The Intermountain Precipitation Experiment (IPEX)

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IPEX—Improving the understanding, analysis, and prediction of precipitation over the complex topography of the Intermountain West

From 1990 to 2000, the five states with the fastest-growing populations in the United States were Nevada (66.3%), Arizona (40.0%), Colorado (30.6%), Utah (29.6%), and Idaho (28.5%) (U.S. Census Bureau Web site, see appendix for lists of all Web addresses discussed in this paper). These states lie within the Intermountain West, the geographic region east of the Pacific coastal mountain ranges, the Cascade Mountains, and Sierra Nevada, and west of the Continental Divide (Fig. 1a). As a result of these population pressures on the Intermountain West, the socioeconomic impacts of winter storms are increasing. Such impacts include public costs of road maintenance, private costs of property damage, disruption to daily commuter traffic and interstate commerce, and threats to public safety arising from snow- or ice-covered roads and avalanches. Although an imperfect dataset (Branick 1997), property damage reported in *Storm Data* from winter storms in Utah cost nearly $100 million over the four winter seasons from 1993/94 to 1996/97 (Blazek 2000).

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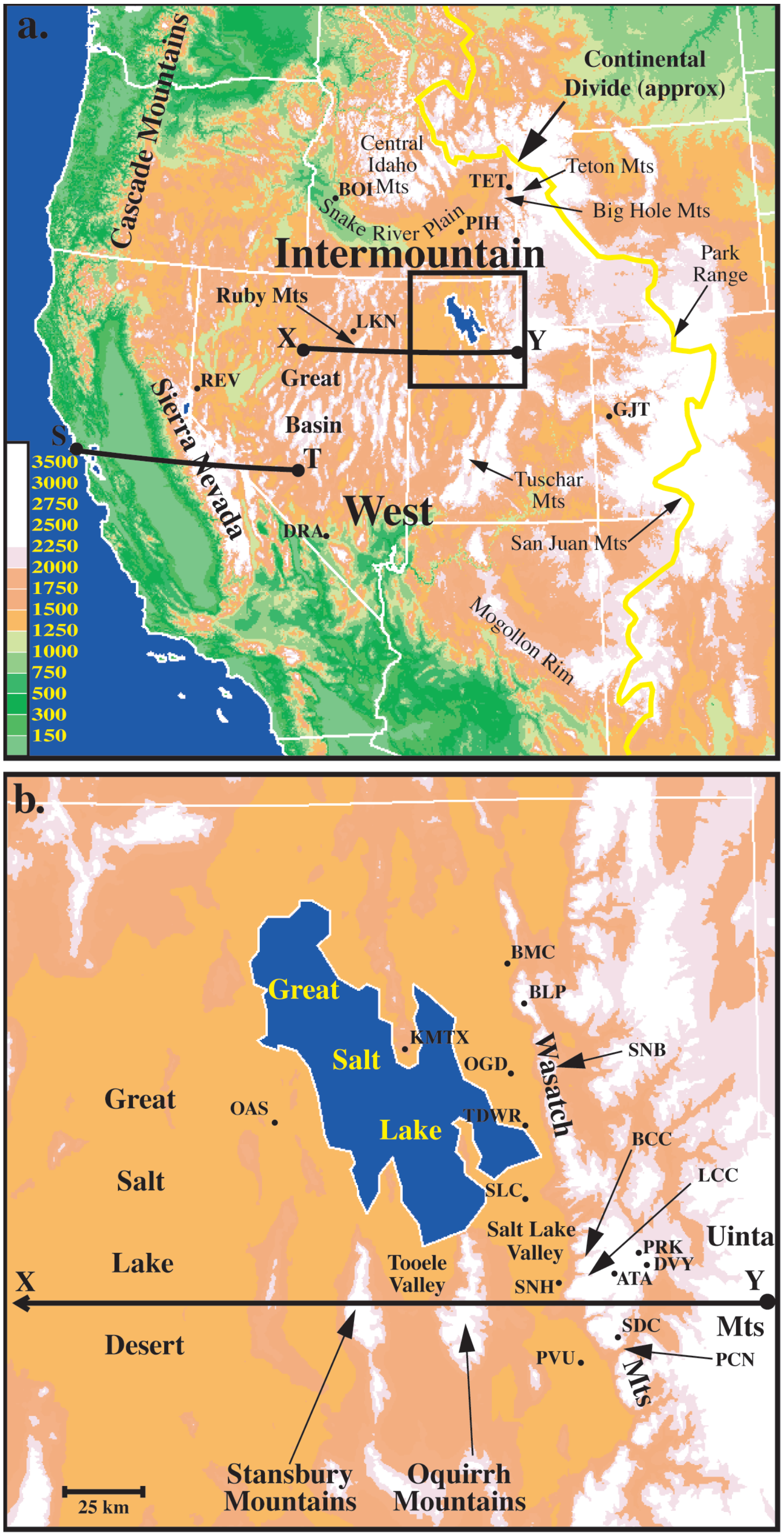


Fig. 1. Major terrain and geographic features of (a) the western United States and (b) northern Utah. Elevation (m, shaded) according to scale in (a). Inset box over northern Utah in (a) denotes position of (b). Line ST in (a) and XY in (b) denote locations of cross sections shown in Fig. 3. Abbreviations in (a): BOI = Boise, ID; DRA = Desert Rock, NV; GJT = Grand Junction, CO; LKN = Elko, NV; PIH = Pocatello, ID; REV = Reno, NV. Abbreviations in (b): CC = Cottonwood Canyon, HIF = Hill Air Force Base, KMTX = Promontory Point WSR-88D, OGD = Ogden, PVU = Provo, SLC = Salt Lake City, SNH = Sandy, TDWR = Salt Lake City Terminal Doppler Weather Radar.

The 11 counties of northern Utah compose one densely populated region of the Intermountain West, where nearly two million people are susceptible to winter storms. The intense vertical relief of the Wasatch Mountains and other nearby mountain ranges, and the surface sensible and latent heat fluxes associated with the Great Salt Lake, frequently contribute to the development of orographic and lake-effect precipitation along the Wasatch Front urban corridor, which includes the cities of Ogden, Salt Lake City, and Provo (Fig. 1b). Populated regions of this urban corridor range in elevation from 1300 to 1800 m (4265 to 5905 ft) and observe annual snowfalls of 110–250 cm (43–98 in.). Strong gradients in annual average snowfall and individual storms are observed, although gradients in individual storms cannot necessarily be predicted based on climatology. Substantial snowfall can be observed at low elevations, including a recent orographic and lake-effect snowstorm that produced accumulations of up to 130 cm (51 in.) in the Salt Lake City metropolitan area from 24 to 26 February 1998 (Slemmer 1998).

Concurrent with the rapid population growth has been a growing interest in outdoor activities. Between the 1982/83 and 1994/95 winter seasons, there was a 58.5% increase in the number of people over the age of 15 living in the United States who participate in downhill skiing (Cordell et al. 1997). Skier days in Utah increased from about 2 million to about 3 million between 1981/82 and 1999/00 (Park City Chamber of Commerce and Visitor's Bureau 2001, personal communication). Recreation-visitor days (defined as 1 person in a national forest for 12 h, 12 people for 1 h, or any combination thereof) in the national forests of the Intermountain West grew from approximately 23 million in 1976 to 35 million in 1992 (L. Lucas 2000, personal communication).

The Wasatch Mountains, which are located immediately east of the Wasatch Front urban corridor and rise abruptly to elevations of more than 3000 m (9843 ft; Fig. 1b), are one of the most popular mountain ranges in the United States for winter recreation. Average annual snowfall in the Wasatch Mountains reaches 1300 cm (512 in.), with record 24-h and storm-total accumulations at Alta ski area of 141 and 267 cm (55.5 and 105 in.), respectively (Pope and Brough 1996). On average, Alta observes 49 days per year with at least 12.5 cm (5 in.) of snowfall and 21 days with at least 25 cm (10 in.). Such snowstorms frequently contribute to increased avalanche hazard, a concern for public safety along mountain highways and in backcountry areas where the number of recreationists is growing. Over the period 1985–2000, the U.S. Forest Service Utah Avalanche Center documented over 1000 human-triggered avalanches in Utah, with most of those occurring in the Wasatch Mountains (B. Tremper 2001, personal communication). These avalanches have partially or totally buried 200 people, resulting in 42 fatalities. Thus, quantitative precipitation forecasting over the Intermountain West, including snow amount and snow-water equivalent (SWE),[1] is important, not only for public safety, but also for the availability of water in this otherwise arid environment. [For a discussion of western U.S. water resource issues, see Reisner (1986).]

Limited forecast skill. Unfortunately, skill in forecasting precipitation in the Intermountain West is lower than in other regions of the country, as demonstrated by the National Centers for Environmental Prediction (NCEP) operational models (e.g., Junker et al. 1992; Gartner et al. 1998; McDonald 1998). While human forecasters can generally improve upon that of numerical model output, forecasters tend to follow closely the trends of the model (Olson et al. 1995), so if the model performs poorly, so do forecasters. For example, P. Roebber (2001, personal communication) examined the correlation between the human-produced 24-h probability-of-precipitation forecasts and the observed probability of precipitation for 81 stations in the United States for winters (December–January–February) from January 1987 to February 1993. A minimum in skill existed in a region from New Mexico northward through Utah, western Colorado, Wyoming, Idaho, and Montana. Forecaster skill over this region was 10%–20% lower than states farther west and 20%–40% lower than states farther east. The reasons for these minima in numerical-model and human-produced forecast skill are likely varied, but include the following:

- Making an accurate forecast begins with an accurate diagnosis of the present situation. The manual and numerical analysis of evolving weather systems depends upon having access to timely and representative observational data. The Intermountain West lies downstream of the data void over the Pacific Ocean and, therefore, access to in situ upstream data to augment remotely sensed observations and assess evolving weather situations is limited. Since initial-condition uncertainty is an important contributor to model error growth (e.g., Langland et al. 1999) and model errors can propagate faster than the phase velocity of synoptic waves (e.g., Errico and Baumhefner 1987), the data void upstream of the Intermountain West is a concern even for short-range forecasts. Improving model initial conditions also involves making better use of the available data through improved data assimilation systems, which remains a substantial problem in regions of complex topography (e.g., Smith et al. 1997).
- Once onshore, these weather systems move through complex terrain and are exposed to substantial regional variability. Williams and Heck (1972) showed that the areal coverage of winter precipitation over regions as small as the Salt Lake City metro area is frequently less than 100% and less than similar areas in the eastern United States, making forecasting probability of precipitation in the Intermountain West difficult. In addition, observing sites in the conventional National Weather Service (NWS)/Federal Aviation Administration (FAA)/Department of Defense surface observing network are often in valleys and frequently unrepresentative of the free atmosphere (e.g., Williams

[1] Snow-water equivalent is a critical variable for avalanche forecasting since it measures the weight, and therefore stress, being added to the snowpack (e.g., McClung and Schaerer 1993; Mock and Birkeland 2000).

1972; Hill 1993; Steenburgh and Blazek 2001, section 3). Even remotely sensed data can be problematic. Accurate estimation of precipitation from the Weather Surveillance Radar-1988 Doppler (WSR-88D; Crum and Alberty 1993; Crum et al. 1998) radar network is limited by radar beam blockage, melting effects of precipitation, anomalous propagation in valley inversions, and mountain-top radars overshooting low-lying precipitation systems (e.g., Westrick et al. 1999; Huggins and Kingsmill 1999; Vasiloff 2001b,c). An example of the last point can be illustrated using the WSR-88D on Promontory Point, Utah (KMTX), situated at 2111 m (6929 ft) above sea level, 823 m (2700 ft) above Salt Lake City (Fig. 2). Consequently, the lowest elevation scan (0.5°) from KMTX overshoots the Wasatch Front urban corridor by 1 km over Ogden (Fig. 2) and 4 km over Provo. Thus, the bulk of valley snowstorms over major population areas often lie beneath the lowest elevation scans of KMTX, and thus accurate quantitative precipitation estimates are problematic.

- In comparison to the relatively broad Cascade Mountains and Sierra Nevada, the mountain ranges of the Intermountain West feature relatively small cross-barrier length scales (order 10 km), are steeply inclined on both the windward and leeward slopes, and are separated by broad lowland valleys that are tens of kilometers in width (Fig. 3). As a result, much of the topography of the Intermountain West is not adequately resolved by present-day forecast models (e.g., White et al. 1999). Errors arise not only from poor representation of local topography, but also the inability to properly simulate how upstream ranges affect the evolution of precipitation systems.
- The kinematic and microphysical processes occurring during orographic precipitation events are not well represented in current models. For example, systematic bias errors have been found in real-time simulations over the Pacific Northwest, which have produced too much precipitation on the windward slopes of the Cascades and too little to the lee (Colle and Mass 2000; Colle et al. 1999b, 2000). These biases may be related to uncertainty in the specification of ice-crystal fall speed (e.g., Colle and Mass 2000), inaccurate parameterization of orographic microphysical processes, or systematic errors in the simulation of the terrain-induced flow field.
- Even if forecasts of liquid precipitation amount were perfect, conversion of such forecasts to snowfall amount is difficult. Since current numerical modeling systems do not explicitly predict snowfall amount, some method must be assumed to estimate the snowfall depth from SWE. One common approach is to assume a 10:1 ratio of freshly fallen snow to SWE, equivalent to a snow density of 100 kg m. Observations of this ratio from freshly fallen snow at six locations across the western United States and Alaska range from less than 5:1 to greater than 25:1 (LaChapelle 1962, reproduced in Doesken and Judson 1997, p. 15; Judson and Doesken 2000). In addition, measuring snowfall has numerous problems including sublimation, compaction, drifting, the frequency of snow-depth measurement (e.g., Doesken and Judson 1997; Doesken and Leffler 2000), and the type of gauge (e.g., Goodison 1978; Groisman et al. 1991; Groisman and Legates 1994).
- These limitations in our ability to observe and model the weather of the Intermountain West ultimately limit our conceptual models of weather systems in complex terrain. The structure and evolu-

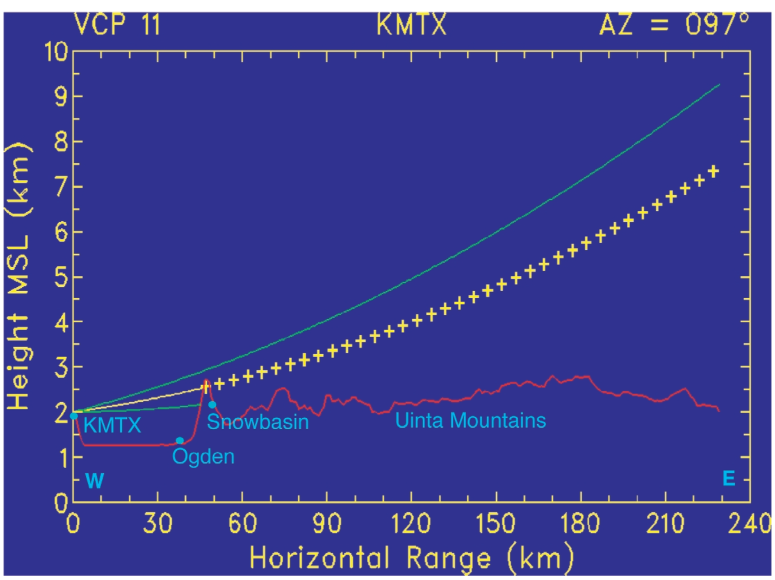


Fig. 2. Simulated vertical cross section from Promontory Point WSR-88D radar (KMTX) along the 97 radial. Black curve represents the earth's surface. Purple arc represents center of lowest beam (0.5°) and purple plus signs represent beam blockage by the Wasatch Mountains. Green arcs represent the half-power beamwidth. (Figure courtesy of Vincent Wood and Rodger Brown, National Severe Storms Laboratory.)

tion of cyclones and fronts and their associated precipitation regions are greatly perturbed by upstream mountain ranges, such as the Cascades, Sierra Nevada, and various ranges of the Great Basin. Thus, Intermountain West forecasters are frequently confronted with weather systems that do not readily conform to generally accepted conceptual models. For example, Williams (1972) stated, "the classical [Norwegian frontal] model, especially with regard to warm fronts and occlusions, fails in many respects to fit observed conditions over the western United States." Without conceptual models of weather systems to draw upon, forecasters have little context within which to place developing weather scenarios and evaluate numerical-model forecast output (e.g., Doswell 1986; Doswell and Maddox 1986; section 2b in Hoffman 1991; Pliske et al. 2001). Further discussion of western United States synoptic-analysis issues can be found in Williams (1972), Hill (1993), Schultz and Doswell (2000), and Steenburgh and Blazek (2001).

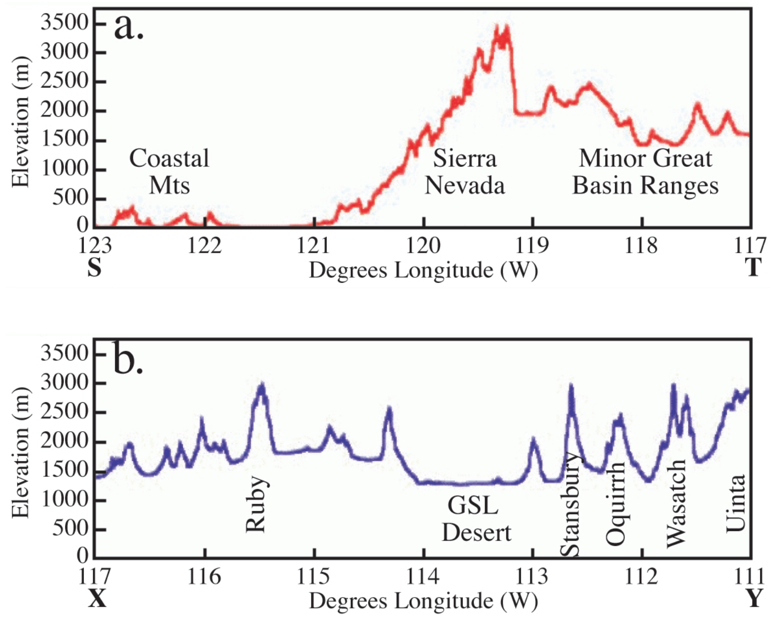


FIG. 3. Meridionally averaged (2 arc min) elevation (m above sea level) along lines (a) ST and (b) XY of Fig. 1b. Major mountain ranges and geographic features annotated. GSL = Great Salt Lake.

Thus, improvements in quantitative precipitation forecasting in mountainous regions require improved 1) observations; 2) understanding of storm, cloud, and precipitation processes; and 3) numerical weather prediction systems, particularly model physics. These needs have also been recognized by several national panels including the U.S. Weather Research Program (Smith et al. 1997; Fritsch et al. 1998) and the National Research Council (1998).

Goals of IPEX. The Intermountain Precipitation Experiment (IPEX) is designed to address challenges 1–3 by providing a first detailed examination of mountainous winter storms with modern sensors. The goals of the research program are the following:

1) To advance knowledge of the kinematic and dynamical structure of orographic precipitation events over the Intermountain West, with an emphasis on the Wasatch Mountains of northern Utah.
2) To understand better the relationships between orographically induced circulations and cloud microphysical processes.
3) To document the mesoscale structure and processes of lake-effect snowstorms produced by the Great Salt Lake, including the relative roles of lake- and terrain-induced circulations.
4) To improve quantitative precipitation forecasts over the Intermountain West through advances in data assimilation, numerical weather prediction, and radar-derived quantitative precipitation estimation from radars in mountainous regions.
5) To explore the electrical structure of continental winter storms.
6) To raise awareness of mountain meteorology and the associated scientific and forecasting challenges at the public, K–12, undergraduate, and graduate levels.

IPEX involves participants from the National Oceanic and Atmospheric Administration (NOAA)/National Severe Storms Laboratory (NSSL), Department of Meteorology, University of Utah and NOAA Cooperative Institute for Regional Prediction, NOAA/Aircraft Operations Center (AOC), Desert Research Institute, School of Meteorology, University of Oklahoma, several NWS Forecast Offices, NWS Western Region Headquarters, NWS Storm Prediction Center (SPC), NWS Hydrometeorological Prediction Center (HPC), Operational Support Facility (OSF, now known as the Radar Operations Center), and Utah Department of Transportation. The IPEX field phase was held in February 2000, during which observations of a variety of precipitation events were collected during seven intensive observing periods (IOPs). Results from the ongoing analysis of field-phase datasets will have positive scientific and socioeconomic benefits for the Intermountain West, including Salt Lake City, host of the 2002 Winter Olympic and Paralympic Games.

This article provides an overview of the IPEX field phase. The next section discusses some of the challenges to improving precipitation forecasting over the Intermountain West. A later section discusses the instrumentation employed during the IPEX field phase and the educational outreach component of IPEX. Another section describes the weather during the IPEX intensive observing periods (IOPs). The last section summarizes IPEX and explores some of the lessons learned by the IPEX team.

PRECIPITATION PROCESSES OVER THE INTERMOUNTAIN WEST. In this section, various features of the winter precipitation processes in northern Utah are described. These include orographic precipitation, lake-effect snowstorms, and lightning in winter storms.

Orographic precipitation. Geographically, the Intermountain West includes the basin and range topography of the Great Basin, which encompasses most of Nevada, Utah, and eastern Oregon, and is characterized by a large number of steeply sloped mountain ranges separated by broad basins of alluvium. In Nevada alone, there are 413 distinct mountain ranges, described in the late 1800s by the geographer Clarence Dutton as "an army of caterpillars marching toward Mexico." Compared to the Sierra Nevada or Cascade Mountains, the mountain ranges of the Great Basin are exceedingly narrow in their zonal extent (Fig. 3). Many other Intermountain West mountain ranges, such as the Teton Mountains of eastern Idaho and western Wyoming and the Ruby Mountains of Nevada, are also narrow in width. One of the more dramatic ranges of the Intermountain West are the Wasatch Mountains, which rise 1200–2000 m in about 5 km on their western slope and 1000–1500 m in about 10 km on their eastern slope (Figs. 1b and 3). In contrast, the central Idaho mountains are relatively large in horizontal extent (roughly 200 km across). In southern Idaho, the crescent-shaped Snake River Plain is a broad, lowland region that is approximately 120 km across and slopes upward in elevation from 900 to 1500 m from west to east.

During the winter season (October–March), the climatological distribution of precipitation is greatly influenced by the topographic features described above (e.g., Taylor et al. 1993; Daly et al. 1994). Ranges of the Great Basin, such as the Ruby and Wasatch Mountains, generally receive five times as much SWE as surrounding lowlands, with precipitation believed to be greatest at or near the mountain crest. In contrast, precipitation over the Sierra Nevada and along some portions of the Cascade Mountains is greatest windward of the crest (e.g., Armstrong and Stidd 1967; Daly et al. 1994). Although precipitation generally increases with elevation in the Great Basin, there are regions where precipitation increases without substantial elevation changes. For example, approaching the Wasatch Mountains from the west, annual precipitation increases from 12.5 cm (5 in.) over the Great Salt Lake Desert to 38 cm (15 in.) in the center of the Salt Lake Valley, despite little change in elevation. This increase in precipitation is related, in part, to the influence of the Great Salt Lake (see next subsection) and blocking by the Wasatch Mountains. Blocking is associated with the turning of the low-level wind direction near the mountains to be more parallel to the mountain range (e.g., Parish 1982; Marwitz 1987; Overland and Bond 1995; Ralph et al. 1999). As a result of the blocking, lower-tropospheric convergence occurs upstream of the mountains, enhancing precipitation even before the topography begins to rise. Farther east, the strong gradients in elevation lead to strong gradients in precipitation. For example, at the western base of the Wasatch, annual precipitation is 60 cm (23.6 in.), while less than 10 km away, the town of Alta averages 143 cm (56.3 in.). Precipitation can also vary among locations in the Wasatch Mountains due to local topographic effects. Dunn (1983) found that heavy precipitation at Alta was favored during northwesterly 700-hPa flow, but Park City was favored during southwesterly through west-northwesterly flow.

During the 1970s and 1980s, a number of field programs examined orographic precipitation processes over the Intermountain West and eastern Rocky Mountains, with numerous publications on orographic storms over the Park Range (e.g., Rauber et al. 1986; Rauber and Grant 1986) and San Juan Mountains (e.g., Marwitz 1980; Cooper and Saunders 1980; Cooper and Marwitz 1980) of Colorado, as well as the Tushar Mountains of central Utah (e.g., Sassen et al. 1986; Long et al. 1990; Sassen et al. 1990). The primary emphasis of these studies was to evaluate the possibility of augmenting snowfall through cloud seeding, with an emphasis on mapping the distribution and evolution of supercooled liquid water in orographic winter storms. Although these studies described some aspects of the kinematic structure of orographic precipitation events, they did not collect dual-Doppler radar observations to describe the three-dimensional flow field; and deploy ground- and aircraft-based thermodynamic and wind observations in sufficient detail to compare to numerical simulations because these research efforts were not the emphasis of cloud-seeding field programs.

More recent field programs have used data from research aircraft, dual-Doppler analysis, mesoscale model simulations, or a combination of these methodologies to examine the influence of terrain-induced circulations on the distribution of precipitation in regions of complex terrain in the United States and Europe. These include the Arizona Program (Klimowski et al. 1998); Coastal Observation and Simulation with Topography Experiment (COAST; Bond et al. 1997); California Landfalling Jets Experiment (CALJET; e.g., Neiman et al. 2001); Mesoscale Alpine Programme (MAP; Bougeault et al. 2001); Pacific Landfalling Jets Experiment (PACJET); and Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE). For example, Bruintjes et al. (1994), Klimowski et al. (1998), and Reinking et al. (2000) found orographic gravity waves modulated cloud water and augmented winter upslope precipitation over the Mogollon Rim of Arizona. In addition, Colle and Mass (1996) employed dual-Doppler analysis to illustrate the three-dimensional flow around the Olympic Mountains during a precipitation event that featured substantial windward enhancement and leeside suppression of precipitation. Braun et al. (1997), Colle et al. (1999a), and Yu and Smull (2000) also used dual-Doppler analyses to examine the interaction of landfalling frontal precipitation systems with coastal orography of the northwestern United States.

During the field phase of IPEX, airborne and ground-based radars, additional upper-air data, National Lightning Detection Network data, and high-density surface observations were used to provide unprecedented coverage of the kinematic structure of precipitating systems over northern Utah and the Wasatch Mountains. Combined with airborne microphysical observations, these data are allowing scientists to examine important questions concerning orographic precipitation processes. What important factors control the mesoscale distribution of precipitation during winter storms in regions of complex terrain? Why do precipitation gradients observed during individual storms deviate substantially from climatology? What factors (e.g., stability, wind direction) affect the enhancement of precipitation upwind of orography, particularly over northern Utah, where the incident flow has been influenced by upstream mountain ranges and the Great Salt Lake? What processes influence spillover, the orographic precipitation carried by the wind over the peaks to reach the lee of mountain ranges (e.g., Fraser et al. 1973; Hobbs et al. 1973; Sinclair et al. 1997)? Is such spillover substantially influenced by mountain-induced gravity waves? To what extent does blocking occur along the Wasatch? As with the San Juan Mountains of Colorado, is such blocking and its associated barrier jet less pronounced than that found upwind of Pacific mountain ranges such as the Sierra Nevada (e.g., Marwitz 1986)? Finally, how do terrain-induced, frontal, and convectively driven circulations impact cloud microphysics and precipitation production, particularly on small spatial and temporal scales? IPEX data is also allowing for the validation and eventual improvement of high-resolution numerical simulations, with specialized observations used to evaluate model forecasts of complex orographic airflows and cloud microphysical processes.

Great Salt Lake–effect snowstorms. Further complicating precipitation processes over northern Utah is the Great Salt Lake, which produces lake-effect snowstorms several times each year in the Wasatch Front urban corridor (Carpenter 1993; Steenburgh et al. 2000). Although typical lake-effect events produce snow accumulations of several centimeters, more intense and long-lived events can also occur: on 17–18 October 1984, up to 69 cm (27 in.) of snow fell in the Salt Lake Valley (Carpenter 1993).

Steenburgh et al. (2000) developed a climatology of lake-effect snowstorms of the Great Salt Lake, identifying two major types of lake-effect structures: solitary wind-parallel bands typically aligned along the major axis of the lake, and broad-area precipitation shields located over and downstream of the southeastern (lee) lake shoreline. Occasionally, both structures occurred simultaneously. Subsequent work by Steenburgh and Onton (2001) and Onton and Steenburgh (2001) examined the 7 December 1998 wind-parallel lake-effect snowband that produced accumulations of up to 36 cm (14.2 in.) in the Tooele Valley. They showed the localized sensible and latent heat fluxes over the Great Salt Lake produced a mesoscale pressure trough, land-breeze circulations, and low-level convergence that led to the development of the snowband. Thus, even though the Great Salt Lake is substantially smaller than any of the Great Lakes, the dynamics controlling the 7 December 1998 lake event were analogous to midlake bands over Lakes Michigan and Ontario (e.g., Peace and Sykes 1966; Passarelli and Braham 1981; Hjelmfelt and Braham 1983; Hjelmfelt 1990; Niziol et al. 1995).

Not as well understood are other types of lake-effect events: those that develop broad-area precipitation shields and those that involve both lake and orographic processes. Broad-area coverage events over the Great Lakes frequently involve horizontal roll convection (e.g., Kelly 1982, 1986), but such rolls have not been observed during broad-area coverage events over the Great Salt Lake, perhaps because the surrounding topography inhibits their development. Although orography plays an important role in many Great Lakes' snowstorms, the scale of topography downwind of the Great Salt Lake is much larger. As a result, terrain-induced circulations may be essential to the development of some apparent lake-effect snowstorms in northern Utah.

One of the IPEX goals is to improve knowledge of lake-effect snowstorms of the Great Salt Lake, with an emphasis on determining the roles of lake- versus terrain-induced mesoscale circulations. Of particular interest is the hypothesis, based on the radar climatology and modeling work presented by Steenburgh et al. (2000), Steenburgh and Onton (2001), and Onton and Steenburgh (2001), that the diurnal evolution of thermally driven circulations, such as land breezes, greatly modulate the intensity of over-lake convergence and subsequent lake-effect precipitation.

Lightning in winter storms. Relatively few studies have examined the climatology and causes of thunder snow (see references within Schultz 1999). In their textbook, MacGorman and Rust (1998, p. 292) noted 1) relationships between the electrical state of winter storms and their snowfall have not been investigated thoroughly, 2) electrical observations within winter storms have been sparse, with no apparent electric-field soundings in the United States, and 3) much of the literature about soundings in other countries has been unclear on whether clouds in which soundings were made were thunderstorms or electrified nonthunderstorm clouds.

As a starting point for a focused region of the country, Schultz (1999) investigated the discriminating factors for lake-effect events in northern Utah with lightning and without lightning. Lake-effect snowstorms with lightning had significantly higher lower-tropospheric temperatures, dewpoints, and surface-to-700-hPa temperature differences (a surrogate for lower-tropospheric lapse rate) and significantly lower lifted indices than lake-effect snowstorms without lightning. In contrast, there was little difference in surface dewpoint depressions between events with and without lightning. Nearly all lake-effect events had virtually no convective available potential energy, regardless of the presence of lightning. These results, however, are not sufficient for understanding why a warmer and moister lower troposphere was necessary for lightning production.

An additional IPEX observational component involved balloon-borne soundings of the electric field (and inferred charge layer structure) within snowbands. This objective was to make a few soundings in a small feasibility project to begin to document the electrical structure of winter storms in the United States.

IPEX DESIGN. Northern Utah was selected for IPEX field operations because of its challenging forecast problems (previous section), its proximity to a large weather-sensitive population (first section), strong topographic relief (Fig. 1b), and the local support available from the SLC NWS Forecast Office and the University of Utah Department of Meteorology. February 2000 was chosen for the field phase of IPEX for several reasons. First, climatologically, the most snowfall and greatest precipitation occurs from December to March (Pope and Brough 1996) and the most likely months for lake-effect snowstorms are November through February (Steenburgh et al. 2000). Second, local forecasters were concerned that January has less consistent snowfalls than January due to more frequent high-amplitude ridges. Third, February 2000 allowed for better availability of observing facilities. Finally, the Salt Lake City Winter Olympic and Paralympic Games will be held during February and early March 2002, so the IPEX field program provides additional insight into weather conditions that may occur. In the rest of this section, the observing systems, forecasting support, operations, and educational outreach aspects of IPEX are discussed.

Observing systems. A variety of specialized observing platforms were employed during IPEX (Table 1): the NOAA P-3 aircraft, two mobile Doppler radars, a deployable vertically pointing Doppler radar, and two NSSL mobile laboratories. These facilities were combined with extensive observing facilities already in place: the surface and upper-air observations collected by the NWS; the WSR-88D on Promontory Point, Utah (KMTX) in addition to other WSR-88Ds; the FAA Terminal Doppler Weather Radar (TDWR) supporting Salt Lake City International Airport (SLC); a mesonetwork of surface observing stations known as the MesoWest Cooperative Networks

Table 1. IPEX observing facilities and modeling systems.

System	Overseeing organization	Number	Measurements	References or frequency
WP-3D (P-3) Orion aircraft (NOAA-43)	NOAA Aircraft Operations Center	1	Doppler radar microphysics flight-level data	
Doppler on Wheels (DOW)	University of Oklahoma	2	Radar reflectivity Doppler velocity	Wurman et al. (1997)
Vertically pointing S-band Doppler radar	National Severe Storms Laboratory, Radian Corporation Salt River Project	1	Radar reflectivity Doppler velocity	Gourley et al. (2000)
Mobile laboratories	National Severe Storms Laboratory	2	Rawinsondes surface data electric field	
Special soundings	National Weather Service (NWS), Salt Lake City, Boise Reno, Elko	4	Rawinsondes	3-hourly
Special soundings	NWS Grand Junction	1	Rawinsondes	6-hourly
Special soundings	Air Resources Laboratory Special Operations and Research Division, Desert Rock	1	Rawinsondes	1800 UTC
Weather Surveillance Radar-1988 Doppler (WSR-88D)	NWS	several	Radar reflectivity Doppler velocity	Crum and Alberty (1993) Crum et al. (1998)
Terminal Doppler Weather Radar (TDWR)	Federal Aviation Administration	1	Radar reflectivity Doppler velocity	Turnbull et al. (1989) Michelson et al. (1990) Vasiloff (2001a)
MesoWest Cooperative Networks	Cooperating agencies organized by University of Utah	2500	Surface data	Horel et al. (2000)
Microwave radiometer	University of Utah Facility for Atmospheric Remote Sensing	1	Integrated water vapor and cloud water	Sassen et al. (2001)
ARPS Data Assimilation System	University of Utah			Hourly
Mesoscale model (MM5)	University of Utah			0000 and 1200 UTC

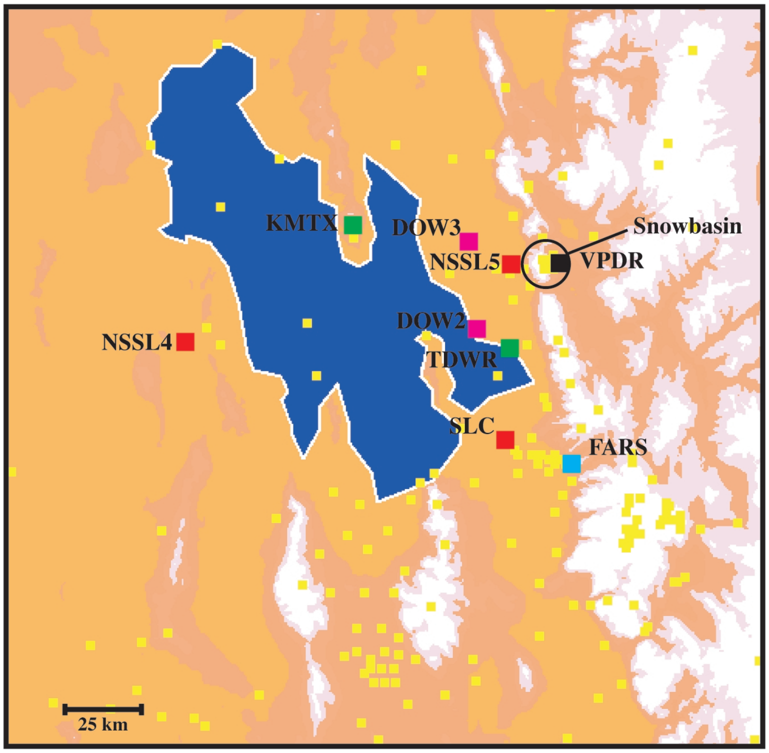


Fig. 4. Locations of IPEX observing systems including the NSSL mobile laboratories (NSSL4 and NSSL5, red squares); Salt Lake City radiosonde station (SLC, red square); Promontory Point WSR-88D radar (KMTX, green square); FAA Terminal Doppler Weather Radar (TDWR, green square); mobile Doppler on Wheels units (DOW2 and DOW3, magenta squares); vertically pointing Doppler radar (VPDR, black square); Facility for Atmospheric Remote Sensing microwave radiometer (FARS, cyan square); and MesoWest observing sites (yellow squares). Operations Center and P-3 base located at SLC.

(Horel et al. 2000); and a dual-frequency microwave radiometer at the University of Utah. Figure 4 depicts the location of these fixed observing sites.

A NOAA WP-3D (P-3) Orion aircraft (NOAA-43) equipped with radars and in situ sensors provided observations of precipitation structure upwind, over, and to the lee of the Wasatch Mountains (Fig. 5). One of the key observing tools was the tail-mounted, X-band Doppler radar (Jorgensen et al. 1983), which scans in quasi-vertical planes oriented sequentially at about 20° fore and aft of the imaginary plane normal to the flight track. The fore–aft scanning technique (Jorgensen et al. 1996) was employed during IPEX, affording the ability to reconstruct the three-dimensional mesoscale airflow within an approximately 80-km-wide volume centered on each flight leg.

In situ sensors were also critically important. These include observations of basic meteorological variables (e.g., temperature, moisture, and wind) along the flight path as well as more detailed observations of cloud and precipitation properties (e.g., particle phase, size, shape, and concentration) from microphysical probes (Knollenberg 1972; Heymsfield and Baumgardner 1985). During IPEX, the aircraft was mounted with the Particle Measuring System (PMS) forward-scattering spectrometer probe (FSSP), the two-dimensional grey cloud probe (2DGC), and the two-dimensional precipitation probe (2DP) as well as the Commonwealth Scientific and Industrial Research Organization King cloud probe. These probes underwent an exhaustive set of repairs and calibrations prior to and during the project, which resulted in one of the highest quality P-3 microphysical datasets collected in many years.

Flight patterns usually involved either an along-barrier racetrack or cross-barrier stack (Fig. 5). The along-barrier racetracks were performed to examine the along-Wasatch variability of orographic precipitation and usually required about 40–60 min to perform. Cross-barrier stacks were used

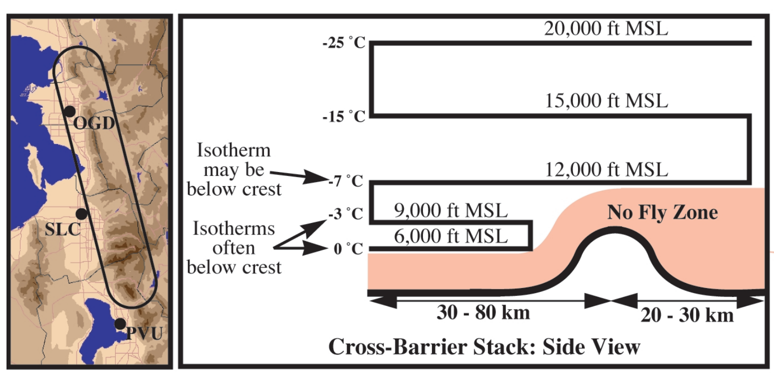


Fig. 5. Schematic of typical along-barrier racetracks and cross-barrier flight stacks with stack-leg temperatures for microphysical sampling. In practice, altitudes vary based on stratification and flight restrictions (e.g., no-fly zone). OGD = Ogden, PVU = Provo, SLC = Salt Lake City.

to examine the variability of cloud and precipitation processes as a function of distance from the barrier and as a function of temperature regime.

The broad (and flight duration limited) coverage provided by the airborne platform was complemented by the University of Oklahoma's Doppler on Wheels (DOW) radar scans. The two DOWs (DOW2 and DOW3) are pulsed, X-band Doppler radars mounted on the back of flatbed trucks (Wurman et al. 1997). During IPEX, the two DOWs were deployed largely to predetermined locations (Fig. 4) on the windward side of the Wasatch; their mobility was exploited during IOPs 1 and 5, however, when DOW2 was deployed to near Tetonia, Idaho, and the Tooele Valley, Utah, respectively. The dual-Doppler baseline typically was about 20 km, and the bisector distance to the crest of the Wasatch was about 20–25 km. With 12 elevation scans, this configuration allowed volume scans of typical orographic clouds within 1 to 2.5 min, with a nominal datapoint spacing of a few hundred meters. Such high-resolution scans are critical to examine the evolution of precipitation features.

A vertically pointing S-band Doppler radar operated jointly by NSSL, Radian Corporation, and the Salt River Project (Gourley et al. 2000) was deployed to provide high temporal resolution reflectivity data for judging quantitative precipitation estimates from WSR-88Ds sited at high altitudes. This radar was developed by NOAA's Aeronomy Laboratory and measures radar reflectivity, Doppler velocity, and other Doppler-radar moments of precipitating clouds at ranges of 0.25 to as high as 20 km. The radar was deployed on the east side of the Wasatch Mountains at the Snowbasin Ski Resort, where radar observations of the lowest 800–1200 m of the atmosphere would be possible, a layer unobservable with the KMTX WSR-88D (Fig. 2).

To examine the three-dimensional wind field over northern Utah, flow modification by topography and boundary layer temperature and moisture modification by the Great Salt Lake, in situ rawinsonde observations were gathered at 3-h intervals at the NWS SLC Forecast Office and by two NSSL mobile laboratories. The NSSL mobile laboratories (NSSL4 and NSSL5) are converted 15-passenger vans equipped with the Mobile Global Positioning System (GPS) and Loran Atmospheric Sounding System (M-GLASS). M-GLASS evolved from a system originally developed for fixed-site use by the Atmospheric Technology Division of the National Center for Atmospheric Research (NCAR) called the Cross-chain Loran Atmospheric Sounding System (CLASS) and was later modified for mobile use (M-CLASS; Rust et al. 1990). Typical deployment sites of NSSL4 and NSSL5 at Oasis at the Utah Test and Training Range in the Great Salt Lake Desert and Ogden Airport, respectively, are indicated in Fig. 4, although their mobility was exploited during IOPs 1 and 5.

When electric-field measurements were called for, NSSL5 flew an instrument train comprising an electric-field meter and a Vaisala RS80 GPS radiosonde on a 600-g balloon. The sonde provided the thermodynamic variables, winds, and balloon location. The basics of this electric-field meter were first described by Winn and Byerley (1975), with the version flown during IPEX described and illustrated in MacGorman and Rust (1998, p. 127). The electric-field meter can sense an electric field E as low as a few hundred Volts per meter and was thus suitable for measuring electrification in weakly electrified clouds, as might be expected during IPEX. [Whereas electric-field maxima in cumulonimbus clouds are typically 75–150 kV m^{-1}, the few electric-field soundings made in Japanese winter storms were < 30 kV m^{-1} (Magono et al. 1983)]. A total of six electric-field meters were flown during IOPs 2, 3, 5, and 6.

The 12-h standard NWS soundings were supplemented by special soundings as frequently as every 3 h during IOPs. The NWS Western Region provided 205 additional radiosonde launches from six field offices in support of IPEX (Table 1).

Surface observations from over 2500 automated stations in the western United States were collected and archived during IPEX. This effort was conducted as part of an ongoing project referred to as MesoWest at the University of Utah and the SLC NWS Forecast Office (Horel et al. 2000). Surface observations in northwestern Utah during IPEX were provided by 28 cooperating government agencies and commercial firms. Over 250 stations are in northern Utah alone (Fig. 4 shows a sampling of the sites closest to the Great Salt Lake and Wasatch Front urban corridor). During the field phase of IPEX, eight additional automated surface stations were deployed, primarily around the Great Salt Lake by the Department of Meteorology and seven additional stations were deployed in Salt Lake City by the Department of Energy's Pacific Northwest Laboratory. All MesoWest stations report temperature, whereas most also report wind and relative humidity. About one-third of these stations provide pressure or precipitation data. Among the precipitation observations that are available in the Wasatch Mountains is an eight-station network of automated precipitation gauges and ultrasonic snow-depth sensors (Vasiloff 1996). Using data collected from many different networks with heterogeneous sensors, siting, standards, and maintenance procedures is a challenge. Automated quality control procedures based upon three-dimensional linear regression are applied to the MesoWest observations (Splitt and Horel 1998; Splitt and Blazek 2000). Additional quality control procedures specific to IPEX precipitation data are described by Cheng (2001).

A dual-frequency microwave radiometer at the University of Utah Facility for Atmospheric Remote Sensing (Sassen et al. 2001) measured the evolution of integrated water vapor and cloud water. The microwave radiometer provides data for characterizing mesoscale and orographic cloud structure and validating mesoscale-model simulations.

Using, and otherwise complementing, the observations were the data analysis and modeling systems at the University of Utah. The Advanced Regional Prediction System (ARPS) Data Assimilation System (ADAS; e.g., Ciliberti et al. 2000) produced hourly analyses at 1-km horizontal grid spacing for northern Utah. The Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Fifth-Generation Mesoscale Model (MM5) is a nonhydrostatic, primitive-equation model (Warner et al. 1992; Dudhia 1993; Grell et al. 1994), which is run twice daily at 12-km horizontal grid spacing in its real-time implementation at the University of Utah (e.g., White et al. 1999; Onton et al. 2001).

Forecasting and operations. Doswell et al. (1986) described the issues related to forecasting for field programs. Specifically, they recognized the distinction between forecasting and decision making for the field program. During IPEX, however, the forecasting process went beyond providing guidance for the Operations Coordination Team (i.e., the IPEX chief scientists and those in charge of the individual research facilities). Because of the direct link between the scientific objectives of IPEX and operational forecasting, using the daily forecasts from the IPEX Operations Center as part of the experiment itself was a natural extension of the objectives of IPEX.

Forecasting during IPEX had several purposes: 1) to predict the weather scenarios possible for field operations and deployments, 2) to provide guidance for possible P-3 missions for flight-level conditions, 3) to examine forecasters' ability to identify scenarios where lake-effect precipitation and cloud-to-ground lightning was possible, and 4) to provide a dataset for future verification of probabilistic and quantitative precipitation/snow forecasts in an operational setting.

The forecast team also prepared a variety of forecast products by 1800 UTC for daily meetings and forecast verification (Table 2). These products were selected based on program needs and the desire to limit the ambiguous validation of forecasts. These forecasts are archived on the Web (see appendix).

Forecasting support for IPEX was defined as daily and long-term prediction, while nowcasting support was defined as short-term (less than 3 h) prediction and real-time support of field operations. Forecasters were drawn from participating IPEX scientists, NWS forecasters (NWS SLC, SPC, HPC, and OSF), and University of Utah students. All forecasting and nowcasting operations for IPEX were conducted from the operations center set up in the briefing room at the NWS SLC Forecast Office, which facilitated interaction between IPEX scientific staff and forecasters with NWS personnel. IPEX forecasting and nowcasting support operated seven days a week for the full field phase of the experiment.

The most critical operations decisions were associated with the deployment of facilities due to the costs involved and the need to predeploy facilities well ahead of expected precipitation events. In addition, the NOAA/AOC P-3 flight management policy specified 24-h alert for take-off time, and crew duty-day rules limited the delays that could be imposed from the specified take-off time. The IPEX Operations Coordination Team met each day to consider IOP strategies. More information regarding the details of IPEX operations can be found in the operations manual on the Web (see appendix).

Educational outreach. IPEX provided an exceptional learning opportunity for undergraduate and graduate students at the University of Utah and an opportunity to capture the scientific curiosity of students through outreach at the K–12 level. Thirty University of Utah students partnered with field-program scientists to execute IPEX IOPs. Undergraduate and graduate students contributed to data collection during IOPs, attended weather briefings and planning meetings, and provided weather support during IPEX forecast shifts. Through direct collaboration with program scientists in hands-on data collection, students gained valuable exposure to meteorological research, and practical experience in observations, electrification, radar, and forecasting. On one no-fly day, 120 local junior high school students toured the P-3.

IPEX also received extensive broadcast and print media coverage throughout the state of Utah and nationally, helping to explain the project's purpose and to educate the public about the complex weather forecasting challenges in the Intermountain West. The extent of the media coverage the experiment received can be illustrated by the experience of one IPEX participant. While skiing at Alta on an off day, he rode the lift with four different people. In each of the conversations, he was asked about why he was in Utah and he explained he was part of a winter weather experiment. Incredibly, three out of the four people he spoke with had heard of IPEX.

Two Salt Lake City newspapers ran stories in advance of the experiment. On the first day of operations, more than a dozen broadcast and print reporters packed into a news conference announcing the start of IPEX. The event featured comments from IPEX participants and tours of the research equipment used in the experiment, including the P-3, NSSL5, and DOW2. The following day, six media representatives were escorted to Snowbasin Ski Resort to view the vertically pointing Doppler radar, the precipitation gauges, and snow sensors. Reporters from three different news organizations rode along on P-3 flights during IOPs. *Powder* magazine interviewed one of the chief scientists. At the end of the intensive operations period, the scientists met with reporters to discuss their successes. *USA Today* gave IPEX national coverage with a four-part story on their Web site and a follow-up article published in the newspaper in March. The Weather Channel ran a story on IPEX during their news segments during two periods in March. Also in March, IPEX scientists were featured in NOAA-supported *Passport to Knowledge: Live from the Storm*, an ongoing series of interactive learning experiences designed to inspire students by providing science information more current than what is typically found in textbooks. The *Passport to Knowledge* broadcast program included

Table 2. Forecast products issued at 1800 UTC each day during IPEX by IPEX forecasters.

MESOSCALE FORECAST DISCUSSION: A technical discussion of the factors influencing the present forecast and forecast decisions. It does not have a strict format or length, but should document the reasoning behind the day's forecast. Discussion of the use and utility of experimental products, such as the Utah MesoWest, MM5, and ADAS is encouraged.
LAKE-EFFECT PRECIPITATION OUTLOOK: Categorical forecasts of the following: if lake-effect precipitation will occur, a solitary wind-parallel band will develop, snow advisory or heavy snow criteria will be met, and if lake-effect precipitation will occur in Davis, Salt Lake, or Tooele Counties. This information is needed for forecast planning and to examine the predictability of lake-effect precipitation.
LIGHTNING OUTLOOK: Categorical and probabilistic forecasts of lightning in the target area. Decisions regarding the deployment of rawinsondes with field mills requires this information. Product will be verified against observations from the National Lightning Detection Network.
PROBABILISTIC PRECIPITATION GRAPHIC: Graphical plots illustrating the probability of precipitation (snow water equivalent) exceeding 0.1 in. in the study area with contours drawn at three levels: 25%, 50%, and 75%.
POINT PRECIPITATION FORECASTS: Precipitation forecasts (snow water equivalent) for four points in the target area. Snowbasin [Middle Bowl, SNI, a midmountain site at 2146 m (7402 ft)], Ogden (OGD), and Salt Lake City (SLC) are 6-h amounts for four 6-h periods starting at 1800 UTC. Alta Central [manual measurement at the base of the mountain 2661 m (8730 ft)] is two 12-h amounts starting at 0000 UTC. Forecasters should be aware of the difficulties of measuring snowfall and liquid water equivalent in complex terrain either manually or with automated gauges.
ENVIRONMENTAL CONDITIONS: Forecasts for products needed for field-program planning or evaluation of operational utility made at 6-h intervals for 30 h. These values are the mean 850–700-hPa potential height ($H = U/N$, where U is the layer-averaged cross-barrier wind speed, and N is the layer-averaged Brunt–Väisälä frequency, both calculated for the layer above any surface-based inversions and below 700 hPa), surface and 700-hPa SLC wind direction and speed, height of 0°, –3°, –7°, –15°, and –25°C isotherms (feet above sea level for flight-planning considerations).
CONTINGENCY OPTION DISCUSSION: Technical discussion of the potential for P-3 reconnaissance near the Teton Mountains of Wyoming and Idaho or the Tushar Mountains of central Utah. This should be completed during periods where flights in the Wasatch Mountains are unlikely.
LONGER-RANGE OUTLOOK: Brief technical discussion of the 2–4-day forecast that considers the potential for IOPs.

footage of the experiment and interviews with researchers. The Web site featured biographies of the lead scientists and diaries from the field. After the completion of IPEX, a 12-min video of highlights, interviews, and an extended news release, a B-roll, was compiled for distribution for future media requests. Some of this footage was used in an *Investigative Reports* program, which aired in January 2001 on the Arts and Entertainment cable network. In all, over 20 print and 25 television spots on IPEX appeared.

THE WEATHER DURING IPEX. Weather during the IPEX field phase fell into two regimes: a dry period before 10 February 2000 characterized by a large-scale ridge over the western United States, followed by an active period when the ridge broke down and the flow became more southwesterly and progressive (Fig. 6). Despite the dry first 10 days of February, northern Utah experienced above-normal precipitation and temperature during the month, although the valleys received less snowfall than usual. For example, Salt Lake City Airport (SLC) was 3.2°C above normal with 4.6 cm (1.80 in.) of precipitation, 146% of normal, but 13.0 cm (5.1 in.) of snow, 55% of normal. Nevertheless, despite the below-normal snowfall at SLC, most mountain stations received 100%–300% of normal precipitation for February. For example, Alta received 26.7 cm (10.53 in.) of precipitation, 154% of normal, and 303.5 cm (119.5 in.) of snowfall, 161% of normal.

The structure and evolution of precipitation during the IPEX period has been investigated by Cheng (2001) based upon precipitation observations from precipitation gauges at 90 stations in northern Utah. As an example of the variability in precipitation observed during IPEX, Fig. 7 contrasts the precipitation observed during IPEX at two mountain locations [Ben Lomond Peak, BLPU1, 2438 m (7999 ft) in elevation, northeast of Ogden; and Alta Guard House, ATAU1 2661 m (8730 ft), adjacent to Alta Ski Area in Little Cottonwood Canyon east of Salt Lake City] to that at two locations in the Salt Lake Valley [Salt Lake City Airport, SLC, 1288 m (4226 ft), and Sandy, SNH, 1450 m (4757 ft)]. The greatest variation in precipitation amount occurred during the period 12–14 February (spanning IOPs 3 and 4) when Ben Lomond Peak received 18.6 cm (7.3 in.) of precipitation while Alta reported only 6 cm (2.4 in.) and less than 1 cm (0.4 in.) was observed in the Salt Lake Valley. In this section, each IOP is briefly described, along with the data collected, and a discussion of scientific issues involved with each event (Table 3). There were no missed opportunities—all significant snow events were explored during IOPs.

31 January 2000: Light persistent snow event over Salt Lake Valley. A relatively weak snow event was forecast for the Wasatch Front in the morning, ending around noon with totals up to an inch at most in the valley. Because the IPEX kick-off press conference was scheduled for this time, it was decided to forgo formal operations. DOW2 did deploy to test its systems and obtain some demonstration data for the press conference. Light snow continued most of the day, with

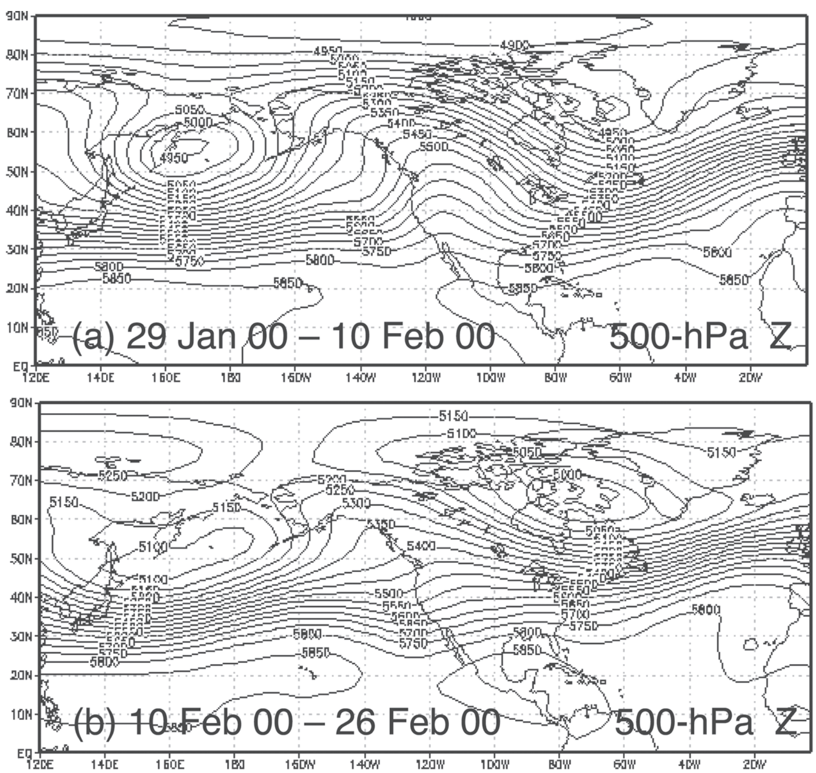


FIG. 6. Composite 500-hPa height (solid lines every 50 m) from the NCEP–NCAR Reanalysis (Kalnay et al. 1996) for (a) first regime during IPEX: 0000 UTC 29 Jan–0000 UTC 10 Feb 2000, and (b) second regime: 0000 UTC 10 Feb–0000 UTC 26 Feb 2000. (Provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at http://www.cdc.noaa.gov.)

a total snowfall at SLC of 10 cm (4 in.).

IOP 1: 5 February 2000: Light snow in the Teton Mountains. On 5 February, a weak weather system with light snow forecast for Idaho and Wymoming led to the deployment of selected equipment to eastern Idaho and northwestern Wyoming. Widespread precipitation was caused by large-scale ascent associated with lower- and midtropospheric warm advection and southwesterly flow ahead of a decaying Pacific frontal system. In addition, stable orographic precipitation was enhanced over the Big Hole and Teton Mountains.

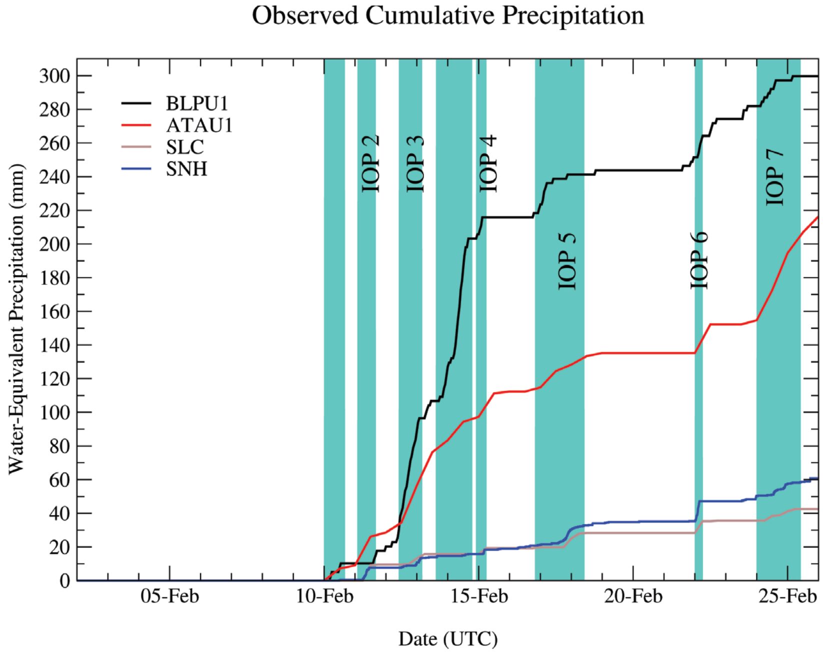


Fig. 7. Cumulative time series of observed precipitation at four sites during IPEX: Alta Guard House (ATAU1, red line); Ben Lomond Peak (BLPU1, black line); Salt Lake City Airport (SLC, brown line); and Sandy (SNH, blue line). Shaded areas represent periods of subjectively determined precipitation events over the IPEX domain, with the events corresponding to the IPEX IOPs labeled. From Cheng (2001).

Initially, widespread reflectivity from the Pocatello KSFX WSR-88D was observed, although little precipitation reached the surface. Subcloud evaporation was likely important over the Snake River Plain due to the high surface dewpoint depressions (e.g., 10°C) at the onset of the event. Eventually, reflectivity was enhanced over the Big Hole and Teton Mountains and rain shadowing in the lee of the Big Hole Mountains resulted in weaker and less frequent reflectivity in the lowlands near Tetonia, Idaho, where DOW2 and NSSL5 were located. Storm-total snowfall in the Teton Mountains was 10–15 cm (4–6 in.) and SWE was 0.79–1.35 cm (0.31–0.53 in.), approximately 5–10 times more precipitation than observed upstream in the Snake River Plain where SWE values of 0.00–0.23 cm (0.00–0.09 in.) were reported. To the lee of the Tetons, up to 14 cm (5.5 in.) of snow was reported by weather spotters near Jackson Hole Airport (JAC)—JAC reported only 0.36 cm (0.14 in.) of SWE, suggesting possible problems with this measurement. Unfortunately, no in situ observations are available in the lowlands near the west side of the Tetons for comparison other than the 5.1–7.6 cm (2–3 in.) of snow reported by NSSL5.

During P-3 flight operations, higher reflectivities were observed on the lee side of the Tetons than on the windward side, corroborating the KSFX data and surface precipitation measurements. The timing of the P-3 mission, however, was such that the leeward enhancement appeared to be due to the precipitation system moving eastward and weakening, rather than due to direct topographic effects. Excellent microphysics data were obtained, however, during a missed-approach ascent and descent at JAC. IOP 1 provided a good test of the equipment, communications, and readiness of the IPEX team because, despite the slow start to IPEX, the next 17 days would bring six IOPs.

IOP 2: 10–11 February 2000: Complex mesoscale circulations over northern Utah. IOP 2 signaled the breakdown of the persistent ridge over the western United States. The first system to reach Utah was associated with an upper-level trough that moved across southern California, Nevada, and Arizona, putting northern Utah in the confluent region of split flow. The synoptic- and mesoscale kinematic and precipitation structure of this convectively neutral/unstable precipitation event was quite complex. At low levels, troughing developed over Nevada and extended across northern Utah. Meanwhile, convection with cloud-to-ground lightning began to develop over central Nevada and Utah. At P-3 take-off time (0307 UTC 11 February), precipitation was evident south of SLC with apparent orographic precipitation enhancement occurring along the Wasatch Mountains near Sundance Ski Area where the SWE precipitation rate was 0.6 cm h (0.25 in. h^{-1}). This orographic enhancement was associated with southwesterly cross-barrier flow to the south of the low-level trough. In contrast, to the north of the trough, precipitation was less widespread, lighter, or nonexistent. Crest-level winds in the Wasatch Mountains and low-level winds over the Great Salt Lake sometimes showed an easterly component and, at times, orographic precipitation enhancement was evident on the east side of the Wasatch Mountains near Deer Valley and Park City ski areas. During 0300–0600 UTC a weak mesoscale circulation center appeared to develop along the trough, move eastward across northern Utah, and dissipate. This interesting kinematic feature appeared to enhance the southwesterly flow and orographic precipitation south of the trough and easterly downslope flow to the north.

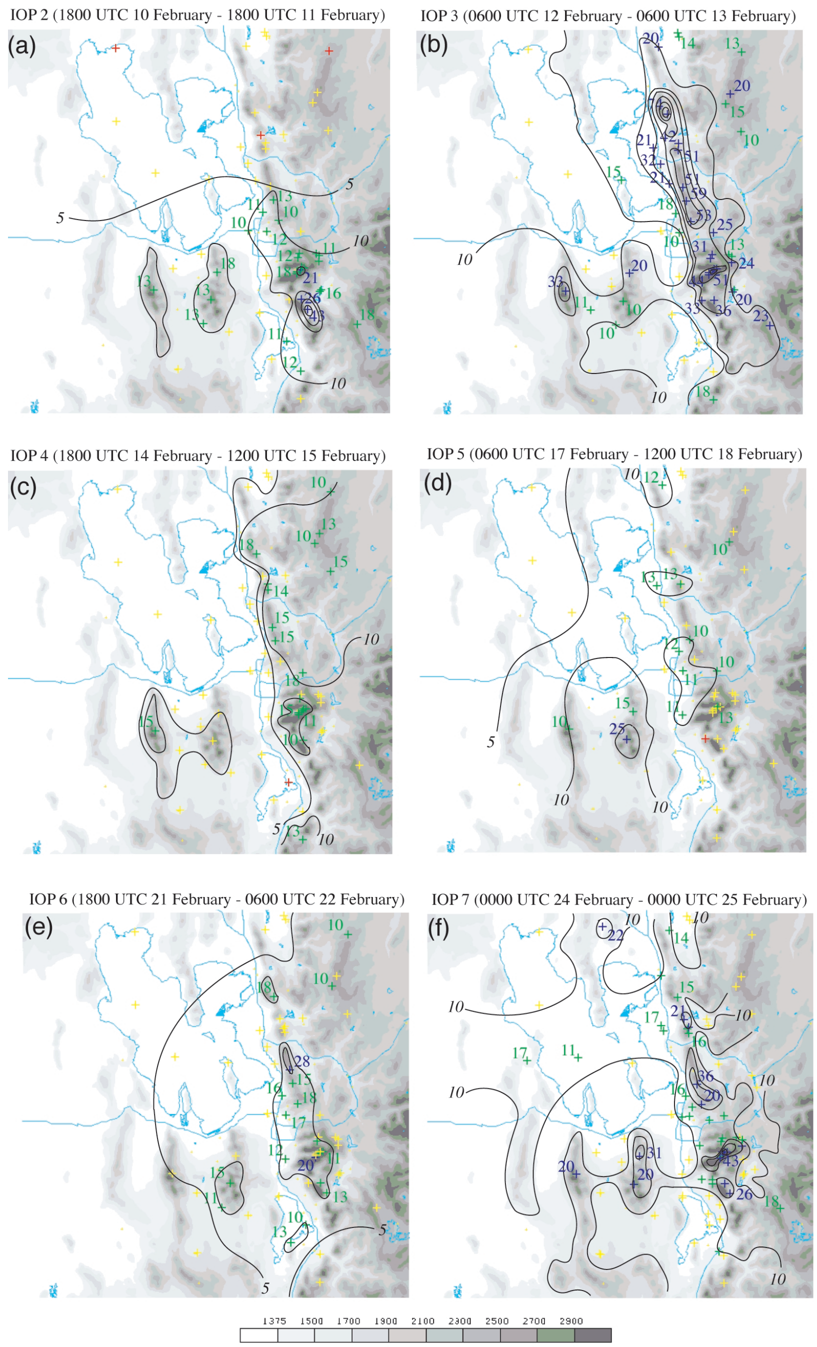
After 0600 UTC, the trough began to weaken and move northward and eastward. From 0700 to 1000 UTC, precipitation had spread northward over the Salt Lake Valley and adjoining mountain ranges. During this period, the KMTX WSR-88D observed the highest reflectivity values over the lowlands rather than the mountains, although data from precipitation gauges did not show such a well-defined relationship, suggesting substantial variability in the radar-reflectivity–snowfall ($Z - S$) relationship.

Throughout IOP 2, IPEX nowcasters struggled to define the precise position of the surface trough due to considerable variability in surface winds over northern Utah. In most respects, the trough was more clearly delineated above the surface layer in P-3 flight-level observations. Because of the kinematic structure of the low-level trough, substantial gradients in storm-total precipitation were observed, not only between lowland and mountain locations, but also along the Wasatch crest (Fig. 8a). Other than in the southern Wasatch near Sundance Ski Area, where persistent and heavy orographic precipitation enhancement was observed throughout the event, the location and intensity of orographic precipitation enhancement var-

Table 3. IPEX IOPs.

IOP	Date	Event	Scientific issues involved
1	5 Feb	Light snow in Tetons	Orographic precipitation distribution
2	10–11 Feb	Complex mesoscale circulation in northern Utah	Origin of low-level trough Mesoscale circulation center Role of trough in precipitation distribution
3	12 Feb	Heavy orographic snowfall and mesoscale trough	Strong precipitation shadowing Unusual trough structure Role of blocking in precipitation distribution
4	14 Feb	Cold front and tornadic bow echo	Origin of conditional instability Role of topography in enhancing helicity Frontal evolution in complex topography Frontal interaction with topography
5	17 Feb	Tooele Valley snowstorm	Evolution of electric-field profile Role of Great Salt Lake in snowband Role of synoptic and mesoscale forcing
6	22 Feb	Unstable southerly flow	Possible mountain waves over Tooele Valley Precipitation distribution
7	23–25 Feb	Slow-moving shallow cold front	Evolution of shallowing cold front Frontal interaction with topography Orographic precipitation distribution

FIG. 8. Spatial distribution of precipitation for six IPEX IOPs from Cheng (2001). Plus signs identify stations reporting precipitation during the period. Red plus signs denote stations reporting zero or trace; yellow plus signs denote stations reporting measurable precipitation, but less than 10 mm; green plus signs denote stations reporting at least 10 mm, but less than 20 mm; and blue markers denote stations reporting at least 20 mm of precipitation. Selected stations are labeled with the observed precipitation totals to the nearest mm. Contours of 5, 10, 20, 30, 40, and 70 mm, where possible, were subjectively analyzed based upon the available data. The 5-mm contour was omitted from (b) and (f) for clarity. Terrain elevation (m) is shaded according to scale at bottom. (a) IOP 2: 1800 UTC 10 Feb – 1800 UTC 11 Feb, (b) IOP 3: 0600 UTC 12 Feb – 0600 UTC 13 Feb, (c) IOP 4: 1800 UTC 14 Feb – 1200 UTC 15 Feb, (d) IOP 5: 0600 UTC 17 Feb – 1200 UTC 18 Feb, (e) IOP 6: 1800 UTC 21 Feb – 0600 UTC 22 Feb, (f) IOP 7: 0000 UTC 24 Feb – 0000 UTC 25 Feb.



ied on both temporal and spatial scales. As a result of the complex mesoscale circulations, IOP 2 highlights the importance of understanding the kinematics and dynamics of the low-level trough, which helped control the position and intensity of the resulting orographic precipitation.

IOP 3: 12 February 2000: Heavy orographic snowfall and mesoscale trough. The heaviest snowstorm to strike the Wasatch Mountains in two years was the focus of IOP 3. In only 12 h, 56 cm (22 in.) of snow fell at Alta Ski Area, which received 81 cm (32 in.) during the entire storm. A 100-m-wide avalanche near Bridal Veil Falls briefly dammed the Provo River, which flows through Provo Canyon. Fortunately, no injuries and no major damage were reported (NCDC 2000, p. 108). A couple hundred people were detained in Big Cottonwood Canyon for 2 h after the sheriff closed the road. By evening, Little Cottonwood Canyon was closed for the night owing to avalanche danger (NCDC 2000, p. 108).

The event occurred ahead of a forward-tilting trough (i.e., the 700-hPa trough axis preceded that at the surface) and featured large-scale southwesterly crest-level flow that gradually veered to westerly, weak low-level warm advection, and near-saturated conditions. Lapse rates from the SLC soundings were initially slightly more stable than moist adiabatic. With crest-level winds oriented normal to the

Wasatch Mountains, substantial orographic precipitation enhancement was observed along the entire Wasatch Crest (Fig. 8b). North of Salt Lake City, lowland precipitation increased across the Great Salt Lake toward the Wasatch Mountains, and in this region, observations from the P-3 Doppler radar showed a broad region of high reflectivity extending well upstream of the Wasatch Mountains (Fig. 9). These observations suggest that ascent associated with blocking may have extended well upstream of the initial mountain slope, as observed upstream of coastal mountain ranges (e.g., Overland and Bond 1995; Ralph et al. 1999).

In lowland regions to the south, such as the Salt Lake Valley, the upstream Oquirrh Mountains produced a precipitation shadow and significantly less precipitation was observed (Fig. 8b). To the lee (east) of the Wasatch, a rapid decrease in precipitation was found with accumulations decreasing by a factor of 2–4 within 10–15 km of the crest. The precipitation reduction was particularly large to the lee of the high topography in the Wasatch, where the cloud-top echo sloped strongly downward (Fig. 9), suggesting that intense leeside subsidence may have limited downstream hydrometeor transport. If the shape of the lee cloud was due to strong leeside subsidence, it resembles that from analytical solutions and numerical-model simulations of flow over two-dimensional idealized topography (e.g., Queney 1948; Durran 1986).

During IOP 3, the P-3 performed four different four-level cross-barrier stacks directly over the DOW dual-Doppler lobe and vertically pointing S-band radar. Combined with detailed MesoWest observations and additional special and supplemental radiosondes near and upstream of the Wasatch, the data collected by these platforms should provide new insights into the factors controlling the broad region of precipitation enhancement upstream of the Wasatch, pronounced precipitation maximum over the crest, and rapid reduction of precipitation to the lee. Such data should also allow for the validation of three-dimensional MM5 simulations of the event initialized with the observed data, as well as comparison to idealized two-dimensional simulations of the precipitation distribution across a narrow, steeply sloped mountain barrier.

IOP 4: 14 February 2000: Cold front and tornadic bow echo. IOP 4 was characterized by a strong, rapidly moving cold front with considerable convective instability near its leading edge. Western California was affected first by this potent storm with 13–15 cm (5–6 in.) of rain, mudslides, and flash floods (NCDC 2000, 20–29). Over the Snake River Plain, a bow echo (Fig. 10) formed with wind gusts behind the convective line typically 30–35 m^{-1} in northern Utah and the

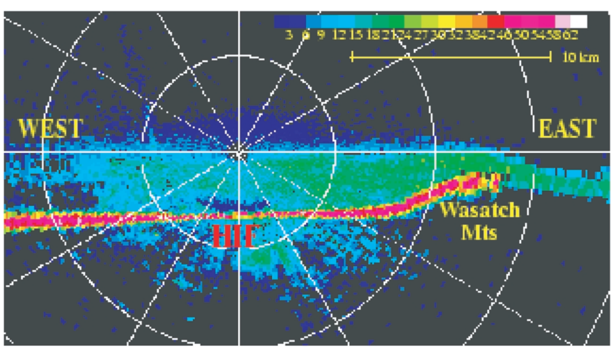


Fig. 9. Radar-reflectivity (dB*Z*) vertical cross section from the P-3 tail Doppler radar at 0023 UTC 13 Feb 2000 during IPEX IOP 3. The P-3 is located at the center of the range rings and is flying into the page, roughly north parallel to the Wasatch Mountains, located to the right of the P-3. Reflectivity and length scales are at upper right. Range rings are every 5 km. The ground is the red reflectivity underneath the P-3. The P-3 is nearly over Hill Air Force Base (HIF) in Ogden at 41.111°N, 111.94°W, 2808 m above ground. The P-3 is heading 344.6, so the orientation of the cross section is approximately west-southwest–east-northeast.

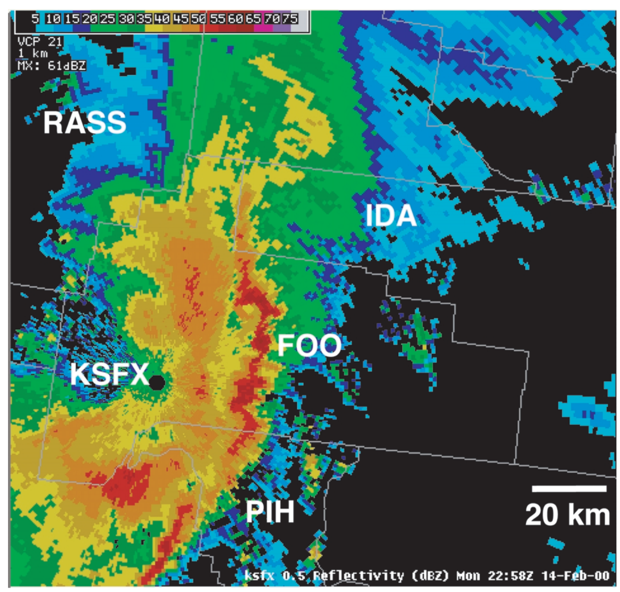


Fig. 10. Radar reflectivity (dB*Z*, colored according to scale at top of figure) from Pocatello WSR-88D (KSFX) at 0.5° elevation angle at 2258 UTC 14 Feb 2000 during IPEX IOP 4. Thin solid gray lines are county boundaries. FOO = Blackfoot, ID; IDA = Idaho Falls, ID; PIH = Pocatello, ID; RASS = NOAA Air Resources Laboratory Field Research Division's 915-MHz radar wind profiler and radio acoustic sounding system. Horizontal length scale is in lower right of figure.

western Snake River Valley, reaching 43 m^{-1} at Minidoka, Idaho. Numerous power outages were reported, semi trucks were blown over, and a section of the roof blew off the Snake River High School auditorium in Blackfoot (FOO). A tornado was reported at the Pocatello Regional Airport (PIH) by a NWS technician and four other tornadoes were reported in the eastern Snake River Valley, causing almost $3.5 million in damage (NCDC 2000, 40–42), including over $1 million in estimated damage to irrigation equipment alone (*Idaho State Journal,* 28 February 2000). Based on a 51-yr climatology, these five tornadoes occurred on the earliest date of the year in which tornadoes have been ever been reported in Idaho, the only ones ever reported in February (D. Schultz and J. Racy 2000, personal communication). The 2100 UTC BOI sounding (Fig. 11) had 184 J kg^{-1} of convective available potential energy (CAPE), 16 m s^{-1} shear in the lowest 2 km, and 392 m^2 s^{-2} storm-relative helicity. Despite the seemingly small instability, the strong shear favored the development of severe convective storms in much the same manner as derecho environments with strong synoptic-scale forcing examined by Evans and Doswell (2001). Because of the presence of the MesoWest, special 3-hourly NWS, NSSL4, and NSSL5 soundings, its close proximity to the Pocatello and Promontory Point WSR-88Ds, and NOAA Air Resources Laboratory Field Research Division's 915-MHz radar wind profiler and radio acoustic sounding system (RASS) in the Snake River Valley, IPEX IOP 4 may have resulted in one of the better documented bow-echo environments to date.

As the convective system moved into northern Utah, the WSR-88D network observed the line of reflectivity values increase to greater than 40 dB*Z*. Pea-size hail, a 7°C temperature drop, and a 5–6 hPa pressure rise accompanied passage at Oasis. Thirty meter per second gusts were common at surface observing stations over the Salt Lake Valley. In Brigham City, Utah, a tree fell and killed a 38-yr-old woman (NCDC 2000, p. 108).

The line weakened as it moved over Ogden and near the Wasatch Front. By evening, the line stalled in a west-northwest–east-northeast orientation across northern Utah and precipitation became largely stratiform. Because of the rapid movement of the system, precipitation amounts were generally less than 10 mm in the valleys and less than 15 mm in the mountains (Fig. 8c). Animation of the radar and further information on this storm can be found on the Web.

Research issues with this Valentine's Day windstorm include the structure, propagation, and evolution of a bow echo in a low CAPE environment; the origin of the convective instability; the possible role of topography in enhancing low-level shear and helicity; the frontal evolution through complex topography of the West; and the eventual frontal interaction with the Wasatch Mountains.

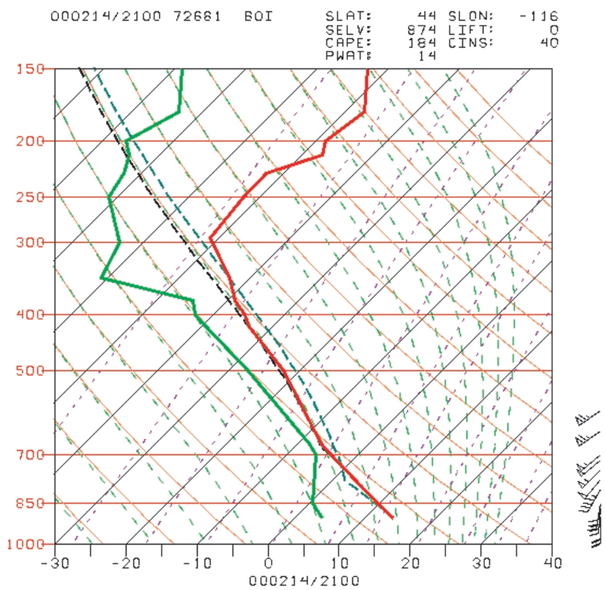


Fig. 11. 2100 UTC 14 Feb 2000 Boise, ID (BOI), sounding on a skew *T*–log*p* diagram (°C and hPa) during IPEX IOP 4. SLAT is the station latitude (whole °N); SLON is the station longitude (whole °W); SELV is station elevation (m); LIFT is lifted index (°C); CAPE is convective available potential energy (J kg); CINS is convective inhibition (J kg); and PWAT is precipitable water (in tenths of an inch). Winds are standard notation (half barb, full barb, and pennant represent 2.5, 5, and 25 m s^{-1}, respectively). The black dashed line represents the path of an air parcel lifted moist adiabatically from the surface and the blue dashed line represents the path of the most unstable air parcel lifted moist adiabatically.

IOP 5: 17 February 2000: Tooele Valley snowstorm. During the early morning of 17 February, a single precipitation band developed along a deformation zone northwest of a surface cyclone over northern Utah. This band extended from the Great Salt Lake southward over the Tooele Valley, with reflectivities approaching 30–35 dB*Z* (Fig. 12), indicative of snowfall rates of 2–4 mm h. The role of the lake in enhancing precipitation in this event was unclear in real time. Precipitation was observed upstream of the lake, and large-scale processes appeared to initiate the band, but sensible and latent heating over the Great Salt Lake

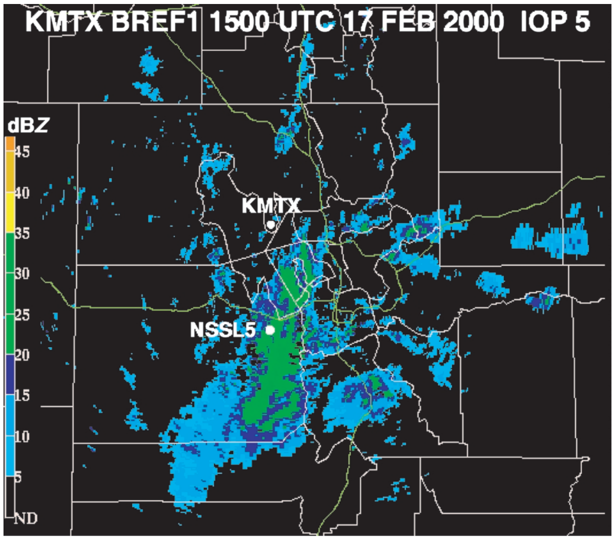


FIG. 12. Radar reflectivity (dBZ, colored according to scale on left side of figure) from Promontory Point (KMTX) WSR-88D at 0.5° elevation angle at 1500 UTC 17 Feb 2000 during IPEX IOP 5. NSSL5 = location of NSSL mobile laboratory NSSL5 during launch of electric-field meter in Fig. 14.

may have enhanced precipitation somewhat. The band lasted for about 10 h before dissipating and giving way to light orographic precipitation showers along the Wasatch. By storm's end, 10–30 cm (4–12 in.) of snow were measured over the Tooele Valley and the surrounding mountains.

Unfortunately, due to an outage in the data transmission system from the Tooele Valley MesoWest sites for several hours, determining the exact precipitation amounts from the automated sites in the Tooele Valley during IOP 5 is not possible. The data retrieved for part of the IOP indicate many of those sites received at least 10 mm. The heaviest precipitation during this IOP appears to be extremely localized, with evidence of only weak orographic enhancement (Fig. 8d; Cheng 2001).

A region of 700-hPa frontogenesis northwest of the low center in a region of strong deformation supported the snowband (Fig. 13). This forcing was associated with ascent on the warm side of the frontogenetical area that formed the snowband. This example illustrates that synoptic- and mesoscale processes can still be important to precipitation structures, even in regions of strong topographic contrasts.

An electric-field meter was flown from NSSL5 into this snowband. The balloon was inflated in and launched from a high-wind launch tube (Rust and Marshall 1989) in moderate to heavy snowfall: there was about 12 cm (5 in.) of snow on the ground at launch and about 2 cm (1 in.) more fell during the 40 min of the flight. The relative humidity with respect to ice ranged from 100% to 115% from the ground up to 5.9 km MSL (not shown), indicating a cloud. Inside the cloud, the large change in the vertical component of the electric field E_z with height, just above an isothermal layer from 1.9 to 2.1 km (Fig. 14a), indicates a region of positive charge between about 2.0 and 2.2 km. Using a one-dimensional form of Gauss's Law (e.g., MacGorman and Rust 1998, 130–131), charge density is estimated to be almost 0.2 nC m^{-3} (Fig. 14b). The peak in the horizontal component of the electric field (E_h) at about 2 km (Fig. 14a) indicates the balloon passed to the side of additional significant charge. A large value of E_h relative to E_z implies the magnitude, but not the existence, of this large positive charge inferred from Gauss's Law may be uncertain. Further aloft, E_z was weakly positive from 2.2 to 4.4 km (Fig. 14a), roughly

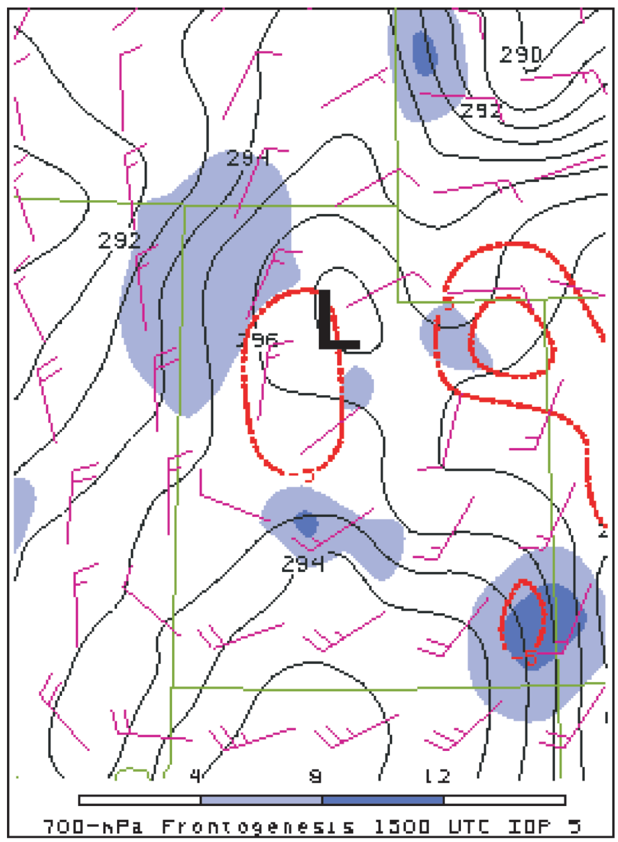


FIG. 13. Initialization of the 1500 UTC 17 Feb 2000 Rapid Update Cycle version 2 during IPEX IOP 5: 700-hPa frontogenesis [0.1°C (100 km 3 h), shaded according to scale at bottom]; 700-hPa potential temperature (solid lines every 1°C); 700-hPa winds (half barb, full barb, and pennant represent 2.5, 5, and 25 m s^{-1}, respectively); and 500-hPa omega (red dashed contours −5 and −10 μb s^{-1}); and L represents location of surface low center.

half the depth of the cloud.

The negative E_z at the ground of about -1.5 kV m^{-1} (Fig. 14a) is an order of magnitude above the typical fair-weather value (about -0.1 kV m^{-1}), suggesting point discharge (corona) may have occurred from the surface. Reiter (1965) found the electric field at the ground was negative at temperatures below 0°C, but positive for temperatures between 0° and 1°C. Reiter's results held whether the ground was inside or below nimbostratus clouds. For this profile (Fig. 14), the transition temperature may not have been reached as the temperature measured at 3 m above the surface (atop NSSL5) was about 0°C. The electric field at higher altitudes and temperatures colder than the 0°C level was mostly negative, in agreement with Reiter's findings.

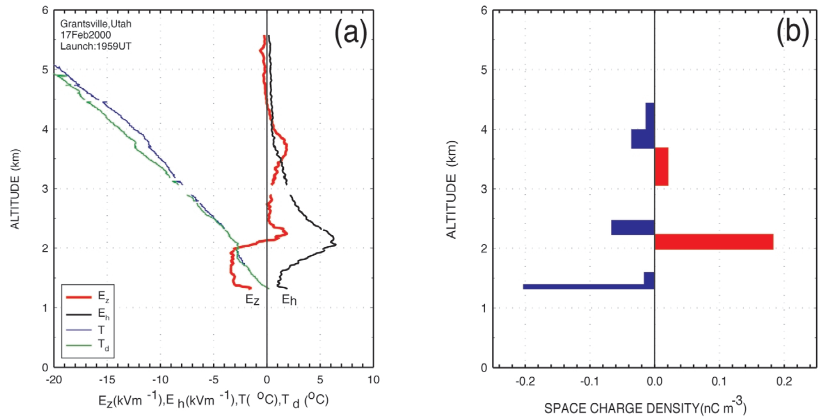


Fig. 14. Electric-field profile in nimbostratus from a balloon launch at 1959 UTC 17 Feb 2000 during IPEX IOP 5. The sounding was made at 40°35.903′N, 112°26.375′W, about 2 km west of Grantsville, UT (location shown in Fig. 12). Vertical scale is altitude in km above sea level. (a) Vertical component of the electric field E_z (kV m^{-1}, red line), horizontal component of the electric field E_h (kV m^{-1}, black line), temperature (°C, blue line), and dewpoint (°C, green line). (b) Space-charge density calculated from one-dimensional form of Gauss's Law (nC m^{-3}).

The magnitude of the electric field with height was well below that generally associated with lightning, and no cloud-to-ground lightning was recorded within hundreds of kilometers for many hours around the flight. Thus, this snowstorm can be described as an electrified, nonthunderstorm nimbostratus. The profile reported here (and indeed the other five electric-field profiles during IPEX) show there can be significant electrification in nimbostratus clouds that do not produce lightning and, even though the cloud is highly stratified, the charge apparently can be nonuniform in its horizontal distribution. Also, the in-cloud electric-field profile from this flight (Fig. 14) was opposite in polarity compared to the previous one on this day (not shown). Thus, there remains quite a bit to explain about electrification in nimbostratus clouds.

IOP 6: 22 February 2000: Unstable southerlies and orographic precipitation. Operations during IOP 6 focused on sampling a convective-precipitation event over northern Utah. Large-scale conditions included a deep upper-level trough that moved through the southwest United States with an associated baroclinic zone moving through northern Utah. The 0000 UTC 22 Februrary SLC sounding had 145 J kg^{-1} of CAPE (not shown), a significant amount for February in northern Utah. Convection developed ahead of this baroclinic zone over western Utah during the afternoon and spread into the Salt Lake Valley. Thunderstorms in southern Utah brought hail 5–10 cm (2–4 in.) deep to New Harmony, Utah (about 10 km west of the northern end of Zion National Park), and 30 m s^{-1} wind gusts to St. George. Many higher-elevation stations reported more than 10 mm (0.39 in.) of precipitation in 6 h, with 12-h amounts as much as 28 mm (1.1 in.; Fig. 8e). The heavy precipitation caused a rockslide in the Storm Mountain Area in Big Cottonwood Canyon in the Wasatch. Little Cottonwood Canyon was also closed overnight because of the storm.

Our goal was to examine the interaction between a convectively driven precipitation event in large-scale southerly flow and the meridionally oriented mountain ranges. Before the P-3 was forced to land because of engine problems, very high cloud liquid water contents were observed in the clouds, often with graupel and large aggregates, as measured by the King cloud probe. Also, mountain waves were observed over two east–west-oriented ridges in the Tooele Valley. Later in the evolution of the event, the upper-level flow became southwesterly and orographic enhancement was observed on the western side of the Wasatch (Fig. 15). Dual-Doppler surveillance was performed throughout the evolution of the event. Because of the prolonged southerlies throughout the event, the orographic enhancement of precipitation at sites in the Wasatch Mountains relative to those along the Wasatch Front was the weakest observed during any of the IOPs. One electric-field meter was launched at 0139 UTC and measured the largest electric fields of

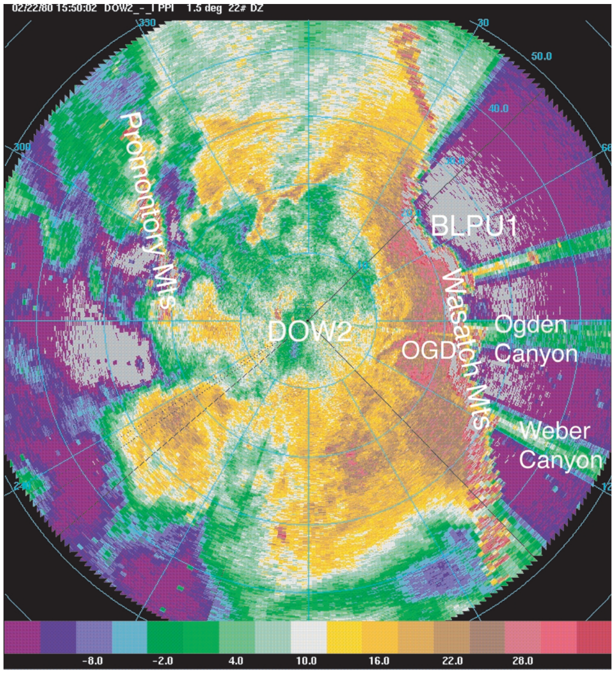


FIG. 15. DOW2 PPI of radar reflectivity (approximately calibrated units of dB, color scale at bottom) from 41°15.032′N, 112°10.824′W (location in Fig. 4) at 0350 UTC 22 Feb 2000 during IPEX IOP 6. BLPU1 = Ben Lomond Peak; and OGD = Ogden.

the project. The maximum vertical electric field E_z was 12 kV m^{-1} at 2.7 km and the maximum horizontal electric field E_h was 28 kV m^{-1} at about 3.0 km. Unfortunately, the thermodynamic data from that flight were not recorded.

IOP 7: 23–25 February 2000: Slow-moving shallow cold front. IOP 7 was characterized by a cold front approaching northern Utah from Nevada. The P-3 flew to northeastern Nevada and intersected the front at 540 hPa around 1140 UTC 24 February when the winds shifted from southerly to southwesterly to northerly and the temperature dropped 3.5°C in 100 km. Radar imagery from the lower-fuselage radar suggested precipitation core and gap regions (not shown), consistent with previous observations of narrow cold-frontal rainbands (e.g., Wakimoto and Bosart 2000, and references therein). By around 1430 UTC 24 February when the cold front arrived at the Wasatch Mountains, the northerlies behind the front were very shallow, only about 500 m deep as indicated by DOW2 (Fig. 16). Unfortunately, the shallowness of the front also prohibited detailed information about the northerlies behind the surface front (located off the right side of Fig. 16). Due to flight restrictions and the shallow nature of the front, the P-3 was unable to perform low-level interrogations of the front. Streamlines in Fig. 17 illustrate the complex structure of the terrain-deformed surface wind field at 1800 UTC 24 February.

Heavy precipitation was falling at Alta and Deer Valley between 0700 and 1200 UTC 24 February, when southeasterly large-scale flow was producing locally heavy orographic precipitation. Precipitation rates dropped off rapidly toward the west down Little Cottonwood Canyon. At about 1100 UTC 24 February, Alta reported 28 cm (11 in.) of new snow, while the White Pine parking lot in Little Cottonwood Canyon, about 5 km downslope and west of Alta, received only 7.6 cm (3 in.). Periods of snowfall were observed after 1200 UTC 24 February in southerly to southeasterly flow until the passage of the cold front.

Approximately twice as much precipitation fell at Snowbasin as at Ogden during the 24-h period ending 0000 UTC 25 February (Fig. 8f). Even climatologically dry areas such as the Great Salt Lake Desert and Great Salt Lake received relatively large amounts of precipitation (Fig. 8f). By the time the storm ended, Alta Guard station received 97 cm (38 in.) of snow, with the benches of the Wasatch receiving as much as 18 cm (7 in.), and SLC receiving just 2.5 cm (1 in.). As much as 10.41 cm (4.10 in.) of SWE fell at Farmington Canyon east of TDWR on the west side of the Wasatch, with 7.62 cm (3.00 in.) at Ben Lomond Peak and 0.69 cm (0.27 in.) at SLC. Interstate 84 near

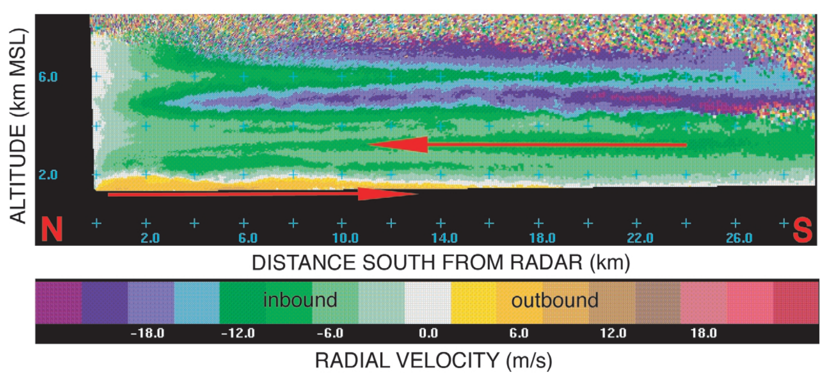


FIG. 16. DOW2 RHI radial velocity (m^{-1}, color scale at bottom) from 41°15.032′N, 112°10.824′W (location in Fig. 4) at 1744 UTC 24 Feb 2000 during IPEX IOP 7. Red arrows indicate the flow direction in the plane of cross section (inbound or outbound), which was along the 175.1 radial.

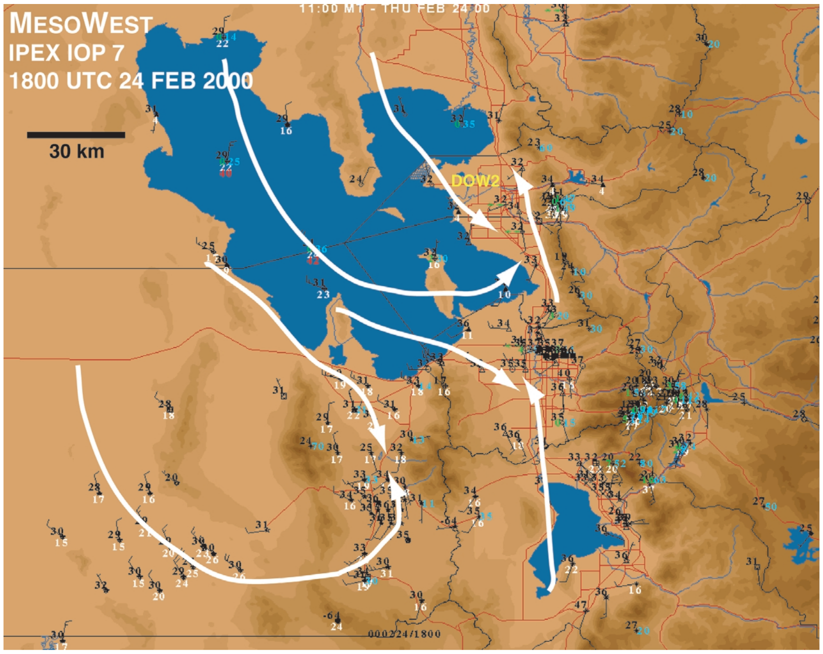


Fig. 17. MesoWest surface observations at 1800 UTC 24 Feb 2000 during IPEX IOP 7. Temperature (°F; black numbers above the station); wind (half barb, full barb, and pennant represent 5, 10, and 50 kt, respectively); gusts greater than 15 knots (white numbers below the station); 1-h precipitation (0.01 in.; green numbers to the left of the station); 6-h precipitation (0.01 in.; blue numbers to the right of the station) are plotted; and lake-surface temperature (°F; red numbers below the station). White arrows are streamlines. Red lines are highways and black lines are county boundaries. DOW2 = location of Doppler on Wheels DOW2. Topography is shaded. Data is not quality controlled.

the Utah–Idaho border was closed on 24 February. The next day around noon an avalanche occurred in Strawberry Bowl at the top of Snowbasin Ski Area along the Wasatch Crest. Five skiers were caught in the slide and two were buried completely; they were quickly dug out, suffering only minor injuries.

Predictability during IPEX. Cheng (2001) examined the performance of the operational forecast models (NCEP's Eta and AVN and University of Utah's MM5) at two mountain locations [Alta Guard House (ATAU1), Ben Lomond Peak (BLPU1)] and two valley locations [Salt Lake City Airport (SLC), Sandy (SNH)]. Cumulative model precipitation amounts for 12-h periods ending 24 h after both the 0000 and 1200 UTC initialization times were interpolated to these four locations. Alta and Salt Lake City were also point-forecast sites for the IPEX forecasters (Table 2). The cumulative time series of observed and forecast precipitation during 2–26 February (Fig. 18) show that the NCEP models underforecast the total precipitation at the mountain locations and overforecast at the valley locations, consistent with previous research (McDonald 1998; Staudenmaier and Mittelstadt 1998). In general, the MM5 forecasts were closer to the observations than were those of the NCEP models, yet still were less accurate than those generated by the IPEX forecasters. Figure 18 suggests the importance of human interpretation in improving upon precipitation amounts output by numerical forecast models.

Another use of the IPEX forecasts is to explore experimental forecast products that could be employed by NWS forecasters in the future (e.g., graphic quantitative precipitation forecast products, graphical probabilistic forecast products). Also, although probabilistic snowfall forecasts have been occurring at Alta since the winter of 1997/98 (see Web site listed in the appendix), verification of probabilistic snow forecasts in an operational setting over a larger area has not been performed. Consequently, forecaster biases are not known for such situations. Thus, IPEX not only adds to the scientific information about weather of the Intermountain West, but provides insight into forecasting as well. These studies on model- and human-forecast performance during IPEX are in progress.

SUMMARY AND LESSONS LEARNED.

During the IPEX field phase, a variety of precipitation and dynamic structures were observed: convective lines, rapidly moving versus slowly moving fronts, isolated precipitation bands, events with orographic precipitation enhancement versus events without apparent orographic enhancement. Obvious lake-effect events, however, were not observed because the flow was mostly westerly and southwesterly and the lower-tropospheric temperature was above normal. The surface data from MesoWest were invaluable in delivering crucial observations from otherwise data-sparse areas. The project benefited from the real-time interaction of NWS/SPC/HPC/OSF forecasters and IPEX scientists focusing on weather that was both typical and atypical of winter weather in northern Utah. Experimental forecast products, such as might

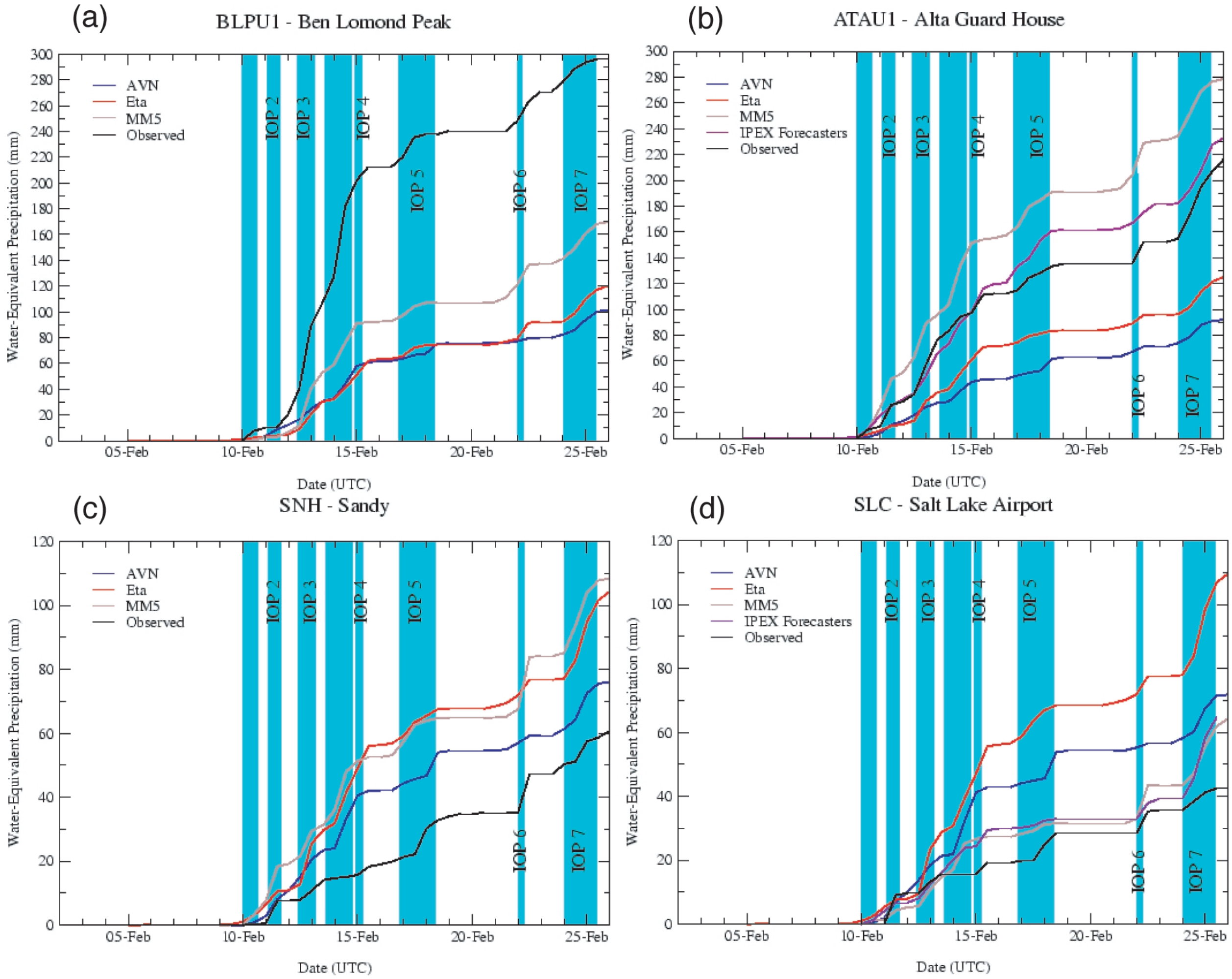


Fig. 18. Cumulative time series of observed (black line) and forecast [Aviation run of global spectral model (AVN), blue line; Eta, red line; MM5, gray line; IPEX forecasters, purple line] precipitation at four sites during IPEX. Shaded areas represent periods of subjectively determined precipitation events over the IPEX domain, with the events corresponding to the IOPs labeled. (a) Ben Lomond Peak, (b) Alta Guard House, (c) Sandy, and (d) Salt Lake City Airport. From Cheng (2001).

be employed in the future by the NWS, were tested and will be evaluated.

Many lessons were learned by the principal investigators while organizing and executing IPEX. These lessons may be helpful to those planning similar projects in the future.

- A conscious decision was made at the outset to plan a small, focused field program with sufficiently broad goals, with no adjunct experiments. Funding for IPEX was absorbed primarily by the contributing organizations. During the course of the project, this characteristic made IPEX manageable, helped with the intended success of the project, and allowed decisions on operations to be made with little contention. Nevertheless, even though no clearly defined lake-effect events occurred, having goals broad enough to cover nonlake-effect events (e.g., orographic precipitation) broadened the scope of the project and led to objectives being successfully met with limited resources.
- IPEX can be considered to have been motivated, but not entirely driven, by hypotheses about winter storm, cloud, and precipitation processes in northern Utah. Our hypotheses helped identify the necessary observational tools and then guided the development of data-collection strategies to best use these tools. Nevertheless, the hypotheses were not so restrictive as to prevent improvised operations during serendipitous events like IOP 4 (previous section), which was not primarily related to

winter or orographic precipitation. As discussed by Blanchard (1996), Langmuir (1948) defined serendipity as the art of profiting from unexpected occurrences, and we believe IPEX succeeded in sampling several unexpected events.

- Operating a research aircraft in a major metropolitan area was not as difficult as we initially feared. Indeed, we typically were able to execute our desired operational strategies, given proper communication of our objective with FAA Air Traffic Control, the P-3 pilots, and flight directors; patience in waiting for adequate breaks in aircraft traffic; and flexibility in flight and scientific strategy. Nevertheless, the most serious limitation was probably selecting P-3 flight altitudes because of enroute air traffic under instrument flight rules (IFR).
- Having mobile platforms such as the mobile laboratories and the DOWs to help target the observations in regions of interesting weather outside of our primary operations area (e.g., as during IOPs 1 and 5) was useful, even in an area where much of the orographic forcing was fixed. We note, however, in a few instances, transit time and other operational considerations (e.g., next-day's staffing) argued against redeploying to another, distant location, since the success and safety of mobile operations are tied to weather, road conditions, and crew status.
- IPEX depended on volunteers to help staff the Operations Center, P-3, DOWs, and mobile laboratories. These volunteers were drawn primarily from a pool of undergraduate and graduate students from the University of Utah, for many of whom IPEX was a unique and invaluable experience. One obvious disadvantage of relying on student volunteers during an academic year is being left short-staffed from inevitable conflicts with classes, very late night/early morning operations, etc., though fortunately not to the point of compromising the success of an IOP.
- The contribution of several NWS Forecast Offices within the experimental domain was key to the success of IPEX. Such contributions, which ultimately should benefit the NWS Forecast Offices themselves, came in the form of special sounding launches at 3-hourly intervals, the use of facilities (specifically, at NWS SLC) for our Operations Center, and the guidance of forecasters with good knowledge of the intricacies of the local weather or, in the case of IOP 4 (previous section), forecasters from the Storm Prediction Center with a good knowledge of convective weather.
- Finally, communicating the goals and results of IPEX to the media was a factor that cannot be underestimated. The increased costs of science need to be justified to the public, who ultimately fund such endeavors. The increased importance of basic and applied research to society needs to be communicated to promote greater advocacy for science. With these ideas in mind, media outreach was included as part of the planning of IPEX. With the help of NOAA Public Affairs officers, a unified public message on the value of scientific research to improve weather forecasting was developed. Although such public education efforts could be viewed as distracting to the success of the science, the chief scientists successfully distributed the workload with one scientist handling media interactions and Web site development along with other science-related tasks, leaving the other IPEX participants to concentrate on the science. The IPEX Web sites allowed the media continued one-stop access to press releases, quotes from participants for media stories, and the latest information about the weather and IPEX operations. Dedication to these Web sites with future research results will ensure longevity of the IPEX message. Experience during IPEX suggests that planning teams involved in future scientific experiments include public outreach, education, and media activities as one of their objectives.

The results of IPEX are already beginning to influence forecasting in northern Utah. The precipitation verification work of Cheng (2001) influenced a push to higher-resolution real-time MM5 simulations at the University of Utah. Cloud microphysical studies and model verification from IOP 3 may lead to improvements in the MM5 microphysical scheme prior to the Olympics. NWS forecasters for the Olympic and Paralympic Games were exposed to preliminary results from IPEX. Over the coming years, further information about IPEX and post-IPEX data analysis can be found in future scientific publications and on the IPEX Web sites listed in the appendix.

ACKNOWLEDGMENTS. Funding for IPEX was provided by the NOAA/National Severe Storms Laboratory Director's Discretionary Fund, NOAA/Cooperative Institute for Regional Prediction at the University of Utah Grants NA87WA0351 and NA97WA0227, and the Utah Department of Transportation. We would like to thank all the individuals who participated in the planning, execution, and data analysis effort for IPEX: the staff of the NOAA/Aircraft Operations Center (James McFadden, A. Barry Damiano, Dave Tennesen, Tim O'Mara, Dave

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APPENDIX. *Web Addresses Cited in Text.*

Intermountain Precipitation Experiment	http://www.nssl.noaa.gov/schultz/ipex http://www.met.utah.edu/jimsteen/IPEX
IPEX forecast products archive	http://www.nssl.noaa.gov/cgi-bin/lst-ipex.cgi?ipex_fcsts
IPEX operations manual	http://www.nssl.noaa.gov/schultz/ipex/ops.html
IPEX IOP 4	http://www.nssl.noaa.gov/schultz/ipex/iop4
P-3 Instrumentation and limitations	http://mrd3.nssl.ucar.edu/aircraft.html
MesoWest	http://www.met.utah.edu/mesowest
ADAS at University of Utah	http://www.met.utah.edu/jhorel/html/adas
Real-time MM5 at University of Utah	http://www.met.utah.edu/jimsteen/mm5
U.S. Census Bureau	http://www.census.gov/population/www/cen2000/phc-t2.html
PACJET	http://www.etl.noaa.gov/programs/pacjet/pacjet.shtml
IMPROVE	http://improve.atmos.washington.edu
USA Today	http://www.usatoday.com
Passport to Knowledge: Live from the Storm	http://www.passporttoknowledge.com/storm/main.htm
Verification of probabilistic snowfall	http://www.wrh.noaa.gov/Saltlake/projects/brench/ alta8.htmforecasts at NWS SLC

REFERENCES

Armstrong, C. F., and C. K. Stidd, 1967: A moisture-balance profile on the Sierra Nevada. *J. Hydrol.,* **5,** 258–268.

Blanchard, D. C., 1996: Serendipity, scientific discovery, and Project Cirrus. *Bull. Amer. Meteor. Soc.,* **77,** 1279–1286.

Blazek, T. R., 2000: Analysis of a Great Basin cyclone and attendant mesoscale features. M.S. thesis, Dept. of Meteorology, University of Utah, 122 pp. [Available online at http://www.met.utah.edu/jimsteen/theses/blazek00_thesis.pdf.]

Bond, N. A., and Coauthors, 1997: The Coastal Observation and Simulation with Topography (COAST) Experiment. *Bull. Amer. Meteor. Soc.,* **78,** 1941–1955.

Bougeault, P., P. Binder, A. Buzzi, R. Dirks, R. Houze, J. Kuettner, R. B. Smith, R. Steinacker, and H. Volkert, 2001: The MAP special observing period. *Bull. Amer. Meteor. Soc.,* **82,** 433–462.

Branick, M. L., 1997: A climatology of significant winter-type weather events in the contiguous United States, 1982–94. *Wea. Forecasting,* **12,** 193–207.

Braun, S. A., R. A. Houze Jr., and B. F. Smull, 1997: Airborne dual-Doppler observations of an intense frontal system approaching the Pacific Northwest coast. *Mon. Wea. Rev.,* **125,** 3131–3156.

Bruintjes, R. T., T. L. Clark, and W. D. Hall, 1994: Interactions between topographic airflow and cloud/precipitation development during the passage of a winter storm in Arizona. *J. Atmos. Sci.,* **51,** 48–67.

Carpenter, D. M., 1993: The lake effect of the Great Salt Lake: Overview and forecast problems. *Wea. Forecasting,* **8,** 181–193.

Cheng, L., 2001: Validation of quantitative precipitation forecasts during the Intermountain Precipitation Experiment. M.S. thesis, Dept. of Meteorology, University of Utah, 137 pp. [Available online at http://www.met.utah.edu/jhorel/homepages/lcheng/thesis.html.]

Ciliberti, C. M., J. D. Horel, and S. M. Lazarus, 1999: An analysis of a cold frontal passage over complex terrain in northwest Utah. Preprints, *Eighth Conf. on Mesoscale Processes,* Boulder, CO, Amer. Meteor. Soc., 459–462.

——, ——, and ——, 2000: Sensitivity experiments with a high resolution data assimilation scheme. Preprints, *Ninth Conf. on Mountain Meteorology,* Aspen, CO, Amer. Meteor. Soc., 413–416.

Colle, B. A., and C. F. Mass, 1996: An observational and modeling study of the interaction of low-level southwesterly flow with the Olympic Mountains during COAST IOP 4. *Mon. Wea. Rev.,* **124,** 2152–2715.

——, and ——, 2000: The 5–9 February 1996 flooding event over the Pacific Northwest: Sensitivity studies and evaluation of the MM5 precipitation forecasts. *Mon. Wea. Rev.,* **128,** 593–617.

——, ——, and B. F. Smull, 1999a: An observational and numerical study of a cold front interacting with the Olympic Mountains during COAST IOP5. *Mon. Wea. Rev.,* **127,** 1310–1334.

——, K. J. Westrick, and C. F. Mass, 1999b: Evaluation of MM5 and Eta-10 precipitation forecasts over the Pacific Northwest during the cool season. *Wea. Forecasting,* **14,** 137–154.

——, C. F. Mass, and K. J. Westrick, 2000: MM5 precipitation verification over the Pacific Northwest during the 1997–99 cool seasons. *Wea. Forecasting,* **15,** 730–744.

Cooper, W. A., and J. D. Marwitz, 1980: Winter storms over the San Juan Mountains. Part III: Seeding potential. *J. Appl. Meteor.,* **19,** 942–949.

——, and C. P. R. Saunders, 1980: Winter storms over the San Juan Mountains. Part II: Microphysical processes. *J. Appl. Meteor.,* **19,** 927–941.

Cordell, H. K., J. Tealsey, G. Super, J. C. Bergstrom, and B. McDonald, 1997: Outdoor recreation in the United States: Results from the National Survey on Recreation and the Environment. U.S. Dept. of Agriculture, Forest Service. [Available online at http://www.fs.fed.us/research/rvur/recreation/publications/Outdoor_Recreation/title.htm.]

Crum, T. D., and R. L. Alberty, 1993: The WSR-88D and the WSR-88D Operational Support Facility. *Bull. Amer. Meteor. Soc.,* **74,** 1669–1687.

——, R. E. Saffle, and J. W. Wilson, 1998: An update on the NEXRAD program and future WSR-88D support to operations. *Wea. Forecasting,* **13,** 253–262.

Daly, C., R. P. Neilson, and D. L. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.,* **33,** 140–158.

Doesken, N. J., and A. Judson, 1997: *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States.* Colorado State University, Department of Atmospheric Science, 86 pp. [Available from Colorado Climate Center, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523-1371.]

——, and R. J. Leffler, 2000: Snow foolin'. *Weatherwise,* **53**, 30–37.

Doswell, C. A., III, 1986: The human element in weather forecasting. *Natl. Wea. Dig.,* **11,** 6–17.

——, and R. A. Maddox, 1986: The role of diagnosis in weather forecasting. Preprints, *11th Conf. on Weather Forecasting and Analysis,* Kansas City, MO, Amer. Meteor. Soc., 177–182.

——, ——, and C. F. Chappell, 1986: Fundamental considerations in forecasting for field experiments. Preprints, *11th Conf. on Weather Forecasting and Analysis,* Kansas City, MO, Amer. Meteor. Soc., 353–358.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State–NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.,* **121,** 1493–1513.

Dunn, L. B., 1983: Quantitative and spacial distribution of winter precipitation along Utah's Wasatch Front. NOAA Tech. Memo. NWS WR-181, 72 pp. [Available from NOAA/NWS, Western Region Headquarters, 125 S. State Street, Rm. 1311, Salt Lake City, UT 84138-1102.]

Durran, D. R., 1986: Mountain waves. *Mesoscale Meteorology and Forecasting,* P. S. Ray, Ed., Amer. Meteor. Soc., 472–492.

Errico, R., and D. Baumhefner, 1987: Predictability experiments using a high-resolution limited-area model. *Mon. Wea. Rev.,* **115,** 488–504.

Evans, J. S., and C. A. Doswell III, 2001: Examination of derecho environments using proximity soundings. *Wea. Forecasting,* **16,** 329–342.

Fraser, A. B., R. C. Easter, and P. V. Hobbs, 1973: A theoretical study of the flow of air and fallout of solid precipitation over mountainous terrain: Part I. Airflow model. *J. Atmos. Sci.,* **30,** 801–812.

Fritsch, J. M., and Coauthors, 1998: Quantitative precipitation forecasting: Report of the Eighth Prospectus Development Team, U.S. Weather Research Program. *Bull. Amer. Meteor. Soc.,* **79,** 285–299.

Gartner, W. E., M. E. Baldwin, and N. W. Junker, 1998: Regional analysis of quantitative precipitation forecasts from NCEP's "early" Eta and Meso-Eta models. Preprints, *16th Conf. on Weather Analysis and Forecasting,* Phoenix, AZ, Amer. Meteor. Soc., 187–189.

Goodison, B. E., 1978: Accuracy of Canadian snow gage measurements. *J. Appl. Meteor.,* **17,** 1542–1548.

Gourley, J. J., K. W. Howard, and H. Winston, 2000: Employment of an S-band vertically pointing radar. Preprints, *WMO Tech. Conf. on Meteorological and Environmental Instruments and Methods of Observation,* Beijing, China, WMO, 281–284. [Available from http://www.wmo.ch/web/www/IMOP/TE-00_IOM-74/TECO2000M_1-3_Weather_Radars_and_Lightning_Detection_Continued.pdf.]

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 138 pp. [Available online at NCAR, P.O. Box 3000, Boulder, CO 80307-3000.]

Groisman, P. Ya., and D. R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc.,* **75,** 215–227.

——, V. V. Koknaeva, T. A. Belokrylova, and T. R. Karl, 1991: Overcoming biases of precipitation measurement: A history of the USSR experience. *Bull. Amer. Meteor. Soc.,* **72,** 1725–1733.

Heymsfield, A. J., and D. Baumgardner, 1985: Summary of a workshop on processing 2-D probe data. *Bull. Amer. Meteor. Soc.,* **66,** 437–440.

Hill, C. D., 1993: Forecast problems in the Western Region of the National Weather Service: An overview. *Wea. Forecasting,* **8,** 158–165.

Hjelmfelt, M. R., 1990: Numerical study of the influence of environmental conditions on lake-effect snowstorms over Lake Michigan. *Mon. Wea. Rev.,* **118,** 138–150.

——, and R. R. Braham Jr., 1983: Numerical simulation of the airflow over Lake Michigan for a major lake-effect snow event. *Mon. Wea. Rev.,* **111,** 205–219.

Hobbs, P. V., R. C. Easter, and A. B. Fraser, 1973: A theoretical study of the flow of air and fallout of solid precipitation over mountainous terrain: Part II. Microphysics. *J. Atmos. Sci.,* **30,** 813–823.

Hoffman, R. R., 1991: Human factors psychology in the support of forecasting: The design of advanced meteorological workstations. *Wea. Forecasting,* **6,** 98–110.

Horel, J., M. Splitt, B. White, and L. Dunn, 2000: MesoWest: Cooperative mesonets in the western United States. Preprints, *Ninth Conf. on Mountain Meteorology,* Aspen, CO, Amer. Meteor. Soc., 265–268.

Huggins, A. W., and D. E. Kingsmill, 1999: Quantitative precipitation estimates from a mountain-top WSR-88D: Data pre-processing considerations. Preprints, *29th Int. Conf. on Radar Meteorology,* Montreal, Quebec, Canada, Amer. Meteor. Soc., 709–712.

Jorgensen, D. P., P. H. Hildebrand, and C. L. Frush, 1983: Feasibility test of an airborne pulse-Doppler meteorological radar. *J. Climate Appl. Meteor.,* **22,** 744–757.

——, T. Matejka, and J. D. DuGranrut, 1996: Multibeam techniques for deriving wind fields from airborne Doppler radars. *J. Meteor. Atmos. Phys.,* **59,** 83–104.

Judson, A., and N. Doesken, 2000: Density of freshly fallen snow in the central Rocky Mountains. *Bull. Amer. Meteor. Soc.,* **81,** 1577–1587.

Junker, N. W., J. E. Hoke, B. E. Sullivan, K. F. Brill, and F. J. Hughes, 1992: Seasonal and geographic variations in quantitative precipitation prediction by NMC's Nested-Grid Model and Medium-Range Forecast model. *Wea. Forecasting,* **7,** 410–429.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kelly, R. D., 1982: A single Doppler radar study of horizontal-roll convection in a lake-effect snow storm. *J. Atmos. Sci.,* **39,** 1521–1531.

——, 1986: Mesoscale frequencies and seasonal snowfalls for different types of Lake Michigan snow storms. *J. Climate Appl. Meteor.,* **25,** 308–312.

Klimowski, B. A., and Coauthors, 1998: The 1995 Arizona Program: Toward a better understanding of winter storm precipitation development in mountainous terrain. *Bull. Amer. Meteor. Soc.,* **79,** 799–813.

Knollenberg, R. G., 1972: Comparative liquid water content measurements of conventional instruments with an optical array spectrometer. *J. Appl. Meteor.,* **11,** 501–508.

LaChapelle, E. R., 1962: The density distribution of new snow. USDA Forest Service, Wasatch National Forest, Alta Avalanche Study Center, Project F, Progress Rep. 2, Salt Lake City, UT, 13 pp.

Langland, R. H., and Coauthors, 1999: The North Pacific Experiment (NORPEX-98): Targeted observations for improved North American weather forecasts. *Bull. Amer. Meteor. Soc.,* **80,** 1363–1384.

Langmuir, I., 1948: The growth of particles in smokes and clouds and the production of snow from supercooled clouds. *Proc. Amer. Philos. Soc.,* **92,** 167–185.

Long, A. B., B. A. Campistron, and A. W. Huggins, 1990: Investigations of a winter mountain storm in Utah. Part I: Synoptic analyses, mesoscale kinematics, and water release rates. *J. Atmos. Sci.,* **47,** 1302–1322.

MacGorman, D. R., and W. D. Rust, 1998: *The Electrical Nature of Storms.* Oxford University Press, 422 pp.

Magono, C., T. Endoh, and T. Taniguchi, 1983: Charge distribution in active winter clouds. *Processes of Atmospheric Electricity,* L.H. Ruhnke and J. Latham, Eds., A. Deepak Pub., 242–245.

Marwitz, J. D., 1980: Winter storms over the San Juan Mountains. Part I: Dynamical processes. *J. Appl. Meteor.,* **19,** 913–926.

——, 1986: A comparison of winter orographic storms over the San Juan Mountains and the Sierra Nevada. *Precipitation Enhancement—A Scientific Challenge, Meteor. Monogr.,* No. 43, Amer. Meteor. Soc., 109–113.

——, 1987: Deep orographic storms over the Sierra Nevada. Part I: Thermodynamic and kinematic structure. *J. Atmos. Sci.,* **44,** 159–185.

McClung, D., and P. Shaerer, 1993: *The Avalanche Handbook.* The Mountaineers, 271 pp.

McDonald, B. E., 1998: Sensitivity of precipitation forecast skill to horizontal resolution. Ph.D. dissertation, University of Utah, 135 pp. [Available from Department of Meteorology, University of Utah, 135 South 1460 East, Salt Lake City, UT 84112.]

Michelson, M., W. W. Shrader, and J. G. Wieler, 1990: Terminal Doppler Weather Radar. *Microwave J.,* **33,** 139–148.

Mock, C. J., and K. W. Birkeland, 2000: Snow avalanche climatology of the western United States mountain ranges. *Bull. Amer. Meteor. Soc.,* **81,** 2367–2392.

National Research Council, 1998: *The Atmospheric Sciences Entering the Twenty-First Century.* National Academy Press, 364 pp.

NCDC, 2000: *Storm Data.* Vol. 42, No. 2, 108 pp.

Neiman, P. J., F. M. Ralph, A. B. White, D. A. Kingsmill, P. O. G. Persson, and D. Gottas, 2001: Orographic precipitation enhancement in the coastal mountains of California during the CALJET field experiment. Preprints, *Symp. on Precipitation Extremes: Prediction, Impacts, and Responses,* Albuquerque, NM, Amer. Meteor. Soc., 33–37.

Niziol, T. A., W. R. Snyder, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Wea. Forecasting,* **10,** 61–77.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting,* **10,** 498–511.

Onton, D. J., and W. J. Steenburgh, 2001: Diagnostic and sensitivity studies of the 7 December 1998 Great Salt Lake-effect snowstorm. *Mon. Wea. Rev.,* **129,** 1318–1338.

——, A. J. Siffert, L. Cheng, W. J. Steenburgh, and B. Haymore, 2001: Regional scale modeling for the 2002 Olympic Winter Games. Preprints, *Ninth Conf. on Mesoscale Processes,* Fort Lauderdale, FL, Amer. Meteor. Soc., J25–J26.

Overland, J. E., and N. A. Bond, 1995: Observations and scale analysis of coastal wind jets. *Mon. Wea. Rev.,* **123,** 2934–2941.

Parish, T. R., 1982: Barrier winds along the Sierra Nevada Mountains. *J. Appl. Meteor.,* **21,** 925–930.

Passarelli, R. E., Jr., and R. R. Braham Jr., 1981: The role of the winter land breeze in the formation of Great Lake snow storms. *Bull. Amer. Meteor. Soc.,* **62,** 482–491.

Peace, R. L., Jr., and R. B. Sykes Jr., 1966: Mesoscale study of a lake effect snow storm. *Mon. Wea. Rev.,* **94,** 495–507.

Pliske, R., B. Crandall and G. Klein, 2001: Competence in weather forecasting. *Psychological Investigations of Competent Decision Making,* J. Shanteau, P. Johnson and K. Smith, Eds, Cambridge University Press, in press.

Pope, D., and C. Brough, Eds. 1996: *Utah's Weather and Climate.* Publishers Press, 245 pp. [Available from Publishers Press, 1900 West 2300 South, Salt Lake City, UT 84119.]

Queney, P., 1948: The problem of air flow over mountains: A summary of theoretical studies. *Bull. Amer. Meteor. Soc.,* **29,** 16–26.

Ralph, F. M., P. J. Neiman, O. G. Persson, J.-W. Bao, J. Schmidt, A. White, and D. Jorgensen, 1999: Blocking by coastal mountains in landfalling Pacific winter storms. Preprints, *Third Conf. on Coastal Atmospheric and Oceanic Processes,* New Orleans, LA, Amer. Meteor. Soc., 368–373.

Rauber, R. M., and L. O. Grant, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part II: Spatial distribution and microphysical characteristics. *J. Climate Appl. Meteor.,* **25,** 489–504.

——, ——, D. Feng, and J. B. Snider, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part I: Temporal variations. *J. Climate Appl. Meteor.,* **25,** 468–488.

Reinking, R. F., J. B. Snider, and J. L. Coen, 2000: Influences of storm-embedded orographic gravity waves on cloud liquid water and precipitation. *J. Appl. Meteor.,* **39,** 733–759.

Reisner, M., 1986: *Cadillac Desert: The American West and Its Disappearing Water.* Viking Penguin, 582 pp.

Reiter, R., 1965: Precipitation and cloud electricity. *Quart. J. Roy. Meteor. Soc.,* **91,** 60–72.

Rust, W. D., and T. C. Marshall, 1989: Mobile, high-wind, balloon-launching apparatus. *J. Atmos. Oceanic Technol.,* **6,** 215–217.

——, R. Davies-Jones, D. W. Burgess, R. A. Maddox, L. C. Showell, T. C. Marshall, and D. K. Lauritsen, 1990: Testing a mobile version of a cross-chain LORAN atmospheric sounding system (M-CLASS). *Bull. Amer. Meteor. Soc.,* **71,** 173–180.

Sassen, K., R. M. Rauber, and J. B. Snider, 1986: Multiple remote sensor observations of supercooled liquid water in a winter storm at Beaver, Utah. *J. Climate Appl. Meteor.,* **25,** 825–834.

——, 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.

——, J. M. Comstock, Z. Wang, and G. G. Mace, 2001: Cloud and aerosol research capabilities at FARS: The Facility for Atmospheric Remote Sensing. *Bull. Amer. Meteor. Soc.,* **82,** 1119–1138.

Schultz, D. M., 1999: Lake-effect snowstorms in northern Utah and western New York with and without lightning. *Wea. Forecasting,* **14,** 1023–1031.

——, and C. A. Doswell III, 2000: Analyzing and forecasting Rocky Mountain lee cyclogenesis often associated with strong winds. *Wea. Forecasting,* **15,** 152–173.

Sinclair, M. R., D. S. Wratt, R. D. Henderson, and W. R. Gray, 1997: Factors affecting the distribution and spillover of precipitation in the southern Alps of New Zealand—A case study. *J. Appl. Meteor.,* **36,** 428–442.

Slemmer, J. W., 1998: Characteristics of winter snowstorms near Salt Lake City as deduced from surface and radar observations. M. S. thesis, Department of Meteorology, University of Utah, 138 pp. [Available from Department of Meteorology, University of Utah, 135 South 1460 East, Salt Lake City, UT 84112.]

Smith, R., and Coauthors, 1997: Local and remote effects of mountains on weather: Research needs and opportunities. *Bull. Amer. Meteor. Soc.,* **78,** 877–892.

Splitt, M. E., and J. Horel, 1998: Use of multivariate linear regression for meteorological data analysis and quality assessment in complex terrain. Preprints, *10th Symposium on Meteorological Observations and Instrumentation,* Phoenix, AZ, Amer. Meteor. Soc., 359–362.

——, and T. Blazek, 2000: Surface pressure data analysis in complex terrain. Preprints, *Ninth Conf. on Mountain Meteorology,* Aspen, CO, Amer. Meteor. Soc., 409–412.

Staudenmaier, M., Jr., and J. Mittelstadt, 1998: Results of the Western Region evaluation of the Eta-10 model. Preprints, *12th Conf. on Numerical Weather Prediction,* Phoenix, AZ, Amer. Meteor. Soc., 131–134.

Steenburgh, W. J., and T. R. Blazek, 2001: Topographic distortion of a cold front over the Snake River Plain and central Idaho mountains. *Wea. Forecasting,* **16,** 301–314.

——, and D. J. Onton, 2001: Multiscale analysis of the 7 December 1998 Great Salt Lake-effect snowstorm. *Mon. Wea. Rev.,* **129,** 1296–1317.

——, S. F. Halvorson, and D. J. Onton, 2000: Climatology of lake-effect snowstorms of the Great Salt Lake. *Mon. Wea. Rev.,* **128,** 709–727.

Taylor, G. H., C. Daly, and W. P. Gibson, 1993: Development of a new Oregon annual precipitation map using the PRISM model. *State Climatol.,* **17**(2), 1–4.

Turnbull, D., J. McCarthy, J. Evans, and D. Zrnic, 1989: The FAA Terminal Doppler Weather Radar (TDWR) Program. Preprints, *Third Int. Conf. on the*

Aviation Weather System, Anaheim, CA, Amer. Meteor. Soc., 414–419.

Vasiloff, S., 1996: Overview of the National Weather Service Western Region radar project. National Weather Service Western Region Tech. Attachment 96-26. [Available online at http://www.wrh.noaa.gov/wrhq/96TAs/TA9626/ta96-26.html.]

——, 2001a: Improving tornado warnings with the Federal Aviation Administration's Terminal Doppler Weather Radar. *Bull. Amer. Meteor. Soc.,* **82,** 861–874.

——, 2001b: WSR-88D performance in northern Utah during the winter of 1998–1999. Part-I: Adjustments to precipitation estimates. Western Region Tech. Attachment 01-01. [Available online at http://www.wrh.noaa.gov/wrhq/01TAs/0102/index.html.]

——, 2001c: WSR-88D performance in northern Utah during the winter of 1998–1999. Part-II: Examples of error sources. Western Region Tech. Attachment 01-02. [Available online at http://www.wrh.noaa.gov/wrhq/01TAs/0103/index.html.]

Wakimoto, R. M., and B. L. Bosart, 2000: Airborne radar observations of a cold front during FASTEX. *Mon. Wea. Rev.,* **128,** 2447–2470.

Warner, T. T., Y.-H. Kuo, J. D. Doyle, J. Dudhia, D. R. Stauffer, and N. L. Seaman, 1992: Nonhydrostatic, mesobeta-scale, real-data simulations with the Penn State University/National Center for Atmospheric Research Mesoscale Model. *Meteor. Atmos. Phys.,* **49,** 209–227.

Westrick, K. J., C. F. Mass, and B. A. Colle, 1999: The limitations of the WSR-88D radar network for quantitative precipitation measurement over the coastal western United States. *Bull. Amer. Meteor. Soc.,* **80,** 2289–2298.

White, B. G., J. Paegle, W. J. Steenburgh, J. D. Horel, R. T. Swanson, L. K. Cook, D. J. Onton, and J. G. Miles, 1999: Short-term forecast validation of six models. *Wea. Forecasting,* **14,** 84–108.

Williams, P., Jr., 1972: Western region synoptic analysis—Problems and methods. NOAA NWS Western Region Tech. Memo. NWSTM WR-71, 71 pp. [Available from NOAA/NWS, Western Region Headquarters, 125 S. State Street, Rm. 1311, Salt Lake City, UT 84138-1102.]

——, and W. J. Heck, 1972: Areal coverage of precipitation in northwestern Utah. *J. Appl. Meteor.,* **11,** 509–516.

Winn, W. P., and L. G. Byerley III, 1975: Electric field growth in thunderclouds. *Quart. J. Roy. Meteor. Soc.,* **101,** 979–994.

Wurman, J. J. Straka, E. Rasmussen, M. Randall, and A. Zahrai, 1997: Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar. *J. Atmos. Oceanic Technol.,* **14,** 1502–1512.

Yu, C.-K., and B. F. Smull, 2000: Airborne Doppler observations of a landfalling cold front upstream of steep coastal orography. *Mon. Wea. Rev.,* **128,** 1577–1603.