CHAPTER 1

INTRODUCTION

One of the most important types of weather forecasts is the quantitative precipitation forecast (QPF). Accurate precipitation forecasts can save lives by preparing people for potentially dangerous flash floods or heavy snow. The amount and distribution of precipitation also has a significant economic impact on agriculture and many energy and recreation industries. However, QPF skill has traditionally been low compared to other forecast variables. The combination of low skill and high socioeconomic importance has led the Science Advisory Committee of the United States Weather Research Program (USWRP) to consider QPF one of the highest priority topics for research (Fritsch et al. 1998).

Since the advent of operational numerical models, forecasters have depended on model guidance, especially for long-range forecasts. While the QPF skill of human forecasters generally improve upon that of model output, forecasters tend to follow closely the trends of the model (Olson et al. 1995). Usually, if a model performs poorly, so do the forecasters. Thus, the improvement of QPF must be accomplished through improvements in the models as well as better understanding of precipitation processes and the shortcomings of model forecasts.

The QPF skill of forecasters at the National Centers for Environmental Prediction (NCEP) has slowly increased over the past three decades (Olson et al. 1995). Further improvement of QPF skill is expected as increased computational power allows for higher- resolution models, ensemble forecasts to capture the uncertainty in the initial conditions, and more accurate treatment of physical processes.

Several studies have shown that models perform better during the cool season than during the warm season (Junker et al. 1989, 1992; Olson et al. 1995). The seasonal variations in skill are attributed to the greater role of convective processes during the warm season, which are more difficult for models to predict due to their small scales relative to the model grid spacing. Precipitation associated with extratropical cyclones is easier to forecast. Junker et al. (1992) showed that model forecast skill is related to the location of storms, with higher skill found along and north of the storm tracks. Since convective events are usually associated with heavy precipitation, it might be expected that forecast skill decreases for wetter events. Lower forecast skill for larger thresholds of precipitation was confirmed by Olson et al. (1995), Gartner et al. (1998), and McDonald (1998). While there tends to be less skill to forecast specific events with large total precipitation, higher skill is favored during wet years compared to dry years (Junker et al. 1992; Olson et al. 1995). One explanation for the lower skill during dry years is that dry years tend to be dominated by large-scale ridging, which is more conducive for scattered, small-scale precipitation.

QPF skill varies significantly across the United States. Studies of several operational models showed significant underprediction of heavy precipitation in the deep South (Junker et al. 1989, 1992; Junker and Hoke 1990). The models are more likely to miss heavy events in the deep South than in the Ohio Valley during the cool season even if the synoptic and mesoscale dynamic and moisture fields forecast by the models are favorable for the production of heavy precipitation in the South (Junker and Hoke 1990). Another area prone to consistently low QPF skill is the intermountain region of the western United States (Junker et al. 1992). Forecasts for the intermountain region are worse than for the West Coast, even though the coastal forecasts suffer from the lack of upstream data (Gartner et al. 1998; McDonald 1998). Part of the problem may be due to model physics, but low resolution and inadequate topographic representation, along with the complexity of the interactions of airflow with orography, may also contribute.

Because individual mountains and mountain ranges act as obstacles to horizontal flow, airflow interacting with orography is typically forced to flow over or around the peaks. Usually, such orographic forcing can initiate or enhance precipitation in certain areas (Houze 1993). For example, orographically-induced low-level clouds can enhance precipitation falling from clouds aloft in a process known as the seeder-feeder mechanism. In a moist, stable environment, precipitating clouds can be formed due to upslope flow and subsequent condensation. If the air is potentially unstable, such upslope flow can trigger convection, which can occur either on the windward slopes or, in cases of strong blockage by the orography, upstream of the mountains. In the daytime, strong heating on the slopes can cause convergence at the peaks, which can also initiate convection. In addition, convective activity can be triggered by convergence on the lee side by air flowing around an isolated peak. A more detailed description of the environmental conditions necessary for different types of orographically-induced or -enhanced precipitation, as well as microphysical aspects of such processes, is given by Banta (1990).

Climatologically, orographic forcing causes enhanced precipitation on the windward side due to upslope flow and a rain shadow effect due to subsidence to the lee of major topographic barriers. This windward enhancement is especially evident during the cool season when large-scale precipitation systems interact with orography. The impact of orographic effects on precipitation varies by location and depends largely on the strength and direction of the flow relative to the terrain. However, due to the localized nature of many of the orographic effects, the distribution of precipitation near complex terrain is difficult to define based upon the current observational networks or current operational models.

Experiments involving a 10-km version of NCEP's Eta model (Eta-10) show the advantages of higher horizontal resolution for QPF in complex terrain. Variations in precipitation distribution such as upslope enhancement, rain shadows, and locations of precipitation maxima are more clearly delineated than in coarser versions of the Eta or other operational models (McDonald 1998; Staudenmaier and Mittlestadt 1998). An evaluation of models of varying resolutions and physical schemes over the western United States by McDonald (1998) shows a slight improvement in skill scores, mostly in the winter, for the higher-resolution models. One problem found in that version of the Eta-10 was that, because convective precipitation was generally underpredicted in high terrain in the operational version of the Eta available at that time (Swanson 1995), modifications were made to the convective parameterization scheme that caused too much precipitation to occur in the valleys (McDonald 1998; Staudenmaier and Mittlestadt 1998).

Colle et al. (1999) verified precipitation forecasts for models of varying resolutions during the cool season in the Pacific Northwest. They evaluated the Eta-10 and the Fifth-Generation Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) at 36- and 12-km resolutions. They found that, of the two MM5 resolutions, the 12-km version performed better overall than the 36-km version. However, the 12-km version predicted too much precipitation on steep windward slopes and too little precipitation on the lee slopes. The Eta-10 also underpredicted precipitation to the lee of mountain rages and overpredicted on the windward slopes. However, much of the Eta-10's overprediction occurred further upstream than the MM5. This was attributed to the Eta-10's lack of horizontal advection of precipitation in the microphysical scheme and problems caused by excessive blocking. Overall, the 12-km MM5 was found to produce the best forecasts, but the Eta-10 had smaller errors at lower thresholds of precipitation.

Further studies involving the MM5 in the Pacific Northwest were performed by Colle et al. (2000). These studies include an additional run of the MM5 at 4-km resolution. Their results showed that although precipitation structures were better resolved at higher resolution, the overall QPF skill at 4-km resolution was not noticeably better than at 12-km resolution. In fact, the 4-km version produced too much precipitation on the windward slopes, more so than at 12 km, especially for cases of light precipitation. The results also showed that while errors in the large-scale forecasts are significant contributors to QPF errors at the coarser resolutions, they are not as important for the 4-km resolution. Thus, it is believed that improving the model's physical schemes might have the most significant impact on improving precipitation forecasts at higher resolutions.

In order to improve the understanding of the dynamics and microphysics of wintertime precipitation processes in complex terrain, the Intermountain Precipitation Experiment (IPEX) was held in the vicinity of Salt Lake City, UT from 31 January-26 February 2000. Specifically, the goals of IPEX are to improve the understanding of orographic and lake-effect precipitation, to validate and improve high-resolution data-assimilation systems and model performance, especially precipitation forecasts, to validate and improve radar estimates of quantitative precipitation, and to study the vertical structure of electric fields in winter storms (Schultz et al. 2000). The location and timing of the field program was chosen in part because the winter Olympics are to be held in that region during February 2002. Results obtained from the field program may be useful for forecasting activities during the Olympics.

Figure 1.1 shows the geography of the region. Salt Lake City is located in a valley between the Oquirrh and Wasatch Mountains. Most of the major metropolitan areas, including the cities of Ogden and Provo, are located north and south of Salt Lake City along the Wasatch Front. The proximity to the mountains of a majority of the Utah population makes the ability to accurately forecast the variability of orographic precipitation extremely important. The Tooele Valley is located to the west of the Salt Lake Valley between the Oquirrh and Stansbury Mountains. To the northwest of Salt Lake City is the Great Salt Lake which, despite its limited size, is capable of producing lake-effect precipitation (Carpenter 1993; Steenburgh et al. 2000; Steenburgh and Onton 2001; Onton and Steenburgh 2001). Lake-effect precipitation from the Great Salt Lake typically affects areas south and east of the lake, where a large portion of the population resides. The area west of the lake is mostly desert.

Interactions between the airflow and the mountains and the lake have an effect on precipitation that is not easy to forecast. Observations and surveys of several winter snowstorms in the Salt Lake City area by Slemmer (1998) show that precipitation distributions in the region can vary greatly by event. IPEX was designed to improve forecasts of the

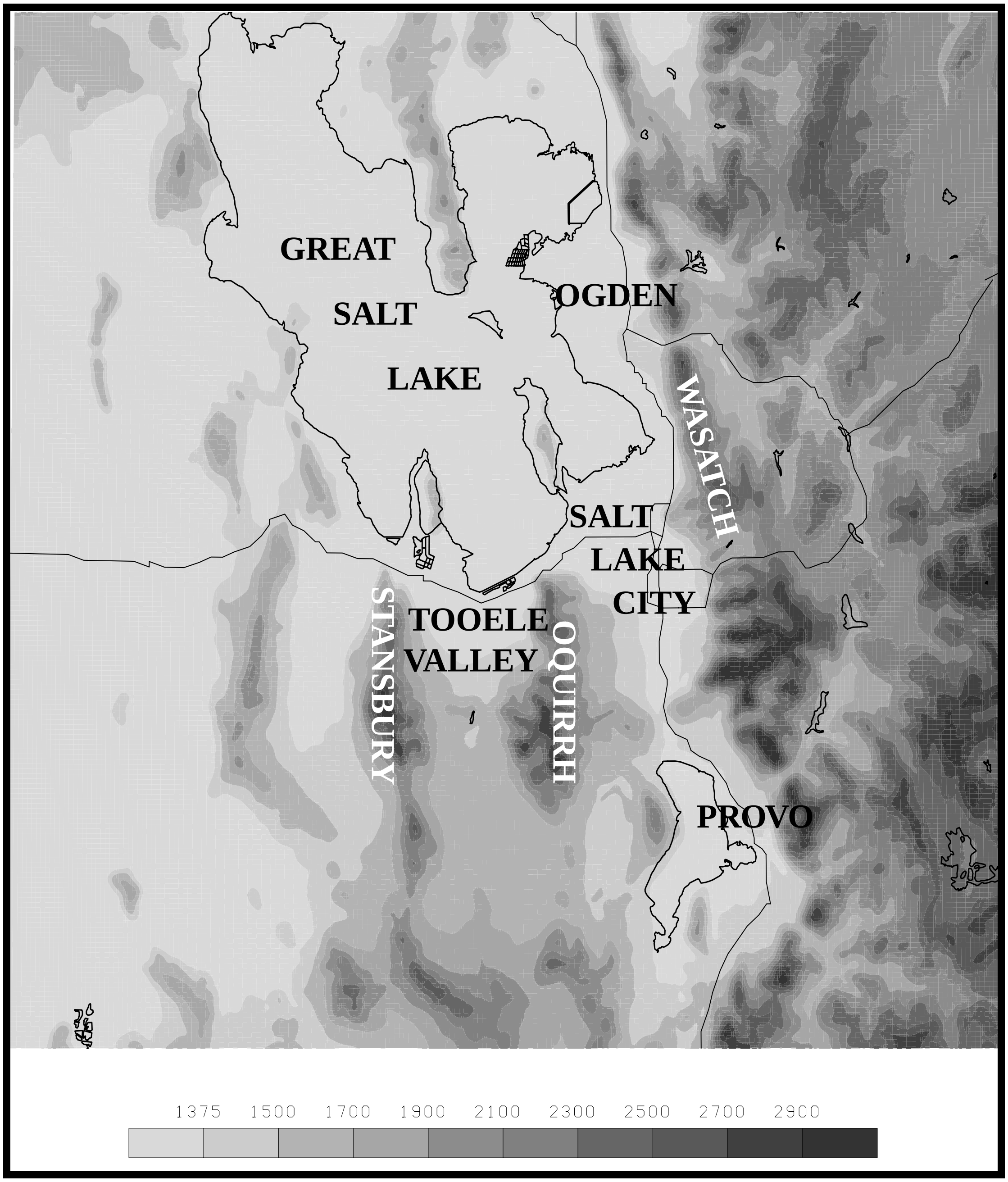

Figure 1.1. The geography of the Salt Lake City area. Terrain elevations (m) are shaded according to the scale at the bottom of the figure.

amount and distribution of precipitation through improved understanding of the complex interactions that modulate wintertime precipitation in the Salt Lake City area.

A variety of observational platforms, both ground-based and in-situ, were utilized during IPEX to document the dynamics and microphysics of precipitation events as they occurred in the region. Throughout the entire IPEX period, data from the Salt Lake City Weather Surveillance Radar-1988 Doppler (WSR-88D) (KMTX) and an extensive mesoscale network of automated and manual surface observational stations were collected and archived. During selected precipitation events, intensive observation periods (IOPs) were called, which mobilized several additional observing platforms. These platforms include a National Oceanic and Atmospheric Administration (NOAA) WP-3D Orion aircraft, which is equipped with radars and a cloud microphysics probe, two University of Oklahoma Doppler on Wheels (DOWs), a National Severe Storms Laboratory (NSSL)/Radian Corporation/Salt River Project vertically-pointing Doppler radar, a University of Utah dual-frequency microwave radiometer, and two NSSL mobile labs equipped with atmospheric sounding systems. One of the mobile labs also has an additional unit capable of making electric field measurements. In addition, the Salt Lake City National Weather Service forecast office (SLC NWSFO), as well as several NWSFOs both upstream and downstream of Salt Lake City, provided meteorological soundings every six hours during the IOPs. For aid in forecasting as well as for research purposes, the MM5 and the Advanced Regional Prediction System (ARPS) Data Assimilation System (ADAS) were run in real time at the University of Utah.

Operations during the field phase were determined on the basis of daily forecasts issued by the IPEX forecast team. These forecasts included orographic, lake-effect, and lightning outlook, detailed probabilistic QPF for the area of interest, and point QPF for four sites. Seven IOPs were held during the field experiment. Due to a dry spell over Utah during the first ten days of the experiment, the first IOP focused on the area surrounding the Teton Range of western Wyoming. The remaining six IOPs were centered around the Wasatch Range of northern Utah.

The purpose of this research is to document the observed distribution of precipitation during IPEX and to validate QPF made during the field experiment. Point forecasts made by IPEX forecasters are evaluated as well as forecasts from three models: the operational Aviation (AVN) and Eta models and the MM5 research model. Many previous validation studies of QPF focus on aggregate skill scores. Due to the relatively small size of the IPEX data set, such statistics applied to the IPEX data may not be representative of the general performance of the models. This research focuses more on model performance on a case-by-case basis. In addition to comparisons of model QPF interpolated to station locations, the variability of predicted precipitation in different climatological zones (e.g., mountainous regions or valleys) is contrasted to that observed. Significant over (under) forecasts can be identified as ones where the mean precipitation forecast for a zone by the model is substantially larger (smaller) than the mean observed precipitation for that zone based upon the predicted and observed variability of precipitation.

This research is intended to complement other IPEX studies underway. Since the dynamics and microphysics of all of the IOPs will be studied in detail by other scientists, their results can be combined with the results of this study to improve forecasting techniques in the intermountain region. Since most of the field activity was centered around the Salt Lake City area, the precipitation event that occurred in the Teton area during IOP

1 will not be studied.

Specific goals of this research are as follows:

- To collect and quality control all available precipitation observations in the Salt Lake City area during the IPEX period and to create a data set of 6- and 24-h precipitation totals.
- To document the spatial structure and temporal evolution of precipitation during IPEX using the observed precipitation data set and radar imagery.
- To evaluate the structure and evolution of the predicted precipitation events within the IPEX domain.
- To compare model QPF variability within different climatological zones to that observed.
- To provide a baseline of model performance for future modeling studies.

Chapter 2 describes the different sources of observed precipitation data as well as methods used to quality control the data. The models being evaluated in this research are described in Chapter 3. Chapter 4 details the distribution of observed precipitation during the IOPs. Chapter 5 compares model precipitation forecasts with the observations. A summary and conclusions are presented in Chapter 6.