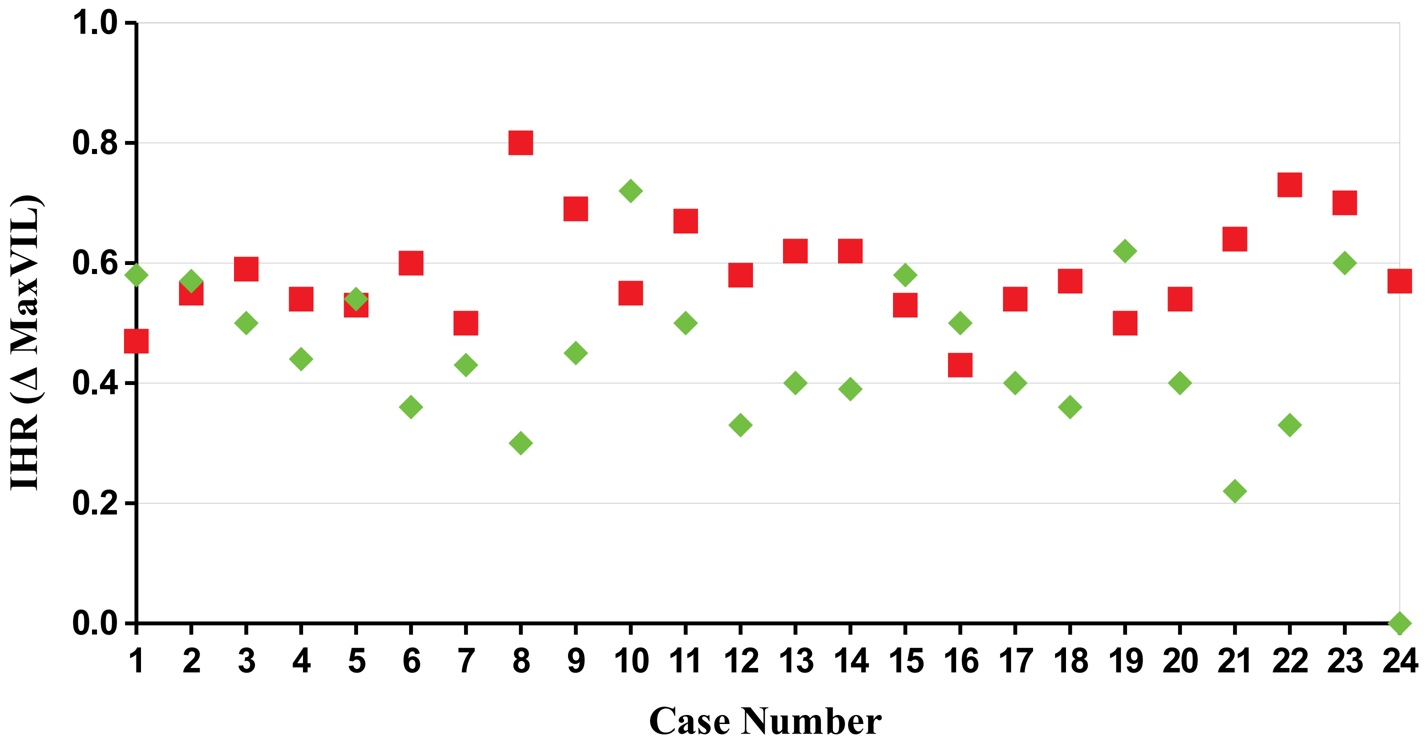
- **Result: Mean HOR is 0.33 during the BSP and 0.43 during the ESP.**

IHR metric using Max VIL indicator



- **Result: Mean IHR is 0.57 during the BSP and 0.46 during the ESP.**

Seeding Effectiveness based on IHR (MaxVIL)



- **Result:**

Preliminary Results

Metric Name	Hail Indicator	Cases	Seeding Effectiveness
Average Hail Indicator	MaxVIL	24	-0.17
Average Hail Indicator	Ar60	24	-0.73
Hail Occurrence Ratio	MaxVIL	24	-0.38
Hail Occurrence Ratio	Ar60	22	-0.12
Increasing Hail Ratio	ΔMaxVIL	24	0.25
Increasing Hail Ratio	ΔAr60	19	0.19

Radar Hail Indicators (H)

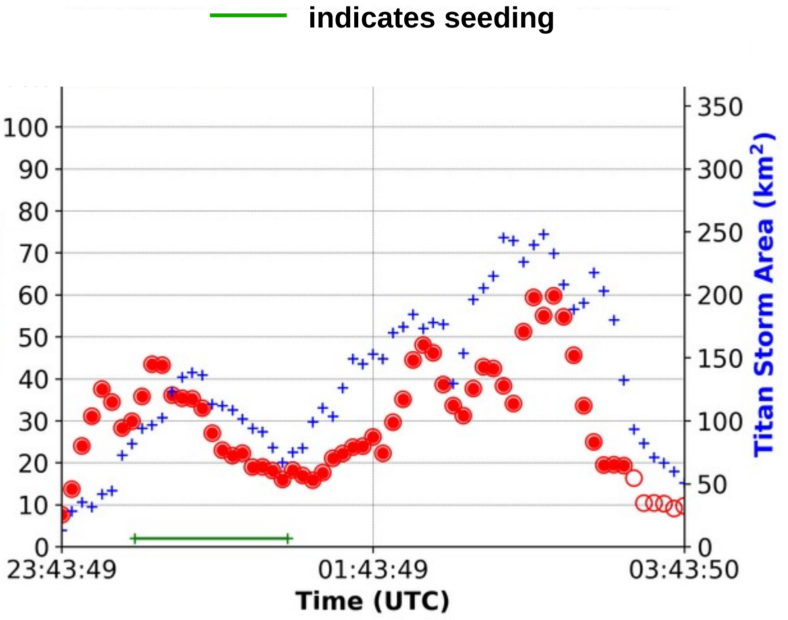
- Storm Area with Composite Reflectivity Greater than 60 dBZ (>60dBZ)

- Maximum Vertically Integrated Liquid (MaxVIL) above melting layer (4 km)

Plotting Indicator Values

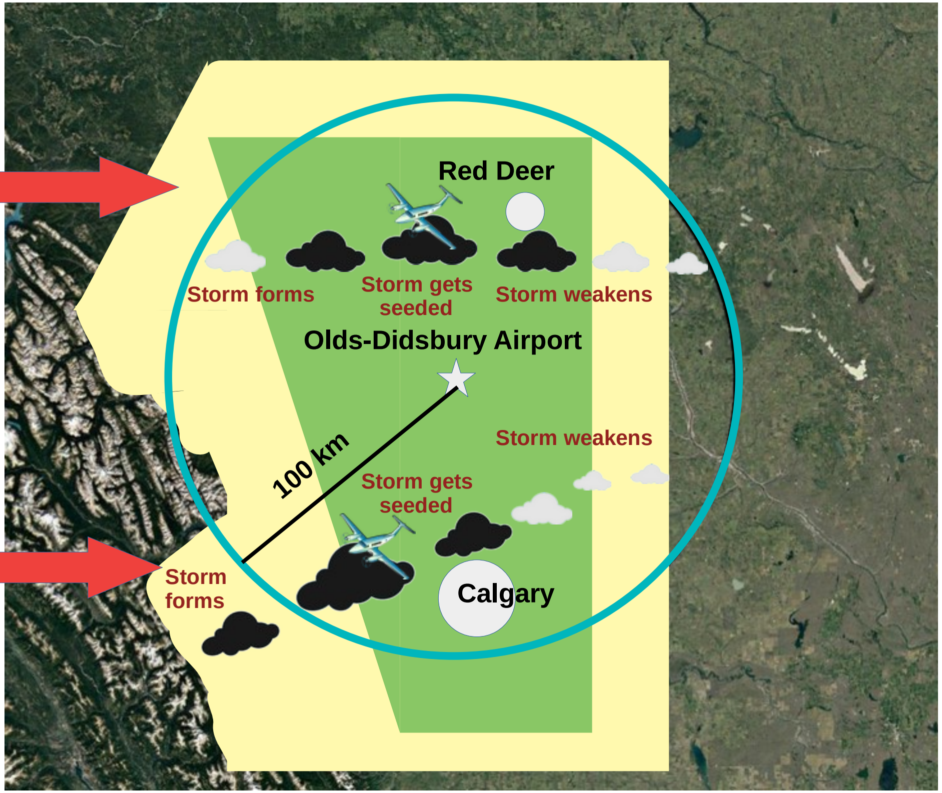
- Metrics are calculated during two different periods of a storm.
    - From start of ASP to 20 minutes after start of seeding which is defined as the Before Seeding Period (BSP).
    - From 20 minutes after start of seeding to 20 minutes after the termination of seeding which is defined as the Effective Seeding Period (ESP).
    - Changes in metric tells us if seeding is effective.

Expected Nature of Plot



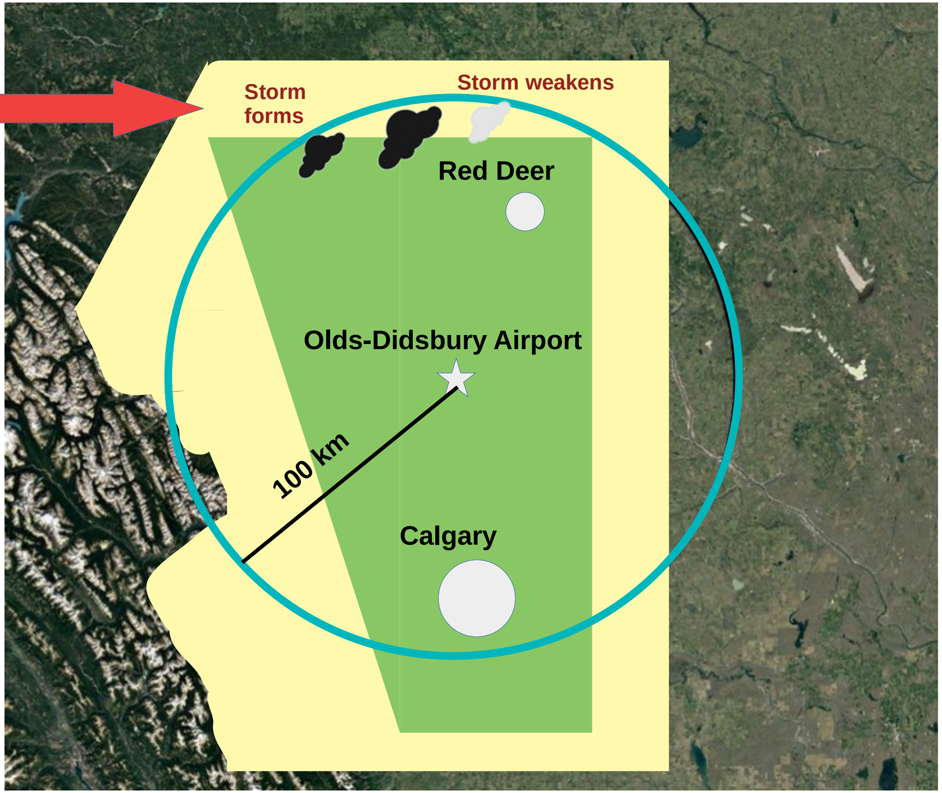
Possible Scenarios Of (Seed) Cases

- **Type 1 – Formation of storm cell and seeding take place inside the 100 km radius and storm stays inside the 100 km ring for at least 10 volume scans after the start of seeding.**
- **Type 2 – Storm forms outside 100 km radius, gets seeded inside the 100 km radius and stays inside the 100 km ring for at least 10 volume scans after the start of seeding.**



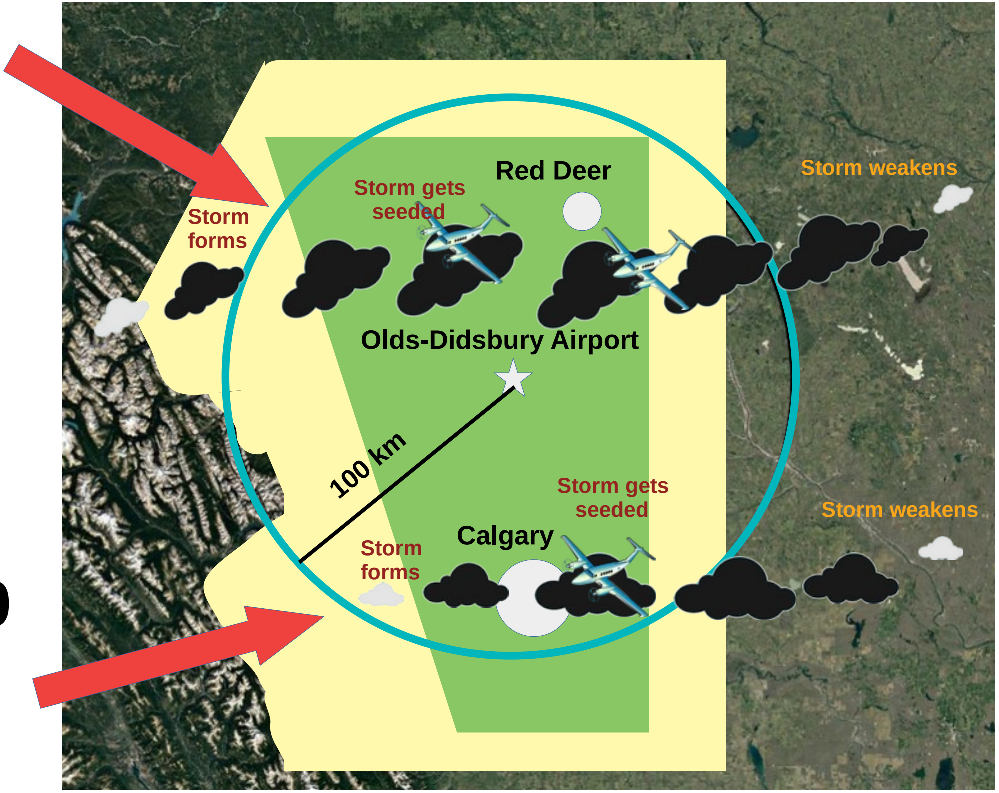
Possible Scenarios Of (Non-Seed) Cases

- **Type 1 – Storm forms, lasts for at least 10 volume scans and decays inside the 100 km radius.**



Possible Scenarios Of (Non-Analysed) Cases

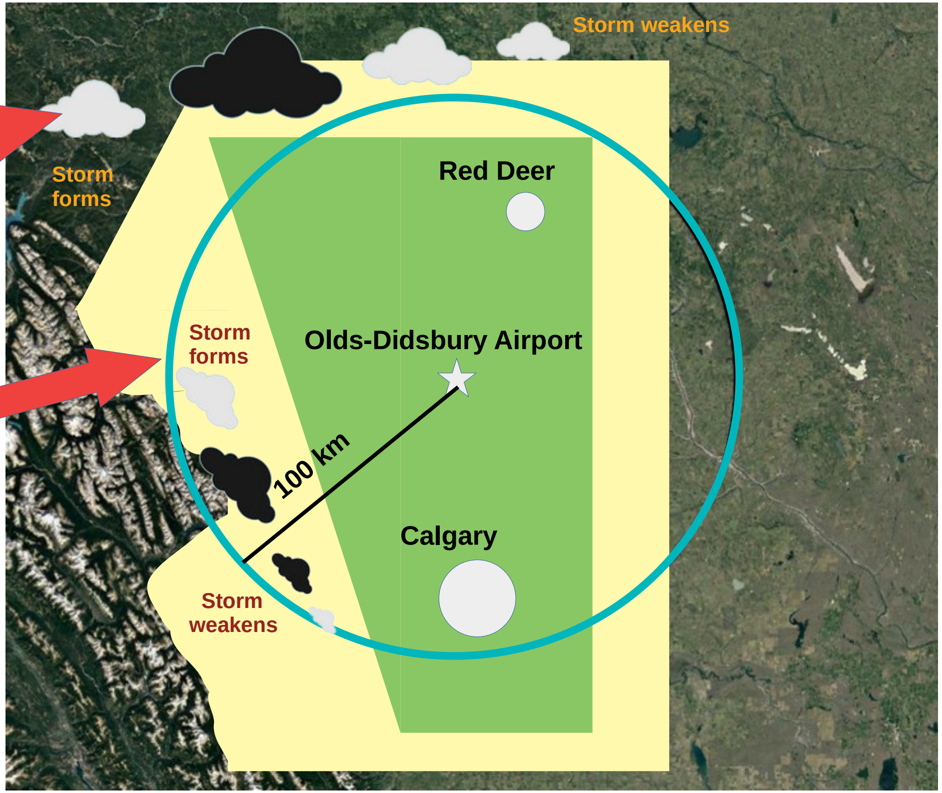
- **Type 1 – Storm is formed outside 100 km, seeded inside the 100 km radius but moves outside the 100 km radius before completing 10 volume scans inside the 100 km ring after the start of seeding.**
- **Type 2 – Storm formation and seeding takes place inside the 100 km radius but moves outside the 100 km radius before completing 10 volume scans inside the 100 km ring after the start of seeding.**



Possible Scenarios Of (Non-Analysed) Cases

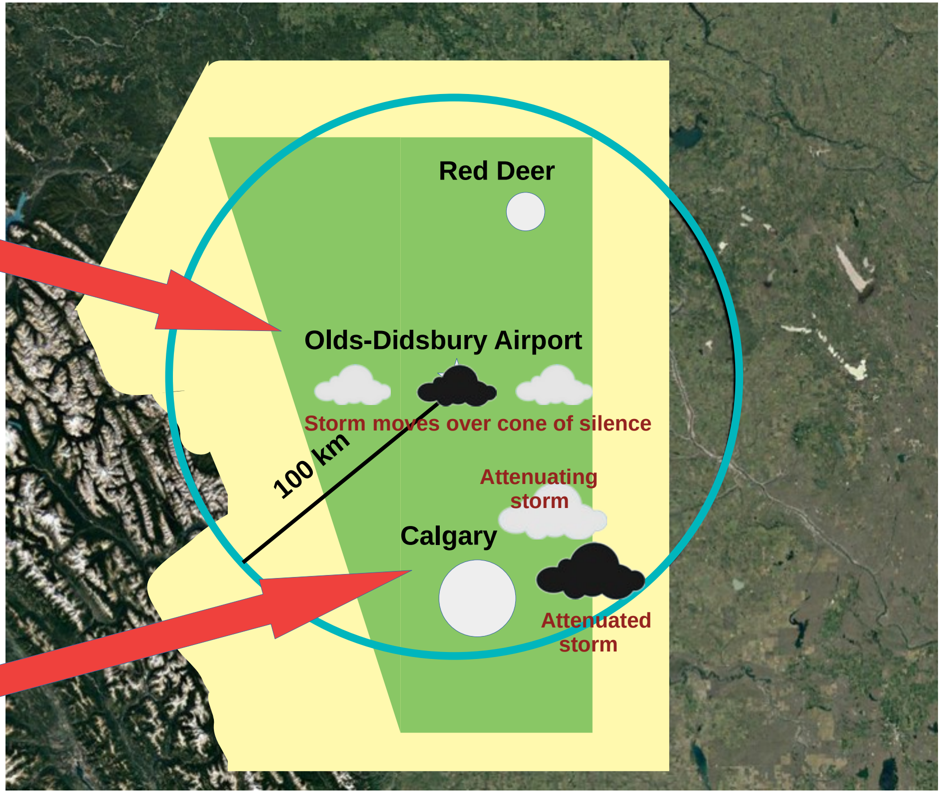
- **Type 3 – Storm forms and dies outside the 100 km radius.**

- **Type 4 – Storm moves over North and South of the foothills of The Rocky Mountains or stays on its foothills.**



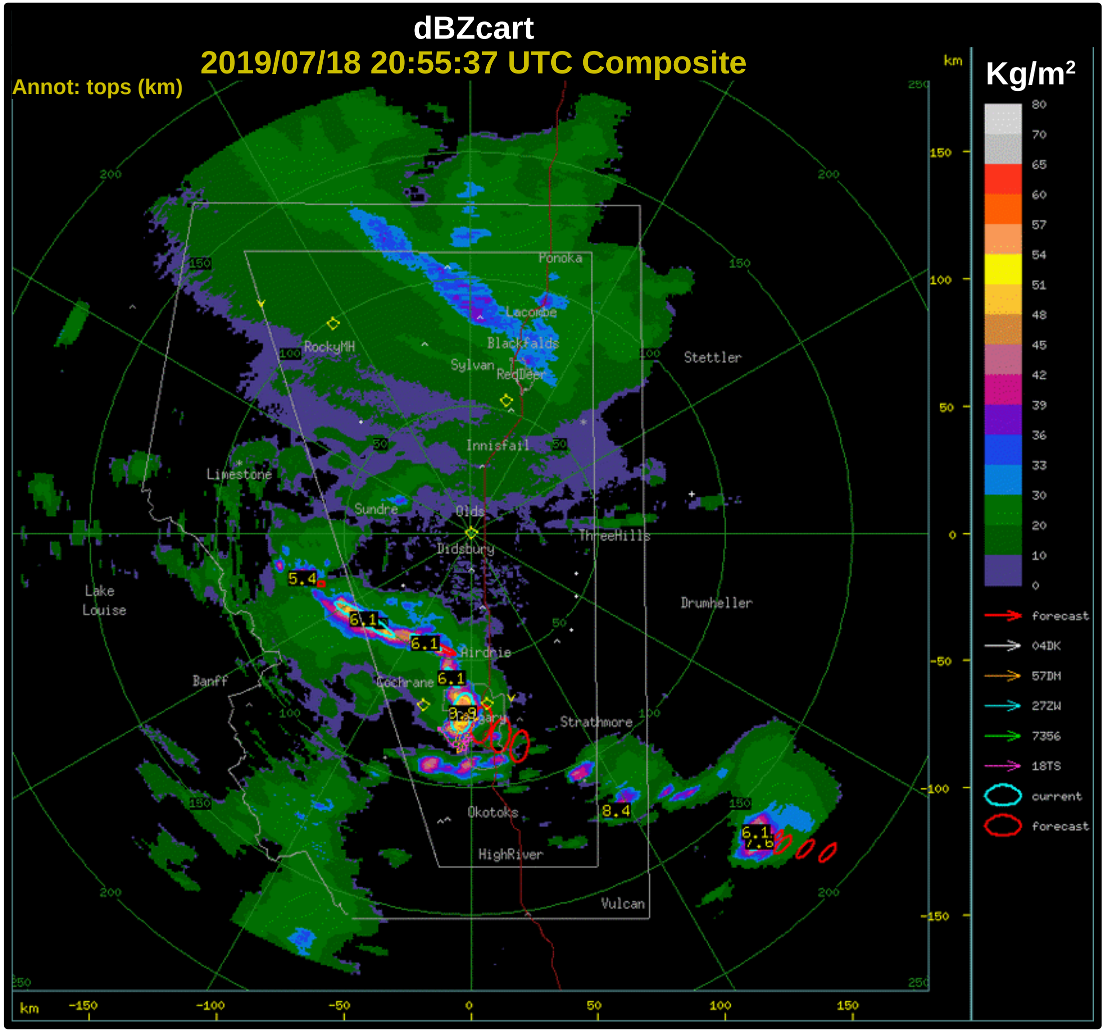
Possible Scenarios Of (Non-Analysed) Cases

- **Type 5 – Storms moving over the radar cone of silence.**
- **Type 6 – Storm cells present behind another storm cell would be attenuated hence such a storm system would not be analyzed.**



Hail Duration Metric: Active Storm Period (ASP)

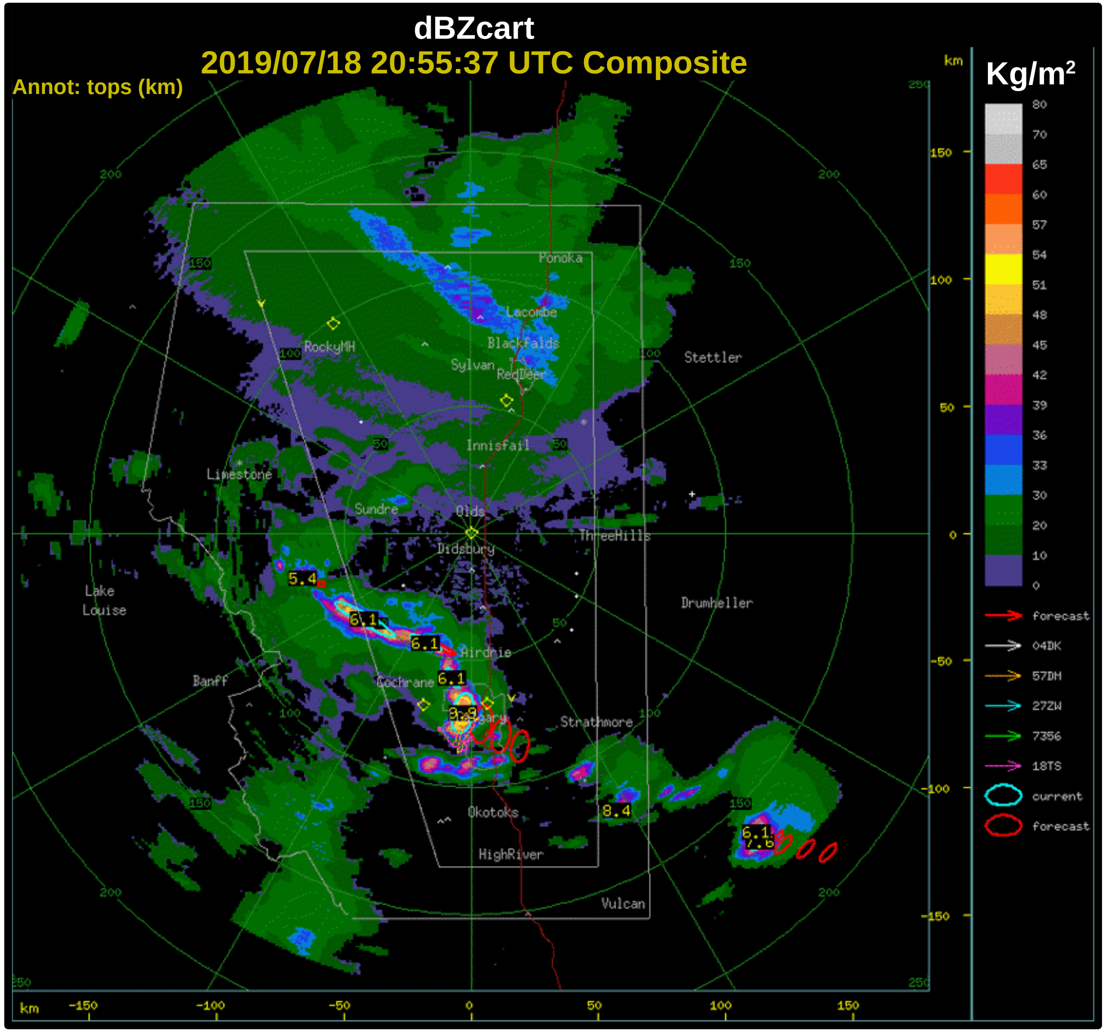
- The period during a storm when there is a potential for hail is called the Active Storm Period (ASP).
- The ASP is the time between when a 45 dBz reflectivity reaches a 8 km height inside the 100 km radius ring until it decrease below 25 dBz at the 8 km level.



Active Storm Period (ASP)

- τ_1 is defined as the time when target case first has 45 dBz reflectivity at a height of 8 km within 100 km for the radar.
- τ_2 is defined as the first time after τ_1 when the target case first decreases below 25 dBz reflectivity at a height of 8 km within 100 km of the radar.

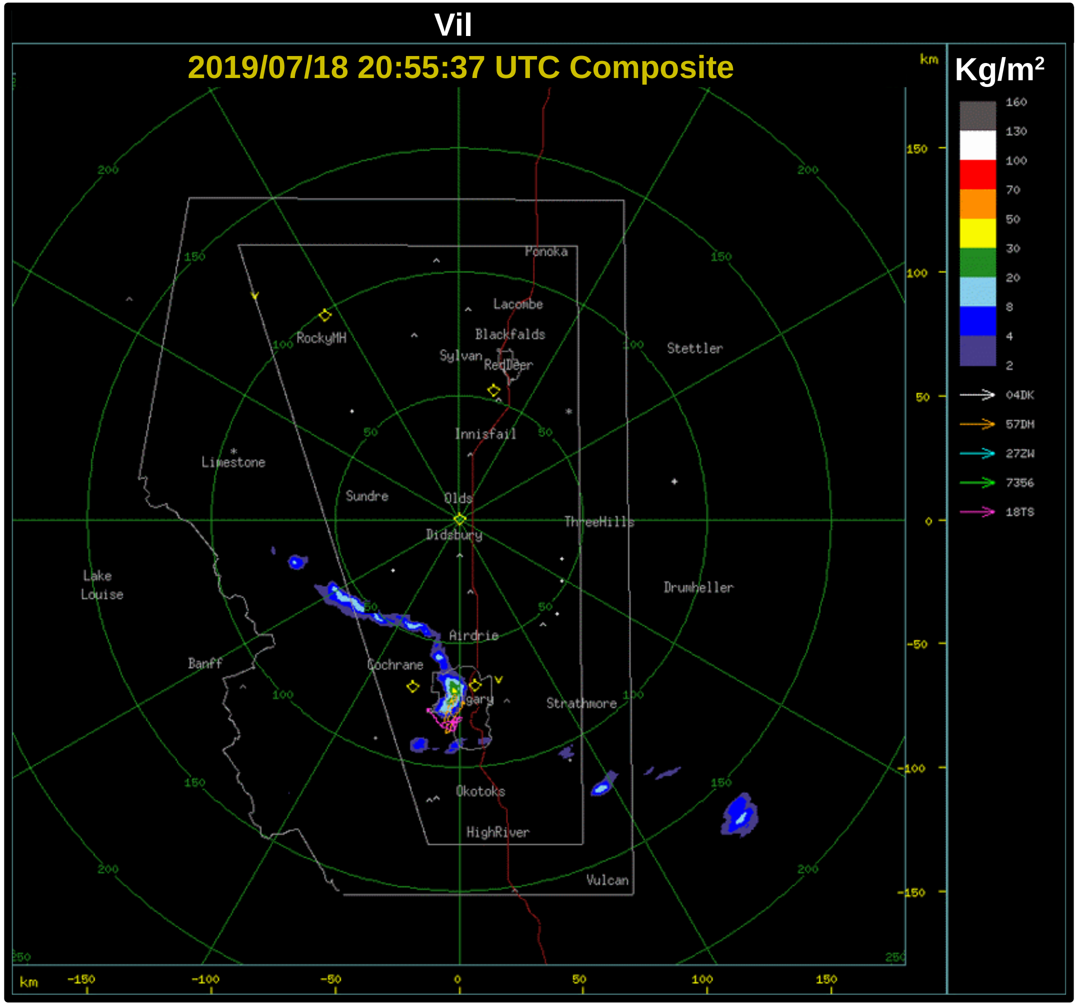
$$ASP = \tau_2 - \tau_1$$



Hail Duration Metric: Hail Likelihood Period (HLP)

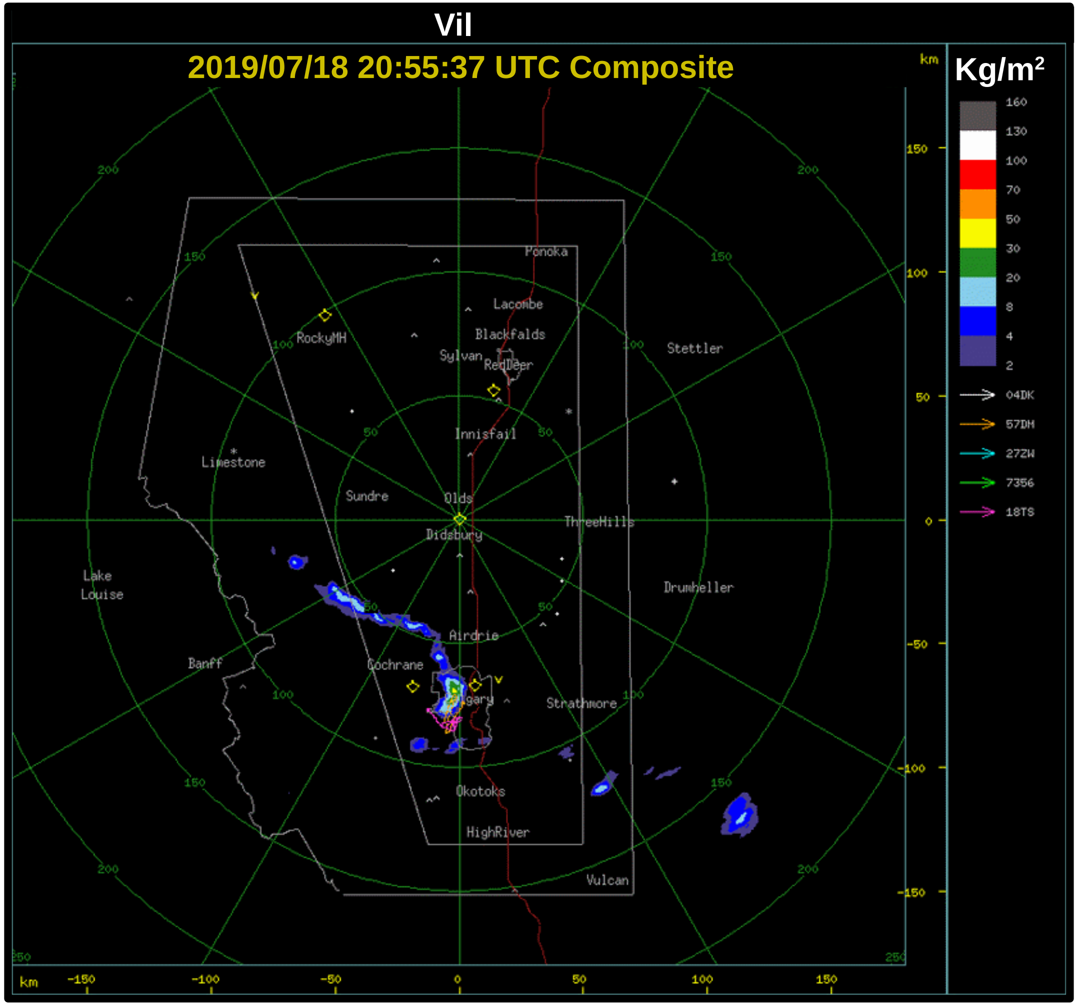
- **The Hail Likelihood Period (HLP) is defined as the duration of Vertically Integrated Liquid Water Content (VIL) above 30 or 70 kg m^{-2} while the target case is inside the 100 km radius ring.**

- **HLP is the period during which hail is actually present in the target case.**



Hail Duration Metric: Hail Likelihood Period (HLP)

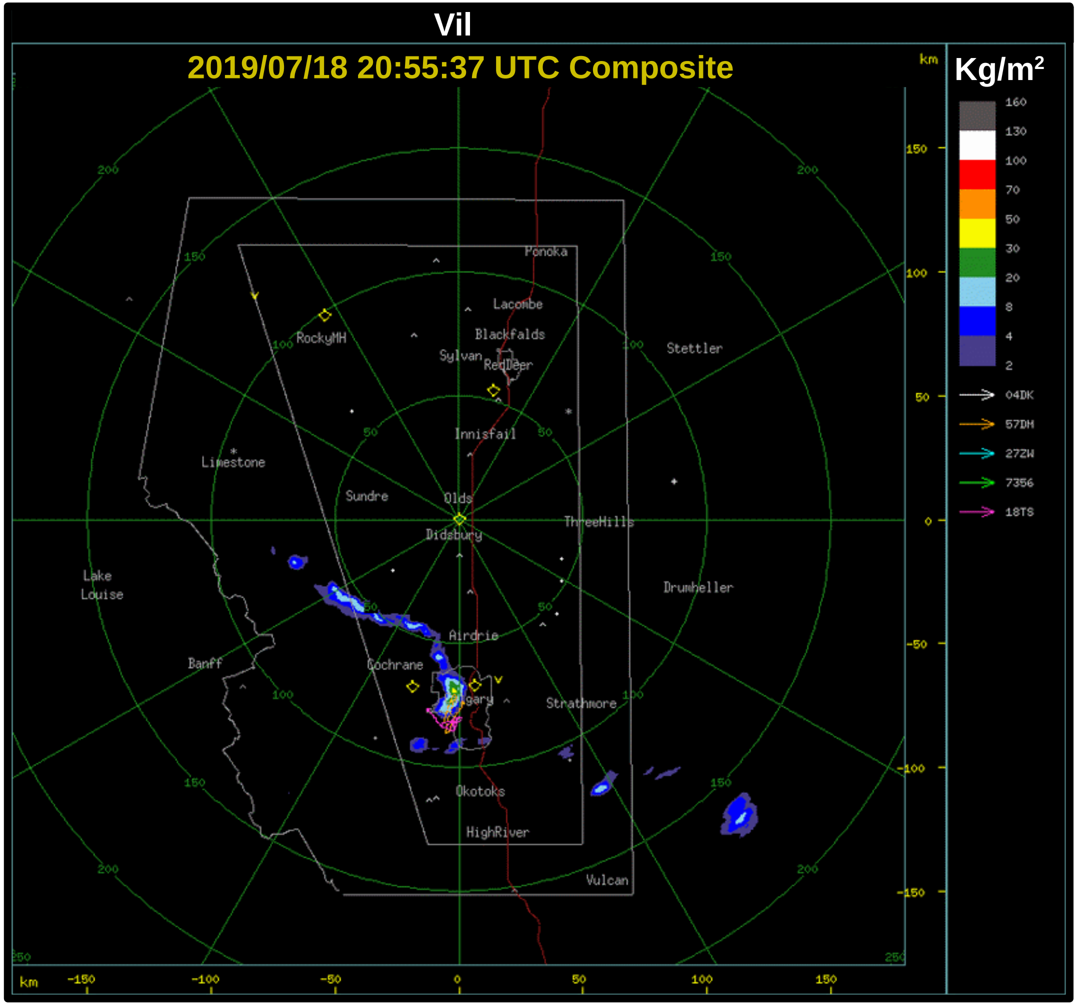
- Two different categories of HLP are used:
  - HLP for a VIL ≥ 30 kg m^{-2} indicating minor hail damage and a HLP corresponding to a VIL ≥ 70 kg m^{-2} indicating severe hail damage.
  - VIL is calculated from radar observations through all heights of the storm.



Hail Likelihood Period (HLP)

- τ_3 is defined as the time when the target case first has a VIL of 30 kg m^{-2} or greater within 100 km of radar.
- τ_4 is defined as the first time after τ_3 when the target case VIL decrease to less than 30 kg m^{-2} within 100 km of the radar

$$HLP_{30} = \tau_4 - \tau_3$$



VIL Metric: Seeding Effectiveness (SE)

- **Formula for seeding effectiveness is given by:**

$$SE_{VIL\,30} = \frac{\bar{H}_n^{VIL\,30} - \bar{H}_s^{VIL\,30}}{\bar{H}_n^{VIL\,30}}$$

- **Similarly for VIL of 70 kg m^{-2}:**

$$SE_{VIL\,70} = \frac{\bar{H}_n^{VIL\,70} - \bar{H}_s^{VIL\,70}}{\bar{H}_n^{VIL\,70}}$$

Area Metric: Start and End Times for Measuring Storm Area

- **The storm area is measured throughout the ASP , for the first time at time τ_1 and for the last time at time τ_2.**

- **τ_1 is the time when storm attains a 45 dBz composite reflectivity value inside the 100 km ring for the first time.**

- **τ_2 is the time when storm weakens to a 25 dBz composite reflectivity value inside the 100 km ring.**

Calculation of Quantities to be Used for Computing Seeding Effectiveness using the Area Metric

- The quantity total area ($Area_T$) is obtained by adding storm areas at every volume scan from time τ_1 to τ_2.

$$Area_T = Area_1 + Area_2 + \ldots + Area_N$$

- Average area (Area) of the storm is calculated by dividing ARSum by the number of volume scans (v) used for that particular storm.

$$\overline{Area_T} = \frac{Area_T}{v}$$

v = number of volume scans

Calculation of Effectiveness using the Area Metric

- **The quantity $Area_{60}$ is obtained by adding the area of storm segments having a composite reflectivity value ≥ 60 dBz (if present) for all volume scans from times τ_1 to τ_2.**

$$Area_{60} = Area\,60_1 + Area\,60_2 + \ldots + Area\,60_N$$

- **Average area with a composite reflectivity ≥ 60 dBz ($avgARSum_{60}$) is calculated by dividing $ARSum_{60}$ by the number of volume scans (v) used for that particular storm.**

$$\overline{Area_{60}} = \frac{Area_{60}}{v}$$

v = number of volume scans

Calculation of Effectiveness using the Area Metric

- **The relative value (AR) of reflectivity ≥ 60 dBz is calculated for one storm using the following formula,**

$$AR = \frac{\overline{Area_{60}}}{\overline{Area_T}}$$

for one storm

- **An average value of AR ($\overline{\text{AR}}$) is computed for all storms studied.**

$$\overline{AR} = \frac{AR_1 + AR_2 + \ldots + AR_Q}{Q}$$

average for Q cases

Calculation of Effectiveness using the Area Metric

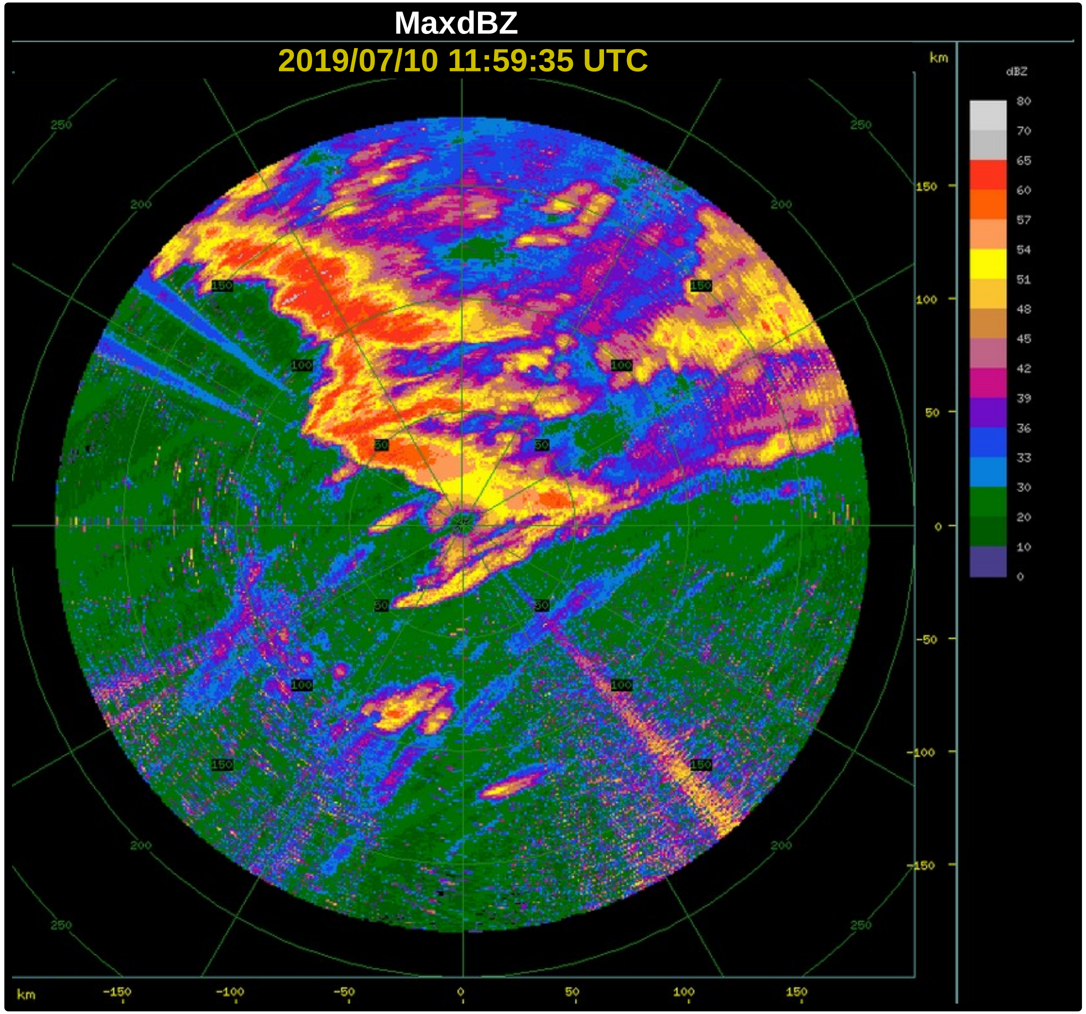
- **The $\overline{AR}$ for all the non-seeded storms is represented as $\overline{AR}_{ns}$**
- **The $\overline{AR}$ for all the seeded storms is represented as $\overline{AR}_{s}$**

- **The seeding effectiveness formula is applied using the avgAR values for non-seeded and seeded storms to calculate the seeding effectiveness.**

$$SE = \frac{\overline{AR}_{ns} - \overline{AR}_{s}}{\overline{AR}_{ns}}$$

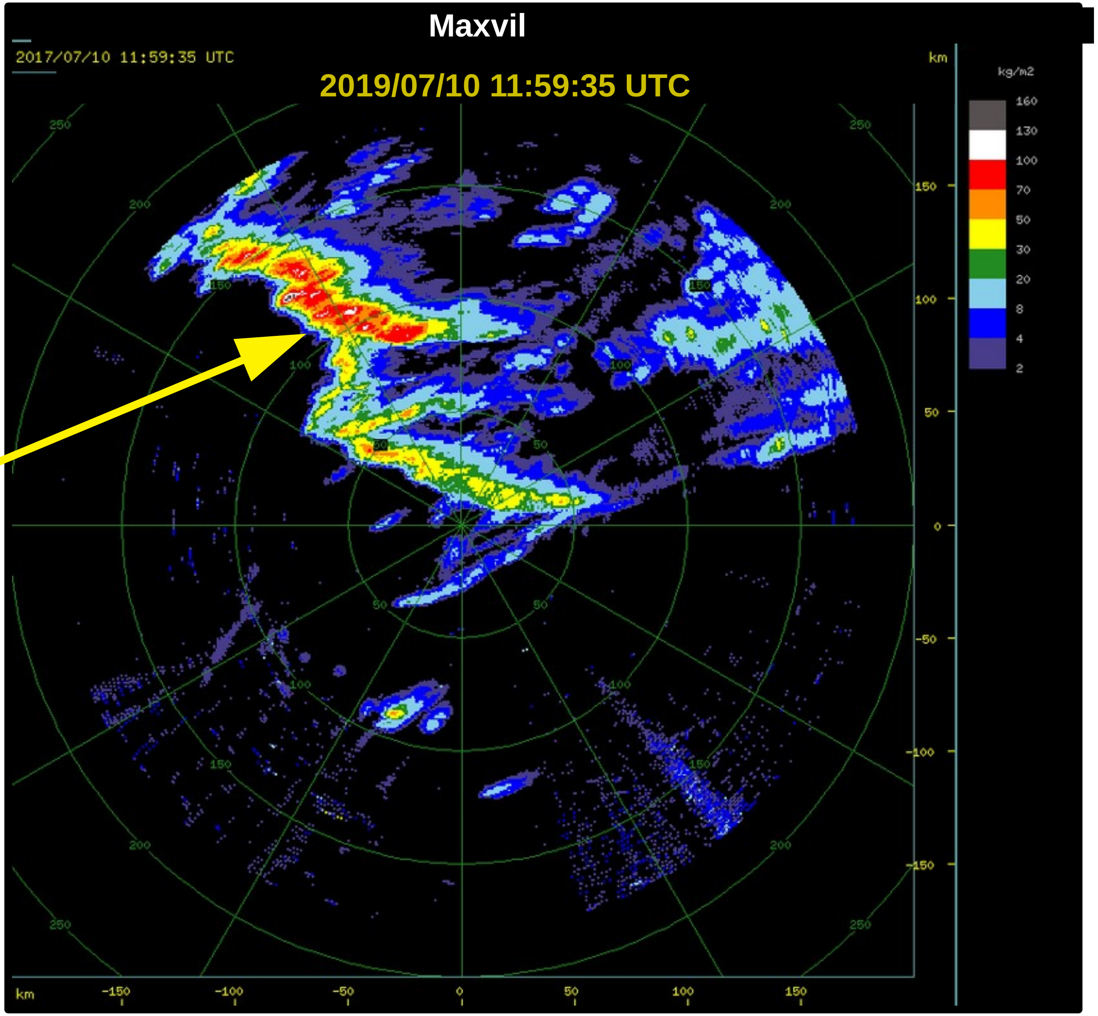
Project Process to Date

- A new computer system (Linux Mint 19.1) has been setup for conducting the analysis.
  - System has Olds radar data from 2007-2017.
  - Olds radar data from 2018 and 2019 has been added.
  - Recently, Strathmore radar data from 2017 has been added.
  - The latest version of LROSE has been setup and tested.



Case Study: 2017 Season

- **28 Seeded cases, 15 Non-Seed cases and 23 Non-Analyzed cases.**
- **Tested the statistical analysis methodology by applying it to the 2017 season.**
  - **Hail was reported on July 9, 2017 North West of the radar site.**
  - **Note the high VIL values, North West of the radar site.**



Maxvil is obtained from Vil from 12 Z on July 9 to 12 Z on July 10

Manual Analysis using VIL Metric: 2017 Season

- **Obtained avgVIL30 value of 0.375 for seeded storms and 0.362 for non-seeded storms.**

- **Percentage Effectiveness = [(0.362 – 0.375)/0.362] x 100 = - 3.5 %**

- **Obtained avgVIL70 values of 0.011 for seeded storms and 0.020 for non-seeded storms.**

- **Percentage Effectiveness = [(0.02 – 0.01)/0.02] x 100 = 50 %**

Conclusion: Manual analysis indicates seeding is not effective. Hence, more non-seeded cases that are meteorologically similar to the seeded ones need to be studied.

Conclusions

- Since all strong storms capable of producing damaging hail near the project area are seeded, not enough non-seeded storms with similar damage potential were found. As a result VIL and Area metric might not be an effective tool for analysis.

- Trend in VIL values in seeded cases should give better idea about impact of seeding and should be used as the primary metric for analysis.

- VIL and Area metric can be used as a secondary metric.

Meanings of Mathematical Formulas Used

For Calculation of Seeding Effectiveness using the VIL Metric :

Active Storm Period (ASP) = $\tau_1 - \tau_2$ — this is the duration of the storms' lifetime

τ_1 — time when storm first attains a 45 dBz reflectivity

τ_2 — time when storm weakens to a 25 dBz reflectivity

Hail Likelihood Period (HLP) = $\tau_3 - \tau_4$ — this is the time duration for which the storm has hail in it

τ_1 — when storm attains a VIL value of 30 kgm-2 or 70 kgm-2

τ_4 — when storm last has a VIL value of 30 kgm-2 or 70 kgm-2

H_n^{VIL30} = (HLP) / (ASP) — time for which a non-seeded storm has hail corresponding to VIL 30 kgm^{-2} compared to it's lifetime

$\overline{H}_n^{VIL30} = H_n^{VIL30} / N$ — average of all H_n^{VIL30} where N is the number of non-seeded storms studied

H_n^{VIL70} = (HLP) / (ASP) — time for which a non-seeded storm has hail corresponding to VIL 70 kgm-2 compared to it's lifetime

$\overline{H}_n^{VIL70} = H_n^{VIL70} / N$ — average of all H_n^{VIL70} where N is the number of non-seeded storms studied

H_s^{VIL30} = (HLP) / (ASP) — time for which a seeded storm has hail corresponding to VIL 30 kgm-2 compared to it's lifetime

$\overline{H}_s^{VIL30} = H_n^{VIL30} / N$ — average of all H_s^{VIL30} where N is the number of seeded storms studied

H_s^{VIL70} = (HLP) / (ASP) — time for which a seeded storm has hail corresponding to VIL 70 kgm-2 compared to it's lifetime

$\overline{H}_s^{VIL70} = H_n^{VIL70} / N$ — average of all H_s^{VIL70} where N is the number of seeded storms studied

$SE_{VIL30} = (\overline{H}_n^{VIL30} - \overline{H}_s^{VIL30}) / \overline{H}_n^{VIL30}$ — seeding effectiveness for VIL ≥ 30 kgm-2

$SE_{VIL70} = (\overline{H}_n^{VIL70} - \overline{H}_s^{VIL70}) / \overline{H}_n^{VIL70}$ — seeding effectiveness for VIL ≥ 70 kgm-2 respectively

Meanings of Mathematical Formulas Used (Contd.)

For Calculation of Seeding Effectiveness using the Area Metric :

$ARSum$ = area of storm at first volume scan + area of storm at second volume scan +...+ area of storm at last volume scan

$\overline{ARSum}$ = $(ARSum) / v$ where, v = number of volume scans used for that storm

$ARSum_{60}$ = area ≥ 60 dBz at first volume scan + area ≥ 60 dBz at second volume scan +...+ area ≥ 60 dBz at last volume scan

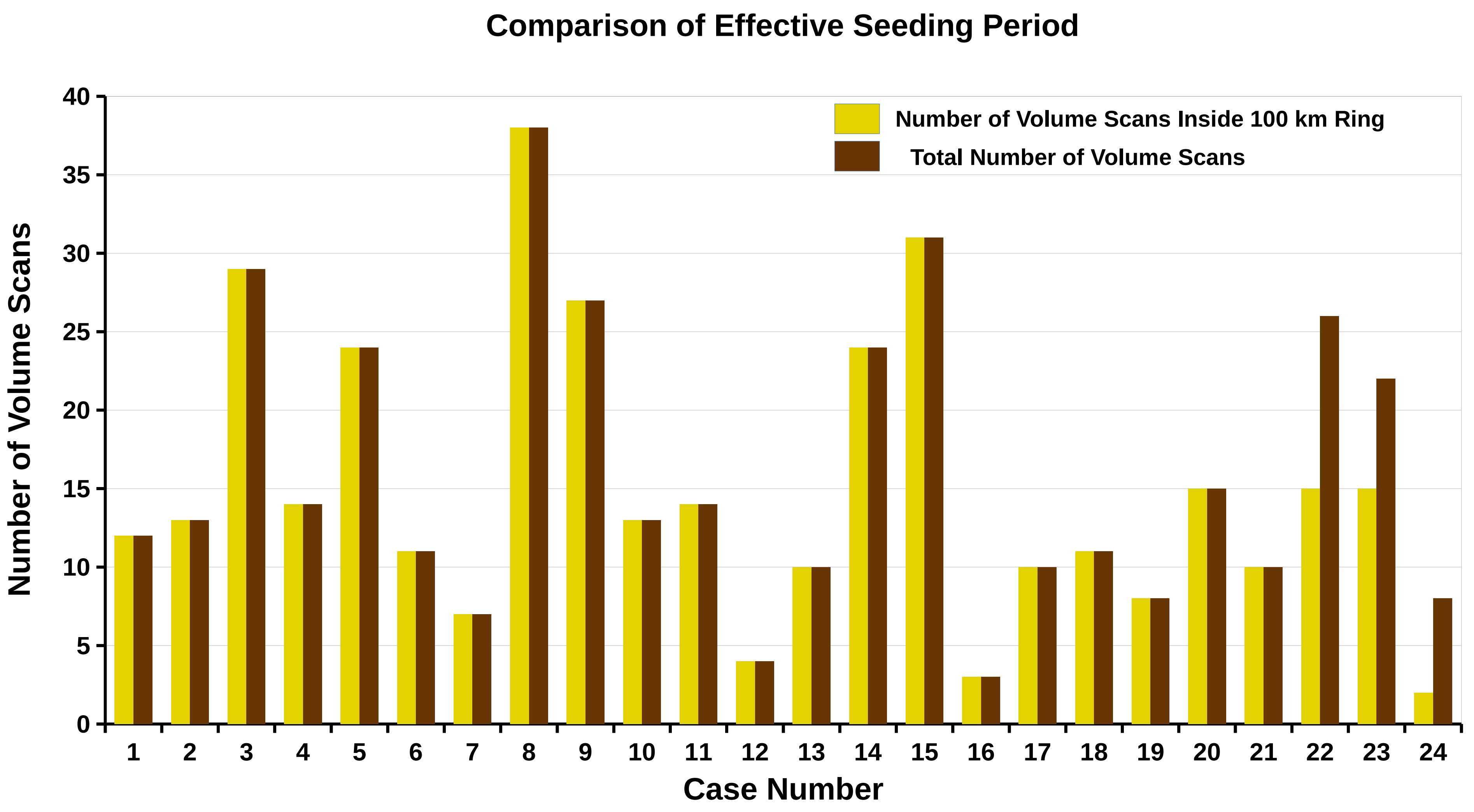
$\overline{ARSum_{60}}$ = $(ARSum_{60}) / v$ where, v = number of volume scans used for that storm

AR = $(avgARSum_{60}) / (avgARSum)$ relative contribution of area ≥ 60 dBz to total storm area for one storm

$\overline{AR}$ = $(AR_1 + AR_2 + \ldots + Ar_q) / Q$ average of all AR values , Q = number of storms studied

$\overline{AR_{ns}}$ = $\overline{AR}$ value for all non-seeded storms

$\overline{AR_{s}}$ = $\overline{AR}$ value for all seeded storms


Comparison of Effective Seeding Period
Number of Volume Scans Inside 100 km Ring
Total Number of Volume Scans
Number of Volume Scans
Case Number
0
5
10
15
20
25
30
35
40
1
2
3
4
5
6
7
8
9
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11
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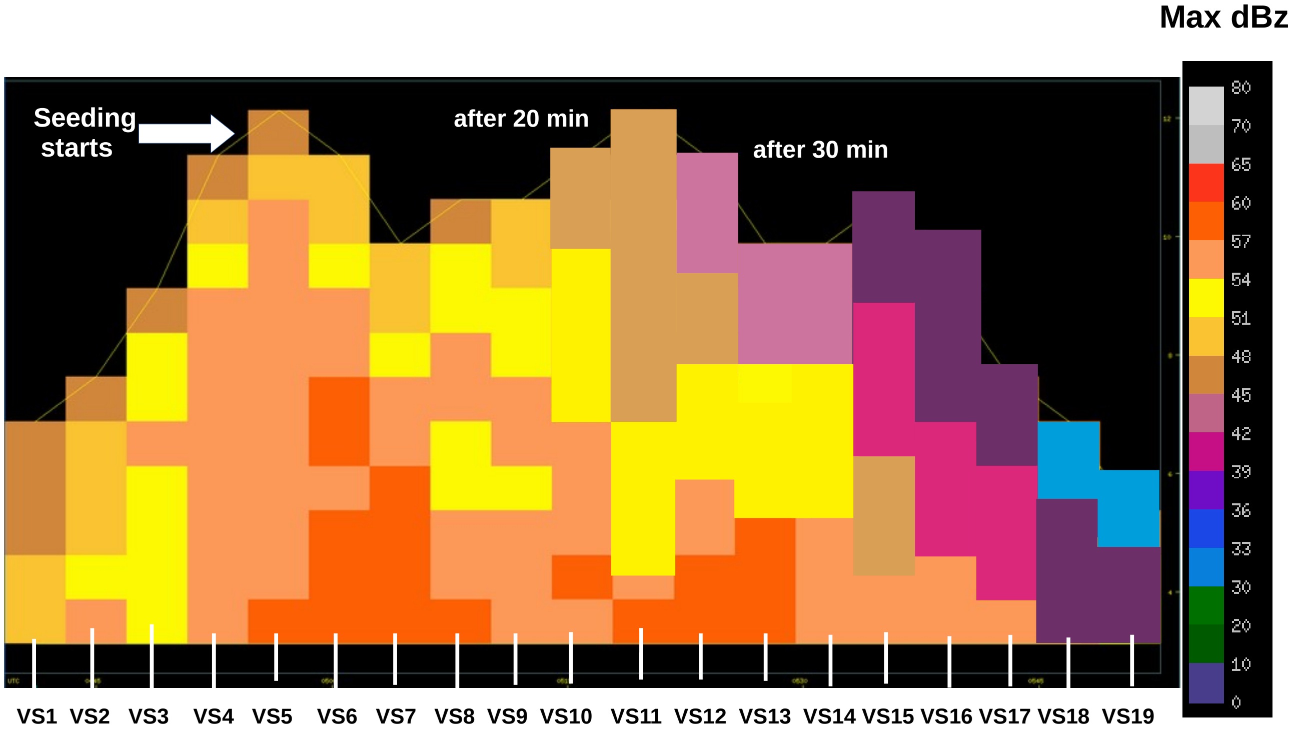
Expected Radar Reflectivity Distribution for Seeded Case

- Reduction in height of 45 dBz observed 20-30 minutes after initiation of seeding.
- Higher reflectivity values should be at lower heights.
- As a result the value of MaxVIL should go down.

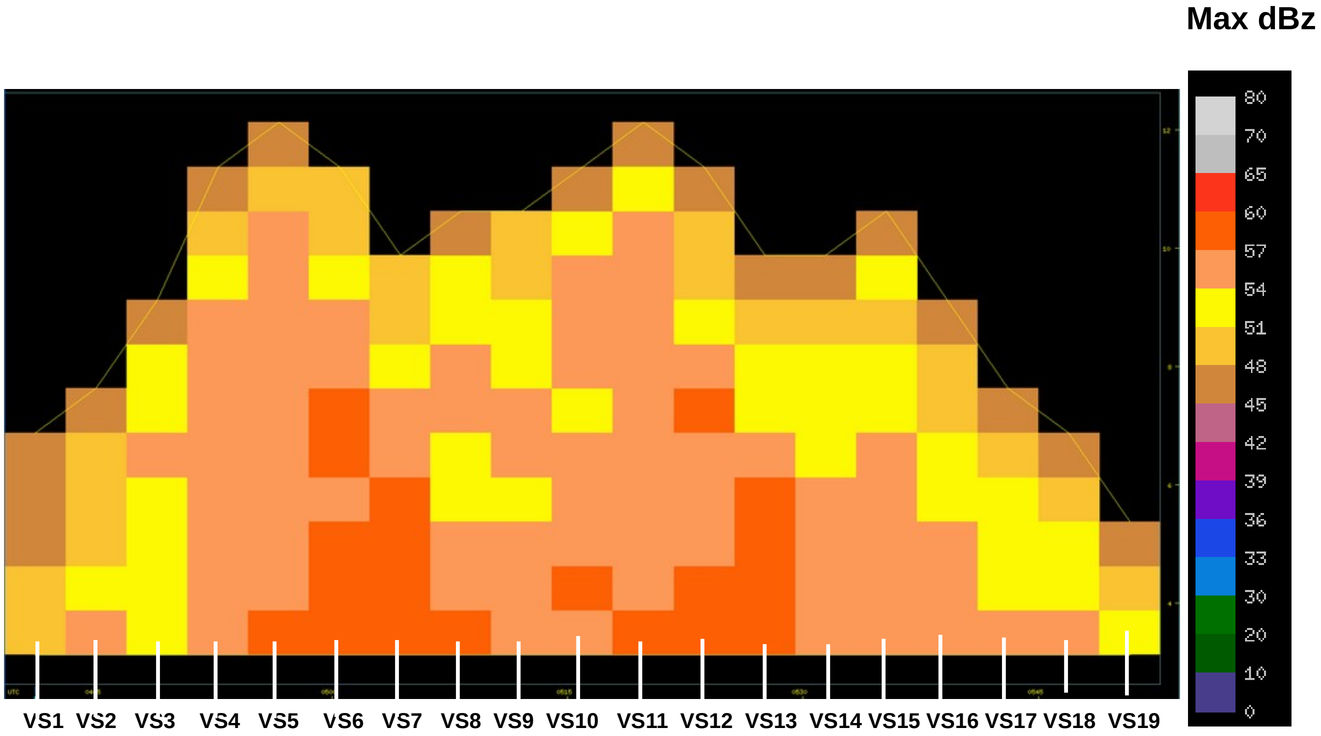


VS = Volume Scan

Radar Reflectivity Distribution for Non-Seed Case

- **Reflectivity ≥ 45 dbz at a height of 8 km or higher during most of the storm's duration**

- **Main Idea – Higher reflectivity at greater and lower heights.**



VS = Volume Scan