UNDERSTANDING UTAH WINTER STORMS

The Intermountain Precipitation Experiment

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IPEX—a wintertime research program in the Salt Lake area—aims to improve models, predictions, and understanding of precipitation in a region that is difficult to observe and forecast

Eighteen million residents are impacted by winter storms each year throughout the Intermountain West (Wilkinson 1997, p. 30)—the geographic region east of the crests of the Sierra Nevada and Cascade Mountains, and west of the Continental Divide (Fig. 1a). Although historically characterized by low population density, the region has experienced rapid population growth. Between the 1990 and 2000 national censuses, the five fastest growing states belonged to the Intermountain West (Nevada, Arizona, Colorado, Utah, and Idaho). For example, Utah experienced a 29.3% increase in population during this 10-yr period. As a result, intermountain winter storms impact a growing population and regional economy.

The socioeconomic impacts of winter storms over the Intermountain West 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-

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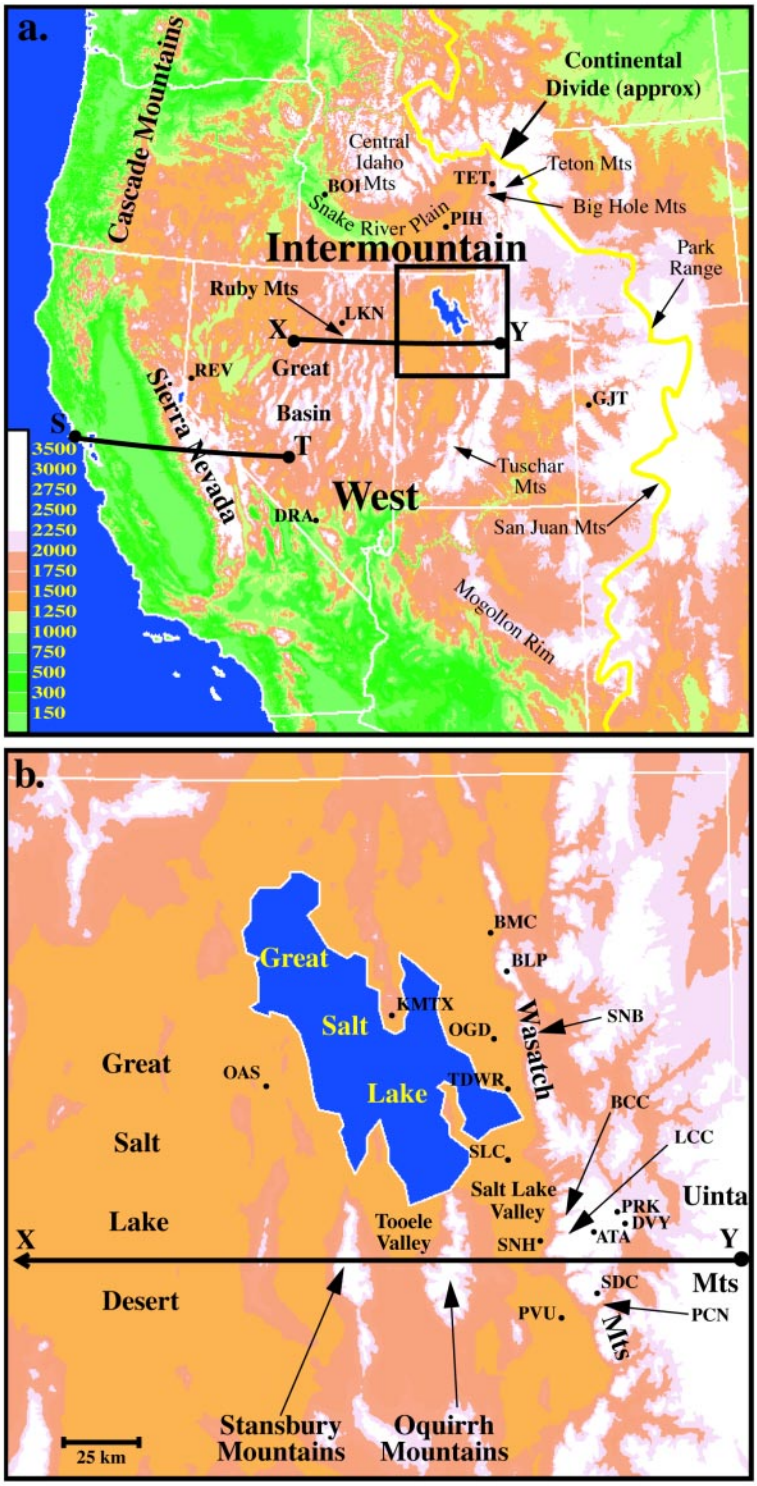

Fig. 1. Major terrain and geographic features of (a) the western United States and (b) northern Utah. Elevation (m, shaded) according to scale in (a). Inset box over northern Utah in (a) denotes location of (b). Cross sections ST and XY (Fig. 3) annotated in (a). Abbreviations in (a): BOI = Boise, ID;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

or ice-covered roads and avalanches. For example, in Utah, where a large fraction of the population lives in the densely populated Wasatch Front urban corridor that includes the cities of Ogden, Salt Lake, and Provo, property damage from winter storms cost nearly $100 million over the four winter seasons from 1993/94 to 1996/97 (Blazek 2000). In conjunction with the growing population, there is a greater number of people in the backcountry. More than 1000 human-triggered avalanches have been reported in Utah during 1985–2000, claiming 200 victims and 42 deaths (B. Tremper 2001, personal communication). Major transportation corridors through mountainous terrain are occasionally closed due to avalanche hazard, while snowfall in low-elevation regions creates gridlock on urban freeways and city streets.

Unfortunately, the skill exhibited by numerical weather prediction models (e.g., Junker et al. 1992; Gartner et al. 1998; McDonald 1998), as well as human forecasters (P. Roebber 2001, personal communication), is lower over the Intermountain West than other regions of the United States. The goal of the Intermountain Precipitation Experiment (IPEX) is to address this challenge by improving the understanding, analysis, and prediction of precipitation and precipitation processes over the complex topography of the Intermountain West.

TOPOGRAPHY AND PRECIPITATION OF THE INTERMOUNTAIN WEST. The Intermountain West includes the basin-and-range topog-

raphy of the Great Basin, which is characterized by a large number of steeply sloped mountain ranges separated by broad basins of alluvium. One of the more dramatic ranges of the Intermountain West is the Wasatch Mountains, which rise 1200–2000 m in about 5 km on their western slope to more than 3350 m (11 000 ft) (Figs. 1b and 3). 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 (e.g., Dunn 1983) and lake-effect (Carpenter 1993; Steenburgh et al. 2000; Steenburgh and Onton 2001; Onton and Steenburgh 2001) precipitation along the Wasatch Front urban corridor. Populated regions of this urban corridor range in elevation from 1300 to 1800 m (4265–5905 ft) and observe annual snowfalls of 110–250 cm (43–98 in.). Average annual snowfall in the Wasatch Mountains reaches 1300 cm (512 in.) at Alta ski area, with record 24-h and storm-total accumulations 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.). Strong gradients in snowfall, both in the annual average and from individual storms, occur, although snowfall distributions from individual storms cannot necessarily be predicted based on climatology. For example, precipitation can 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. Substantial snowfall also can be observed at low elevations, as in the 24–26 February 1998 orographic and lake-effect snowstorm that produced up to 130 cm (51 in.) in the Salt Lake City metropolitan area (Slemmer 1998).

LIMITED FORECAST SKILL. Unfortunately, skill in forecasting precipitation in the Intermountain West is lower than in other regions of the country, as demonstrated by 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) evaluated the skill of human-produced 24-h probability-of-precipitation forecasts 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 prognosis 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, in situ upstream data to augment remotely sensed observations and assess evolving weather situations are 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, 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 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 melting effects of precipitation, anomalous propagation in valley inver-

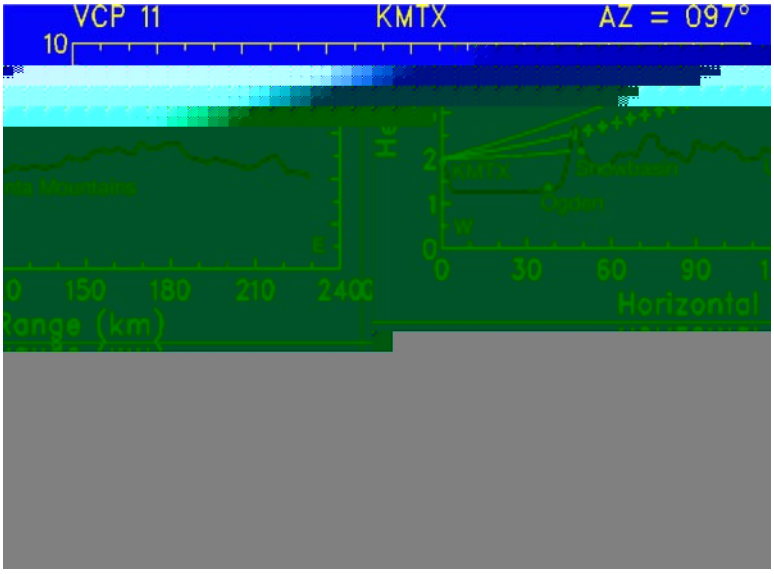

Fig. 2. The WSR-88D on Promontory Point, Utah (KMTX)—situated at 2111 m (6929 ft) MSL, 823 m (2700 ft) above Salt Lake City—illustrates the difficulty in using radar over complex terrain. The lowest elevation scan (0.5°) from KMTX overshoots the Wasatch Front urban corridor by 1 km over Ogden (as shown here) and 4 km over Provo (not shown). Thus, the bulk of valley snowstorms over major population areas often lie beneath the lowest elevation scans of KMTX. This figure simulates a vertical cross section from KMTX along the 97° radial. The red curve represents the earth's surface, the yellow arc represents the center of the lowest beam (0.5°), yellow plus signs represent beam blockage by the Wasatch Mountains, and the green arc represents the half-power beamwidth. (Courtesy of Vincent Wood and Rodger Brown, National Severe Storms Laboratory.)

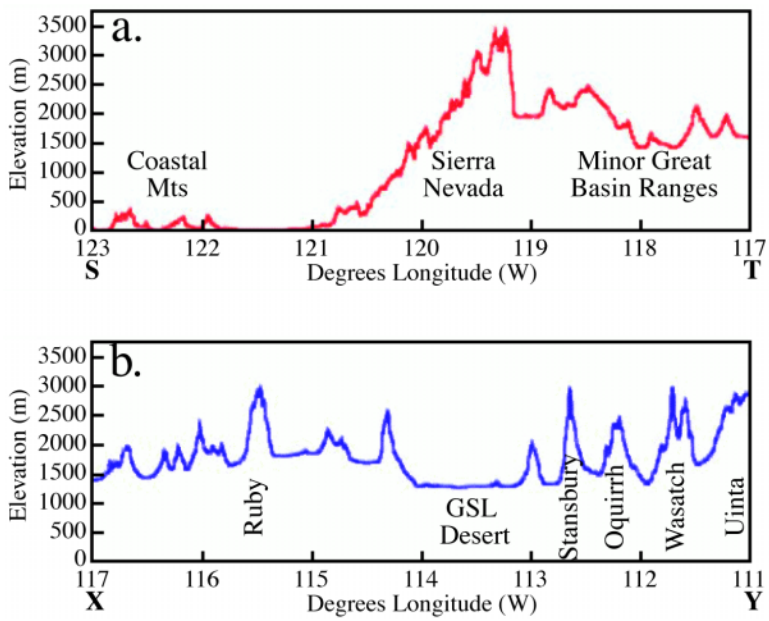

Fig. 3. Meridionally averaged (2 arc minutes) elevation (m MSL) along lines (a) ST and (b) XY of Fig. 1b. Major mountain ranges and geographic features annotated. GSL = Great Salt Lake.

sions, radar beam blockage, and mountaintop radars overshooting low-lying precipitation systems (e.g., Westrick et al. 1999; Huggins and Kingsmill 1999; Vasiloff 2001b,c). The last two points are demonstrated by Fig. 2, in which the lowest elevation angle beam from the Promontory Point WSR-88D radar (KMTX) overshoots the cities in the Salt Lake Valley (like Ogden) and much of the beam is blocked to the east side of the Wasatch.

- In comparison to the relatively broad Sierra Nevada and Cascade Mountains, 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. In Nevada alone, the flow is disrupted by 413 distinct mountain ranges, described in the late 1800s by the geographer Clarence Dutton as "an army of caterpillars marching toward Mexico."
- 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.

1999, 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 the water equivalent. One common approach is to assume a 10:1 ratio of freshly fallen snow to water equivalent, equivalent to a snow density of 100 kg m^{-3}. Observations of this ratio from freshly fallen snow at 6 locations across the western United States and Alaska range from less than 5:1 to greater than 50:1 [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 evolution 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. 2002). 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).

THE GOALS OF IPEX. 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).

The field campaign and associated research program known as IPEX is designed to address the above three challenges with the goals of 1) advancing 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) understanding better the relationships between orographically induced circulations and cloud microphysical processes; 3) documenting 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) improving 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) exploring the electrical structure of continental winter storms; and 6) raising 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), the University of Utah Department of Meteorology and the NOAA Cooperative Institute for Regional Prediction, the NOAA Aircraft Operations Center (AOC), the Desert Research Institute, the University of Oklahoma School of Meteorology, several NWS forecast offices, the NWS Western Region Headquarters, the NWS Storm Prediction Center (SPC), the NWS Hydrometeorological Prediction Center (HPC), the Operational Support Facility (OSF, now known as the Radar Operations Center), and the Utah Department of Transportation.

OBSERVATIONAL TOOLS. 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). A variety of specialized observing platforms were employed during IPEX (Fig. 4). Extensive observing facilities were already in the area, including the Salt Lake City radiosonde station (SLC), Promontory Point WSR-88D radar (KMTX), the FAA Ter-

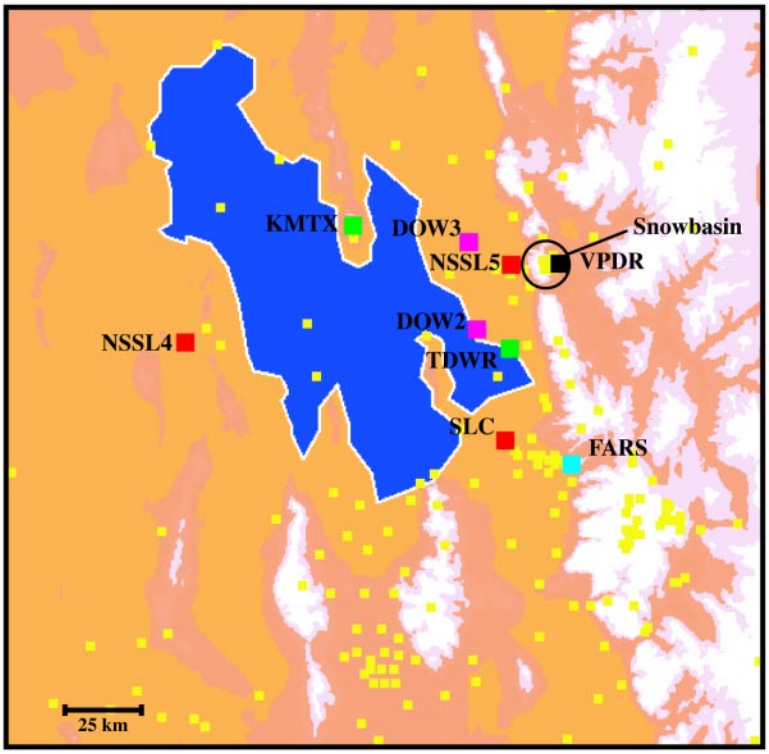

Fig. 4. Observing platforms employed during IPEX: Salt Lake City radiosonde station (SLC, red square), Promontory Point WSR-88D radar (KMTX, green square), FAA Terminal Doppler Weather Radar (TDWR, green square), Facility for Atmospheric Remote Sensing microwave radiometer (FARS, cyan square), MesoWest surface observing stations (yellow squares; Horel et al. 2000, 2002b), NSSL mobile laboratories (NSSL4 and NSSL5, red squares), mobile Doppler on Wheels units (DOW2 and DOW3, red squares), vertically pointing Doppler radar (VPDR, black square), Operations Center and P-3 base located at SLC (red square). More information about the instrumentation during IPEX can be found in the electronic supplement (http://ams.allenpress.com).

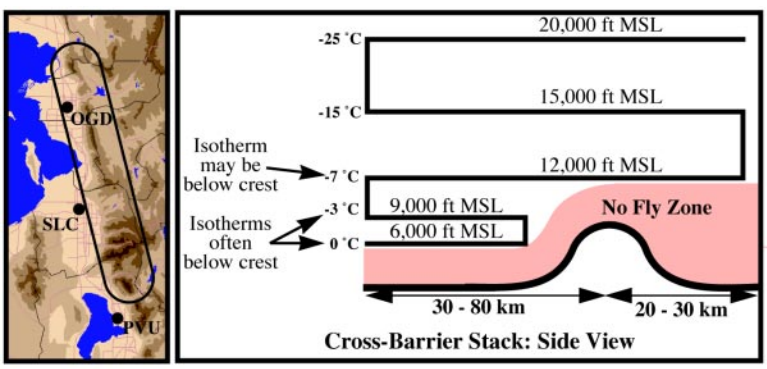

Fig. 5. Schematic of typical along-barrier racetracks and cross-barrier flight stacks with stack-leg temperatures for microphysical sampling. In practice, altitudes vary based on stratification and flight restrictions (e.g., the no-fly zone). OGD = Ogden, PVU = Provo, and SLC = Salt Lake City.

minal Doppler Weather Radar (TDWR; Turnbull et al. 1989; Michelson et al. 1990; Vasiloff 2001a), the Facility for Atmospheric Remote Sensing microwave radiometer (FARS; Sassen et al. 2001), and a special network of surface observing stations (Horel et al. 2000, 2002b). The last, a joint program of the University of Utah and the National Weather Service called MesoWest, provides observations from some 2500 automated stations in the West—over 250 of them in northern Utah.

During IOPs, soundings were released by the NWS SLC Forecast Office, five other locations in the western United States, and by two NSSL mobile laboratories as often as every 3 h. The NSSL mobile laboratories (NSSL4 and NSSL5) are converted 15-passenger vans equipped with the Mobile GPS and Loran Atmospheric Sounding System (M-GLASS).

Even though orographic forcing is largely fixed, it helped to have mobile platforms such as the mobile NSSL laboratories, the NOAA P-3 aircraft, and the two University of Oklahoma Doppler on Wheels (DOWs)—truck-mounted pulsed X-band radars (Wurman et al. 1997). During IPEX, the two DOWs were deployed largely to predetermined locations on the windward side of the Wasatch. The mobility of the DOW and NSSL vehicles was exploited during IOPs 1 and 5.

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). 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). 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. Cross-barrier stacks were used to examine the variability of cloud and precipitation processes as a function of distance from the barrier and as a function of temperature regime.

A vertically pointing S-band Doppler radar operated jointly by NSSL, the Radian Corporation, and the Salt River Project (Gourley et al. 2000), was deployed to provide high temporal resolution reflectivity data for estimating precipitation quantitatively from WSR-88Ds sited at high altitudes. The radar was deployed on the east side of the Wasatch Mountains at Snowbasin Ski Resort, to take measurements of the lowest 800–1200 m of the atmosphere—a layer unobservable with the KMTX WSR-88D (Fig. 2). More information about the instrumentation during IPEX and operations can be found in section 3 of the electronic supplement.

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) produced hourly analyses at 1-km horizontal grid spacing for northern Utah (Ciliberti et al. 1999, 2000). 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 was run twice daily at 12-km horizontal grid spacing in its real-time implementation at the

IPEX OUTREACH

IPEX provided an exceptional learning opportunity for students at many levels. Thirty University of Utah students partnered with IPEX scientists to collect data during IOPs, attend weather briefings and planning meetings, and provide weather support during IPEX forecast shifts. The students gained valuable exposure to meteorological research, and practical experience in observations, electrification, radar, and forecasting. The project also captured the scientific curiosity of 120 local junior high school students who toured the P-3 on one no-fly day.

IPEX received extensive media coverage, helping to explain the project's purpose and to educate the public about the complex weather-forecasting challenges in the Intermountain West. 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 other instrumentation.

Reporters from three different news organizations flew on the P-3 during the IOPs. *Powder* magazine interviewed one of the chief scientists. At the end of the field phase, the scientists met with reporters to discuss their successes. *USA Today* covered IPEX with a four-part story on their Web site and a newspaper article 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 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 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 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.

University of Utah (e.g., White et al. 1999; Onton et al. 2001).

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 temperatures during the month, although the valleys received less snowfall than usual.[1]

[1] Salt Lake City Airport (SLC) was 3.2°C above normal for February 2000 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 data 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] with that at two locations in the Salt Lake Valley [Salt Lake City Airport, 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.

During IPEX, seven IOPs were declared. There were no missed opportunities—all significant precipitation events were explored during IOPs. In this section, each IOP is briefly described (IOP 5 is discussed in the sidebar on p. 201), along with the data collected, and a discussion of scientific issues involved with each event (Table 1).

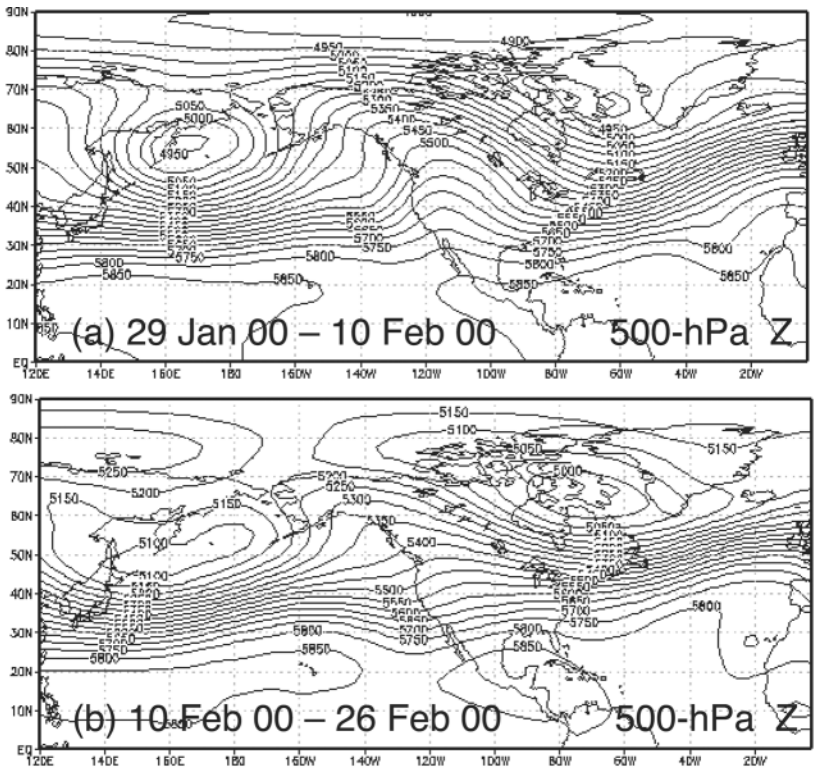

Fig. 6. Composite 500-hPa height (solid lines every 50 m) from NCEP Reanalysis (Kalnay et al. 1996) for (a) the first regime during IPEX: 0000 UTC 29 Jan 2000 to 0000 UTC 10 Feb 2000, and (b) the second regime: 0000 UTC 10 Feb 2000 to 0000 UTC 26 Feb 2000. (Provided by the NOAA CIRES Climate Diagnostics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

IOP 1: 5 February 2000—Light snow in the Teton Mountains. On 5 February, a weak weather system moved through Idaho and Wyoming. The light snow was caused by large-scale ascent associated with lower- and mid-tropospheric southwesterly warm advection ahead of a decaying Pacific frontal system, enhanced by stable orographic precipitation over the Big Hole and Teton Mountains. Initially, widespread reflectivity from the Pocatello WSR-88D (KSFX) was observed, although little precipitation reached the surface. Eventually, reflectivity increased over the Big Hole and Teton Mountains with precipitation shadowing in the lee of the Big Hole Mountains resulting 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.) with 0.79–1.35 cm (0.31–0.53 in.) water equivalent, approximately 5–10 times more precipitation than observed upstream in the Snake River Plain where water equivalent 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). Unfortunately, no in situ observations were 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. Microphysics data were also obtained 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 was a result of the breakdown of the persistent ridge over the western United States, putting northern Utah in the confluent region of split flow. The first weather system to reach Utah in 10 days was associated with an upper-level trough that moved across southern California, Nevada, and Arizona. 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

Table 1. 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

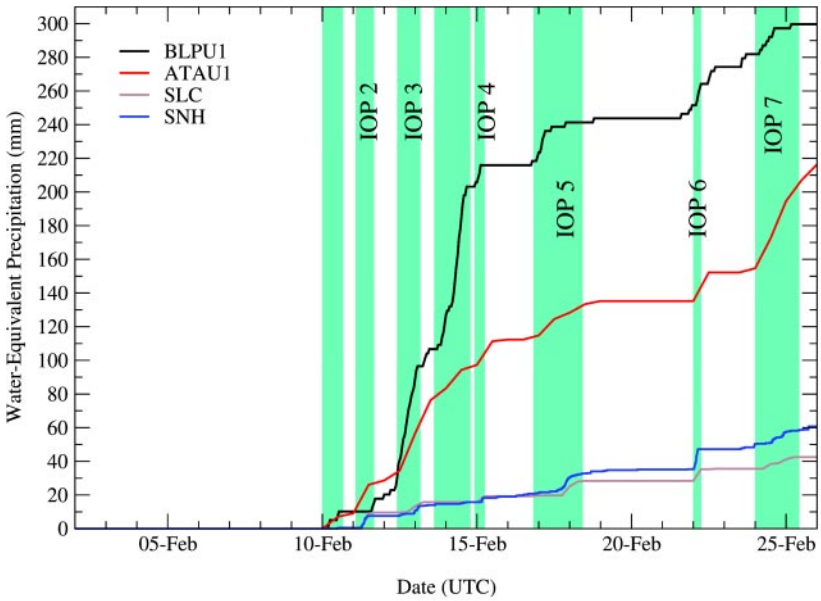

Fig. 7. Cumulative time series of observed precipitation at four sites during IPEX: Alta Guard House (ATAU1, red line), Ben Lomond Peak (BLPU1, black line), Salt Lake City Airport (SLC, brown line), and Sandy (SNH, purple line). Blue shaded areas represent periods of subjectively determined precipitation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

where the water equivalent precipitation rate was 0.6 cm h^{-1} (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, resulting in substantial gradients in storm-total precipitation, not only between lowland and mountain locations, but also along the Wasatch crest (Fig. 8a). 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 biggest snowstorm to strike the Wasatch Mountains in 2 yr 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 damned the Provo River, which flows through Provo Canyon. A couple of 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 an unusual trough structure (i.e., the 700-hPa trough axis appeared to be decoupled from, and 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), reminiscent of blocking, as observed upstream of the Sierra Nevada (e.g., Parish 1982; Marwitz 1987), San Juan Mountains of Colorado (e.g., Marwitz 1980, 1986), and the Pacific 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 (Fig. 8b). To the lee (east) of the Wasatch, accumulations rapidly decreased by a factor of 2–4 within only 10–15 km of the crest. The precipitation reduction was particularly impressive to the lee of the high topography in the Wasatch, where the cloud-top echo sloped strongly downward (Fig. 9), suggesting intense leeside subsidence may have limited downstream hydrometeor transport, resembling that from analyti-

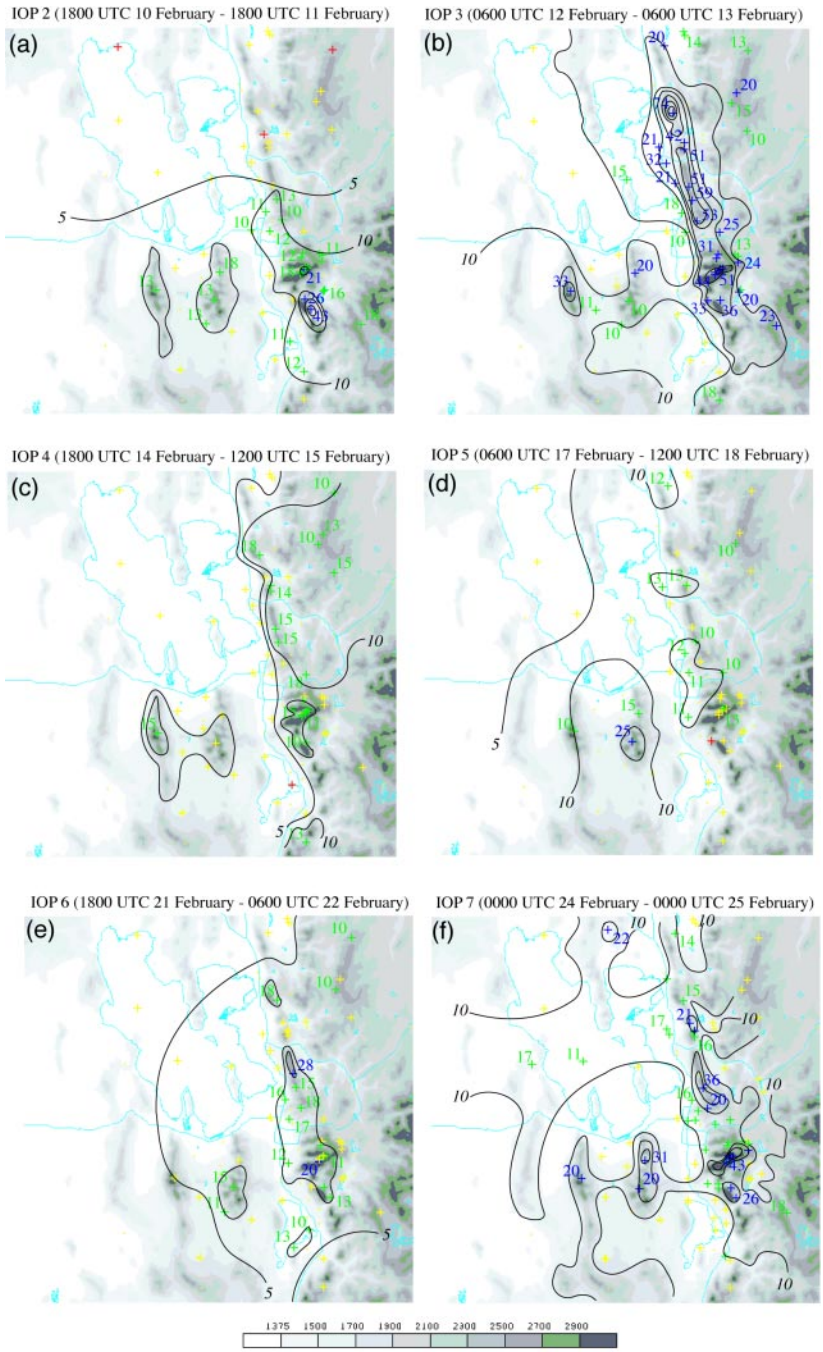

Fig. 8. Spatial distribution of precipitation for six IPEX IOPs from Cheng (2001). Plus signs identify stations reporting precipitation during the period. Red plus signs denote stations reporting zero or trace; yellow plus signs denote stations reporting measurable precipitation, but less than 10 mm; green plus signs denote stations reporting at least 10 mm, but less than 20 mm; and blue plus signs denote stations reporting at least 20 mm of precipitation. Selected stations are labeled with the observed precipitation totals to the nearest millimeter. Contours of 5, 10, 20, 30, 40, and 70 mm, where possible, were manually 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–06 UTC 22 Feb. (f) IOP 7: 0000 UTC 24 Feb–0000 UTC 25 Feb.

cal 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 (e.g., Fig. 5) 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 (Cox et al. 2001). 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

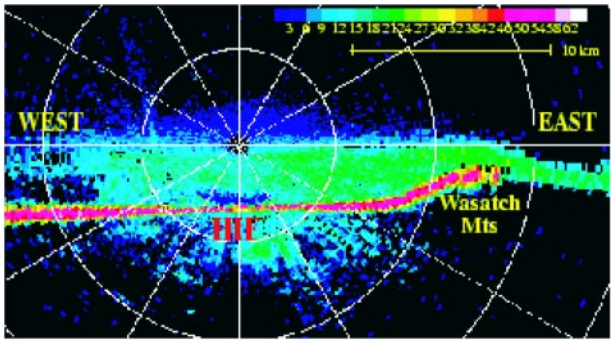

Fig. 9. Radar-reflectivity (dBZ) vertical cross section from the P-3 tail Doppler radar at 0023 UTC 13 Feb 2000 during IPEX IOP 3. The P-3 is located at the center of the range rings and is flying into the page, roughly north, parallel to the Wasatch Mountains located to the right of the P-3. Reflectivity 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.

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 s^{-1} in northern Utah and the western Snake River Valley, reaching 43 m s^{-1} at Minidoka, Idaho. Numerous power outages occurred, 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 an 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 ever been reported in Idaho, the only ones ever reported in February (D. Schultz and J. Racy 2000, personal communication). The 2100 UTC Boise, Idaho (BOI) sounding (Fig. 11) had 184 J kg^{-1} of convective available potential energy (CAPE), 16 m s^{-1} shear in the lowest 2

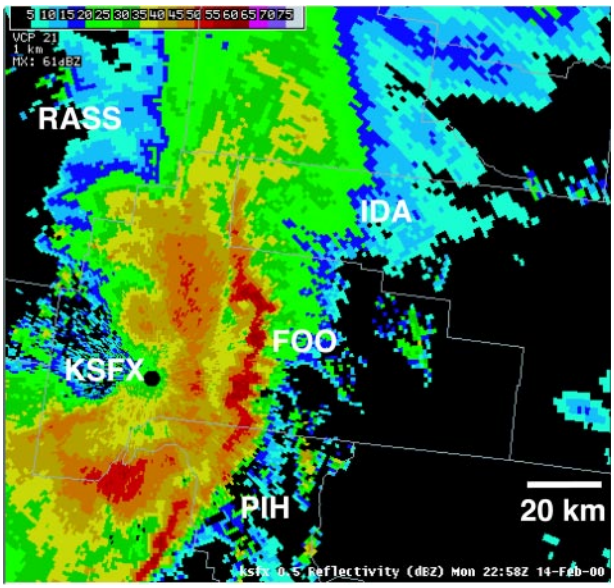

Fig. 10. Radar reflectivity (dBZ, colored according to scale at top of figure) from Pocatello WSR-88D (KSFX) at 0.5° elevation angle at 2258 UTC 14 Feb 2000 during IPEX IOP 4. Thin solid gray lines are county borders. FOO = Blackfoot, Idaho; IDA = Idaho Falls, Idaho; PIH = Pocatello, Idaho; and RASS = 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.

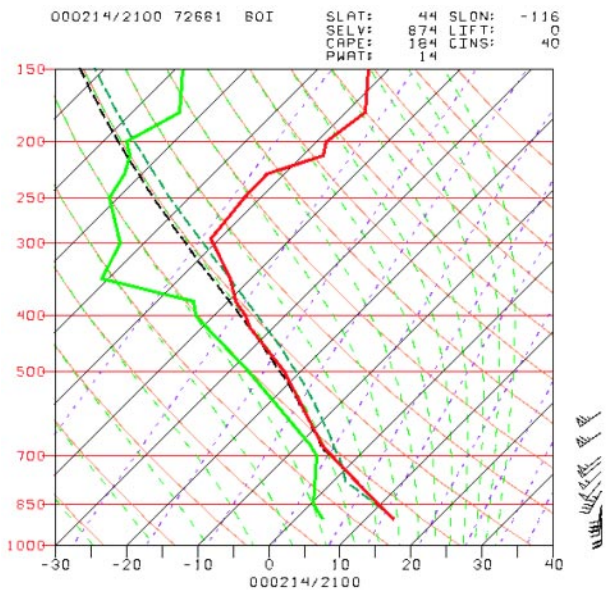

Fig. 11. 2100 UTC 14 Feb 2000 BOI sounding on a skew *T*–log*p* diagram (°C and hPa) during IPEX IOP 4. SLAT is the station latitude (whole °N); SLON is the station longitude (whole °W); SELV is station elevation (m); LIFT is lifted index (°C); CAPE is convective available potential energy (J kg^{-1}); CINS is convective inhibition (J kg^{-1}); 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.

Relatively few studies have examined the climatology and causes of thundersnow (see review by Schultz 1999). MacGorman and Rust (1998, p. 292) noted that electrical observations within winter storms have been sparse, with no apparent electric-field soundings in the United States. Therefore, one IPEX objective was to make balloon-borne soundings of the electric field (and inferred charge layer structure) within snowstorms, to begin to document the electric structure of winter storms in the United States.

During IPEX, the NSSL5 crew flew a 1200-g balloon towing an instrument train comprising a Väisälä RS80 GPS radiosonde and an electric-field meter. 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 fields measured 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.

During IOP 5 on 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 dBZ (Fig. 12), indicative of snowfall rates of 2–4 mm h^{-1}. The band lasted for about 10 h before dissipating and giving way to light orographic precipitation showers along the Wasatch. 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. By storm's end, 10–30 cm (4–12 in.) of snow were measured over the Tooele Valley and the surrounding mountains.

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 flight. 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. Farther aloft, E_z was weakly positive from 2.2 to 4.4 km (Fig. 14a), roughly 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.

The magnitude of the electric field with height was well below that generally associated with lightning. The National Lightning Detection Network did not record any cloud-to-ground strokes within hundreds of kilometers for many hours around the flight, no lightning was obvious from data collected by the ground-based electric-field sensor on NSSL5, and human observers did not observe any lightning. Thus, this snowstorm can be described as an electrified, nonthunderstorm nimbostratus. During IOP 6, an electric-field meter measured the largest electric fields of 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. These profiles (and indeed the other four electric-field profiles during IPEX) show that 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 winter nimbostratus clouds.

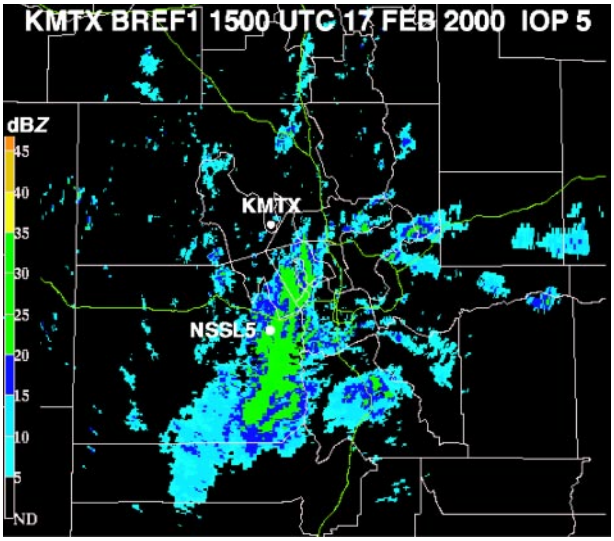

Fig. 12. Radar reflectivity (dBZ, colored according to scale on left side of figure) from KMTX WSR-88D at 0.5° elevation angle at 1500 UTC 17 Feb 2000 during IPEX IOP 5. NSSL5 = location of NSSL mobile laboratory NSSL5 during launch of electric-field meter in Fig. 14.

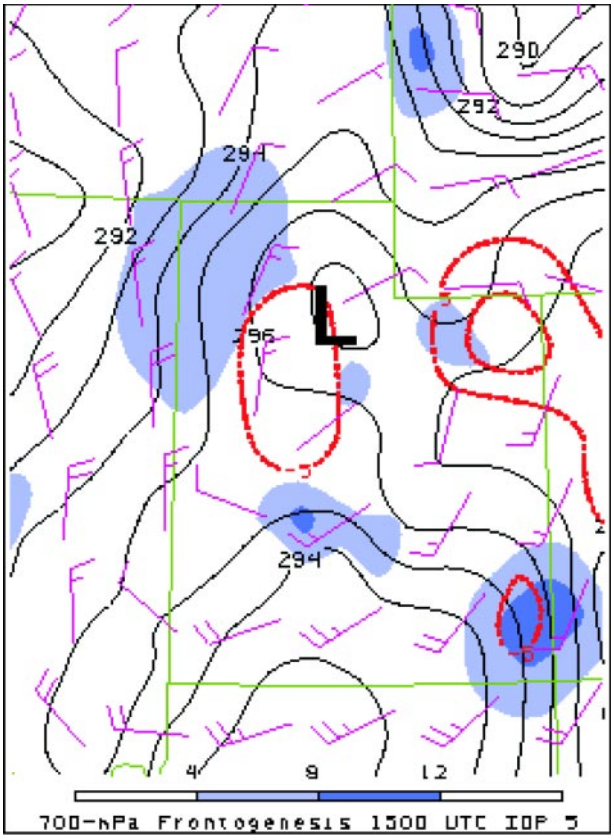

Fig. 13. Initialization of the 1500 UTC 17 Feb 2000 Rapid Update Cycle version 2 during IPEX IOP 5: 700-hPa frontogenesis [0.1°C (100 km 3 h)$^{-1}$, shaded according to scale at bottom], 700-hPa potential temperature (solid lines every 1°C), 700-hPa winds (half barb, full barb, and pennant represent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

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, as examined by Evans and Doswell (2001). IPEX IOP 4 may be one of the better documented bow-echo environments to date 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.

As the convective system moved into northern Utah, the WSR-88D network observed the line of reflectivity values increase to greater than 40 dBZ. Pea-size hail, a 7°C temperature drop, and a 5–6-hPa pressure rise accompanied passage at Oasis, Utah. 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-year-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 online at http://www.nssl.noaa.gov/~schultz/ipex/iop4.

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.

IOP 6: 22 February 2000—Unstable southerlies and orographic precipitation. Large-scale conditions during IOP 6 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 February SLC sounding (not shown) had 145 J kg^{-1} of CAPE, 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.

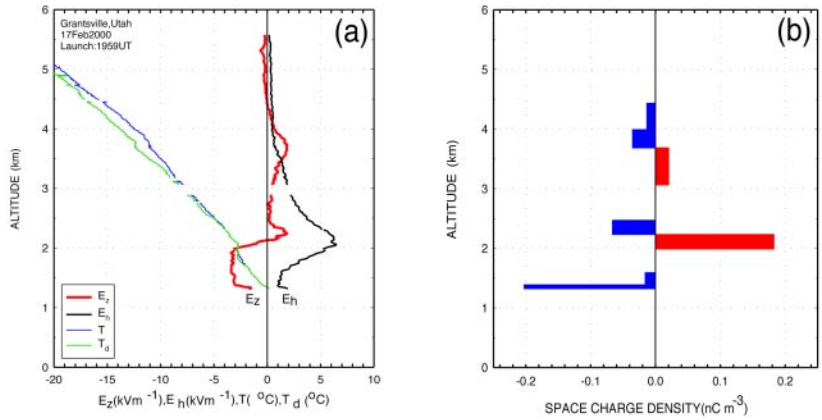

Fig. 14. Electric-field profile in nimbostratus from a balloon launch at 1959 UTC 17 Feb 2000 during IPEX IOP 5. The sounding was made at 40°35.903′N, 112°26.375′W—about 2 km west of Grantsville, UT (location shown in Fig. 12). Vertical scale is altitude (km MSL). (a) Vertical component of the electric 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}).

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. 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.

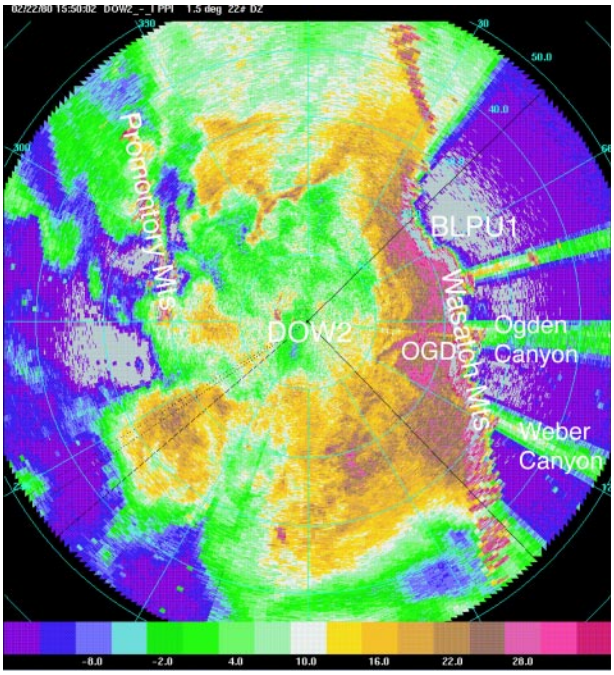

Fig. 15. DOW2 plan position indicator (PPI) of radar reflectivity along the 1.5° elevation angle scan (approximately calibrated units of dBZ, color scale at bottom) from 41°15.032′N, 112°10.824′W (location in Fig. 4) at 0350 UTC 22 Feb 2000 during IPEX IOP 6. BLPUI = Ben Lomond Peak, and OGD = Ogden.

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 within 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

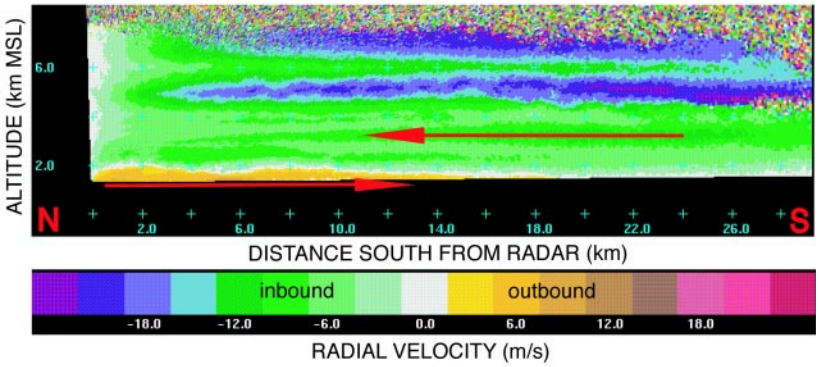

Fig. 16. DOW2 range–height indicator (RHI) radial velocity (m s^{-1}, color scale at bottom) from 41°15.032′N, 112°10.824′W (location in Fig. 4) at 1744 UTC 24 Feb 2000 during IPEX IOP 7. Red arrows indicate the flow direction in the plane of cross section (inbound or outbound), which was along the 175.1°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

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 UTC 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.

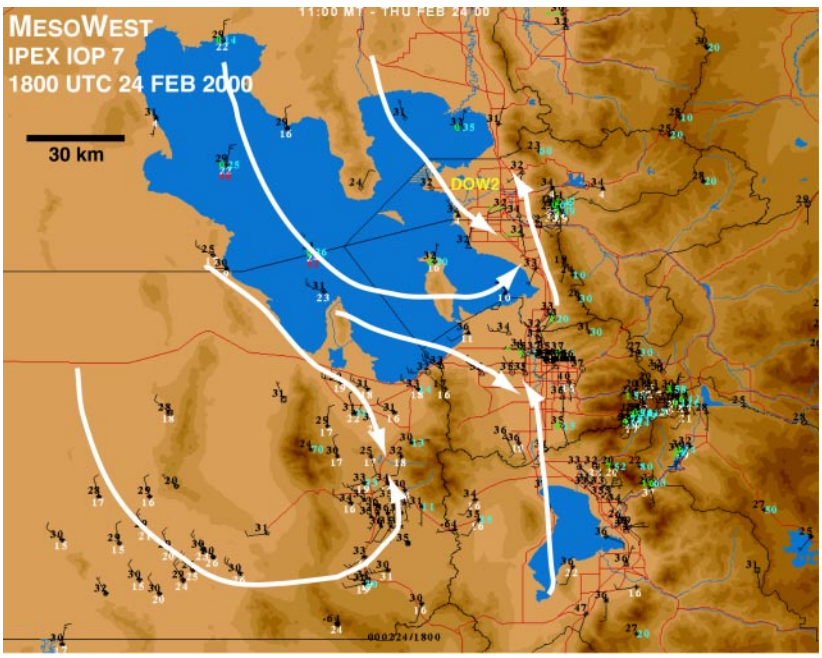

Fig. 17. MesoWest surface observations at 1800 UTC 24 Feb 2000 during IPEX IOP 7. Temperature (°F; black numbers above the station), wind (half barb, full barb, and pennant represent 5, 10, and 50 kt, respectively), gusts greater than 15 knots (white numbers below the station), 1-h precipitation (0.01 in.; green numbers to the left of the station), 6-h precipitation (0.01 in.; blue numbers to the right of the station), and lake-surface temperature (°F; red numbers below the station) are plotted. 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.

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 water equivalent 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 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.

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, and events with orographic precipitation enhancement versus events without apparent orographic enhancement. Our initial impressions were that the warm period in February resulted in more convective phenomena than are typically seen at that time in northern Utah. Another observation was how often lower-tropospheric features were decoupled from mid- and upper-tropospheric features, as in IOPs 2 and 3. 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 graphical probabilistic forecast products, such as might be employed in the future by the NWS, were tested and will be evaluated.

We learned many lessons while organizing and executing IPEX that may help others planning similar projects in the future.

- IPEX was intentionally small and focused with no adjunct experiments. Decisions on operations were made with little contention. Funding for IPEX was absorbed primarily by the contributing organizations. In addition, 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. Nevertheless, the goals were sufficiently broad, allowing improvised operations during serendipitous events like IOP 4, 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 some unexpected events.
- Operating a research aircraft in a major metropolitan area was not as difficult as we initially feared. It required communication 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 strategies. The most serious limitation was probably selecting P-3 flight altitudes because of enroute air traffic under instrument flight rules (IFR).
- Even though much of the orographic forcing was fixed, having mobile platforms was useful. Sometimes, however, transit time and other opera-

PREDICTABILITY DURING IPEX

Cheng (2001) examined the performance of the operational forecast models [NCEP's Eta and aviation run of the Global Spectral Model (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. The cumulative time series of observed and forecast precipitation during 2–26 February (Fig. 18) show the NCEP models underforecast the total precipitation at the mountain locations and overforecast 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 amount 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 issued at Alta since the winter of 1997/98 (L. Dunn 2001, personal communication), 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.

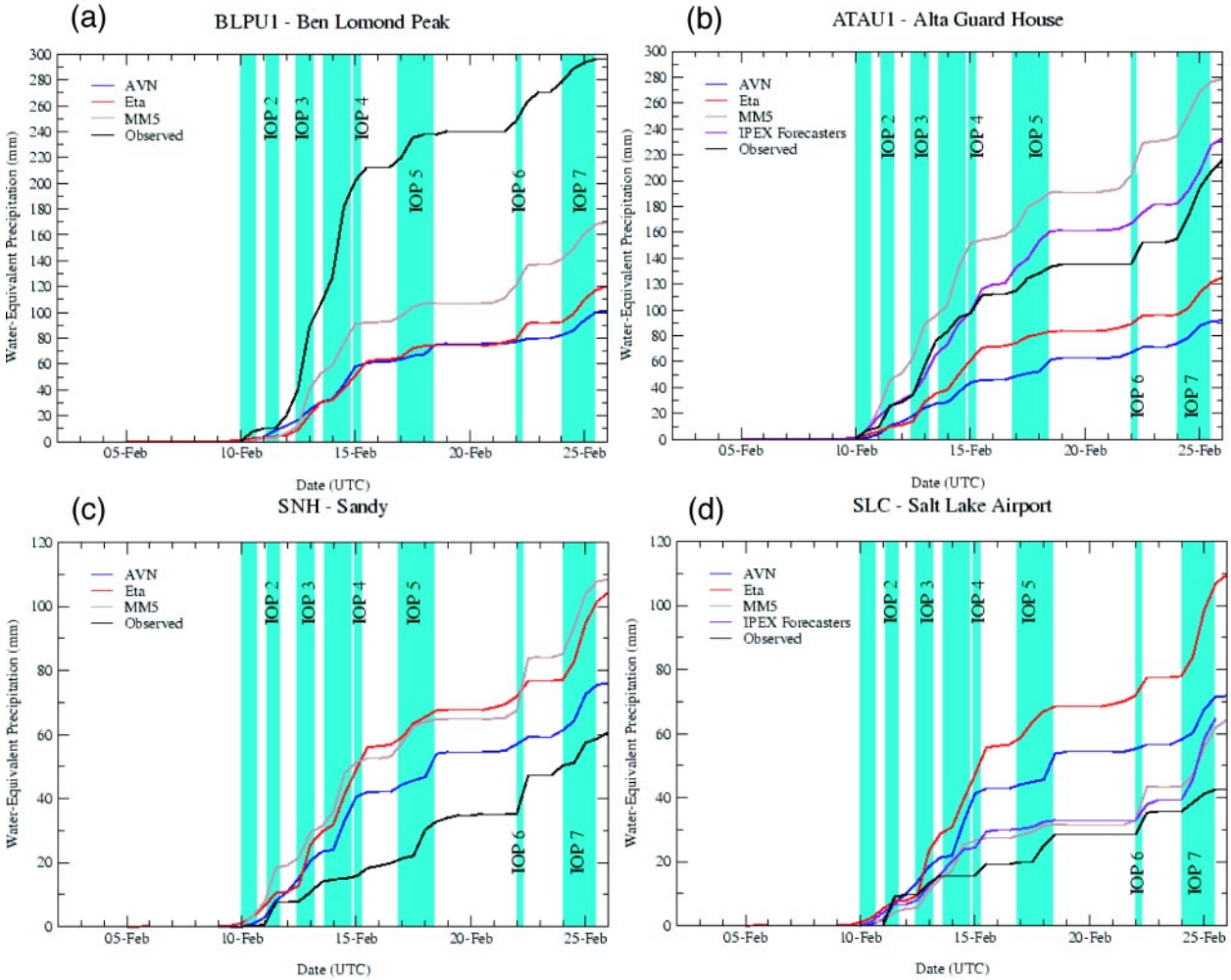

Fig. 18. Cumulative time series of observed (black line) and forecast (AVN, blue line; Eta, red line; MM5, gray line; IPEX forecasters, purple line) precipitation at four sites during IPEX. Shaded areas represent periods of subjectively determined precipitation events over the IPEX domain, with the events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

tional 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. Most volunteers were 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. During IPEX, however, we were fortunate that these issues did not compromise the success of any IOPs.
- The contribution of the NWS was key to the success of IPEX. Such contributions, which ultimately should benefit the NWS offices themselves, came in the form of special sounding launches at 3-h intervals, the use of facilities 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, 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 costs of science need to be explained to the public, who ultimately fund such endeavors. The increased importance of basic and applied research to society needs to be commu-

nicated to promote greater advocacy for science. NOAA Office of Public and Constituent Affairs officers helped develop a unified public message on the value of scientific research to improve weather forecasting. 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, reducing the demands on the scientists. Dedication to these Web sites with future research results will ensure longevity of the IPEX message.

The results of IPEX are already beginning to influence forecasting in northern Utah. The precipitation verification work of Cheng (2001) demonstrated some of the biases of the numerical weather prediction models over northern Utah. Patterns reminiscent of blocking (as observed in IOP 3) may help forecasters identify potentially significant lowland storms. NWS forecasters for the Olympic and Paralympic Games (e.g., Horel et al. 2002a) 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 site (http://www.nssl.noaa.gov/~schultz/ipex).

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