Studying the Mechanistic Impacts of Cloud Seeding on Snowfall with Insights from a Cloud Microphysical Model

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Studying the Mechanistic Impacts of Cloud Seeding on Snowfall with Insights from a Cloud Microphysical Model

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❖ Introduction

- Cloud seeding is the most common weather modification technique and dates back to 1946.
- Cloud seeding is the process of adding substances to clouds to encourage precipitation and mitigate hail damage (Henneberger et al., 2023).
- As a result of cloud seeding there is between a 12% and 16% increase in precipitation (Manton et al., 2011 and 2017).
- Cloud seeding can be Hygroscopic or Glaciogenic (warm and cold cloud seeding, respectively).
- A glaciogenic seeding introduces silver iodide (AgI) as an ice nucleating particle into the cloud with a temperature below freezing to enhance the ice/mixed phase of the cloud.

❖ Cloud seeding criteria

- Supercooled Liquid Water,
- Low temperature; the optimum temperature range is between -5°C to -15°C.
- Atmospheric instability; there should be no inversion or stable layer between the height of the cloud and the generator.
- Wind direction and speed.

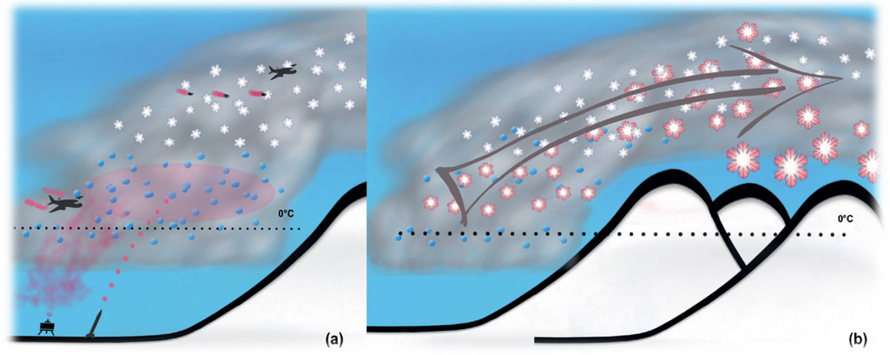

Figure 1. Glaciogenic seeding of an orographic wintertime cloud (Flossmann, 2019).

❖ Goals

- Enhancing the understanding of cloud seeding mechanisms.
- Conducting numerical simulations on a microphysical scale as a robust predictive tool to better quantify the impacts of cloud seeding.
- Improve the ice-phase parameterization in weather and climate models.

❖ Model description

- The model used is the Snow Growth Model for Rimed Snowfall (SGMR; Erfani, 2016)
- The model is accurate, with a short runtime, analytical and computationally cheap, and particularly useful when observations are nonexistent or uncertain.
- Cloud base and top height, cloud base and top temperature, ice water content at cloud top, liquid water content at cloud top, etc. are the initial input data.
- Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017) reanalysis data and the Clouds and the Earth's Radiant Energy System (CERES; Doelling et al., 2016) satellite observations are two major data sources.

❖ Conceptual model

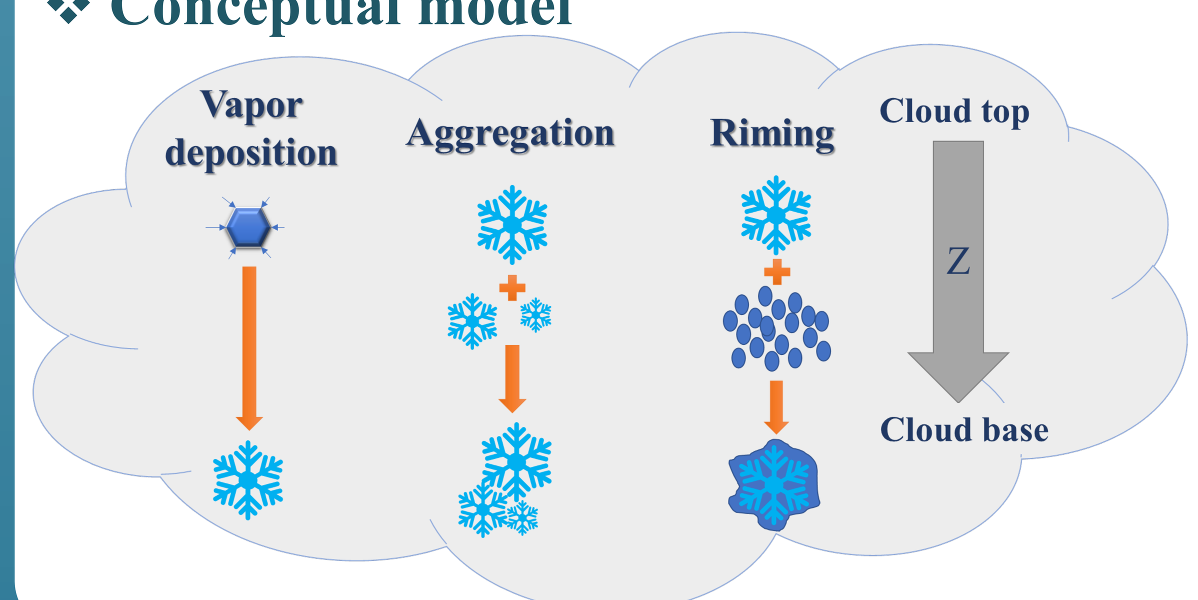

Figure 2. Illustrates the ice particle growth mechanisms, including (a) vapor deposition, (b) aggregation of ice crystals, and (c) riming of ice crystals from the top to the base of the cloud.
The microphysical processes included in SGRM are diffusion or deposition (diff), aggregation (agg), and riming (rim).

❖ Model inputs

Unit	Variable	Mid-Low clouds (700-500 mb)	
		Event1	Event2
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

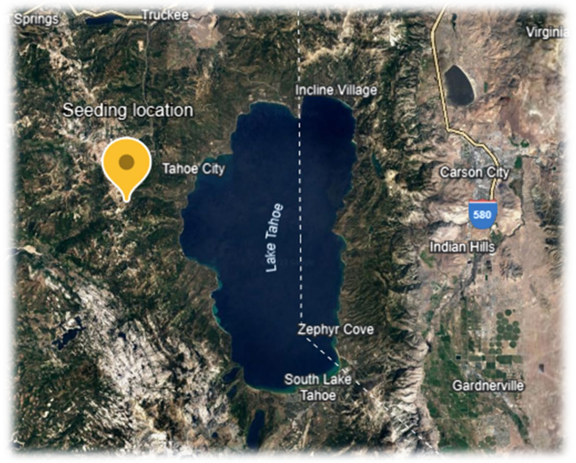

Figure 3. Case study of the research: Tahoe area

❖ Model output and key findings

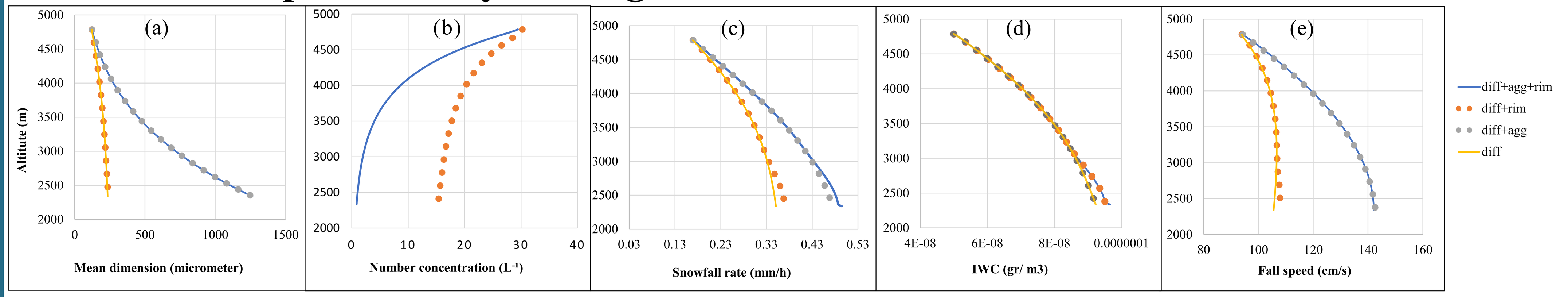

Figure 4. Impact of seeding event 1 (09/03/2021) for four scenarios, which are the combination of Diffusion, Aggregation, and Riming on (a) Mean particle dimension, (b) Number concentration, (c) Snowfall rate, (d) Ice Water Content (IWC), and (e) Fall speed.

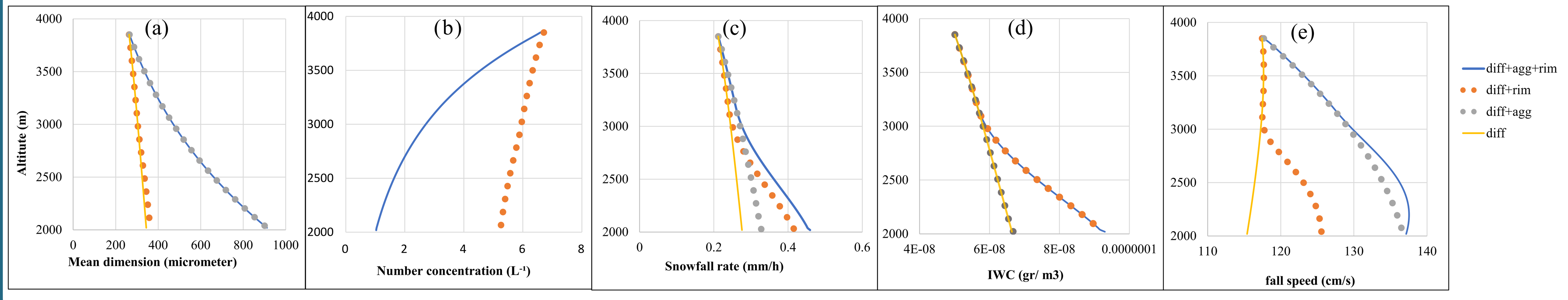

Figure 5. Impact of seeding event 2 (16/12/2021) for four scenarios, which are the combination of Diffusion, Aggregation, and Riming on (a) Mean particle dimension, (b) Number concentration, (c) Snowfall rate, (d) Ice Water Content (IWC), and (e) Fall speed.

❖ Results

1. IWC (ice water content) and LWC (liquid water content) within the clouds are crucial for the strength of snowfall.
2. The analytical SGMR successfully simulates in-cloud alteration of particles.
3. 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 accretion.
4. Due to the aggregation process, ice crystals collide and adhere to each other, forming larger particles. Consequently, aggregation results in a decrease in the number of ice particles, but an increase in their sizes.
5. The effect of riming on both particle dimension and number concentration is minimal because the accretion of cloud drops on ice particles does not change the number of ice particles and it only fills in their interstices without altering their maximum dimension.

❖ Next steps

1. Add the nucleation process as another ice particle growth mechanism to the SGMR model.
2. Develop a Machine Learning Algorithm and Conduct Statistical Analysis (e.g., R-value and Standard Error) to identify the ML model with the highest metrics.
3. Study the sensitivity of ML predictions to temporal and spatial resolution. Investigate the consistency of ML models with previous studies.

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Abstract (250 words or less):

Cloud seeding is a weather modification technique aimed at enhancing precipitation by introducing various substances (e.g., silver iodide) in clouds. The primary concept behind glaciogenic cloud seeding is to introduce ice nuclei into mixed-phase clouds that contain many supercooled water droplets but lack sufficient ice crystals. Achieving a balance between efficiency and precision often requires sacrificing some degree of accuracy, given the computational cost of including numerous microphysical processes in climate models.

The objective of this research is to enhance our understanding of cloud seeding mechanisms and to conduct numerical simulations on a microphysical scale as a robust predictive tool to better quantify the impacts of cloud seeding.

This research employs the Snow Growth Model for Rimed Snowfall (SGMR) to investigate the vertical evolution of ice particle size spectra based on relative humidity and available liquid water content (LWC) in clouds as well as ice water content (IWC) at the top of clouds. This 1-dimensional Lagrangian model is formulated through a series of analytically interconnected procedures, encompassing ice crystal nucleation, vapor deposition, aggregation, cloud updrafts, and riming thereby providing the estimates of snowfall rates. The model provides an accurate description of the microphysical processes with reduced computation time.

This study focuses on the cloud seeding cases in the Tahoe area, where the ground-based generators are utilized during real-time cloud seeding operations. We also used MERRA-2 reanalysis data to retrieve vertical profiles of meteorological conditions as well as CERES satellite observations to extract cloud variables at the top of clouds. These are used to force the SGMR for several case studies. The results indicate that both IWC and LWC within the clouds are crucial for the strength of snowfall.

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