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Cloud Seeding Effects on Snowfall: Insights from Microphysical Model and Satellite Remote Sensing

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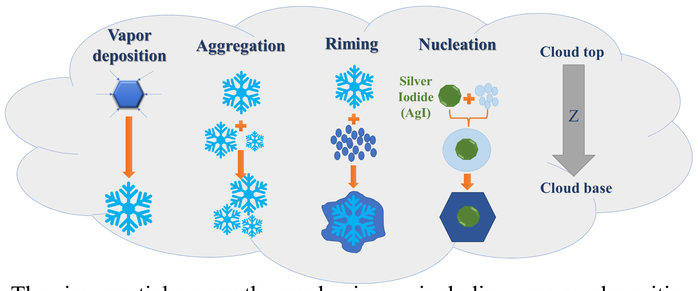
❖ Introduction

Cloud seeding, as outlined in the process of adding substances to clouds to encourage precipitation and mitigate hail damage (Henneberger et al., 2023), has proven to yield a significant 12-16% increase in precipitation (Manton et al., 2011 and 2017). This weather modification technique can take two forms: Hygroscopic or Glaciogenic, known as warm and cold cloud seeding, respectively. In glaciogenic seeding, silver iodide (AgI) is introduced as an ice nucleating particle into clouds with temperatures below freezing, enhancing the ice/mixed phase of the cloud.

❖ Cloud Seeding Criteria

Successful cloud seeding requires supercooled liquid water, temperatures between -5°C to -15°C, atmospheric instability (no inversions or stable layers), and suitable wind direction and speed to guide particles into the clouds.

❖ Conceptual model



The ice particle growth mechanisms, including vapor deposition, aggregation, riming of ice crystals, and nucleation from the top to the base of the cloud are illustrated above. These constitute the microphysical processes integrated into SGRM. The simulation of ice nucleation encompasses condensation, deposition, contact, and immersion processes.

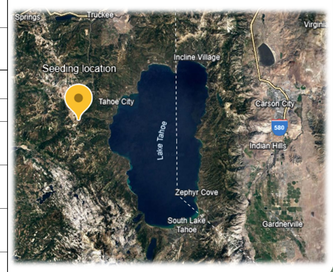
❖ Model and Data Description

- The Snow Growth Model for Rimed Snowfall (SGMR; Erfani, 2016) is an analytical and computationally cost-effective model with a short run time which is particularly useful when observations are nonexistent or uncertain.
- Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017) reanalysis and the Clouds and the Earth's Radiant Energy System (CERES; Doelling et al., 2016) satellite observations are two major data sources to initialize and force SGMR.

❖ Model Inputs

Unit	Variable	Mid-Low clouds (700-500 mb)	
		Event1 (09/03/2021)	Event2 (16/12/2021)
km	Cloud Top Height	4.811	3.87
Km	Cloud Base Height	2.338	2.019
C	Cloud Top Temperature	-25	-13
C	Cloud Base Temperature	-9	-3
g/m^3	Liquid Water content	0.1	0.249
g/m^3	Ice Water content	0.092	0.118

Case study over the **Tahoe area**



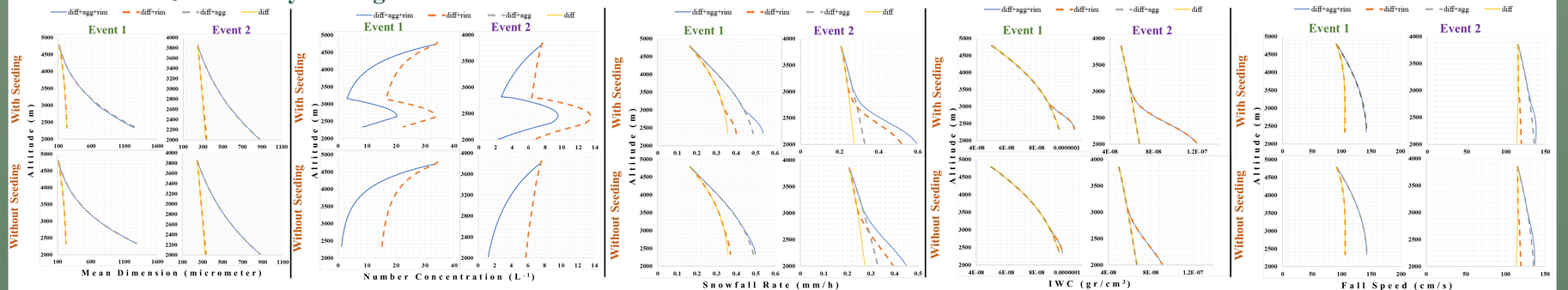
❖ Goals

- We aim to deepen our understanding of cloud seeding mechanisms over the western United States.
- We explore cloud seeding mechanisms from a microphysical point of view and leverage satellite remote sensing perspectives in our investigation.

❖ Accomplishments

- Enhanced the understanding of cloud seeding mechanisms.
- Conducted numerical simulations on a microphysical scale as a robust predictive tool to better quantify the impacts of cloud seeding and ice-phase parameterization.

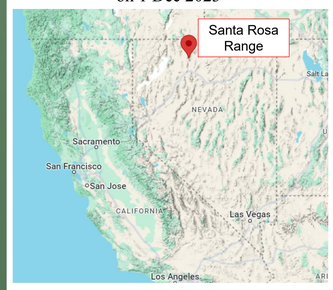
❖ Model output and key findings

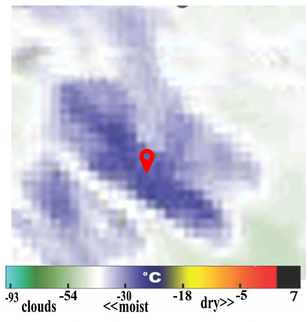


Impact of event 1 (09/03/2021) and event 2 (16/12/2021) with and without considering nucleation for four scenarios, which are the combination of Diffusion, Aggregation, and Riming on: Mean particle dimension, Number concentration, Snowfall rate, Ice Water Content (IWC), and Fall speed.

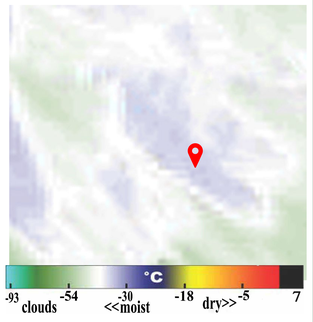
❖ GOES Satellite Observations

Cloud seeding over Santa Rosa mountains on 1 Dec 2023

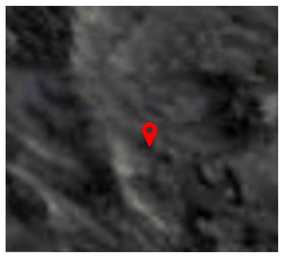




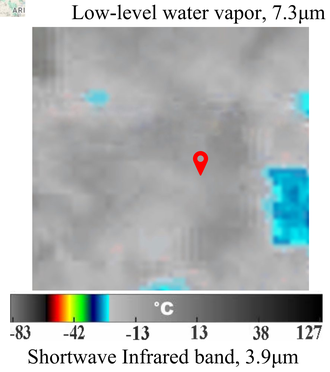
Low-level water vapor, 7.3µm



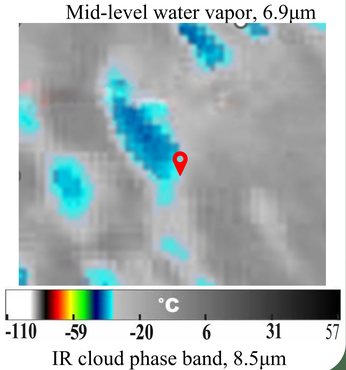
Mid-level water vapor, 6.9µm



Snow/Ice band, 1.61µm



Shortwave Infrared band, 3.9µm



IR cloud phase band, 8.5µm

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❖ Results

1. The analytical SGMR successfully simulates in-cloud alteration of particles.
2. IWC (ice water content) and LWC (liquid water content) within the clouds are crucial for the strength of snowfall.
3. Nucleation during the seeding induces a significant change in number concentration and snowfall rate while representing a minor impact on mass-weighted fall speed.
4. Vertical profile of IWC represents an increase from cloud top to cloud bottom due to the phase change from vapor to ice through vapor diffusion and the accumulation of cloud droplets on the ice surface via riming.
5. Aggregation results in a decrease in the number of ice particles, and an increase in their sizes.
6. Water vapor bands of GOES observations depict the impact of cloud seeding on the enhancement of moisture over the region.
7. Comparing the snow/ice and the shortwave IR bands of the GOES satellite observations suggests that the amount of large ice crystals is reduced while snow is presented over the region during the seeding event.

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Cloud seeding is a weather modification technique aimed at enhancing precipitation by introducing various substances (e.g., silver iodide) into clouds. The basic idea behind glaciogenic cloud seeding is to add ice nuclei to mixed-phase clouds that have numerous supercooled water droplets while not sufficient ice crystals. While striking a balance between efficiency and precision usually involves sacrificing accuracy, the inclusion of a multitude of microphysical processes in climate models are computationally expensive.

The goal of this study is to gain further insight into the mechanisms of cloud seeding and develop machine learning algorithms as a powerful predictive tool to better quantify the effects of cloud seeding. This research employs the Snow Growth Model for Rimed snowfall (SGMR) that predicts the vertical evolution of ice particle size spectra based on the relative humidity or supersaturation. The model is formulated in terms of analytically interrelated procedures involving ice crystal nucleation, vapor deposition, aggregation, and cloud updrafts and it thereby estimates snowfall rate. The model provides an accurate description of the microphysical processes with reduced computation time.

We aim to conduct various model experiments initialized with different meteorological conditions under seeding vs. non-seeding scenarios. We will use an ensemble of in-situ and satellite remotely sensed observations to develop an ML-based model in order to further investigate changes in snowfall due to cloud seeding.

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