TOWARDS THE IMPROVEMENT OF WINTER OROGRAPHIC CLOUD SEEDING IN UTAH

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LIST OF ACRONYMS AND ABBREVIATIONS

AgI........Silver Iodide
ASCII........AgI seeding cloud impact investigation
AWRA........American Water Resources Association
DWRe ....Division of Water Resources
HRRR........High Resolution Rapid Refresh
MSL........Mean Sea Level
NAM........North American Model
NAWC........North American Weather Consultants
NCAR........National Center for Atmospheric Research
SLW........supercooled liquid water
UCC........Utah Climate Center
WMA........Weather Modification Association
WRF ....Weather Research and Forecast
WWMPP ....Wyoming Weather Modification Pilot Project

EXECUTIVE SUMMARY

The Utah Climate Center (UCC) has completed its evaluation of cloud seeding conditions over the mountains of Utah, identifying potential improvements in several long-running programs aimed at increasing snow accumulation across the state. Through the creation of multiple cross-sections over different mountain ranges, the center offers the Utah-Focused Forecasting Model, a tool for ascertaining the primary variables for cloud seeding — temperature and the presence of supercooled liquid water — over most of the state's mountains, providing guidance for seeding operations.

Suitable seeding conditions were evaluated over most of the mountains in Utah, with the state's mountains separated into four regions and 24 range segments to offer greater specificity of relevant average atmospheric conditions. Weather Research and Forecast (WRF) data that were simulated by the National Center for Atmospheric Research (NCAR) covering the Continental United States (CONUS) were used to evaluate the seeding conditions. The NCAR CONUS data has 4 km horizontal and 3-hour temporal resolution covering 13 winter seasons from 2000-01 to 2012-13. The suitable seeding conditions are defined as when the top level of the lower atmosphere (generally considered to be indicated by 700 mb of pressure, found at roughly 10,000 feet mean sea level, which is near the mountaintop height for many of Utah's ranges) is colder than -8^{o}C (or -5^{o}C in some cases that will be further explained) in the presence of supercooled liquid water (SLW) in orographic clouds.

While this study primarily focused on identifying suitable seeding conditions, regardless of the seeding methods, low-level stability, which affects the vertical motion of air parcels, is also a critical variable for ground-based seeding, which is the prevailing method used in Utah. It is important to note that low-level stability was not considered in this evaluation, and further research into the impact of this variable would offer even more accurate seeding conditions.

By calculating the frequency of suitable seeding conditions for all four regions and 24 range segments, the UCC found that Utah's Northern Region has more favorable conditions for cloud seeding than the state's Central and Southern regions. In the Northern Region, the suitable seeding condition frequency (meeting the -8^{o}C temperature threshold in the presence of SLW) is about 30% of the entire season.; in some of the southern mountains the frequency is less than 10%. The percentage of individual precipitating storms that can be seeded to enhance snowfall over the mountains also varies from north to south, but averages 40-50%. Additionally, the UCC identified some clouds (2-6% during the winter season) that may not precipitate but are nonetheless suitable for seeding; because the lifetime of these clouds may not last for more than few hours, however, measurements of SLW and seeding decisions would need to be made in real time.

The WRF forecast model with 3-km horizontal resolution is also being run by the UCC, and the cloud seeding forecast products will be available in a UCC-dedicated website (https://climate.usu.edu/cloudSeeding/index.php) in a real time. The model is initialized North American Model (NAM), four times a day. Forecasts of vertical profiles of liquid water and temperature over different mountain ranges are available in real time for forecasting periods up to 84 hours. These forecast products will provide guidance that may improve cloud seeding operation

1. INTRODUCTION

1.1. Background

Cloud seeding, the process of introducing substances that alter the microphysical characteristics within a cloud to create precipitation, has been used to augment Utah's snowpack for nearly half a century. The process is often initiated via ground-based generators that release particles into the air that enhance the concentration of ice crystals by nucleating new crystals or freezing water droplets. In Utah, this process is mainly focused on enhancing the main source of water in the western United States: natural cold-season precipitation in the mountains. Heavy winter snowfall in this region is the result of orographic effect, the forcing of air over mountain barriers, leading to cooling that can cause the air to reach the saturation point, thus forming clouds.

Orographic clouds are often suitable for seeding because they are typically quite young and rich in supercooled liquid water (SLW) as air is lifted rapidly above the condensation level. Orographic clouds are also a rather amenable target for ground-based seeding, as they are often shallow and persistent.

Two types of cloud seeding are in practice: hygroscopic (warm cloud) seeding and glaciogenic (cold cloud) seeding. Glaciogenic seeding, which is the focus on this report, uses agents, such as silver iodide (AgI), that initiate ice formation in clouds that are colder than ~-5°C and that have SLW. The fundamental hypothesis underlying the use of glaciogenic cloud seeding of orographic cloud systems is that a cloud's natural precipitation efficiency can be enhanced by converting SLW to ice upstream and over a mountain range in such a manner that newly-created ice particles, growing by diffusion (the growth of ice crystals by vapor diffusion at the expense of supercooled droplets), riming (the collection of supercooled water droplets onto an ice crystal surface) and/or aggregation (the accumulation of ice crystals in long chains), can fall as additional snow over a specified target area.

Although there have been many randomized experiments and field work focused on cloud microphysics (National Research Council, 2003; Garstang et al., 2005) the efficacy of glaciogenic seeding remains poorly understood. This was the broader motivation for two recent field campaigns. The first campaign focused on ground-based seeding: the AgI (silver iodide) Seeding Cloud Impact Investigation (ASCII) was conducted over the Sierra Madre and Medicine Bow ranges in southern Wyoming in early 2012 and 2013, respectively (Pokharel and Geerts, 2016). The second campaign, the 2017 Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment (SNOWIE-17) focused on airborne seeding (Tessendorf et al., 2019). Both campaigns collected rich airborne and radar observations to study cloud-microphysical processes. The orographic clouds sampled in both campaigns produced at least some natural snowfall, i.e. there were no ice-free orographic clouds, although a few orographic cloud layers with very few ice crystals ($<1\ L^{-1}$) were detected in SNOWIE, and these proved to be quite seedable, at least from an aircraft (French et al., 2018). The Wyoming clouds contained smaller amount of supercooled liquid water and ice than the mountains in Idaho, which gets significantly more moisture from atmospheric rivers, which are relatively long, narrow regions in the atmosphere that transport most of the water vapor from Pacific to the Western United States, bringing heavy snow or rain in coastal states and some neighboring states.

One of the key challenges to these and other experiments is that cold-season orographic clouds are not always stratiform, or layered, in nature. Indeed, the presence of conditions leading to vertical instability, such as an orographic lift of warmer rising air, may produce embedded convective clouds (e.g., Rotunno and Houze, 2007). This can create challenges for understanding the results of seeding, since the nature of a cloud affects both natural and artificially altered ice initiation, as well as snow growth processes, with depositional growth generally dominating in stratiform clouds while riming is more prevalent in convective clouds (Houze, 2014). Moreover, sometimes, typically in post-frontal situations that introduce significant cold shifts, only shallow convective clouds (those with a depth of less than ~2 km) are present over the mountains. The impact of seeding on precipitation is harder to isolate in convective clouds, because of natural variability. It also may be found only downwind of the mountain, as shown in one ASCII-12 case studies (Pokharel et al., 2014a,b), especially if the instability is released close to the mountain crest (Jing and Geerts, 2015). Most of the snowfall from stratiform clouds, meanwhile, occurs on the windward side of the mountain.

Despite the uncertainties resulting from the highly variable nature of orographic clouds, Utah is a leading state for winter orographic cloud seeding operations, with a history dating back to the mid-1970s. North American Weather Consultants (NAWC) has operated winter orographic cloud seeding programs that target mountain barriers in central and southern Utah since 1974, while most other Utah mountain barriers have been targeted since 1988. Figure 1.1 includes the mountain barriers that are target areas and the locations of ground-based silver iodide generators. This is a common strategy; most winter research and operational cloud seeding programs in the western United States, some dating back to the 1950s, have targeted mountain barriers. These barriers have considerably more snowpack accumulation than lower elevation areas to begin with, but since upwind slopes are also frequent zones of accumulation of supercooled liquid water during the passage of winter storms (Griffith, et al, 2013; Super, 1999; Stauffer, 2001) they are also ideal for glaciogenic seeding.

Cloud seeding operations in Utah are regulated by the Utah Division of Water Resources (DWRe) through legislation passed in 1973. Both a license and a permit are required to conduct cloud seeding programs in Utah. This legislation also authorized the DWRe to share costs with local sponsors, which have included other state agencies, water conservancy districts and cities. In recent years, the three Lower Colorado River Basin States (Arizona, California and Nevada) have also provided funds to augment existing winter cloud seeding programs in the three Upper Colorado River Basin States (Colorado, Utah and Wyoming) that contribute flows to the Colorado River. This augmentation has included extension of seeding operational periods and the addition of specialized equipment to these programs (e.g., remotely operated ground-based seeding generators, ground-based icing meters and microwave radiometers).

Although clouds can also be seeded via aircraft, for the winter programs in Utah, NAWC has used ground-based, manually operated silver iodide generators. These generators are generally located on the upwind sides of targeted mountain barriers usually in valley or foothill areas. Figure 1.2 is a photo of one of these generators located at Bear River City, Utah. NAWC has

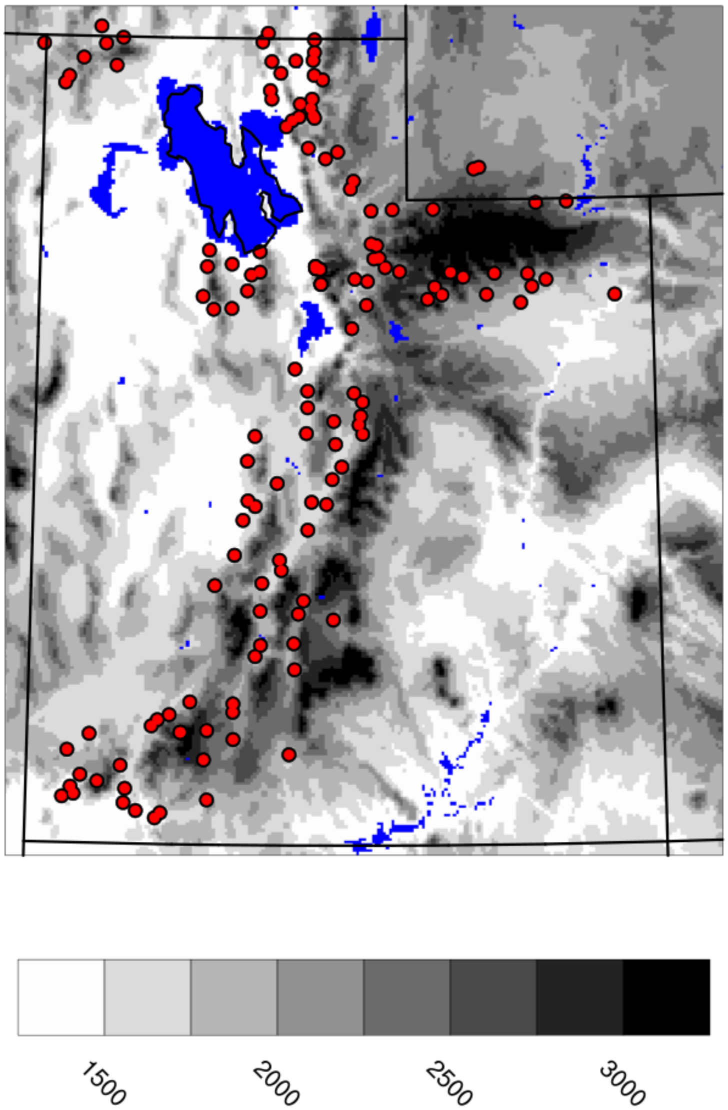

Figure 1.1: Terrain map (gray scale in m) with ground based seeding generators (red symbols) located over the upstream of mountain ranges in Utah.

installed approximately 150 of these generators in Utah. During the winter operational season, NAWC-experienced project meteorologists monitor the approach and passage of winter storms and use various tools to determine whether storms may be susceptible to seeding and which generators should be activated to impact the target areas. These tools include:

• National Weather Service (NWS) surface and upper-air observations and forecasts. Atmospheric forecasts models, like the WRF-based HRRR model, that predict precipitation, upper-level temperatures, clouds, and cloud water contents (including supercooled liquid water).

• The National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory (NOAA HYSPLIT) model, which can be used to predict the transport and diffusion of seeding materials (like silver iodide) from ground-based generators.

• Video cameras that provide views of clouds in remote locations.
Special ground-based icing rate meters at high elevation remote locations that can detect the presence of supercooled liquid water in real-time.

• The Utah Division of Water Resources, working with NAWC, has also developed seeding suspension criteria in order to identify periods when seeding should not be conducted (e.g., flood events). NAWC project meteorologists suspend seeding when any of the suspension criteria are met.

Despite these significant investments and processes, there have been persistent questions as to whether cloud seeding, as currently implemented, is effective.

Earlier research in the Wasatch Mountains indicated that significant liquid water does exist during winter to support seeding (Huggins, 1995; Sassen and Zhao, 1993; Sassen et al., 1990). Other studies have shown that ground-based seeding generators located on the windward side of the Wasatch Plateau appeared to be a more reliable transport of silver iodide material over the Wasatch Plateau than valley-based generators (Super, 1999; Huggins and Sassen, 1990), possibly because boundary layer inversions are common in several Utah valleys during winter, thus seeding plumes may not reach the target area if they are below the inversion layers. However, given the substantial variables at play, none of this work was sufficient to put to rest the myriad questions about cloud seeding effectiveness.

In the past decade, however, new developments in observational and computer modeling approaches have laid the foundation to advance the state of the science regarding cloud seeding (Xue et al. 2013a,b, Geerts et al., 2013, Tessendorf et al., 2015, Pokharel and Geerts, 2016, Pokharel et al., 2017, 2015; French et al., 2018, Rasmussen et al., 2018, Tessendorf et al., 2019, Rauber et al., 2019; Flossmann et al., 2019). Intriguing results from recent projects like SNOWIE (Tessendorf et al., 2019) have showed that, in the right conditions, cloud seeding with AgI does effectively enhance ice crystal production and local precipitation (French et al., 2018, Tessendorf et al., 2019). This has the potential to spur new interest in operational cloud seeding. However, there is still a critical need to evaluate the conditions that are most amenable for effective cloud seeding. That is the main objective of this study.


Figure 1.2: Cloud seeding generator that is located at Bear River City, UT turn on during the suitable seeding condition targeting the orographic clouds over the mountain.

1.2. Objective

The success of cloud seeding depends on the accurate identification of favorable atmospheric conditions, including the presence of supercooled liquid water and cloud temperatures suitable for silver iodide seeding. Because the tools available to conduct real-time measurements of these atmospheric variables are very limited, forecast models are relied upon to make seeding decisions during operation periods. The result is a high degree of uncertainty as to whether these seeding operations are having the desired effect.

The goals of this study are to estimate the frequency in which atmospheric conditions are amenable to cloud seeding throughout Utah, and to develop a high-resolution, real-time operational forecast model to provide forecast products geared toward cloud seeding decision making. Thus, in this report, the UCC will seek to address these research questions:

I. *How often do suitable conditions occur in winter clouds over Utah's mountains?*

II. *Does the high-resolution model provide useful seeding guidance?*

Since Utah has multiple mountain ranges with different orientations, the proposed objectives cannot be generalized to cover every range. Also, because many ranges are quite large and diverse, even a contiguous range may not be suitable for a singular description of ideal seeding conditions. As such, for the purpose of this study, the UCC has separated the state's mountains into four regions and 24 smaller range segments to offer greater specificity of relevant average atmospheric conditions. (This is further explained in Section 1.3.)

The Utah cloud seeding program has utilized various models to guide seeding operations, but models that are built with a specific focus on Utah's diverse climate and geography, along with higher resolution, may be useful, particularly to North American Weather Consultants (NAWC), which has been the major consultant for cloud seeding operations in Utah for several decades. Additionally, this high-resolution model might be utilized to benefit farmers, ski resort operators, water managers, and other stakeholders.

1.3. Mountain Ranges

Utah's mountain ranges are located from north to south and east to west with unique orientations and several parallel mountains and valleys. Existing cloud seeding programs cover most of these ranges, and this study considers a few other ranges that are not currently being targeted for seeding. (A topographical map including the targeted mountain ranges is included in Figure 1.3. and location details are given in Table 1.1) The top elevations of these ranges varies from about 6,000 feet to higher than 13,000 feet from mean Sea Level (MSL). The higher peaks are generally located in the Northern and Uinta regions while the Southern mountains tend to have lower elevations. In addition to this geographical and topographical variability, these mountain ranges experience different weather conditions related to suitable seeding conditions (e.g. supercooled liquid water, temperature, and precipitation).

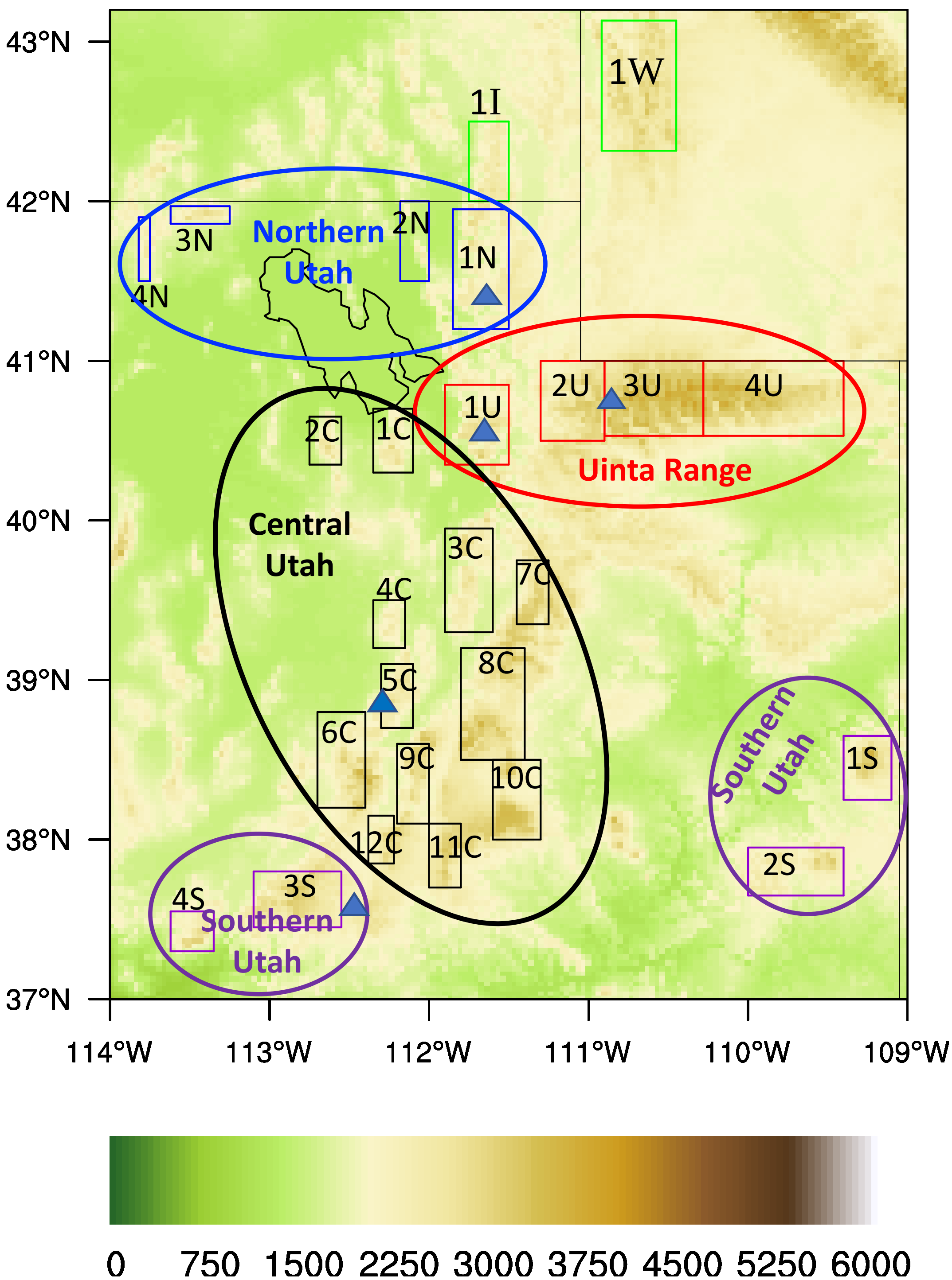

Figure 1.3: Utah Mountain ranges separated for this study to find the seeding condition. The ranges are divided into 24 mountains and 4 regions in Utah and also included two ranges from Idaho (1I) and Wyoming (1W). The Northern Utah mountains are divided into 4 ranges (1N-4N), Uinta mountain into 4 ranges (1U-4U), Central Utah mountains are divided into 12 ranges (1C-12C), and Southern Utah mountains are into 4 ranges (1S-4S). Blue triangles show the location of SNOTEL sites that are used to compare with model precipitation.

TABLE 1.1: Utah mountain ranges targeted to develop the suitable cloud seeding condition climatology

target mountain region	name/location	number	latitude	longitude
northern Utah	East of Cache Valley	1N	41.2-41.95N	111.85-111.5W
	West of Cache Valley	2N	41.5-42N	112.18-112W
	North of West Box Elder	3N	41.86-41.97	113.62-113.25
	West of West Box Elder	4N	41.5-41.9	113.85-113.75W
Uinta	Wasatch	1U	40.35-40.85N	111.9-111.5W
	West Uinta	2U	40.5-41N	111.3-110.9W
	Central Uinta	3U	40.53-41N	110.9-110.28W
	East Uinta	4U	40.53-41N	110.28-109.4W
Central Utah	East of Toole	1C	40.3-40.7N	112.35-112.1W
	West of Toole	2C	40.35-40.65N	112.75-112.55W
	East of Mona	3C	39.3-39.95N	111.9-111.6W
	East of Oak City	4C	39.2-39.5N	112.35-112.15W
	South of Oak City	5C	38.7-39.1N	112.3-112.1W
	East of Monroe	6C	38.2-38.8N	112.7-112.4W
	East of Mt. Pleasant	7C	39.35-39.75N	111.45-111.25
	South of Mt. Pleasant	8C	38.5-39.2N	111.8-111.4W
	East fo Piute	9C	38.1-38.6N	112.2-112W
	East of Loa	10C	38-38.5N	111.6-111.3W
	North of Garfield	11C	37.7-38.1N	112-111.8W
	West of Garfield	12C	37.85-38.15N	112.38-112.22W
Soutehrn Utah	East of Moab	1S	38.25-38.65N	109.4-109.1W
	San Juan	2S	37.65-37.95N	110-109.4W
	East of Cedar City	3S	37.45-37.8N	113.1-112.55W
	North of St. Goerge	4S	37.3-37.55N	113.65-113.35W
Idaho	East of Preston	1I	42-42.5N	111.75-111.50W
Wyoming	East of Afton	1W	42.317-43.133N	110.917-110.450

The state's cloud seeding programs run during the winter season, from November 1 to April 30, with some programs running for longer periods than others when suitable conditions exists. In general, because the Northern Region gets colder weather than the Southern Region, cloud seeding operations can be expected for longer periods in the north, while the mountain in the Central Region will fall in between.

The majority of the ground-based generators for these programs are located on the upwind sides of mountain barriers, targeted for southerly to westerly wind flow. A few generators, however, can be found on the lee of the mountains to take advantage of conditions in which upslope flow occurs opposite the prevailing wind flow, thus allowing seeding operations to run throughout a greater diversity of wind conditions.

As previously noted, because considering one major mountain barrier to be representative of all of Utah mountains would likely be vastly misleading, these ranges were separated into 24 range segments (small boxes in Figure 1.3) and four regions (ovals/circles in Figure 1.3). Since some of these areas did not have universally used names, descriptors were based on directionality from nearby municipalities or counties, and assigned a number (as shown in Table 1). This simplified the process for providing detailed information for each barrier.

Most mountain ranges in Utah are oriented north-to-south, while the Uintas and some of the southern mountains have different orientations (Griffith, et al, 2013). The Uinta mountains, for instance, have an east-west orientation, with the majority of current seeding generators located on the south side of the mountains.

1.3.1 Northern Region

The UCC has considered four range segments that are located in Northern Utah. The barriers have been named East of Cache Valley (1N), West of Cache Valley (2N), North of Box Elder (3N), and West of Box Elder (4N). 1N, 2N, and 4N have north-south orientations while 3N is oriented east-west. All northern Utah mountains are located around the same latitude, but 3N and 4N are smaller in size than 1N. Meanwhile, 2N has uniquely steeper slopes on both windward and leeward sides.

1.3.2 Uinta Region

The Uintas are unusual due to their east-west orientation. These mountains also include the state’s highest point of elevation, Kings Peak, with an altitude of 13,528 feet (4,123 meters) MSL and are the most poleward range in the world that rises above 13,000 feet but has no modern glaciers. Because the Uintas span about 100 miles, the range may experience different atmospheric conditions from east to west. Consequently, the UCC chose to divide this range into four segments; Wasatch (1U), West Uinta (2U), Central Uinta (3U) and East Uinta (4U) (Figure 1.3).

1.3.3 Central Region

The Central Region separated into 12 range segments of varying sizes. Most of the mountain barriers are oriented north-south. This region includes two mountain barriers located on the west of Salt Lake City; East of Tooele (1C) and West of Tooele (2C). The mountain segments to the south of Provo are named East of Mona (3C), East of Oak City (4C), South of Oak City (5C), East of Monroe (6C), East of Mt. Pleasant (7C), and South of Mt. Pleasant (8C). The other mountain barriers, located further south, are named East of Piute (9C), East of Loa (10C), North of Garfield (11C), and West of Garfield (12C). The height of these mountain barriers varies from 8,000 to higher than 11,000 feet MSL.

1.3.4 Southern Region

Four mountain barriers were chosen from southern Utah that are located in the southeast and southwest corners of the state (Figure 1.3). The orientation of the southeast mountains is north-south for the barrier named East of Moab (1S) and east-west for the barrier named San Juan (2S) while both of the southwest barriers are orientated northeast-southwest, including East of Cedar

City (3S) and North of St. George (4S). The highest peaks in these mountains are higher than 10,000 feet MSL.

1.4. Definition of Suitable Seeding Conditions

Identifying atmospheric conditions that represent suitable seeding situations over Utah's mountains is critical to the production of positive seeding impacts. Liquid water that forms over the mountain when the orographic flow of an air parcel reaches saturation level (lifting the condensation level) is the primary ingredient in this complex recipe. The presence of water, however, is not enough: Cloud temperature is critical to convert those liquid droplets into ice when silver iodide is injected into the clouds. AgI has been shown to activate at temperatures as warm as -5^{o}C (DeMott 1995, 1997) but the activation rate doubles from that level at temperatures of -8^{o}C (DeMott 1997). At present, however, it is not possible to measure the liquid water content and cloud temperature of every cloud over every barrier. Thus, regional and global forecasting models must be used, and the resolution and accuracy of the measured variables are critical for seeding decisions. While other atmospheric and cloud conditions, including low-level stability, may impact the effectiveness of ground-based seeding, this study aims to identify suitable seeding climatology regardless of seeding technique.

A prediction of the distribution of liquid water in winter orographic clouds can be obtained from the proposed forecasting model, potentially providing guidance for cloud seeding decision making in advance of the cloud's arrival over seeding generators and mountain barriers. The model also offers an estimate of the vertical profile of liquid water and temperature. The cross-sections that are shown in Figure 1.4 covers most of the Utah mountains and a few mountains from neighboring states (Idaho and Wyoming).

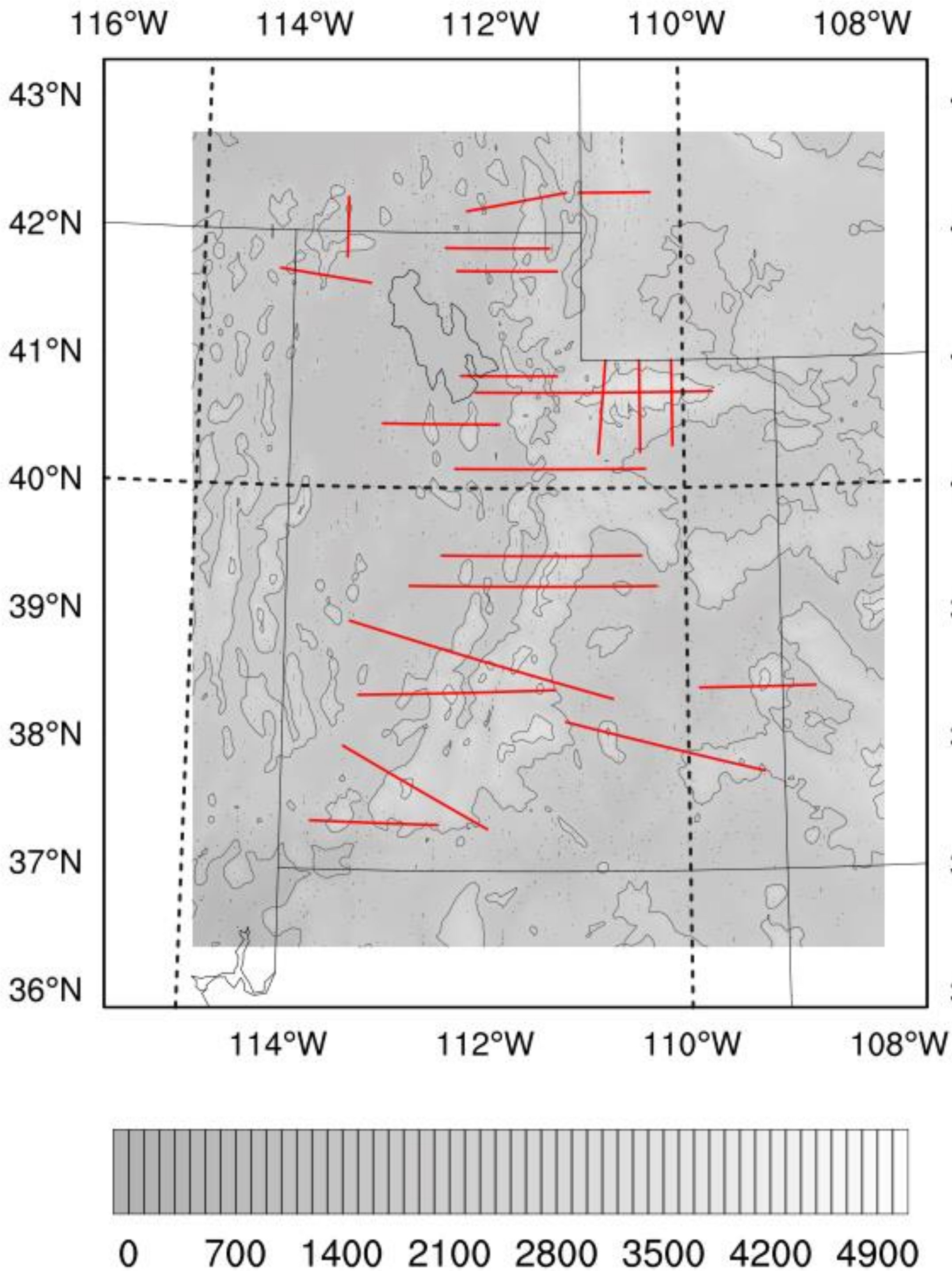

Figure 1.4: Cross-sections used for the WRF model forecast of vertical profile of liquid water and temperature over different mountain ranges.

2. DATA AND METHODOLOGY

2.1. Data Sources

The main data used in this study come from the Weather Research and Forecasting (WRF) model that was run by NCAR (Liu et al., 2016). The NCAR simulation has 4 km horizontal resolution with 51 vertical levels and covers the period from October 2000 to September 2013. The model covers the Continental United States (CONUS, hereafter called NCAR CONUS) and has all the variables UCC needed to pursue the objectives of this study, with 2-D data that included precipitation and vertically integrated super-cooled liquid water, data for which are available in 1 hour temporal resolution. The 3D data, meanwhile, including temperature and winds, are available in 3-hour temporal resolution.

Data from radiosondes that were launched from Salt Lake City from 2000 to 2013 were utilized to validate the NCAR CONUS simulated temperature, with a focus on the temperature at 700 mb altitude. More than 3,900 soundings were considered to compare the simulated 700 mb temperature with observed values. A comparison of precipitation between NCAR CONUS data and observations has been conducted in different studies (Liu et al., 2017; Prein et al., 2017). The UCC also considered SNOTEL data from five stations (shown by triangles in Figure 1.3) that cover southern to northern Utah mountain ranges to evaluate the model-simulated precipitation over the mountains in Utah. The SNOTEL data were used to validate the WRF precipitation during the seeding season for the given period. (Results are discussed in the next section.)

2.2. Methodology used to define suitable seeding conditions

The factors that permit suitable ground-based glaciogenic seeding conditions include temperature, liquid water, wind speed and direction, and stability. However, the amount of liquid and temperature ranges deemed suitable vary in different studies (Griffith et al., 2013; Breed et al., 2014; Pokharel et al., 2016). In western U.S. mountains, natural orographic clouds tend to have low ice crystal concentrations at temperatures warmer than -15^{o}C (DeMott et al., 2010), although secondary ice formation and blowing snow may contribute significant additional ice crystals (Geerts et al., 2015). Silver iodide (AgI) can be activated at temperatures as warm as -5^{o}C (DeMott 1995; DeMott 1997) and the activation rate increases by two orders at a temperature of -8^{o}C (DeMott 1997). AgI seeding creates more ice nuclei in clouds which have abundant supercooled droplets but low ice crystal concentrations. The additional nuclei can convert existing supercooled liquid droplets into ice crystals by diffusional growth, and riming and aggregation.

The recent randomized seeding program known as the Wyoming Weather Modification Pilot Program (WWMPP) used a 700 mb temperature of -8^{o}C or colder to perform the seeding experiments (Breed et al., 2014) while another recent field campaign, the AgI Seeding Cloud Impact Investigation (ASCII), used a 700 mb temperature of -5^{o}C (Pokharel and Geerts, 2016). Utah’s barriers have varying heights and orientation, such that a single threshold may not be applicable. For example, for a few Utah barriers, the 700 mb level could be above the mountain crest, while for others it could be below the crest. If the 700 mb level is above the mountaintop then orographic cloud bases could be warmer than the 700 mb temperature (-5^{o}C). In that case, this higher temperature may not be the right threshold, although storms with embedded convection may loft the AgI seeding material to higher, colder levels where the AgI would be effective. Lacking embedded convection, however, it may be appropriate to consider the colder temperature (-8^{o}C) criteria. The opposite may be true for the higher barriers, where the mountaintop height is above the 700 mb level. In this case, the warmer threshold (-5^{o}C) may be appropriate. Many operational winter cloud-seeding programs utilize a temperature threshold warmer than that used in the WWMPP research program (Griffith et al., 2013, 2009). UCC utilized both temperature threshold in this analysis.

2.3. Methodology developed to improve cloud seeding operations: Forecast Model

Because cloud seeding operations have been conducted for many decades in Utah, seeding operators (mainly NAWC) have used different atmospheric models to inform operational decisions. Most recently, NAWC has used the High Resolution Rapid Refresh (HRRR) model, which provides forecasts out to 18 hours. The UCC's Utah Focused High Resolution Forecasting Model would provide better temporal and spatial coverage. UCC is running a WRF model that is initialized four times a day (00Z, 06Z, 12Z, and 18Z) with 3-hourly forecasts out to 84 hours. The WRF is being run on a server in the University of Utah's Center for High Performance Computing. The model is running with 2 km horizontal resolution (convection permitting) with 45 vertical levels, and output data are available with 3-hourly temporal resolution. The model is downscaled from the North American Model (NAM) to 2 km, covering all of Utah (and some parts of the neighboring states, providing a buffer area outside the main target regions for a smooth transition for the model).

2.3.1. Cross-sections over different mountain segments

The UCC selected multiple cross-sections over each of the segments in Utah to provide forecasts of vertical profiles of temperature and supercooled liquid water distributions. The selected segments with cross-section locations are shown in Figure 1.4. Forecasting of supercooled liquid water and temperature along these cross-sections is available in 3-hour increments out to 84 hours. The forecasts of liquid water have not been validated versus independent data sets, such as those available from microwave radiometer observations, but these cross-sections can be modified in the future upon request from DWRe or NAWC. The cross-sections can be used to depict temperature and the vertical profile of liquid water. Temperatures colder than -5^{o}C at 700 mb are used as a threshold by NAWC but, to offer greater flexibility given the variability of this threshold, five temperature lines are plotted in each cross-section including 0, -5, -10, -15, and -20^{o}C. Additionally, potential temperature lines are plotted to depict the mountain waves and flow patterns over these segments.

3. OBSERVATIONS AND MODEL DATA COMPARISON

3.1. Precipitation

The NCAR CONUS data have been used extensively to study precipitation and have been validated, but have not previously been used for cloud seeding research. To apply this data, UCC compared the model precipitation data with SNOTEL data from the different mountain segments across Utah. UCC additionally considered five SNOTEL sites to compare with WRF simulation. The information of SNOTEL stations and average precipitation from WRF and SNOTEL is given in Table 3.1. UCC then considered daily data and calculated the cumulative precipitation from November 1 to October 31 for each year from 2000-01 to 2012-13. The location of the SNOTEL sites are shown in Figure 1.3. The comparison of SNOTEL with WRF revealed a mixed result indicating a wet bias (in which the WRF shows more precipitation than SNOTEL) over the northern mountains and a dry bias (in which WRF shows less precipitation than SNOTEL) in the southern mountains, as shown by Liu et al. (2017) in previous study. However, a comparison of the average value over these mountain segments shows good agreement (Figure 3.1).

Table 3.1: Five SNOTEL sites location and altitude. These sites are used to compare with WRF model precipitation during winter season (Nov-Mar) from 2000/01 to 2012/13 period. Average values of WRF precipitation and bias from observation (SNOTEL) are also given.

station	**lat**	**lon**	**elevation**	**precipitation, mm (Nov-Mar)**			
			(ft)	**SNOTEL**	**WRF**	**WRF bias, %**	**bias**
Trial Lake	40.68	-110.95	9992	449	495	20	wet
Agua Canyon	37.52	-112.27	8900	226	225	0.3	no bias
Horse Ridge	41.32	-111.45	8199	341.5	394	15	dry
Brighton	40.60	-111.58	8766	412	440	7	dry
Pine Creek	38.88	-112.25	8734	288	258	11	dry

The WRF precipitation data were used to calculate the long-term average winter precipitation from November to March over Utah, as shown in Figure 3.3a, showing the greatest precipitation over mountains and, in particular the northern mountains. Among all of the segments studied, those in the Uinta Region get the most precipitation, and a greater snowpack, because of that region's different orientation and significant height, which produces large orographic clouds in westerly, south easterly to northerly winds.

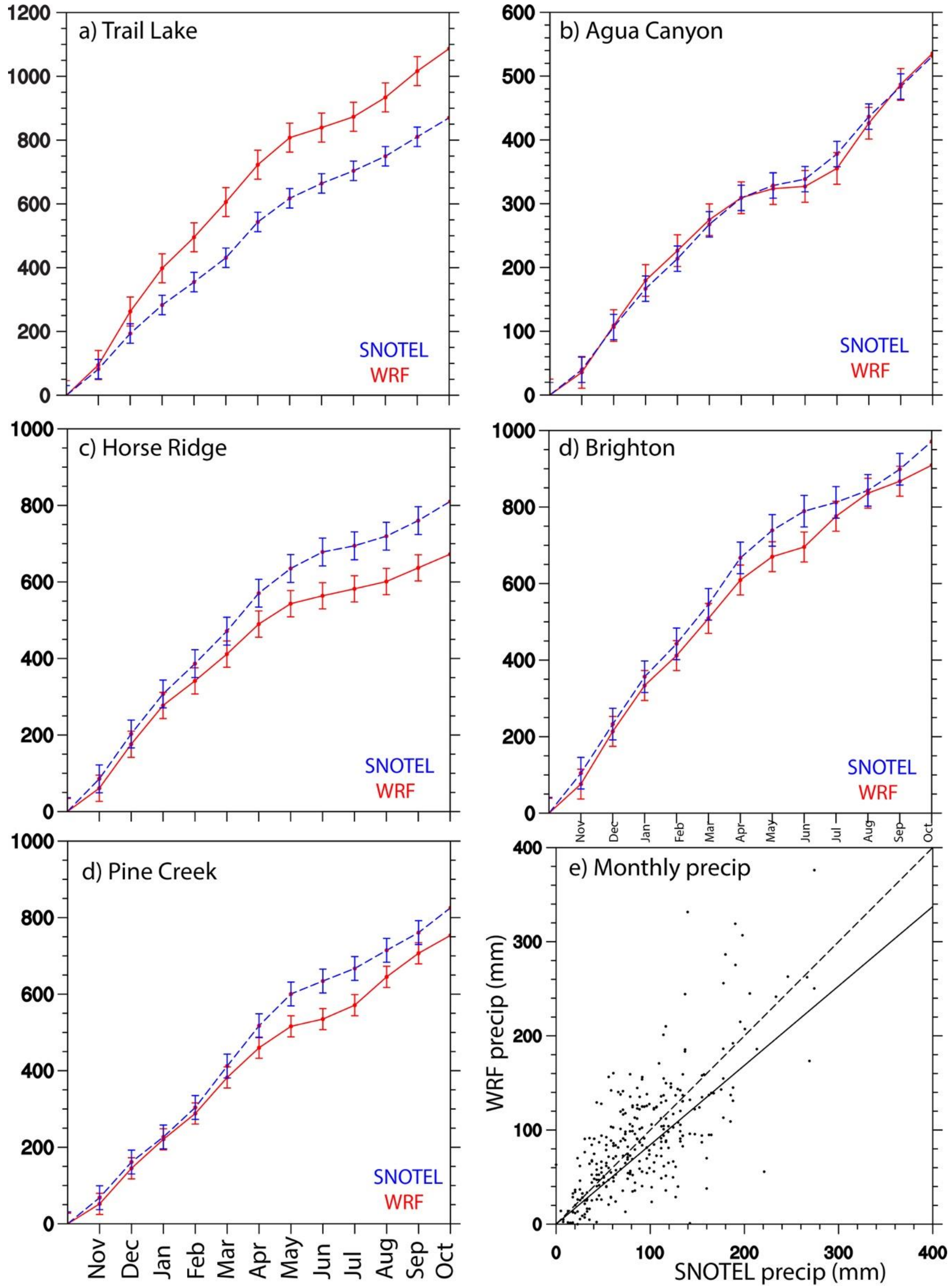

Figure 3.1: Comparison of precipitation between WRF and SNOTEL data over four different locations in Utah mountains.

3.2. Temperature

Temperatures in the NCAR CONUS data were validated against the 700 mb temperature based on radiosonde sounding data from 2000 to 2013. The model data is highly correlated with observations (r^2=0.96, Figure 3.2a), however the model shows a slightly warm bias during colder atmospheric conditions. In warmer temperatures, meanwhile, the model shows a small cold bias. This opposite bias could be associated with frontal passage timing that may not be captured by the WRF. The plot between temperature difference in the observation-model vs. observed temperature is shown in Figure 3.2b. Since the temperature produced by NCAR CONUS almost perfectly matched with observation, UCC did not apply any bias correction on temperature data. However both -5 and -8^{o}C thresholds are considered for the suitable seeding condition evaluation. These two results indicate how much seeding conditions may vary. Because some peaks are above 700 mb, UCC further looked the model data for temperature from the surface to 1,000 meters across Utah. The average temperature during winter over Utah is shown in Figure 3.3b. The distribution of lower level (surface to 1,000 meters above ground level (AGL)) atmospheric temperature, for instance, clearly shows that the Uinta region is much colder than other regions.

3.3. Liquid water

A comparison of liquid water estimates with observations is critical to validate the model since SLW is major component for glaciogenic cloud seeding. SLW measurements were not available from Utah during the NCAR CONUS simulation period, but radiometer-measured liquid water data were available at Moab and Roosevelt from the winter of 2017/18 and the winter of 2018/19. (Additional liquid water data was being collected by the NAWC from Brian Head during winter of 2019/20.) The radiometer data from Roosevelt will be compared with a new WRF simulation that is being planned during 2020.

Previous measurements using radiometer and polarization lidar (Sassen et al., 1990; Huggins, 2007) have shown that SLW exists more than 50% of the time in winter orographic clouds formed over the mountains in Utah. Sassen et al. (1990) also found that existing ice crystals in orographic clouds may not always consume available SLW, resulting in precipitation. This supports the cloud seeding hypothesis that by injecting more ice nuclei into the clouds, the abundant supercooled droplets will be more easily converted into ice, bolstering the natural precipitation processes. The NCAR CONUS model simulated average liquid water during the winter, (November through March,) showing higher values over the mountain segments, with the greatest values over the northern mountains (Figure 3.3c). There were also greater values for north-south oriented mountains than east-west oriented mountains, such as those in the Uinta Range, even though the Uintas are much colder and taller with a higher precipitation range. This indicates that dominant westerly winter winds produce less liquid water over the Uintas, especially over the eastern segment of that region.

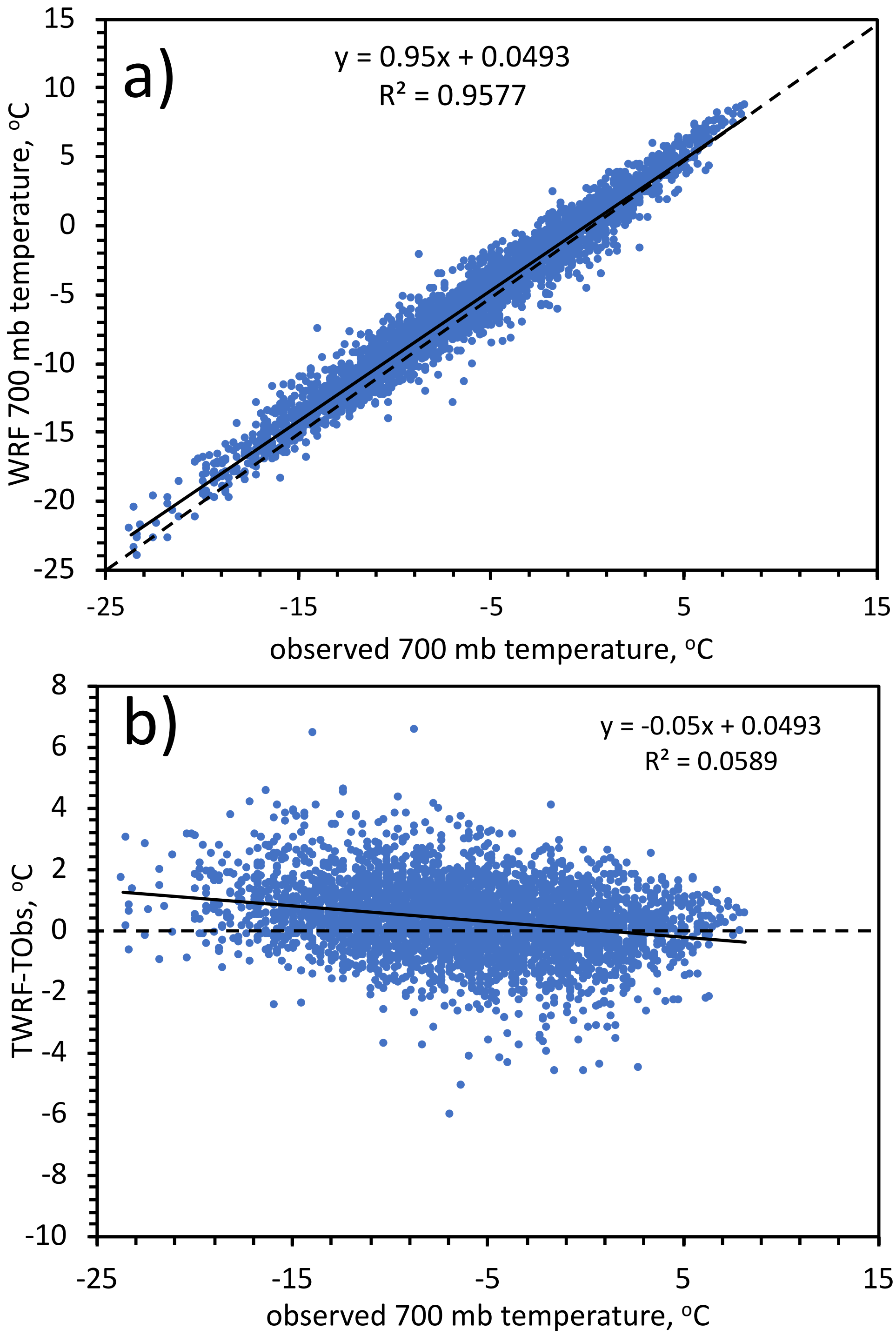

Figure 3.2: Comparison of 700 mb temperature measured by sounding that was released from Salt Lake City, Utah with WRF temperature at 700 mb level. The data are used from 2000 to 2013 for the months of November to February from 3850 soundings. Upper panel a) shows the scatter plot of observation vs. WRF data and lower panel b) shows the observation temperature vs. WRF bias (WRF-observation). Solid line in both panels shows the linear regress line and dashed line in upper panel is one-to-one line and in lower panel is the line for zero value or no bias line.

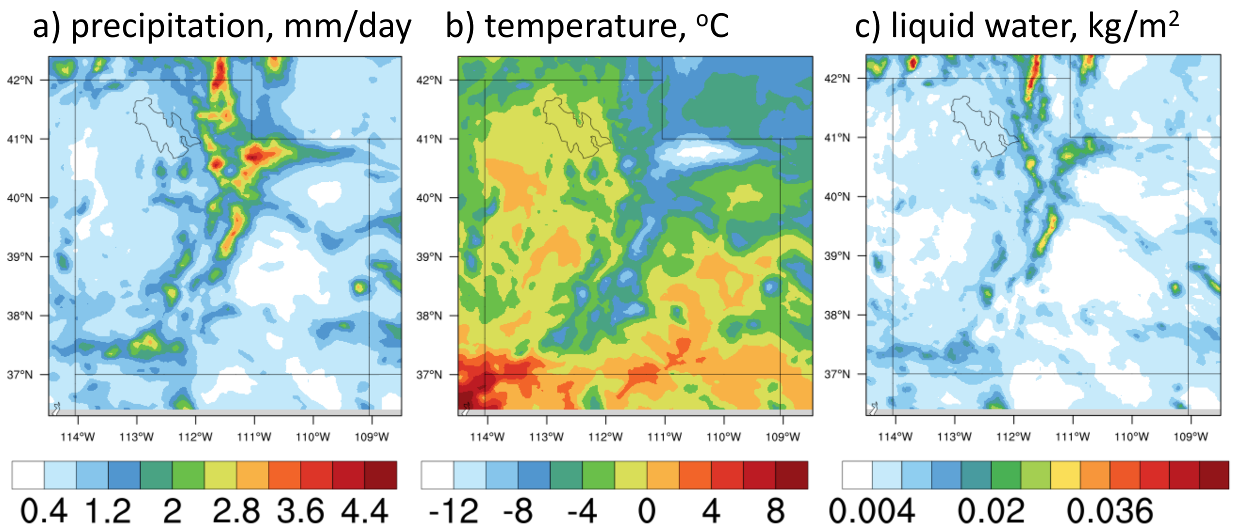

Figure 3.3: Average precipitation in mm/day (a), surface to 1 km above ground level (agl) in ^{o}C (b) and vertically integrated cloud liquid water in kg/m^2. These average values are calculated from NCAR WRF simulation considering data from 2000/01 to 2012/13 winter season (5 months, November to March).

4. ATMOSPHERIC CONDITIONS OVER DIFFERENT MOUNTAIN RANGES

4.1. Mountain Level Temperature

As noted, AgI has been shown to activate at temperatures as warm as -5°C (DeMott 1995, 1997), with a doubled effect by -8°C (DeMott 1997). However, in very cold clouds, additional ice nuclei may not increase precipitation efficiency since the concentration of effective natural ice nuclei increases exponentially with decreasing temperatures. As such, clouds that are colder than -15°C (~700 mb) or cloud top temperatures that are colder than ~ -25°C are not suitable for seeding. (Griffith, et al, 2013). There is, however, no agreement on what the lower threshold cut-off point is, and storms at these extremely low temperatures at 700 mb are rare.

The UCC calculated the frequency of instances when temperatures reach the appropriate thresholds over the mountain segments. The frequency of given temperature thresholds is calculated for each box during the winter season, as shown in Figure 1.3. The 700 mb temperature that is defined as the mountain level temperature was colder than -5°C more than 55% of the time over the northern Utah mountains and Uinta Range, a bit less than half the time in the central Utah segments, and less than 40% over the southern mountains (Figure 4.1a). The frequency is lower at the -8°C temperature threshold, with the 700 mb temperature reaching that threshold 35% of the time in the northern Utah and Uinta Range, while the central and southern mountains reach that threshold less than 30% of the time.

For individual segments, the highest frequency of reaching the -8°C threshold was observed over the Uinta mountains, while the southern mountains (north of St. George, 4S in Figure 1) had the lowest frequency (~17%) for reaching this threshold.

The monthly distribution of the average frequency of temperatures colder than -8°C (-5°C) for mountain ranges over the four regions are shown in Figure 4.2a (Figure 4.2b). While February had the greatest frequency, the difference between that and December, January and March was not significant.

4.2. Supercooled Liquid Water (SLW)

The most important atmospheric variable for glaciogenic seeding is supercooled liquid water, and orographic flow produces SLW in both precipitating and non-precipitating clouds. The presence of SLW, however, depends on other factors including windspeed, boundary layer turbulence, mountain slope and height, and the presence of ice nuclei/ice particles. Orographic clouds that are located far from the direct source of ice nuclei (for instance, dust from Utah's west desert) have more supercooled droplets than nuclei, and thus are prime for seeding.

The frequency (and amount) of SLW varies significantly in Utah's mountains, as shown in Figure 4.1b (and Figure 3.3c). The frequency of SLW is calculated considering all five months (November through March) irrespective of cloud presence or precipitation. The Northern and Uinta regions have SLW more than 30% of the time during the winter while the Southern Region includes SLW around 20% the time. The Central Region has SLW about 30% of the time however the number varies for individual segments within each region. It should be noted that year to year variation of SLW is significant and dependent on seasonal changes in atmospheric conditions or moisture sources.

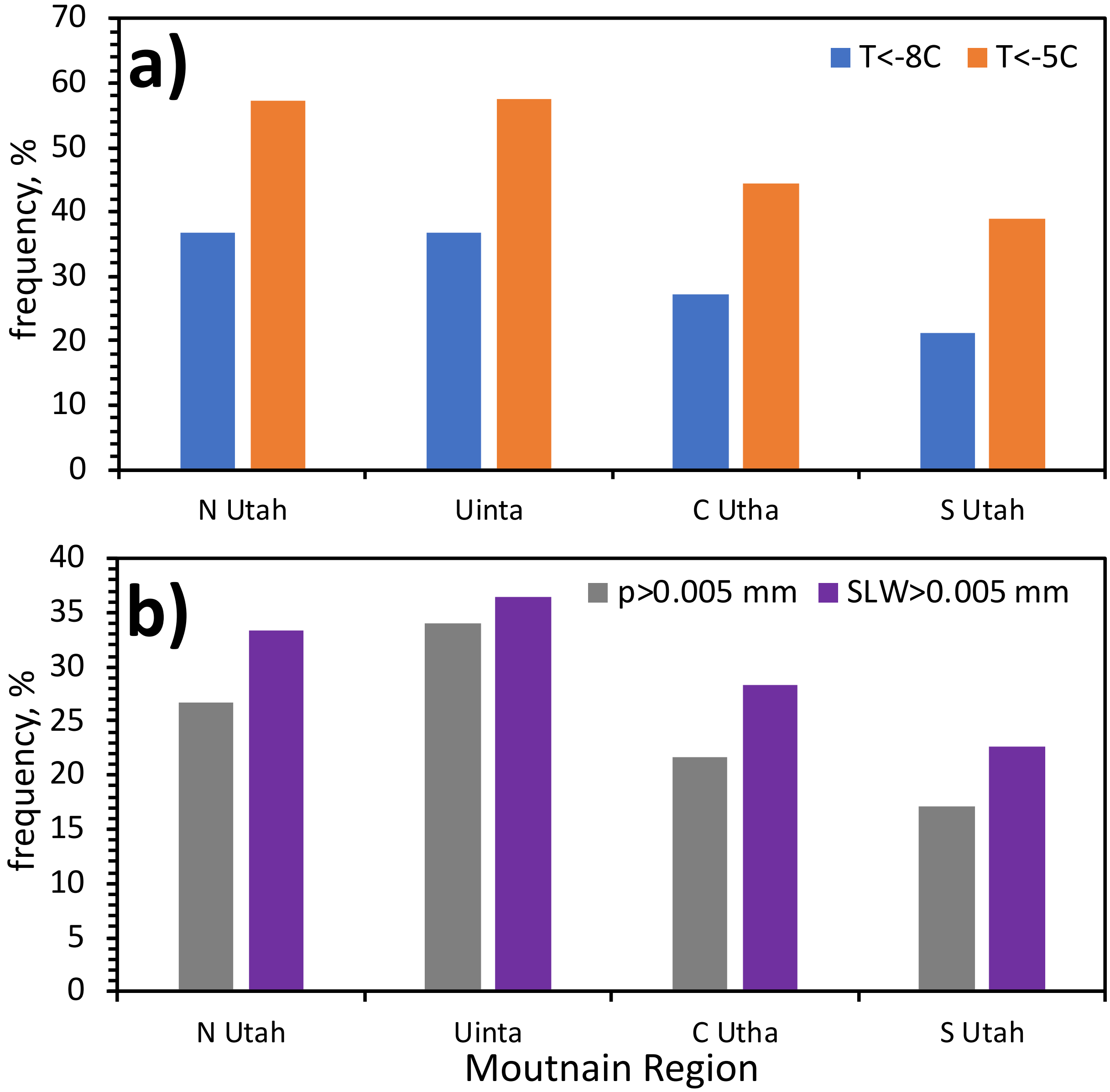

Figure 4.1: Average atmospheric condition over different mountain regions (given in Figure 1 and Table 1) based on the 13 years WRF simulation from November to March. Upper panel a) shows the Frequency of 700 mb temperature for less than -5 ^{o}C (orange) and -8 ^{o}C (blue), and lower panel b) shows the frequency of precipitation (>0.005 mm/hr, gray) and supercooled liquid water (SLW, purple).

4.3. Precipitation

Similar to SLW, precipitation frequency also decreases from north to south over Utah's mountains (Figure 4.1b). However, the precipitation frequency is less than the SLW frequency and this is consistent for all mountain segments. This indicates that not all clouds with SLW produced precipitation. More frequent precipitation (~35% of the winter season) occurs over the Uinta Region while the Northern Region receives precipitation ~26% of the season. The Central and Southern Regions, meanwhile, get precipitation for about 22% and 18% of the winter season, respectively. The monthly distribution of precipitation frequency (Figure 4.2b) shows that precipitation occurs more frequently in December in the Northern and Uinta regions, shifting to be dominant over the Central and Southern regions in February. November has the lowest precipitation frequency for all regions and the other two months have about the same frequency of precipitation. The precipitation frequency also varies from year to year and the interannual variation of precipitation frequency is observed for all measured precipitation (SNOTEL data) as well. This variation is consistent for all mountain ranges that show similar year-to-year variations. Since there is only 13 years of model data, however, the above conclusions may not be climatologically representative.

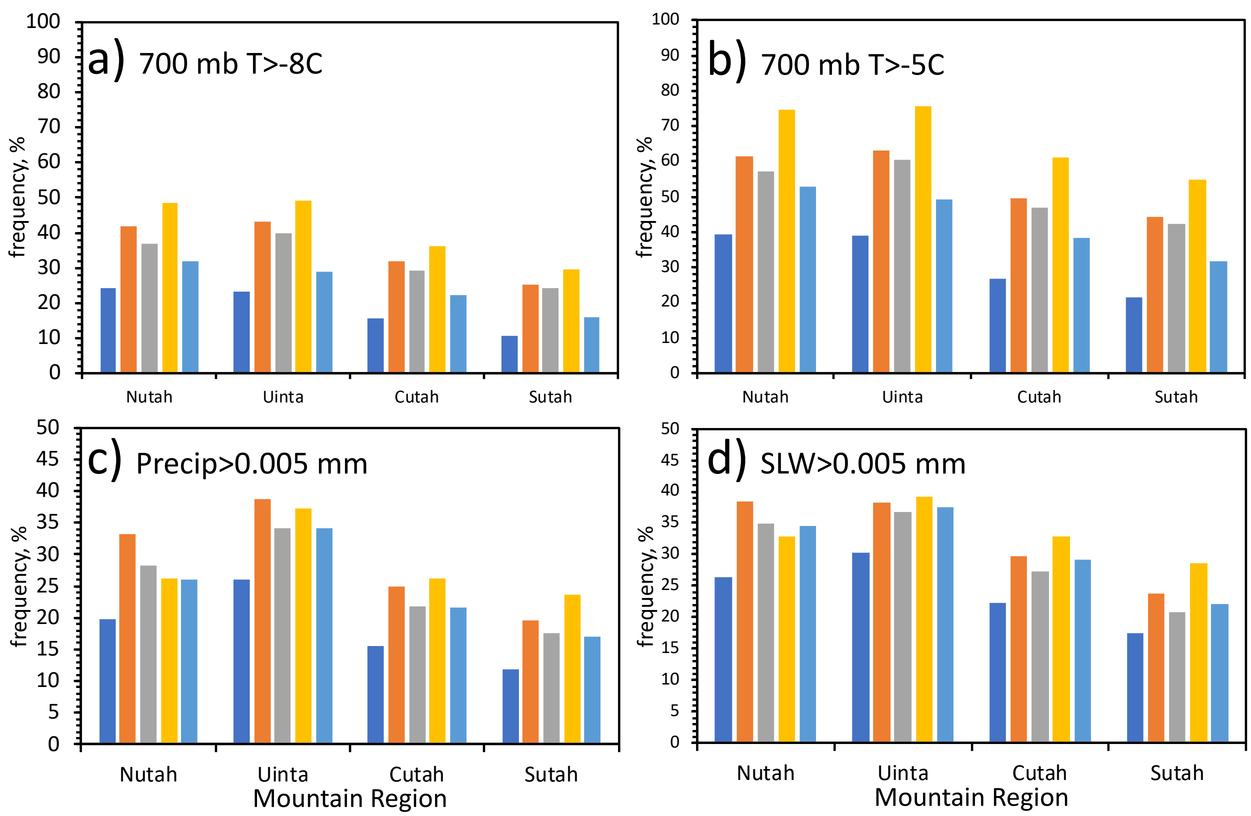

Figure 4.2: Monthly average atmospheric conditions frequency that are calculated from 13-years WRF data over four regions in Utah. Upper left panel a) shows the frequency of 700 mb temperature colder than -8°C, upper right panel b) shows the frequency of 700 mb temperature colder than -5°C, lower left panel c) shows the frequency of precipitation larger than 0.005 mm/3hr, and lower right panel d) shows the frequency of SLW larger than 0.005 mm.

5. SEEDING CONDITION EVALUATION

5.1. Suitable Seeding Conditions Climatology

The suitable seeding conditions are calculated considering two temperature thresholds in addition to the presence of SLW as discussed in Section 2.2. Both temperature thresholds (colder than -5 and -8C) are considered at 700 mb level for each of the individual mountain segments. The average suitable seeding condition for each region is shown in Figures 5.1 and 5.2. However the suitable seeding condition frequency for individual mountain segments (Figure 1.3) are shown in Figures 5.3 and 5.4 considering all winter months and considering precipitation period only, respectively. Results from both temperature thresholds of -8^{o}C and -5^{o}C are shown in left and right panels in Figures 5.3 and 5.4, respectively. The year-to-year variations are significant and correspond to dry and wet winter years in Utah. Although interannual and monthly variation of suitable seeding conditions were evaluated over each mountain segment, the discussion is focused on the four regions (Figure 1.3).

5.1.1. Northern Region

The Northern Region shows high potential for winter orographic seeding (Figure 5.1), with suitable seeding conditions covering about 25% of the winter season at the -5^{o}C 700 mb threshold or 16% at the -8^{o}C threshold. It should be noted that these numbers are calculated based on two variables (temperature and SLW) relative to all winter periods in five months (November through March). This rate will, of course, vary from month to month and year to year, and it is important to note that low-level stability has not been considered in this analysis; inversions would likely impact ground-based seeding in some situations. According to this analysis, November has the lowest frequency for all the regions for both temperature thresholds (Figure 5.2) while all regions have the highest suitable seeding condition frequency in either December or February. The UCC additionally looked at the frequency of suitable conditions considering only precipitation periods. This showed about 60% and 40% of precipitating storms are suitable for glaciogenic seeding when the temperature is colder than -5^{o}C and -8^{o}C, respectively.

According to the UCC's analysis, the segment located east of Cache Valley (1N) showed a high potential for seeding, at about 20% (30%) of all periods (Figure 5.3a,b) and 57% (72%) of precipitating storms (Figure 5.4a,b) for temperature threshold -8^{o}C (-5^{o}C). The other three northern region segments (2N, 3N, and 4N) also showed significant suitability for seeding, at 13-19% of all periods and 52-56% of precipitating clouds for temperature threshold -8^{o}C. This will be further discussed in the following sections.

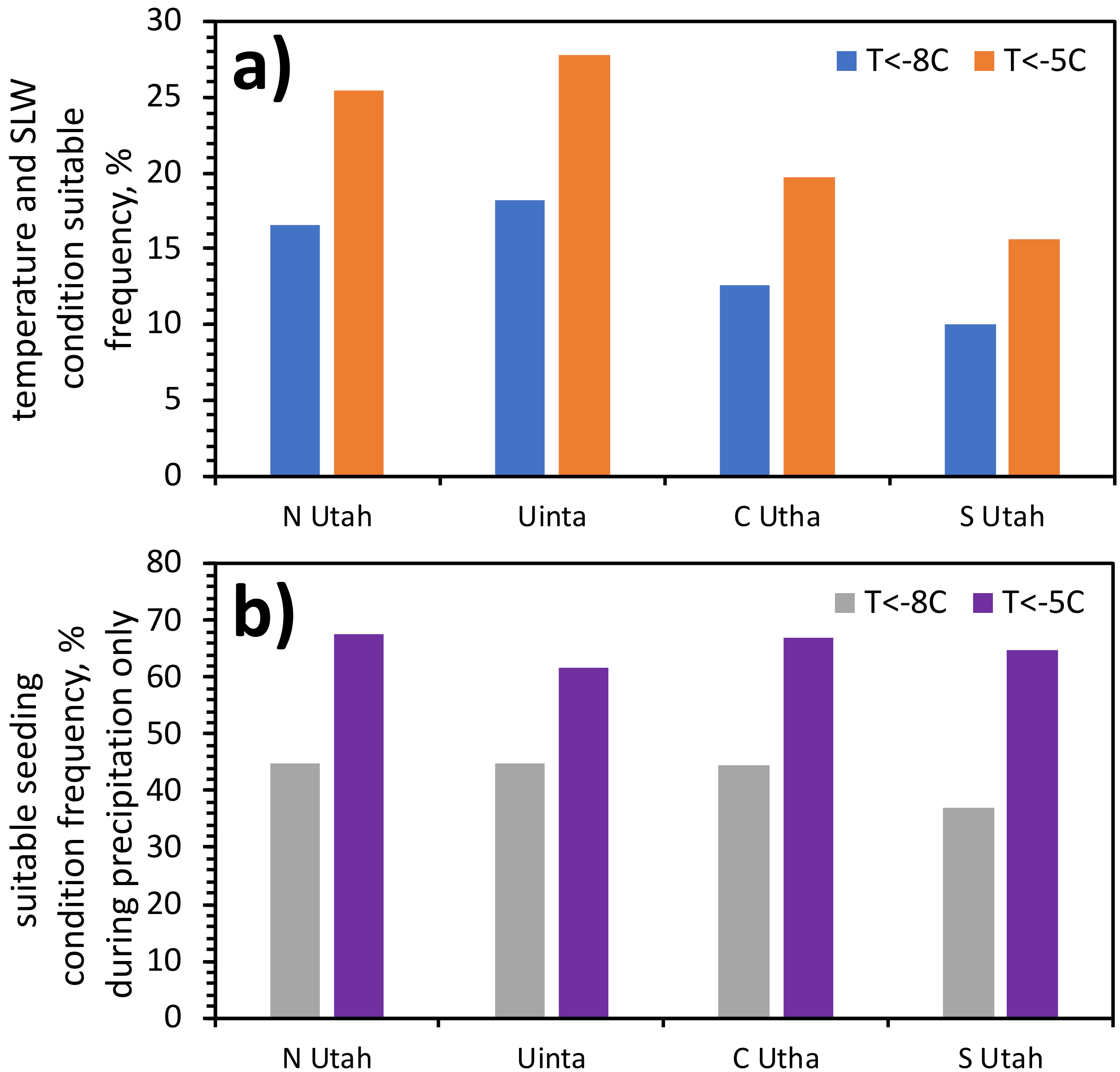

Figure 5.1: Average suitable seeding condition frequency (%) over the mountains that are located in four different regions in Utah (Figure 1) based on 13 years average. Upper panel a) shows the suitable seeding condition frequency (%) when SLW presents and 700 mb temperature less than -8ºC (blue bars) and -5ºC (orange bars) and lower panel b) shows the suitable seeding condition frequency (%) during precipitating only when 700 mb temperature is less than -8ºC (gray bars) and -5ºC (purple bars).

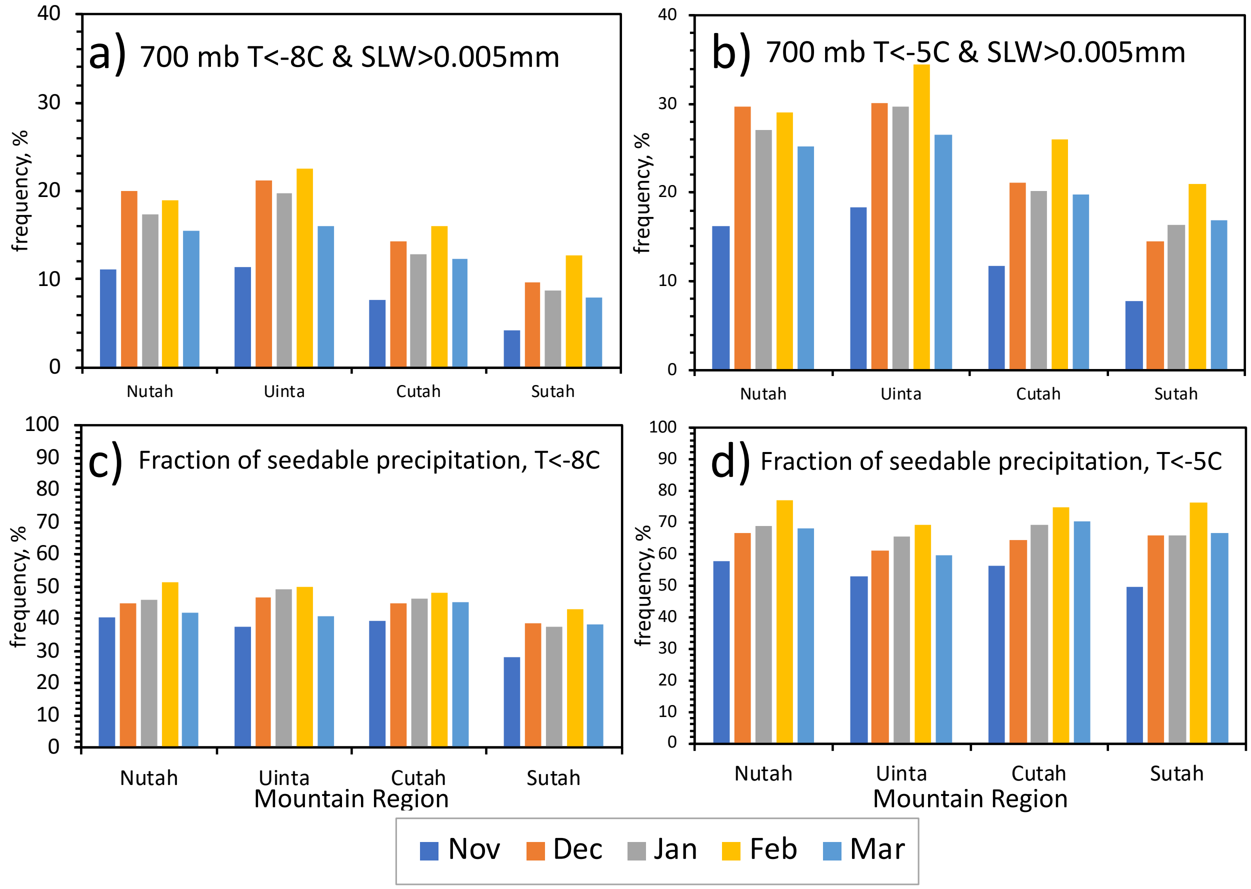

Figure 5.2: Monthly average suitable seeding condition statistics over different mountain ranges in Utah from November to March based on 2000-2013 WRF data. Upper left panel a) shows the suitable condition frequency (%) when 700 mb temperature less than -8^{o}C during the presence of SLW, upper right panel b) is similar to a) but 700 mb temperature less than -5^{o}C during the presence of SLW during whole month. The lower panel shows the fraction of precipitation suitable (LSW available) when 700 mb temperature less than -8^{o}C (lower left panel, c) and less than -5^{o}C (lower right panel, d).

5.1.2. Uinta Region

The Uinta Mountains are not only important to Utah but also to the Lower Basin States of the Colorado River. These mountains contribute significant streamflow from several north and south slope drainages to three different rivers. Notably, the Uinta Region has high potential for glaciogenic seeding, with about 28% and 18% of suitable conditions frequencies for the -5 and -8^{o}C temperature thresholds at 700 mb, respectively, with existence of SLW (Figure 5.1a). Considering only periods when clouds are precipitating, the frequency of suitable seeding conditions is from 61% to 45% for the -8^{o}C and -5^{o}C temperature thresholds, respectively (Figure 5.1b). The range of frequencies varies during the winter, with the lowest frequency in November and highest in either December and/or February (Figure 5.2). The result is consistent for both temperature thresholds with higher frequencies for warmer temperatures (<-5^{o}C) compared to -8^{o}C threshold as would be expected (Figure 5.2). Since inversion is a major issue on the upwind side of the Uintas, however, these numbers would be lower if low level stability was factored into the analysis.

The UCC looked at individual segments of the Uinta Region, and the suitable seeding condition frequency segments is shown for both temperature threshold (<-8^{o}C and <-5^{o}C) in Figure 5.3. These analyses indicated the Central Uinta segment (3U) had a slightly higher frequency of suitable seeding conditions, at 21% and 31% of the winter period for two temperature thresholds, respectively. The West Uinta segment (2U) showed a comparable number (20% and 30%). The Wasatch and East Uinta segments (1U and 4U) showed a lower frequency (~15% and 25%). During precipitation events, the analysis indicated that nearly 45% and 65% of precipitating clouds over the Uinta as a whole are suitable for glaciogenic seeding for two temperature thresholds, respectively (Figure 5.4). It should be noted that all these numbers for individual mountain segments are calculated considering precipitating storms with two temperature thresholds at 700 mb (<-8^{o}C and <-5^{o}C) when SLW was forecasted without considering low level stability.

5.1.3. Central Region

Several mountain segments are included in the Central Region, and atmospheric conditions in these segments vary. Broadly speaking, though, the conditions are suitable for seeding across the region, albeit less frequently than over the Northern and Uinta regions. The average frequency for suitable seeding is about 20% at the 700 mb temperature less than -5^{o}C while the number goes down to 13% when -8^{o}C temperature is considered with SLW (Figure 5.1a). The UCC analysis suggests that during precipitation events, the suitable conditions varied from 45% to 67% at the -8 and -5^{o}C thresholds, respectively (Figure 5.1b). Similarly, these rates vary from month to month and, as is the case with other mountains, November has the lowest frequency while the other remaining four months (December through March) show about the same frequencies (Figure 5.2). The monthly distribution is similar for both temperature thresholds even though the warmer temperature (-5^{o}C) shows ~22% more time for suitable cloud seeding compared to -8^{o}C temperature for all months (Figure 5.2) and this is consistent with the annual average value (Figure 5.1).

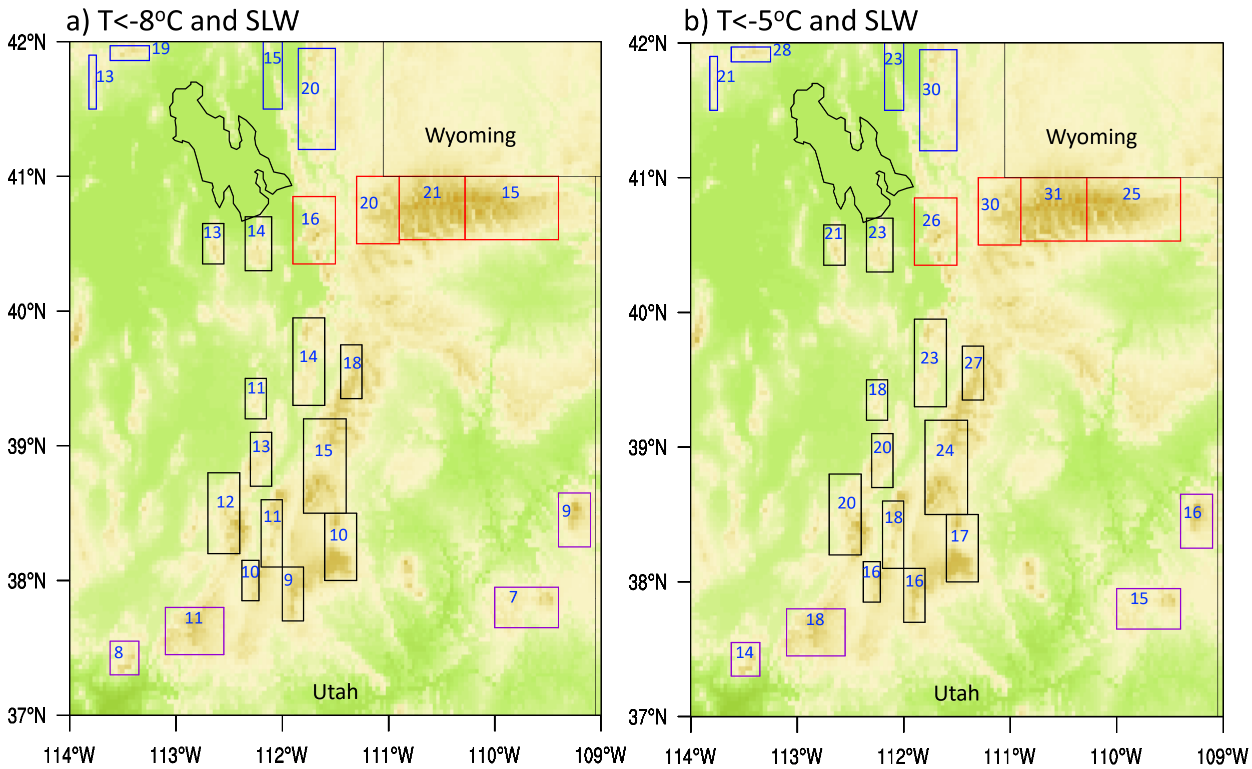

Figure 5.3: Frequency (%) of suitable seeding condition over 24-mountain segments in Utah. The suitable seeding condition is considered when 700 mb temperature less than -8 °C (left panel) and -5 °C (right panel) with SLW larger than 0.005 mm for winter season from November to March considered the data from 2000-2013 of CONUS WRF.

Since this region had the largest number of mountains (12 segments), the variation of suitable seeding frequencies was expected to be large. Indeed, the two mountain segments located on the East (1C) and West (2C) of Toole County show a suitable seeding frequency of about 14%, which is smaller than the frequency in the North and Uinta regions (Figure 5.3). The highest frequencies were estimated to occur near Mt. Pleasant (7C and 8C) with 18-15% frequency. The lowest estimated frequency (9%) was estimated to occur over the segments located near Garfield (11C and 12C) in the southern part of the Central Region (Figure 5.3). The other mountain segments in this region have average frequencies of about 12%. These numbers are based on the colder than -8°C temperature at 700 mb in the presence of SLW.

When examining only periods of precipitation, the frequency of suitable seeding conditions varied from 41% to 65% over the southern part of Central Utah, and 51% to 73% over the mountains in the northern part of this region for the temperature thresholds of -8 °C and -5 °C, respectively (Figure 5.4a and 5.4b). This frequency during only precipitation periods (Figure 5.4) does not exactly correlate with the frequency for all periods (Figure 5.3) since a few cases show higher values for only precipitation periods (~40%) while the frequency of all-period seeding conditions is lowest (9% and 16% for two temperature thresholds in Figure 5.3a,b) over the southcentral segments (10C and 11C in Figure 1.3) in this region. The average frequency of suitable conditions for seeding is about 45% over the Central Region when only precipitating periods are considered. All these numbers for individual mountain segments are calculated considering both 700 mb temperature thresholds (<-8°C and -5°C) when SLW is predicted to be present without considering low level stability in left and right panels of Figures 5.3 and 5.4.

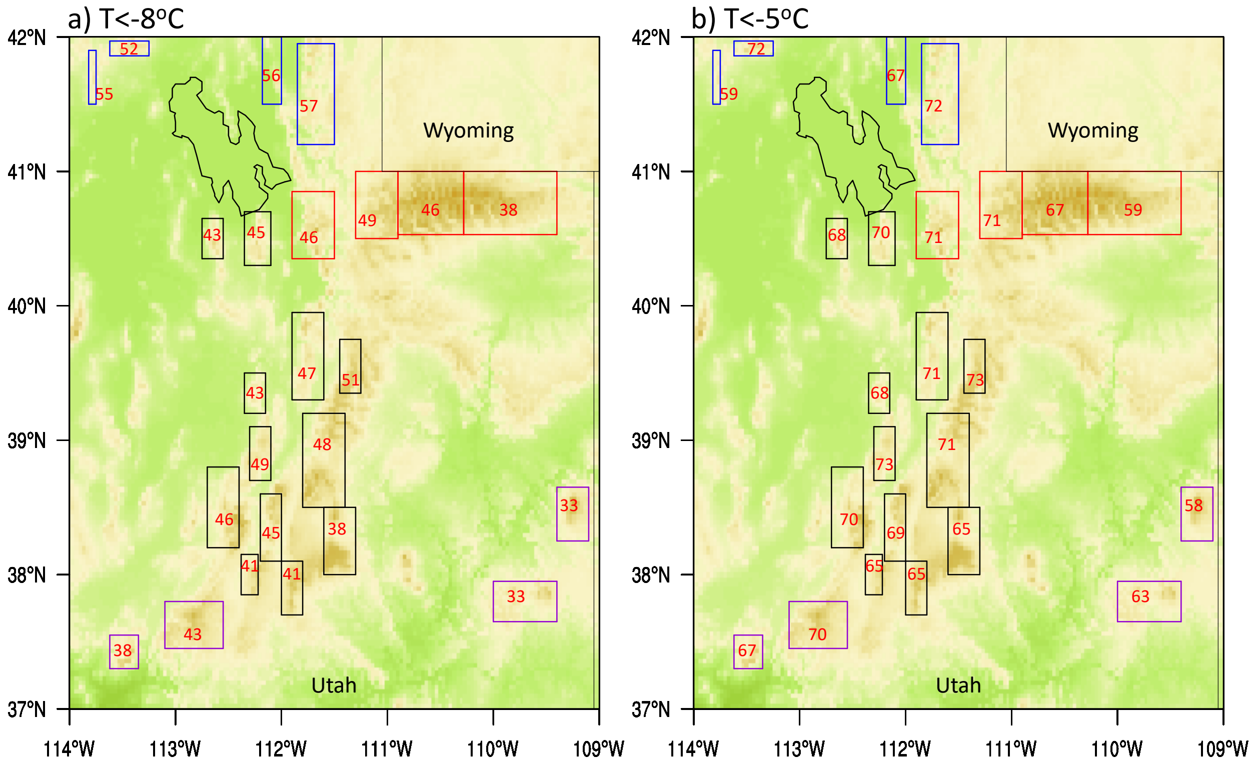

Figure 5.4: Frequency (%) of precipitating storms when suitable seeding condition occurs over 24-mountain segments in Utah. The suitable seeding condition is considered when 700 mb temperature less than -8 °C (left panel) and -5 °C (right panel) with SLW larger than 0.005 mm for winter season from November to March. The data for this analysis considered from 2000-2013 of CONUS WRF.

5.1.4. Southern Region

The UCC considered four mountain segments in the Southern Region and estimated suitable seeding condition frequencies were the lowest in these areas among the other mountain segments in the state. In the Southern Region, cloud seeding may be possible about 10% of the time when considering 700 mb temperatures at -8°C. This number increased to 16% when a -5°C temperature threshold was considered (Figure 5.1a). During precipitation events, the frequency of suitable seeding conditions was 37% and 65% for the two temperature thresholds, -8 and -5°C respectively, in the presence of SLW (Figure 5.1b).

As in other regions, suitability varied from segment to segment. The San Juan Mountains (2S) are suitable for seeding during only about 7% (15%) of the winter for -8°C (-5°C) temperature threshold, while the East of Cedar City segment (3S) showed an 11% (18%) suitability frequency for -8°C (-5°C) temperature threshold (Figure 5.3). The other two mountains in southern Utah (East of Moab, 1S, and North of St. George, 4S, in Figure 1.3 and Table 1) show 9% (16%) and

8% (14%) frequency of suitable seeding conditions for the -8°C (-5°C) temperature threshold (Figure 5.3). The frequency is smallest over the southern mountains as this region is warmer relative to other regions and winter precipitation is lighter than in other regions. When UCC considered only precipitation periods, the frequencies varied from 33% (63%) for the San Juan Mountains to 43% (70) over the mountains (3S) East of Cedar City for the -8°C (-5°C) temperature threshold (Figure 5.4). Other segments on the East of Moab (1C) shows 33% (58%) frequency and 38% (67%) for the North of St. George segment for the -8°C (-5°C) temperature threshold (4C). Southern Utah may produce convective orographic clouds during the spring season (March through May), however, and that period could be suitable for seeding as well, although further research would be needed on this topic.

5.2. Suitable seeding condition for non-precipitating cloud

UCC also analyzed conditions in which precipitation did not occur but clouds were suitable for seeding in the presence of SLW with the right temperature (both <-8°C and <-5°C are considered). The frequency of the suitable seeding conditions for non-precipitating cloud is shown in Figure 5.5 for individual mountain segments. The number varies from 2% (4%) to 6% (9%), with a greater frequency over the northern mountains and a smaller frequency over the Central and Southern segments for the -8°C (-5°C) temperature threshold.

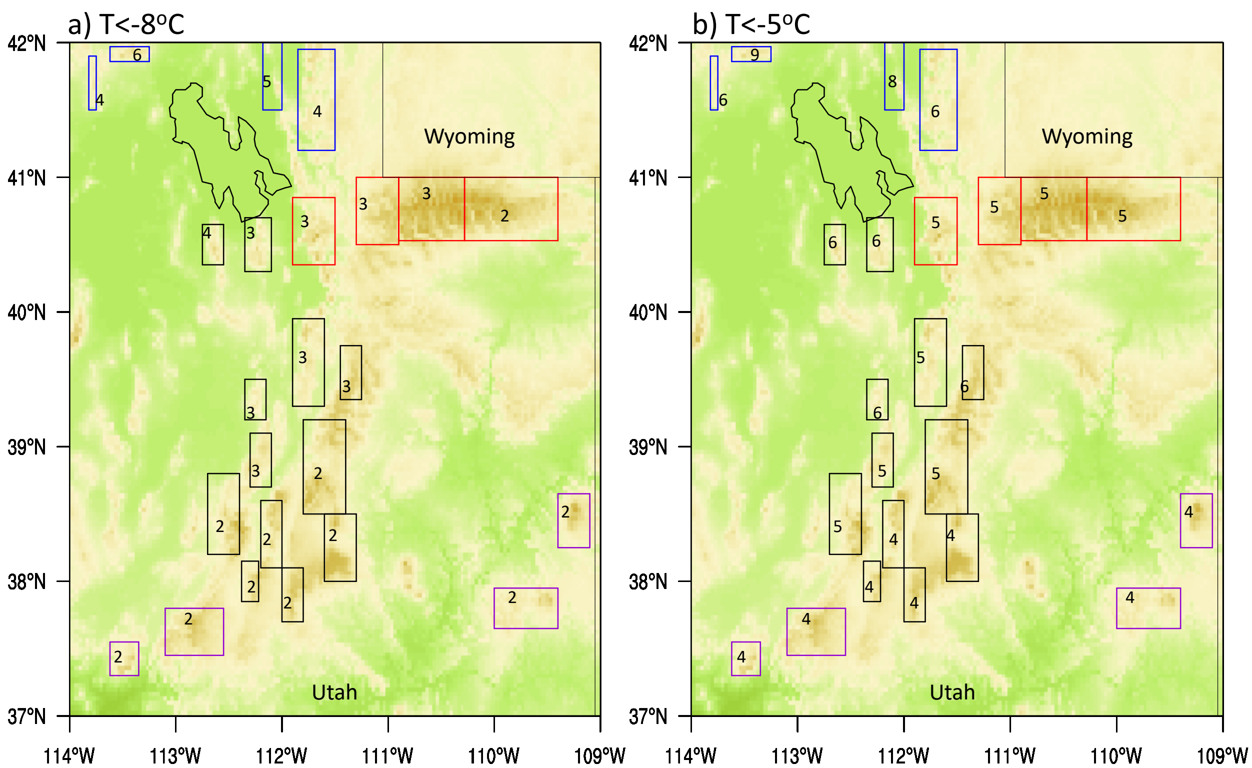

Figure 5.5: Frequency (%) of non-precipitating storms when suitable seeding condition occurs over 24-mountain ranges in Utah. The suitable seeding condition is considered when 700 mb temperature less than -8 °C (left panel) -5 °C (right panel) with SLW larger than 0.005 mm for winter season from November to March when precipitation was not simulated. The data for this analysis considered from 2000-2013 of CONUS WRF.

While it is important to note that non-precipitating clouds can be suitable for seeding, producing mountain snow in times in which it might not otherwise occur at all, non-precipitating orographic clouds may not exist for long periods (often these clouds do not exist for more than few hours). As such, to take advantage of this finding, it would be critical to track these clouds in near-real-time, and measurements of supercooled liquid water by radiometer could be extremely helpful for finding the right non-precipitating clouds and the right timing for seeding.

5.3. Year-to-year variations of suitable seeding conditions

Suitable seeding conditions appear to vary from year to year, tracking with winter precipitation totals that also show significant interannual variability. UCC further looked at annual variations of suitable seeding condition frequencies using the -8^{o}C threshold and the existence of SLW relative to all winter period (Figure 5.6a). The frequency was highest in the Uinta Region but varied from 14% during 2006-2007 winter to 25% during the 2007-2008 winter. The Southern Region had the lowest suitability frequency among the four regions, with 7% suitability in the 2004-2005 winter and 13% during the 2007-2008 winter. The Northern Region has comparable numbers to the Uinta Region, with year-to-year variation from 14% to 22%. The Central Region, meanwhile, showed suitability variations from 9% to 17%. The greatest frequency of suitability occurred during the same year (2007-08 winter season) in all four regions, while the lowest frequency occurred in the 2004-05 winter season in the Central and Southern regions, while the Northern and Uinta regions had the lowest frequency during 2006-07 winter season.

The UCC further looked at the fraction of precipitation that could be seeded and found similar variations (Figure 5.6b) as seeding condition frequency that considered all winter period (Figure 5.6a). The Northern Region has the highest potential for seedable precipitation (37-57% of precipitating clouds) while the Uinta Region has slightly less, with 34% to 55% of precipitating clouds showing suitability for seeding during the analyzed 13-year periods from 2000-2012. The Central and Southern regions showed comparable amounts of precipitating clouds that could be seeded, albeit with a high range of year-to-year variation, with 26-55% variation in the Central Region and 17-50% in the Southern Region. All these conditions are calculated based on the 700 mb temperature of less than -8^{o}C in the presence of SLW over each mountain and region without considering the low-level stability that may reduce these numbers, mainly for the mountains that have frequent winter inversions on the upwind side. This included segments in both the Northern and Uinta regions.

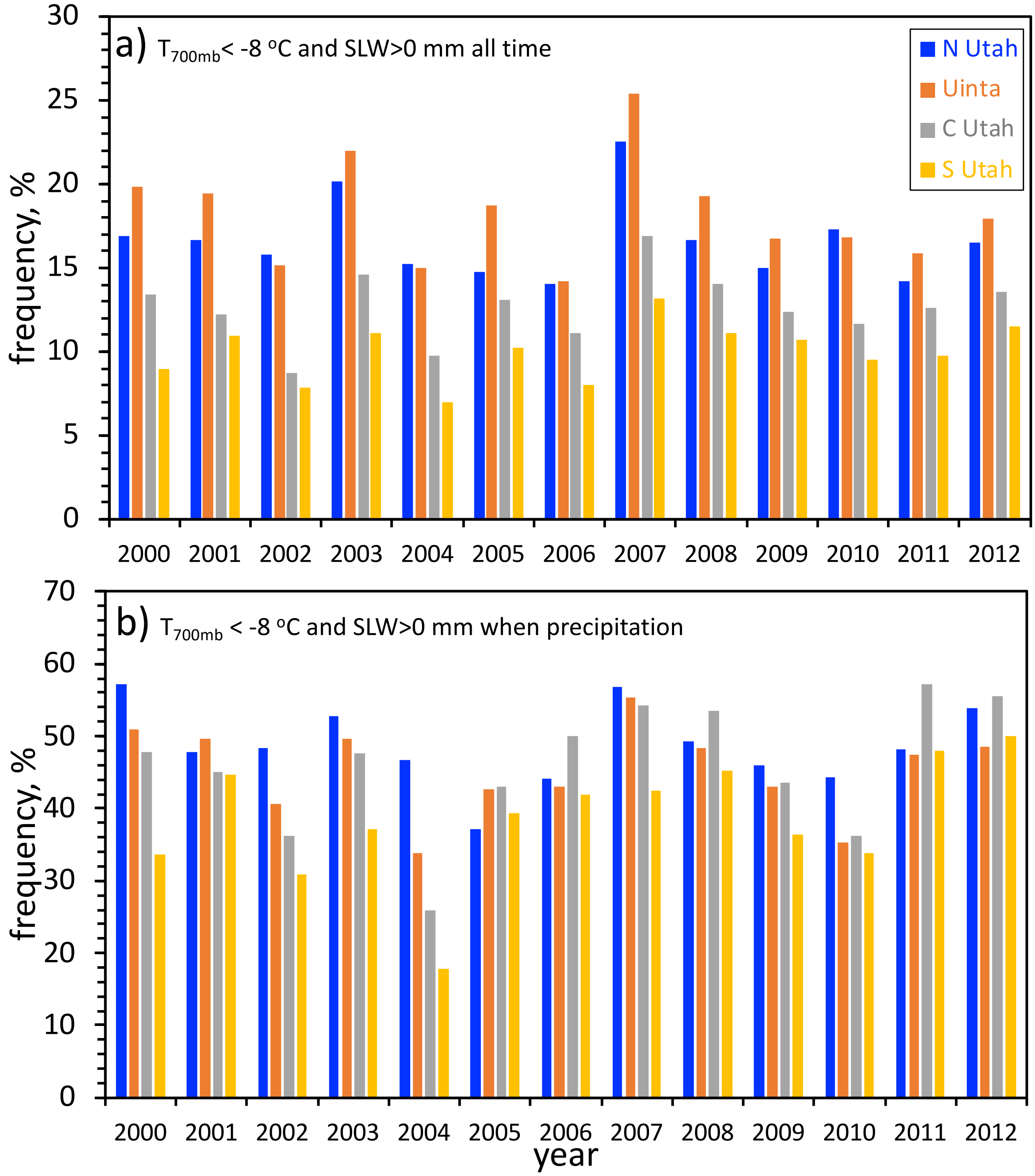

Figure 5.6: Suitable seeding condition year-to-year variations in winter season (November to March) from 2000-2001 to 2012-2013. Upper panel a) shows the seeding condition frequency (%) relative to all time when 700 mb temperature is smaller than -8 °C and SLW larger than 0.005 mm and lower panel b) shows the seeding condition frequency relative to precipitation time with same seeding condition in a).

5.4. Spatial distribution of suitable seeding condition

The UCC has developed a frequency map that considered the entire winter season (November through March) for different variables, including the entirety of the state, as shown in Figure 5.7. Since few mountains are above 700 mb, the average temperature was calculated from the surface to 1 km above ground level (T_{1km}). The frequency of occurrence when T_{1km} is lower than -8°C is shown in Figure 5.7a, clearly showing this condition is most common over the Uinta Mountains. When SLW frequency was evaluated in this way, (Figure 5.7b) the highest values were identified over the Uinta and Northern regions; this pattern is similar for precipitation frequency (Figure 5.7c). When two variables (T_{1km} and SLW) are combined (Figure 5.7d) the frequency becomes smaller than the individual frequency since both conditions need to be met. And when three variables (T_{1km}, SLW and precipitation) were considered (Figure 5.7e) the frequency of suitable seeding conditions is even smaller. In 5.7f, the frequency is calculated considering only precipitating periods, showing that more than 60% of precipitating clouds are suitable for seeding, a number that is comparable for the Central and Northern regions, although it should be noted that the Central and Southern regions receive less precipitation than the Uinta and Northern regions and these numbers (Figure 5.7f) are suitable seeding condition relative to precipitating period.

5.5. Limitations

This study focuses on mountain segments that have been targeted for winter orographic cloud seeding or have potential for seeding in future. The climatic condition, orientation, and altitude of these mountain segments vary significantly and further seeding criteria (e.g. low-level stability, wind direction, and cloud top temperature) are not included in this study, nor is an evaluation of ground-based versus airborne seeding operations. These additional variables are potentially important for developing efficacious seeding criteria (Griffith, et al, 2013) and will be considered in the future in studies of specific mountains. Thus, UCC considers this analysis as the first step to evaluate suitable seeding conditions over all the mountain segments in Utah, providing a larger picture of seeding potential.

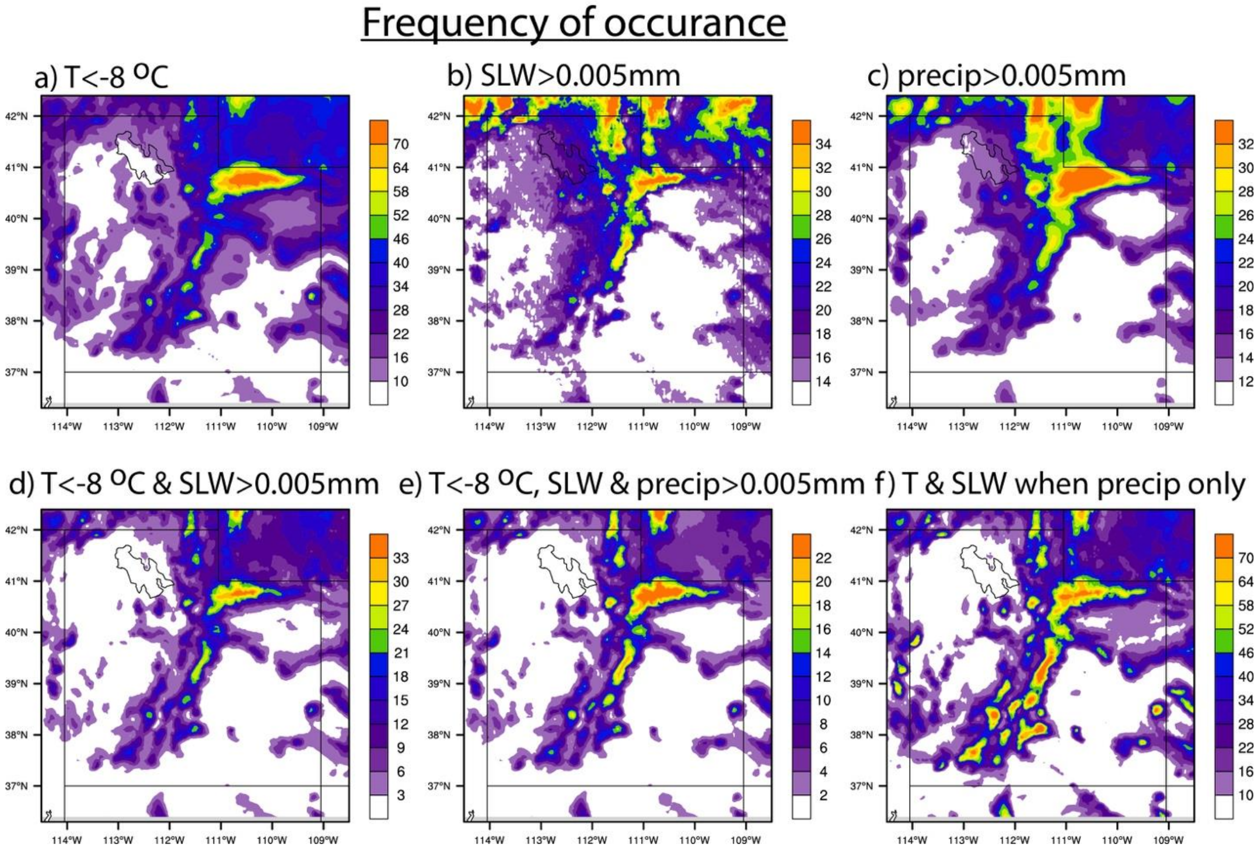

Figure 5.7: Spatial distribution of atmospheric condition during different scenarios. a) Frequency of occurrence of temperature (T) less than -8°C (average from surface to 1 km agl), b) frequency of occurrence of SLW>0.005 mm, c) frequency of occurrence of precipitation greater than 0.005 mm, d) frequency of occurrence of T<-8°C and SLW>0.005mm, e) frequency of occurrence of T<-8°C, SLW>0.005mm, and precip>0.005mm, and f) fraction of precipitation or frequency of occurrence when T<-8°C and SLW>0.005mm when precipitation occurs.

6. HIGH RESOLUTION FORECASTING MODEL

The UCC is running the Weather Research and Forecast (WRF) model from January 2019. The WRF model is downscaled 12-km horizontal resolution North American Model (NAM) to 2-km resolution covering the state of Utah. The domain of the model is shown in Figure 1.4. The WRF model is run four times a day (00Z, 06Z, 12Z, 18Z) forecasting 84 hours with 3 hourly output.

6.1. Model output and validation

Since validation is the first step for gaining confidence on model products, UCC compared rawinsonde data from Salt Lake City with WRF forecasts as shown in Figure 6.1. The WRF model shows good agreement with observations and captures the vertical profile of temperature and dew point temperature. The wind profile of WRF is also comparable with observations. In winter, several Utah valleys, have colder temperatures at the ground level than above ground level, with temperatures increasing with height at the lower levels of elevation. These winter inversions restrict the dispersion of seeding materials released from ground- based seeding generators over the mountains. WRF model has some difficulty capturing shallow layers of inversions, from those near ground level to those in the middle of the atmosphere (~650 mb in Figure 6.1a).

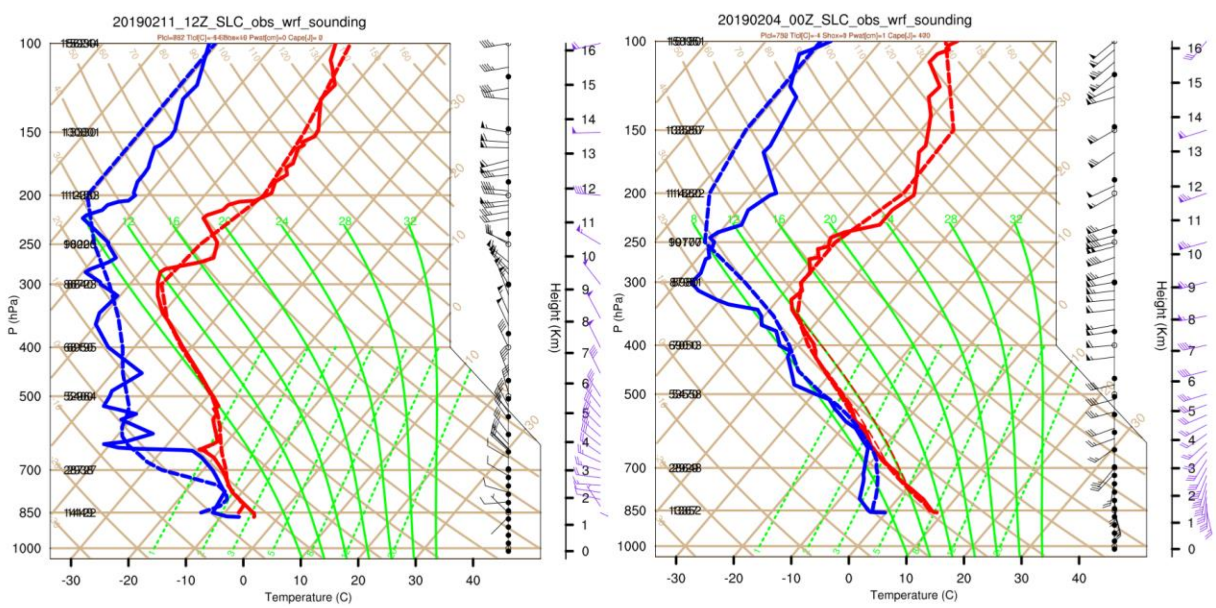

Figure 6.1: Comparison of vertical profile of temperature (red line), dewpoint temperature (blue line), and wind speed and direction (wind barb) from observation (solid line and black wind barbs) and WRF forecast (dashed line and purple wind barbs). Right panel is from 11 Feb 2019 and right panel is form 4 Feb 2019 and radiosondes were released from Salt Lake City.

The UCC also looked at the main variable, supercooled liquid water, which is vital for cloud seeding operations. In lieu of processed radiometer data from the Uinta Basin during the winter of 2018-19, UCC examined radiometer plots from raw data and compared those plots with WRF output cross-sections of the Uinta Mountains (Figure 6.2). A comparison was also made with the

HRRR model output (not shown), showing that the WRF forecast produced the right location and time of the measured supercooled liquid water. The WRF forecast shows a reasonable comparison with observation and is able to forecast the liquid water as early as 30 hours before the weather system hits the mountain, providing sufficient time for the preparation of seeding operations. Overall performance of the WRF model has shown that it is capable of identifying supercooled liquid water over different mountain ranges during different weather systems (deeper vs. shallow clouds) well in advance.

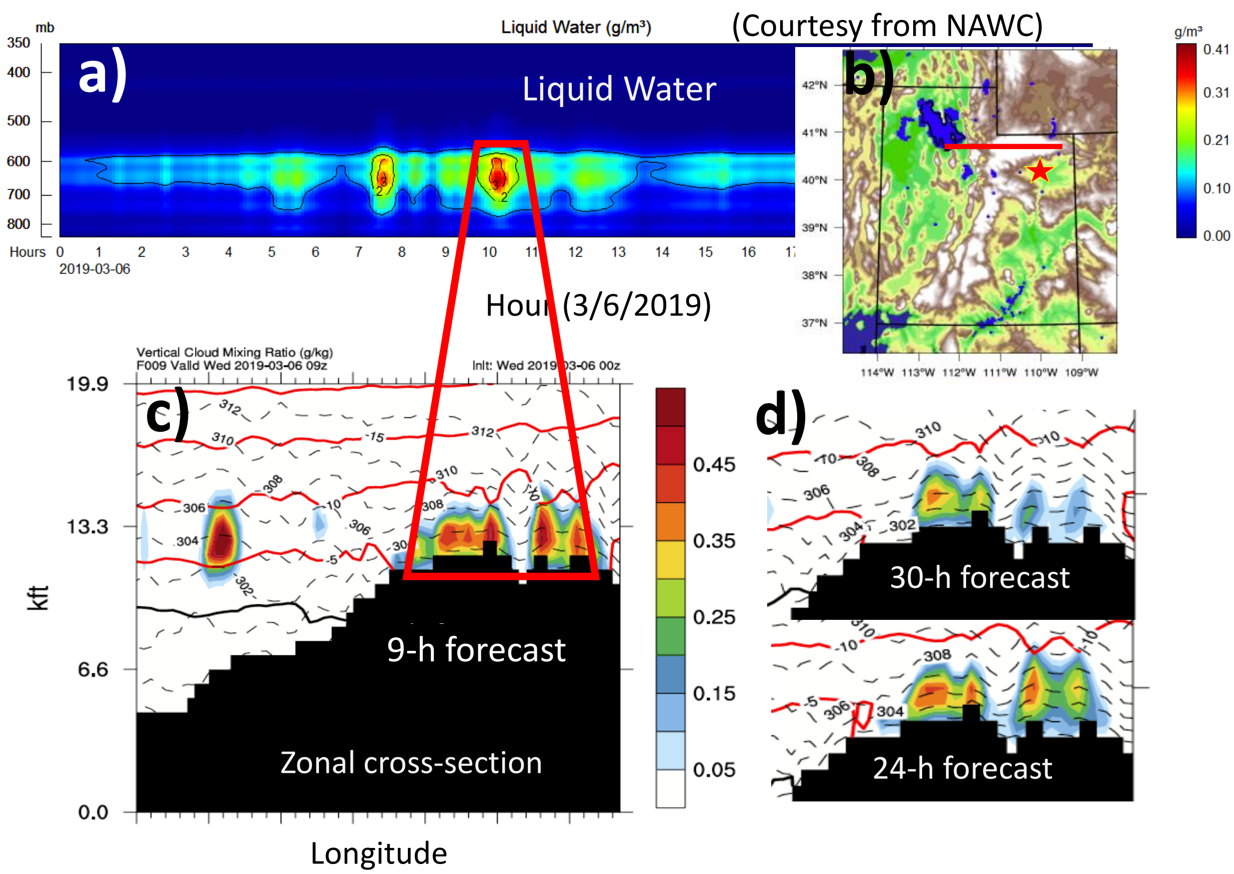

Figure 6.2: Supercooled liquid water (SLW) comparison between observation and WRF model form 6 March 2019 over the Uinta Mountain. a) shows the liquid water measured by the radiometer located at Roosevelt, Utah targeting the Uinta Mountain, b) shows the cross-section over Uinta Mountain to display the WRF simulated liquid water, and c) and d) shows the vertical cross-section of temperature (red line), potential temperature (dashed line) and liquid water (color filled) forecast of 09Z that was initialized at 00Z of 6 Mar and 00Z of 5 Mar, respectively over the Uinta mountain. The model can forecast supercooled liquid over the mountain advance in time that will help to make the seeding decision and preparation.

6.2. Forecast products and utilization for cloud seeding operation

The UCC has developed a dedicated website, hosted by the Utah Climate Center, with forecasting products that are useful for the conduct of Utah cloud seeding operations. It can be found at https://climate.usu.edu/cloudSeeding/index.php. This site will provide cross-sections over various mountain ranges in Utah using real-time data and the WRF forecast model The main focus of the WRF model is to utilize the forecasting product for cloud seeding operations. Since several mountain ranges are targeted for cloud seeding in this forecast, it includes graphical plots of vertical cross-sections over different mountain ranges. These cross-sections include temperature (blue contour), potential temperature (black contour), and cloud liquid water (color shaded) as shown in Figure 6.3. The forecast products will be expanded with further useful information in a Utah map that includes precipitation, vertically integrated cloud liquid water, and wind are some examples. The improvements to the website will continue in coming years.

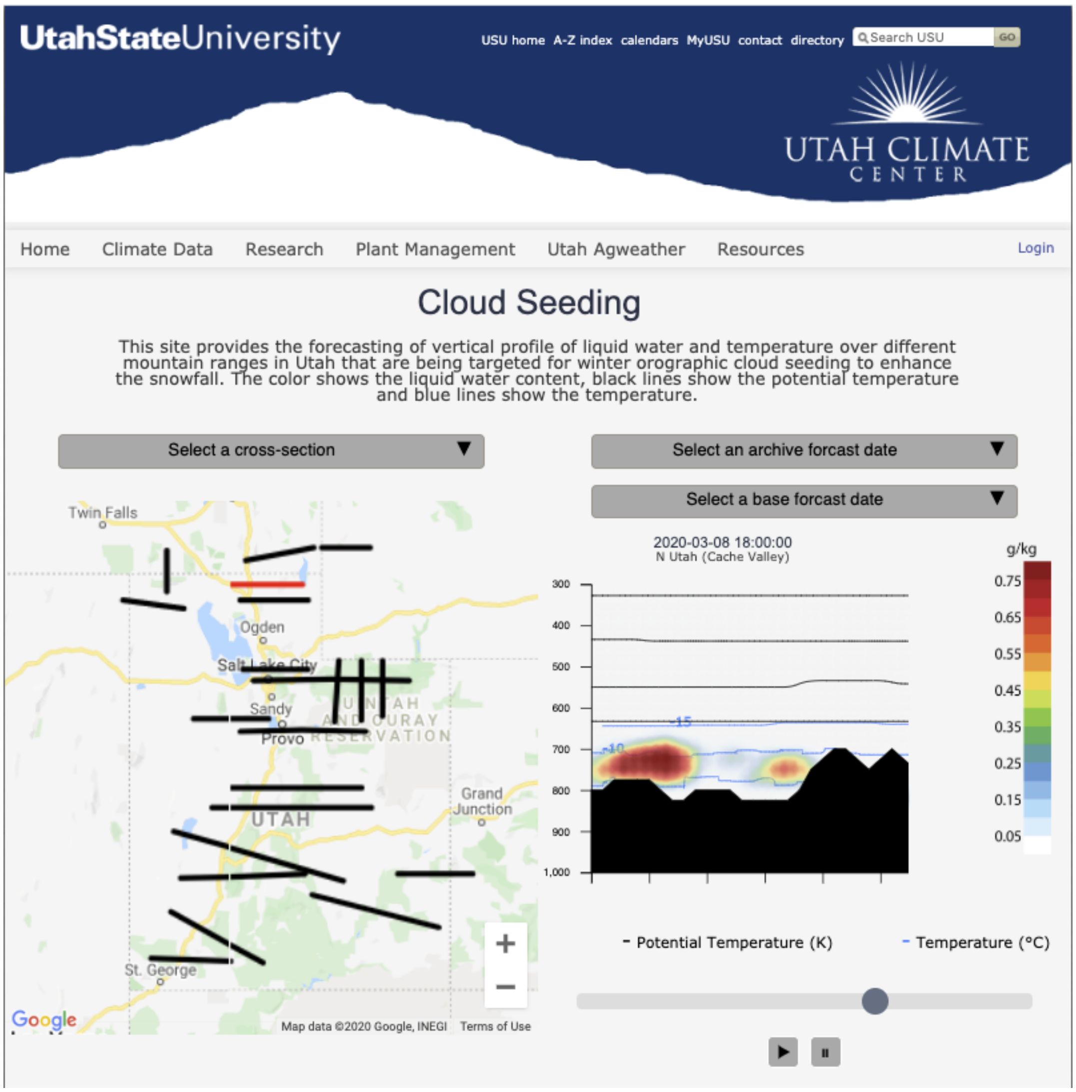

Figure 6.3: The weather forecasting products that are useful for the Utah cloud seeding operation available almost in real time at UCC website ([https://climate.usu.edu/cloudSeeding/index.php).](https://climate.usu.edu/cloudSeeding/index.php)

7. ACTIVITIES

The UCC conducted several meetings with DWRe and NAWC during the project period. Progress reports were presented and comments and suggestions were included to make this study useful for cloud seeding operations and also to improve the quality of the work.

Additionally, UCC personnel visited a cloud seeding generator site at Bear River City and a radiometer site at Roosevelt. The visit was targeted to demonstrate the cloud seeding-related instruments to graduate students and scientists from Utah State University.

This work was presented at a Weather Modification Association (WMA) annual meeting that was held in Phoenix, Arizona, in April 2019. The UCC also presented further progress at the American Water Resources Association (AWRA) annual conference in Salt Lake City in November 2019 and at the American Meteorological Society's annual meeting in Boston, Massachusetts in January 2020. For the first time in history, a weather modification session was organized at the AWRA conference, highlighting cloud seeding programs in the western U.S. and introducing these efforts to a broader audience interested in water resources.

8. SUMMARY AND FUTURE DIRECTION

Using NCAR CONUS model data, the UCC has evaluated suitable orographic cloud seeding condition over Utah's mountains. The data used in this study come from the November-through-March winters of 2000-2001 to 2012-2013. Three hourly model data with 4-km horizontal resolution was used to estimate suitable seeding conditions. These conditions were calculated based on 700 mb temperature and vertically integrated supercooled liquid water (SLW). UCC used a minimum threshold of 0.005 mm for the SLW and two temperature thresholds, -5 and -8^{o}C at 700 mb, to define suitable seeding conditions. The frequency of suitable seeding conditions was calculated for the entire winter season, during only precipitation, and without any precipitation for each of the 24 range segments.

It was observed that Utah's mountains are often suitable for glaciogenic cloud seeding during the winter, but suitability tends to decrease from the Northern to Central regions and again from the Central to Southern regions. To wit, the fraction of precipitating clouds that are suitable for seeding includes nearly 55% (70%) of storms over the Northern Region, about 45% (70%) over the Central Region, and about 35% (60%) over the Southern Region for temperature threshold -8^{o}C (-5^{o}C). Additionally, this study identified opportunities to seed from 4 to 9% of non-precipitating clouds, during the winter season, offering a key opportunity to augment additional snowfall.

The WRF forecasting model was adapted to provide guidance for cloud seeding operations in Utah. Cross-sections over different mountain ranges were selected to forecast the vertical profile of liquid water and temperature that are the most important parameters for winter cloud seeding. These forecasting products are available on the Utah Climate Center website (https://climate.usu.edu/cloudSeeding/index.php).

Future work should focus on additional atmospheric conditions, including stability and cloud top temperature, that can impact seeding effectiveness, and also examine ground-based vs. airborne seeding. The feasibility of airborne seeding in Utah needs to be examined according to the American Society of Civil Engineers Guidelines (ASCE 2016). (These guidelines state that for a program to be implemented it must be considered to be both technically and economically feasible.) The current WRF forecast model also needs to be validated using radiometer liquid water observations that will help to improve the model. Sensitivity tests will be conducted and forecast products will be improved in coming years. If confidence in model performance is established, the model may be used to estimate seeding impacts on precipitation. The correlation between observed precipitation and model-predicted precipitation would need to be high for this application to be viable.

REFERENCES

ASCE, 2016: Guidelines for Cloud Seeding to Augment Precipitation. ASCE Manuals and Reports on Engineering Practice No.81, American Society of Civil Engineers, Reston, Virginia.

Breed, D., R. Rasmussen, C. Weeks, B. Boe, and T. Deshler, 2014: Evaluating winter orographic cloud seeding: Design of the Wyoming Weather Modification Pilot Project (WWMPP). J. Appl. Meteor. Climatol., 53, 282-299.

DeMott, P. J., 1995: Quantitative descriptions of ice formation mechanisms of silver iodide-type aerosols. Atmos. Res., 38, 63–99.

DeMott, P.J., 1997: Report to North Dakota Atmospheric Resource Board and Weather Modification Incorporated on tests of the ice nucleating ability of aerosols produced by the Lohse airborne generator. Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 15 pp.

DeMott, P.J., and Coauthors, 2010: Predicting global atmospheric ice nuclei distributions and their impacts on climate. Proc. Natl. Acad. Sci. USA, 107, 11 217-11 222.

Flossmann, A.I., M. Manton, A. Abshaev, R. Bruintjes, M. Mutakami, T. Prabhakaran, and Z. Yao, 2019: Review of advances in precipitation enhancement research. Bull. Amer. Meteor. Soc. DOI:10.1175/BAMS-D-18-0160.1

French, J.R., Friedrich, K., Tessendorf, S., Rauber, R., Geerts, B., Rasmussen, R., Xue, L., Kunkel, M., Blestrud, D., 2018. Precipitation formation from orographic cloud seeding. Proc. Natl. Acad. Sci. U. S. A. https://doi.org/10.1073/pnas.1716995115.

Garstang, M., R. Bruintjes, R. Serafin, H. Orville, B. Boe, W. Cotton, and J. Warburton, 2005: Finding common ground. Bull. Amer. Meteor. Soc., 86, 647–655.

Geerts, B., B. Pokharel, K. Friedrich, D. Breed, 917 R. Rasmussen, Y. Yang, Q. Miao, S. Haimov, B. Boe, E. Kalina, 2013: The AgI Seeding Cloud Impact Investigation (ASCII) campaign 2012: overview and preliminary results. J. Wea. Mod., 45, 24-43.

Geerts, B., B. Pokharel, and D. Kristovich, 2015b: Blowing snow as a natural glaciogenic cloud seeding mechanism. Mon. Wea. Rev., 143, 5017–5033.

Griffith, D., Solak, M.E., and Yorty, D.P., 2009: 30+ Winter Seasons of operational cloud seeding in Utah. J. Wea. Mod., 41, 23-37.

Griffith et al. (2013)…………….

Houze Jr., R., 2014. Cloud Dynamics. International Geophysics Series Vol. 104, 2nd edition. (496 pp.).

Huggins, A. W., 1995: Mobile microwave radiometer observations: Spatial characteristics of supercooled cloud water and cloud seeding implications. J. Applied Meteorology, 34, 432-446.

Huggins, A. W., 2007: Another wintertime cloud seeding case study with strong evidence of seeding effects. J. Wea. Mod., 39, 9–36.

Huggins, A. W., and K. Sassen, 1990: A high altitude ground-based cloud seeding experiment conducted in southern Utah, J. Weather Modification, 22, 18-29.

Jing, X., Geerts, B., 2015. Dual-polarization radar data analysis of the impact of ground based glaciogenic seeding on orographic clouds. Part II: convective clouds. J. Appl. Meteor. Climatol. 54, 2099–2117.

Liu, C. *et al.*, 2017: Continental-scale convection-permitting modeling of the current and future climate of North America. *Clim. Dynam.* http://dx.doi.org/10.1007/s00382-016-3327-9 .

National Research Council (NRC), 2003: Critical Issues in Weather Modification Research. National Academy Press, 123 pp.

Pokharel, B., B. Geerts, X. Jing, K. Friedrich, K. Ikeda, and R. Rasmussen, 2017: A multi-sensor study of the impact of ground-based glaciogenic seeding on clouds and precipitation over mountains in Wyoming. Part II: Seeding impact analysis. *Atmos. Res.,* 183, 42-57.

Pokharel, B., and B. Geerts, 2016: A multi-sensor study of the impact of ground-based glaciogenic seeding on clouds and precipitation over mountains in Wyoming. Part I: Project description. *Atmos. Res.,* 182, 269-281.

Pokharel, B., Geerts, B., Jing, X., 2014a. The impact of ground-based glaciogenic seeding on orographic clouds and precipitation: a multi-sensor case study. J. Appl. Meteor. Climatol. 53, 890–909.

Pokharel, B., Geerts, B., Jing, X., Friedrich, K., Aikins, J., Breed, D., Rasmussen, R., Huggins, A., 2014b. The impact of ground-based glaciogenic seeding on orographic clouds and precipitation: a multi-sensor case study. Atmos. Res. 147-148, 162–181.

Pokharel, B., Geerts, B., Jing, X., 2015. The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: a case study of shallow orographic cloud with large supercooled droplets. J. Geophys. Res. 120, 6056–6079.

Prein, A.F., Rasmussen, R.M., Ikeda, K., Liu, C., Clark, M.P., and Holland, G.J., 2017: The future intensification of hourly precipitation extremes. Nature Climate Change, 7, 48-52.

Rasmussen, R.M., S.A. Tessendorf, L. Xue, C. Weeks, K. Ikeda, S. Landolt, D. Breed, T. Deshler, and B. Lawrence, 2018: Evaluation of the Wyoming Weather Modification Pilot Project (WWMPP) Using Two Approaches: Traditional Statistics and Ensemble Modeling. J. Appl. Meteor. Climatol., 57, 2639–2660.

Rauber, R.M. et al., 2019: Wintertime orographic cloud seeding – A Review. J. Appl. Meteor. Climatol., 58, 2117-2140.

Rotunno, R. and R.A. Houze, 2007: Lessons on orographic precipitation from the mesoscale Alpine program. Q. J. Royal Meteorological Society, 133, 811-830.

Stauffer, N.E., 2001: Cloud Seeding: The Utah Experience. J. Wea. Mod., 33, 63-69.

Sassen, K., and H. Zhao, 1993: Supercooled liquid water clouds in Utah winter mountain storms: Cloud-seeding implications of a remote sensing dataset. J. Applied Meteorology, 32, 1548-1558.

Sassen, K., A. W. Huggins, A. B. Long, J. B. Snider, and R. J. Meitín, 1990: Investigations of a Winter Mountain Storm in Utah. Part II: Mesoscale Structure, Supercooled Liquid Water Development, and Precipitation Processes. *J. Atmos. Sci.*, **47**, 1323–1350.

Super, A. B., 1999: Summary of the NOAA/Utah Atmospheric Modification Program: 1990–1998. J. Wea. Modif., 31, 51–75.

Tessendorf, S.A., and Coauthors, 2019: A transformational approach to winter orographic weather modification research: The SNOWIE project. Bull. Amer. Meteor. Soc., 71-92.

Tessendorf, S. A., B. Boe, B. Geerts, M. J. Manton, S. Parkinson, 717 and R. Rasmussen 2015: The future of winter orographic cloud seeding, a view from scientists and stakeholders. Bull. Amer. Meteor. Soc., 96, 2195-2198.

Xue, L., A. Hashimoto, M. Murakami, R. Rasmussen, S. Tessendorf, D. Breed, S. Parkinson, P. Holbrook, and D. Blestrud, 2013a: Implementation of a Silver Iodide Cloud Seeding Parameterization in WRF: Part 1: Model Description and Idealized 2D Sensitivity Tests. J. Appl. Meteor. Climatol., 52, 1433-1457.

Xue, L., S. Tessendorf, E. Nelson, R. Rasmussen, D. Breed, S. Parkinson, P. Holbrook, and D. Blestrud, 2013b: Implementation of a Silver Iodide Cloud Seeding Parameterization in WRF: Part 2: 3-D Simulations of Actual Seeding Events and Sensitivity Tests. J. Appl. Meteor. Climatol., 52, 1458-1476.