Weather Support for the 2002 Winter Olympic and Paralympic Games

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Public, private, and academic groups are working together to provide special observations, advanced modeling, and areawide and site-specific forecasts to help the Winter Games operate smoothly and alert the athletes, games organizers, and the public to impending hazardous weather.

The 2002 Winter Olympic and Paralympic Games will be held in the vicinity of Salt Lake City (SLC), Utah, during February–March 2002. Approximately 3500 athletes will compete in 15 sports that will take place at five outdoor and five indoor venues. A weather support system has been developed to provide weather information for the Games. This system is managed by the weather support group in the sports department of the Salt Lake Olympic Committee (SLOC) and involves meteorologists from government agencies, private firms, and the University of Utah. Weather forecast operations begin several days prior to the opening ceremonies on 8 February, continue through the closing ceremonies on 24 February, and resume for the Paralympics from 7 to 16 March.

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Planning for the weather support system began in 1995, shortly after the selection of SLC by the International Olympic Committee as the site for the 2002 Games. Early development of this weather support system was done by individuals at the University of Utah and the National Weather Service (NWS) SLC Weather Forecast Office (WFO). Further development of the system has involved many people at SLOC, WFO, NWS Western Region Scientific Services Division, the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Regional Prediction (CIRP) in the Department of Meteorology at the University of Utah, and a private sector forecasting group associated with KSL, the local National Broadcasting Company (NBC) television affiliate.

Indoor and outdoor venues for the 2002 Winter Olympic and Paralympic Games span a broad area of northern Utah (Fig. 1). Indoor venues are concentrated in the Salt Lake Valley, but one venue is located in Ogden to the north and another is located in Provo to the south. This metropolitan corridor is called the Wasatch Front, has an elevation of ~1300 m, and covers a north–south distance of 110 km to the west of the Wasatch Mountains along Interstate 15 (I-15). The five outdoor venues lie on the eastern flanks of the Wasatch Mountains. A large number of spectators will travel from accommodations located up to 100 km away from the venues. For example, on the

FIG. 1. Locations of Olympic venues (numbers 1–10) and the sports at those venues (icons). Opening and closing ceremonies (11), medals plaza (12), and the Salt Lake City International Airport (13) are shown as well as icons for locations of park and ride sites. Outdoor venues are Snowbasin Ski Area (2), Utah Olympic Park (6), Park City Mountain Resort (7), Deer Valley Resort (8), and Soldier Hollow (9). Figure courtesy of the Salt Lake City Corporation.

first day of competition (9 February), many spectators will travel across the Wasatch Mountains on Interstate 80 to watch mogul skiing at Deer Valley (16 000 people), ski jumping at the Utah Olympic Park (22 000), and cross-country skiing at Soldier Hollow (20 000) (Loomis 2001).

Significant weather events have affected all past winter Olympics. For example, weather-related delays for alpine ski events occurred during the 1984 Sarajevo, 1992 Albertville, and 1998 Nagano Games, while warm temperatures and high winds affected operations during the 1988 Calgary Games. Adverse weather (e.g., heavy snowfall, strong winds, low visibility due to fog or snow, or avalanches) may delay or postpone events associated with the 2002 Winter Games. Snow and ice-covered streets and highways within the Wasatch Front and over the Wasatch Mountains could impede road access to the venues by athletes and spectators while limited visibility and high winds could hamper aviation operations over mountain passes. The safety, health, and comfort of spectators who may be outdoors for several hours could be affected by heavy snow or rain, extreme wind chills, or snow and ice on walkways. An extended stable period with cold air trapped in the valleys could lead to poor air quality that may result in respiratory problems for athletes and spectators. Still other activities affected by weather include snow making; construction, safety, and durability of temporary outdoor facilities and displays; outdoor ceremonies (opening and closing ceremonies at the University of Utah and medal award presentations in downtown SLC); outdoor celebrations in cities throughout northern Utah; operation of parking lots at venues and transportation hubs; and emergency and security operations related to the spill or release of hazardous materials.

In addition, almost all aspects of outdoor competition are impacted by less extreme weather events on an event day. Ski jumper safety can be a concern even in light winds if the winds are gusty. The ability to compete for medals in nordic or alpine ski events requires proper preparation and waxing of ski bases for the snow conditions that are observed during an event. A day prior to the men's or women's downhill, top-rated skiers and their teams evaluate current and future weather and snow conditions to select starting positions that they hope will provide them with the best conditions for their run.

The Olympic weather support system must meet the diverse requirements of the 2002 Winter Games in the context of the winter weather often experienced in northern Utah. Typical and extreme weather conditions observed during past winters in northern Utah will be summarized in the next section. An overview of the weather support system will be presented in section 3 followed by a more detailed discussion of the support activities provided by CIRP. The potential legacies of the weather support system will be summarized in section 5.

LOCAL CLIMATES AND HAZARDOUS WEATHER.

Local climates. The interaction of atmospheric flows with the complex terrain of northern Utah contributes to the development of a variety of microclimates. We summarize here the typical weather likely to be experienced by the athletes and spectators on the basis of long-term records (over 30 yr) available at valley stations and some mountain locations. Records at several of the outdoor venues were available only for the past several years (see section 4a).

Wasatch Front early morning temperatures are typically below freezing [average minimum temperature around –4°C (25°F) in February and –1°C (30°F) in March]. Afternoon maximum temperatures are usually above 4°C (40°F) in February and above 10°C (50°F) in March. About five snowstorms occur in the Wasatch Front during February with average snowfall during the month around 28 cm (11 in.). Snowstorms are equally likely during the Paralympic Games during March. Stable episodes coupled with heavy fog in the valleys occur occasionally, with roughly an 8% chance that fog develops on any particular day in February near the SLC airport.

Mountain valleys to the east of the Wasatch Mountains, including the Ogden Valley northeast of the Snowbasin venue and the Heber Valley near the Soldier Hollow venue (see Fig. 2 for locations), are at higher elevations (~1900 m) than the Wasatch Front (~1300 m). Temperatures tend to be significantly lower in the morning, while afternoon temperatures are similar to those of the Wasatch Front. The number of storms with precipitation falling as snow rather than rain is slightly higher in the mountain valleys than in the Wasatch Front with mean February snowfall amounts varying from 28 cm (11 in.) in the Ogden Valley to 41 cm (16 in.) in the Heber Valley.

The outdoor venues, located within 50 km of downtown SLC, vary in elevation from 2826 m (9270 ft) at the top of the Snowbasin men's downhill course to 1670 m (5480 m) at the Soldier Hollow cross-country/biathlon course. There are tremendous variations in the weather and climate at these venues. Snowbasin, for example,averages 193 cm (76 in.) of snowfall during February near the top of the men's downhill course, while Soldier Hollow averages only 48 cm (19 in.) during the same period. At Snowbasin, winds may exceed 30 m s^{-1} at the ridgetops at the same time that the winds remain less than 5 m s^{-1} at the base of the mountain.

Hazardous weather. Examination of February and March weather conditions during the past 30 yr illustrates that northern Utah experiences many types of widespread hazardous weather conditions, including low temperatures, heavy snowfall, and high winds. Long-term records at the Salt Lake City, Hill Air Force Base, and Provo airports have been used to determine the frequency of occurrence of rain, snow, fog, high

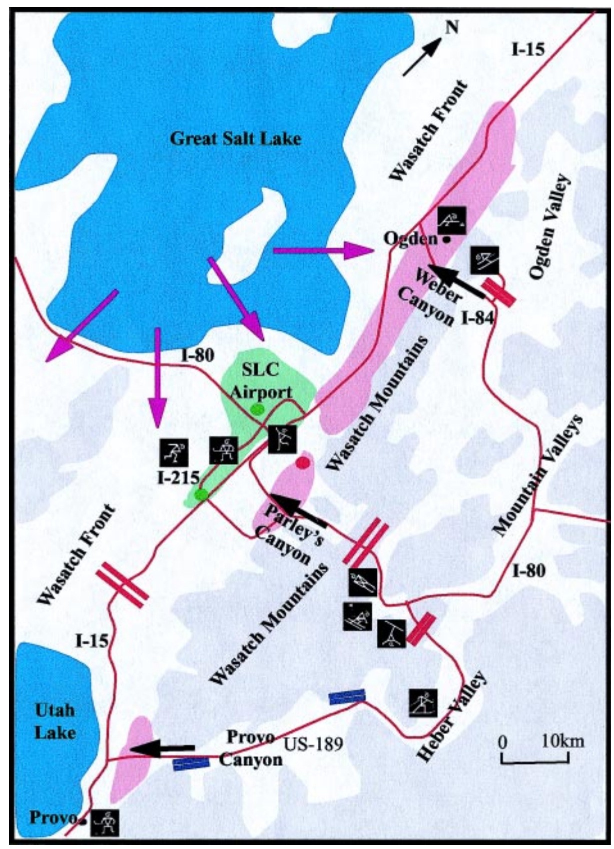

Fig. 2. Local hazardous weather that often occurs in preferred geographic areas includes ice fog in the lowest elevations of the Salt Lake Valley (green shading), which affects aviation at the SLC airport (green dot) and surface travel near the southern intersection of I-215 and I-15 (green dot); lake-effect snowbands, which tend to form downstream of the Great Salt Lake parallel to the direction of the prevailing wind flow (pink arrows); downslope wind storms (red shading) to the west of the Wasatch Mountains, including near Olympic Stadium (red dot); blizzard conditions over mountain passes (double red lines); and avalanches along major roadways (double blue lines). Terrain above 2000 m is shaded and icons denote the locations of indoor and outdoor venues.

wind, and extreme cold temperature. (Summaries of this research are available via the Internet at http://www.met.utah.edu/olympics.) February arctic air outbreaks, which occur on average once every 4 yr, have led to temperatures below −18°C (0°F) and prolonged periods below −9°C (15°F) in the Salt Lake Valley. During the February Olympic period, the record snowfall during a 24-h period varies from 48 cm (19 in.) along the Wasatch Front to over 100 cm (40 in.) in the mountains. Strong gusty winds, often lasting several hours prior to the passage of fronts, are common.

Some hazardous weather tends to recur in preferred locations as summarized in Fig. 2. Ice fog develops along the bottom of the Salt Lake Valley, which often affects operations at the SLC International Airport, and contributes to hazardous driving conditions near the intersection of I-215 and I-15 (Fig. 2). As noted earlier, there is an 8% chance that fog will develop on a given February day near the SLC airport. Prolonged ice fog events also occur, on average, every few years. In February 1985, dense fog was reported at SLC for 22% of the Olympic period. Hazardous driving during snowstorms is also a common occurrence over major passes, which climatologically observe measurable snowfall on around one-third of the days during the Olympic period. Avalanche hazard can also result in the closure of U.S. Route-189 (U.S.-189) in Provo Canyon (Fig. 2). Easterly gap winds occur most mornings at many canyon mouths (e.g., Weber Canyon on the Interstate-84 corridor and Parley's Canyon on the Interstate-80 corridor). Downslope windstorms with winds in excess of 30 m s^{-1} typically develop once or twice each winter to the west of the Wasatch Range and extend out a few kilometers into the Wasatch Front (see Fig. 2). Such downslope conditions, combined with enhanced drainage circulations during early morning, can lead to particularly strong winds at the canyon mouths. With winds in excess of 20 m s^{-1} occurring 8% of the time on the University of Utah campus, strong winds could affect opening or closing ceremonies.

A major winter season forecast challenge for Utah meteorologists, and a concern for Winter Games logistics, are lake-effect snowstorms produced by the Great Salt Lake. Such snowstorms can produce snowfalls of 10–30 cm (4–12 in.) in the Wasatch Front (see Fig. 2), and have contributed to lowland storm total accumulations of as much as 130 cm (50 in.) (Carpenter 1993; Slemmer 1998; Steenburgh et al. 2000). Installation of the NWS Weather Surveillance Radar-1988 Doppler (WSR-88D) radar at Promontory Point in 1994, and subsequent development and expansion of MesoWest (see section 4a), provided an opportunity for rapid progress in the understanding of Great Salt Lake–effect snowstorms prior to the Olympics. Steenburgh et al. (2000), Steenburgh and Onton (2001), and Onton and Steenburgh (2001) describe the large-scale characteristics and mesoscale structure of Great Salt Lake–effect snowstorms.

While each winter over the past 30 yr produced examples of adverse conditions that might affect the hosting of the Olympic and Paralympic Games, a series of particularly severe events occurred during February 1986, which include the following:

- 12–13 February—a very wet storm over the Wasatch Front and Wasatch Mountains with 60–90 cm of snow in the mountains; Many naturally released avalanches occurred; on Interstate-80 (the major pass across the Wasatch Mountains), 60 cm of snow fell with blizzard conditions reported;
- 14–17 February—warm temperatures with heavy rains in the valleys and over the lower slopes of the Wasatch Mountains; heavy snow at higher elevations led to avalanches and mud slides: a couple of homes were destroyed in the central Wasatch Mountains; a 55 m s^{-1} wind gust was recorded at the Park City Ski Resort (site of Olympic snowboarding and giant slalom events); the Snowbasin Ski Resort (site of Olympic downhill and super giant slalom events) was closed;
- 18 February—a record high minimum temperature of 11°C for February was observed at the SLC airport; snowmaking at the Soldier Hollow cross-country venue would have been impossible from 14 to 18 February; and
- 19 February—a squall line traversed northern Utah with a 54 m s^{-1} gust at the Park City Ski Resort. Morgan County was declared a disaster area as a result of flooding (considerable traffic to the Snowbasin Ski Resort will travel through Morgan County).

OLYMPIC WEATHER SUPPORT: ORGANIZATION AND ROLES.

Organization. Olympic weather support has traditionally been led by the host country's primary weather agency. For example, weather support for the 1996 Centennial Olympic Games held in Atlanta, Georgia, was led by the NWS (McLaughlin and Rothfusz 1996; Rothfusz et al. 1998), while weather support for the Sydney 2000 Olympic and Paralympic Games was provided by the Australian Bureau of Meteorology. Because of the complex weather-related needs of the Olympics, many other groups have often become involved in weather support activities. For example, 25 federal and state agencies and commercial firms and 15 components of the National Oceanographic and Atmospheric Administration assisted the NWS Southern Region for the Atlanta Games (McLaughlin and Rothfusz 1996; Powell and Rinard 1998; Snook et al. 1998; Johnson et al. 2000). Olympics also have served as opportunities to showcase new technology and test new forecast techniques (Snook et al. 1998; Keenan et al. 2000).

Meteorological services prior to and during the 1998 Nagano Winter Olympic Games were provided by the Japan Weather Association, the largest private weather organization in Japan, under contract from the Nagano Area Organizing Committee. Weather delays during the Nagano Games were greatly mitigated by long-term meteorological planning and development of a sophisticated and detailed forecast system.

The organization of the weather support system for the 2002 Winter Games differs from the ones used for previous Olympics. Table 1 summarizes the groups that will provide weather support during the Games. The primary weather forecasting responsibilities for the Olympics are shared by NWS and KSL forecasters. Forecasters from other government agencies will provide forecasts for specific Olympic-related applications. Other groups, including CIRP, have developed resources that will be used by the forecasters. We review the roles of each group in the following sections.

SLOC Weather Support Group. Staff members in the SLOC sports department manage and coordinate weather support for SLOC operations. SLOC is responsible for weather support for the athletes, sports officials, SLOC staff, accredited media, and national and international Olympic committees. One of the SLOC's biggest challenges is to facilitate close coordination among all forecasting groups to ensure that consistent forecasts are issued. The SLOC weather support group also manages weather volunteers, including undergraduate and graduate students at the University of Utah and other local residents. The weather volunteers assist venue forecasters and provide supplemental weather observations required for the events. Official manual weather observations are started 1 h before each outdoor event begins and continue at 15-min intervals throughout the event.

SLC Weather Forecast Office. The NWS role in support of the 2002 Winter Games is to provide public forecasts and warnings to protect lives and property, in accord with its mission. The SLC WFO will be referred to as the Weather Operations Center (WOC) during the Olympics. In addition to the regular SLC WFO staff, five forecasters from other NWS WFOs and one forecaster from the National Severe Storms Laboratory were selected to participate in WOC operations. Four of the six supplementary NWS forecasters will be assigned to the WOC at any given time during the Games. Two Advanced Weather Information and Processing Systems (AWIPS) workstations have been added to the WOC for use by the supplementary forecasters to access and display observations and numerical guidance. The supplementary NWS forecasters issued practice forecasts during World Cup events that were held in February–March 2001.

In addition to routine WFO operations, the supplementary NWS forecasters will be responsible for coordinating warnings and forecasts with the KSL forecasters, as well as forecasters at the Aviation Security Operations Center (ASOC) at Hill Air Force Base. They will also issue a Hazardous Winter Weather Potential product twice each day that focuses on each of the primary transportation corridors connecting the Wasatch Front with the venues to the east of the Wasatch (see Figs. 1 and 2). This product includes forecasts of weather, wind, temperature, wind chill, and precipitation type and amount. Forecasts of weather, wind, temperature, and snowfall amount are also made for the avalanche zones along U.S.-189 (Fig. 2). The Utah Department of Transportation will use these forecasts as part of their winter road maintenance and avalanche control operations along with forecasts issued by Northwest Weathernet (see the section titled "Other groups"). The supplementary NWS forecasters will field media inquiries from both SLOC-accredited and nonaccredited media organizations that may otherwise overwhelm the existing WFO staff.

Figure 3 summarizes the flow of information through the WOC. The primary source of weather information at the WOC will be received from AWIPS. Additional observations will flow from the venues and from CIRP. The NWS will distribute weather guidance to many users through a public Web site and other routine distribution methods. NWS products will also be inserted into the protected communications system operated by the Utah Olympic Public Safety Command, which is a consortium of local, state, and federal security and safety agencies. Other components of the data flow required for the Olympics will be described later.

KSL weather team. A team of 13 private sector meteorologists has the responsibility to provide detailed

Table 1. Groups providing weather support during the 2002 Winter Olympic and Paralympic Games. Bold type denotes the primary weather forecasting groups.

Organization	Staffing	Role	Activities	Customers
SLOC Weather Support Group	SLOC sports staff	Manage weather support for the Olympics and Paralympics	Coordinate delivery of weather information; manage weather volunteers	SLOC staff; athletes; sports officials; SLOC-accredited media
NWS SLC (WFO)	Routine staffing + six additional forecasters	Provide and coordinate weather guidance for northern Utah	Issue routine weather forecasts, warnings, and special Olympic-related forecasts	Public; SLOC accredited and nonaccredited media; public safety, security, and transportation officials
KSL weather team	Private weather forecasters	Provide detailed weather guidance for venue operations	Issue forecasts for outdoor venues; conduct official SLOC weather briefings	Spectators at outdoor venues; accredited media; SLOC staff; athletes; sports officials; national and international Olympic committees
CIRP	Faculty, staff, and students	Support weather operations	Provide MesoWest and venue observations and numerical guidance from the Intermountain Weather Forecast System; support weather data transmission to SLOC	SLOC staff; athletes; sports officials; forecasters
NWS Western Region Headquarters	Scientific Services Division staff	Support distribution of weather information via FSL FX-Net	Monitor data delivery	Venue forecasters; forecasters at ASOC
ASOC	Hill Air Force Base forecasters	Support medical and security aviation operations	Provide forecasts and briefings for pilots	Pilots flying to/from venues
Utah Avalanche Center	U.S. Forest Service avalanche forecasters	Advise security personnel near venues and backcountry travelers regarding avalanche potential	Issue avalanche forecasts	Security officials and backcountry skiers
Northwest Weathernet	Private weather forecasters	Advise Utah Department of Transportation personnel regarding weather impacts on winter road maintenance	Issue weather and pavement condition forecasts	Utah Department of Transportation staff

Table 1. Continued.

Organization	Staffing	Role	Activities	Customers
Defense Threat Reduction Agency	Staff from government agencies	Support operations to mitigate hazardous spills or releases	Provide guidance as needed	Security officials
Utah Division of Air Quality	Air Monitoring Center staff	Monitor air quality	Issue restrictions on wood burning and driving	Public

microscale weather forecasts for the five outdoor venues (Fig. 4). These forecasts will be used primarily by the athletes, sports managers, team captains, venue managers, Olympic officials, and on-site spectators. Four members of the KSL team will work in the WOC while seven other members will be located at the five mountain venues. The remaining two members of the team provide overall coordination and will give briefings to Olympic and SLOC officials in SLC at least twice each day. Weather briefings will also be provided to SLOC-accredited media at the Olympic Media Center.

The KSL venue forecast team was assembled by Mark Eubank, KSL chief meteorologist, and is composed of meteorologists who have extensive experience forecasting the weather in northern Utah. The team consists of retired NWS meteorologists and personnel from six private forecasting companies: WeatherCycles, Inc.; WeatherBank, Inc.; WeatherFacts, Inc.; Meteorological Solutions, Inc.; EM-Assist; and Alta Forecasting. The venue forecast team was assembled during 1999 and has two winters of on-site forecast experience for pre-Olympic and World Cup testing and training events.

The KSL forecasters have the responsibility to "funnel" the overall weather picture down to the microscale of each venue. A joint weather phone conference will be conducted each morning by the venue, WOC, and ASOC forecasters. Mesoscale forecasts will be sent to each venue from the WOC, and the KSL venue forecasters will then interpret the information and apply it to the microscale. Briefings at each venue will be given routinely two to three times a day or more often if needed. The venue forecasters will have on-site access to the latest weather observations, graphics, and model data using FX-Net (see the section titled "NWS Western Region headquarters") and also have access to weather products over the Internet. Weather forecasts will be issued three times daily at 0600, 1200, and 1800 LST. Updates will be issued as needed. The first 13 h of each forecast period will consist of hourly forecasts followed by 3-hourly forecasts out to 60 h. Forecast fields include sky cover, precipitation type and amount, air temperature, wind direction, wind speed, wind gusts, wind chill, visibility, humidity, and snow temperature.

NOAA Cooperative Institute for Regional Prediction. CIRP assists in the coordination of weather support activities by SLOC and the various forecast groups. (CIRP received funding from the U.S. Congress during fiscal years 1997–2001 to help prepare and support the operational forecast responsibilities of the Olympic

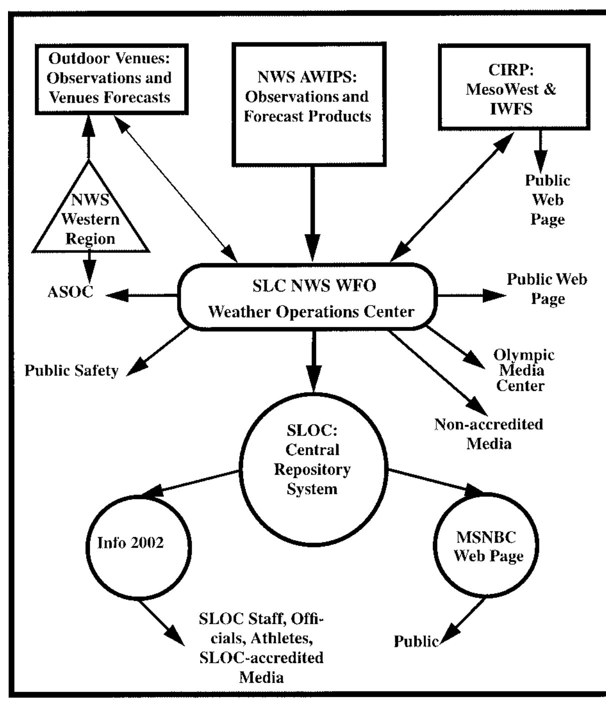

Fig. 3. Data flows to the WOC via AWIPS broadcast from the outdoor venues and from CIRP. NWS Western Region broadcasts weather products using FX-Net to the outdoor venues and to the ASOC. Routine NWS and special Weather Operations Center products are distributed to many users. Products sent to the SLOC Central Repository System are made available to the general public via the MSNBC Web page and to SLOC staff, officials, athletes, and accredited media via Info 2002.

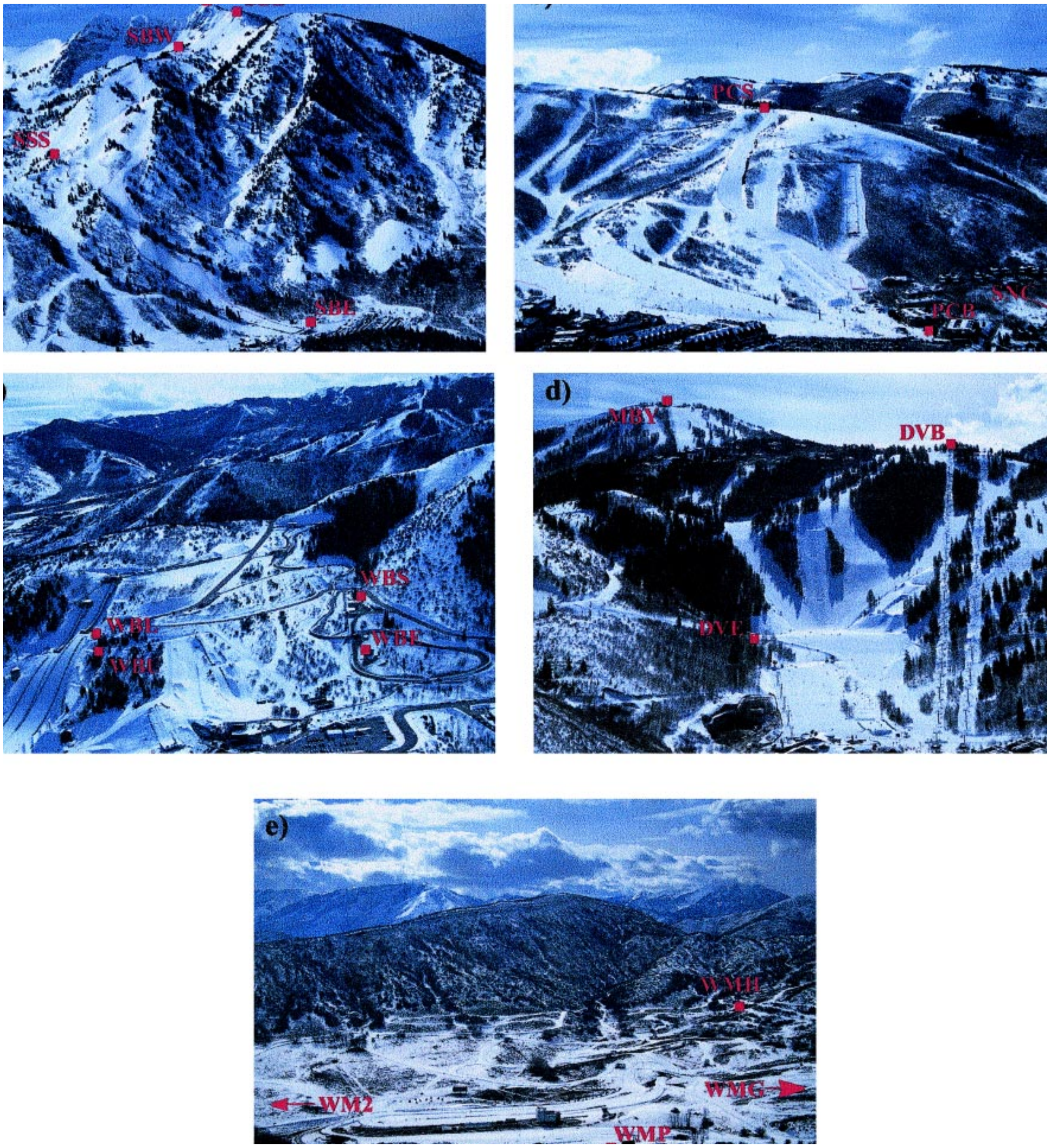

Fig. 4. Locations of the weather stations (red three-letter MesoWest identifiers) in the vicinity of the competition areas at the outdoor venues: (a) Snowbasin Ski Area, (b) Utah Olympic Park, (c) Park City Mountain Resort, (d) Deer Valley Resort, and (e) Soldier Hollow. A total of 29 weather stations are deployed at the outdoor venues; some lie outside the competition areas. Photos by D. Quinney.

weather support system.) The Olympic weather support project at the University of Utah contributes to the educational, research, and public service missions at the university. Olympic-related activities under way in CIRP will be summarized in greater detail in the section titled "CIRP support activities."

NWS Western Region headquarters. The NWS Western Region Scientific Services Division has set up AWIPS servers to feed data to the outdoor venues where it can be viewed on the FX-Net system. This PC-based system was designed by NOAA's Forecast Systems Laboratory as a vehicle to allow meteorologists to look at the AWIPS dataset on a lower-cost platform fed by narrow bandwidth communications. Hence, the KSL venue forecasters have access to the same datasets as the NWS and KSL forecasters at the WOC. The venue forecasters tested the FX-Net software during the past winter and were satisfied with its performance.

Aviation Security Operations Center. ASOC forecasters will provide forecasts and briefings to pilots flying to venues. A communications line and FX-Net system have been installed at the ASOC at Hill Air Force Base to facilitate coordination between WOC and ASOC forecasters. To support helicopter and other aviation traffic landing at outdoor venues, the U.S. Air Force will also deploy Tactical Meteorological Observing System (TMOS) portable weather stations near the Snowbasin, Olympic Park, Park City, and Soldier Hollow outdoor venues, as well as at one location to the west of the mountain pass between Salt Lake City and Park City (see Fig. 5). TMOS provides continuous reports of wind, temperature, moisture, ceiling, visibility, liquid equivalent precipitation, and present weather.

Utah Avalanche Center. The U.S. Forest Service Utah Avalanche Center is located at the WOC. In addition to their normal duty to advise backcountry travelers (skiers, snowmobilers, snowshoers) on avalanche potential, the avalanche forecasters will provide guidance to security personnel on avalanche risks around the backcountry perimeters of avalanche-prone venues.

Other groups. Some weather forecast activities are largely autonomous from the weather support system outlined previously. For example, Northwest Weathernet has provided the Utah Department of Transportation with road weather and pavement condition forecasts for several winters and will continue to do so during the Olympics and Paralympics. The Defense Threat Reduction Agency (DTRA) will provide specialized forecasts to mitigate hazardous spills or releases. Ambient air quality is monitored by the Utah Air Monitoring Center to protect the health of Utah citizens and Olympic visitors. All of these additional monitoring and forecasting activities rely to some extent upon MesoWest observations (see section titled "MesoWest and SnowNet) and other resources in common with the other forecast groups.

CIRP SUPPORT ACTIVITIES.

Research has been under way since the creation of CIRP in 1996 to improve the understanding and prediction of atmospheric flows in complex terrain. For example, the Intermountain Precipitation Experiment (IPEX) was held during February 2000 in the vicinity of SLC to improve the understanding, analysis, and prediction of precipitation over the complex orography of the Intermountain West [see the companion article in this issue by Schultz et al. (2002)]. Besides basic and applied research on Utah weather (see the section titled "Local climates and hazardous weather"), CIRP faculty, staff, and students have contributed to the Olympic effort in three general areas: monitoring current weather conditions in northern Utah and around the West, real-time mesoscale modeling, and direct support activities for the Olympic weather support system. These activities are summarized below.

MesoWest and SnowNet. A number of weather networks were operational in northern Utah when the Winter Olympics were awarded to Salt Lake City in 1995. Work was under way at that time by forecasters at the SLC WFO and researchers at the Univer-

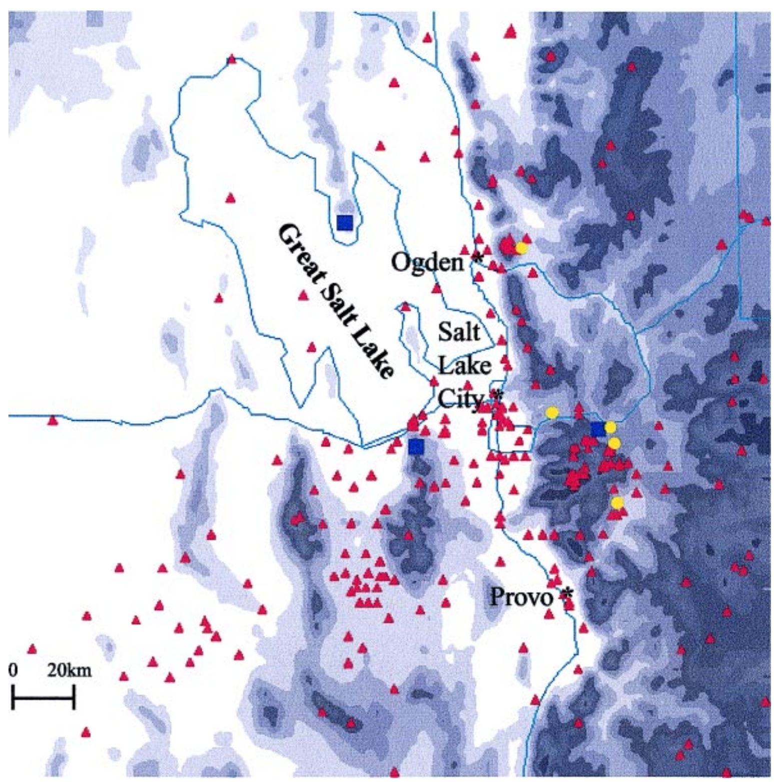

FIG. 5. Locations (red triangles) of 278 weather stations of Salt Lake City that are available for the 2002 Winter Olympic Games. Blue squares denote weather stations that collect weather information from other remote weather stations by radio and that are maintained as part of SnowNet by CIRP. Yellow circles denote locations of air force TMOS stations. Successively darker shading denotes higher terrain.

sity of Utah to collect the observations from those networks for use in weather forecasting and research. Nonetheless, it was recognized that additional collaboration with SLOC, commercial firms, and local, state, and federal agencies was necessary to support the weather needs of the games organizers, athletes, and the weather forecast team. Since documentation of weather conditions prior to the Olympics was required for planning (and during the Olympics for operations), additional weather sensors and weather stations were needed at venues and other key locations in northern Utah. Beginning in 1996, weather equipment has been installed cooperatively by SLOC, CIRP, the NWS, the Utah Department of Transportation, and the commercial firms and state agencies managing the outdoor Olympic venues. Portable weather stations manufactured by Campbell Scientific, Inc., that were deployed by the NWS Southern Region for the 1996 Atlanta Summer Olympic Games were made available to the NWS Western Region after the Summer Games were completed. Also during 1996, the NWS Western Region and the National Severe Storms Laboratory began a research project in the vicinity of SLC designed to validate WSR-88D radar algorithms in regions of complex terrain. In support of this project, weather equipment was deployed at eight locations (four within the Wasatch Front and four at Olympic venues).

A unique partnership has evolved since 1996 within the government, commercial, and research communities to share weather information in northern Utah and throughout the western United States. Initially referred to as the Utah Mesonet, the collection of data outside of Utah led to its redesignation as MesoWest in January 2000 [see the companion article in this issue by Horel et al. (2002)]. During February–March 2002, weather observations will be available from over 278 locations in the northern Utah region shown in Fig. 5. These weather stations are owned and operated by 15 commercial firms, eight local and state agencies, and nine federal agencies. Weather data are collected at 5–60-min intervals via ethernet, phone, cellular phone, radio, satellite, and meteor burst technologies and relayed to the University of Utah. Throughout the western United States, MesoWest is dominated by the large federal networks that support primarily the aviation, fire weather, and water resource communities. In northern Utah, we have worked closely with the private sector and local and state agencies that operate weather stations for a variety of specific purposes, including water resource management, air quality monitoring, winter road maintenance, equipment development, agriculture, ski area operations, and emergency management.

As part of a combined effort of the SLC WFO and CIRP, the WFO operates four computers that collect weather observations by phone and radio from Campbell Scientific weather stations deployed by commercial firms and government agencies. This collection effort is called SnowNet and radio base stations are maintained at the Promontory Point WSR-88D radar site, Farnsworth Peak, and Olympics Sports Park to provide radio coverage across the Great Salt Lake, over the Wasatch Front, and at the Sports Park venue, respectively (Fig. 5). Weather observations are collected from 27 sites at the 5 outdoor Olympic venues (Fig. 4). All weather stations report wind, temperature, and relative humidity, while at least one station at each venue has additional liquid equivalent precipitation, snow depth, and pressure sensors. Weather aides at the outdoor venues will help verify automated measurements, especially snowfall. Weather stations are also located in close proximity to all of the indoor venues within the Wasatch Front (see Fig. 5).

As a means to integrate the surface observations in northern Utah for use in nowcasting and forecast verification, surface analyses of temperature, wind, and relative humidity are generated using the ARPS Data Analysis System (ADAS) on a 1-km horizontal grid every 15 min (Lazarus et al. 2002, manuscript submitted to *Mon. Wea. Rev.*). These analyses are made available, along with the surface observations, via the Internet to all potential users as well as distributed for use in AWIPS at the WOC and FX-Net at the outdoor venues (Fig. 3).

Real-time mesoscale modeling. For the past 3 yr, CIRP has provided modeling support to WFO operations in the form of twice-daily real-time model guidance. These activities have allowed for hands-on use of the modeling system by WFO and KSL forecasters, and the development of model output statistics (MOS) equations that provide point-specific forecasts for Olympic venues and other weather-sensitive locations. The modeling system is known as the Intermountain Weather Forecast System (IWFS) and is based on the nonhydrostatic Pennsylvania State University–National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5) version 3 (Grell et al. 1995). Since July 1998, IWFS has featured an outer domain with 36-km grid spacing that covers the western United States and a nested domain with 12-km grid spacing that covers Utah and portions of adjacent states. The most recent configuration (September 2001) includes an expanded 12-km domain and an inner nest with 4-km grid spacing (Fig. 6). Forecasts produced with the new configuration were used by Olympic forecasters for several months prior to the Winter Games. Major parameterizations include the explicit moisture scheme of Hsie et al. (1984) with improvements to allow for ice-phase microphysics below 0°C (Dudhia 1989), the Kain and Fritsch (1993) cumulus parameterization, the Hong and Pan (1996) Medium-Range Forecast (MRF) boundary layer, and the Dudhia (1989) cloud-interactive radiation scheme.

Initial and lateral boundary conditions are provided by the National Centers for Environmental Prediction (NCEP) Eta Model, with ADAS (see section titled "MesoWest and SnowNet") used to incorporate MesoWest observations into the near-surface initial conditions. A second simulation is run, but available at a later time, using the NCEP Aviation model. The IWFS runs on a Linux cluster, a group of networked

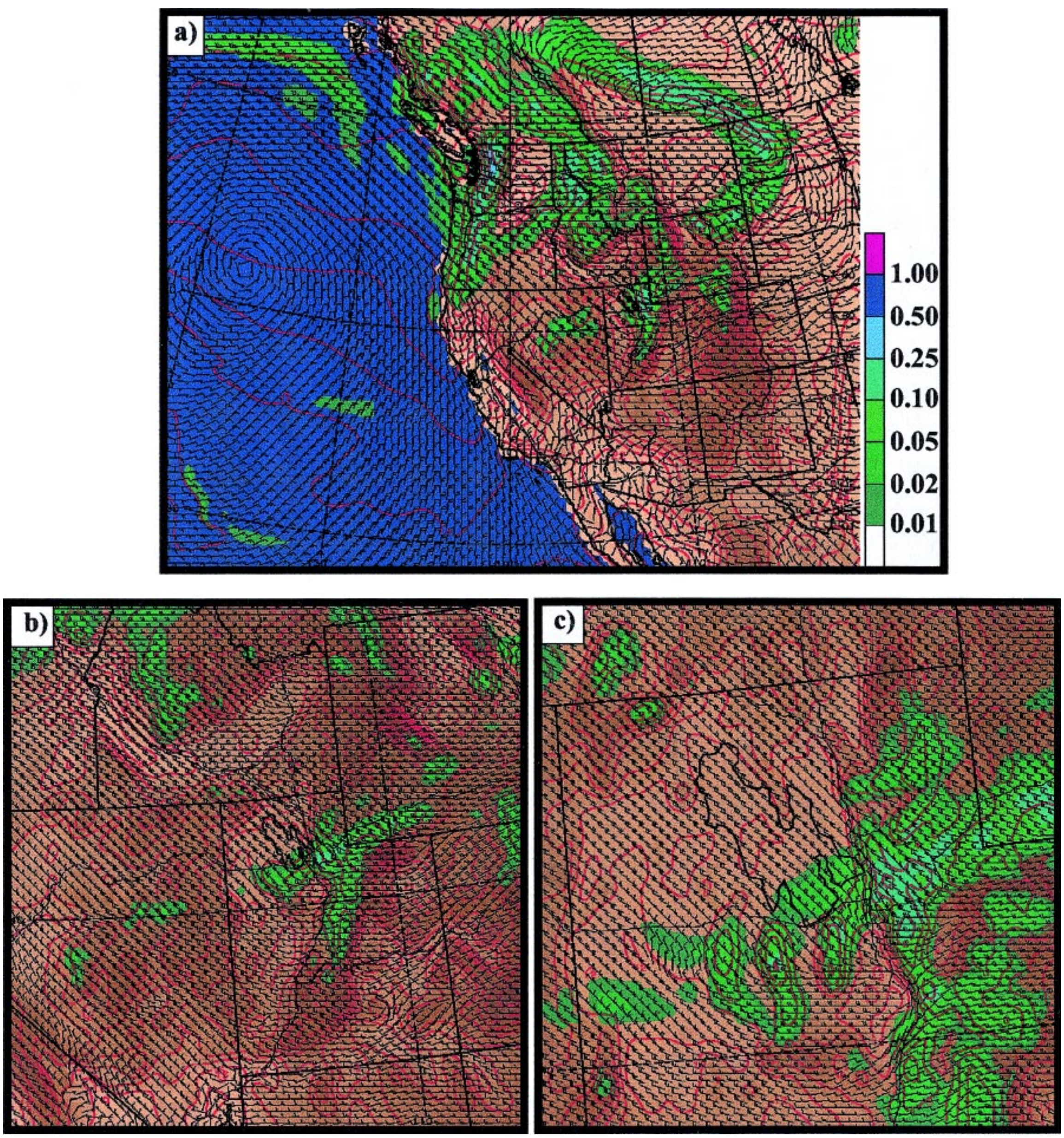

Fig. 6. Example IWFS forecast of 10-m wind (vectors), 40-m temperature (contours, °C), and 3- or 1-h precipitation totals [mm; according to the scale in the right margin of (a)]: (a) 36 (3-h precipitation), (b) 12 (1-h precipitation), and (c) 4 km (1-h precipitation). Thirty-hour forecast initialized 1200 UTC 22 Oct 2001 valid 1800 UTC 23 Oct 2001.

personal computers running the Linux operating system. Using sixteen 1.3-GHz Advanced Micro Devices Athlon processors, a 36-h forecast (with all 3 domains) requires 70 min to complete. Since Eta Model output grids are typically available by 0300 LST (1500 UTC), and additional time is needed for initial condition generation, model postprocessing, and file transfers, hourly model output from IWFS is typically available to forecasters in AWIPS and FX-Net by 0445 LST (1645 UTC).

MM5-based model output statistics (MM5-MOS) provide hourly forecasts of temperature, dewpoint, wind speed, and wind direction at the outdoor venues and other weather sensitive locations (e.g., Table 2). At venues with substantial variability in surface weather conditions, MM5-MOS is available for multiple observing sites. MM5-MOS was used by Olympic forecasters during test events held during the 2000/01 winter season and was upgraded during summer 2001 using a 3-yr period of observations and forecasts. (Model products and MM5-MOS can be accessed online at http://www.net.utah.edu/olympics.)

SLOC support activities. CIRP faculty and staff have worked closely with SLOC staff to develop access to weather information required for Olympic planning and operations. Considerable effort has been required to develop software to route weather information to the SLOC computer networks while maintaining secure networking for all organizations. The Info 2002 computer system has been designed by SLOC for the athletes, Olympic organizers, and SLOC-accredited media while SLOC and MSNBC (the cable news network and Internet news service partnership between Microsoft and NBC) have jointly developed the official public Internet site for the Winter Games (http://www.saltlake2002.com).

As summarized schematically in Fig. 3, weather reports from automated weather stations at the venues are collected routinely. (Automated weather observations are also accessed manually on a personal computer operated by a weather volunteer at the venue.) Supplemental information (e.g., sky condition and snow temperature) required by SLOC is collected by weather volunteers before, during, and after competition; entered into a spreadsheet; and transmitted automatically to the WOC. Forecasts issued by the venue forecasters are also transmitted automatically to the WOC. These reports (along with all requested NWS products such as zone forecasts, advisories, watches and warnings, and transportation corridor forecasts) are then processed and transferred automatically to the SLOC Central Repository System for use by the Info 2002 and MSNBC public Web site.

LEGACY. The states that compose the Intermountain West are undergoing significant population increases and the socioeconomic impacts of winter storms in this region are high (Schultz et al. 2002, in this issue). The weather support infrastructure developed for the Winter Olympics will have long-term benefits to the public throughout the Intermountain West. The improved tools (MesoWest, ADAS, and IWFS) will be in place to monitor and predict storms throughout the Intermountain West during all seasons. The experience gained from the application of these tools by skilled NWS and private forecasters will likely prove invaluable to continued improvements in both operational and research models. In addition, the ongoing research related to lake-effect snowstorms and orographic precipitation will help to improve the understanding of winter weather in complex terrain. Improved understanding benefits not only Olympic forecasts, but other weather prediction activities over northern Utah, including public forecasts and warnings by the NWS and avalanche prediction by the Utah Department of Transportation and Utah Avalanche Center.

The dense network of MesoWest observations in northern Utah has been utilized for other research applications. For example, the Department of Energy Vertical Transport and Mixing (VTMX) experiment was held in the Salt Lake Valley during October 2000, in part, as a result of the existing infrastructure that is supported by government agencies and commercial firms (Doran et al. 2002). Additional field programs are likely to occur in this region as a result of the existing data resources and the many scientific questions arising from the complex airflow over the Wasatch Front, Great Salt Lake, and adjacent mountains. The comprehensive datasets collected during the Olympics, IPEX, VTMX, and future field programs will be invaluable to study mountain weather processes.

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Table 2. Sample MOS temperature, dewpoint, relative humidity, and wind speed and direction forecast for a location at the soldier Hollow venue. Forecast based on the IWFS forecast initialized at 1200 UTC 12 UTC 16 Nov 2001. Precipitation values based on raw model output.

Soldier Hollow Low (WM2, 1689 m)							
Time/date (Local)	Temper-ature (°F)	Dew-point (°F)	Relative Humidity (%)	Wind Speed (mph)	Wind Direction (°)	Precip in last hour (in.)	Total accumulated precip (in.)
0800 16 Nov	19.1	16.3	92.6	0.2	S (197)	0.00	0.00
0900 16 Nov	22.1	16.9	80.1	0.6	SW (212)	0.00	0.00
1000 16 Nov	27.6	19.5	69.2	0.9	S S (192)	00.0	0.00
1100 16 Nov	34.7	21.7	57.6	1.1	SE (125)	0.00	0.00
1200 16 Nov	40.2	22.1	50.8	1.2	SE (135)	0.00	0.00
1300 16 Nov	45.4	22.7	45.3	1.2	SE (155)	0.00	0.00
1400 16 Nov	49.4	21.9	39.3	1.6	S (177)	0.00	0.00
1500 16 Nov	46.6	20.5	42.1	1.7	SW (208)	0.00	0.00
1600 16 Nov	43.8	19.3	44.6	1.8	SW (224)	0.00	0.00
1700 16 Nov	40.0	19.5	50.6	2.1	SW (236)	0.00	0.00
1800 16 Nov	35.5	20.9	61.0	2.0	SW (235)	0.00	0.00
1900 16 Nov	33.1	21.4	66.0	2.1	SW (229)	0.00	0.00
2000 16 Nov	32.4	22.3	69.6	2.0	SW (215)	0.00	0.00
2100 16 Nov	31.8	22.6	71.7	2.0	SW (225)	0.00	0.00
2200 16 Nov	30.5	22.3	73.7	1.8	SW (234)	0.00	0.00
2300 16 Nov	29.2	21.4	73.3	1.7	SW (245)	0.00	0.00
2400 17 Nov	28.3	20.4	73.6	1.9	SW (241)	0.00	0.00
0100 17 Nov	27.6	19.4	73.8	1.8	SW (236)	0.00	0.00
0200 17 Nov	27.0	18.9	75.4	1.5	SW (233)	0.00	0.00
0300 17 Nov	25.8	18.7	77.7	1.3	SW (235)	0.00	0.00
0400 17 Nov	24.6	18.7	80.0	1.3	SW (237)	0.00	0.00
0500 17 Nov	22.9	18.4	82.5	1.3	SW (238)	0.00	0.00
0600 17 Nov	23.1	18.7	82.0	1.2	SW (236)	0.00	0.00
0700 17 Nov	23.2	19.0	80.6	1.0	SW (235)	0.00	0.00
0800 17 Nov	24.8	19.4	78.4	0.7	SW (229)	0.00	0.00
0900 17 Nov	29.2	20.9	72.6	1.0	SW (211)	0.00	0.00
1000 17 Nov	33.8	22.6	66.5	1.1	S (195)	0.00	0.00
1100 17 Nov	38.8	24.1	57.6	1.2	S (170)	0.00	0.00
1200 17 Nov	43.4	23.3	51.4	1.3	S (167)	0.00	0.00
1300 17 Nov	47.2	22.4	47.8	1.5	S (174)	0.00	0.00
1400 17 Nov	50.0	21.7	45.6	1.6	S (180)	0.00	0.00
1500 17 Nov	48.2	23.0	49.3	1.8	SW (207)	0.00	0.00
1600 17 Nov	46.3	24.1	54.6	1.8	SW (224)	0.00	0.00
1700 17 Nov	44.4	23.5	59.1	2.0	SW (235)	0.00	0.00

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REFERENCES

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

Doran, C., J. Fast, and J. Horel, 2002: The VTMX 2000 Campaign. *Bull. Amer. Meteor. Soc.,* in press.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.,* **46,** 3077–3107.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1995: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 122 pp. [Available from UCAR Communications, P.O. Box 3000, Boulder, CO 80307.]

Hsie, E.-Y., R. A. Anthes, and D. Keyser, 1984: Numerical simulation of frontogenesis in a moist atmosphere. *J. Atmos. Sci.,* **41,** 2581–2594.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.,* **124,** 2322–2339.

Horel, J., and Coauthors, 2002: MesoWest: Cooperative mesonets in the western United States. *Bull. Amer. Meteor. Soc.,* **83,** 211–225.

Johnson, J. T., M. D. Eilts, D. Ruth, W. Goodman, and L. Rothfusz, 2000: Warning operations in support of the 1996 centennial Olympic Games. *Bull. Amer. Meteor. Soc.,* **81,** 543–554.

Kain, J. S., and J. M. Fritsch, 1993: Convective parameterization for mesoscale models. The Kain–Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.,* No. 46, Amer. Meteor. Soc., 165–170.

Keenan, T., and Coauthors, 2000: The Sydney 2000 Forecast Demonstration Project. *Bull. Aust. Meteor. Oceanogr. Soc.,* **13,** 63–66.

Loomis, B., 2001: First Saturday of the Games will offer a key test for Olympic organizers. *Salt Lake Tribune,* 9 February, electronic ed.

McLaughlin, M., and L. Rothfusz, 1996: The National Weather Service: Weather and the XXVI Olympiad. NWS Southern Region Headquarters, 55 pp. [Available from NWS Southern Region Headquarters, 819 Taylor St., Rm. 10A26, Fort Worth, TX 76102.]

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.

Powell, M. D., and S. K. Rinard, 1998: Marine forecasting at the 1996 centennial Olympic games. *Wea. Forecasting,* **13,** 764–782.

Rothfusz, L. P., M. R. McLaughlin, and S. K. Rinard, 1998: An overview of NWS weather support for the XXVI Olympiad. *Bull. Amer. Meteor. Soc.,* **79,** 845–860.

Schultz, D., and Coauthors, 2002: Understanding Utah winter storms: The Intermountain Precipitation Experiment. *Bull. Amer. Meteor. Soc.,* **83**, 189–210.

Slemmer, J. W., 1998: Characteristics of winter snowstorms near Salt Lake City as deduced from surface and radar observations. M.S. thesis, Dept. of Meteorology, University of Utah, 138 pp. [Available from Dept. of Meteorology, University of Utah, 145 South 1460 East, Rm. 209, Salt Lake City, UT 84112-0110.]

Snook, J. S., P. A. Stamus, and J. Edwards, 1998: Local-domain mesoscale analysis and forecast model support for the 1996 centennial Olympic games. *Wea. Forecasting,* **13,** 138–150.

Steenburgh, W. J., 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.