MESOWEST: COOPERATIVE MESONETS IN THE WESTERN UNITED STATES

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By surmounting the technical difficulties of collecting, integrating, and disseminating surface observations from many different organizations, MesoWest is able to provide research and operational meteorologists with useful, real-time data from the western states.

One of the major goals of the United States Weather Research Program is to advance the capabilities of the nation's weather observing system. In the western United States, this system includes over 350 automated and manual reporting surface stations deployed and maintained by the National Weather Service (NWS), Federal Aviation Administration, and Department of Defense. Since the Automated Surface Observing System (ASOS) stations comprise the majority of these stations, the resulting network will be referred to here as the ASOS network. The ASOS network is designed primarily to meet the needs of the weather and aviation communities and observations are currently reported hourly with updates at more frequent intervals when specific weather criteria are met.

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The scientific community has provided guidance on critical issues and research opportunities to the Weather Research Program through a series of meetings and published summaries. The Second Prospectus Development Team of the Weather Research Program recommended that more, and better, observations are needed over the mountainous terrain of the western United States due to the complexity of the orographically disturbed airflow and the often unrepresentative nature of the existing observations (Dabberdt and Schlatter 1996). Smith et al. (1997) summarize some of the societal impacts of terrain-induced flows over the western United States. They recommend, in part, that detailed mesoscale datasets be acquired to improve understanding of the physical processes responsible for the multiscale effects of complex terrain, including orographic precipitation and trapping of cold air in basins and valleys. Fritsch et al. (1998) note that many surface weather observing networks are not currently available to the national centers for operational forecasting. They recommend that there is a need to (i) improve accessibility to such datasets for the entire meteorological community; (ii) standardize the quality control and format of the data; (iii) look into the feasibility of es-

TABLE 1. Severe weather statement issued by the Salt Lake City WSFO that included information obtained from MesoWest (MesoWest observations in bold type).

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WWUS34 KSLC 122252 COR
SVSSLC
UTC003-011-035-049-057-122315-
SEVERE WEATHER STATEMENT...CORECTED ZONE IN HEADER
NATIONAL WEATHER SERVICE SALT LAKE CITY UT
450 PM MDT TUE JUN 12 2001
...STRONG THUNDERSTORM WARNING ALONG THE WASATCH FRONT
UNTIL 515PM...
A SEVERE THUNDERSTORM WARNING FOR HIGH WINDS WILL CON-
TINUE ALONG THE WASATCH FRONT UNTIL 515 PM. THIS WARNING
COVERS THE AREA FROM NEAR BRIGHAM CITY IN SOUTHEAST BOX
ELDER COUNTY SOUTH TO THE PROVO AREA IN UTAH COUNTY. A
LINE OF SEVERE THUNDERSTORMS HAVE PRODUCED WIDESPREAD
WIND DAMAGE. NUMBEROUS REPORTS OF TREES AND POWER LINES
DOWN ALONG WITH BUILDING DAMAGE HAVE BEEN RECEIVED BY THE
NATIONAL WEATHER SERVICE. SOME OF THE STRONGER GUSTS
INCLUDE...84 MPH AT LAKESIDE...77 MPH NEAR DUGWAY...74 MPH
IN SANDY...71 MPH OVER THE GREAT SALT LAKE...68 MPH IN
MAGNA...63 MPH IN NORTH SALT LAKE...60 MPH FOOT HILL AREA
OF SALT-LAKE CITY.
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tablishing a data archive center; and (iv) improve methods to process and assimilate the mesoscale data into operational model analysis and initialization schemes.

To improve monitoring of weather hazards on the mesoscale and climate variability across the nation, the NWS has begun to test the automation of the current NWS Cooperative Weather Observer (Coop) Network to form a national mesonet. Such automation could potentially provide weather observations in real time from over 5000 sites around the country (Dombrowsky 2001). This effort stems from the recommendations of the NWS Modernization Committee (1998).

Thousands of automated environmental monitoring stations, independent of the ASOS and Coop networks, have already been installed in the United States. Meyer and Hubbard (1992) and Tucker (1997) surveyed the deployment of automated weather stations in the entire United States and western United States, respectively. Hubbard and Sivakumar (2001) provide a comprehensive summary of many of the current automated networks that are available in the United States. As noted in all of these surveys, each observing network has been designed to meet the needs of the agency or firm that installed it. The Oklahoma Mesonet, for example, was designed for agricultural, hydrological, and meteorological monitoring and consists of at least 1 station in each county of the state, or approximately 1 station per 32 km (Brock et al. 1995). A mesonet run by the National Oceanic and Atmospheric Administration Air Resources Laboratory Field Research Division (Carter and Keislar 2000) exemplifies a network designed for emergency response. The characteristics of the observations vary considerably from one network to another: number of stations deployed, types of weather parameters, station siting, spacing between stations, method of transmission of the observations, reporting interval, quality control procedures, frequency at which observations are available, and format of the observations.

Observational data heterogeneity of the automated environmental networks in the United States is often presumed to be a significant obstacle for their use in operational applications. However, since the spatial coverage of the ASOS network is insufficient to capture many of the local and mesoscale weather phenomena that impact the public, all NWS Weather Forecast Offices (WFOs) already strive to obtain access to manual and automated observations of current weather conditions in their county warning areas. Table 1 is an example of the application by a Salt Lake City NWS forecaster of all available observations, including spotter reports and mesonet observations, to warn the public about impending hazardous weather conditions.

The local arrangements at WFOs for access to automated weather stations rely upon specialized software or resources that vary from one data provider to another. The Local Data Acquisition and Display (LDAD) software developed by the Forecast Systems Laboratory (Jesuroga et al. 1998) is available to utilize local observations in the Advanced Weather Interactive Processing System (AWIPS). Many WFOs in the western United States (e.g., Boise, Idaho; Boulder, Colorado; Cheyenne, Wyoming; Great Falls, Missouri; Missoula, Montana; Monterey, California; Reno, Nevada; Salt Lake City, Utah; and Seattle, Washington) are collecting, and redistributing via the Intenet, observations from automated weather stations. In some instances, these activities have built upon collaborative projects with nearby universities such as with the Real-time Environmental Information Network and Analysis System (REINAS) Project (Nuss et al. 1998) or the Northwest Regional Modeling Consortium (www.atmos.washington.edu/~cliff/consortium.html) and with federal agencies (National Interagency Fire Center and NOAA Forecasts Systems Laboratory). Effective utilization of these data resources is hampered, however, by the effort required at the WFO to preprocess the data for use in AWIPS and by the absence of established procedures to distribute data in a common format from one WFO to another.

As a cost-effective supplement to the current ASOS network, software has been developed to access weather observations at automated stations throughout the western United States. The program to collect, process, archive, integrate, and disseminate these observations is referred to as MesoWest (Horel et al. 2000; Splitt et al. 2001) and includes weather information at over 2800 stations in the western United States including ASOS observations. While the average station separation from one ASOS station to its nearest neighbor is 44 km in the western United States, MesoWest provides enhanced spatial coverage such that the average station separation is lowered to roughly 15 km.

Development of MesoWest began during 1994 as a collaborative effort between researchers at the University of Utah and forecasters at the Salt Lake City WFO (Stiff 1997; Slemmer 1998). MesoWest was initially referred to as the Utah Mesonet and was intended to collect automated observations throughout Utah from a number of government and private sources, process the observations into a common format, and redistribute them to forecasters at the WFO. The name was changed to MesoWest in January 2000 to reflect the greater emphasis on data collection outside of Utah.

The objectives of MesoWest are the following:

- to improve timely access to real-time weather observations for NWS operations;
- to improve integration of observations for use in nowcasting, forecast verification, and as input to operational and research forecast systems; and
- to provide access to available environmental data resources for research and education on weather processes in the western United States.

MesoWest is not designed to be a long-term climate archive or a repository for field programs, though some field program data have been stored in the MesoWest database. The state climatology programs and the Western Region Climate Center provide access to long-term climatic records in the western United States.

Financial support for the Utah Mesonet was provided initially by the Cooperative Program for Operational Meteorology, Education, and Training (COMET). Support for MesoWest has continued from the National Weather Service as part of the activities of the NOAA Cooperative Institute for Regional Prediction (CIRP). The Institute conducts a broad program of research that includes effort toward improving weather and climate prediction in regions of complex terrain. MesoWest is an important component of the applied research and development underway at CIRP. The geographic range of MesoWest over the western United States is intended to focus research and development on applications common to that region, for example: weather forecasting in complex terrain, water resource management, fire weather, and air quality in urban basins.

DATA PROVIDERS. MesoWest relies upon informal arrangements to access provisional weather data from participating organizations. If an organization requests a formal Memorandum of Understanding, then that document is negotiated between the organization and a local WFO. Provisional refers to the fact that these data are made available "as is" and have undergone minimal or no quality control procedures by the station owner at the time the data are collected.

The appendix lists the sources of data available to MesoWest. Currently, weather information is available from 47 public and 23 commercial sources. The data are received either directly over the Internet from these sources or indirectly after collection and retransmission by a data provider (see the appendix). The number of organizations participating indirectly is much higher than that evident in the appendix, since many networks [Colorado Basin River Forecast Center (CBRFC), California Nevada River Forecast Center (CNRFC), Remote Automated Weather Stations (RAWS), Snowpack Telemetry (SNOTEL)] e.g., reflect cooperative ventures between a number of agencies. The sources of environmental information listed in the appendix have no obligation to share their provisional data with other users as they have installed the equipment to meet the needs of their customers (e.g., water resource managers, fire management personnel, air quality decision makers, farmers, winter road maintenance personnel, ski area operators, military personnel, or emergency managers).

Figure 1a shows the locations of MesoWest stations from which data were available during 18–21 June 2001. This period is representative of typical

MesoWest operations in that some networks listed in the appendix were temporarily unavailable (e.g., Wyoming Department of Transportation). Particularly dense coverage is evident in northern Utah and the Sierra Mountains in California while the northeastern Arizona and southeastern Utah region remains the least monitored area in the western United States (Tucker 1997). We currently receive the most observations from California and the fewest from New Mexico (Fig. 1b).

The majority of stations available in MesoWest outside of the ASOS network (Fig. 1c) come from two sources: the interagency RAWS network coordinated by the Bureau of Land Management and U.S. Forest Service (Fig. 1d) and the SNOTEL network operated by the U.S. Department of Agriculture Natural Resources Conservation Service (Schaefer and Paetzold 2001; Fig. 1e). These networks are operated primarily for fire (RAWS) and water resource (SNOTEL) management purposes and provide critical observations in remote locations of the western United States. Other federal, state, and local agencies provide access to 650 stations while roughly 100 stations are available from commercial firms (Fig. 1f). These other government agencies and commercial firms that supply data to MesoWest are estimated to have spent collectively over $10 million to install their stations and spend close to $1 million in maintenance costs per year.

Each source of environmental observations exhibits topographic biases (Briggs and Cogley 1996). For example, the ASOS network in the western United States is dominated by stations located at airports in valleys (Fig. 2), while the SNOTEL and RAWS networks supply observations primarily at high elevation. Many of the smaller networks also provide observations over limited elevation ranges. As a result of integrating observations from all of the networks, MesoWest helps to mitigate the topographic biases found in individual networks (Fig. 2).

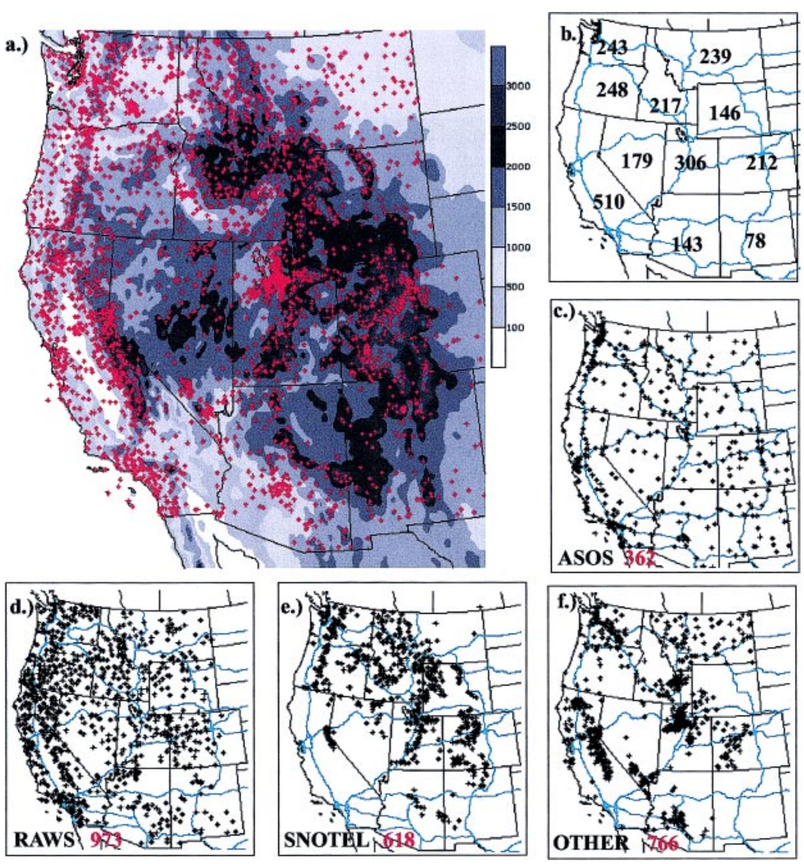

Fig. 1. (a) Locations of MesoWest stations reporting observations during 18–21 Jun 2001 superimposed upon the terrain of the western United States. Higher terrain is denoted by successively darker shading. (b) Number of stations in each state. Locations of stations currently available from (c) surface aviation network (ASOS); (d) Bureau of Land Management (RAWS); (e) Soil Conservation Service (SNOTEL); (f) other government agencies and commercial firms. Total number of stations available from each network is shown in red.

The environmental platforms deployed in the field are accessed by one or more communication methods. These methods include ethernet, phone, cellular phone, radio, satellite, and meteor burst. Based on the needs of the data provider, the frequency at which the data platform is queried varies from every 5 min to once a day with daily delivery accounting for less than 2% of the data. Once the data are collected by the source agency or firm or combined from multiple sources by a data provider, MesoWest obtains the data via FTP, web retrievals, or via Unidata's Local Data Manager (LDM) software (Fulker et al. 1997).

MesoWest collects and processes the weather observations both synchronously and asynchronously. The synchronous portion of the processing cycle is scheduled every 15 min: a master script initiates FTP calls to some networks, collects data transmitted to an FTP server at

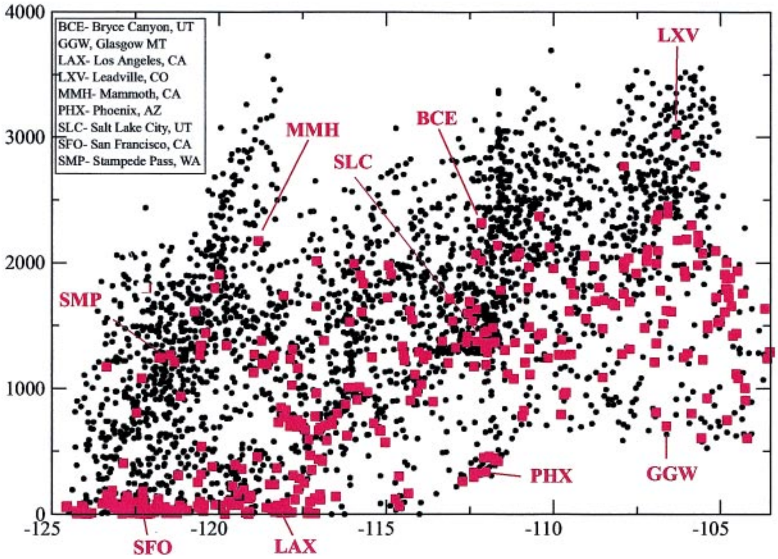

FIG. 2. Distribution of MesoWest stations as a function of longitude and elevation (m). Red squares denote ASOS stations while black dots denote other MesoWest stations. Selected ASOS station identifiers are provided for reference.

the University of Utah, quality controls the data, inserts the data into a database, and generates graphics.

Figure 3 provides a snapshot of the number of stations available from MesoWest as a function of the latency between the valid time of the observation and the time the observation is available to users over the Internet. Roughly 300 ASOS stations are available within 10 min of the valid time and the average latency for ASOS stations available via MesoWest is 8 min. Over 400 RAWS stations usually report within 10–20 min while the average latency for all RAWS stations is 29 min. The relatively long latency for SNOTEL observations (74 min) arises from a number of factors: the network is designed for daily monitoring of snowpack conditions; the meteor burst technology is a cost-effective, but a slower, method of data transmission (Schaefer and Paetzold 2001); and the SNOTEL and MesoWest processing cycles are unsynchronized. The remaining stations have average delays of 51 min; however, upward of 200 of these stations typically report within 20 min of the valid time. To reduce these latencies as much as possible, we are moving currently toward greater reliance on asynchronous processing in which each data stream is processed as soon as it is available, inserted into the database, and the data retransmitted immediately via LDM.

MESOWEST DATABASE. Data from 1997 to the present are stored at CIRP in a MySQL database (duBois 2000). MySQL is an open source relational database management system that is reliable and efficient. Roughly 7 mbytes of data are accumulated per day, half of which are the indices to search rapidly within the relational database tables. Currently, the MySQL database consists of 12 tables of data organized to provide efficient access. As shown in Fig. 4, weather observations are grouped into eight tables for quick access (the two METAR tables apply to ASOS stations only). Surface environmental conditions that are often measured along with atmospheric conditions, for example, pavement state, fuel moisture, soil, and water-body properties, are also available in four tables.

The NWS Western Region Scientific Services Division maintains a separate MySQL database using the same architecture as the one at CIRP. This database is used for an operational Web-based application, referred to as the "observation monitor," at WFOs, throughout the Western Region. The relational database provides convenient access to current weather within geographic bounds that are sorted according to user preferences by the intensity of wind gusts, extreme temperature, limited visibility, etc.

Figure 5 summarizes the number of stations reporting the primary weather variables. Temperature observations are most abundant followed by precipi-

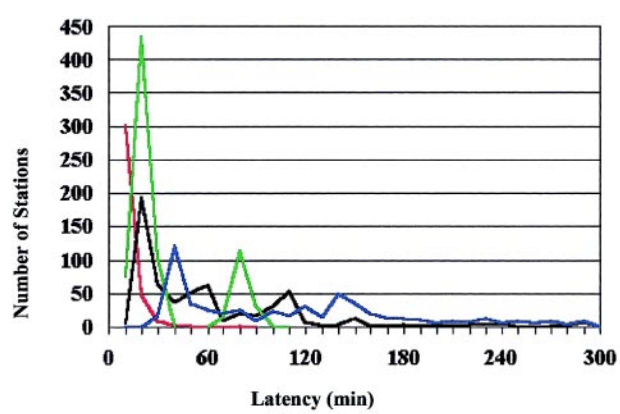

FIG. 3. Number of stations from ASOS (red line), RAWS (green line), SNOTEL (blue line), and all other MesoWest sources (black line) during 12 Jun 2001 as a function of each station's average latency between the valid time of the observation and the database insertion time. Stations are grouped into 10-min bins, i.e., the first data point of each line refers to stations with average delays between 0 and 10 min.

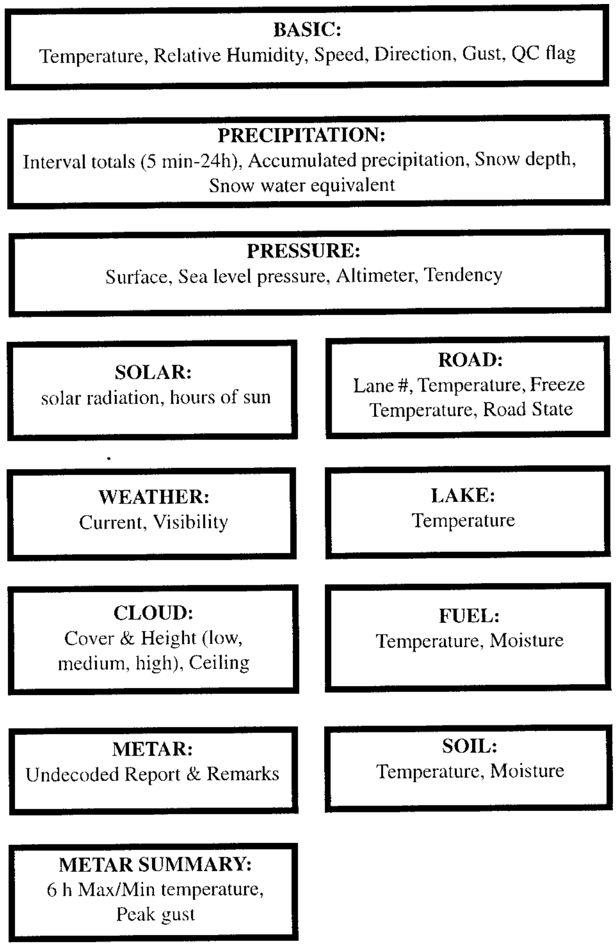

FIG. 4. MySQL data tables used to store MesoWest data. Every observation is accompanied by a station identifier and observation time. Metadata is stored separately in 12 additional tables.

tation, wind, and relative humidity observations. In contrast to ASOS observations that represent a snapshot of weather conditions, the MesoWest observations are usually averages over the duration of the reporting interval, typically from 5 min to an hour. Precipitation remains the most difficult quantity to properly utilize in the database as a result of the variety of the types of sensors used (e.g., unheated tipping buckets, heated tipping buckets, weighing gauges, snow pillows, acoustic snow depth sensors); variables available to monitor snowfall (e.g., snow water equivalent, snow depth, interval snow amount, storm total); and reporting interval (e.g., running totals or precipitation amounts during intervals from 5 min to 24 h). The use of database metadata aides in the handling of these more complicated data streams, whereas previously many precipitation sensors were grouped into a single parameter without metadata differentiating the types. The database also allows for storing multiple values of a parameter type at a given station (e.g., temperature sensor #1 and temperature sensor #2), though data users generally only require a single near-surface value to be delivered. Care has to be taken when adding such information to the current tables so that table sizes remain efficient.

A real-time quality control flag for each station observation is available in the database. Using provisional data collected from many different networks, with heterogeneous sensors, sensor heights, siting, standards, and maintenance procedures is a challenge. Many networks have their own quality assurance procedures in place and maintain long-term archives of the quality-controlled data. These quality-control procedures are often completed several hours to days after the observations are taken in order to allow for temporal consistency and manual checks to be applied to the data (similar procedures are used for the Oklahoma Mesonet; Shafer et al. 2000). In order to apply uniform quality assurance to all MesoWest observations as they are collected, automated quality control is performed upon receipt of the data and a single quality control flag is assigned to an entire observation received from a station. The quality control flag ("good," "caution," "suspect") is assigned to observations based upon range checks and other quick algorithms (e.g., gust/sustained wind ratio criteria), three-dimensional statistical regression (Splitt and Horel 1998), and a manual blacklist. While the use of a single quality control flag is problematic in that some users could discard good data collected at a site, delivery of a single flag is efficient and better suited for the software of our data users. NWS forecasters and other users help to identify potential problems with observing stations. Data providers are forwarded information when their instrumentation appears to be malfunctioning if an appropriate con-

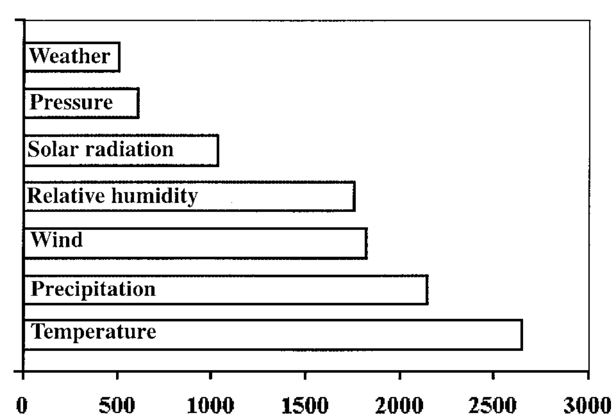

FIG. 5. Number of MesoWest stations reporting selected weather variables from 18 to 21 Jun 2001.

tact exists and in many instances servicing can be conducted by station owners within a short time frame depending on season and station location. Automated quality control algorithms for precipitation remain to be implemented.

The MySQL database developed at the University of Utah provides an efficient way to manage the metadata required to describe the stations and sensors deployed. Since stations in some networks (e.g., RAWS) are continually being added, moved, or discontinued, software has been developed to update our metadata daily and broadcast these updates to users. The minimum metadata required for a station are simply the station name, latitude, longitude, elevation, parameter types (and their units). However, we have developed the capability to store considerably more metadata information and have detailed metadata available for many stations in northern Utah. Access to a good portion of this metadata is available on the MesoWest Web page by individual station. Stations are stored in the database by a National Weather Service station identifier when one has been assigned; otherwise, a 3–5 letter/number string that does not conflict with other NWS identifiers is used.

While database metadata information provides a framework to address issues related to nonuniform data, this capacity is not yet fully developed as data users have been primarily concerned with access to the data and data providers often have extensive metadata available at their own Internet sites. While wind sensor heights can vary between 2 (e.g., Agrimet stations) and 7 m or more (e.g., RAWS wind sensors are installed at a standard height of 20 feet, but can be higher depending on ground cover or obstructions) our primary data users generally use all observations as representative of near-surface conditions. Combining sensors with different siting characteristics is practical in the complex terrain of the west where vertical and horizontal variations normally outweigh variations due to sensor siting. Data users familiar with the MesoWest have confidence in the quality of the siting for the overwhelming number of stations as all participating networks are professional organizations.

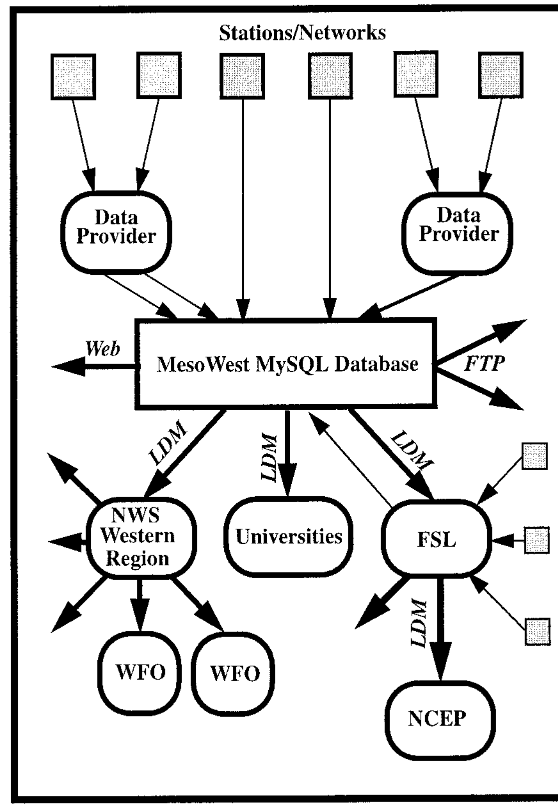

Fig. 6. Data from individual stations and networks in the western United States are transmitted to the MesoWest database through multiple paths: some are received directly from networks (center paths), some are collected by data providers and passed along in the original data format (left paths), while others are collected by data providers, processed, and passed along in a common format (right paths). Data are available from the MesoWest database via the Web, FTP, and LDM. See section 4 for further details on dissemination of data from MesoWest.

DISSEMINATION. We encourage all data sources to allow the provisional data to be used without restriction. Data sources choose whether observations can be distributed without restriction or subject to the following disclaimer:

> Data contained in MesoWest arise from cooperative arrangements with many different educational institutions, public agencies and commercial firms. The data are intended to be used by personnel in governmental agencies to protect lives and property, by the public for general information, and by individuals at educational institutions and government agencies for instructional and research purposes. Any other uses of the data from one or more stations must receive written approval from the agencies that installed the weather sensors. . .

The disclaimer primarily affects commercial use and requires commercial users to obtain permission from the government or commercial source to use their data. MesoWest has no exclusive access or rights to the data available from the government and commercial sources. For example, long-term archives of RAWS and SNOTEL data are also maintained by

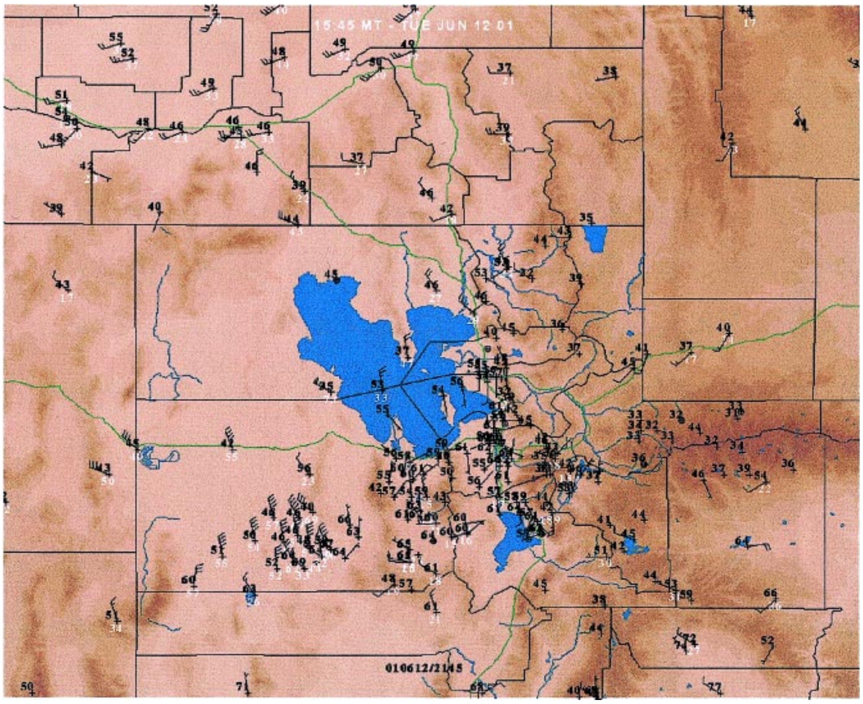

FIG. 7. Routine graphical product generated every 15 min from MesoWest observations in northwestern Utah. Plotted are the most current observations during the hour ending at 2145 UTC 12 Jun 2001 of temperature (°F, in black plotted to upper left of station), wind gusts greater than 15 kt (in white plotted below station) and wind (kt, plotted as barbs). Observations are filtered to remove the most densely spaced observations.

the Western Region Climate Center at the Desert Research Institute. We also adhere to any dissemination restrictions of the data providers who provide datasets obtained from multiple sources.

While we encourage data providers to allow the provisional data to be used without restriction, inappropriate use of the data obtained through MesoWest could lead to termination of access to the data for all users. All data providers express concern that the provisional data may be used inappropriately; these problems can be mitigated through user access to accurate metadata that describes the strengths and limitations of the data platform.

Our policy is not to restrict access to MesoWest data to any potential user. Software has been written to provide MesoWest data access over the Internet via the Web, FTP, and LDM. Figure 6 summarizes the flow of information through the MesoWest database. Data from individual stations are available via the Web (www.met.utah.edu/mesowest) as soon as received. Current and past conditions at every station can be obtained as text summaries, time series, or spatial maps. Users can find weather observations available from stations closest to each zipcode in the western United States and closest to over 400 000 locations (cities and towns, major landmarks, geographic features, etc.). Specialized interfaces for winter road maintenance (Horel et al. 2001) and fire weather (Ciliberti et al. 2001) applications are also available.

As part of the MesoWest processing cycle, the following steps are completed every 15 min. Text files containing all observations in the past hour and past day are created in several formats for distribution to WFOs, operational and educational users for real-time display in N-AWIPS (National Centers AWIPS), and modeling groups for data assimilation. These files are placed on an anonymous FTP server, and, as shown in Fig. 6, LDM is used to transmit the files to WFOs in the NWS Western Region, universities, and the NOAA Forecast Systems Laboratory (FSL).

The MesoWest data are disseminated to the WFOs through the Western Region's Wide Area Network as a combined data stream of local observations that can be directly ingested into AWIPS using the LDAD software developed by FSL. In addition, MesoWest data are incorporated into regional and local analyses at WFO's through the use of the MAPS Surface Assimilation System (MSAS) and Local Analysis and Prediction System (LAPS) developed by the Forecast Systems Laboratory (Miller and Benjamin 1992; Albers et al. 1996). Special procedures are in place for transmitting data to the Salt Lake City WFO from the University of Utah and vice versa. A T-1 communication link is used to transfer graphical images and text files to the WFO. Graphical images and text files are displayed on the WFO's intranet and public Web pages (www.wrh.noaa.gov/Saltlake/). Salt Lake City WFO forecasters depend routinely upon MesoWest to provide "ground truth" on weather conditions around the state.

After collection of data from other sources, FSL transfers the combined data via LDM to the National

Centers for Environmental Prediction (NCEP) and other users. Data flows from some data providers to NCEP outside of the MesoWest program. For example, precipitation amounts are disseminated by the River Forecast Centers to NCEP and other NWS offices; however, temperature and wind observations obtained from their local sources are typically available only via MesoWest. Other modeling groups besides NCEP that access MesoWest data either via FTP or LDM currently include the following: FSL, National Center for Atmospheric Research, and the U.S. Army Test and Evaluation Command.

SURFACE ANALYSES. Data assimilation procedures synthesize irregularly spaced observations onto a regular grid. Surface analyses are generated at CIRP by combining the MesoWest data with a background field provided by the National Centers for Environmental Prediction RUC2 analysis (Ciliberti et al. 2000; Lazarus et al. 2002, manuscript submitted to *Wea. Forecasting*). These analyses rely upon the computationally inexpensive University of Oklahoma Advanced Regional Prediction System Data Analysis System (ADAS). The background field is created by interpolating the RUC2 analysis at 40-km resolution to the ADAS grid. This initial field is modified by MesoWest surface observations collected from the hour leading up to the valid time. MesoWest quality control flags are applied to the input dataset so that stations considered suspect are not used in the analysis. Additional quality control is performed on the MesoWest observations as part of the standard analysis procedure. Several configurations of ADAS run operationally at the University of Utah: surface analyses at 10-km resolution over the western United States at 15-min intervals, 1-km surface analyses over northwest Utah at 15-min intervals, and 1-km horizontal resolution three-dimensional analyses over northwest Utah every hour. Additional surface analyses are created twice daily (at 0000 and 1200 UTC) in order to initialize the surface fields of the University of Utah Intermountain Weather Forecast System (see the accompanying article by Horel et al. 2002). The ADAS 10-km surface analyses over the western United States are being distributed via LDM to selected NWS offices for testing and evaluation. An operational version of ADAS run every 15 min at Western Region will also soon be available to all forecast offices for verification of the forecast grids to be issued as part of the NWS Interactive Forecast Preparation System.

To illustrate the utility of the data available from MesoWest and the value added by performing gridded surface analyses, we examine the surface response to an unseasonably cold upper-level trough that moved across the western United States on 12 June 2001. A series of severe weather statements incorporating MesoWest observations were issued by the Salt Lake City WFO, including the one in Table 1. Information available to forecasters during the preparation of the severe weather statements included Fig. 7, which shows the line of thunderstorms moving to the southeast across the Great Salt Lake at 2145 UTC (1545 MT) with strong winds and cold temperatures behind the squall line. Figure 8 depicts the MesoWest data from this time period with weather radar information and exemplifies how the data can be viewed using N-AWIPS.

Graphics from the ADAS 10-km surface analysis over the western United States for the same time pe-

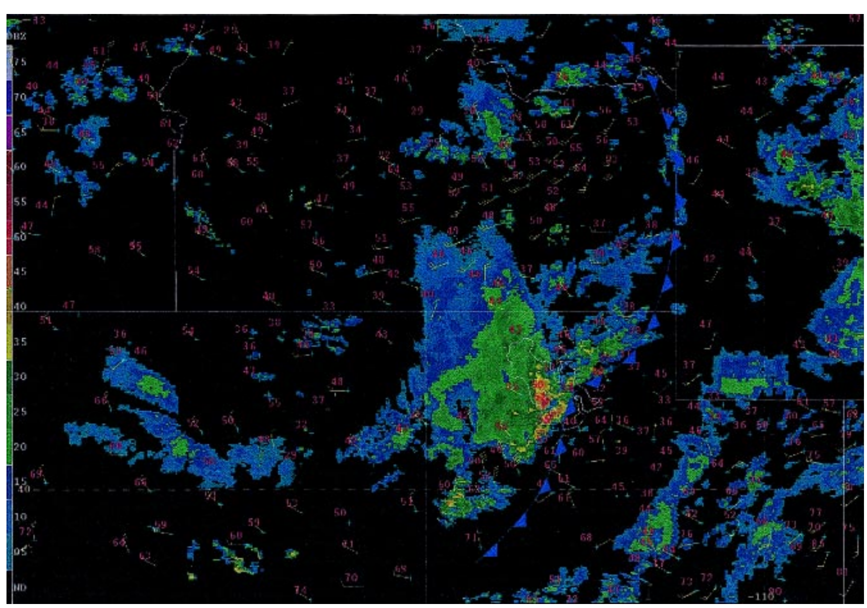

Fig. 8. MesoWest data with radar reflectivity. Most current observations during the hour ending at 2145 UTC 12 Jun 2001 of temperature (°F, in red plotted to upper left of station), wind (kt, plotted as barbs), and reflectivity (dB*Z*, shaded according to scale on the left). Cold front is in blue.

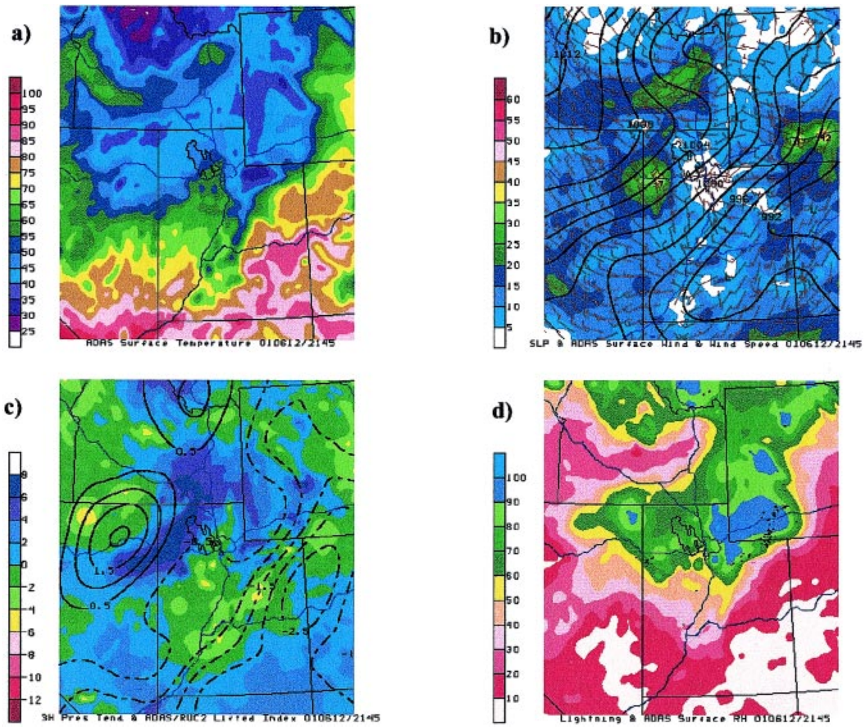

Fig. 9. ADAS surface analysis real-time product value at 2145 UTC 12 Jun 2001. (a) Temperature (°F shaded according to the scale on the left), (b) sea level pressure (mb), vector wind (kt), and wind speed (kt, shaded according to the scale on the left), (c) lifted index (shaded according to scale on the left) and 3-h pressure change (0.5 mb interval; solid contours indicate increasing pressure while dashed contours indicate decreasing pressure), and (d) relative humidity (in %, shaded according to scale on the left).

riod are displayed in Fig. 9. These graphics provide context for the environment in which the squall line is embedded. For example, the cold temperature and strong wind behind the line of thunderstorms are evident as well as rising pressure and greater near-surface stability. Figure 10 shows the differences between the surface temperature at 2145 UTC 12 June 2001 and the temperature 24 and 6 h earlier, respectively. Significantly colder temperatures compared to the day before are evident from southern Utah to the Montana–Canada border. Figure 10b shows that the weather system passing through Utah has significantly reduced the typical afternoon heating evident in other parts of the west.

DISCUSSION. MesoWest is based upon voluntary sharing of provisional weather observations by governmental and commercial organizations who collect observations throughout the western United States. MesoWest would not be possible without the efforts of many federal, state, and local agencies, educational institutions, and commercial firms. MesoWest helps many of these organizations in turn by integrating their observations with neighboring ones, which can facilitate their own operations. Also, the automated quality control algorithms and data monitoring programs developed for MesoWest operations help to identify data providers' equipment and communication problems.

Some networks have established paths to distribute environmental observations to large user communities, for example, fire weather (RAWS), water resource (SNOTEL), and agriculture (Bureau of Reclamation AGRIMET); many other data sources do not. MesoWest enhances the utilization of resources expended on the installation and maintenance of weather equipment by dissemination of the weather information to many additional user communities that normally would not have access to these data. For example, some of the most avid users of MesoWest are television broadcasters, skiers, hang gliders, and windsurfers.

MesoWest continues to evolve as additional networks are available electronically in real time. Not all organizations that collect weather observations in the western United States participate in the MesoWest program. Some are unaware that the program exists; others decline to participate, as they prefer to control access to their data directly. Nonetheless, we estimate conservatively that there are several thousand existing environmental monitoring stations in the western United States remaining to be accessed and it is reasonable to expect the number of weather stations deployed to increase. Further, there are many automated observing stations deployed that currently measure hydrological and geophysical parameters only (e.g., streamflow, river gauge height, fuel temperature). Weather instrumentation could be added at a much reduced cost to those stations compared to the resources required to deploy and maintain a comparable number of new stations.

The agencies and firms that install and maintain networks for their own needs provide an invaluable service to operational forecasters and the research community by allowing their data to be accessed. Most of these individuals have little time or incentive to meet siting, recording, and reporting standards imposed by another agency. While there is a distinct advantage to having stations conform to standards related to siting and equipment, we believe the availability of real-time observations outweighs the current lack of uniformity.

MesoWest and similar activities at other research universities and government agencies have already led to improved operations at NWS WFOs. Many of the automated reports available in the western United States are in remote locations where there are no trained spotters available to monitor developing weather conditions or severe conditions already underway. These surface observations help to corroborate WSR-88D radar signatures of hazardous weather and fill in gaps resulting from radar beam blockage. MesoWest data have also been used for training exercises at the Salt Lake City WFO and research studies at the WFO and NWS Western Region Scientific Services Division on forecasting problems such as lake-effect snowstorms, canyon and gap winds, microbursts, and evaluation of radar precipitation algorithms. MesoWest is also an integral part of the weather support required for the 2002 Winter Olympic and Paralympic Games (see the companion article by Horel et al. 2002).

MesoWest data are being used effectively for many other applications besides NWS operations. MesoWest is used extensively for winter road maintenance and road construction scheduling in Utah (Horel et al. 2001). The Maintenance Decision Support System under development by a consortium of national laboratories and funded by the Federal Highway Administration is using MesoWest data for prototype development and field testing of advanced decision support components for winter road maintenance.

Two field programs in northern Utah (Intermountain Precipitation Experiment; Schultz et al. 2002; and Vertical Mixing and Transport Experiment; Doran et al. 2002, manuscript submitted to *Bull. Amer. Meteor. Soc.*) have relied extensively on real-time access to MesoWest for operations and the MesoWest archive for later analysis. A number of research studies have been completed (Steenburgh and Blazek 2001; Stewart et al. 2002, manuscript submitted to *Bull. Amer. Meteor. Soc.*) and others are underway utilizing the MesoWest database. Based upon feedback from users, MesoWest is being used for many other research studies, including evaluation of energy savings resulting from year-round daylight savings time, wind energy potential, and environmental stresses on plant communities.

Considerable debate remains regarding the utility of surface observations in complex terrain for initialization of numerical models. Models that do not adequately resolve the observed terrain tend to adjust the initial state quickly over a period of a few hours to conform to circulations driven by the model's terrain (Paegle et al. 1990). Hence, surface observations used to define the initial state are rapidly filtered away. MesoWest surface observations are just beginning to be included in the initial state of operational and research models with sufficiently high resolution to resolve many of the observed local circulations and temperature and moisture gradients. Additional research remains to be completed to assess whether forecast skill in high-resolution models is improved as a result of more complete specification of the initial state in regions of complex terrain.

The aforementioned uses of the MesoWest data streams have required the development of an array of data delivery pipelines to the users. As summarized in Fig. 6, the communication web required to transfer weather information from local data sources to the national level exemplified by NCEP appears complex. Currently, one national strategy being proposed to harness the potential of the existing surface observing resources is to collect those observations centrally and then distribute them to all customers. This approach is a useful one for national-scale applications

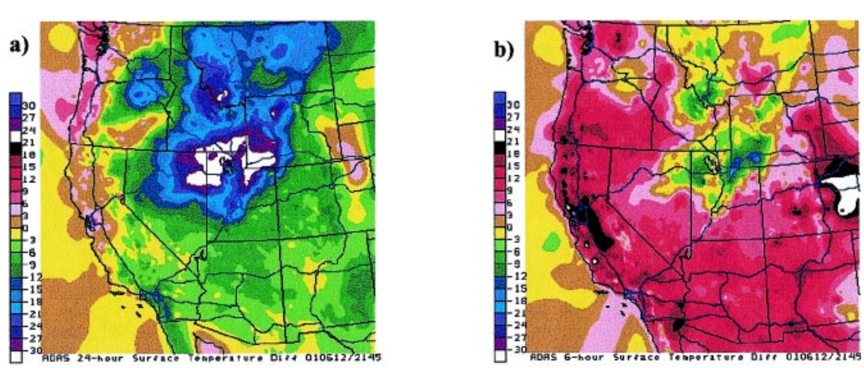

FIG. 10. Real-time ADAS product of the difference in surface temperature (in °F shaded according to scale at the left) between the ADAS analysis valid at 2145 UTC 12 Jun 2001 and the ADAS analysis: (a) 24 h earlier (2145 UTC 11 Jun), (b) 6 h earlier (1545 UTC 12 Jun).

that are not overly sensitive to the inherent latencies between the valid time of the observation and the time the observation is available for use. However, the value of timely weather observations is greatest locally. Rather than centralized collection on a national basis, considerable promise lies through facilitation of local collection points that distribute observations via LDM to many end users at the local, regional, and national level. LDM aids the exchange of environmental information in an effective, and decentralized, manner. Many WFOs are already filling this local data collection role, although they have limited resources to do so. In addition, LDM is implemented at only a few WFOs to broadcast local data resources nationally.

Research universities and government agencies have spent considerable effort to develop and sustain local and regional mesonets that are based upon cooperation with other agencies and commercial firms. As summarized by Brown and Hubbard (2001), most of these efforts remain underfunded and would be enhanced by a national strategy that encourages and supports continued research and development on effective methods to collect, archive, and distribute environmental data.

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APPENDIX. MesoWest sources of environmental observations as of August 2001. Italics denote a commercial organization. Data providers combine observations from many sources and make them available to MesoWest after their data collection cycle is completed. The primary area of the network and number of stations available currently are also provided.

Network name	Source	Data provider	Area	No.
AGRIMET	Bureau of Reclamation Great Plains Region		Montana	12
AGRIMET	Bureau of Reclamation Pacific Northwest Region		Idaho/Washington	50
ALTA	*Alta Ski Area*	Salt Lake City WFO	northern Utah	5
ARL FRD	NOAA ARL Field Research Division		eastern Idaho	33
ARL SORD	NOAA ARL Special Operations and Research Division		southern Nevada	31
ASOS	National Weather Service	Salt Lake City WFO and Unidata	all western states	362
AZ ALERT	Maricopa County, Arizona Flood Control District		Maricopa County, Arizona	24
AZMET	University of Arizona		Arizona	23
BEAVER	*Beaver Mountain Ski Resort*	Salt Lake City WFO	southern Utah	1
BOULDER	NCAR/other research institutions	Boulder WFO/Forecast Systems Laboratory	northern Colorado	6
BRIGHTON	*Brighton Ski Resort*	Salt Lake City WFO	northern Utah	1
BRIDGER	*Bridger Bowl Ski & Snowboard Resort*	Salt Lake City WFO	Montana	1
BEAR RIV	Bear River Wildlife Refuge	Salt Lake City WFO	northern Utah	2
BIG SKY	*Big Sky Ski & Summer Resort*	Salt Lake City WFO	Montana	1
CAMPBELL	*Campbell Scientific, Inc.*		northern Utah	3

Network name	Source	Data provider	Area	No.
CANYON	*The Canyons*	Salt Lake City WFO	northern Utah	3
CBRFC	Water agencies in multistate region	Colorado Basin River Forecast Center	Arizona, Colorado, Idaho, Nevada, Utah, Wyoming	74
CIRP	University of Utah	Salt Lake City WFO	northern Utah	6
CNRFC	Water agencies in California and Nevada	California Nevada River Forecast Center	California, Nevada	161
CUP	Central Utah Water Conservancy District	U.S. Bureau of Reclamation	Utah	9
DEER VALLEY	*Deer Valley Resort*	Salt Lake City WFO	northern Utah	2
DENVER	Denver Urban Drainage and Flood Control District	Forecast Systems Laboratory	Colorado	15
DNR	Utah Department of Natural Resources	Salt Lake City WFO	northern Utah	2
DUGWAY	U.S. Army Dugway Proving Grounds		western Utah	21
HMMN	Hanford Meteorological Monitoring Network	University of Washington	Washington	29
ITD	Idaho Transportation Department		Idaho	9
JACKSON	*Jackson Hole Mountain Resort*		Wyoming	4
JUDD	*Judd Communications*	Salt Lake City WFO	Salt Lake City, Utah	1
KBCI	*KBCI, Boise, Idaho*		Idaho	15
KEN	*Kennecott Copper*		Salt Lake Valley, Utah	11
KSL	*KSL, Salt Lake City, Utah*	Salt Lake City WFO	Bountiful, Utah	1
LAS VEGAS	Clark County Flood Control District		Clark County, Nevada	23
LASAL	Manti-La Sal Avalanche Forecast Center	Salt Lake City WFO		1
MAC	McCall Avalanche Center	Salt Lake City WFO	Payette, Idaho	1
MSI	*Meteorological Solutions, Inc.*		Salt Lake City, Utah	1
MT DOT	Montana Department of Transportation	Great Falls WFO	Montana	54
NPS	National Park Service	Salt Lake City WFO	northern Utah	1
NAVPS	Naval Postgraduate School	Bay Area Mesoscale Initiative	Monterey, California	10
NV DOT	Nevada Department of Transportation		Nevada	18
NW AVAL	Northwest Avalanche Center	University of Washington	Washington	17
PAC	*PacifiCorp*	Salt Lake City WFO	Kemmerer, Wyoming	1
PKC	*Park City Mountain Resort*	Salt Lake City WFO	northern Utah	3
RAWS	Wildland fire agencies	Boise WFO/National Interagency Fire Center	all western states	973

Network name	Source	Data provider	Area	No.
REINAS	Real-time Environmental Information Network and Analysis System	Bay Area Mesoscale Initiative	Monterey, California	2
SARC	Southern Agricultural Research Center		Montana	1
SNOWBIRD	*Snowbird Ski and Summer Resort*	Salt Lake City, WFO	northern Utah	2
SCR	Salt Creek Wildlife Refuge	Salt Lake City WFO	northern Utah	1
SEVIER	Sevier River Water Users Association		central Utah	4
SLC/WR	Salt Lake City WFO/NWS Western Region		northern Utah	13
SLOC	*Salt Lake Organizing Committee*	Salt Lake City WFO	northern Utah	3
SNOWBASIN	*Snowbasin Ski Resort*	Salt Lake City WFO	northern Utah	7
SNOTEL	National Resources Conservation Service	National Water and Climate Center	all western States	618
SOLITUDE	*Solitude Mountain Resort*	Salt Lake City WFO	northern Utah	1
SUN VALLEY	*Sun Valley Resort*	Salt Lake City WFO	central Idaho	2
SUNDANCE	*Sundance Resort*	Salt Lake City WFO	northern Utah	2
TAD	U.S. Army Deseret Chemical Agent Disposal Facility		Tooele County, Utah	9
TOOELE	Tooele County Emergency Mgmt.		Tooele, Utah	27
UAFC	Utah Avalanche Forecast Center	Salt Lake City WFO	northern Utah	3
UAQ	Utah Department of Air Quality	Salt Lake City WFO	Utah	17
UCC	Utah Climate Center		Utah	26
UDOT	Utah Department of Transportation	SLC WFO	Utah	24
WA DOT	Washington Department of Transportation	University of Washington	Washington	29
WAAQ	Washington Department of Ecology	University of Washington	Washington	20
WCR	*Wolf Creek Ranch*	Salt Lake City WFO	northern Utah	1
WYDOT	Wyoming Department of Transportation	Cheyenne WFO	Wyoming	23

REFERENCES

Albers, S., J. McGinley, D. Birkenheuer, and J. Smart 1996: The Local Analysis and Prediction System (LAPS): Analyses of clouds, precipitation, and temperature. *Wea. Forecasting,* **11,** 273–287.

Briggs, P. R., and J. G. Cogley, 1996: Topographic bias in mesoscale precipitation networks. *J. Climate,* **9,** 205–218.

Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, 1995: The Oklahoma mesonet: A technical overview. *J. Atmos. Oceanic. Technol.,* **12,** 5–19.

Brown, P. W., and K. G. Hubbard, 2001: Lessons from the North American experience with automated weather stations. *Automated Weather Stations for Application in Agriculture and Water Resources Management,* K. G. Hubbard and M. V. K. Sivakumar, Eds., WMO/TD No. 1074, 21–28 pp.

Carter, R. G., and R. E. Keislar, 2000: Emergency response transport forecasting using historical wind field pattern matching. *J. Appl. Meteor.,* **39,** 446–462.

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

——, ——, and M. Splitt, 2001: Applications of MesoWest to fire weather. Preprints, *Fourth Symp. on Fire and Forest Meteorology,* Reno, NV, Amer. Meteor. Soc., 88–91.

Dabberdt, W. F., and T. W. Schlatter, 1996: Research opportunities from emerging atmospheric observing and modeling capabilities. *Bull. Amer. Meteor. Soc.,* **77,** 305–323.

Dombrowsky, R., 2001: The COOP Network Modernization Initiative. *Automated Weather Stations for Application in Agriculture and Water Resources Management,* K. G. Hubbard, and M. V. K. Sivakumar, Eds., WMO/TD No. 1074, 183–186 pp.

duBois, P., 2000: *MySQL.* New Riders Publishing, 756 pp.

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

Fulker, D., S. Bates, and C. Jacobs, 1997: Unidata: A virtual community sharing resources via technological infrastructure. *Bull. Amer. Meteor. Soc.,* **78,** 457–468.

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

——, ——, and S. Conger, 2001: Application of road weather information systems in the western United States. Preprints, *17th Int. Conf. on Interactive Information and Processing Systems,* Albuquerque, NM, Amer. Meteor. Soc., 211–214.

Hubbard, K. G., and M. V. K. Sivakumar, Eds., 2001: *Automated Weather Stations for Application in Agriculture and Water Resources Management: Current Use and Future Perspectives.* WMO/TD No. 1074, 248 pp.

Jesuroga, R. T., C. Subramaniam, and P. A. Miller, 1998: The AWIPS Local Data Acquisition and Dissemination System. Preprints, *14th Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* Phoenix, AZ, Amer. Meteor. Soc., 368–370.

Meyer, S. J., and K. G. Hubbard, 1992: Nonfederal automated weather stations and networks in the United States and Canada: A preliminary survey. *Bull. Amer. Meteor. Soc.,* **73,** 449–457.

Miller, P. A., and S. G. Benjamin, 1992: A system for the hourly assimilation of surface observations in mountainous and flat terrain. *Mon. Wea. Rev.,* **120,** 2342–2359.

Nuss, W. A., D. E. Long, P. E. Mantey, A. Pang, E. C. Rosen, and J. Paduan, 1998: The Real-time Environmental Information Network and Analysis System (REINAS). *Naval Res. Rev.,* **50,** 24–30.

NWS Modernization Committee, 1998: *Future of the National Weather Service Cooperative Observer Network.* National Academy Press, 65 pp.

Paegle, J., R. Pielke, G. Dalu, W. Miller, J. Garratt, T Vukicevic, G. Berri, and M. Nicolini, 1990: Predictability of flows over complex terrain. *Atmospheric Processes over Complex Terrain, Meteor. Monogr.,* No. 45, Amer. Meteor. Soc., 285–298.

Horel, J., T. Potter, L. Dunn, W. J. Steenburgh, M. Eubank, M. Splitt, and D. J. Onton, 2002: Weather support to the 2002 Winter Olympic and Paralympic Games. *Bull. Amer. Meteor. Soc.,* **83**, 227–2400.

Schaefer, G. L., and R. F. Paetzold, 2001: SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network). *Automated Weather Stations for Application in Agriculture and Water Resources Management,* K. G. Hubbard and M. V. K. Sivakumar, Eds., WMO/TD No. 1074, 187–194 pp.

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

Shafer, M. A., C. A. Fiebrich, D. S. Arndt, S. E. Fredrickson, and T. W. Hughes, 2000: Quality assurance procedures in the Oklahoma mesonetwork. *J. Atmos. Oceanic Technol.,* **17,** 474–491.

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 Room 209, Salt Lake City, UT 84112-0110.]

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

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

——, ——, and B. G. White, 2001: Data collection, processing, and quality control for MesoWest. *Automated Weather Stations for Application in Agriculture and Water Resources Management,* K. G. Hubbard and M. V. K. Sivakumar, Eds., WMO/TD No. 1074, 211–218 pp.

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

Stiff, C. J., 1997: The Utah Mesonet. M.S. thesis, Dept. of Meteorology, University of Utah, 138 pp. [Available from Dept. of Meteorology, University of Utah, 145 South 1460 East Room 209, Salt Lake City, UT 84112-0110.]

Tucker, D. F., 1997: Surface mesonets of the western United States. *Bull. Amer. Meteor. Soc.,* **78,** 1485–1495.