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10.11 INGEST, INTEGRATION, QUALITY CONTROL, AND DISTRIBUTION OF OBSERVATIONS FROM STATE TRANSPORTATION DEPARTMENTS USING MADIS

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1. INTRODUCTION

In the last several years, there has been a tremendous expansion in the number of non-National Weather Service (NWS) automated weather stations, and groups of weather stations (commonly referred to as "mesonets"), operating across the United States. The expansion reflects the need by many organizations for frequent, densely spaced, real-time surface observations to aid in, for example, agricultural monitoring, energy and transportation planning, emergency management, fire management, and meteorological research and education. To fill these needs, many state and local government agencies, public utility companies, research organizations, educational institutes, and private industries have installed mesoscale meteorological observing systems. Among these systems are the Environmental Sensor Stations (ESS) installed and operated by state departments of transportation. It is estimated that more than 1300 ESS sites have been installed nationwide to provide observations of meteorological variables such as pressure, temperature, and winds, and road variables such as pavement temperature and road condition.

As the importance of mesonet observations becomes better established, new applications become apparent, and the costs of instrumentation and communications continue to decrease, the trend for the new installation and expansion of these networks is expected to continue. There is also growing recognition among the mesonet data providers that, although the installation of individual mesonets will likely remain fueled by the specific needs of the installing organizations, integration of the data from the various mesonets would benefit all. Integrating their observations with those from a collocated or neighboring mesonet, for example, can facilitate and extend the operations of an individual state transportation department by helping them better assess, track, and plan for an approaching winter storm.

Combining data from various sources, including public and private, local, and national, can also increase the accuracy of automated quality control (QC) and data monitoring procedures designed to identify individual erroneous observations, as well as longer-term hardware and communication failures. These procedures are generally based on comparing neighboring observations through the use of “spatial consistency” checks and are therefore greatly aided by an increased density in the observational database. Although many mesonet data providers do not have the budget or capability to implement such procedures themselves, sharing their observations with organizations that do, can result in substantially improved maintenance of their own instruments.

In addition, the integration of mesonet observations into the NWS database promises to improve nowcasting and forecast verification, and also has the potential to enable numerical weather prediction models to better capture local and mesoscale weather phenomena. Acquisition of mesonet data can dramatically increase the number and frequency of observations available to forecasters and enable them to “fill in the holes” in the NWS surface dataset (both spatially and temporally) and, as such, help them to better identify and predict mesoscale phenomena. Many of the automated mesonet reports, for example, are in remote locations with no trained spotters available to help the forecasters monitor developing weather conditions or severe conditions already underway. Integration of the mesonet observations into the NWS database also allows for their ingest into the analysis and data assimilation systems which produce the objective numerical weather prediction outputs heavily used in all areas of NWS weather forecasting. The NWS National Centers for Environmental Prediction (NCEP), in particular, stands to benefit from the national-scale integration of mesonet observations into the NWS database.

Despite these considerations, however, a true national-scale integration of mesonet observations has not yet been undertaken. To fill this need, NOAA's Forecast Systems Laboratory (FSL) has implemented a system to ingest, integrate, quality control, and distribute mesonet observations on a national scale through its Meteorological Assimilation Data Ingest System (MADIS) (Barth and Miller 2002). MADIS currently ingests over 5600 mesonet observations from across the country, and supplies the quality controlled observations to other meteorological organizations. Organizations already receiving MADIS data feeds include NCEP, the National Center for Atmospheric Research (NCAR), several private meteorological firms, and major universities. Although many of the mesonet observations are available without restrictions, all are proprietary to the data providers, and are subject to restrictions by those providers.

2. MADIS SYSTEM DESCRIPTION

2.1 *Overview*

The difficulties of combining the data from different mesonet sources has long posed a problem for the meteorological community. The characteristics of mesonets vary considerably from one to another. For example, the number of stations, types of variables reported, observation units, observation time stamps, reporting interval, and format of the observations all vary among different mesonets. In fact, the heterogeneity of the many different automated environmental networks in the U.S. was long thought to be a significant obstacle for operational appli-

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cation of the observations from those networks. The NWS, however, recognizing these observations as a cost-effective supplement to their own surface observation network, provided funding to FSL in 1997 to build and implement the Local Data Acquisition and Dissemination (LDAD) system (Jesuroga et al. 1998) as part of their Advanced Weather Interactive Processing System (AWIPS) installed in each NWS Weather Forecast Office (WFO). LDAD was designed to allow each individual WFO to ingest mesonet observations (in any format), combine the observations from different mesonet data providers, and integrate them with other AWIPS datasets by converting the observations to standard AWIPS observation units, time stamps, and formats.

Once integrated into the AWIPS database at each WFO, LDAD also provides for the quality control of the observations, as well as their display on forecaster workstations either as an individual dataset or in combination with other AWIPS datasets such as NWS surface observations, satellite observations, and model grids. The LDAD quality control programs (Miller et al. 1998, Miller and Barth 1999) take advantage of the AWIPS integration of the mesonet observations by first combining them with NWS surface observations before applying automated quality control checks. This allows each mesonet observation to be compared with the (well-maintained) NWS observations in their immediate area. Integration of the mesonet observations on AWIPS also allows for their ingest into analysis and data assimilation systems running on the AWIPS computers. Mesonet observations, for example, are automatically ingested into both the Local Analysis and Prediction System (LAPS)(Albers et al. 1996) and Mesoscale Analysis and Prediction System (MAPS) Surface Assimilation System (MSAS) (Miller and Barth 2002) programs implemented on AWIPS.

The implementation of LDAD on AWIPS was completed in 1999, and is now used by many NWS WFOs to ingest and process mesonet observations. FSL then began the project of implementing its LDAD technology to ingest, quality control, and integrate mesonet observations on a national scale through MADIS.

2.2 *Ingest*

Table 1 and Figure 1 show the mesonet observations processed by MADIS on 23 September 2002. Among these are ESS sites from ten state departments of transportation. Figure 2 shows the MADIS ESS sites. ESS observations from Utah, Montana, Wyoming, Nevada, Washington, Oregon, and Idaho are provided by the NOAA Cooperative Institute for Regional Prediction (CIRP) at the University of Utah, which provides “MesoWest” data from the Cooperative Mesonets in the Western U.S. (Horel et al. 2002). Figures 3a and b show the increase in surface stations by adding Iowa Department of Transportation (DOT) ESS sites to the NWS database. In this case, adding ESS sites more than doubles the surface observations available.

New stations are added continuously to the MADIS database as new mesonets are included, and new stations are added to the existing mesonets. A particularly large addition is expected in early 2003 as a result of an agreement between the NWS and AWS Convergence Technologies, Inc., which plans on sending over 4000 mesonet stations to FSL. See the MADIS web mesonet page (FSL 2003a) for an up-to-date list of the mesonets available. For a real-time display of MADIS surface observations see the FSL Surface Data Display (FSL 2003b).

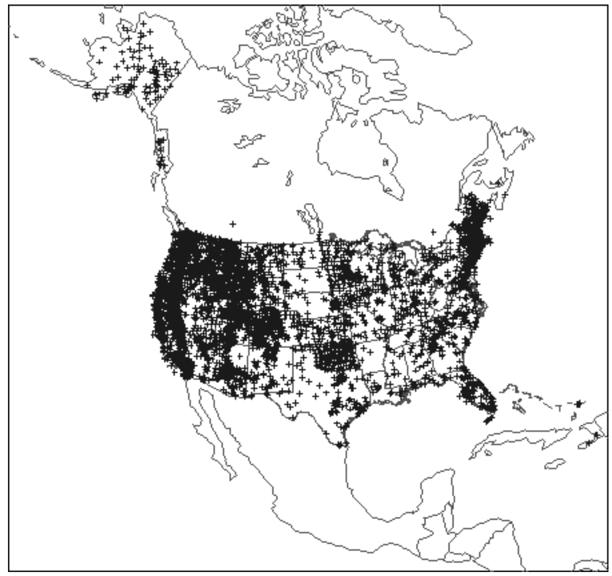

Figure 1. Station locations of the mesonet observations ingested into MADIS on 23 September 2002.

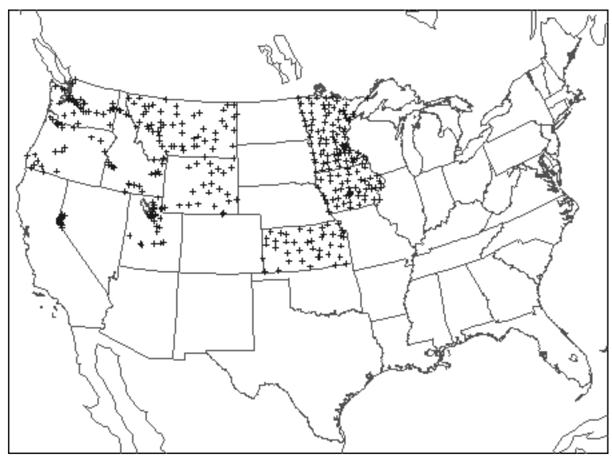

Figure 2. Station location of the ESS sites ingested into MADIS on 23 September 2002.

To ingest mesonet observations, MADIS requires real-time access to the observations, and also information on the number and location of the mesonet stations, as well as information on the type, frequency, and units of the observations reported. Access to the observations is generally accomplished via the internet, either through an ftp or web server. The input format required for the observations is a simple text, comma-separated-value (CSV) format. MADIS, however, also allows for the FSL implementation of “preprocessors” to convert mesonet observations from their native format to the required CSV format. This effectively allows MADIS to ingest observations in any format.

Mesonet	Provider ID	# of Sites	Coverage
Aberdeen Proving Grounds	APG	6	Maryland
Citizen Weather Observing Program	APRSWXNET	938	Global
AWS Convergence Technologies	AWS	100	New England
Anything Weather	AWX	65	CONUS
Florida Mesonet	FL-Meso	29	Florida
Ft Collins Utilities	FTCOLLINS	5	Colorado
Goodland,KS WFO Mesonet Stations	GLDNWS	13	CO/KS/NE
Gulf of ME Ocean Observing System	GoMOOS	9	Gulf of Maine
FSL GPS Meteorological	GPSMET	212	U.S.
Hydro-Met Automated Data System	HADS	54	New England
Iowa Department of Transportation	IADOT	50	Iowa
Boulder,CO WFO Mesonet Stations	INTERNET	9	Colorado
Kansas Department of Transportation	KSDOT	41	Kansas
Multi-Agency Profiler Surface	MAP	14	CONUS
Cooperative Mesonets in Western U.S.	MesoWest	1844	West CONUS
Minnesota Department of Transportation	MNDOT	92	Minnesota
Physical Ocean Real-Time System	NOS-PORTS	34	CONUS
Cooperative Observer Program	NWS-COOP	105	New England
Oklahoma Mesonet	OK-Meso	120	Oklahoma
Remote Automated Weather System	RAWS	1498	U.S.+Canada
CO SchoolNet	SCHLNET	61	Colorado
Denver Urban Drainage	UDFCD	19	Colorado
Weather for You	WXforYou	329	U.S.+Canada
	Total Current Stations	**5647**	

Table 1. Mesonet observations ingested into MADIS on 23 September 2002.

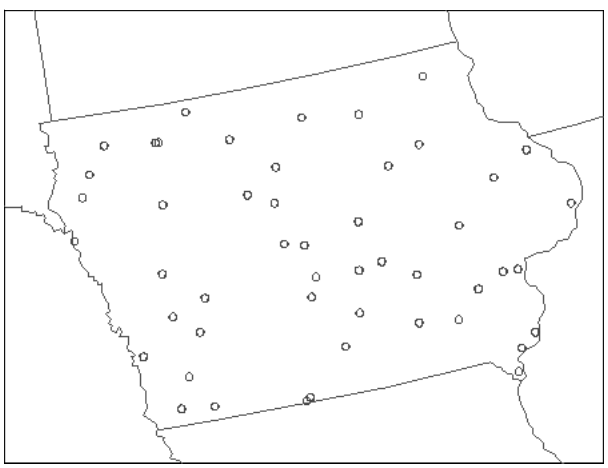

Figure 3a.

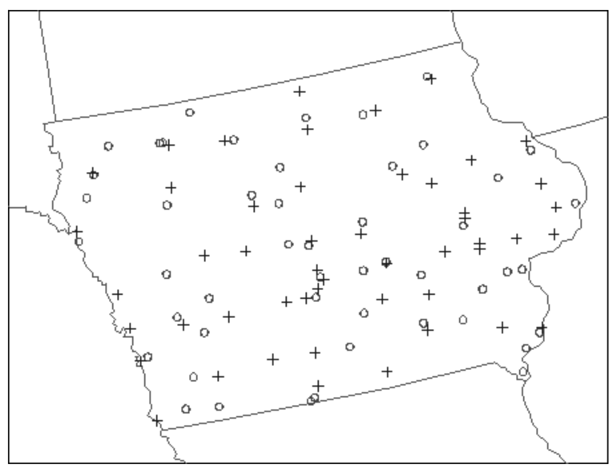

Figure 3b.

Figure 3a & b. MADIS surface stations within the state of Iowa on 23 September 2002 a) NWS surface stations and b) NWS surface stations plotted with Iowa Department of Transportation ESS sites. Circles indicate the NWS stations; crosses the ESS sites. Adding the ESS sites to the MADIS database more than doubles the surface observations available.

Since stations in some networks (such the National Interagency Fire Center's Remote Automated Weather System), are continually being added, moved, or discontinued, software has also been developed as part of MADIS to update mesonet station locations weekly, and broadcast these updates to users. The minimum metadata information required for each station is the station name, latitude, longitude, elevation, observation types and units. However, considerably more metadata information may be stored within the MADIS database if available.

Once ingested, MADIS combines the observations from different mesonet data providers, converts the observations to standard observation units and time stamps, and writes them to common mesonet data files.

2.3 *Quality Control*

MADIS also supplies mesonet data providers and users with QC and station monitoring information, both through the QC information supplied within the mesonet data files, and through monitoring statistics displayed on MADIS web pages.

Two types of automated QC checks, static and dynamic, are utilized by MADIS. The checks are, for the most part, provided by the NWS AWIPS Techniques Specification Package (TSP) 88-21-R2 NOAA/NWS (1994). The static QC checks are single-station, single-time checks which, as such, are unaware of the previous and current meteorological situation described by other observations. The MADIS checks falling into this category are validity checks, which compare observed values to TSP-specified tolerance limits, and internal consistency checks which enforce reasonable meteorological relationships among observations measured at a single station. The static checks are very useful, but can have difficulty with statistically reasonable but invalid data. To address these issues, and refine and enhance the QC information, MADIS also utilizes two types of dynamic QC checks: temporal consistency checks which restrict the temporal rate of change of each observation to a set of (other) TSP-specified tolerance limits, and spatial consistency checks which compare observed values to estimated values derived using observations at neighboring locations.

To improve their accuracy, the spatial consistency checks utilize all of the surface observations available in the MADIS database. These include observations from the mesonets shown in Table 1, as well as NWS land and ocean surface observations. The checks were originally developed as part of a surface assimilation system (Miller and Benjamin 1992) developed at FSL as part of MAPS. The surface system, known as MSAS, has been running at FSL since 1986, and at NCEP since 1989, where it is known as the Rapid Update Cycle (RUC) Surface Assimilation System (RSAS). QC results from the MSAS and RSAS systems have been used for several years by the Profiler Control Center to monitor the quality of the stations in the Profiler (Miller and Fozzard 1994) and GPS Meteorological (GPSMET) Surface Observing Systems, by the NWS to monitor the quality of stations in their Automated Surface Observing System (ASOS) network (Miller and Morone 1993), and by the NWS to monitor the quality of mesonet observations ingested into the AWIPS systems via LDAD.

The results of the QC checks are stored in the MADIS mesonet data files through a series of flags which indicate the results of each check. Single character "data descriptors" are also computed and stored to give an overall opinion of the quality of each observation by combining the information from the various QC checks.

MADIS also keeps statistics on the frequency and magnitude of the observational errors encountered for the NWS sea-level pressure (SLP), potential temperature, dewpoint, and wind observations associated with each surface station ingested. Hourly statistics are updated four times an hour to provide the total number of observations for each variable, the number of observations that failed the QC checks, the station names for the failed observations, and the error and threshold values for each of the failed observations. The error is defined as the difference between the observed value and the estimated QC value computed in the spatial consistency check. Daily, weekly, and monthly summaries of the percentage of failed observations, and the average and root mean square (rms) errors for individual stations and for all stations combined are also calculated and stored. Stations from different networks are kept statistically separate. Local mesonets, for example, are stratified by the Provider ID shown in Table 1; for example, "IADOT" for the Iowa DOT and "MNDOT" for the Minnesota DOT.

The QC statistics are reported on the MADIS web pages (FSL 2003c) in the form of hourly, daily, weekly, and monthly QC messages. Figure 4 shows the IADOT hourly message for 20 September 2002 at 1500 UTC.

IADOT HOURLY QUALITY CONTROL MESSAGE (PAGE 1 OF 1)

20-SEP-2002 1500 UTC	SLP (MB)	POT TEMP (DEG F)	DEW PNT (DEG F)	DD (DEG)	FF (KNTS)
TOTAL OBS	0	160	160	160	160
QST OBS	0	0	2	0	0
PERCENT QST	0.00	0.00	1.25	0.00	0.00
IA041			-9(7)		
IA041			-9(7)		

ERROR = ANALYSIS - OB. **OB. ERROR (ERROR THRESHOLD)**

Figure 4. Hourly QC message for Iowa Department of Transportation stations on 20 September 2002 at 1500 UTC. The station listed had two dewpoint temperature observations that were found bad by the MADIS QC checks.

Statistics for the total number of observations reported by the network ("TOTAL OBS"), the total number of observations that failed the QC checks ("QST OBS"), and the percentage of failed observations ("PERCENT QST") are given at the top of each page of the hourly message. "QST" represents "questionable" observations. Errors and spatial consistency check threshold values for the failed observations are listed in the columns. Figure 4 shows that the Iowa DOT station "IA041" reported two dewpoint temperature observations in the hour that failed the QC checks. All other observations reported passed the QC. Note that Iowa DOT stations do not report NWS sea-level pressure (SLP).

Stations listed in the hourly QC messages are either in error due to hardware or software failure, or are unrepresentative of the observation scale and, as such, are susceptible to diurnal, mesoscale, and terrain effects. To help distinguish between the two situations, daily, weekly, and monthly (4-week) summaries of the hourly QC messages are also provided. The summaries include the percentage of failed observations and the average error and rms error for individual stations and for all stations combined. Figure 5 shows part of the daily QC message for ASOS stations on 15 September 2002. As with the hourly messages, all stations in the network are used to calculate the statistics reported at the top of each page, but only stations that have failed the QC checks are listed in the individual sta-

ASOS DAILY QUALITY CONTROL MESSAGE (PAGE 3 OF 9)

15-SEP-2002 00-23 UTC	SLP (MB)	POT TEMP (DEG F)	DEW PNT (DEG F)	DD (DEG)	FF (KNTS)
TOTAL OBS	17820	41955	41753	40097	40097
QST OBS	261	878	754	567	569
PERCENT QST	1.46	2.09	1.81	1.41	1.42
KGEY		11/ 11/ 29			
KGUC		15/ 15/ 46			
KPWK			30/ 30/ 88		
KSHR		10/ 10/ 42			
KSPW			13/ 12/ 75		
KSUS			12/ 11/ 50		
KWRL		12/ 11/ 38			
KYIP	2/ -2/100				
MMML			19/-19/100		

ERROR = ANALYSIS - OB. RMS ERROR/MEAN ERROR/PERCENT QST

Figure 5. Daily QC message for NWS Automated Surface Observing System (ASOS) stations on 15 September 2002 from 0000 - 2300 UTC.

tistics. Stations with large percentages of failed observations are most likely experiencing hardware or software failures. For example, the QC message in Figure 5 shows KYIP (Ypsilanti, MI) as reporting bad SLP observations 100% of the time. The rms errors for the station are also identical to the absolute value of the mean error, an indication that a persistent bias exists in the observations. The fact that the error is negative further indicates that the observations are biased high. Based on this information, ASOS officials are currently investigating the SLP observations measured at KYIP. Similar QC statistics in the past have revealed serious sensor failures which, when repaired, caused the percentage of observations failing the QC checks to go back down to zero (Miller and Barth 1999).

See the MADIS web pages (FSL 2003c) for more information on MADIS QC techniques and outputs.

2.4 *Distribution*

FSL provides access to the MADIS database free of charge. Subscriptions to real-time datafeeds, as well as requests for archived data, can be obtained by filling out a data application form available from the MADIS web pages (FSL 2003c). These data are available via either ftp or using Unidata's Local Data Manager (LDM) software. In addition to mesonet observations, MADIS provides access to Meteorological Aviation Report (METAR), Surface Aviation Observation (SAO), and maritime surface observations, as well as, radiosonde, automated aircraft, multi-agency profiler, and NOAA Profiler Network upper-air observations.

To accommodate restrictions placed on their observations by data providers, MADIS supports four different distribution categories: 1) no distribution; 2) distribution to NOAA organizations only; 3) distribution to government, research, and educational organizations only; and 4) full distribution. When requested, different observations from a single data provider can also be placed in separate categories. For example, meteorological observations from the Minnesota DOT are currently in distribution category 4, while their road observations are in category 3.

Many different organizations currently access the MADIS database. Among these organizations are NCEP, NCAR, the Kennedy Space Flight Center, the University of Utah, Penn State University, the University Corporation for Atmospheric Research (UCAR), Mississippi State University, Embry-Riddle Aeronautical University, the National Ocean Service, the University of Alaska, the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, the University of North Dakota, Hampton University, the National Aeronautics and Space Adminstration (NASA) Marshall Space Flight Center, Texas A&M University, Denver Urban Drainage and Flood Control District, Oregon State University, the University of Hawaii, and several private meteorological organizations and companies.

MADIS also has the advantage of easy coordination with NWS WFOs. Since the LDAD system is the basis for mesonet ingest, integration, and QC both within MADIS and at the WFOs, observations, metadata, and "preprocessors" (necessary to convert mesonet observations from their native format to LDAD format) can be easily shared. As such, MADIS can easily implement mesonet ingest technology already developed at WFOs, and can also easily assist WFOs with ingesting mesonet observations that they are not yet familiar with. MADIS currently supplies several WFOs with mesonet observations, metadata, preprocessors, and instructions for LDAD ingest. Among the WFOs accessing mesonet data from MADIS are the Melbourne, FL and Miami, FL forecast offices (Blottman et al. 2002, Santos and Pfost 2002), as well as the Sterling, VA; Taunton, MA; Burlington, VT; Corpus Christi, TX; La Crosse, WI; Upton, NY; Grey, ME; Grand Forks, ND; and Bohemia, NY offices.

At NCAR, MADIS supports the Federal Highway Administration-supported winter road Maintenance Decision Support System (MDSS) (Mahoney and Myers 2003). At FSL, MADIS mesonet observations are used to test development versions of LAPS, MSAS, RSAS, and also the NCEP Rapid Update Cycle (RUC) data assimilation systems (Benjamin et al. 2002).

2.5 *Data Formats, Software Support, and Documentation*

MADIS datasets are stored in network Common Data Form (netCDF) files (Unidata 2003) which are compatible with AWIPS and AWIPS-based systems like FSL's FX-NET workstation (Madine et al. 2002). Users with access to such systems can copy the files directly to those systems for display. MADIS files are also compatible with LAPS analysis software available from the LAPS web pages (FSL 2003d), and with the assimilation software associated with the community-developed Weather Research and Forecasting (WRF) model (WRF 2003).

Users familiar with netCDF are free to write their own access software. For users not familiar with netCDF, software to easily read, interpret, and process the observation and QC information within the data files is provided via free download from the MADIS web pages (FSL 2003c). The software, referred to the MADIS Application Program Interface (API), completely hides the underlying netCDF format from the user, and also automatically handles many of the implementation details that arise in data ingest routines. The API, for example, makes it easy to pull only those observations from a particular mesonet from the integrated data files, or to read only those observations contained in a specified geographic region. Source code for the API software, and precompiled binary versions for many types of computer systems can be downloaded from the MADIS web site. Supported systems include Linux platforms and several different Unix and Windows platforms. Instructions are also provided for building the API from source code, if desired.

Utility programs for each MADIS dataset are also included in the API package. These programs can be used to read station information, observations and QC information for a single time, and then output them to a text file. The operation of each program is controlled by a text parameter file that allows the user to exercise all of the options included in the MADIS system. The programs can be run as needed to access MADIS files stored on the user's system, or can be run as time-scheduled tasks to get data keyed to the current time.

Extensive documentation for the MADIS system is available on the MADIS web pages (FSL 2003c). The documentation for each dataset includes details such as the extent of geographic coverage, the volume of data, and the real-time schedule for the data. Also included are lists of the reported variables (annotated with their units) processing and interpretation notes, and a list of the QC algorithms that have been applied. The QC documentation includes a detailed description of the algorithms used for each of the automated checks, and the details needed to understand the QC data structures that accompany the observations. API documentation includes installation instructions, tutorial programs, and sample data, as well as detailed descriptions of the API subroutines and examples of parameter files for use with the utility programs.

3. CONCLUSIONS

Through MADIS, the technical cability to ingest, integrate, quality control, and disseminate national-scale mesonet observations has been established. Much more work, however, remains. In particular, many more mesonet datasets remain to be accessed, and additional quality control techniques must be developed. MADIS, for example, currently ingests only about 400 of the estimated 1300 ESS sites, and no QC has yet been applied to the road variables reported by those stations. In addition, more research is needed in how best to effectively utilize mesonet observations. The latter is best accomplished, in our opinion, by providing the data to as wide an audience as possible.

In fact, while the use of mesonet data has been steadily increasing, some in the meteorological community are yet to be convinced of the value of these observations. Their main concern seems to be the variety of standards associated with the mesonet networks. While it is true that the siting and quality of these “complementary” observations may or may not meet established NWS observation standards, we believe that the availability, number, and temporal frequency of real-time mesonet observations outweigh the current lack of uniformity. Moreover, it is certainly clear that the value of these data for research and forecasting can only be thoroughly assessed if attempts are first made to gather and use the observations.

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