SW Montana Cloud Seeding Feasibility Study

Univ of Montana Western, Dillon, MT

September 17, 2024

Michael Downey – DNRC, Water Resources Division

Photo by George Bakos - Unsplash

Agenda

- What is cloud seeding and how does it work?
- Where is cloud seeding being done?
- Feasibility of cloud seeding in Southwest Montana
- Cloud seeding FAQ

Cloud Seeding as a Tool for Water Management

Feasibility in Southwest Montana

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NCAR

NSF

Sept. 17, 2024

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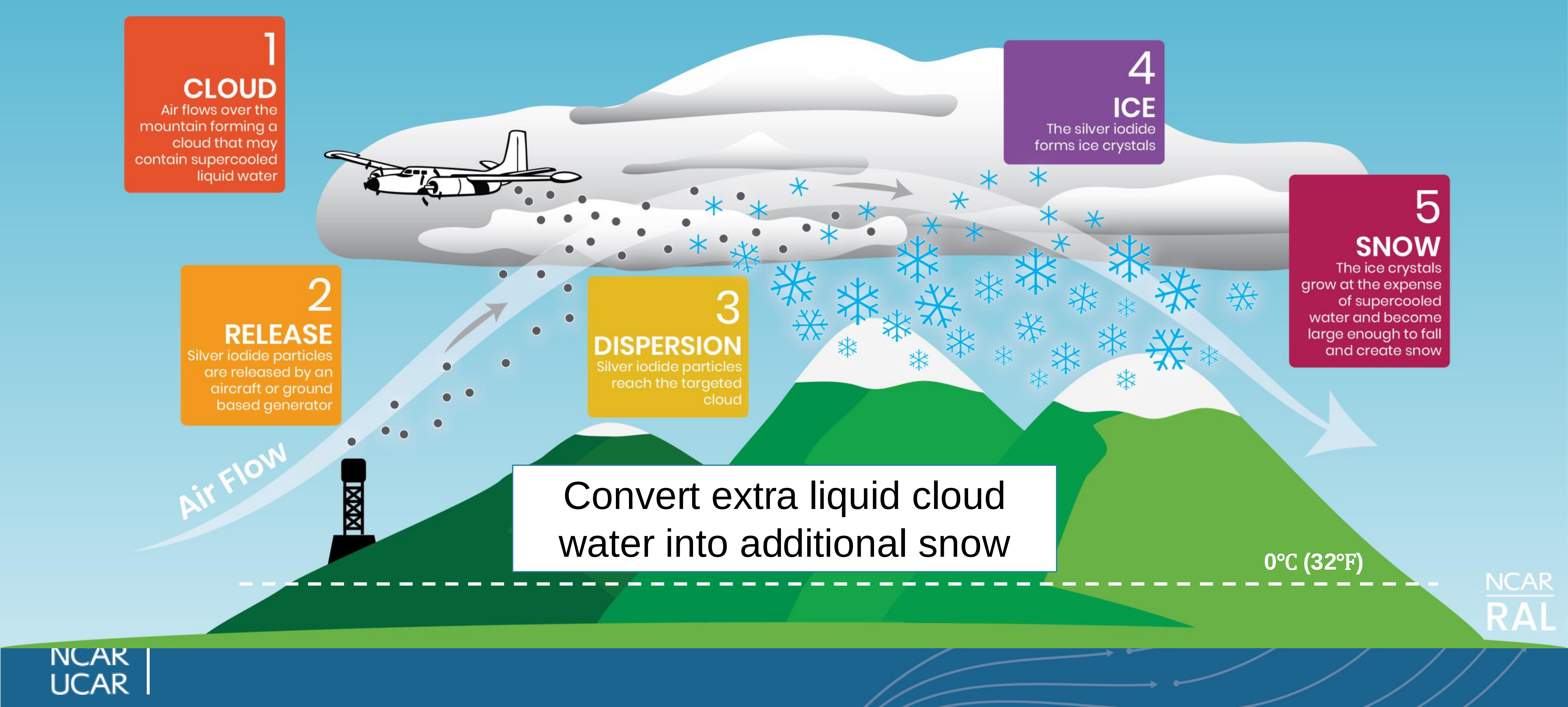
The goal of winter orographic cloud seeding is to increase snowpack (and subsequent streamflow)



Convert extra liquid cloud water into additional snow

Aircraft Seeding

Demonstration of flare ignition, actual dispersion occurs in cloud

Wing mounted "Burn-in-Place" (BIP) flares

Belly Mounted Ejectable (EJ) flares

- Burn-in-Place (BIP) flares are released in cloud
  - Plane flies through cloud when conditions are sustainable for the aircraft
- Ejectable (EJ) flares are released above cloud
  - Plane flies above cloud when conditions in cloud present hazardous to the aircraft and crew

Images Courtesy of Idaho Power Company and Ice Crystal Engineering

Remote Ground Generators

Base Platform ~9 feet from ground

Images Courtesy of Idaho Power Company

The Origins of Cloud Seeding

New York dry ice seeding 1946 (Life Magazine)

Early work in cloud seeding by Schaefer and Langmuir in 1946

—1946—

Proof of concept that liquid clouds could be seeded to produce ice, which would deplete the liquid cloud

It has taken over 70 years to prove the entire seeding conceptual model

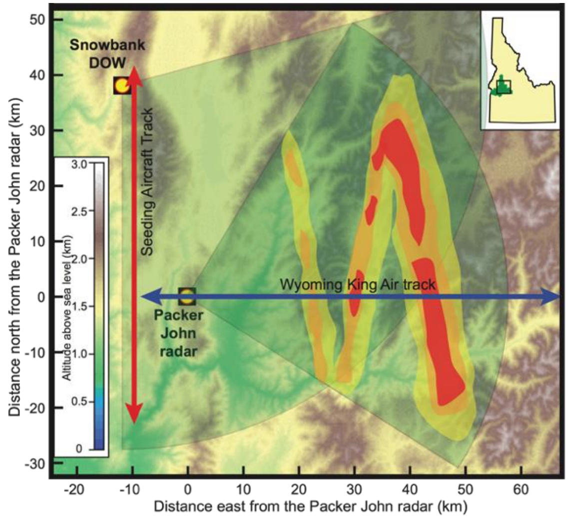
- Challenges with large natural variability of weather made it hard to isolate effects due to seeding
- Limited observations and computer modeling capabilities

SNOWIE data proves cloud seeding concept

Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment
January 7–March 17, 2017

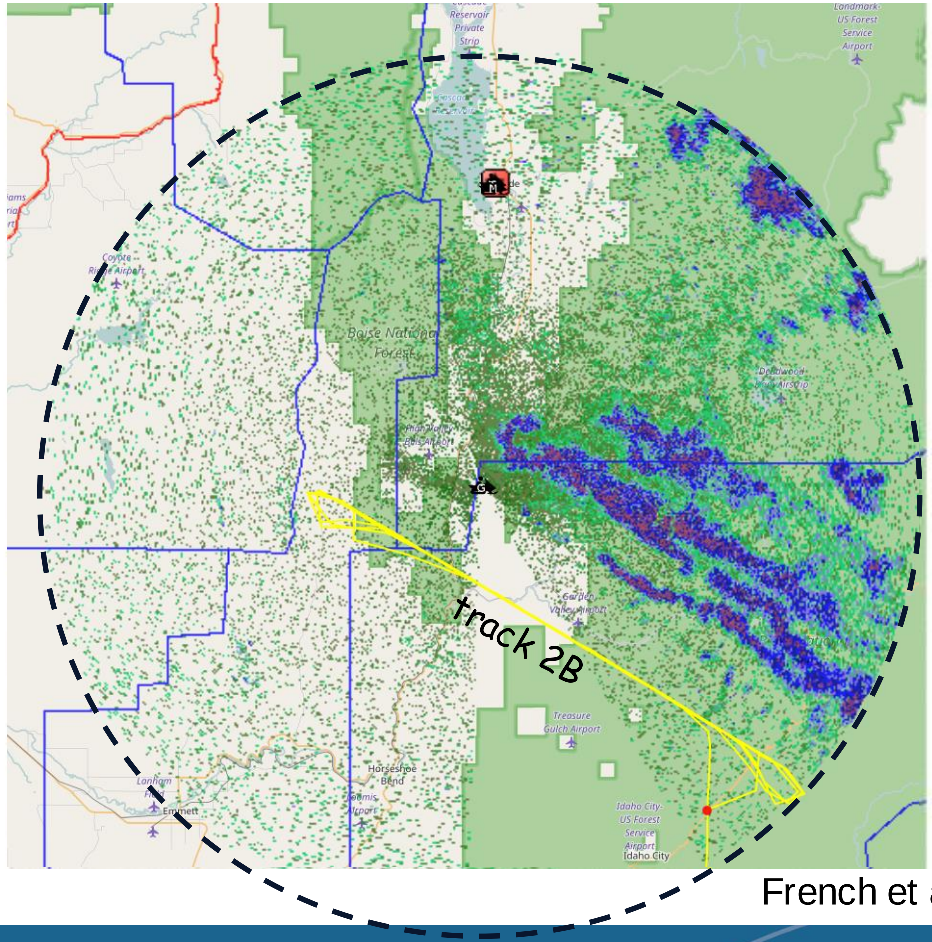
Hypothesized seeding plume dispersion

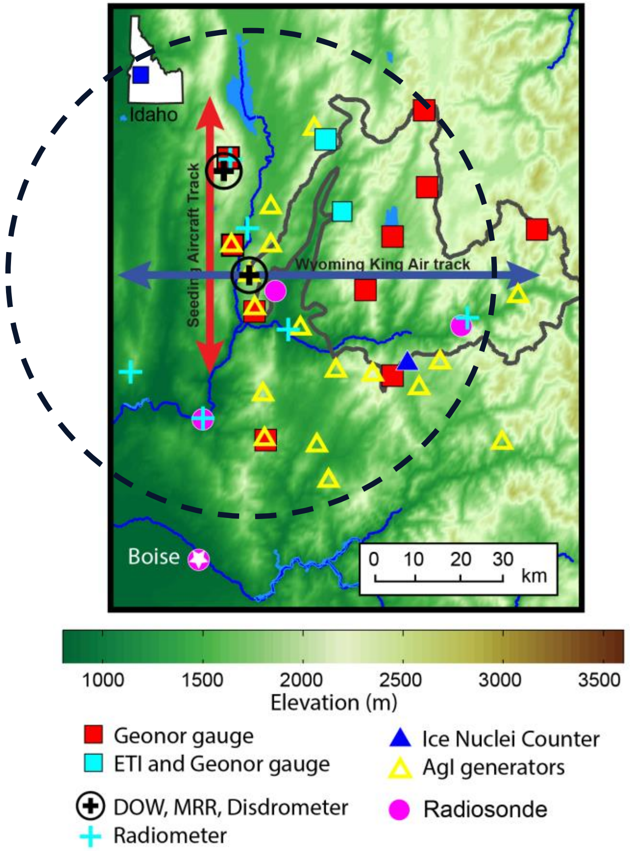
Wind



The "zig zag" pattern is an unambiguous seeding signature from airborne seeding

DOW radar reflectivity + seeding aircraft track





French et al. (2018) PNAS, Tessendorf et al. (2019) BAMS

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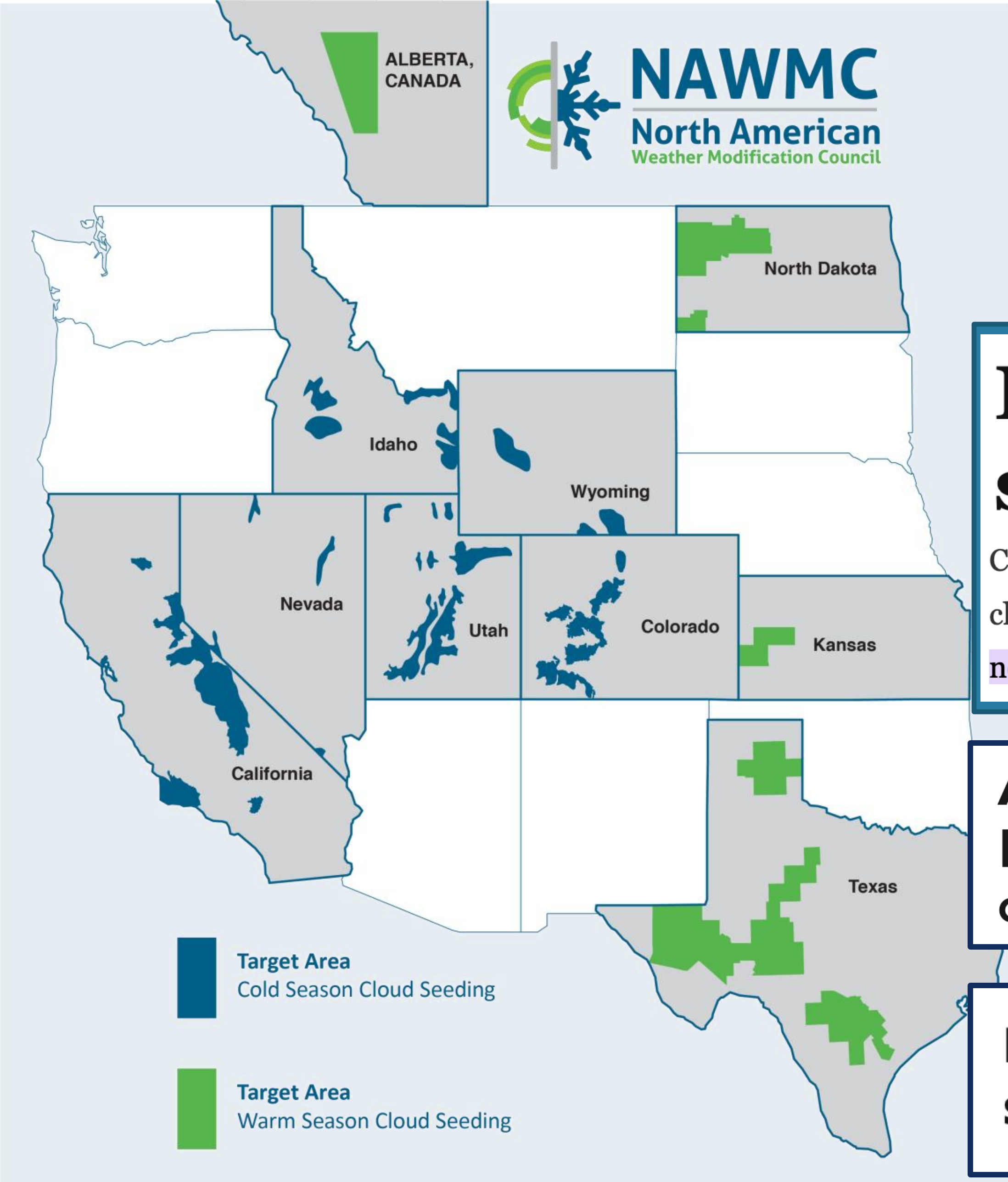
Cloud seeding is conducted in many parts of the western U.S.



Feds spend $2.4 million on cloud seeding for Colorado River

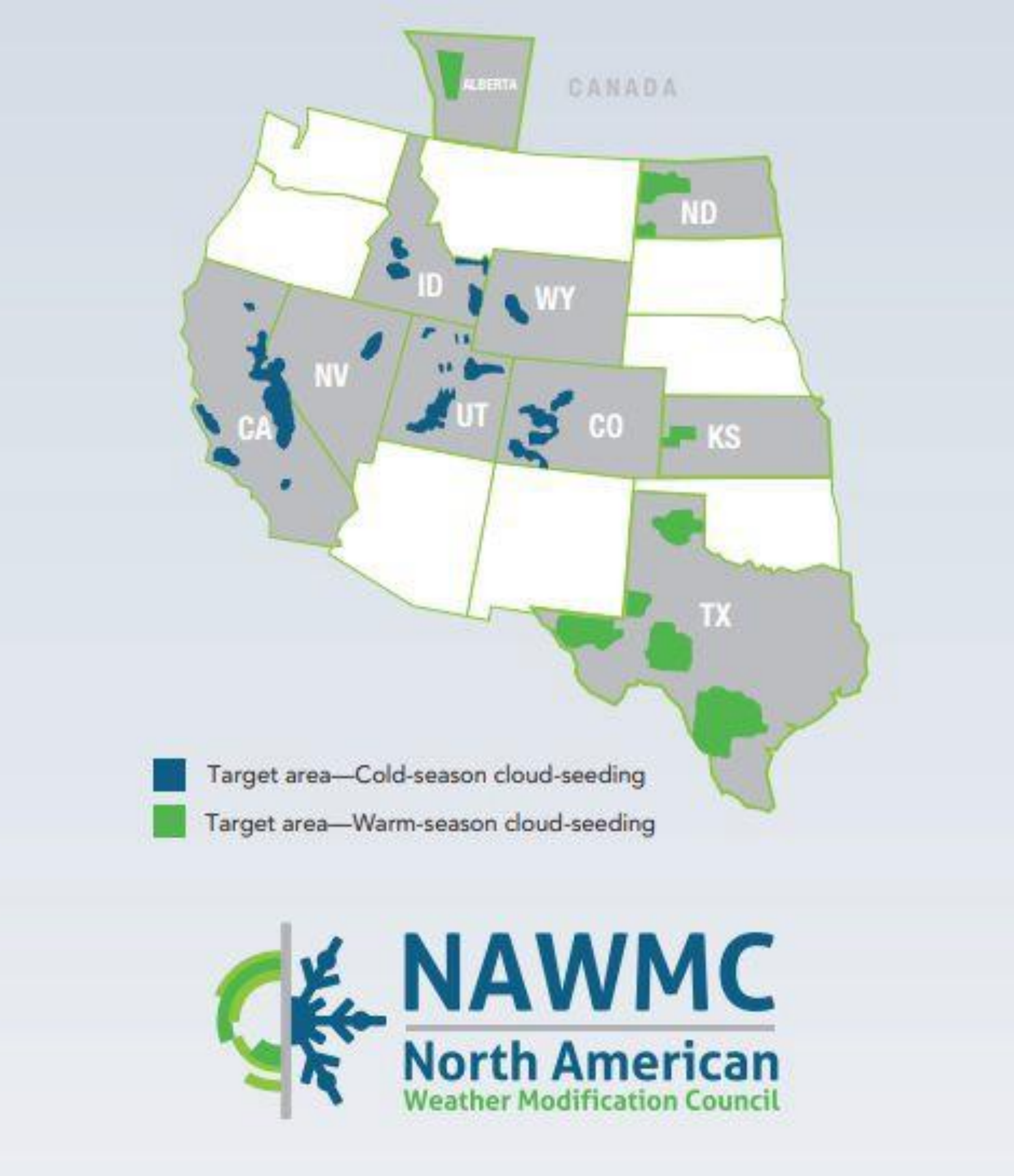
Colorado, Utah and Wyoming each spend between about $1 million and $1.5 million a year for cloud seeding. Utah's legislature recently expanded their investment in cloud seeding programs in next year's state budget, allocating more than $14 million.

As Central Oregon Suffers Extended Drought, Lawmakers Consider Seeding Clouds

Other Western states have long used the process to create extra moisture.

New Mexico approves plans for cloud seeding in the southeast portions of the state

CLOUD SEEDING IN NORTH AMERICA



Utah Collaborative Cloud Seeding Program

Launched in the early 1950's. Continuous operation since 1973

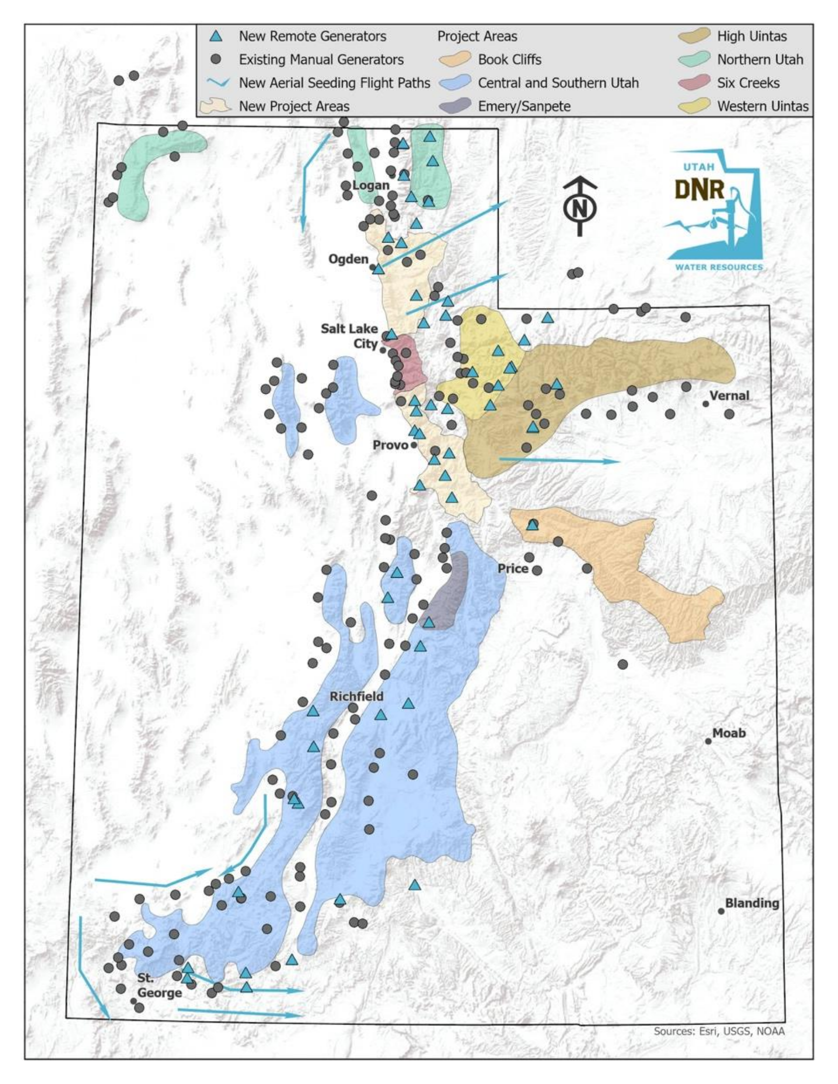
One time only funding 12M in 2023
Annual state contribution increased to 5M

Historically, $250K state funding, $250K local, $200K lower basin states

Program relies upon network of remote, manual and airborne operations.

Manually operated ground generators cost ≈ $3,000 each vs ≈$50,000 each for remote generators.

Water generated from cloud seeding costs Between $2 and $15 per square foot.



IDAHO COLLABORATIVE CLOUD SEEDING PROGRAM

West Central

Mountains Project

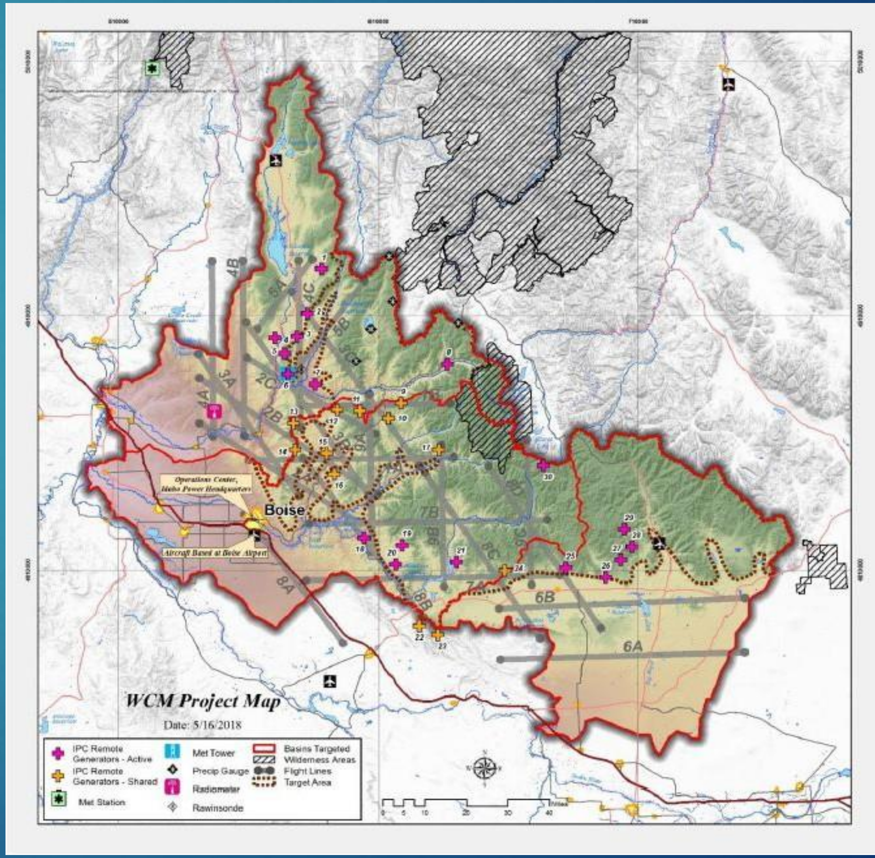
Estimated Average Additional Runoff (Unregulated) & Current Project Costs (Annually)

Boise River Basin– 273 KAF | $910K

Wood River Basin – 112 KAF | $670K

Payette River Basin* – 223 KAF | $870K

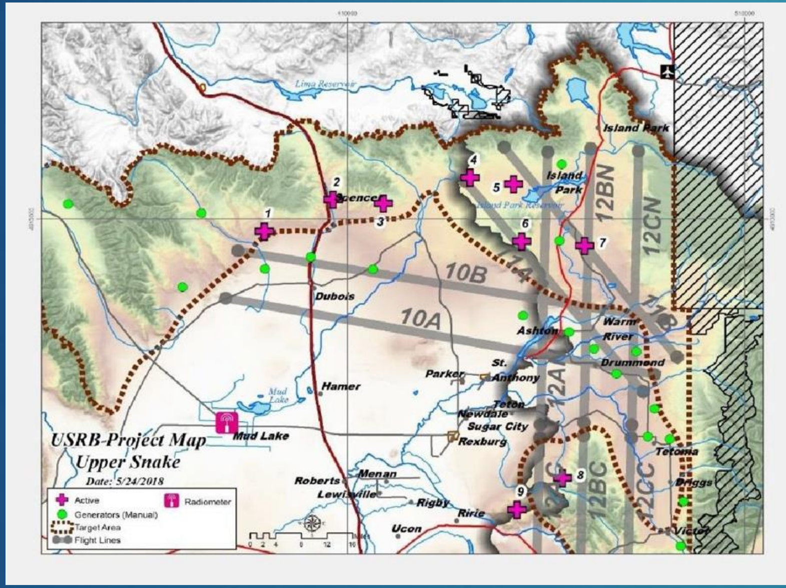
WCM Total: 608 KAF |$2.45M



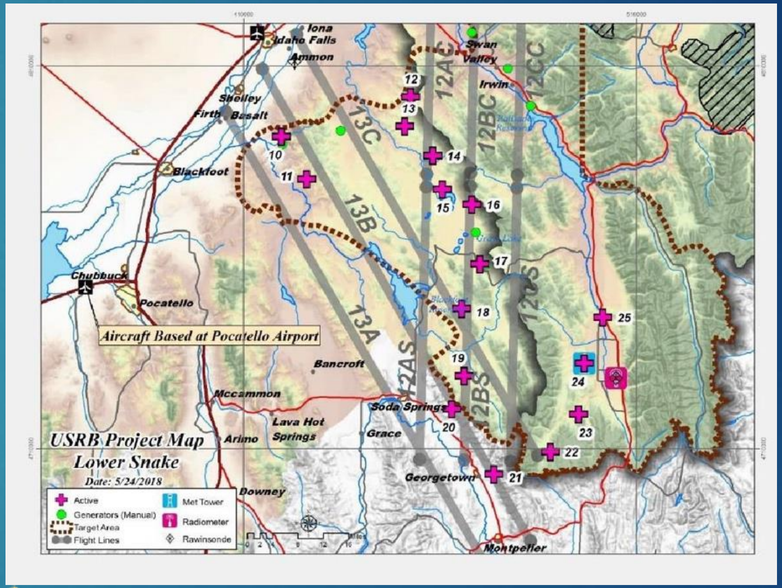
**Independent project operated by Idaho Power Co in coordination with the Collaborative. 100% Funded by IPC.*

Idaho Collaborative Cloud Seeding Program

Upper Snake River Basin Projects



Northern Upper Snake 168 KAF



Southern Upper Snake 464 KAF

Upper Snake River Basin – 632 KAF | $1.54M

Wyoming Collaborative Cloud Seeding Program

- 2004 to 2016 – Feasibility Studies – Wind River, Medicine Bow, Sierra Madre, Salt and Wyoming mountain ranges
- 2015 to 2017 – Siting and design Studies Medicine Bow, Sierra Madre, Laramie, Big Horn mountain ranges
- 2014 to present – Ground based operations Wind River Range
- 2018 to Present – Aerial operations in Sierra Madre, Medicine Bow
- 2018 to Present – Aerial operation Never Summer Range (funding from state of Colorado).
- Funding – $2 million in state funding appropriated for 2024 – 2026
- Cost Share ≈ 37% state, ≈ 63% other partners.

Montana Feasibility Study

Study Goals:

- Goal #1: Assess the potential for cloud seeding to augment snowpack and subsequent streamflow in select target mountain ranges in southwestern Montana.
- Goal #2: Complete a preliminary cost/benefit analysis and preliminary program design based upon weather/climate analysis.
- Goal #3: Support development of public engagement and education activities and materials related to cloud seeding.

Montana Feasibility Study

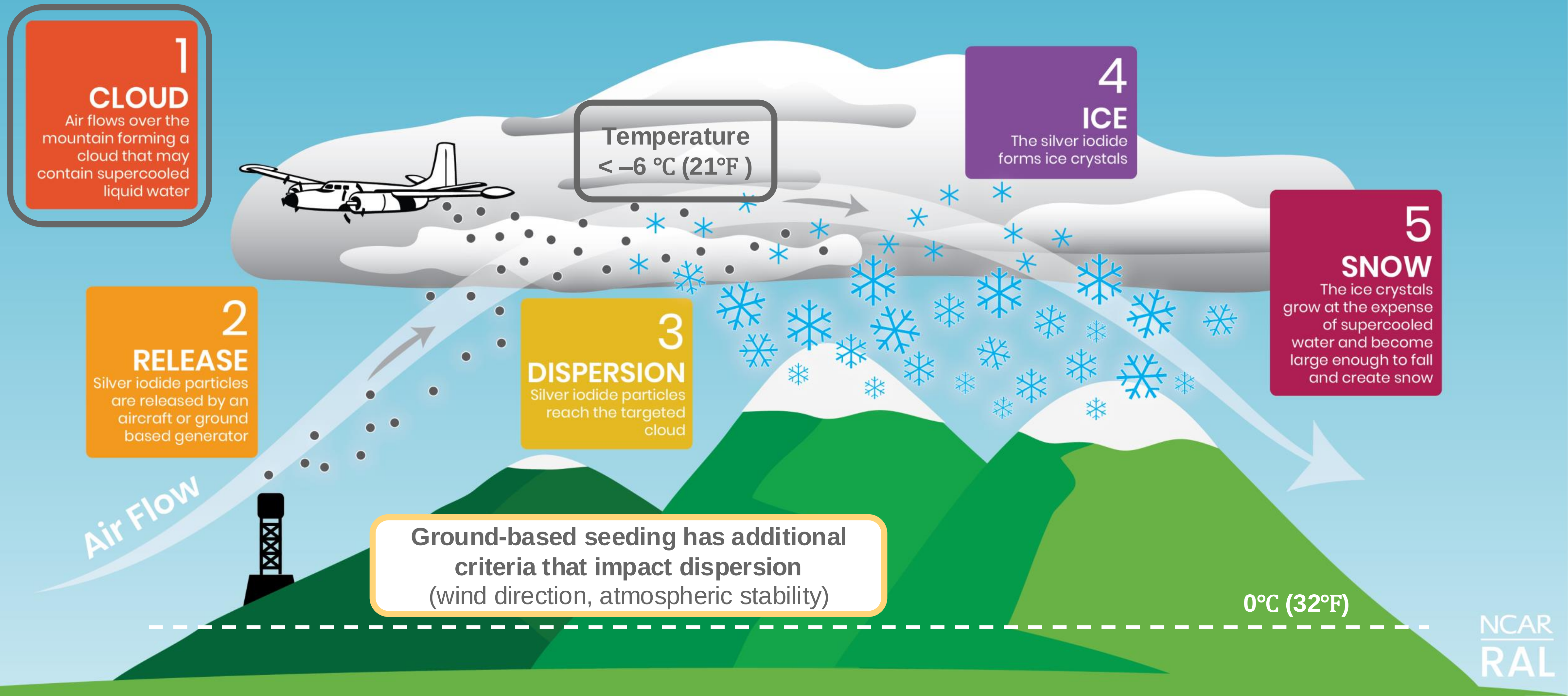
Study Deliverables:

- Preliminary report including results of the feasibility analysis for current and future climate scenarios and a summary of design options that will be tested with model simulations. (October 2024).

- Final report including modeling results and identification of cloud-seeding program design(s) with associated cost-benefit analysis. (February 2025).

- Program design guidance for a 3-5 year cloud seeding pilot project, including estimated costs (February 2025).

<u>Two key criteria :</u> 1) Supercooled liquid water (SLW)
2) Temperature for silver iodide to nucleate ice



First Step: Feasibility Study is Needed

Clouds can contain supercooled liquid water (SLW)

- Candidates for cloud seeding

Not every mountain range or storm is the same

- <u>Important to study the climatology of weather conditions </u>to determine when, where, and how to seed
- Some mountains or storms are more amenable to seeding, and some are better targeted by ground-based seeding than airborne seeding, and vice versa

Feasibility and Design Components

Climatology Analysis

How often are there opportunities for seeding clouds in this region?

What are the characteristics of clouds in this region?

Preliminary Design

What methods of cloud seeding might target the clouds in this region most effectively?

Test and Refine Design

How effective are each design option at targeting and enhancing precipitation in this region?

Which combination of design options is recommended?

Analyze historical data:

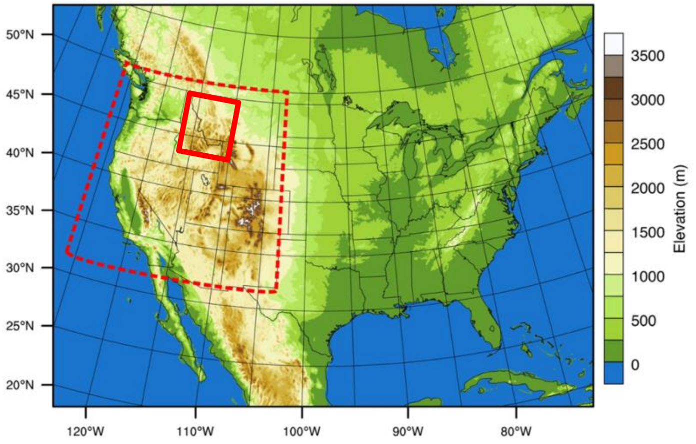
- Temperature
- Supercooled liquid water (SLW)
- Precipitation
- Winds
- Atmospheric stability

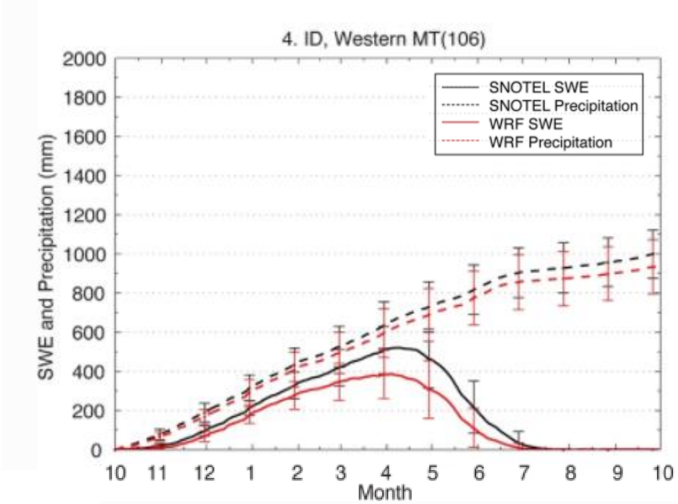
Approach for Climatology Analysis

Analysis of Historical Data

- Observations required for assessing the potential for cloud seeding are not routinely collected
  - Weather balloons provide vertical profiles of temperature (limited)
  - No routine measurements of SLW
- High-resolution, long-term model simulations provide a new opportunity
  - 40-year (1980-2020) 4-km grid spacing WRF model simulation over the CONUS = “**CONUS404**”
  - Shown to realistically reproduce precipitation observations
  - Includes 3D information on temperature, SLW, winds, etc.

Weather Research and Forecasting (WRF) model
CONUS Simulation Domain



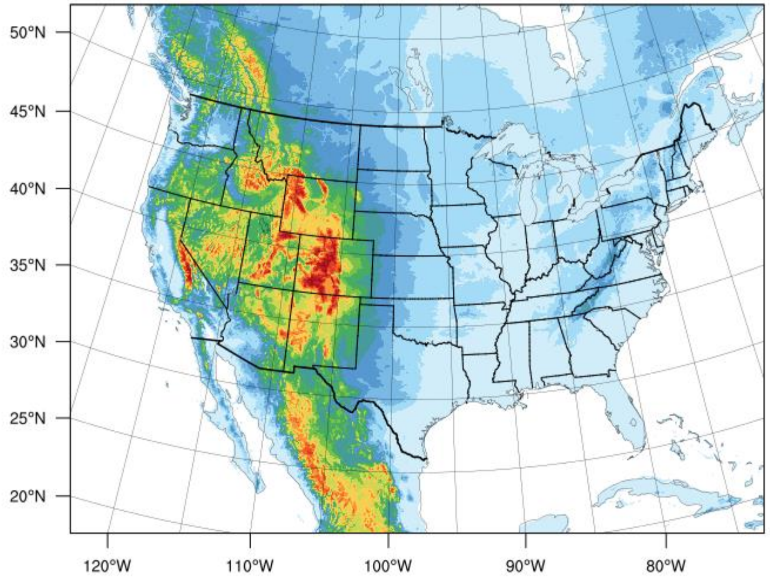


Ikeda et al. (2021)

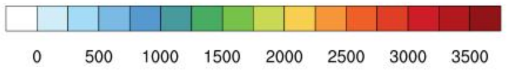
High-resolution model simulations of realistic precipitation in the mountains

Precipitation accumulation over one water year

CONUS404 Simulation



1979-2022

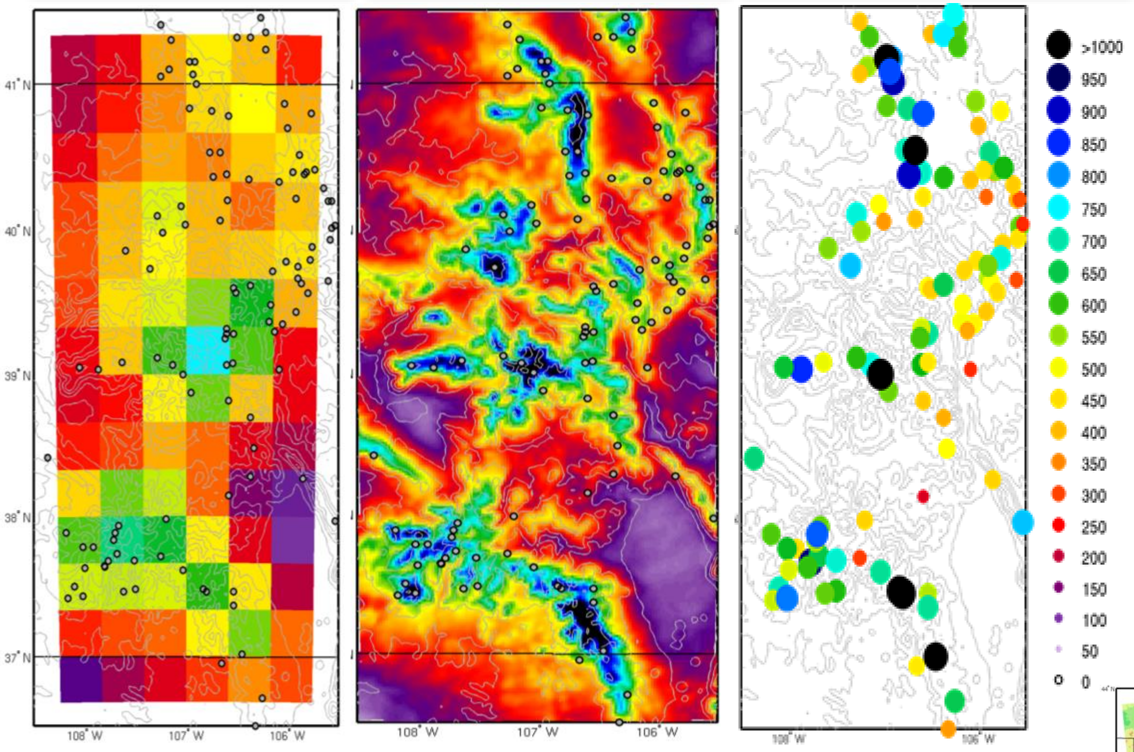


36 km

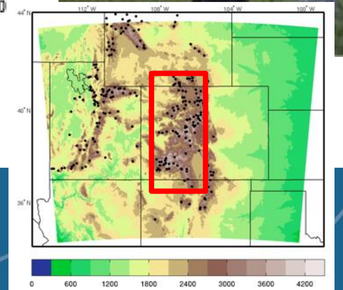
2 km

SNOTEL Obs.

SNOTEL Gauge



Colorado Headwaters Region



USGS
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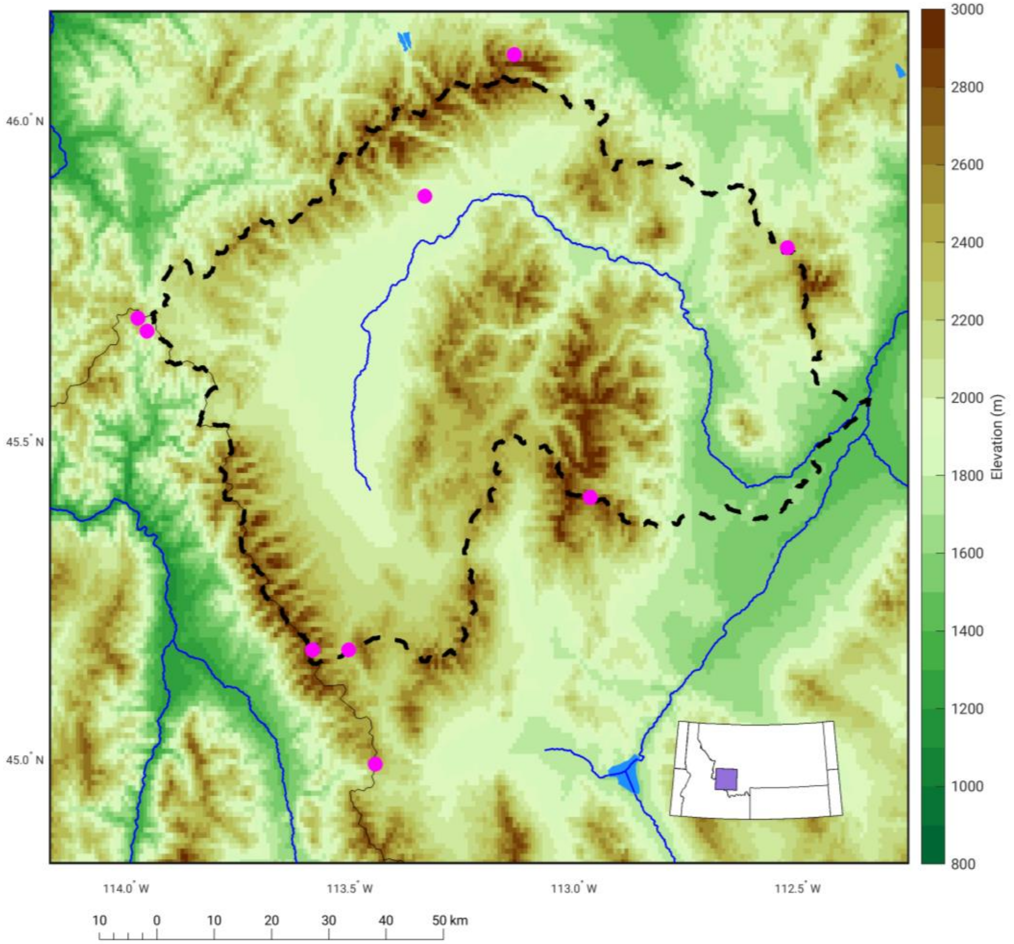
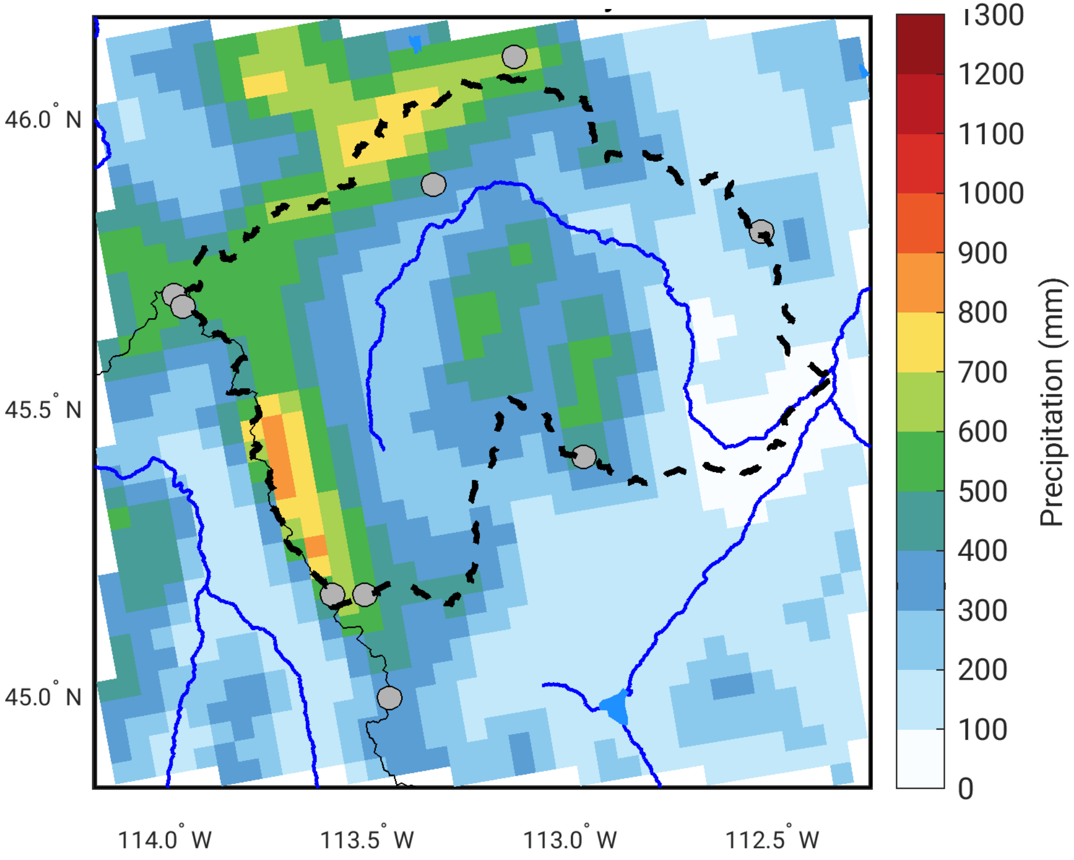
Rasmussen et al. (2011)

Region of Current Study: Big Hole Watershed

Map of Region of Study and SNOTEL gauge sites



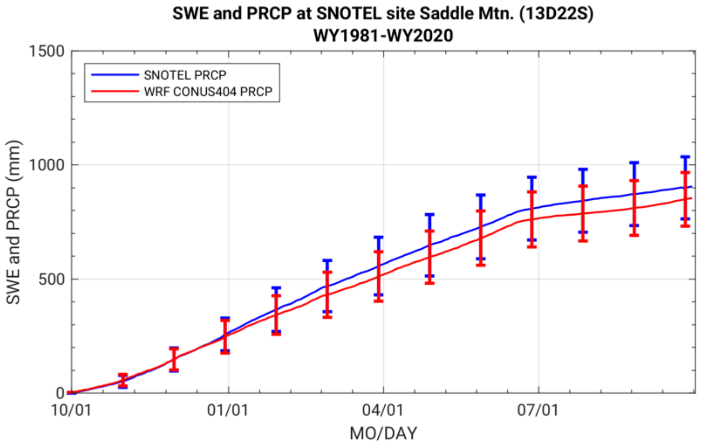
40-year Average
Wintertime Precipitation Accumulation

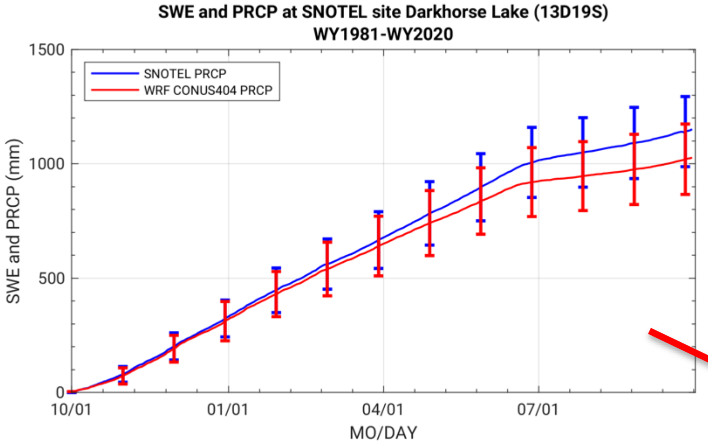


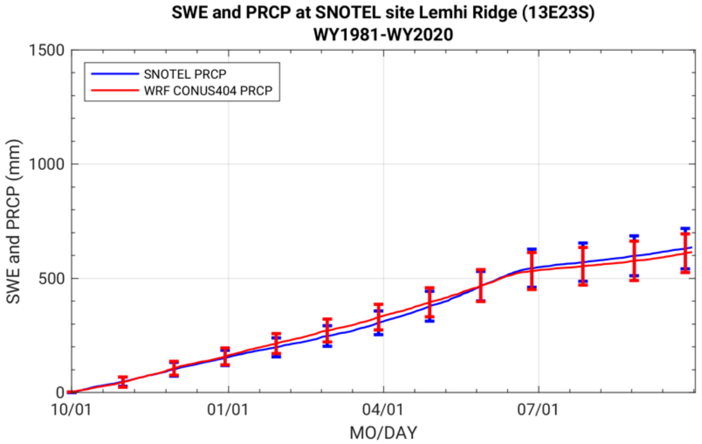
Most precipitation falls on the west and northern mountain ranges surrounding the basin

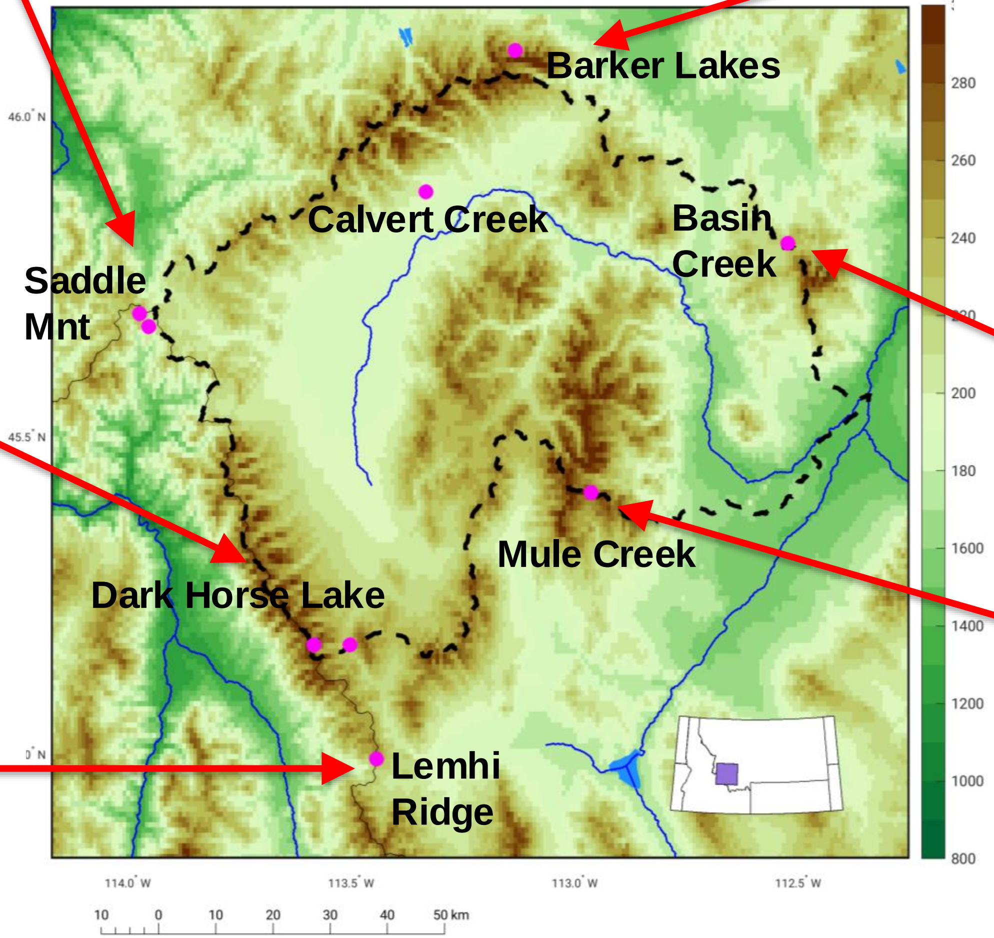
Comparison of CONUS404 model and observations

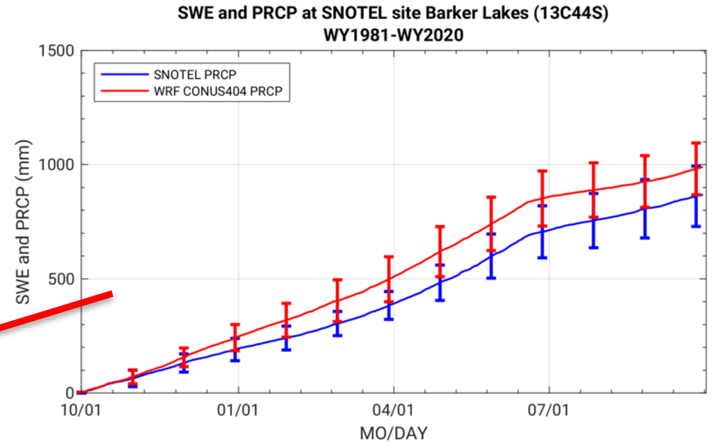
CONUS404 agrees well with most SNOTEL observations especially in winter months

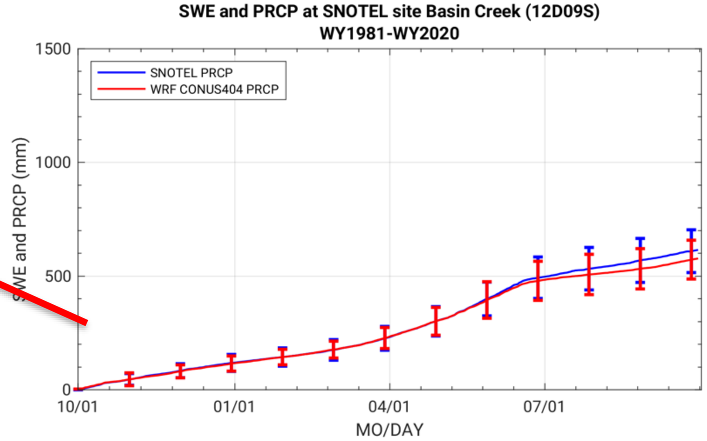


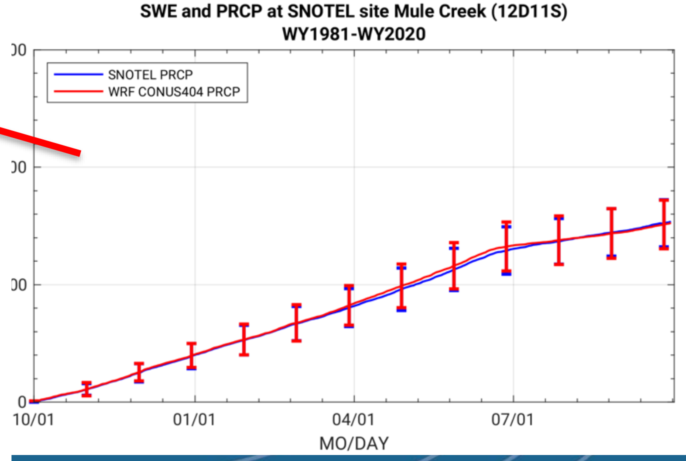




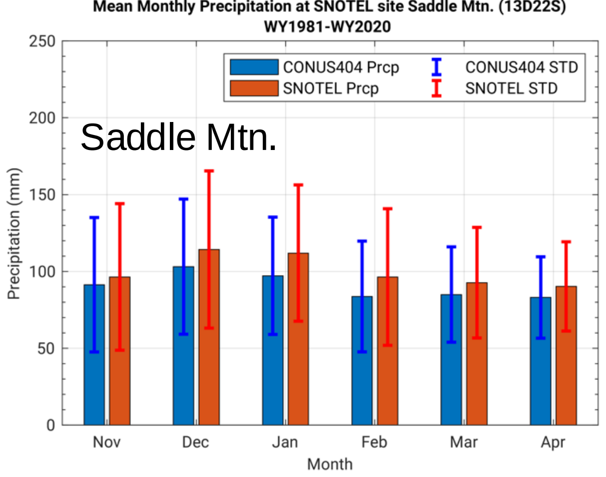


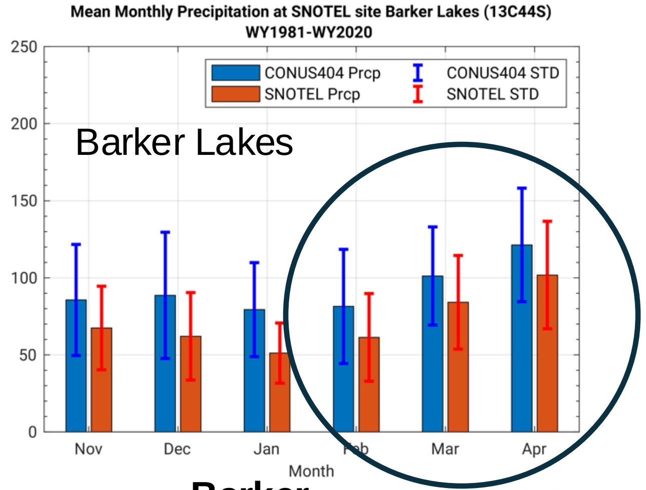


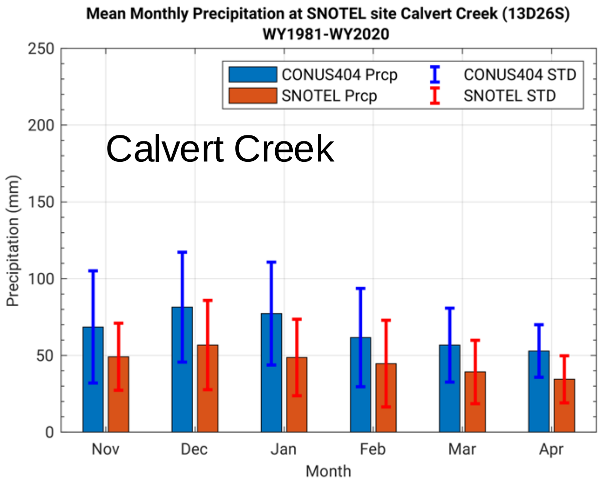


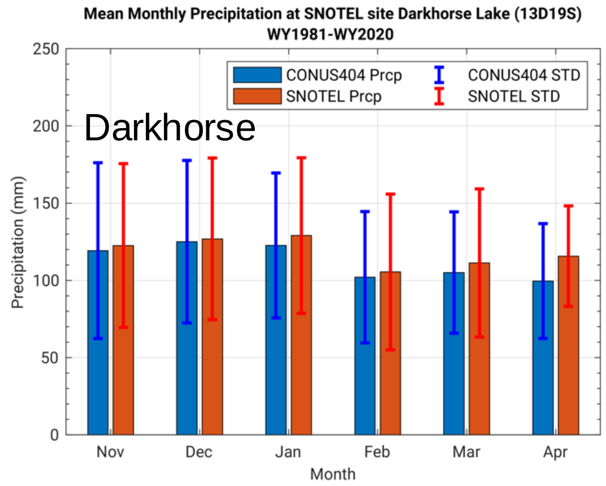


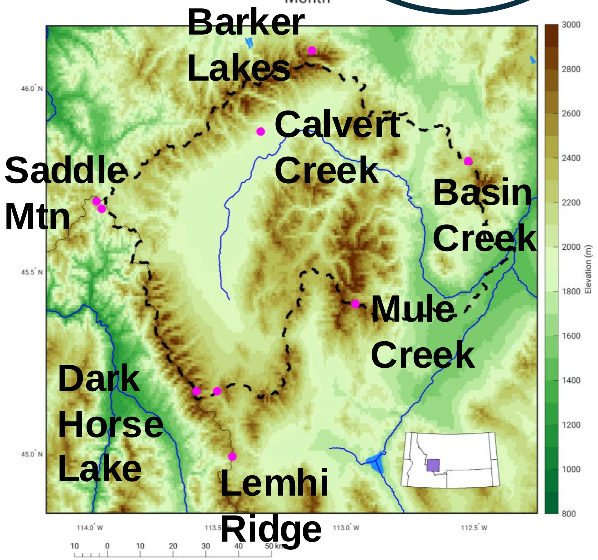
Precipitation trends by month

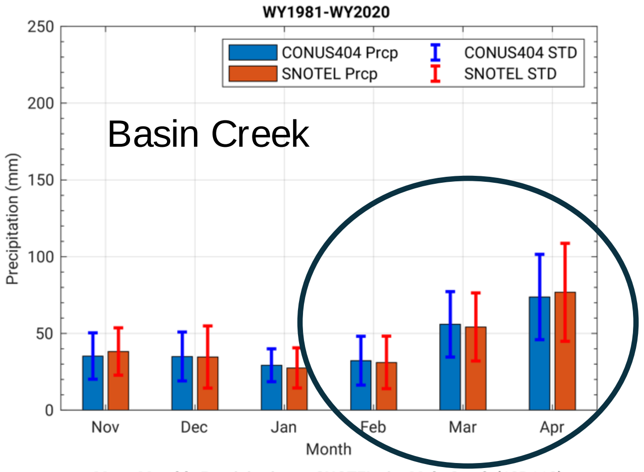


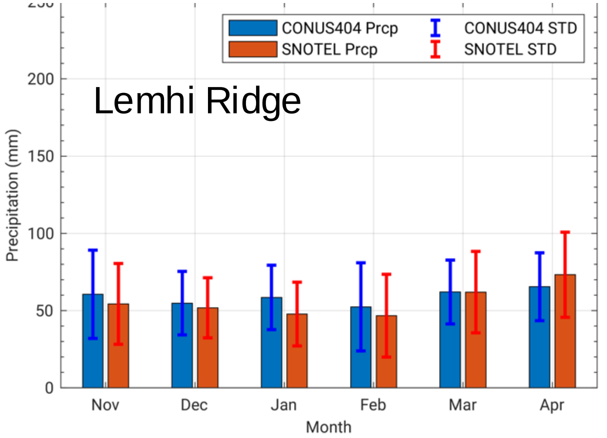




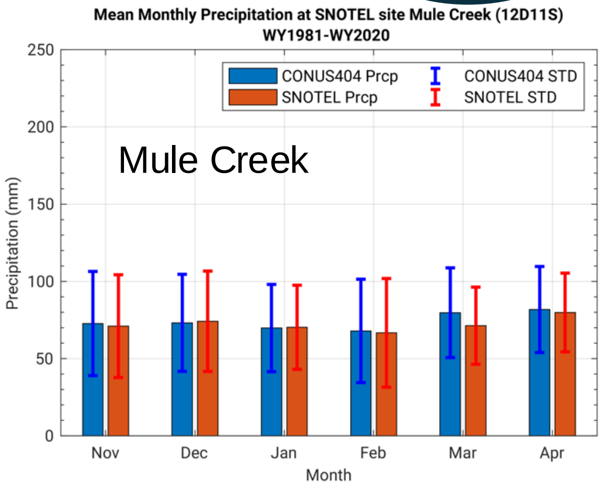






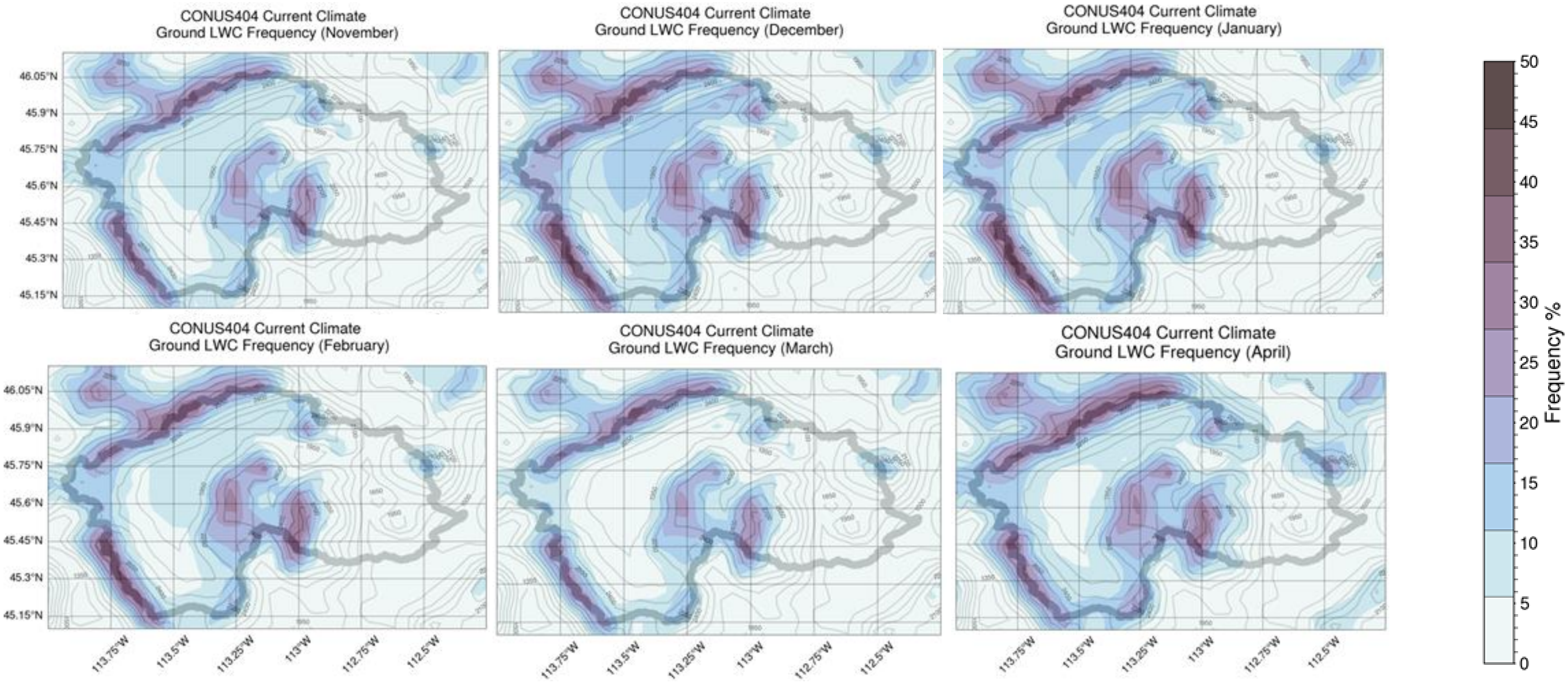


Wy1981-wy2020 average of monthly precipitation from Nov. - Apr. evaluated at SNOTEL sites.

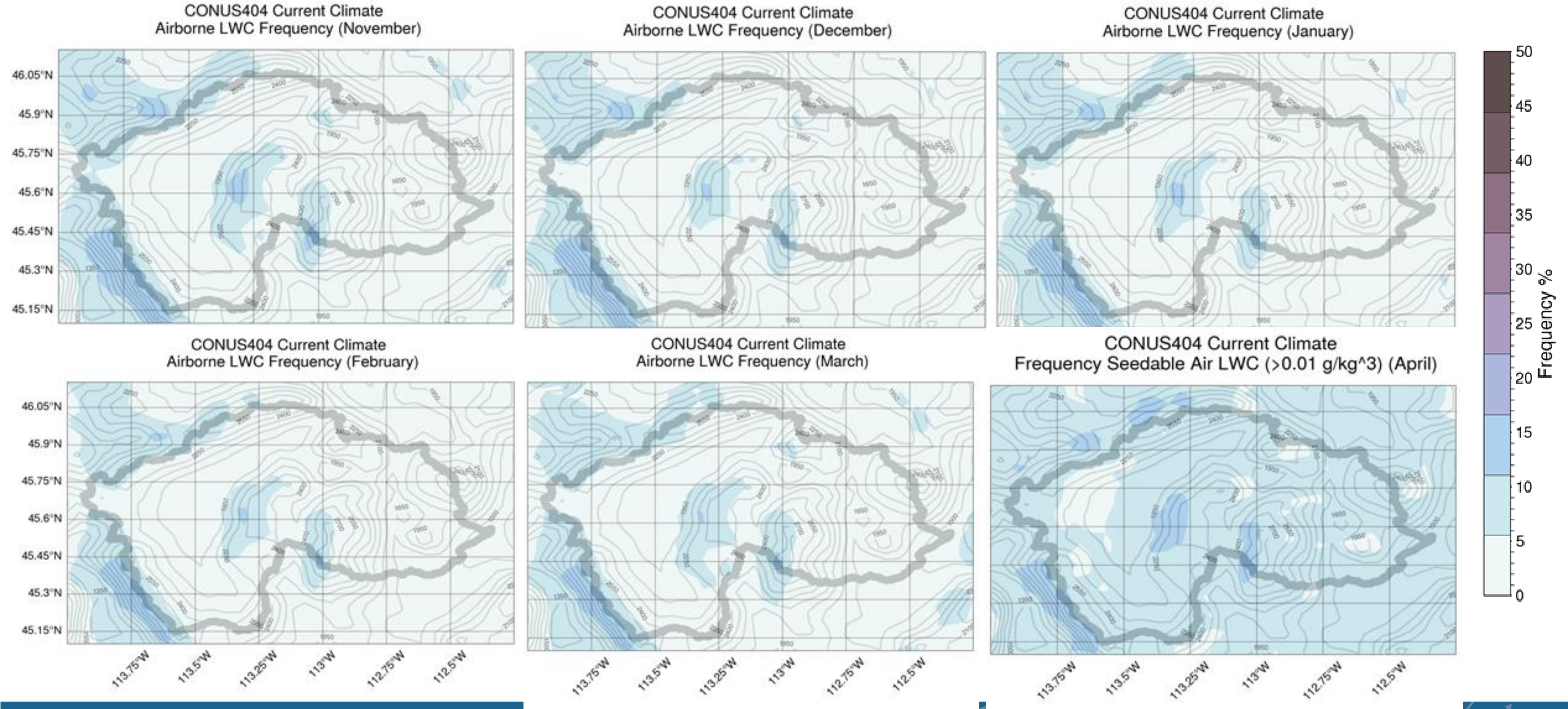


- Sites with most precipitation in winter are northern and western sites
- Basin Creek and Barker Lakes increase in spring
- Saddle Mtn and Darkhorse have most precipitation in early winter

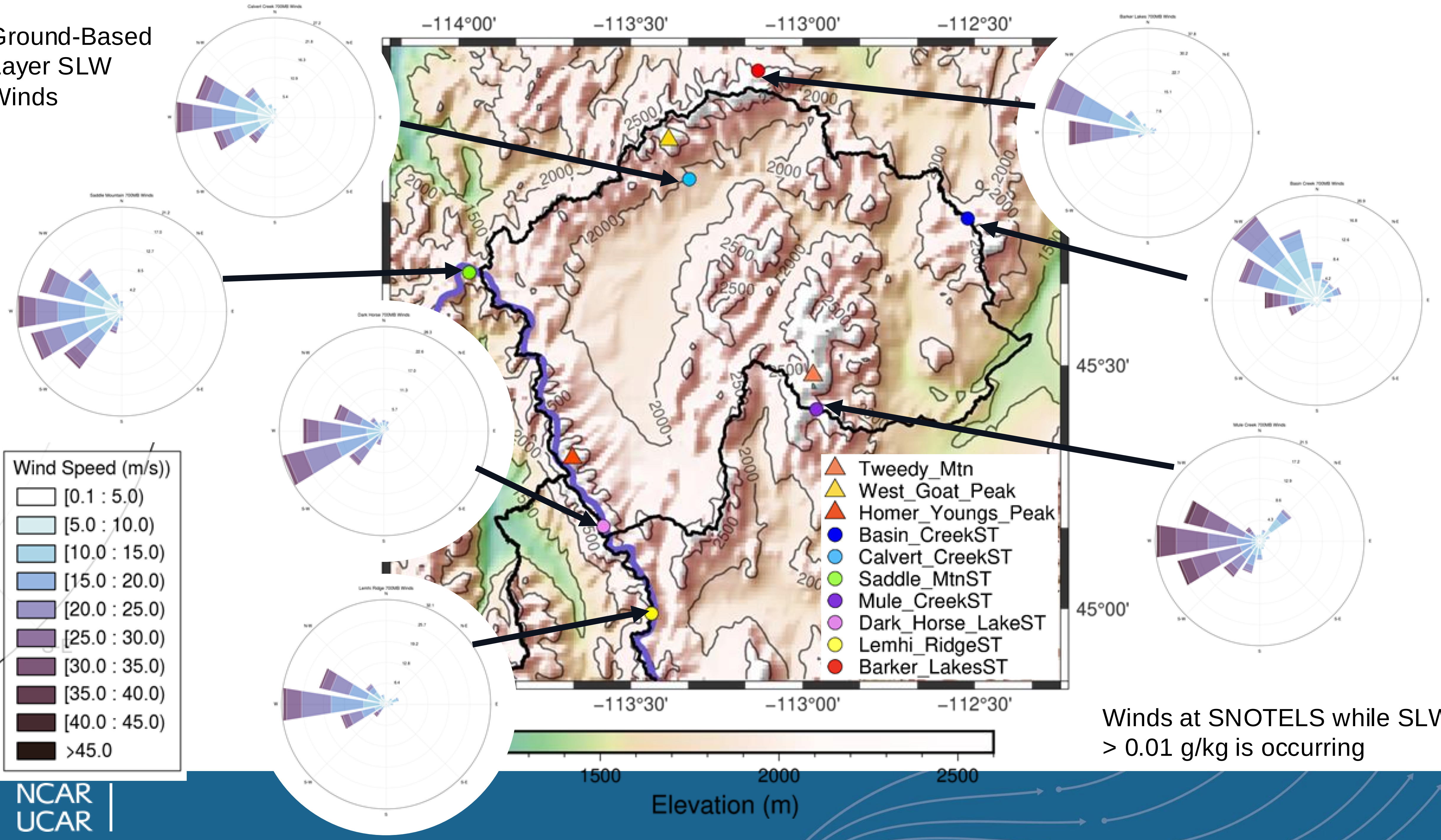
SLW frequency in Ground-based seeding layer by month



SLW frequency in Airborne seeding layer by month



Ground-Based Layer SLW Winds



Winds at SNOTELS while SLW > 0.01 g/kg is occurring

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Climatology Summary

- Precipitation and cloud seeding opportunities are greatest in the western and northern portions of the Big Hole Watershed
- Ground-based layer of the atmosphere has more frequent SLW
  - However, dispersion criteria that impacts ground seeding is still being investigated (e.g., flow blocking) which may limit some of the opportunities
- Wind regimes impacting the western Big Hole during seedable conditions are generally west-southwest
  - There is some northwesterly flow impacting the northern region (Anaconda Range)
  - There is some (generally infrequent) easterly flow impacting the eastern portion of the watershed

Focus on western portion of the watershed for potential designs for west, southwest, and some northwest flow

Feasibility and Design Components

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What methods of cloud seeding might target the clouds in this region most effectively?

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How effective are each design option at targeting and enhancing precipitation in this region?

Which combination of design options is recommended?

Analyze historical data:

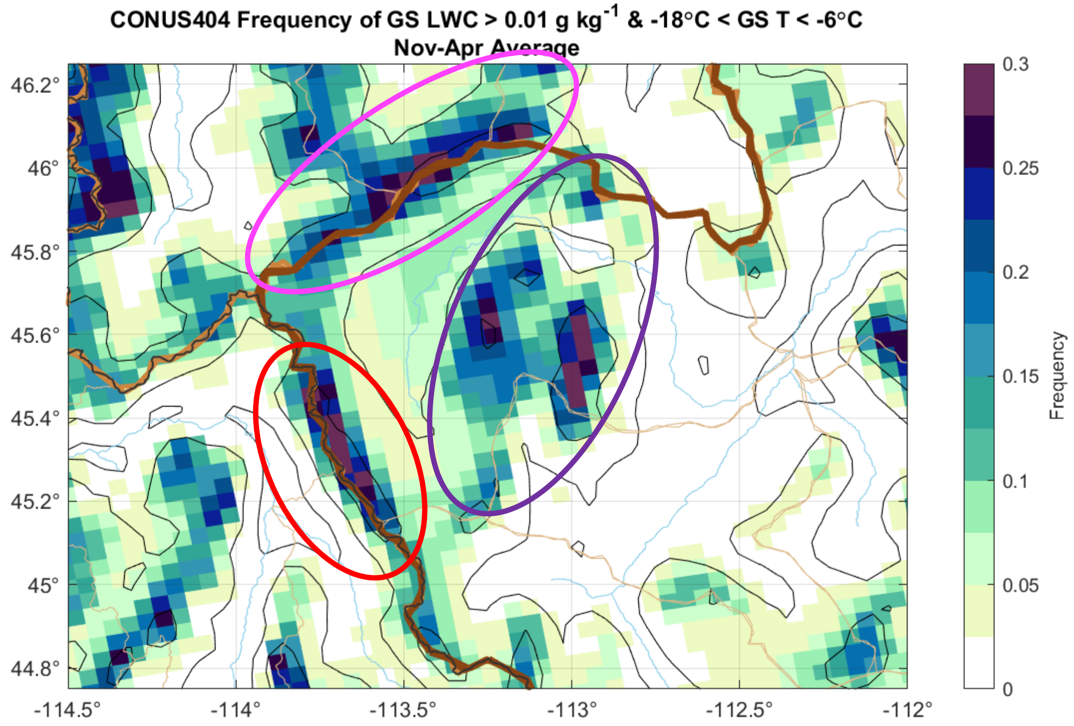
- Temperature
- Supercooled liquid water (SLW)
- Precipitation
- Winds
- Atmospheric stability

Review climatology results

- Place hypothetical ground-based generator locations
- Identify possible aircraft tracks

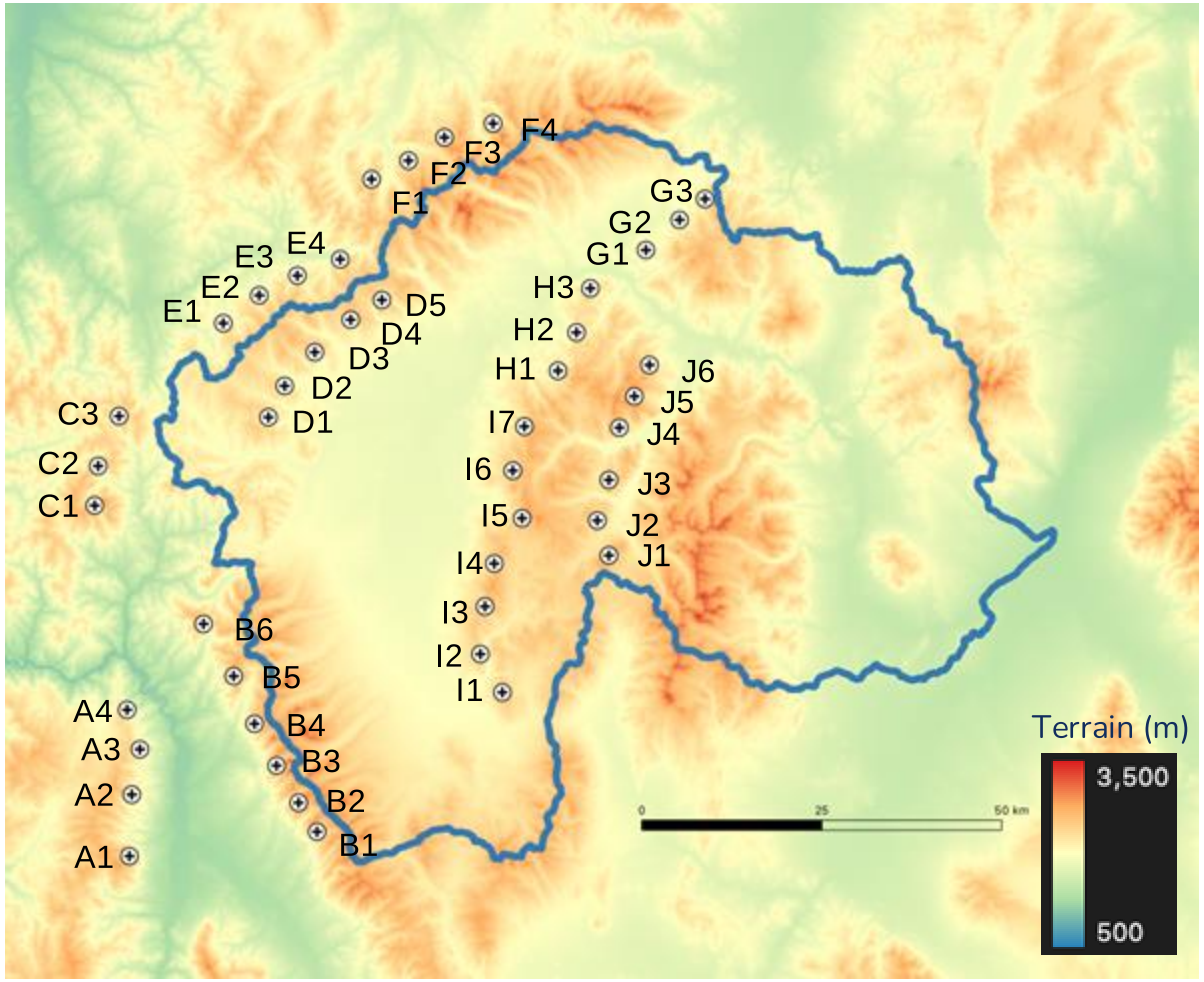
Ground-based Seeding Preliminary Design Options

Nov-Apr Average Frequency for Ground-based Seeding



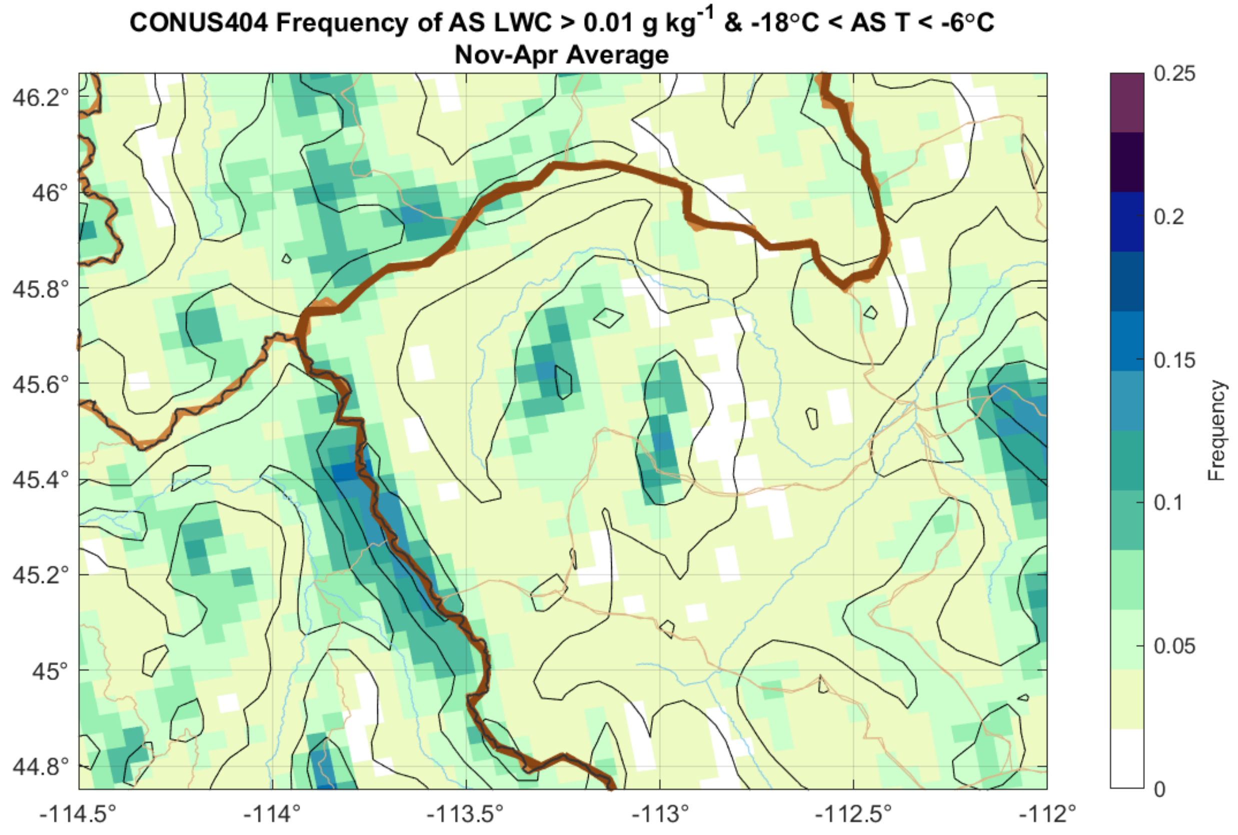
A & B Groups
C, D, E, F Groups
G, H, I, J Groups

Hypothetical Ground-based Seeding Generator Sites

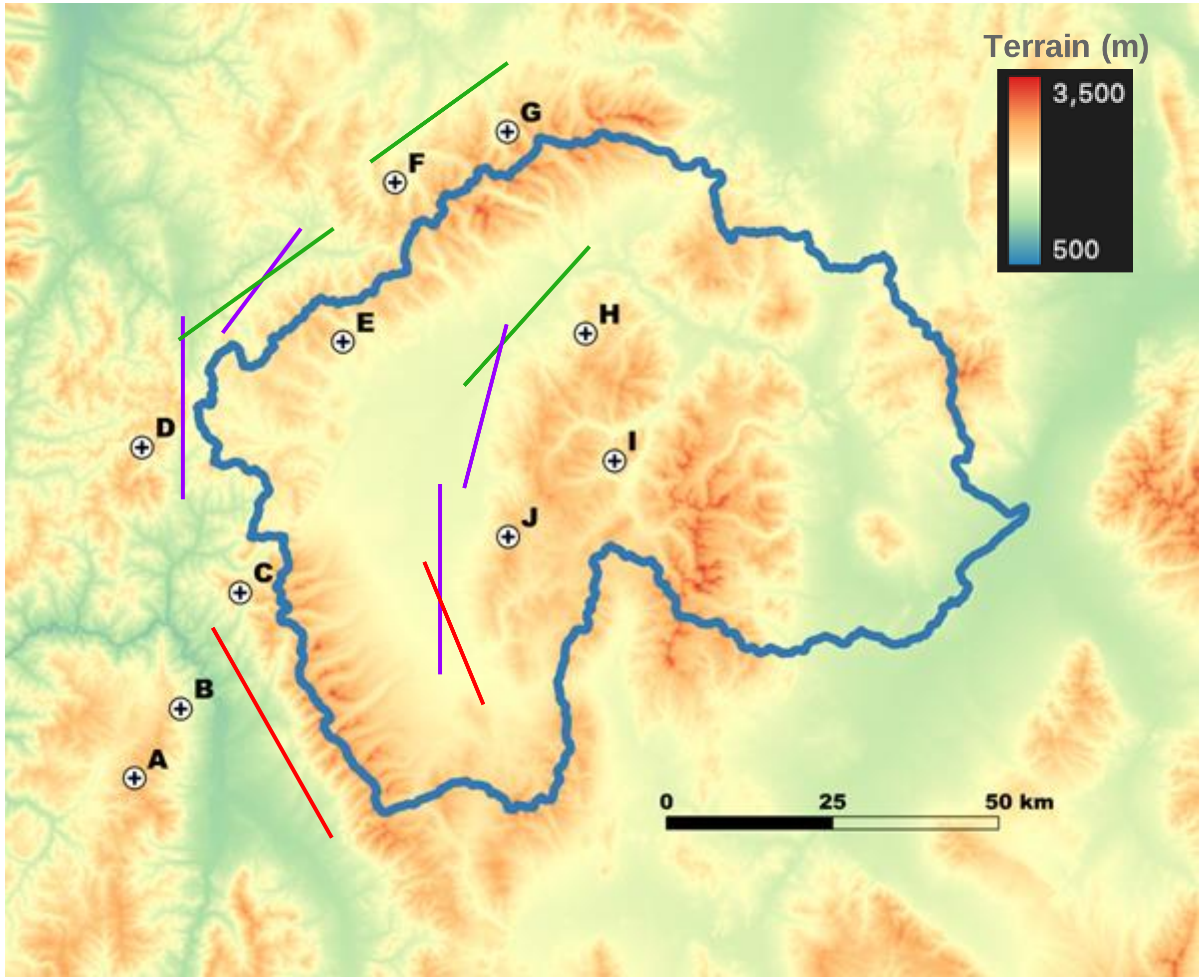


Airborne Seeding Preliminary Design Options

Nov-Apr Average Frequency for Airborne Seeding



Hypothetical Airborne Seeding Flight Tracks



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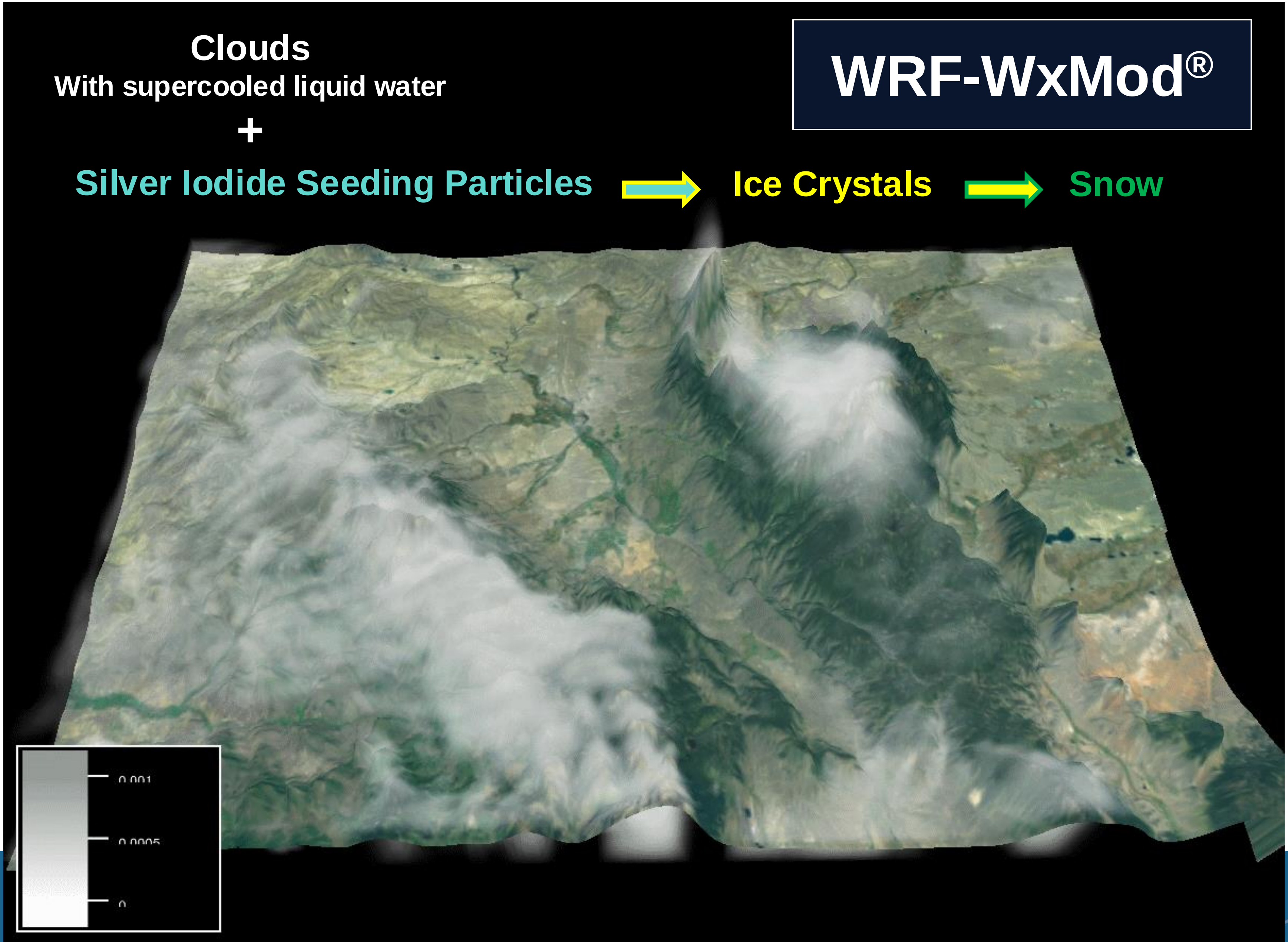
Review climatology results
- Place hypothetical ground-based generator locations
- Identify possible aircraft tracks

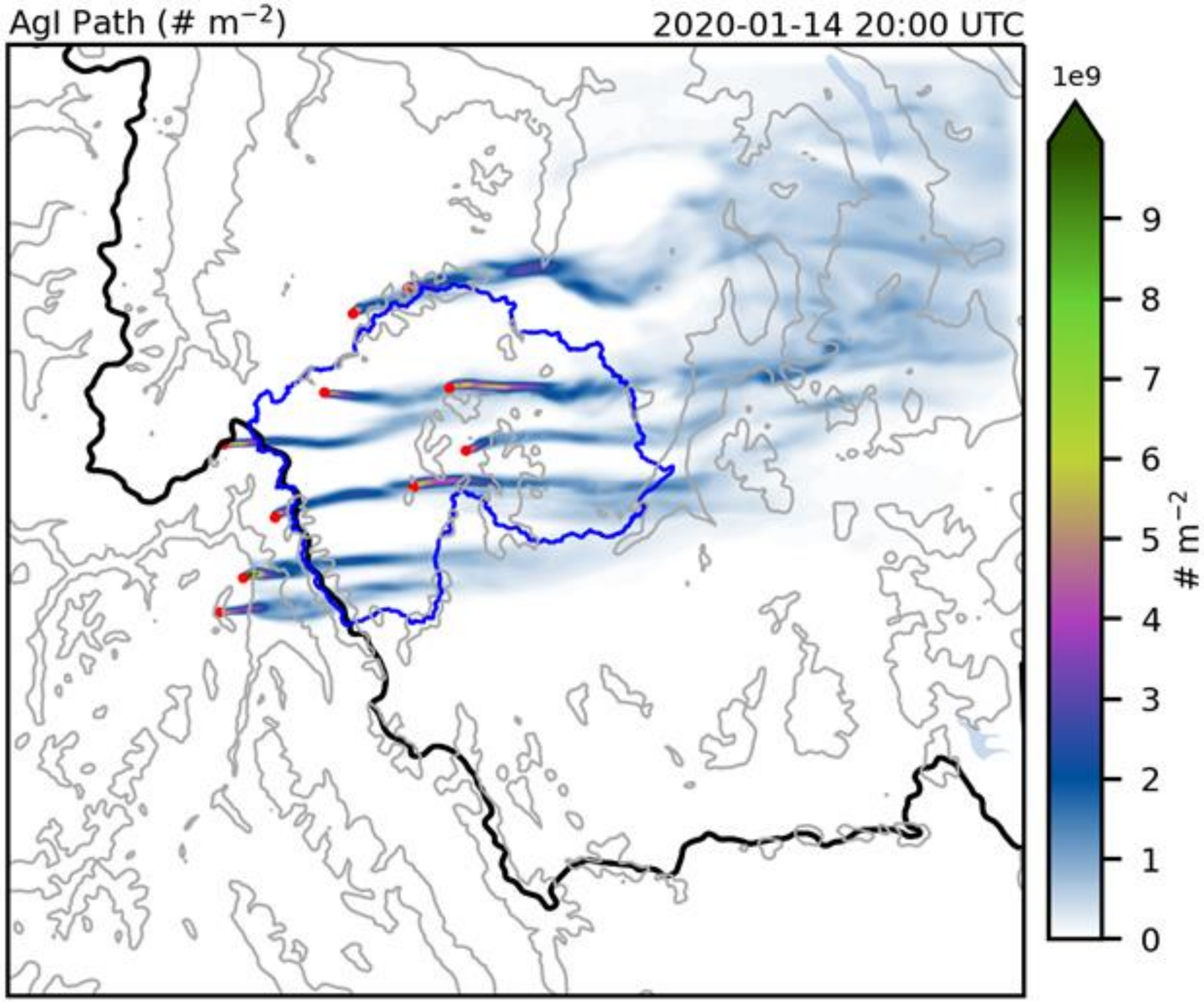
Simulations of cloud seeding
- Test each group of generators or flight tracks individually and combined
- Identify the options with optimal simulated results

Simulations of Cloud Seeding



Xue et al. (2013)

Testing Potential Seeding Designs with WRF-WxMod



- Preliminary results showing the silver iodide plume dispersion from select hypothetical ground generators in each group
- We will run a simulation testing each group separately and together
- We will map and quantify the simulated change in precipitation from each of those simulations to produce recommendations for the most effective designs

Summary

Recent studies have proven that cloud seeding works to enhance precipitation in winter orographic clouds

Most western U.S. states currently conduct cloud seeding aiming to enhance snowpack

A feasibility study is first needed to assess the opportunities for seeding in a given region

Preliminary results show most opportunities for cloud seeding in the western portion of the Big Hole basin

FAQ

- **Concern about extra area effects**
  - Does cloud seeding remove water from the sky that would have been precipitation elsewhere?
  - "Are we robbing Peter to pay Paul?"

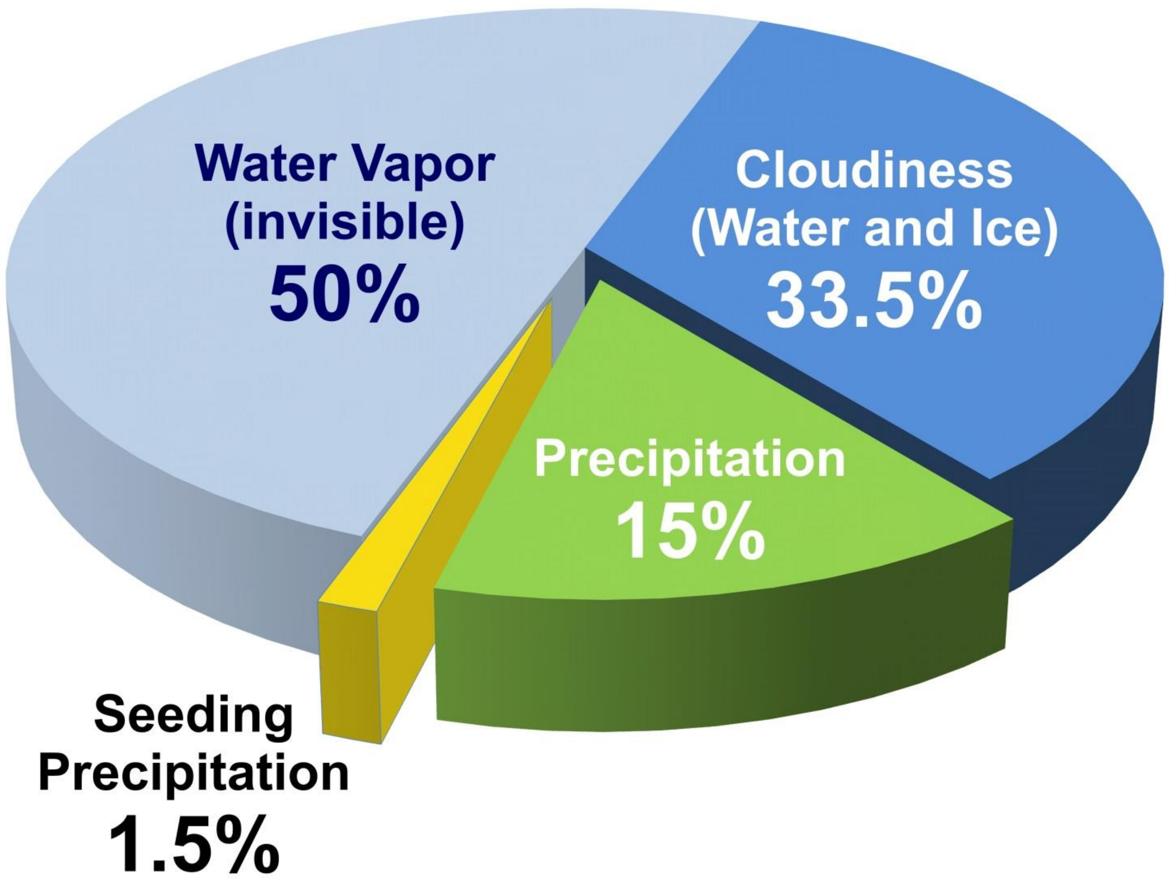
- **Concerns about potential environmental impacts**
  - Does cloud seeding with Silver Iodide lead to dangerous levels of silver in snow and water?

- **Concerns about potential to contribute to flooding and weather hazards**
  - Will cloud seeding create floods?

What are the extra area effects of cloud seeding?

- Conceptually, the **effect outside of the target area is estimated to be very small**
  - Challenging to detect the intended effect, extra area effects may be even more diffuse
- New modeling capabilities present new opportunities to better address this question

Conceptual Water Vapor Budget



FAQ

- **Concern about extra area effects**
  - Does cloud seeding remove water from the sky that would have been precipitation elsewhere?
  - "Are we robbing Peter to pay Paul?"

- Water vapor budget calculations suggest a very small impact (<1%)
- Challenging to detect the intended effect, extra area effects may be even more diffuse
- With new modeling capabilities, this needs to be addressed in a more robust way

- **Concerns about potential environmental impacts**
  - Does cloud seeding with Silver Iodide lead to dangerous levels of silver in snow and water?

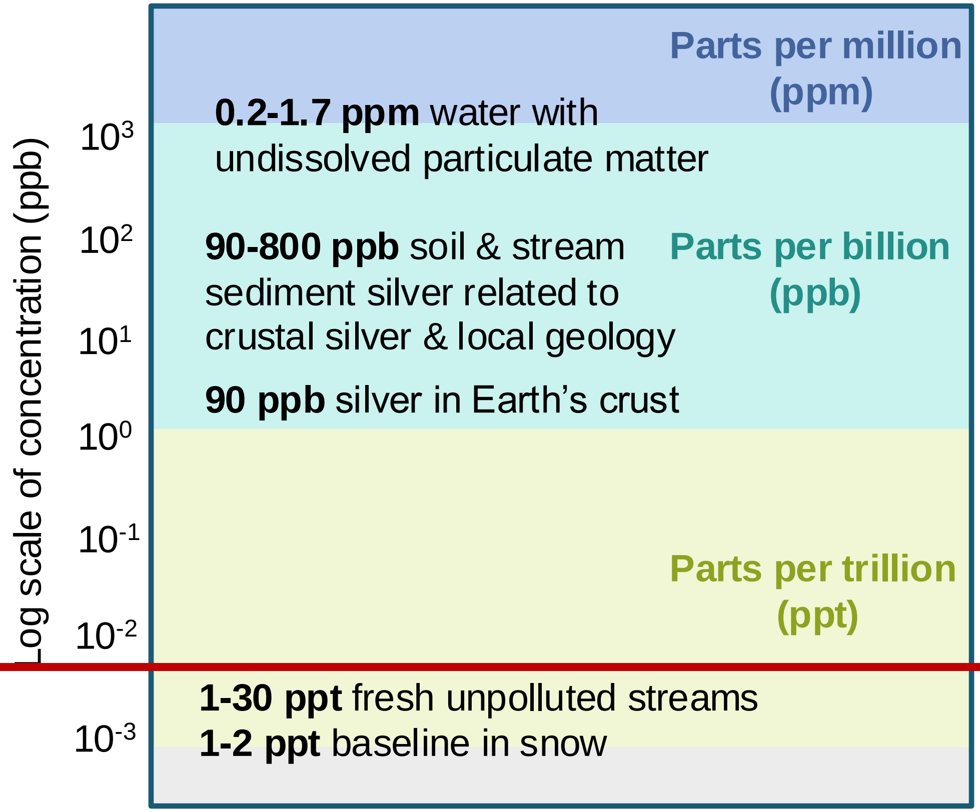
- **Concerns about potential to contribute to flooding and weather hazards**
  - Will cloud seeding create floods?

Environmental Impacts of Cloud Seeding

Trace chemistry analyses of snow, water, and soil samples have shown a **negligible environmental impact from seeding operations**

Trace chemistry measures amounts of chemicals in such small concentrations that clean gear and clean procedures are required

Values of Silver Concentration



<u>Wyoming Pilot Program:</u>
4-6 ppt baseline in snow
1-36 ppt baseline in streams

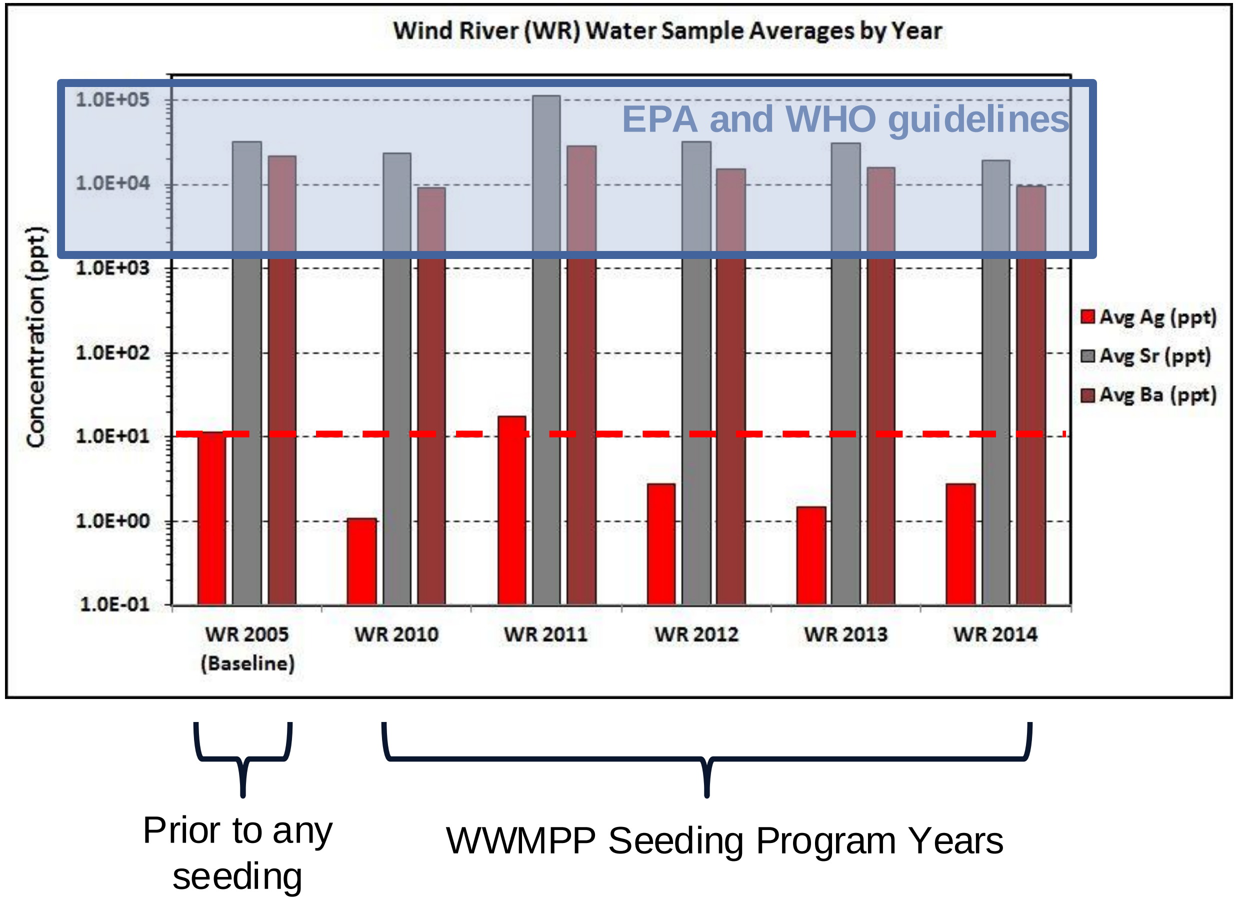
Far less than would be expected from other (background) sources of silver

Environmental Impacts of Cloud Seeding

- Silver in water measured during seeding was the same order of magnitude as the baseline from years before seeding experiment started

- Several orders of magnitude less than values considered hazardous to environmental system or human health

Silver in Water Samples from WWMPP



(From the WWMPP Report)

FAQ

- **Concern about extra area effects**
  - Does cloud seeding remove water from the sky that would have been precipitation elsewhere?
  - “Are we robbing Peter to pay Paul?”

> - Water vapor budget calculations suggest a very small impact (<1%)
> - Challenging to detect the intended effect, extra area effects may be even more diffuse
> - With new modeling capabilities, this needs to be addressed in a more robust way

- **Concerns about potential environmental impacts**
  - Does cloud seeding with Silver Iodide lead to dangerous levels of silver in snow and water?

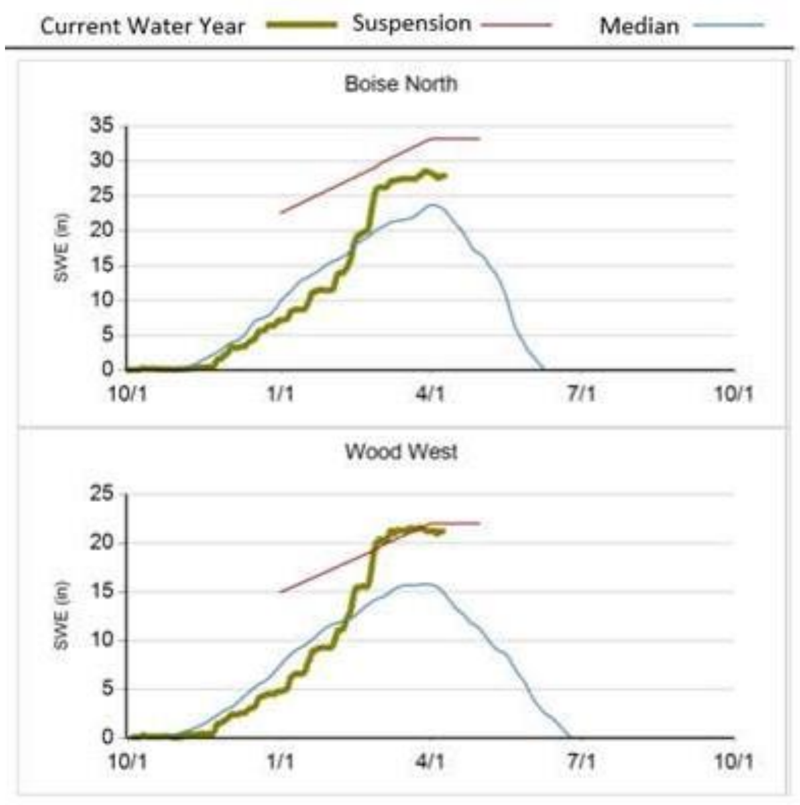
> - Trace chemistry analysis of snow samples indicates measured silver amounts are similar to background levels in the absence of seeding
> - Several orders of magnitude below any levels that might pose health and environmental concerns

- **Concerns about potential to contribute to flooding and weather hazards**
  - Will cloud seeding create floods?

Suspension Criteria

- Most operational cloud-seeding programs establish suspension criteria to suspend seeding when hazardous conditions could be likely
- Reasons for suspension include, but are not limited to:
  - Unusually heavy snowpack in the target area,
  - Extreme avalanche danger,
  - Unusually severe winter storms, as forecast by the National Weather Service,
  - Insufficient reservoir capacity for expected runoff, and
  - Direction to suspend (for any other reason) from client/stakeholders

Snow Water Equivalent (SWE) accumulation



Courtesy Idaho Power Company

FAQ

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> Hazards are mitigated by using suspension criteria so that no seeding is done in potentially hazardous situations

Further Training Opportunities

Free Online Training Module:

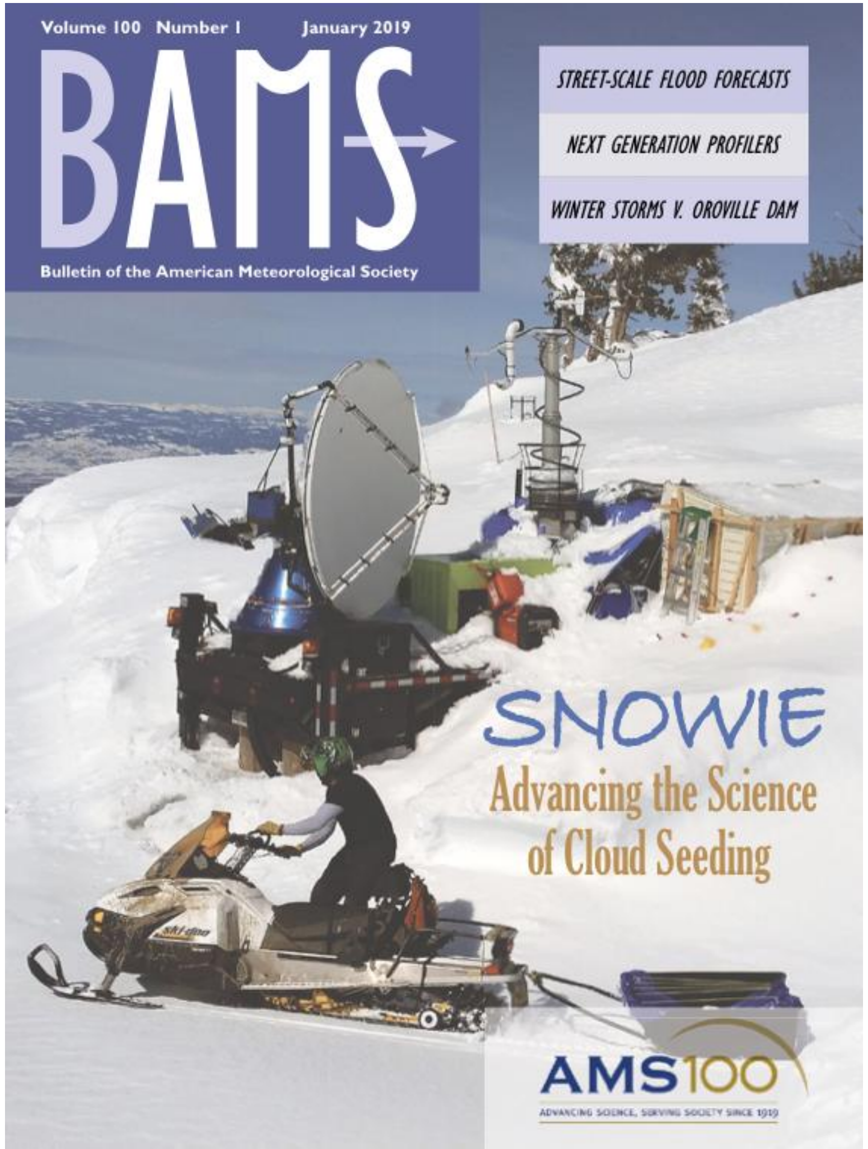
Produced by the COMET Program
https://www.meted.ucar.edu/USBR/cloud_seeding/

You will be asked to create an account to access this training module and any others in the catalog

Thank you!

Questions?

Contact me at saraht@ucar.edu



Tessendorf, S.A., and co-authors, 2019: **A transformational approach to weather modification research: The SNOWIE project**. *Bull. Amer. Meteor. Soc.*, **100**, 71–92, doi: 10.1175/BAMS-D-17-0152.1